INTEGRATED LAND USE AND WATER USE IN WATER MANAGEMENT AREAS, WITH A VIEW ON FUTURE CLIMATE AND LAND USE CHANGES

Report to the

WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

BACKGROUND AND RATIONALE

Accurate quantification of the water balance in catchments is fundamentally important in the planning, management and allocation of water resources, especially in arid and semiarid regions. Some components of the water balance, such as evapotranspiration (ET), streamflow and groundwater recharge are directly related to land use. Although water uses by domestic population and industry are fairly well-documented, the quantification of water used by different land use types (e.g. agriculture and natural vegetation) is often problematic over large spatial and temporal scales. Ground-based (i.e. *in situ*) measurement and modelling methods are available, however they are resource-demanding and limited in space and time. Recent advances in remote sensing technologies have made the modelling of water balance components and the monitoring of water use at regional/national scales and at high frequencies possible.

Satellite-based technologies for the determination of water use from vegetated areas are becoming increasingly available in South Africa and several products have been tested. The common conclusion from previous studies is that more work is needed to improve the accuracy of satellite-derived ET products (in absolute terms), however these products are fairly reliable in identifying the status quo and relative changes in water use from different land uses, between different climatic regions, and over time. A dataset of ET was recently produced using the ETLook algorithm for 2014/15 at 250 m spatial resolution (Van Niekerk et al., 2018) and a time series of monthly ET was produced with MOD16 for the period 2000-2012 at ~1 km resolution (Jovanovic et al., 2015) for the whole country. This provided the opportunity for an unprecedented in-depth country-wide analysis of the linkages between land use and water use in order to add value to, process and interpret the wealth of information derived from satellite-based products. Therefore, this project proposed to determine water use from agricultural land, natural ecosystems and urban areas (domestic and industrial water use) using a combination of remote sensing and geographical information system (GIS) products in support of decisions taken at Water Management Areas (WMAs) level, as well as at local government level (provincial and municipality). In particular, the research proposed to provide a national analysis of integrated land use and water use in the context of future climate and land use changes.

OBJECTIVES AND AIMS

The overall aim of the project was to determine water use from agricultural land, natural ecosystems and urban areas (domestic and industrial water use) using a combination of remote sensing and geographical information system (GIS) products, and provide the information in the format of user-friendly summary sheets and guidelines for integrated land and water use at WMA/provincial/municipal level.

AIM 1

To identify and quantify the current relationships between water use and land use at national and WMA/provincial/municipal scales.

AIM 2

To relate historic (15 years or longer) changes in water use to climate variability and land use changes.

AIM 3

To develop scenarios of future land use and climate changes and model their likely effects on water use.

METHODOLOGY

The methodology and approach included different sources of spatial data that were processed and analysed to generate linkages between land use and water use for different spatial scales and over different time scales. Spatial data were collected from the following main sources of information:

- WARMS (Water Authorisation and Registration Management System) database obtained from the National Office of the Department of Water and Sanitation. WARMS data were primarily used to have an account of the registered volumes of water used by different sectors (agriculture, industrial, urban etc.).
- Land use/cover (National Land Cover NLC map for 2013/14). The NLC map was used to determine linkages between land use and ET calculated with algorithms based on satellite imagery (MOD16 and ETLook).
- ETLook ET countrywide data (250 m resolution) for the period August 2014 to July 2015 were used to provide an account of the current status of ET from different land uses (in particular agriculture and natural vegetation).
- MOD16 ET countrywide data for the period 2000-2012 at ~1 km resolution (Mu et al., 2011). This spatial time series of data was used to determine historic linkages between

ET, land use (in particular agriculture and natural vegetation) and climatic variables, and to project scenarios of water use as a function of changes in land use and climate.

- Biophysical spatial data were obtained: Digital Elevation Models (Shuttle Radar Topography Mission (SRTM) at 90 m and 30 m spatial resolution, Stellenbosch University Digital Elevation Model (SUDEM) at a 5 m spatial resolution); a coarse scale geological map (Council for Geoscience); average soil depth and soil clay content (Land Types database provided by the Agricultural Research Council (ARC)). The purpose of these data was to determine the main drivers of water use (Variable Importance List, VIL) through machine learning techniques, specifically Random Forest (RF) and Classification and Regression Tree Analysis (CART).
- Municipal water use data were obtained from the City of Cape and City of Mbombela to account for volumes of water that are distributed through the water supply system to residential/industrial urban areas.

Spatial data were analysed at three scales:

- National scale in order to give an overview of land use and water use countrywide.
- Provincial scale to account for geographic and climatic differences, e.g. ET of grassland in semi-arid climate is different from ET of grassland in humid areas.
- Two case study areas were identified during the inaugural Reference Group meeting of the project, namely the Inkomati catchment and the wider Cape Town area, in order to carry out a more detailed study, to capture site-specific linkages between land use and water use, and to demonstrate the potential of the approach combining remote sensing and GIS to support informed decision-making at specific sites.

Spatial data were also analysed for three time scales:

- The current status of land use and water use was analysed using primarily monthly ETLook data from August 2014 to July 2015 and the latest NLC map for 2013/14.
- Historic linkages between land use and water use were analysed using the MOD16 monthly ET time series (2000-2012), the NLC map for 2013/14 and the land cover derived from Landsat images for 1990. Areas of no change between 1990 and 2013/14 were extracted for each land cover type. These areas were used to determine mathematical relationships between water use and climatic variables (rainfall, air temperature and vapour pressure deficit, VPD) for each land cover. Rainfall data were obtained from the South African Weather Services and the long-term annual rainfall map of Schulze (2006). Air temperature and VPD were obtained from NASA/GMAO Modern Era Retrospective Analysis (MERRA). The derived mathematical relationships were in the form of multiple regression equations.

- The multiple regression equations were used to project linkages between land use and water use and to produce a user-friendly tool (web application) for calculating changes in water use as a function of projected land use and climatic changes.

RESULTS AND DISCUSSION

Current status of water and land use

Based on WARMS data (updated up to August 2016), the highest water use volumes are registered at national level for taking water and storing water. The third highest water use is disposal of wastewater. By water resource types, water abstraction takes place primarily from water schemes, rivers/streams, boreholes and dams, with negligible abstractions registered from spring/eye and wetlands. The highest water withdrawals per sector are from agricultural irrigation (64.8% of the total), water supply services (14.7%), urban industry (13.3%), mining (4.3%) and non-urban industry (1.6%). Total water uses in each region (province) depend mainly on the economic activities and associated land uses. High water withdrawals are associated with urban regions, whilst high water storages are associated with high rainfall areas. Large scale irrigation with wastewater is limited to Breede-Gouritz (0.15 billion m^3 a^{-1}) and Eastern Cape (0.07 billion m^3 a^{-1}). It appears that such practice is under-used in arid and semi-arid regions, especially Lower Orange, Lower Vaal or North West. Discharging wastewater is associated with urban areas and industry. Removing underground water is mainly associated with dewatering mines. In all regions, the largest water use is for agricultural irrigation, except Gauteng. Industrial water use is the highest in Gauteng, KwaZulu-Natal, Mpumalanga and the Western Cape, which are the most industrialized regions. A large portion of industrial water use in KwaZulu-Natal and Mpumalanga is from non-urban industries. Water use for mining is the highest in Mpumalanga, followed by North West, Lower Vaal, Gauteng and Free State. The reader should bear in mind that the data are a good reflection of the general trends in water use, however much updating of the WARMS database took place since August 2016 and an up-to-date version of the WARMS database can be obtained from the Department of Water and Sanitation (DWS).

Satellite-derived ET (MOD16 and ETLook) provided quantified values of consumptive water use from natural and cultivated land. Apart from waterbodies, land covers under natural forests, plantations, cultivated cane and perennial crops contribute the most to water use per unit area (mm a^{-1}) at national scale. In many regions, cultivated annual crops consume less water per unit area than grasslands and low shrublands. In absolute terms (Mm^{-3} a^{-1}), grasslands and low shrublands use the most water at national scale because they cover the largest areas. One should, however, interpret these values with caution as there are large variations attributed to climatic conditions because land covers are spread over diverse regions and they are heterogeneous. The resolution of the satellite-derived ET data may also play a significant role. The median of ET is often below the average, indicating that most of the data are spread in the lower range of ET with some extreme high values for each land cover. By province, Mpumalanga uses the most water per unit area, most likely because it receives high rainfall and is characterized by vegetation types and land uses that consume more water than other provinces. Conversely, the Northern Cape uses the least water per unit area. The Eastern Cape is the largest user of water (in $Mm^3\ a^{-1}$), even though it is relatively small (14%). The Limpopo and Free State are also large users of water. In terms of size, they are comparable with the Western Cape (10%), but consume more than double the water. Based on RF and CART analysis, land cover and mean annual rainfall have the most significant influence on ET. Average soil clay content ranks third by importance because it determines water available to plants for ET. In the wider Cape area, soil depth and elevation are stronger drivers of ET than rainfall.

The volume of water registered in WARMS for sector agriculture – irrigation is far less than the volume of water consumed from cultivated land, as estimated with satellite-derived ET countrywide. Irrigation is in most cases used to supplement rainfall and it therefore contributes only a fraction of ET. It should be considered that not all irrigators are registered countrywide, and especially that satellite coverage includes both irrigated and rainfed land. Satellite-derived products give the opportunity to perform large scale water use validation, bearing in mind there are uncertainties in the estimates. The volume of water evaporating from non-agricultural vegetated land outweighs by far the agricultural water consumption estimated with satellite products and the volume of water registered in WARMS for agriculture. The non-agricultural vegetated land includes woodlands/open bush, wetlands, thicket/dense bush, plantations, low shrublands, indigenous forests, grasslands and fynbos. There may be therefore a case for better planning of these lands in terms of water resources management, although this is influenced by many environmental, social and economic factors, and local conditions. At national level, the total volume of water that evaporates from urban areas is more than double the water supplied to industry and domestic users. This is particularly the case in high rainfall areas. There may, therefore, be a case for capturing some of the rainwater before it reaches the ground and evaporates in urban areas (e.g. rainwater harvesting).

MOD16 and ETLook compared relatively well in terms of spatial representation of ET, considering that the two products provide ET at different resolutions and use different models. Both ET estimation methods appear to be suitable to indicate areas of low ET and hotspots of high ET. They generally provide realistic and similar spatial patterns of ET, although in absolute terms ETLook appears to provide a wider range of values compared to MOD16 (higher ET in the high range and lower ET in the low range) due to the principles and mechanisms adopted in the algorithms. This was evident from the maximum and minimum values, although the standard deviations of ET were in the same range for both MOD16 and ETLook, for most land covers.

Historical water and land use

Historically, water use registrations in WARMS have been increasing steadily in South Africa, especially since bulk registrations took place in the years 2000-2003. A rise in WARMS registrations also occurred in the last two years when intensive updating of the WARMS database took place. Water use registrations for irrigation were the highest countrywide, followed by water supply services, urban industry and mining. Water use registrations for non-urban industry overtook the mining sector in the last four years. Irrigation was the highest water user in all provinces, except in Gauteng where urban industry was the highest user of water.

Amongst provinces, the Northern Cape showed the largest area of change by comparing NLC1990 and NLC2013/14, but the least in terms of percentage (24%). The largest percentage change was observed in Limpopo (48%). Amongst land covers, thicket/dense bush and woodland/open bush showed the largest increase in area nationally, whilst grasslands and low shrubland displayed the largest decrease. Urban areas increased, whilst a concern is the shrinking of wetlands and fynbos. More profitable perennial crops increased at the expense of annual crops.

Urban water use data from the City of Cape Town indicated a steady increase from 2005/06 to 2014/15, in particular due to the domestic water use increase. Total water use dropped in the last two years (197 $Mm^3\ a^{-1}$) since water restrictions have been introduced by the City of Cape Town to mitigate drought. In the wider Cape, indigenous forests, plantation woodlots and thicket dense bush recorded the highest ET and mines recorded the lowest per unit area. Shrubland fynbos and wetlands are somewhere in the mid-range of water consumption per unit area. In absolute terms, the largest water consumers in the wider Cape are shrubland fynbos, cultivated commercial annuals and cultivated perennials because they cover the largest areas. The total volume of water that evaporates from the Cape urban areas is less than half the water supplied to industry and domestic users. This is due to rainfall occurring predominantly in winter when ET is low, low ET during the dry summer, and large water demand. There may be therefore a case for re-use of some of the water in urban areas. By combining MOD16 ET data from natural vegetation and suburb water use data obtained from the City of Cape Town (2005-2012), it was interesting to observe that ET from natural vegetation ranged between ~2,500 and ~13,000 $m^3 ha^{-1} a^{-1}$, whereas water use in urban areas was between 0 and ~13,000 $m^3 ha^{-1} a^{-1}$. It appeared that MOD16 ET from natural vegetation varied depending on climatic conditions, in particular rainfall, whereas the water use in urban suburbs increased during this period.

In the Inkomati catchment, MOD16 ET water consumption ranged between ~2,200 and ~16,400 $m^3 ha^{-1} a^{-1}$ (2005-2012). High ET values per unit area occurred mainly along the escarpment (plantations/woodlots to the central west), in the Lowveld (cultivated perennial crops to the north) and in the southern parts of the catchment (sugarcane cultivation). The south-western (Highveld) and north-eastern (Kruger Park) parts of the catchment show generally low ET. The least recorded median ET was in mines. By far the highest water consumers in the Inkomati (expressed in $Mm^3 a^{-1}$) were thicket/dense bush, woodlands/open bush, grassland and plantations/woodlots, and the lowest were low shrublands and urban area. The total volume of water that evaporates from urban areas is nearly double the water supplied to industry and domestic users. There may be therefore a case for capturing some of the rain before evaporation occurs (e.g. rainwater harvesting).

Historic climatic data (rainfall, air temperature, vapour pressure deficit) and MOD16 ET displayed larger variability over large and heterogeneous areas, and smaller variability in small provinces with homogeneous landscapes. The highest correlations (R^2) of multiple regression functions (correlations between MOD16 ET and climatic variables) were generally obtained in wetter climates (e.g. KwaZulu-Natal) and associated land covers (e.g. indigenous forests), and the lowest in drier areas (e.g. Northern Cape) and associated land covers (e.g. shrubland fynbos). Rainfall (positive correlation) and vapour pressure deficit (negative correlation) are generally the two main climatic drivers of ET nationally.

The Inkomati covers a larger and more heterogeneous area compared to the wider Cape. As a result, historic rainfall, air temperature, vapour pressure deficit and MOD16 ET generally displayed larger variability than the Cape. Based on the multiple regression analysis, MOD16 ET was generally positively correlated to air temperature and negatively correlated to vapour pressure deficit both in the Cape and Inkomati. MOD16 ET was negatively correlated to rainfall in the Cape, and positively correlated in the Inkomati. In the Inkomati, the adjusted R^2 values ranged from 0.71 to 0.88 for the various land cover classes. In the wider Cape area, adjusted R^2 values were lower, between 0.10 and 0.47, due to drier climate and more heterogeneous land cover distribution compared to Inkomati.

Projections of water and land use

The multiple regression equations formulated from historic data of MOD16 ET and climatic variables (rainfall, air temperature and VPD) were built into the Water Use Scenario Builder (Water USB), a user-friendly web application for estimating changes in water use (mm and $Mm^3\ a^{-1}$) as a result of changes in land use and climate. The Water USB developed in this project can be used by provinces and other local government organs and institutions in order to plan land and water use, as demonstrated for the two case study sites, wider Cape and Inkomati. It is envisaged that numerous applications of this tool are possible. The tool was developed primarily in response to the needs of the two case study areas voiced by the City of Cape and the Inkomati-Usuthu Catchment Management Agency during a stakeholder workshop in November 2017. For example, the tool can facilitate the City of Cape Town in projecting and planning water use changes as a result of densification and population increase, expansion of urban edge, formalization of informal settlements, increase in agricultural land use, behavioural changes of the population and changes in legislation. In the Inkomati-Usuthu Water Management Area, the tool can facilitate projecting and planning water use changes as a result of immigration and population changes, formalization of informal settlements, mineral exploration and mining, as well as changes in crop types (e.g. establishment of tree plantations). The main target users are therefore water managers and planners in the two case study site areas (Municipalities, Catchment Management Agencies, Department of Water and Sanitation). The Water USB enables users to answer practical questions on the relation between land use and water use, such as:

- How will ET change with increased or decreased air temperature and humidity (vapour pressure deficit)?
- How will ET change with increased or decreased rainfall?
- How will water use change in a region if a certain land cover is expanded/reduced?
- What will the effect of climate variability be on water use?
- How can water allocation be planned for different land covers in future?
- Which land uses will provide leverage to manage water in catchments?
- What are the recommended land uses for conserving water in future?

The multiple regression equations used in the Water USB tool are specific for the land cover at the two case study sites. However, the tool can be expanded fairly easily to other geographical regions (e.g. all nine South African provinces), because the background data already exist and they have been processed to generate multiple regression equations for each land cover in each province. It is recommended that the Water USB be run by the research team using plausible scenarios designed by target users, in order to facilitate the interpretation of data and results.

The information processed and interpreted during the course of the project was synthesized and packaged in the form of mini-posters. The mini-posters, including graphical and tabular summaries, present an overview of the state of land and water use, as well as guidelines and recommendations for integrated land and water use. Because the state of land and water use is highly location-specific, mini-posters were produced for each province, two case study sites (Inkomati and wider Cape area) and the national scale.

CONCLUSIONS

This project succeeded in providing best estimates of current and historic land and water uses and their linkages at different spatial scales (national, provincial and case studies), by using primary sources of nationwide data such as WARMS, land cover maps and satellite-derived ET (MOD16 and ETLook). Multiple regression formulae were generated from historic land cover data, MOD16 and climatic variables per province and per land cover/use group. The multiple regression formulae were used to inform the Water Use Scenario Builder, a user-friendly web application for calculating changes in water use (mm and $Mm^3\ a^{-1}$) as a result of changes in land use and climate.

To our knowledge, research integrating land and water use using remote sensing data has not been done previously at this scale. Although the study was not meant to determine all components of the water balance and available water (e.g. runoff, surface water storage or groundwater storage), it is envisaged that the results will be invaluable to inform systematic water resource assessment, management and planning. The results are also essential to understand the spatial and temporal variability of water use as a consequence of different land uses. Interpretation of the linkages between land use and water use provides support to policy and decision-making on future land use planning, allocation and management, which are fundamental activities to secure sustainable development.

The data processed and results obtained in this project were overwhelming given the volume of spatial data at national scale, and the most salient outcomes are difficult to outline and single out, as the relevant outcomes depend on specific applications and users. The information was provided per Water Management Area (WMA), province or municipality (where applicable) and it is envisaged to be of major interest to water managers in WMAs and local government (provincial and municipal level). The guidelines and recommendations can potentially answer a number of practical site-specific questions for water managers, with a view on future climate and integrated land and water management. The outputs produced in this project were not meant to answer all questions that water managers may have at specific sites due to the large scale of research (countrywide). However, this project report provides and demonstrates a glimpse of the capabilities of combining remote sensing and GIS to solve water resources management problems.

RECOMMENDATIONS FOR FUTURE RESEARCH

Some general recommendations are given below based on the findings of the project:

- The general land use types and population density, taking into account the expected growth rates, are likely to remain more or less the same across the country in the short term. However, increased industrial development and urbanization are likely to impact on industrial water use, scheme or water supply water sectors as well as increase marginal land. Such changes need to be factored in future water use planning and allocation.
- Agriculture is the dominant user of water resources in 11 out of the 12 areas for which data were analysed, with the exception of Gauteng. Encouraging or incentivizing more efficient farming practices in future may reduce the volumes used in agriculture and hence reduce the burden on water resources.
- The current trend of water restrictions and water shedding in certain provinces is partly due to improper planning of water resources and reduced rainfall events. The WARMS data show that there is an existing pool of wastewater streams which is in essence an available water-reuse source for South Africa that could potentially reduce the burden on water resources.
- The limited use of boreholes countrywide leaves scope for increased groundwater use (or conjunctive surface and groundwater use) in nearly all provinces. While there may be a large number of unregistered users falling into this category, the validation and verification process countrywide may yield a better understanding of the extent of this resource’s use.
- Conservation efforts need to be strengthened to prevent loss of biodiversity countrywide, in particular shrubland fynbos (Eastern Cape, Northern Cape, Western Cape), wetlands and indigenous vegetation, and to reduce desertification (Free State, Northern Cape, North-West).
- Non-commercial and non-conservation land can be traded off to reduce bush encroachment and water use.

The objectives and outcomes of this project should be linked with government priorities as per the National Development Plan – 2030 (NDP):

- Analysis of water requirements in respect of water already allocated versus the determination of the reserve and actual water use in the area under the jurisdiction of water management institutions (irrigation boards and water user associations) to allow allocation to subsistence and smallholder producers including determination of the available source of water (dams, river, groundwater etc.) in the water management areas.
- Determination of water consumption by different forestry species.
- A number of specific sites require urgent attention for detailed investigation, such as the City of Tshwane where water demand growth is very high.

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LIST OF SYMBOLS AND ABBREVIATIONS

a	Coefficient of the multiple regression analysis
AIC	Akaike's Information Criterion in the Auto-Regressive and Moving Average analysis
AoNC	Area of No Change
ARC	Agricultural Research Council
ARIMA	Auto-Regressive and Moving Average analysis
b	Coefficient of the multiple regression analysis
BIC	Bayesian Information Criterion in the Auto-Regressive and Moving Average analysis
BNV	Bare none vegetated land cover group
c	Coefficient of the multiple regression analysis
CART	Classification and Regression Tree Analysis
CBD	Central Business District
CCA	Cultivated commercial annuals land cover group
CCN	Cultivated cane land cover group
CPE	Cultivated perennial land cover group
CSU	Cultivated subsistence land cover group
d	Number of differences term in the Auto-Regressive and Moving Average analysis
DST	Department of Science and Technology
DWS	Department of Water and Sanitation
ET	Evapotranspiration (mm)
ETLook	Algorithm making use of satellite imagery to calculate evapotranspiration (mm)
GIS	Geographic Information System
GMAO	Global Modelling and Assimilation Office
GRS	Grassland land cover group
INF	Indigenous forest land cover group
LSB	Low shrubland land cover group
MCDSS	Multi-Criteria Decision Support System
MERRA	Modern Era Retrospective Analysis of NASA/GMAO
MMD	Monthly Mean Difference
MNS	Mines land cover group
MOD16	Algorithm making use of MODIS satellite imagery to calculate evapotranspiration (mm)

MODIS	Moderate Resolution Imaging Spectroradiometer located on NASA's Terra and Aqua satellites
MRA	Multiple Regression Analysis
MTEF	Medium Term Expenditure Framework
NASA	National American Space Agency
NDP	National Development Plan
NLC	National Land Cover
p	Auto-regressive term in the Auto-Regressive and Moving Average analysis
PHA	Philippi Horticultural Association
PO	Process of Order in the Auto-Regressive and Moving Average analysis
PWD	Plantations/Woodlots land cover group
q	Moving average term in the Auto-Regressive and Moving Average analysis
R^2	Coefficient of determination
RF	Random Forest analysis
RMSE	Root Mean Square Error
SAWS	South African Weather Services
ScMM	monthly mean rainfall raster obtained from Schulze (2006) long-term monthly rainfall data (mm $month^{-1}$)
SEBAL	Surface Energy Balance Algorithm for Land making use of satellite imagery to calculate evapotranspiration (mm)
SEBS	Surface Energy Balance System algorithm making use of satellite imagery to calculate evapotranspiration (mm)
SFRA	Stream flow reduction activities
SHF	Shrubland fynbos land cover group
SRTM	Shuttle Radar Topography Mission (SRTM) for digital elevation model at 90 m and 30 m spatial resolution
T	Air temperature (°C)
TDB	Thicket/Dense bush land cover group
UCM	Urban commercial land cover group
UIF	Urban informal land cover group
UIN	Urban industrial land cover group
UOT	Urban others land cover group
URS	Urban residential land cover group
USR	Urban sport and recreation land cover group
VIL	Variable Importance List
VPD	Vapour Pressure Deficit (kPa)

WARMS	Water Authorisation and Registration Management System database of the Department of Water and Sanitation
Water USB	Water Use Scenario Builder
WMA	Water Management Area
WOB	Woodland/Open bush land cover group
WSUD	Water Sensitive Urban Design
WTB	Waterbodies land cover group
WTL	Wetlands land cover group

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1 INTRODUCTION

1.1 Background and rationale

It is widely recognized that accurate quantification of the water balance in catchments is fundamentally important in the planning, management and allocation of water resources, especially in arid and semiarid regions. It is also well-known that some components of the water balance, such as evapotranspiration (ET) (Jovanovic et al., 2011), streamflow (Bugan et al., 2012) and groundwater recharge (Jovanovic et al., 2013) are directly related to land uses. Although water uses by domestic population and industry are fairly well-documented, the quantification of water used by different land use types (e.g. agriculture and natural vegetation) is often problematic over large spatial and temporal scales. Ground-based (i.e. *in situ*) measurement and modelling methods are available (Jovanovic et al., 2018), however they are resource-demanding and limited in space and time. Recent advances in remote sensing technologies have made the modelling of water balance components and the monitoring of water use at regional/national scales and at high frequencies possible.

Satellite-based technologies for the determination of water use from vegetated areas are becoming popular in South Africa and several products have been tested. Examples include the Surface Energy Balance Algorithm for Land – SEBAL (Meijninger and Jarmain, 2014), Surface Energy Balance System – SEBS (Gibson et al., 2014) and the Moderate Resolution Imaging Spectrometer based – MOD16 (Jovanovic et al., 2015). The common conclusion from previous studies carried out in South Africa is that more work is needed to improve the accuracy of satellite-derived ET products (in absolute terms), however these products are fairly reliable in identifying the status quo and relative changes in water use from different land uses, between different climatic regions, and over time.

Satellite-based products that can be used to estimate land surface processes are becoming increasingly available. A dataset of ET was recently produced using the ETLook algorithm for 2014/15 at 250 m spatial resolution (Van Niekerk et al., 2018) and a time series of monthly ET was produced with MOD16 for the period 2000-2012 at ~1 km resolution (Jovanovic et al., 2015) for the whole country. This provided the opportunity for an unprecedented in-depth country-wide analysis of the linkages between land use and water use in order to add value to, process and interpret the wealth of information derived from satellite-based products. Therefore, this project proposed to determine water use from agricultural land, natural ecosystems and urban areas (domestic and industrial water use) using a combination of remote sensing and geographical information system (GIS) products in support of decisions taken at Water Management Areas (WMAs) level, as well as at local government level (provincial and municipality). In particular, the research proposed to provide a national analysis of integrated land use and water use in the context of future climate and land use changes. The study responded to the following research questions:

- What is the current status of land and water use in South Africa?
- What are the historic changes in water use (in the last 15 years) and how can they be linked to climatic variability and major changes in land use?
- What are the expected future water uses as determined by plausible land use change and adaptation scenarios?

1.2 Aims and objectives

The overall aim of the project was to determine water use from agricultural land, natural ecosystems and urban areas (domestic and industrial water use) using a combination of remote sensing and geographical information system (GIS) products, and provide the information in the format of user-friendly summary sheets and guidelines for integrated land and water use at WMA/provincial/municipal level.

The specific objectives of the project were:

1) To identify and quantify the current relationships between water use and land use at national and WMA/provincial/municipal scales.
2) To relate historic (15 years or longer) changes in water use to climate variability and land use changes.
3) To develop scenarios of future land use and climate changes and model their likely effects on water use.

1.3 Methodology and approach

The methodology and approach included different sources of spatial data that were processed and analysed to generate linkages between land use and water use for different spatial scales and over different time scales. Spatial data were collected from the following main sources of information:

- WARMS (Water Authorisation and Registration Management System) database obtained from the National Office of the Department of Water and Sanitation. WARMS data were primarily used to have an account of the registered volumes of water used by different sectors (agriculture, industrial, urban etc.).

- Land use/cover (National Land Cover NLC map for 2013/14). The NLC map was used to determine linkages between land use and ET calculated with algorithms based on satellite imagery (MOD16 and ETLook).
- ETLook ET countrywide data (250 m resolution) for the period August 2014 to July 2015 were used to provide an account of the current status of ET from different land uses (in particular agriculture and natural vegetation).
- MOD16 ET countrywide data for the period 2000-2012 at ~1 km resolution (Mu et al., 2011). This spatial time series of data was used to determine historic linkages between ET, land use (in particular agriculture and natural vegetation) and climatic variables, and to project scenarios of water use as a function of changes in land use and climate.

Spatial data were analysed at three scales:

- National scale in order to give an overview of land use and water use countrywide.
- Provincial scale to account for geographic and climatic differences, e.g. ET of grassland in semi-arid climate is different from ET of grassland in humid areas.
- Two case study areas were identified during the inaugural Reference Group meeting of the project, namely the Inkomati catchment and the wider Cape Town area, in order to carry out a more detailed study, to capture site-specific linkages between land use and water use, and to demonstrate the potential of the approach combining remote sensing and GIS to support informed decision-making at specific sites.

Spatial data were also analysed for three time scales:

- The current status of land use and water use was analysed using primarily monthly ETLook data from August 2014 to July 2015 and the latest NLC map for 2013/14.
- Historic linkages between land use and water use were analysed using the MOD16 monthly ET time series (2000-2012), the NLC map for 2013/14 and the land cover derived from Landsat images for 1990. Areas of no change between 1990 and 2013/14 were extracted for each land cover type. These areas were used to determine mathematical relationships between water use and climatic variables (rainfall, air temperature and vapour pressure deficit, VPD) for each land cover. Rainfall data were obtained from the South African Weather Services. Air temperature and VPD were obtained from NASA/GMAO Modern Era Retrospective Analysis (MERRA). The derived mathematical relationships were in the form of multiple regression equations.

- The multiple regression equations were used to project linkages between land use and water use and to produce a user-friendly tool (web application) for calculating changes in water use as a function of projected land use and climatic changes.

The main outputs of the project are:

- A Water Use Scenario Builder (web application) for calculating changes in water use as a function of projected land use and climatic changes for two case study sites (Inkomati catchment and wider Cape Town area).
- 12 mini-posters (national, 9 provinces and two case study sites) that summarize the data processed during the course of the project in tabular and graphical formats, and provide guidelines and recommendations for water planning, allocation and management.

The focus of data processing was on relating the water use to specific land uses and determining the statistical ranges of water use. To our knowledge, research integrating land and water use using remote sensing data has not been done previously at national scale. Although the study was not meant to determine all components of the water balance and available water (e.g. runoff, surface water storage or groundwater storage), it is envisaged that the results will be invaluable to inform systematic water resource assessment, management and planning. The results are also essential to understand the spatial and temporal variability of water use as a consequence of different land uses. Interpretation of the linkages between land use and water use provides support to policy and decision-making on future land use planning, allocation and management, which are fundamental activities to secure sustainable development. The information is provided per Water Management Area (WMA), province or municipality (where applicable) and it is envisaged to be of major interest to water managers in WMAs and local government (provincial and municipal level). The guidelines and recommendations can potentially answer a number of practical site-specific questions for water managers, with a view on future climate and integrated land and water management. The outputs produced in this project were not meant to answer all questions that water managers may have at specific sites due to the large scale of research (countrywide). However, this project report provides and demonstrates a glimpse of the capabilities of combining remote sensing and GIS to solve water resources management problems.

1.4 Report structure

This final report is not meant to present all data generated and processed during the course of the project because these are available in the Deliverables of the project. A very large amount of data from databases and satellite imagery has been generated and processed for the whole country and there are innumerable ways to present and discuss these data. The final report is meant to summarize the most relevant and general information to give a glimpse of the countless opportunities that satellite-derived information can provide in support of land and water use planning and management. It is envisaged that more detailed studies can be conducted that can inform decision-makers in solving site-specific problems.

The final report is structured in the following chapters:

Chapter 1 is the introductory chapter that describes the rationale behind the research, the aims and the approach.

Chapter 2 overviews the material and methods used, the data acquisition processes and data preparation.

Chapter 3 analyses the current status of water and land use by quantifying relationships at different geographic scales (national, WMA, provincial and case studies).

Chapter 4 analyses the historic trends in water use, land use and climatic variables, and it quantifies the relationships at different geographic scales (national, WMA, provincial and case studies) with the aid of statistics and multiple regressions.

These relationships derived from historic data are then used to project water use for different scenarios of land use and climatic changes. This is described in Chapter 5. A web application tool – the Water Use Scenario Builder – is described that can be used to project water use as a function of land and climate changes for two case study sites (Inkomati and wider Cape Town area).

The wealth of spatial data and information was used to draw some conclusions (Chapter 6) and recommendations (Chapter 7) in the format of mini-posters that summarize the outcomes of data processing for South Africa, per province and for two case study sites (Inkomati and wider Cape Town area).

Finally, capacity building actions (Chapter 8), references (Chapter 9) and data in Appendixes are presented.

2 METHODS AND MATERIAL

2.1 National, provincial and case study sites

Countrywide spatial data of water and land use were analysed at national and provincial scales (Figure 2.1). Given the variety of climates, land uses and environmental conditions across the country and provinces, two additional case study sites were analysed in order to demonstrate applications of the approach and methods to site-specific problems. Table 2.1 and Figure 2.2 summarize the quaternary catchments included in the case study investigation in the Cape and Inkomati areas. The wider Cape case study area spans from the City of Cape Town and Cape Peninsula to include the quaternary catchments that feed the main sources of the water supply system to the city (Theewaterskloof, Steenbras, Berg River, Wemmershoek and Voëlvlei dams). The Inkomati case study area is part of the Inkomati-Usuthu Water Management Area.

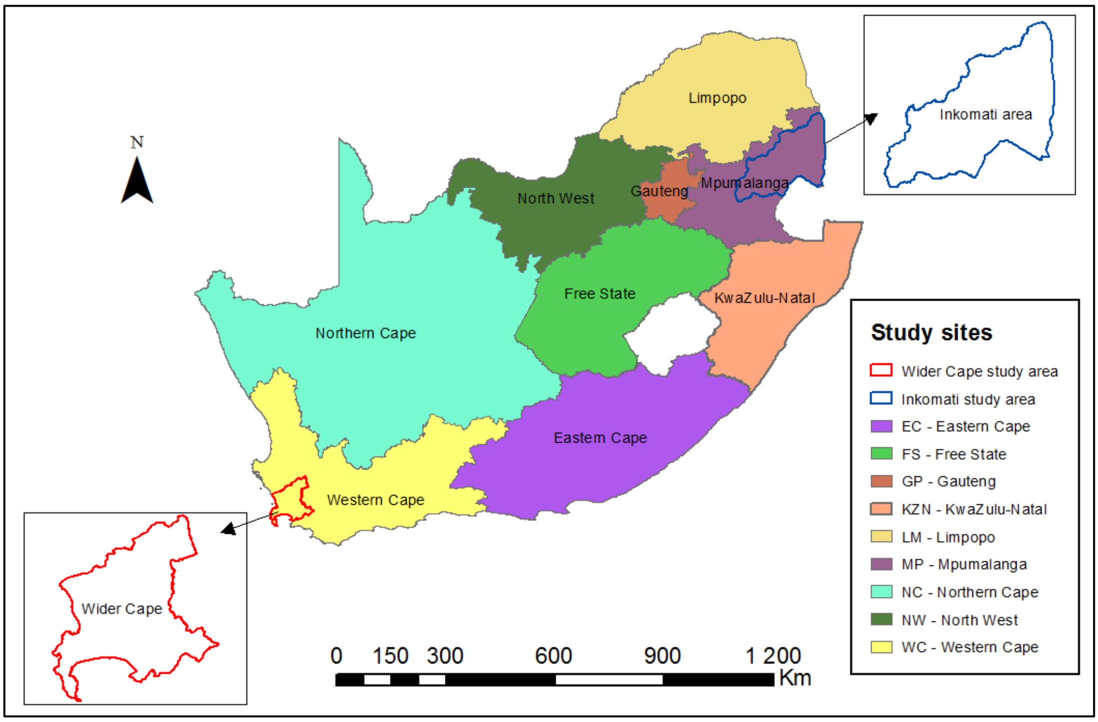


Figure 2.1

Spatial scales of water and land use investigation: national, provincial and case study sites (Inkomati and wider Cape area).

TABLE 2.1

Quaternary catchments considered in the WARMS analysis for the two case study sites (wider Cape area and Inkomati catchment).

Study site	Water Management Area	Quaternary catchments
Wider Cape area	Berg/Olifants	G21B; G21C; G21D; G21E; G21F G10A; G10B; G10C; G10D; G10E; G10F G22A; G22B; G22C; G22D; G22E; G22F; G22G; G22H; G22J; G22K G40A; G40C
	Breede/Gouritz	H60A; H60B; H60C
Inkomati catchment	Inkomati/Usuthu	X11A; X11B; X11C; X11D; X11E; X11F; X11G; X11H; X11J; X11K X12A; X12B; X12C; X12D; X12E; X12F; X12G; X12H; X12J; X12K X13A; X13H; X13J; X13K; H13L X14A; X14B; X14D; X14E; X14F; X14G; X14H X21A; X21B; X21C; X21D; X21E; X21F; X21G; X21H; X21J; X21K X22A; X22B; X22C; X22D; X22E; X22F; X22G; X22H; X22J; X22K X23A; X23B; X23C; X23D; X23E; X23F; X23G; X23H X24A; X24B; X24C; X24D; X24E; X24F; X24G; X24H X31A; X31B; X31C; X31D; X31E; X31F; X31G; X31H; X31J; X31K; X31L; X31M X32A; X32B; X32C; X32D; X32E; X32F; X32G; X32H; X32J X33A; X33B; X33C; X33D X40A; X40B; X40C; X40D

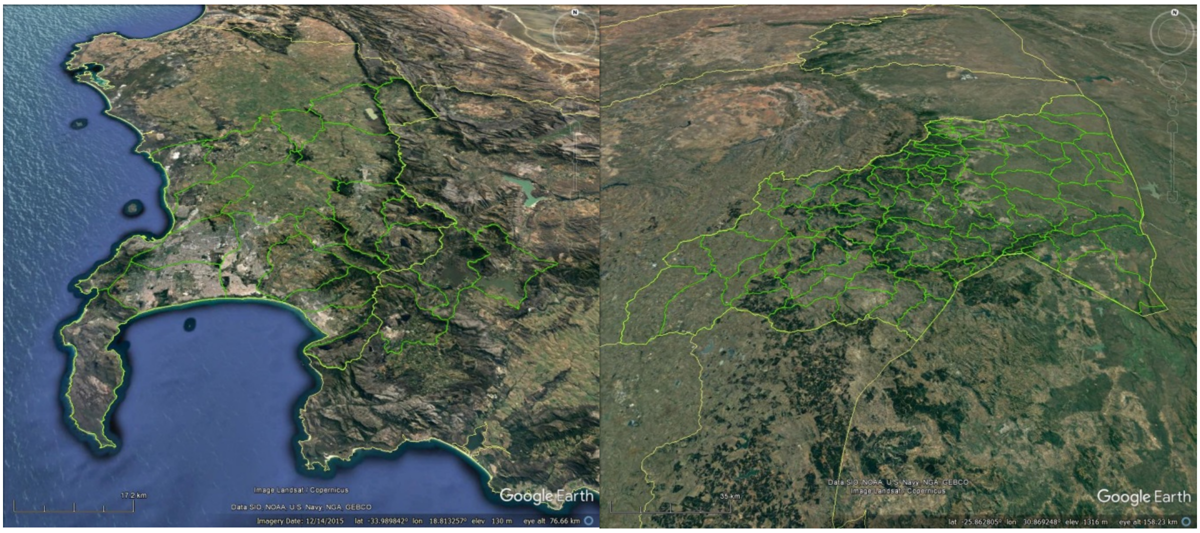


Figure 2.2

Google Earth view of the quaternary catchments considered for the wider Cape (left) and for the Inkomati (right) case studies. Water Management Areas are delineated in yellow, whilst quaternary catchments are delineated in green.

2.2 Data acquisition

2.2.1 Biophysical data

Digital elevation data

Elevation derivatives, such as slope gradient, are known to influence water availability and may consequently also determine water use at local scales. Relevant digital elevation data included those of the Shuttle Radar Topography Mission (SRTM) at 90 m and 30 m spatial resolution (Figure 2.3), which are freely available, and the Stellenbosch University Digital Elevation Model (SUDEM) at a 5 m spatial resolution (which is available for use in this project). Figure 2.4 shows an example of slope gradient map derived from the SRTM DEM.

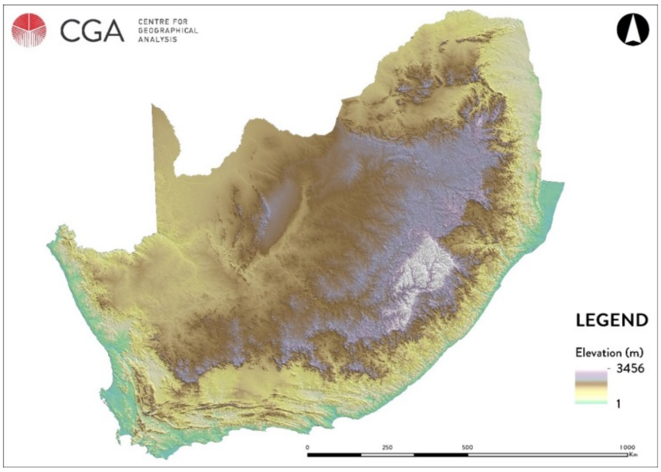


Figure 2.3

Shuttle Radar Topography Mission (SRTM) 30 m digital elevation model for South Africa.

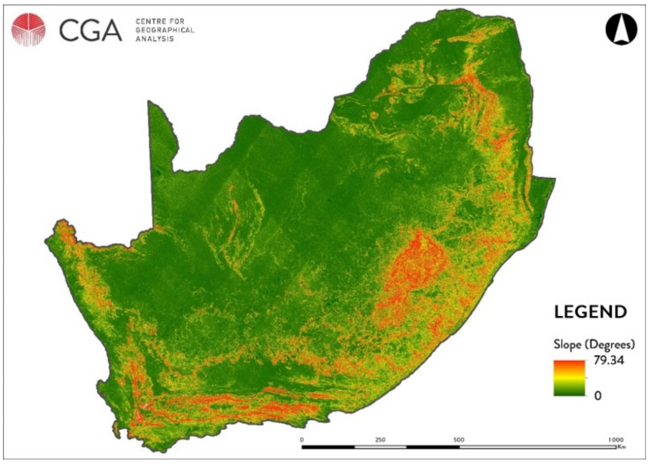


Figure 2.4

Slope gradient as generated from the 30 m Shuttle Radar Topography Mission (SRTM) digital elevation model for South Africa.

Geological data

Geology is known to be a key factor in groundwater availability and it was consequently considered in this study. A coarse scale geological map generated by the Council for Geoscience in 1997 was used for this purpose. The map includes major geological groups (Figure 2.5).

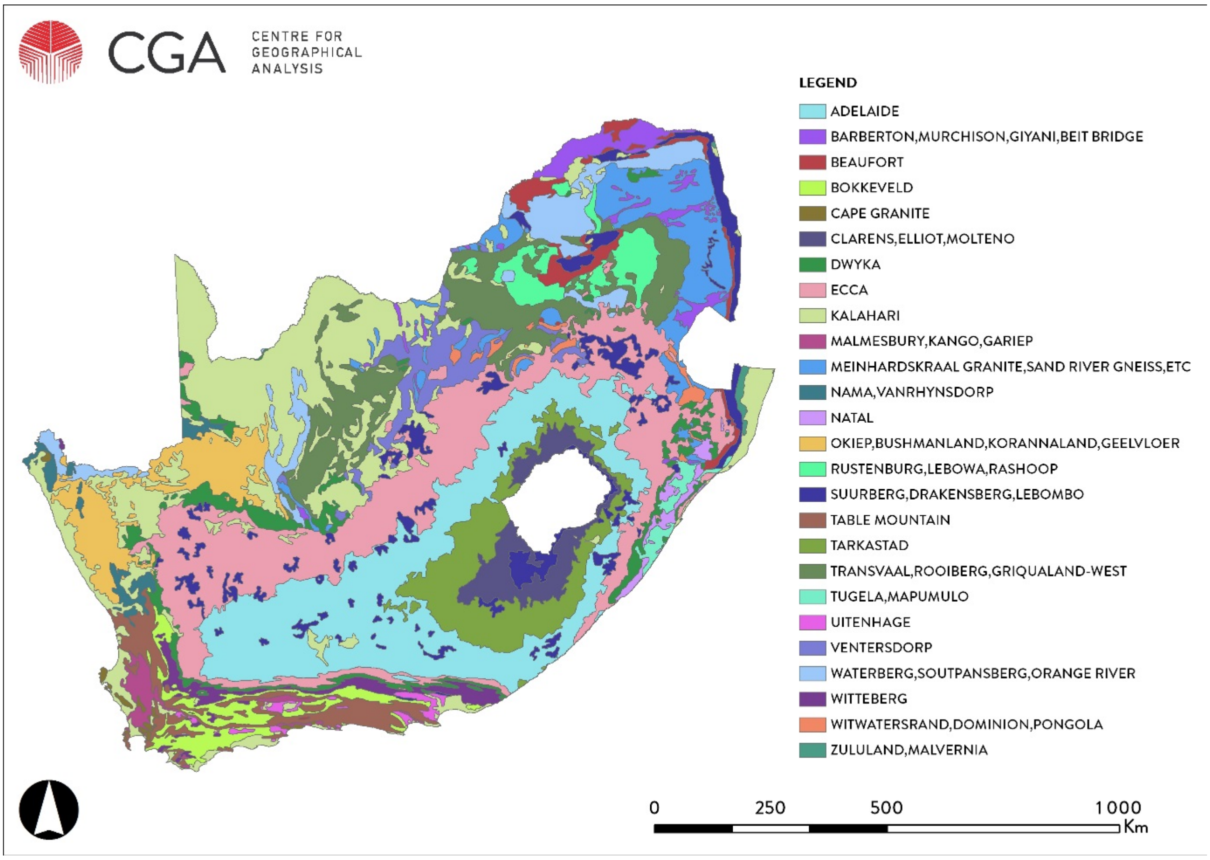


Figure 2.5

Generalized geology map for South Africa (source: Council for Geoscience).

Soil data

Soil properties determine the rate at which surface water permeates the earth’s surface, and also how long water remains available for use by vegetation. Average soil depth (Figure 2.6) and soil clay content (Figure 2.7) information were extracted from the Land Types database provided by the Agricultural Research Council (ARC) (Van Niekerk, 2008).

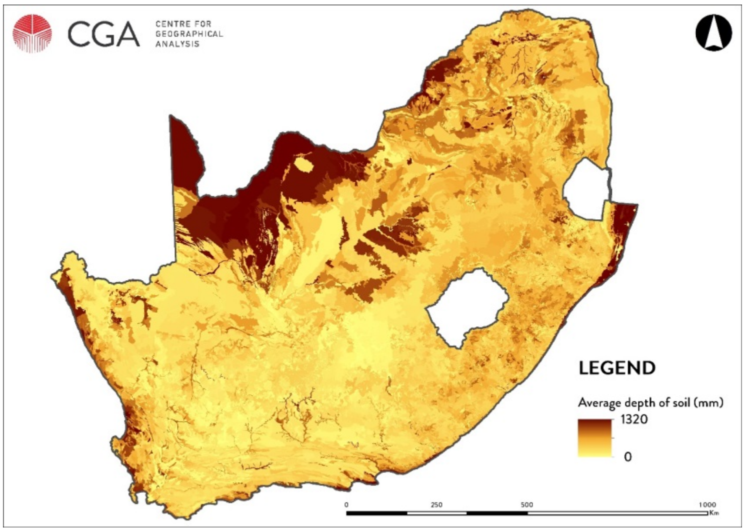


Figure 2.6

Average soil depth for South Africa (source: Land Types database provided by the Agricultural Research Council (ARC); Van Niekerk, 2008).

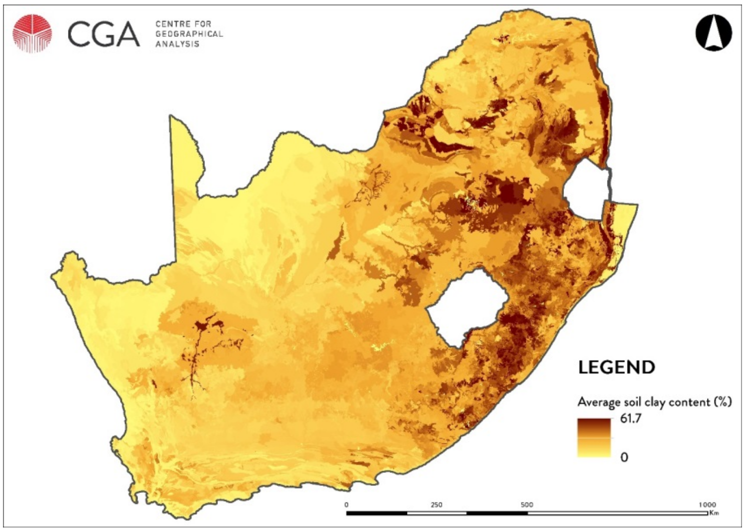


Figure 2.7

Soil clay content for South Africa (source: Land Types database provided by the Agricultural Research Council (ARC); Van Niekerk, 2008).

2.2.2 WARMS database

Data available in the WARMS database were obtained from the National Office of the Department of Water and Sanitation (DWS). It should be borne in mind that WARMS is not a database of actual water uses. Rather, WARMS data refer to the registered (licensed) water volumes. The Registration Guide of DWS (2000) provides explanatory information and definitions of water uses in line with the National Water Act (Act 36 of 1998; NWA, 1998). Water users requiring registration are: Individuals (e.g. farmers, small-holders, land-owners or lessees); Communities (e.g. communal enterprises, traditional farmers groups); National or Provincial Government; Companies and businesses (e.g. partnerships, public companies, private companies, companies not for gain, guarantee companies, foreign companies, incorporated private companies, closed corporations etc.); Water User Associations and Water Services Providers (e.g. Water Boards); and Local Government. It should be noted that households are not required to be registered if the water use is part of the services offered by a water services provider such as a municipality or a Water Board. In this case, the municipality or Water Board must register its use.

The guidelines document (DWS, 2000) spells out permissible (lawful) uses of water and the conditions for General Authorisation to use water without a licence (Government Gazette No. 20526, dated 8 October 1999). The guidelines (DWS, 2000) also provide an overview of the registration forms and how to complete them. Eleven different water uses are listed in Section 21 (a) to (k) of the National Water Act (NWA, 1998). The registered water uses and their attributes that were considered in this project are summarized in Table 2.2. They were obtained from DWS as updated up to August 2016. DW761 includes large dams, but also small dams for which licence to store water is issued. Licences were not issued for both storing water and for irrigation use of this water. DW764 was included in the analysis although this is not water use, but differential water use. DW765 represents wastewater reuse for irrigation. DW766 is water discharged into a surface water resource and therefore re-entering the water resource system. DWS767 refers to the disposal of wastewater into evaporation dams where it evaporates or it may re-enter the water resource system. DW805 refers to the removal of underground water that is thereby put back into the water resource system.

TABLE 2.2 Registration forms and water use description, units of registered water use and attribute classes considered in the analysis.			
Registration form number	**Water use description**	**Units of water use**	**Attribute classes**
DW760	***Taking water from a water resource***	$m^3\ a^{-1}$	Water use sector Resource type
DW761	***Storing water***	m^3	Customer type Waste/clean water
DW764	Engaging in a stream flow reduction activity: ***Commercial afforestation***	$m^3\ a^{-1}$	Customer type
DW765	Engaging in a controlled activity: ***Irrigation of any land with waste or water containing waste*** generated through any industrial activity or by a waterwork	$m^3\ a^{-1}$	Customer type Waste-generating sector
DW766	***Discharging waste or water containing waste into a water resource*** through a pipe, canal, sewer, sea outfall or other conduit	$m^3\ a^{-1}$	Customer type
DW767	***Disposing of waste*** in a manner which may detrimentally impact on a water resource	$m^3\ a^{-1}$	Customer type Waste-generating sector
DW805	***Removing, discharging or disposing of water found underground*** if it is necessary for the efficient continuation of an activity or for the safety of people	$m^3\ a^{-1}$	Customer type

2.2.3 National land cover maps

Land use and cover are not only important input variables for water consumption (ET) modelling, but they are also critical to establish the relationships between water and land use. Land cover is the physical material of the Earth's surface as opposed to land use, which is seen as the manner which humans are utilising land. National land cover (NLC) products for South Africa exist for the time periods of 1990, 1994, 2000 and 2013 produced by collaborations between the government and the private sector. The product of 1994 (NLC1994) was produced using Landsat imagery from 1994 and 1995 and was manually generated through visual interpretation of 1:250,000 scale paper maps (Ngcofe and Tompson, 2015). NLC1994 has a total of 31 land cover classes. The 2000 map (NLC2000) was created using Landsat imagery of the years 2000 and 2001 and was the first land cover map generated from digital imagery (Ngcofe and Tompson, 2015). NLC2000 contains 48 land cover classes. The 2013/14 product (NLC2013/14) is the most recent land cover product. This product was produced using multi-seasonal Landsat imagery from the years 2013 and 2014. The 2013/14 NLC has a total of 72 land cover classes (Figure 2.8). The methodology used for generating the 2013/14 NLC was also applied to historical Landsat imagery to create a 1990 product (NLC1990, Figure 2.9).

In order to rationalize data processing, the 72 land cover classes of NLC 2013/14 (Figure 2.8) were grouped into sensible and workable categories. Twenty-one land cover/use groups were produced and these are summarized in Table 2.3 (groupings are shown in Appendix A). The groups were also consistent with the classification used in the NLC 1990 map (Figure 2.9). The generalized classification scheme not only enabled comparison, but also reduced complexities in the estimation and interpretation of water use per land cover class. Generalized land groups from the NLC1990 (Figure 2.9) and NLC2013/14 (Figure 2.8) maps were used in this project for detection of changes in land cover over that time period.

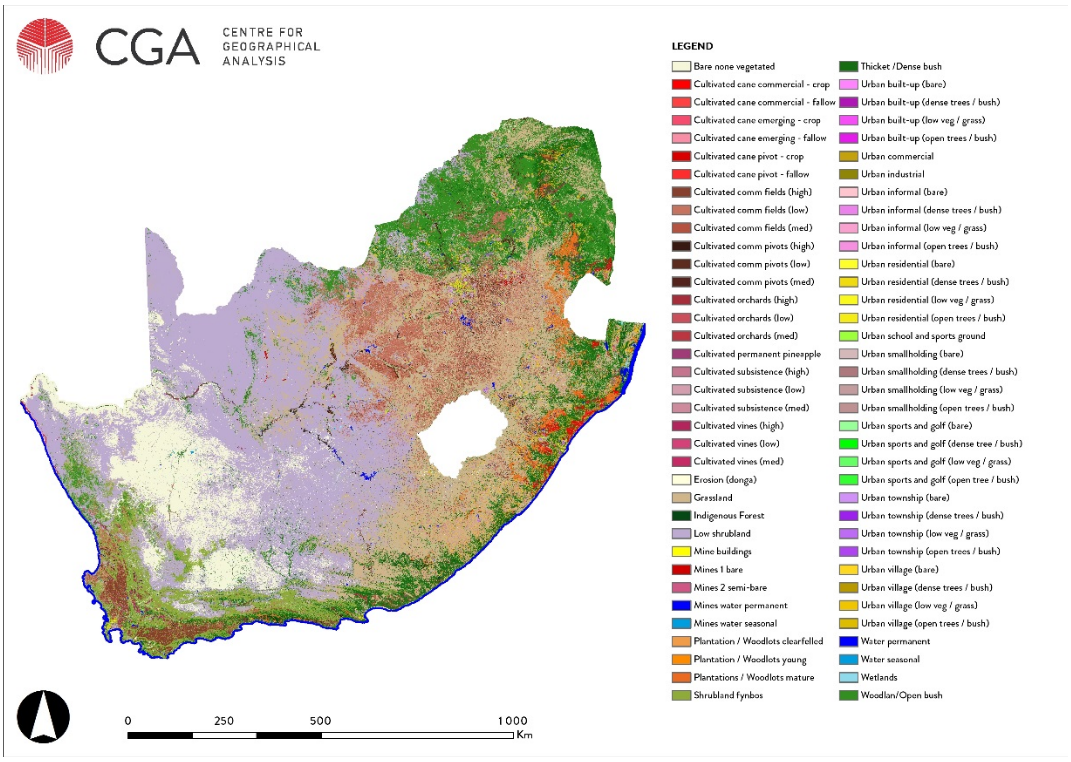


Figure 2.8

National Land Cover map of 2013/14 for South Africa.

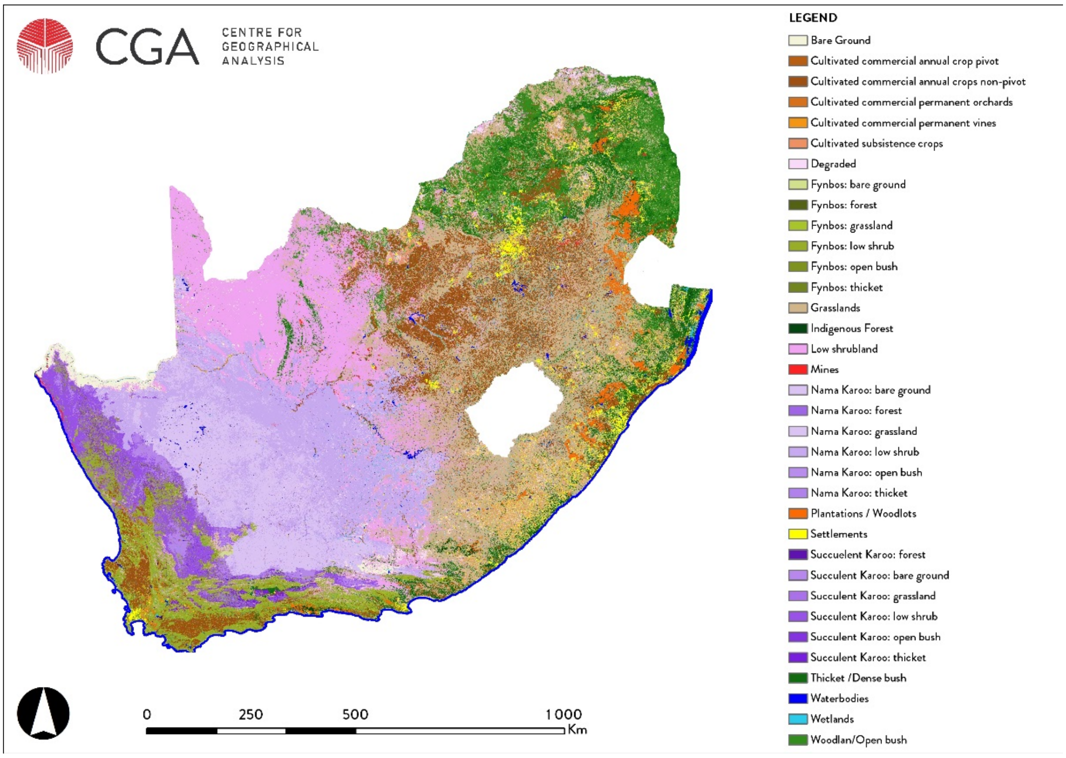


Figure 2.9

National Land Cover map of 1990 for South Africa.

TABLE 2.3

Land cover/use groups generalized from the NLC (2013/14) map and corresponding acronyms used in this report.

Land cover/use groups	**Acronym**
Waterbodies	WTB
Wetlands	WTL
Indigenous Forest	INF
Thicket /Dense bush	TDB
Woodland/Open bush	WOB
Grassland	GRS
Shrubland fynbos	SHF
Low shrubland	LSB
Cultivated commercial annuals	CCA
Cultivated perennial	CPE
Cultivated subsistence	CSU
Cultivated cane	CCN
Plantations / Woodlots	PWD
Mines	MNS
Bare none vegetated	BNV
Urban commercial	UCM
Urban industrial	UIN
Urban informal	UIF
Urban residential	URS
Urban sport and recreation	USR
Urban others	UOT

2.2.4 MOD16 evapotranspiration

The MOD16 ET algorithm was developed by Mu et al. (2007) from the original model of Cleugh et al. (2007), and later improved by Mu et al. (2011). The MOD16 product estimates global ET from ground-based meteorological observations and remote-sensing data from the Moderate Resolution Imaging Spectroradiometer (MODIS) located on NASA's Terra and Aqua satellites (Justice et al., 2002). The MODIS sensor works on a spatial resolution of approximately 1 km and 250 m, making it potentially suitable for applications in water resources management. The images contain 36 spectral bands in the wavelength range of 0.4 to 14.4 μm.

Thirteen years (2000-2012) of monthly and annual MOD16 ET data were obtained and processed for the whole country on a 0.912 km x 0.912 km pixel basis. The year 2012 was selected to represent the current status of water consumption (evapotranspiration). The year 2012 was also found to be a year of fairly average rainfall and ET (Jovanovic et al., 2015). Lushozi (2019) corroborated that the rainfall occurring in the relatively short time period of 2000-2012 falls within the range of natural variability, as he demonstrated using long-term measured rainfall data (1950-2012). The period 2000-2012 was therefore deemed to be representative of the general climate in the country. Years 2000-2012 were used to examine temporal trends in ET and to develop multiple regression equations between ET and climatic variables (rainfall, air temperature and VPD) for each land cover/use group.

2.2.5 ETLook evapotranspiration

Current ETLook evapotranspiration data were generated by eLEAF Competence Centre for the purpose of WRC project No. K5/2401 led by Stellenbosch University (SU). The dataset consists of actual and potential transpiration, transpiration deficit, evaporation, evaporation of intercepted water, transpiration deficit, actual biomass production and rainfall at one month intervals from August 2014 to July 2015.

2.2.6 Climatic data (rainfall, temperature and vapour pressure deficit)

Two rainfall data sets were used in the study to represent rainfall spatially. The first data set consisted of ground station data obtained from the South African Weather Services (SAWS). The data acquired were monthly rainfall totals (mm) from 2000 to 2012 for representative stations located across all nine provinces (Figure 2.10). The number of stations in each province was as follows: Gauteng (8), KwaZulu-Natal (13), Free State (8), Mpumalanga (7), North West (9), Northern Cape (11), Eastern Cape (11) Western Cape (11) and Limpopo (7). The full list of the station names and geographic coordinates can be found in Deliverable 5a of this WRC project No. K5/2520. The second dataset was the mean annual rainfall (MAR) from the Schulze (2006) long-term annual rainfall map (Figure 2.11). Both datasets were used to generate spatial layers of monthly rainfall for 2000-2012 to correlate with satellite derived MOD16 ET.

Average air temperature and VPD were obtained from NASA/GMAO Modern Era Retrospective Analysis (MERRA) at spatial resolution of 0.5˚x 0.66˚. These data were extracted and apportioned to fit the spatial resolution of ~1 km of MOD16 ET (Jovanovic et al., 2015). Average annual temperatures were also obtained from Schulze (2006) (Figure 2.12).

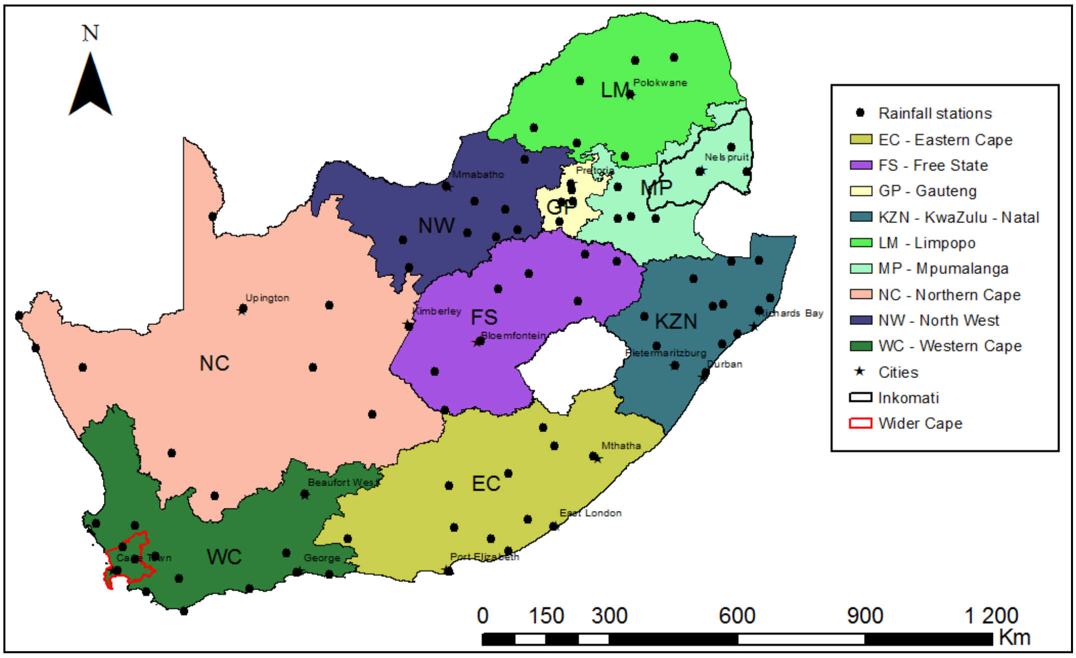


Figure 2.10

Rainfall stations used for monthly rainfall data obtained from the South African Weather Services.

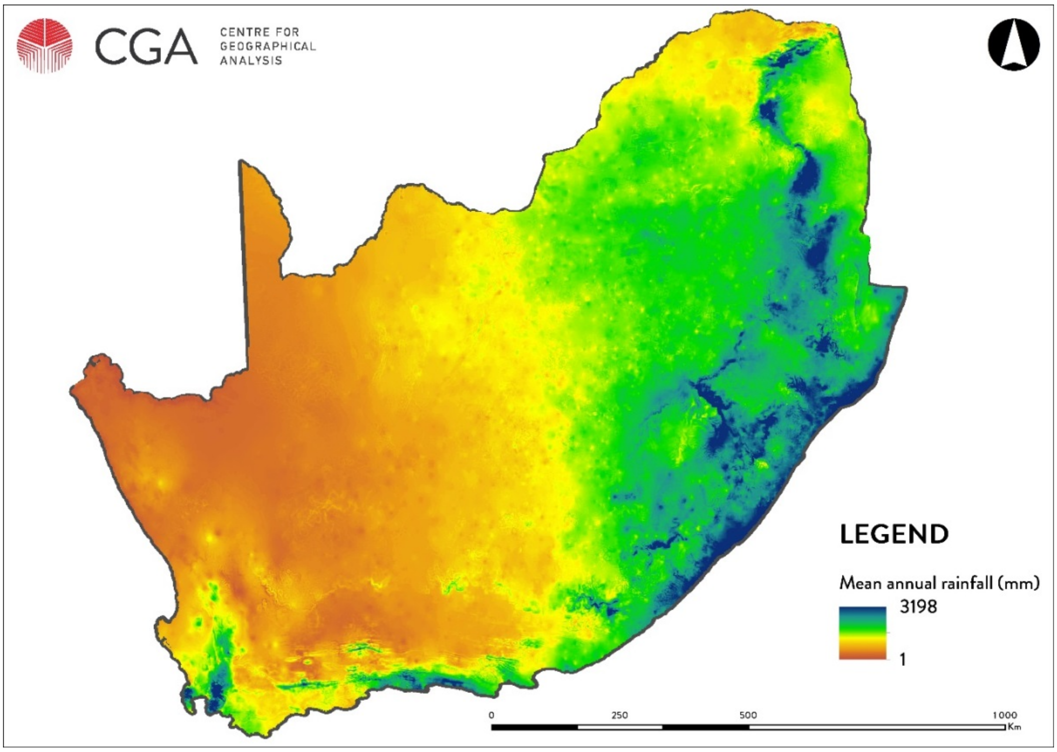


Figure 2.11

Mean annual rainfall map obtained from Schulze (2006).

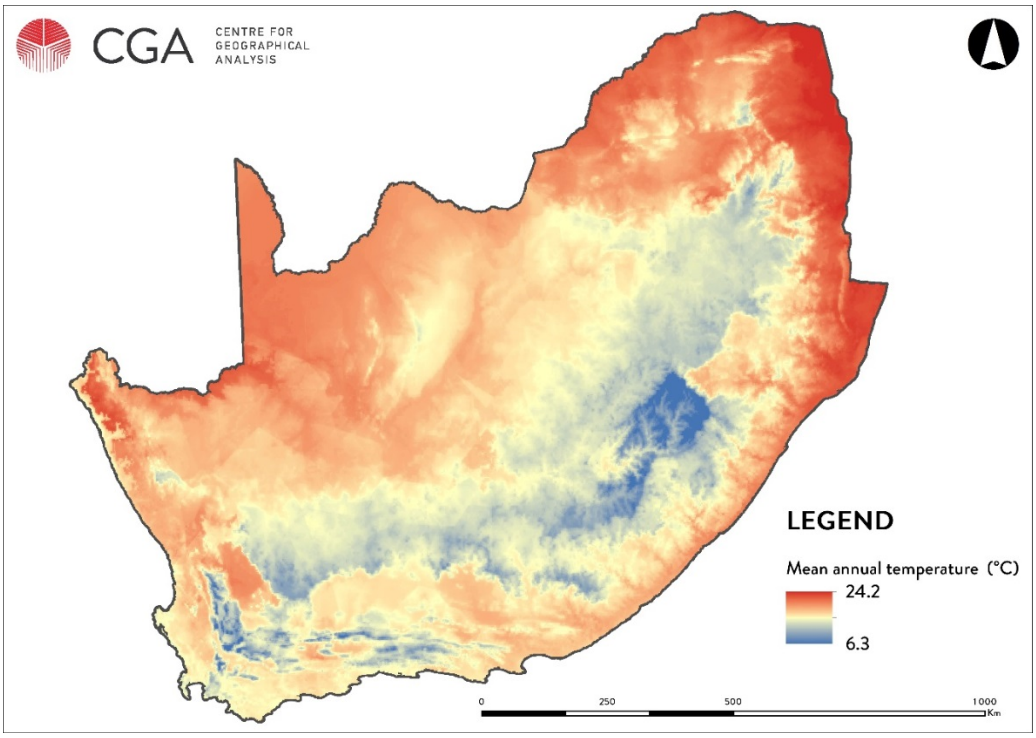


Figure 2.12

Mean annual temperature map obtained from Schulze (2006).

2.2.7 Urban water use data (Cape Town and Mbombela)

Municipal water use data are a good indication of the volumes of water that are distributed through the water supply system to residential/industrial urban areas.

Three sets of data were obtained from the City of Cape Town through a formal agreement:

- Bulk monthly water uses by broad categories (e.g. domestic, industrial, commercial, other) from July 2005 to June 2017.
- Shape files of Cape Town suburbs (a total of 793 suburbs).
- Average daily annual demand per suburb for the period May 2016 – April 2017 (residential and industrial).

Data of urban water use of Mbombela (major urban area in the Inkomati case study site) were also obtained from the City of Mbombela and GLS Consulting for the Period 2005-2015.

3 CURRENT STATE OF LAND USE AND WATER USE

3.1 Approach

The main purpose of this Chapter was to analyse the current status of water and land use in the country (Objective 1 of the project). The current state of water use and land use is presented using primarily WARMS data (registered and active water users, database updated at August 2016), the NLC 2013/14 map, as well as satellite-derived MOD16 ET data (2012) and ETLook data (2014/15). Data were analysed at National, provincial and case study site scales (Inkomati and wider Cape area). Primary observations and findings are discussed in the Sections below. More detailed analyses can be found in Deliverables 1 and 3 of this WRC project No. K5/2520.

3.2 WARMS database

3.2.1 National scale analysis

All data from the WARMS database presented in this report refer to registrations entered in the database up to August 2016. The reader should bear in mind that the data are a good reflection of the general trends in water use, however much updating of the WARMS database took place since August 2016 and an up-to-date version of the WARMS database can be obtained from the Department of Water and Sanitation (DWS).

Figure 3.1 represents the total water use volumes per year registered in WARMS for different types of water uses at national scale. In order to get an overview of the current status quo, all data with water use registration closure before 2012 were omitted from the analysis.

The following findings were observed:

- The highest water use volumes were registered at National level for taking water (18.5 billion m^3 a^{-1}) and for storing water (5.2 billion m^3). The third highest water use type was disposal of wastewater (4.5 billion m^3 a^{-1}).
- Discharging wastewater was 1.2 billion m^3 a^{-1}, removing underground water was 1.1 billion m^3 a^{-1} and afforestation was 1.0 billion m^3 a^{-1}.
- A minor water use was found to be irrigation with wastewater at about 0.3 billion m^3 a^{-1}.
- Water taking is classified into different water resource types, namely water schemes, rivers/streams, boreholes, dams, the registration for the other resource types being negligible (spring/eyes, estuaries, lakes and wetlands).

- A fraction of 28.3% of the total water used is taken from the registered dam capacity, the remaining portion being taken from groundwater, directly from rivers, dams that are not registered and other sources.
- The figures indicate that discharging wastewater, removing underground water and especially disposing wastewater are substantial water uses due to industrial and mining activities. There is scope to increase the wastewater reuse because only a fraction of wastewater is reused for irrigation.
- The total water withdrawals for the country were calculated to be 18.5 billion m^3 a^{-1} for the selected period since 2012, as compared to 12.5 billion m^3 a^{-1} estimated by Frenken (2005) in 2000.
- The highest water withdrawals per sector are for agricultural irrigation (12.0 billion m^3 a^{-1} or 64.8% of the total), water supply services (2.7 billion m^3 a^{-1} or 14.7%), urban industry (2.5 billion m^3 a^{-1} or 13.3%), mining (0.8 billion m^3 a^{-1} or 4.3%) and non-urban industry (0.3 billion m^3 a^{-1} or 1.6%). The withdrawal for other sectors is negligible (aquaculture, watering livestock, power generation, recreation, schedule 1, urban use excluding industrial and domestic).
- Irrigation is therefore the major water user countrywide. It is interesting to note that urban and non-urban industry combined use more water than water supply services.

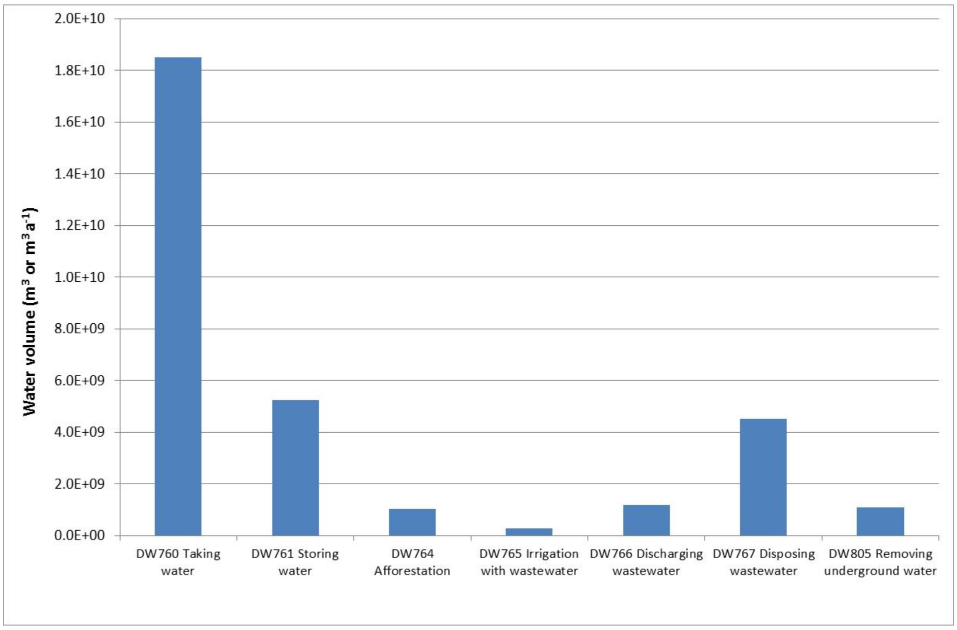


Figure 3.1

Total water volumes registered in WARMS at national scale per type of water use

3.2.2 Provincial scale analysis

Figure 3.2 represents the water volumes per year registered in WARMS per region (WMA or DWS office) for different types of water use.

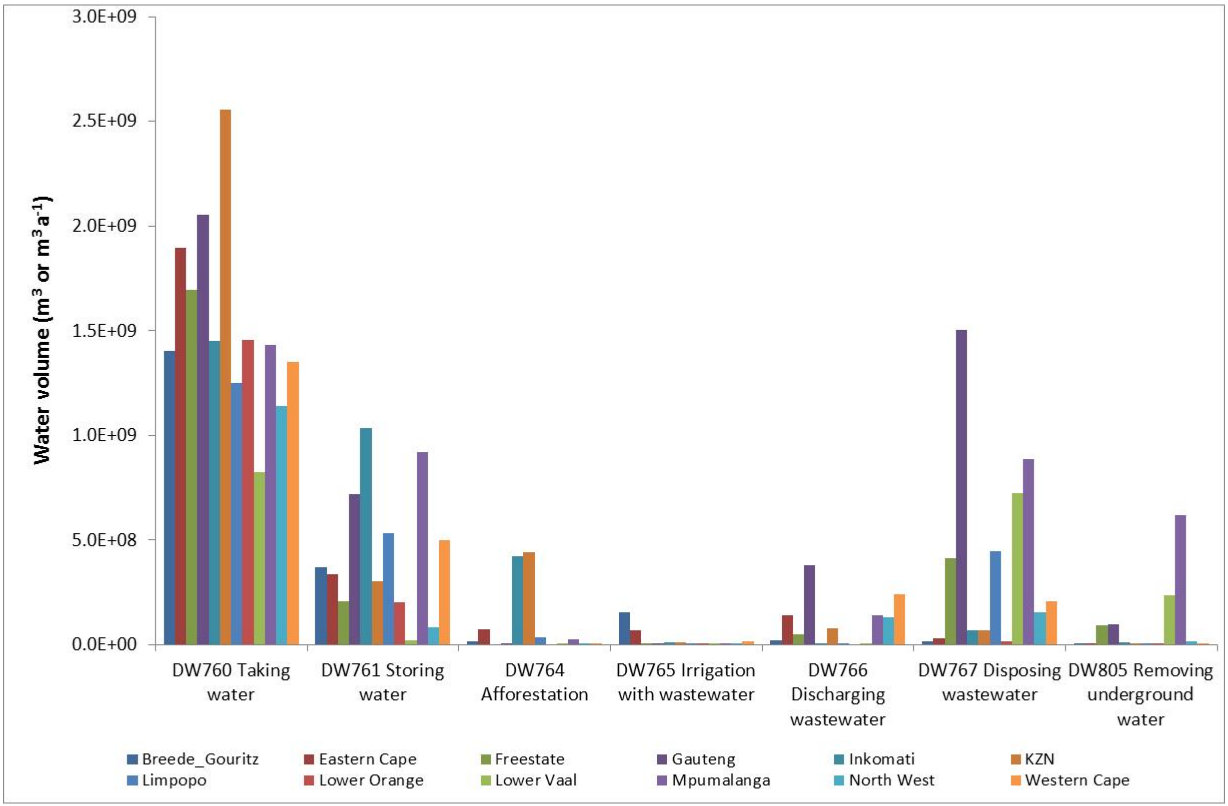


Figure 3.2

Water volumes per year registered in WARMS per region (WMA or DWS office) for different types of water use

The following findings can be observed:

- Total water uses in each region depend mainly on the economic activities and associated land uses.
- Not all regions have all water uses. For example, no registrations for afforestation were made in the Free State and Lower Orange, and no registrations for discharging wastewater were made in the Lower Orange because these activities do not occur in these regions.
- High water withdrawals are associated with urban regions. The highest withdrawals are in KwaZulu-Natal (2.6 billion m^3 a^{-1}), followed by Gauteng (2.1 billion m^3 a^{-1}) and Eastern Cape (1.9 billion m^3 a^{-1}).

- Low water withdrawals are associated with rural areas and small regions, such as Lower Vaal (0.8 billion $m^3 a^{-1}$) and North West (1.1 billion $m^3 a^{-1}$).
- High water storages are associated with high rainfall areas. The highest water storage is in Inkomati-Usutu (1.0 billion m^3) and Mpumalanga (0.9 billion m^3)
- Lower water storages are associated with drier climates, low water use and flatter topographies. The lowest storage is in the Lower Vaal (0.02 billion m^3, most of the water is already barraged upstream) and North West (0.08 billion m^3).
- Water uses registered for afforestation may reduce streamflow. The highest volume reductions from afforestation are registered for KwaZulu-Natal and Inkomati-Usutu (0.4 billion $m^3 a^{-1}$) as well as for the Eastern Cape (0.07 billion $m^3 a^{-1}$), Limpopo (0.04 billion $m^3 a^{-1}$) and Mpumalanga (0.03 billion $m^3 a^{-1}$). Negligible streamflow reductions due to afforestation were registered in the remaining regions.
- Large scale irrigation with wastewater is limited to Breede-Gouritz (0.15 billion $m^3 a^{-1}$) and Eastern Cape (0.07 billion $m^3 a^{-1}$). Although irrigation with wastewater is registered in all regions, it is influenced by the size of the area and population numbers. It appears, however, that such practice is under-used in arid and semi-arid regions, especially Lower Orange, Lower Vaal or North West.
- Discharging wastewater is associated with urban areas and industry. Lower Orange has no records of discharging wastewater.
- It is interesting to note that, in some regions, irrigation with wastewater is higher than the volume of wastewater discharged. This is the case of the Lower Orange, Lower Vaal, Inkomati-Usuthu and especially in the Breede-Gouritz, where 7 times more wastewater is used for irrigation than the wastewater registered as discharged. The discharging and disposing of wastewater should be used in conjunction in this context, as wastewater irrigation may make use of either wastewater discharged or wastewater disposed in evaporation ponds.
- Removing underground water is mainly associated with dewatering mines. The highest volumes were recorded for Mpumalanga (0.6 billion $m^3 a^{-1}$), Lower Vaal (0.2 billion $m^3 a^{-1}$), Gauteng (0.1 billion $m^3 a^{-1}$) and Free State (0.09 billion $m^3 a^{-1}$).

Figure 3.3 provides a summary of water taking data in WARMS per region (WMA or DWS office) and per sector.

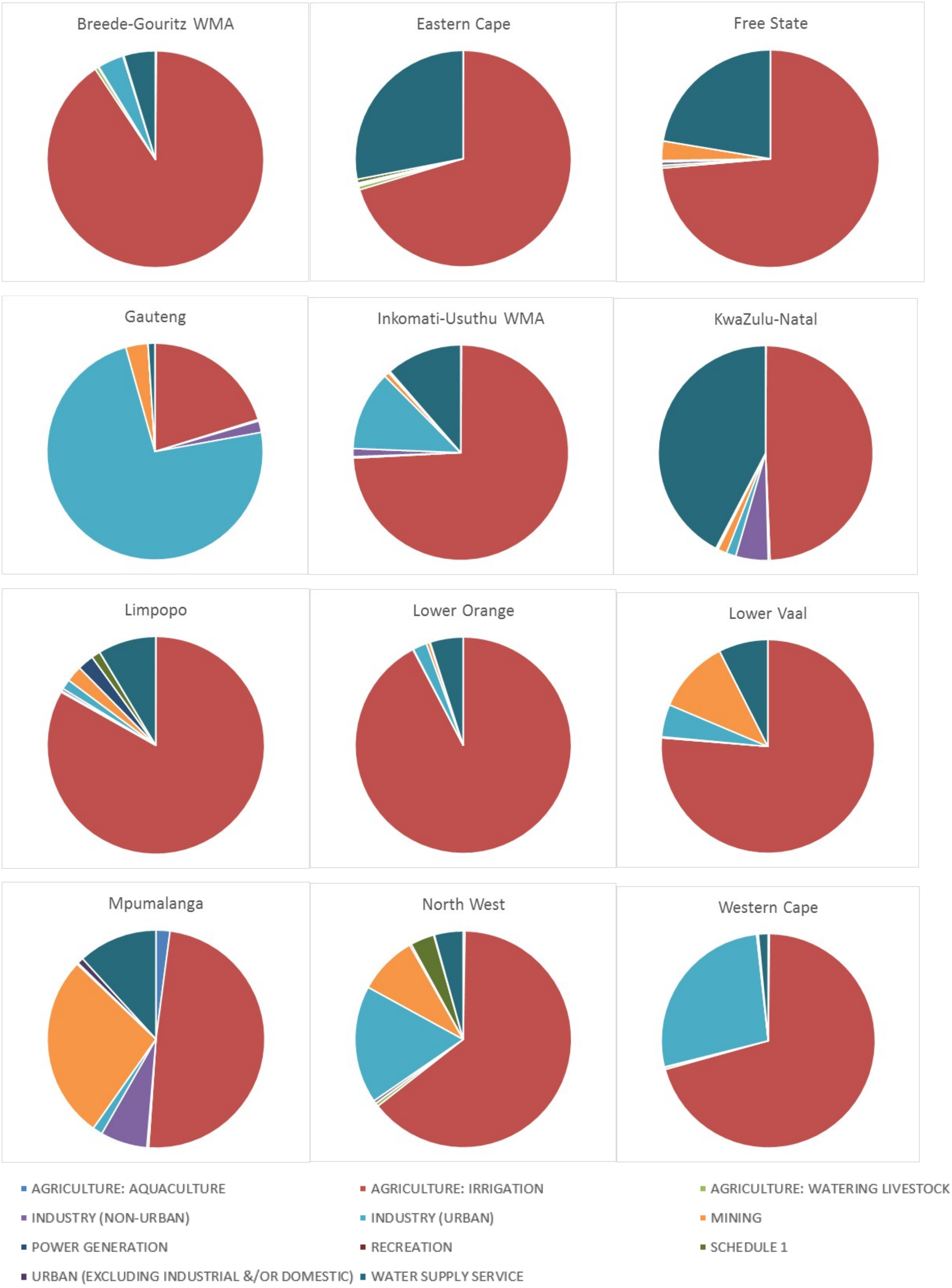


Figure 3.3

Water volumes registered in WARMS for taking water per region (WMA or DWS office) for different sectors

The following was observed:

- The total volumes registered for taking water indicated that water uses by sector are highly dependent on the activities in the regions.
- Water use for aquaculture is by far the most represented in Mpumalanga (0.03 billion $m^3\ a^{-1}$) compared to the other regions.
- In all regions, the largest water use is from agricultural irrigation, except Gauteng.
- Water use for livestock watering is negligible compared to other sectors (0.3% of total countrywide).
- Industrial water use is the highest in Gauteng, KwaZulu-Natal, Mpumalanga and the Western Cape, which are the most industrialized regions.
- A large portion of industrial water use in KwaZulu-Natal and Mpumalanga is from non-urban industries.
- Water use for mining is the highest in Mpumalanga (0.4 billion $m^3\ a^{-1}$), followed by North West (0.1 billion $m^3\ a^{-1}$), Lower Vaal (0.09 billion $m^3\ a^{-1}$), Gauteng (0.07 billion $m^3\ a^{-1}$) and Free State (0.05 billion $m^3\ a^{-1}$), which is one or more orders of magnitude more than in other areas.
- By far the largest water use in power generation is in Limpopo (0.03 billion $m^3\ a^{-1}$).
- The largest volumes of water registered for recreation are in North West and Eastern Cape, however the values are in general much lower compared to the other sectors (0.04% of total countrywide).
- The largest volumes registered as schedule 1 were recorded for North West (0.04 billion $m^3\ a^{-1}$) followed by Limpopo (0.02 billion $m^3\ a^{-1}$) and Eastern Cape (0.01 billion $m^3\ a^{-1}$).
- The largest volume of water registered as urban use (excluding industrial and domestic) is in Mpumalanga (0.01 billion $m^3\ a^{-1}$), although the values for this sector are much lower compared to the other sectors (0.11% of total countrywide).
- According to registrations, KwaZulu-Natal has the largest volume of water withdrawn for water supply services (1.1 billion $m^3\ a^{-1}$), followed by Eastern Cape (0.5 billion $m^3\ a^{-1}$) and Free State (0.4 billion $m^3\ a^{-1}$). However, it should be considered that the management of water supply services may be the domain of Municipalities, such as in the case of Cape Town or Johannesburg.

3.2.3 Case study analysis: Wider Cape

Figure 3.4 represents the total water volumes per year registered for different types of water use and in percentages for the wider Cape area. The largest portion of registered volumes is for taking water (798 $Mm^3\ a^{-1}$ or 64.9% of all registered water uses). Substantial volumes are also registered for discharging and disposing of wastewater (229 $Mm^3\ a^{-1}$ and 194 $Mm^3\ a^{-1}$ respectively), more than half of the water taken (53%).

The largest users of water in the Cape Town area are water services providers, water use associations and companies respectively (Figure 3.5). The largest water use sectors according to WARMS records are agricultural irrigation and industry (urban); all other water use sectors show negligible use in comparison to irrigation and industrial uses. With respect to resource type, water is predominantly sourced from schemes and rivers/streams, with boreholes, dams and springs showing negligible water use. With a large number of municipal water use data unspecified (342 $Mm^3\ a^{-1}$), the Cape Winelands (formerly Boland) and Overberg municipalities show the largest volumes amongst specified municipalities (309 $Mm^3\ a^{-1}$ and 101 $Mm^3\ a^{-1}$ respectively). The quaternary catchments (drainage region codes) with the largest volumes of water used are G22G, G10C, and G10F.

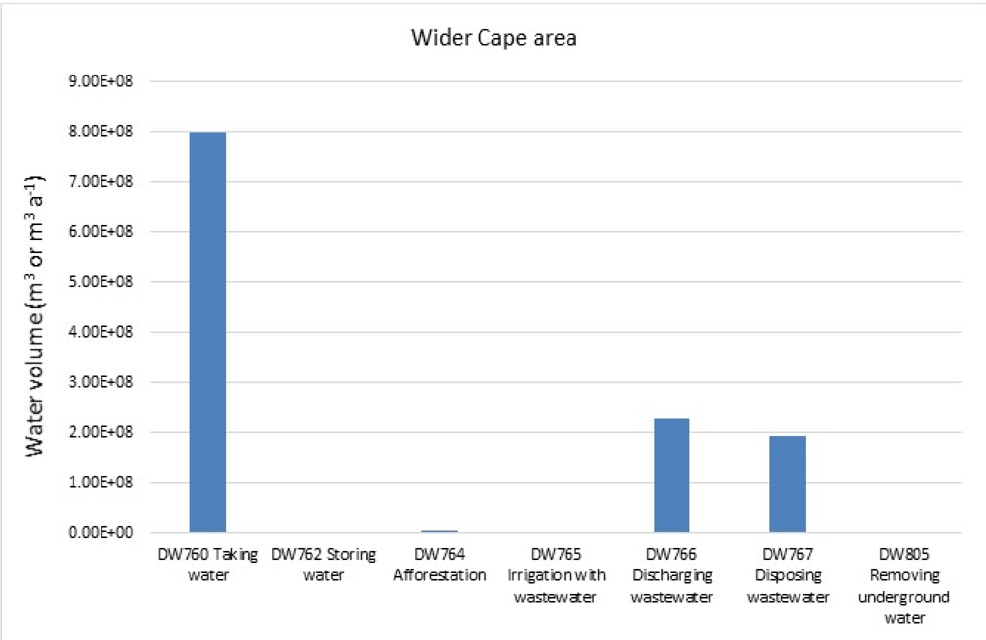


Figure 3.4

Total water volumes registered per type of water use in the wider Cape area.

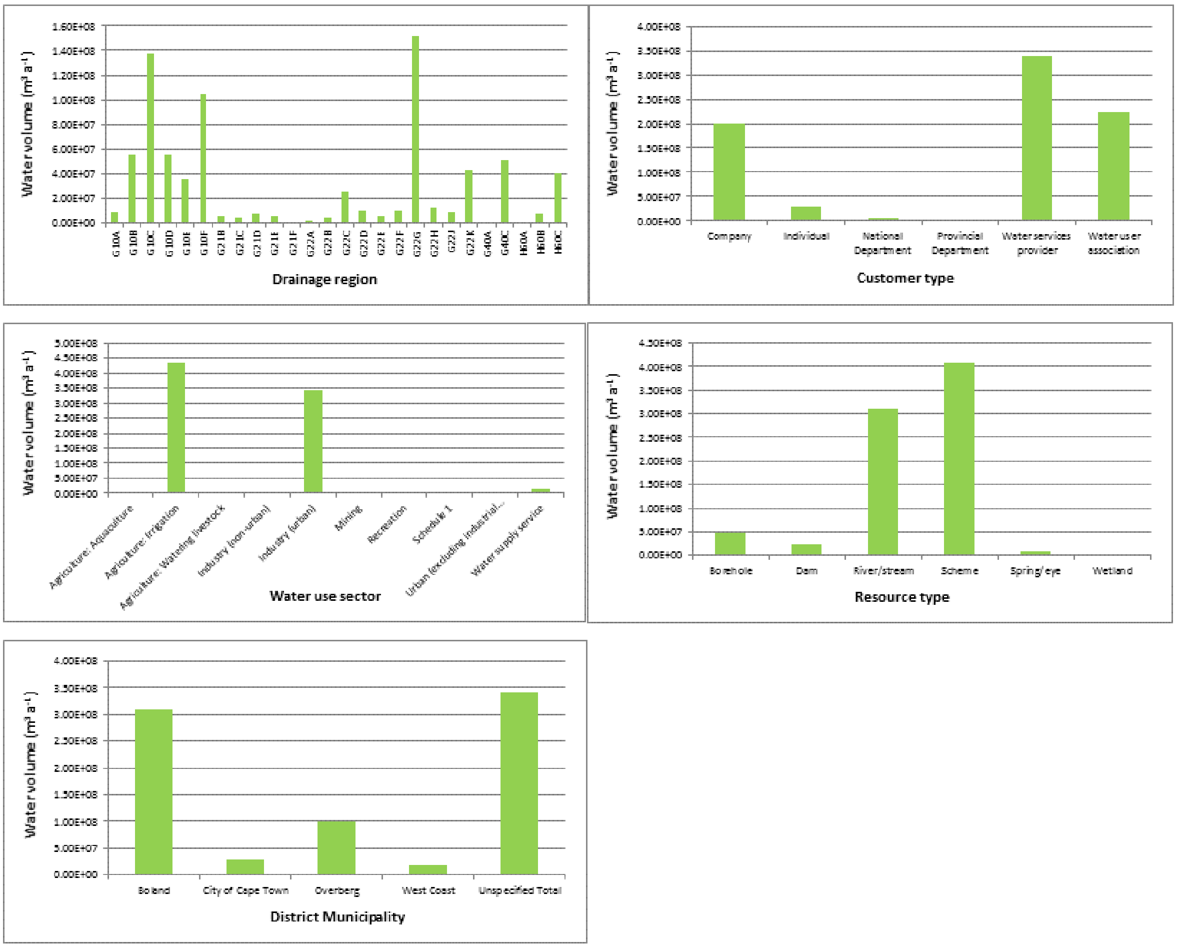


Figure 3.5

Water volumes (m^3 a^{-1}) of WARMS database in the wider Cape area for taking water from a water resource.

Cape Winelands municipality has the largest volumes of water accounted for under water storage in dams (0.9 Mm^3). Dams are managed predominantly by companies, water services providers and individuals. Quaternary catchments with the largest volumes recorded include G10D and G22H. Commercial afforestation is practised predominantly by companies and water services providers in the Cape Winelands and Overberg municipalities (3.3 Mm^3 a^{-1} and 2.2 Mm^3 a^{-1} respectively). Quaternary catchments G40C, G10E, and G10C are the biggest stream flow reducing catchments for the purposes of afforestation. Only quaternary catchment H60B shows substantial records of re-use of water containing waste for irrigation (0.02 Mm^3 a^{-1}). The largest water use sectors include industry-agro processing, non-point source and wineries. The largest water re-use occurs in the Overberg municipality, with Cape Winelands, the City of Cape Town and the West Coast municipalities re-using much smaller volumes of wastewater. This may indicate that there is more room for re-use of water especially in Cape Town.

Quaternary catchment G22C is by far the greatest discharger of wastewater via a conduit (152 Mm^3 a^{-1}). This discharge is only from water services providers in the form of urban and domestic sewerage. Better sewerage treatment methods may avail large volumes of water for re-use to the City of Cape Town. Waste disposal in a manner that it could detrimentally impact a water resource is predominantly done by water services providers and companies. The dominant waste type is urban and domestic sewerage. The quaternary catchments with the largest registered waste disposal volumes are G22C and G22D. Mine dewatering or dewatering of areas where new pipelines are to be installed or pumping of groundwater as a safety precaution are major activities in mining areas and urban/domestic sewerage works. Cape Winelands municipality has the largest volumes registered under this code (0.21 Mm^3 a^{-1}). With the large volumes of urban and domestic sewerage produced in this area, there may be more room for re-use of treated effluent, if treatment is to a good enough standard. Re-use of water is registered for predominantly five quaternary catchments (G10C, G10E, G22F, G40A and G40C). Non-potable water can be used for alternate uses such as fire-fighting, or water features and possibly gardening depending on the quality.

3.2.4 Case study analysis: Inkomati

For the Inkomati catchment, the largest quantities of registered water volumes were for taking water (1,356 Mm^3 a^{-1} or 79.2% of all registered water uses; Figure 3.6). Considering customer type, it was evident that water user associations are the biggest users of water in the Inkomati catchment, with companies and water service providers being 2nd and 3rd biggest users of water in the catchment (Figure 3.7). When assessed in terms of use per district municipality, Ehlanzeni was by far the biggest user of water (958 Mm^3 a^{-1}) using about 70% of the resource in the catchment. Water use sector analysis showed that agricultural irrigation was by far the largest registered user of water (1,058 Mm^3 a^{-1}, close to 80%), with water supply services and industry being 2nd and 3rd respectively. The largest proportion of water registered for use in the catchment comes from schemes (about 47% – this could be either surface or groundwater) and rivers/streams (45%), with dams and boreholes representing a much lower percentage of resources used.

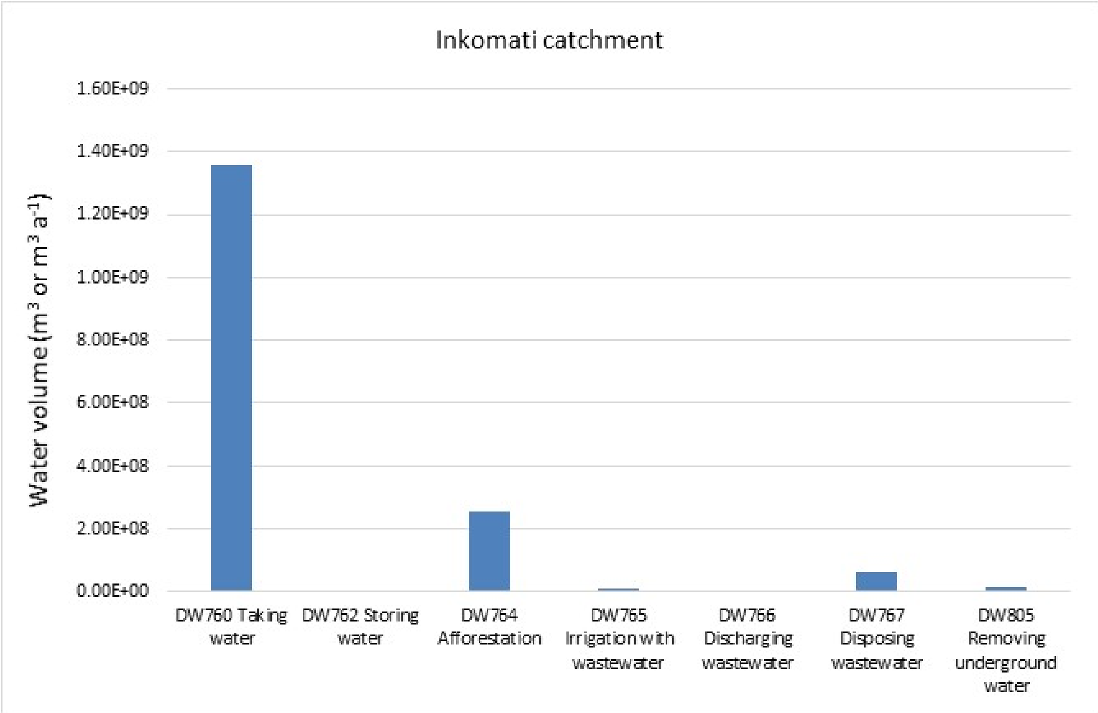


Figure 3.6

Total water volumes registered per type of water use in the Inkomati catchment.

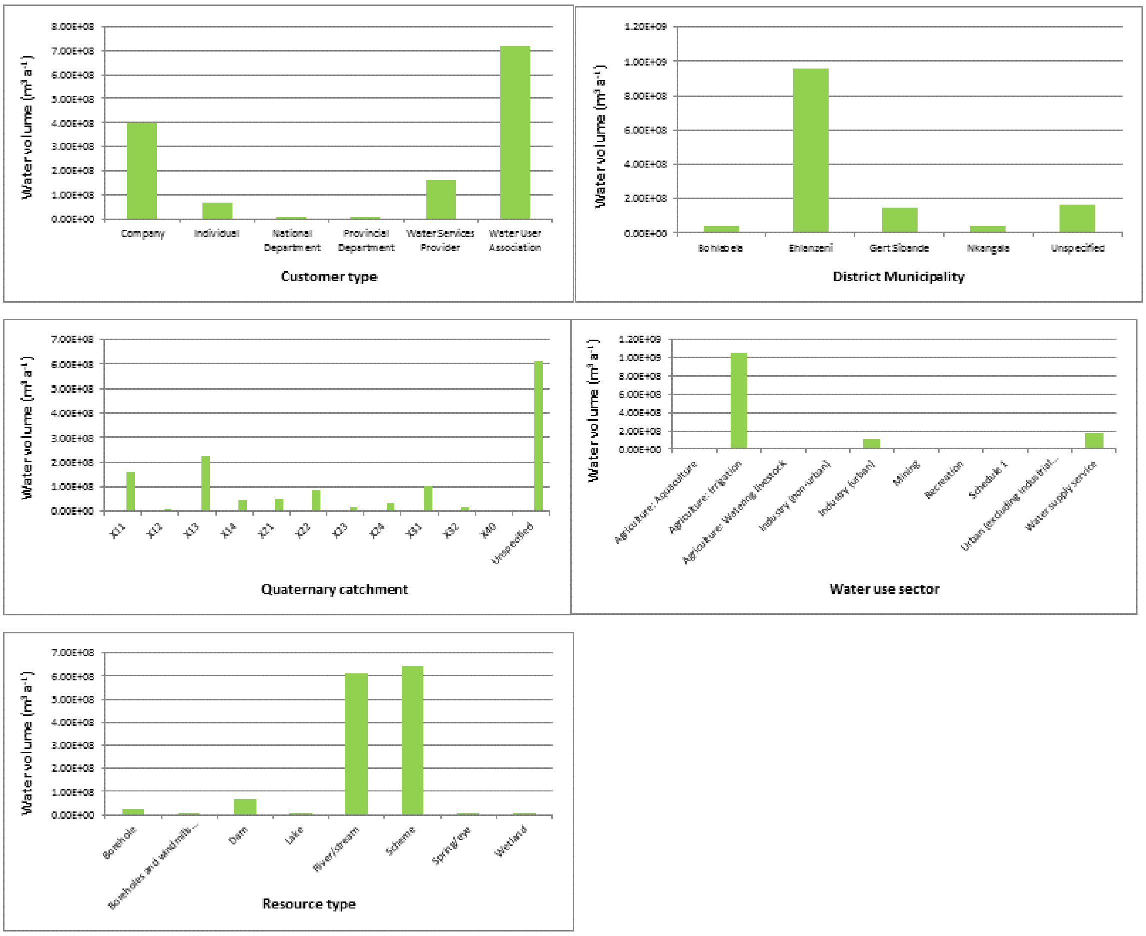


Figure 3.7

Water volumes (m^3 a^{-1}) of WARMS database in the Inkomati catchment for taking water from a water resource.

For storing water in dams that require safety registration, registered customer type is predominantly companies, with individual licenses being the 2nd most. Ehlanzeni municipality is the one with the highest number of storage dams and volumes (4.81 Mm^3 a^{-1}). Large dams in the Inkomati area are spread across many quaternary catchments. Catchment X13 has the largest volume of stored water (2.38 Mm^3), with X31 and X11 having the 2nd and 3rd largest volumes of stored water. The dominant customer type commercial afforestation is companies. Ehlanzeni municipality has the largest total volume of water used under this registration code (186 Mm^3 a^{-1} or 72.5% of all municipalities). Catchments X31, X22, and X21 have the largest recorded volumes registered. Nearly all quaternary catchments practise commercial afforestation in the Inkomati catchment area. Wastewater reuse refers predominantly to industrial waste or waste from waterworks. Catchment X21 shows the largest volumes of re-use for irrigation (10.1 Mm^3 a^{-1} or 85.3% of all catchments). The dominant waste generating activity or industry is the pulp and paper industry, with power generation having the second highest volumes. Other waste generating sectors seem to use negligible amounts compared to the above-mentioned sectors. Ehlanzeni municipality is the district municipality with the highest re-use volume (11.5 $Mm^3 a^{-1}$ or 97.7% of all municipalities).

For discharging of waste or water containing waste into a water resource via a pipe or conduit, the largest volumes are discharged by water service providers. Ehlanzeni municipality shows the largest volumes (2.43 $Mm^3 a^{-1}$ or 42% of specified municipalities), while a large percentage of wastewater discharge is not specified within the dataset (3 $Mm^3 a^{-1}$ or 52%). Catchments X21, W23 and X31 have the largest disposal volumes. The largest wastewater generating sectors are urban/domestic sewerage, gold mining and agriculture/aquaculture. This shows that there is room for more water re-use in the catchment possibly for irrigation related activities. Companies are listed with the largest volumes of disposal of wastewater that may impact on water resources. Ehlanzeni, Gert Sibande, and Nkangala are the municipalities with the largest volumes of wastewater discharge registered. Catchments X11, X22, and X21 have the largest wastewater disposal registered. The largest contributing waste generating sectors are the gold mining industry, urban/domestic sewerage, and the pulp and paper industry. Removing, discharging or disposing of water found underground include activities such as dewatering or pumping from boreholes. Ehlanzeni, Gert Sibande and Nkangala municipalities have the largest volumes registered for this code. Activities are linked mainly to companies and occur mainly in catchments X11, X21 and X12.

Across all types of water use, the predominant customer is represented by companies, except in the category of discharging waste or water containing waste into a water resource by a conduit, where water services providers are the customer type discharging the largest volumes (wastewater treatment plants/municipal treatment facilities). This shows that there is room for water re-use in the Inkomati catchment; depending on the quality of wastewater, it may be suitable for some non-potable uses (e.g. fire-fighting). The Ehlanzeni municipality is the biggest user of water in the Inkomati management area according to WARMS registration data. Ehlanzeni also re-uses the largest volumes of wastewater.

3.3 MOD16 evapotranspiration

3.3.1 National scale analysis

The annual MOD16 ET satellite-derived data for 2012 (Figure 3.8) were overlaid on the NLC2013/14 map in a geographical information system (GIS). MOD16 ET values were then extracted for each land cover class according to the land cover/use groups described in Table 2.3 using a zonal statistics spatial algorithm in ESRI's ArcMap. The water consumption (ET) data estimated with MOD16 extracted for each land cover/use group at national scale are summarized in Table 3.1 (average, median, minimum, maximum, standard deviation in mm a^{-1}, and total in m^3 a^{-1}).

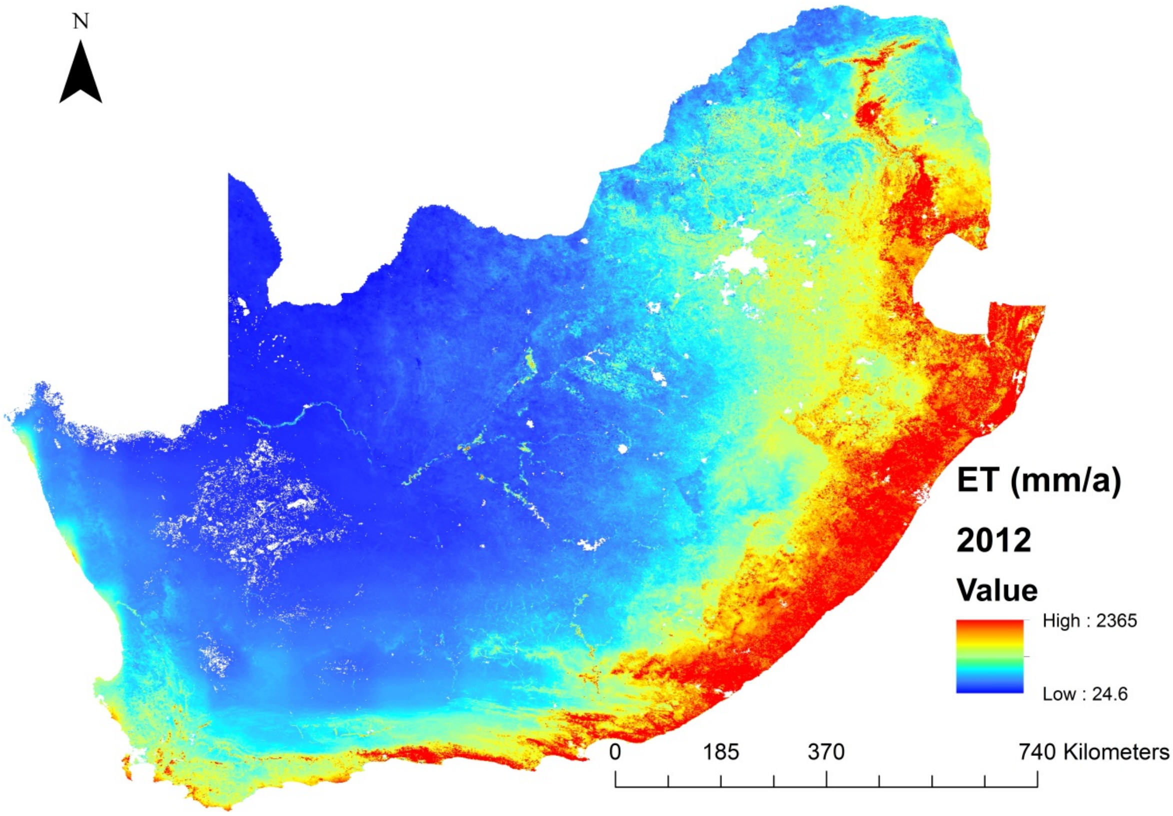


Figure 3.8

Annual MOD16 evapotranspiration data for 2012 on a 0.912 km x 0.912 km pixel basis.

TABLE 3.1 MOD16 evapotranspiration (ET) for each land cover/use group for the year 2012 at national scale (in descending order according to average ET).							
Land cover class grouping	**Area (ha)**	**Evapotranspiration (ET)**					
		Average ET ($mm\ a^{-1}$)	**Total water consumption ($x\ 10^6\ m^3\ a^{-1}$)**	**Maximum ET ($mm\ a^{-1}$)**	**Minimum ET ($mm\ a^{-1}$)**	**Median ET ($mm\ a^{-1}$)**	**Standard deviation ($mm\ a^{-1}$)**
Cultivated cane	354507.21	884	3132.61656	1639	331	866	211
Indigenous forests	325527.48	801	2606.82604	1844	129	772	313
Cultivated subsistence	1537085.25	574	8818.87006	1844	45	590	260
Urban others	1679195.79	572	9603.24945	1827	32	581	264
Plantations/Woodlots	1400767.56	557	7805.06315	2365	39	491	314
Cultivated perennial	407692.62	526	2143.59987	1565	49	455	286
Urban residential	232745.13	489	1137.27851	1548	37	424	266
Urban industrial	42001.38	476	200.127942	1422	45	415	264
Wetlands	768567.51	444	3412.29652	1840	42	401	237
Urban commercial	39329.28	440	173.18518	1410	37	392	243
Thicket/Dense bush	6218391.06	423	26321.6814	2365	25	368	260
Water bodies	344260.53	417	1434.72149	1647	27	375	241
Urban informal	190101.69	386	733.106239	1276	45	325	235
Woodland/Open bush	9118093.41	353	32156.4842	1799	25	293	248
Cultivated commercial annuals	8216788.41	350	28762.5702	1727	40	317	190
Grasslands	19476771.7	341	66322.8497	1844	25	275	243
Fynbos shrublands	4157729.91	300	12473.9966	1727	58	256	170
Mines	245002.68	268	656.060137	1469	25	229	175
Bare soil	9738274.95	234	22761.971	1718	25	161	197
Low shrublands	27829582.1	205	56916.725	1648	25	158	157
TOTAL	92322415.62	343	287573.27933	2365	25	276	250

The following observations can be made from the data in Table 3.1:

- The highest average ET per MOD16 pixel (~1 km) was recorded for cultivated cane (884 mm a^{-1}) and indigenous forests (801 mm a^{-1}).
- Cultivated land (subsistence and perennial) features high water consumption, 574 mm a^{-1} and 526 mm a^{-1} respectively.
- Land commercially cultivated with annual crops has lower ET (350 mm a^{-1}) compared to perennial crops, which is understandable because annual crops are not cultivated/irrigated throughout the year.
- Grasslands consume slightly less water (341 mm a^{-1}) than land with annual crops.
- Plantations/Woodlots exhibit high water consumption (557 mm a^{-1}).

- Wetlands, thicket/dense bush and woodland/open bush are somewhere in the mid-range of ET compared to other land covers.
- Fynbos and low shrublands consume little water, 300 mm a^{-1} and 205 mm a^{-1} respectively, because they occur predominantly in arid and semi-arid areas.
- ET from mines is amongst the lowest in the list (268 mm a^{-1}).
- Water consumption from bare soil is low compared to other land covers. However, these data may be over-estimated, as they may be affected by adjacent land due to the coarse resolution of MOD16 ET.
- Urban land (residential, industry, commercial, informal and others) recorded relatively high MOD16 ET. However, it should be noted that the physics underlying MOD16 is not consistent with the principles driving evaporation from urban land, and the data should be treated with caution. Many MOD16 ET pixels lying in urban areas show data out of range and they were not used in the analysis.
- Similarly, MOD16 ET is not set up to estimate evaporation from water bodies, hence the low estimated ET for this land cover (417 mm a^{-1}). This ET originates rather from land adjacent to water bodies due to the coarse resolution of MOD16. MOD16 ET values for water bodies were therefore not considered reliable.
- Total water consumption values expressed in 10^6 m^3 a^{-1} depend largely on the area representing a land cover. Grasslands and shrublands cover very large areas, and although ET from these land covers is relatively low, the total water consumption is the highest amongst the land covers.
- On the other hand, urban land use and mines cover the smallest areas and their total water consumption in 10^6 m^3 a^{-1} is low.
- Maximum and minimum values for all land covers exhibited relatively wide ranges, indicating that specific conditions may occur in different geographic and climatic areas.
- The values also indicate that the median is below the average, except for some land covers with high ET, indicating that most of the data are spread in the lower range of ET with some extreme high values for each land cover.
- Substantial variation in ET occurs for the same land cover, as evidenced by the high standard deviations in particular for indigenous forests and plantations/woodlots, due to the high spatial variability of these types of vegetation.

Although the MOD16 data refer to actual evapotranspiration from open land and the WARMS data to registered water allocations, it was deemed worth to compare MOD16 ET results with some variables presented in the WARMS data analysis:

- The volume of water registered in WARMS for sector agriculture – irrigation is 11,997 $Mm^3\ a^{-1}$ (12,097 $Mm^3\ a^{-1}$ including aquaculture and livestock watering). The volume of water consumed from cultivated land (subsistence, perennial, commercial annuals and cane) is 42,858 $Mm^3\ a^{-1}$, as estimated with MOD16. It should be considered that not all irrigators are registered countrywide, and especially that MOD16 ET includes both irrigated and rainfed land.
- Detailed validation of agricultural water use is under way in different regions of the country. The actual ET values should be clearly defined as conceptually different from reference or potential ET. Satellite-derived products give the opportunity to perform large scale validation exercises. It should also be considered, however, that uncertainties exist in the satellite-derived estimations and that the resolution of satellite imagery may not always be consistent and sufficiently detailed for high definition of crop and field boundaries.
- The volume of water evaporating from non-agricultural vegetated land amounts at 208,016 $Mm^3\ a^{-1}$, and it outweighs by far the agricultural water consumption estimated with MOD16 and the volume of water registered in WARMS for agriculture. The non-agricultural vegetated land includes woodlands/open bush, wetlands, thicket/dense bush, plantations, low shrublands, indigenous forests, grasslands and fynbos. There may be therefore a case for better planning of these lands in terms of water resources management, although this is influenced by many environmental, social and economic factors, and local conditions.
- The total volume of water registered in WARMS for industry (urban and non-urban), urban (excluding industrial and/or domestic) and water supply services is 5,508 $Mm^3\ a^{-1}$. The total volume of water that evaporates form urban land uses (residential, industrial, commercial, informal and others) is 11,847 $Mm^3\ a^{-1}$. The total volume of water that evaporates from urban areas is more than double the water supplied to industry and domestic users. There may be therefore a case for capturing some of the rainwater before it reaches the ground and evaporates in urban areas (e.g. rainwater harvesting).
- The volume of water registered in WARMS for mining is 787 $Mm^3\ a^{-1}$, whilst the volume of water that evaporates from mine land is 656 $Mm^3\ a^{-1}$. Most of the water allocated to mines evaporates from mine land, which leaves behind brines, concentrates and solid waste that need to be disposed of, or managed.

3.3.2 Provincial scale analysis

The analysis of water consumption obtained with MOD16 for each land cover was also done per province. Figure 3.9 summarizes the MOD16 ET data per province and land cover. Detailed statistical data per province can be found in Appendix B and Deliverable 1a of the project. From Figure 3.9, the following was deduced:

- MOD16 is strongly driven by land cover (type and area) and climatic conditions (rainfall).
- Some land covers are not represented in all provinces such as indigenous forests in the Northern Cape. Fynbos is represented only in the Western Cape, Eastern Cape and Northern Cape. Cultivated cane occurs only in KwaZulu-Natal and Mpumalanga.
- The highest MOD16 ET values were associated with land covers such as indigenous forests, cultivated perennial crops and plantations, as well as with high rainfall regions (KwaZulu-Natal, Eastern Cape and Mpumalanga).
- The lowest MOD16 ET values were recorded for land covers such as low shrublands, fynbos shrublands and woodland/open bush, in low rainfall provinces such as North West, Free State and especially the Northern Cape.
- The highest average annual ET was recorded for indigenous forests in the Western Cape (959 mm a^{-1}), followed by cultivated perennial crops in KwaZulu-Natal (928 mm a^{-1}). Sugarcane had also a high ET peaking in KwaZulu-Natal at 905 mm a^{-1}.
- The lowest average annual ET was recorded in the Northern Cape for low shrublands (99 mm a^{-1}), grasslands (109 mm a^{-1}) and woodland/open bush (111 mm a^{-1}).
- Exceptions to general land cover and geographical (climatic) trends were observed. Examples are high MOD16 ET recorded for cultivated perennials, indigenous forests and plantations in Mpumalanga and Limpopo, as these land covers occur mainly along the escarpment with higher rainfall compared to the provincial average. Similarly, the Eastern Cape exhibited exceptions to trends with high MOD16 ET recorded for cultivated subsistence land. These are also land covers characterized by large spatial variability.

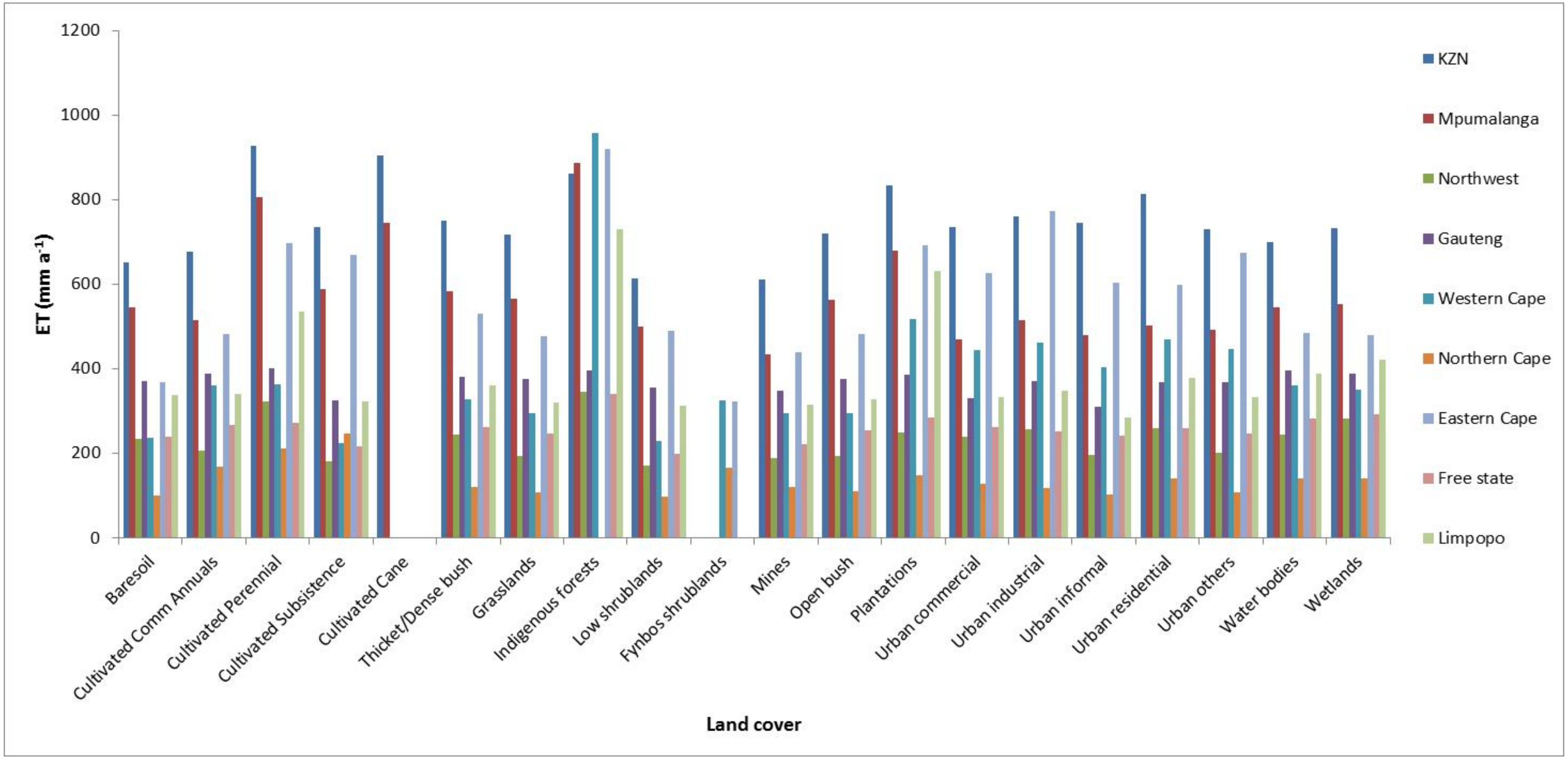


Figure 3.9

MOD16 evapotranspiration (ET) per land cover and per province.

3.3.3 Case study analysis: Wider Cape

Figure 3.10 presents the spatial distribution of MOD16 ET for the wider Cape area (year 2012). It is visible from the map that high ET values occur mainly in the Cape Flats where shallow groundwater is present, and in the surrounding hills possibly from irrigated commercial crops. The high ET estimated on the peninsula could be due to humid conditions in the vicinity of the ocean, and resolution effects. The missing (blank) pixels denote data out of range, predominantly in areas where waterbodies occur (large dams) and in densely urbanized areas. Table 3.2 presents the zonal statistics of ET estimated with MOD16 for each land cover in the wider Cape area (year 2012). More detailed statistical data, frequency distributions and analyses of monthly MOD16 ET data are available in Deliverable 3 of the project. The following observations can be made from the data in Figure 3.10 and Table 3.2:

- In the wider Cape area, the highest average annual ET estimated with MOD16 was for indigenous forests (828 mm a^{-1}) followed by plantations/woodlots (530 mm a^{-1}).
- Thicket/dense bush, woodlands/open bush and urban sports and recreation had annual MOD16 ET between 483 mm a^{-1} and 487 mm a^{-1}.
- The average annual MOD16 ET of all other land uses was between 386 mm a^{-1} for cultivated commercial annuals and 446 mm a^{-1} for cultivated perennial crops. Perennial crops are cultivated/irrigated for longer periods in the year compared to commercial annual crops and therefore they exhibited higher water consumption.
- Grasslands consume slightly more water than cultivated annuals but less than cultivated perennials in the Cape.
- Shrubland fynbos and wetlands are somewhere in the mid-range of water consumption.
- Total water consumption values expressed in 10^6 m^3 a^{-1} depend largely on the area representing a land cover, so the largest water consumers in the Cape are shrubland fynbos, cultivated commercial annuals and cultivated perennials, and the lowest water consumers are mines.
- Maximum and minimum values for all land covers exhibited relatively wide ranges, indicating that specific conditions may occur in different geographic and climatic areas. Standard deviations were the highest for indigenous forests and plantations/woodlots, due to the high spatial variability of these types of vegetation.
- The values also indicate that the median is slightly below the average, except for indigenous forests, indicating that most of the data are spread in the lower range of ET with some extreme high values (outliers) for each land cover.

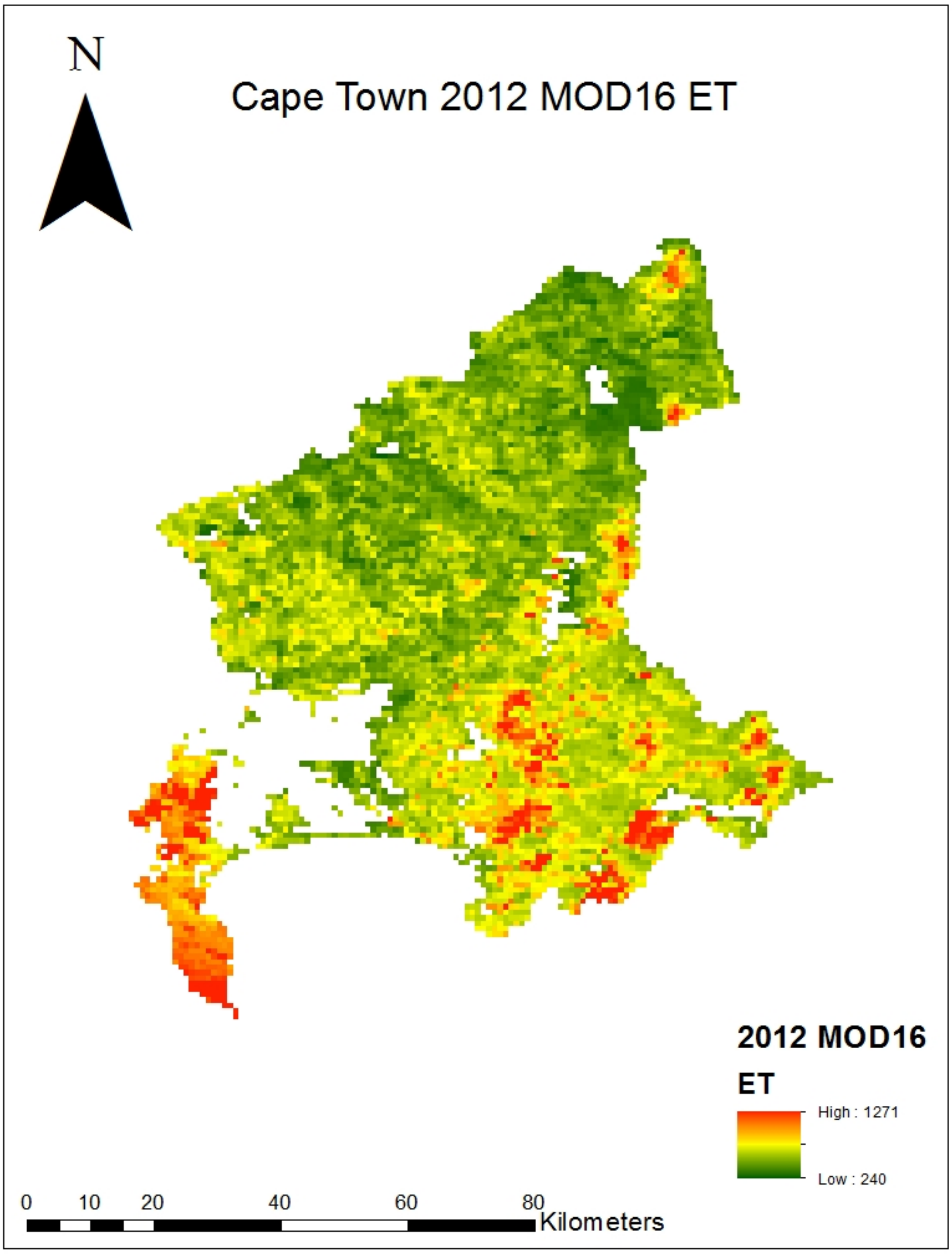


Figure 3.10

Yearly MOD16 evapotranspiration (mm a^{-1}) of the Cape Town area for 2012.

TABLE 3.2

MOD16 evapotranspiration (ET) for each land cover/use group for the year 2012 in the wider Cape area (in descending order according to average ET).

Land cover class grouping	Area (ha)	Evapotranspiration (ET)					
		Average ET (mm a^{-1})	Total water consumption (x $10^6 m^3 a^{-1}$)	Maximum ET (mm a^{-1})	Minimum ET (mm a^{-1})	Median ET (mm a^{-1})	Standard deviation (mm a^{-1})
Indigenous Forest	7765.11	828	3.967062	1271	471	842	195
Plantations / Woodlots	16708.77	530	67.38052	1249	258	484	191
Thicket /Dense bush	479.07	487	259.6776	1271	241	452	144
Woodland/Open bush	53292.33	484	46.92424	1242	241	458	119
Urban sports and recreation	9704.79	483	14.802	1271	245	440	168
Urban residential	34285.86	464	56.75587	1271	245	411	174
Cultivated perennial	192085.9	446	309.8385	1242	260	417	127
Urban others	8409.42	434	29.16163	1186	241	408	123
Shrubland fynbos	135098.8	430	825.745	1271	241	408	108
Wetlands	69440.85	424	70.78024	1249	241	405	102
Waterbodies	12707.55	416	32.32599	1271	241	388	108
Urban commercial	1028.61	411	7.579945	1271	261	384	111
Bare none vegetated	2775.15	410	11.39164	1271	241	396	104
Urban industrial	1845.54	409	7.959023	1232	241	385	119
Grassland	1947.6	407	139.6898	1271	241	390	106
Low shrubland	5945.67	402	33.78866	1242	241	398	96
Cultivated commercial annuals	12223.35	386	521.5365	1143	241	380	62
Mines	3062.79	379	3.897239	763	260	366	69
Urban informal	6719.58	358	21.29092	1143	241	336	91
TOTAL	575526.8	452	2464.492	1271	241	405	122

MOD16 ET data (actual evapotranspiration from open land) were compared to WARMS data (registered water allocations; Section 3.2.3). Bearing in mind the limitations of this comparison that were already explained in the National scale analysis (Section 3.3.1), the following observations were made:

- The volume of water registered in WARMS for sector agriculture – irrigation was 433 $Mm^3 a^{-1}$ (439 $Mm^3 a^{-1}$ including aquaculture and livestock watering). The volume of water consumed from cultivated land (cultivated perennial and commercial annuals) was 831 $Mm^3 a^{-1}$ as estimated with MOD16.

- The volume of water evaporating from non-agricultural vegetated land amounted at 1,448 $Mm^3\ a^{-1}$, and it outweighed the agricultural water consumption estimated with MOD16 and the volume of water registered in WARMS for agriculture.
- The total volume of water registered in WARMS for industry, mining, urban and water supply services is 358 $Mm^3\ a^{-1}$. The total volume of water that evaporates from urban land uses (mines, commercial, industrial, informal, commercial, residential, sports and recreation and others) was 141 $Mm^3\ a^{-1}$. The total volume of water that evaporates from urban areas is less than half the water supplied to industry and domestic users. There may be therefore a case for re-use of some of the water in urban areas.

3.3.4 Case study analysis: Inkomati

Figure 3.11 presents the spatial distribution of MOD16 ET for the Inkomati catchment (year 2012). High ET values occurred mainly along the escarpment (plantations/woodlots to the central west), in the Lowveld (cultivated perennial crops to the north) and in the southern parts of the catchment (sugarcane cultivation). The south-western (Highveld) and north-eastern (Kruger Park) parts of the catchment show generally low ET. The missing (blank) pixels are due to data out of range, predominantly in densely urbanized areas. Table 3.3 presents the zonal statistics of ET estimated with MOD16 for different land uses in the Inkomati catchment (year 2012). More statistical information, frequency distributions and monthly MOD16 ET analyses are available in Deliverable 3 of this project. The following observations can be made from the data in Figure 3.11 and Table 3.3:

- In the Inkomati catchment, the highest annual water consumption was estimated for plantations/woodlots (1009 mm a^{-1}), indigenous forests (999 mm a^{-1}), followed by cultivated perennials (830 mm a^{-1}), cultivated cane (775 mm a^{-1}) and thicket/dense bush (683 mm a^{-1}). The lowest water consumption was estimated for mines (509 mm a^{-1}). Water consumption for other land covers varied from 531 mm a^{-1} for urban others to 652 mm a^{-1} for wetlands.
- Cultivated commercial annual crops and cultivated subsistence land showed lower water consumption (567 and 577 mm a^{-1}, respectively) compared to cultivated perennials and cane (830 and 775 mm a^{-1}, respectively), possibly due to the latter being more intensive agricultural systems. Grasslands consumed on average 575 mm a^{-1}, very similar to annual crops and cultivated subsistence land.
- By far the highest water consumers in the Inkomati catchment (expressed in $Mm^3\ a^{-1}$) were thicket/dense bush, woodlands/open bush, grassland and plantations/woodlots, and the lowest were low shrublands and urban area.

- Standard deviations were the highest for plantations/woodlots and indigenous forests. The median was generally close or below the average values, with some exceptions such as for plantations/woodlots.

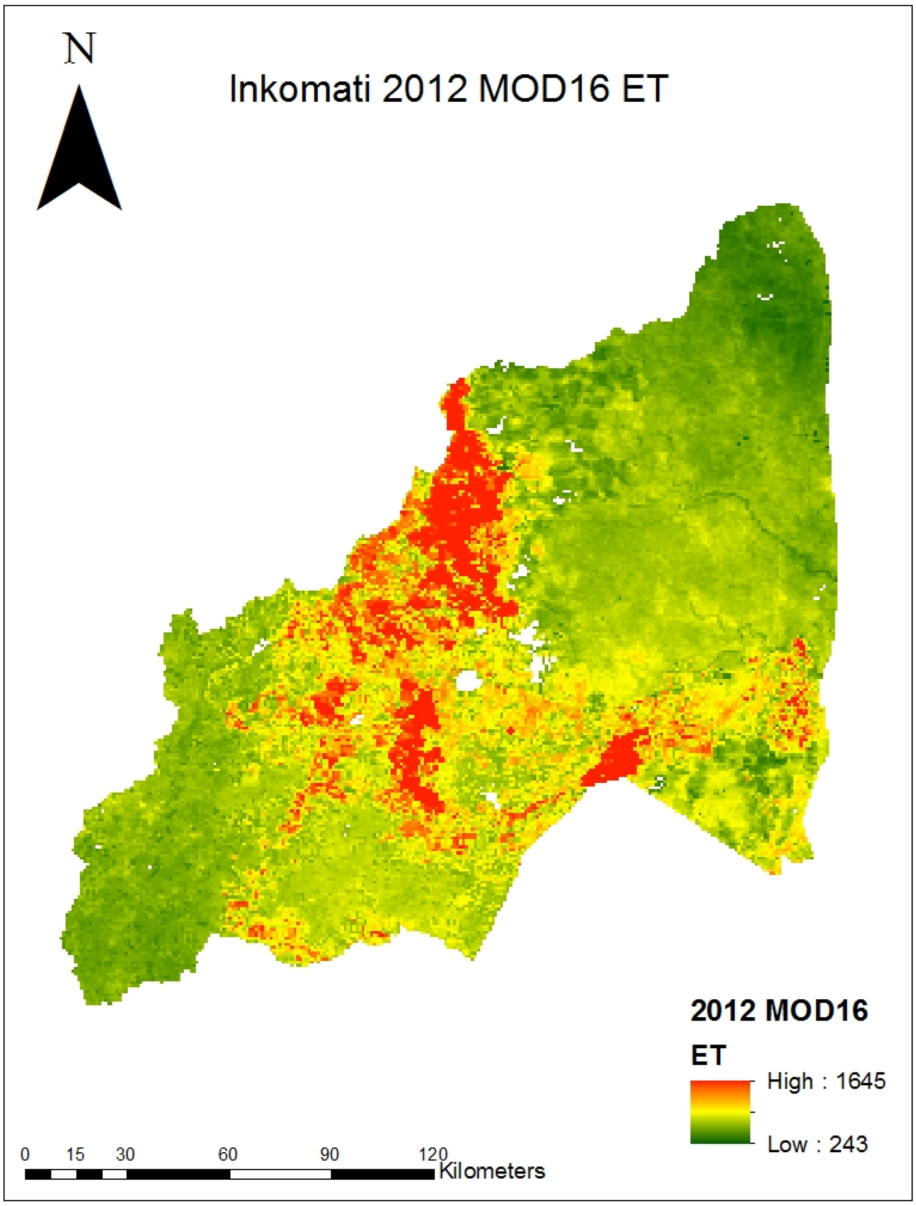


Figure 3.11

Yearly MOD16 evapotranspiration (mm a^{-1}) in the Inkomati catchment for 2012.

TABLE 3.3
MOD16 evapotranspiration (ET) for each land cover/use group for the year 2012 in the Inkomati area (in descending order according to average ET).

Land cover class grouping	Area (ha)	Evapotranspiration (ET)					
		Average ET (mm a^{-1})	Total water consumption (x 10^6 m^3 a^{-1})	Maximum ET (mm a^{-1})	Minimum ET (mm a^{-1})	Median ET (mm a^{-1})	Standard deviation (mm a^{-1})
Plantations / woodlots	8250.84	1009	3923.86	1645	302	1057	273
Indigenous Forest	39964.05	999	231.46	1423	430	997	240
Cultivated perennials	23163.57	830	343.61	1431	349	813	217
Cultivated cane	651590.7	775	476.42	1469	331	722	230
Thicket /Dense bush	684765	683	4447.33	1600	243	652	172
Wetlands	675283.5	652	260.46	1412	291	611	183
Urban industrial	8801.73	649	5.82	1355	397	627	155
Urban sports and recreation	109131.9	647	6.65	1366	338	650	146
Waterbodies	41414.31	611	50.43	1453	291	555	231
Urban residential	31697.28	609	31.34	1189	307	601	112
Bare none vegetated	61439.49	580	25.52	1431	284	534	160
Cultivated subsistence	388694	577	182.83	1227	331	580	92
Grassland	4302.81	575	3882.52	1600	243	560	131
Urban commercial	4399.65	574	3.21	1134	338	544	165
Cultivated commercial annuals	558.09	567	619.16	1369	364	542	113
Urban informal	898.02	563	44.43	1342	338	570	95
Woodland/Open bush	7887.15	550	3764.58	1645	243	546	123
Low shrubland	5147.73	550	48.38	1600	247	532	154
Urban others	1027.08	531	405.64	1436	294	507	123
Mines	76461.48	509	21.89	1369	325	469	137
TOTAL	2824878	652	18775.53	1645	243	575	163

Comparing MOD16 ET results to WARMS data (Section 3.2.4), and bearing in mind the limitations of the comparison:

- The volume of water registered in WARMS for sector agriculture – irrigation was 1,054 Mm^3 a^{-1} (1,058 Mm^3 a^{-1} including aquaculture and livestock watering). The volume of water consumed from cultivated land (cultivated perennial and commercial annuals, cultivated subsistence and cane) was 1,622 Mm^3 a^{-1}, as estimated with MOD16.
- The volume of water evaporating from non-agricultural vegetated land amounted at 16,559 Mm^3 a^{-1}, and it outweighed by far the agricultural water consumption estimated with MOD16 and the volume of water registered in WARMS for agriculture.

- The total volume of water registered in WARMS for industry, mining, urban and water supply services was 297 $Mm^3\ a^{-1}$. The total volume of water that evaporates from urban land uses (mines, commercial, industrial, informal, commercial, residential, sports and recreation and others) is 519 $Mm^3\ a^{-1}$. The total volume of water that evaporates from urban areas is nearly double the water supplied to industry and domestic users. There may be therefore a case for capturing some of the rainwater before it reaches the ground and evaporates in urban areas (e.g. rainwater harvesting).

Comparing the Cape study area (Section 3.3.3) and the Inkomati catchment, the following considerations can be made:

- Some land covers are not present in both study areas: shrubland fynbos is not present in the Inkomati catchment, while cultivated cane and cultivated subsistence do not occur in the Cape area. The MOD16 ET estimated for the Inkomati catchment was higher compared to the wider Cape area, indicating the difference in climatic regions.
- The highest MOD16 ET values at both study sites were associated with land covers such as indigenous forests, cultivated perennial crops and plantations. The lowest MOD16 ET values were recorded for land covers such as low shrublands, mines and urban areas.
- Maximum and minimum values for all land covers in the Inkomati catchment exhibited higher variability than in the Cape area.
- Total water uses in $Mm^3\ a^{-1}$ were much higher in the Inkomati catchment because it covers a much larger area of 28,249 km^2 compared to 5,755 km^2 of the Cape study site.

3.4 ETLook evapotranspiration

3.4.1 National scale analysis

Actual ET derived from ETLook for the period August 2014-July 2015 is shown on the map in Figure 3.12. By overlaying on the NLC2013/14 map in GIS, ETLook values were extracted for each land cover according to the land cover/use groups described in Table 2.3. A projected *Albers Equal Area (Africa)* coordinate system was used. The water consumption (ET) data estimated with ETLook and extracted for each land cover/use group at national scale are summarized in Table 3.4 (average, median, minimum, maximum, standard deviation in $mm\ a^{-1}$, and total in $m^3\ a^{-1}$). Statistical analyses for monthly values of ET are available in Deliverable 1b of this project.

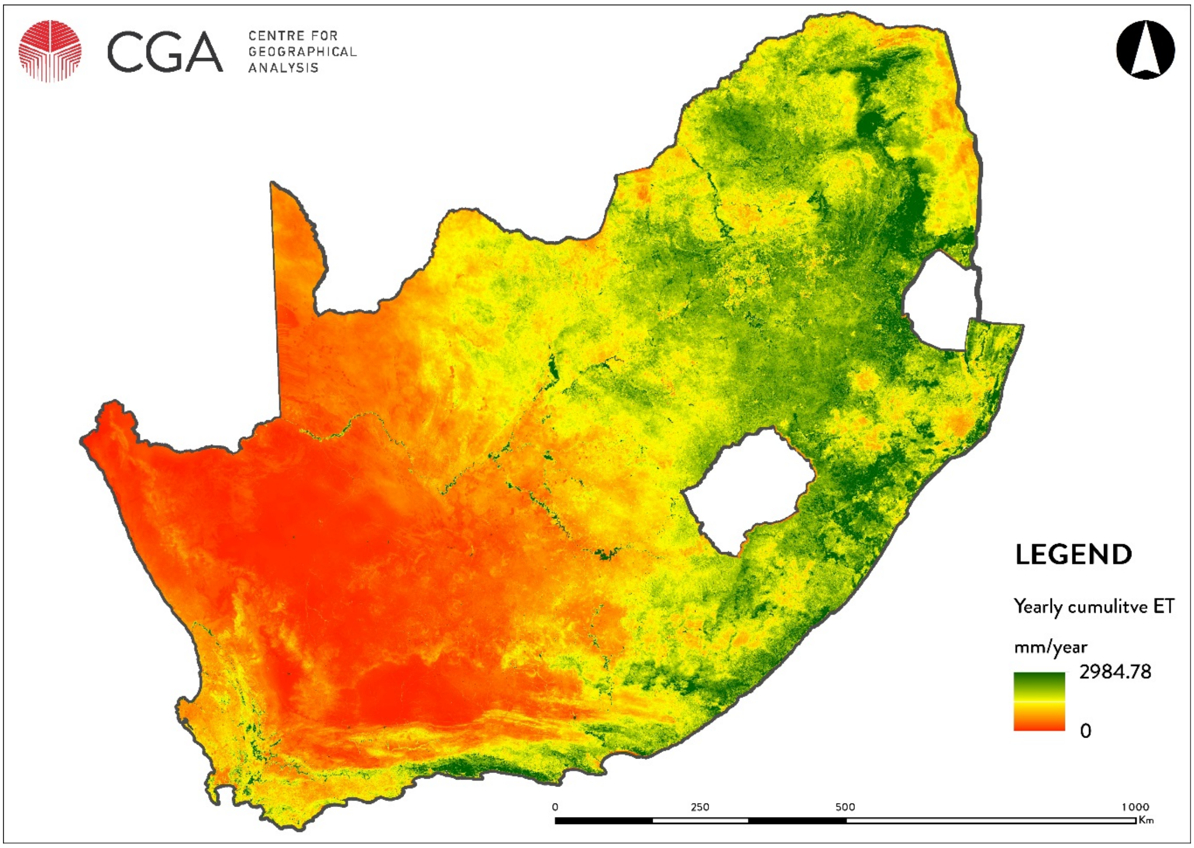


Figure 3.12

Annual ETLook evapotranspiration data from August 2014 to July 2015 at 250 m resolution.

TABLE 3.4

ETLook evapotranspiration (ET) for each land cover/use group for the year 2014/15 at national scale (in descending order according to average ET).

Land cover class grouping	Area (ha)	Evapotranspiration (ET)					
		Average ET (mm a^{-1})	Total water consumption (x 10^6 m^3 a^{-1})	Maximum ET (mm a^{-1})	Minimum ET (mm a^{-1})	Median ET (mm a^{-1})	Standard deviation (mm a^{-1})
Waterbodies	344260.53	1463	5036.98	3066	2	1779	806
Indigenous forest	325527.48	848	2761.81	2684	34	864	219
Plantations/woodlots	1400767.56	837	11724.7	2920	12	838	222
Cultivated cane	354507.21	787	2790.22	2359	145	776	201
Cultivated perennial	407692.62	752	3065.52	2795	7	720	339
Wetlands	768567.51	618	4748.98	2969	3	615	308
Thicket/dense bush	6218391.06	532	33094.28	3066	2	537	212
Cultivated commercial annuals	8216788.41	520	42767.56	3031	2	525	180
Cultivated subsistence	1537085.25	513	7879.56	2965	19	507	139
Grasslands	19476771.66	489	95155.72	3036	2	494	158
Urban other	1679195.79	438	7353.53	2870	6	431	128
Woodland/open bush	9118093.41	435	39667.35	3066	2	445	177
Urban residential	232745.13	411	956.82	2672	4	423	158
Urban industrial	42001.38	351	147.58	2652	5	346	154
Urban commercial	39329.28	349	137.27	2598	5	349	146
Urban informal	190101.69	331	629.96	2562	6	329	114
Mines	245002.68	285	698.18	2999	2	295	175
Shrublands fynbos	4157729.91	257	10677.05	2457	2	229	160
Low shrublands	27829582.11	201	55995.9	3066	2	167	136
Bare soil	9738274.95	49	4786.36	3036	2	25	92
TOTAL	92322415.62	-	330075.33	3066	2	-	-

From Figure 3.12 and Table 3.4, it is clear that, apart from waterbodies, natural forests (848 mm a^{-1}) and plantations (837 mm a^{-1}) contribute the most to absolute water use at national scale. Cultivated annuals consume less water (42,768 Mm^3 a^{-1}) than grasslands and low scrublands, with the former consuming most water (95,156 Mm^3 a^{-1}). One should, however, interpret these values with caution as there are large variations in the extracted values. These variations are likely attributed to climatic conditions, but the resolution of the ET data (250 m) may also play a significant role. Many of the land cover/use areas (polygons) are small (as small as 30 x 30 m) which means that ET values are heavily influenced by neighbouring land cover/use. A small bare area located adjacent to a waterbody will likely have abnormally large ET values. Efforts to reduce such contaminations (through sampling of “pure” pixels) are on-going.

For a classification analysis on potential drivers of water use, machine learning techniques, specifically Random Forest (RF) and Classification and Regression Tree Analysis (CART) (Salford Systems Predictive Modeller), were implemented. CART is a robust decision tree classifier designed for data mining and predictive modelling (Steinberg and Golovnya, 2007). RF, as defined by Breiman (2001), is an ensemble of unpruned CART-like tree classifiers (Pal, 2005; Gislason et al., 2006). Unlike CART and other common decision tree classifiers, RF is less sensitive to overfitting (Breiman, 2001) and has been shown to be an effective feature selection tool (Gislason et al., 2006; Cutler et al., 2007).

Because CART and RF rely on categorical target classes, ET values were grouped into ordinal levels of water use (low to high) using the natural breaks algorithm (Jenks, 1967). A total of 100 points were randomly selected from each of the classes to ensure an evenly distributed training dataset. Each point was used to extract values from each of the spatial datasets described in Sections 2.2.1 and 2.2.6 (elevation, slope, geology, average soil depth, soil clay content, mean annual rainfall and mean annual temperature). These values were used as inputs to the machine learning algorithms.

The output of CART and RF is a classification, classification accuracy measures and variable importance lists (VILs). The VILs summarize the contribution of a particular feature to the classification success and gives recognition to the variables for which significance is hidden by other variables in the process of tree building (Steinberg and Golovnya, 2007). The VILs essential function is to reduce the feature dimensionality and the computational requirement, while preserving the overall accuracy of the classification (Yu et al., 2006; Laliberte et al., 2007). In this case, the VIL may highlight potential drivers of water use.

The CART slightly outperformed the RF classification, both achieving relatively good overall accuracies with 73% and 72.3% respectively. The VILs are summarized in Tables 3.5 and 3.6. The two datasets that had the most significant influence on the machine learning models were the NLC2013/14 land cover and the mean annual rainfall.

TABLE 3.5 Variable importance list for the Classification and Regression Tree Analysis (CART) of ETLook evapotranspiration at national scale.		
Spatial data set	**Percentage importance (%) (large tree size, 45 nodes)**	**Percentage importance (%) (small tree size, 14 nodes)**
Land cover/use groups	100	100
Mean annual rainfall	68.88	63.47
Average soil clay content	45.81	38.22
Slope	39.93	33.92
Average soil depth	39	32.43
Elevation	21.55	14.8
Geology	13.57	7.25
Mean annual temperature	8.92	3.46

TABLE 3.6 Variable importance list for the Random Forest (FR) classification of ETLook evapotranspiration at national scale.	
Spatial data set	**Percentage importance (%)**
Mean annual rainfall	100
Land cover/use groups	73.87
Average soil clay content	32.07
Average soil depth	24.74
Slope	23.49
Elevation	7.33
Geology	2.86
Mean annual temperature	2.83

3.4.2 Provincial scale analysis

Table 3.7 summarizes the water use estimations per province. On average, Mpumalanga uses the most water per unit area (686 mm a^{-1}), most likely because it receives high rainfall and is characterized by vegetation types and land uses that consume more water. Conversely, the Northern Cape uses the least water per unit area (215 mm a^{-1}). Despite being the largest province (29.9% of the surface area), the Northern Cape consumes less water overall (in m^3 a^{-1}) than most of the other smaller provinces. The Eastern Cape is the largest user of water (16.6%), even though it is relatively small (14%). The Limpopo and Free State are also large users of water. In terms of size they are comparable with the Western Cape (10%), but consume more than double the water. Climatic variations are the most likely drivers of these large differences in water use. The ETLook ET statistics of the nine provinces can be found in Deliverable 3 of this project.

TABLE 3.7
Summary of water use (evapotranspiration) per province obtained with the ETLook algorithm.

Province	Area		Evapotranspiration		
	Km^2	%	Average (mm a^{-1})	Total (Mm^3 a^{-1})	%
Eastern Cape	169,626	14.0	526	70,678	16.6
Limpopo	122,452	10.1	681	64,359	15.1
Free State	128,612	10.6	513	60,499	14.2
Kwa-Zulu Natal	92,062	7.6	613	55,688	13.0
North West	116,078	9.6	547	51,095	12.0
Mpumalanga	78,691	6.5	686	49,807	11.7
Northern Cape	362,020	29.9	215	39,904	9.3
Western Cape	126,182	10.4	348	25,772	6.0
Gauteng	16,927	1.4	587	9,242	2.2

3.4.3 Case study analysis: Wider Cape

Figure 3 shows yearly ET for the Cape Town study area, whilst the zonal statistics is presented in Table 3.8.

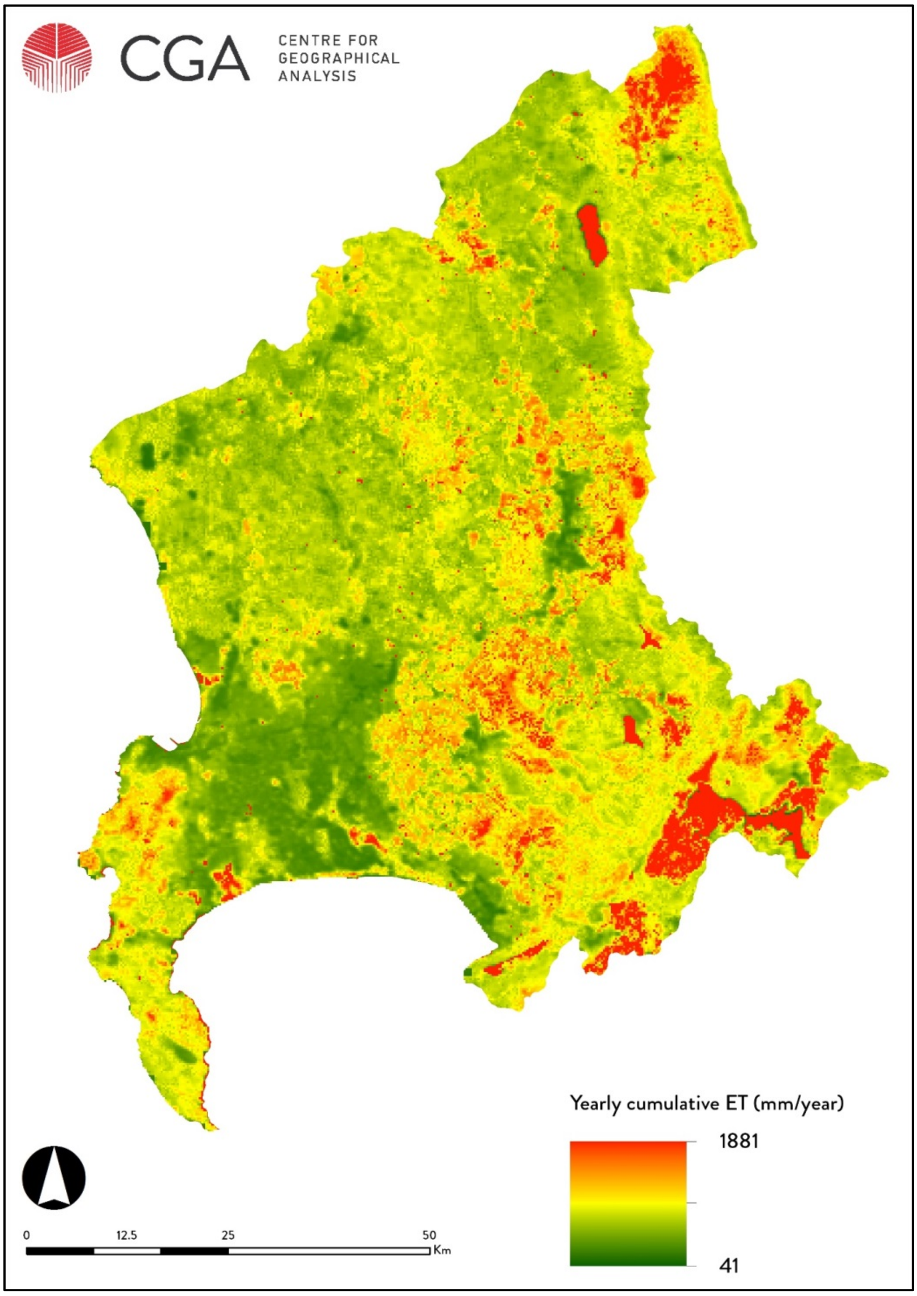


Figure 3.13

ETLook evapotranspiration ET (mm a^{-1}) of the Cape Town area for the 2014/15 period.

TABLE 3.8 Evapotranspiration for each land cover/use group for the year 2014/15 in the Cape study area (in descending order according to average ET).							
Land cover class grouping	Area (ha)	Evapotranspiration (ET)					
		Average ET (mm a^{-1})	Total water consumption (x 10^6 m^3 a^{-1})	Maximum ET (mm a^{-1})	Minimum ET (mm a^{-1})	Median ET (mm a^{-1})	Standard deviation (mm a^{-1})
Waterbodies	12740	1227	202	1881	42	1586	611
Indigenous Forest	18250	682	3.32	923	361	698	112
Cultivated perennial	480	584	378	1875	42	532	230
Plantations / Woodlots	58610	485	60.9	1869	104	465	186
Wetlands	10210	455	68.7	1881	42	376	269
Thicket/Dense bush	36500	430	235	1875	42	400	191
Woodland/Open bush	204650	413	41.1	1879	42	402	152
Shrubland fynbos	9870	369	725	1879	42	354	139
Grassland	136120	337	116	1879	42	317	137
Cultivated annuals	70980	335	440	1881	43	323	92
Bare none vegetated	13090	313	9.49	1881	46	297	240
Urban sport and recreation	1240	307	19.4	1787	69	269	170
Low shrubland	3190	305	31	1865	58	314	113
Mines	7350	268	2.51	1850	75	201	236
Urban others	5930	268	22.2	1849	68	247	142
Urban residential	14000	232	62	1806	68	207	110
Urban industrial	29910	197	9.16	1812	69	155	134
Urban commercial	7230	196	13	1783	68	177	104
Urban informal	9000	165	21.5	1824	72	154	72
TOTAL	649340	-	2459	1881	42	-	-

Shrubland fynbos is the largest user of water (725 Mm^3 a^{-1}, or 26.6%), mainly because it is the dominant land cover (31.5%) in the region (Table 3.8). On average, shrubland fynbos uses 354 mm a^{-1}, which is much lower than other land covers. For instance, indigenous forests use 698 mm a^{-1}, but because they cover a relatively small area (0.1% of the region), their cumulative water consumption is only 3.3 Mm^3 a^{-1} (0.1% of total water used). Overall, natural vegetation contributes 43.6% to the total water use in the region. Cultivation and plantations are the second largest land use/cover (31.4%), with perennial crops (mostly irrigated) being an intensive user (532 mm a^{-1}). However, given that they only cover 10.9% of the surface area, they contributed to only 13.8% of the annual water used in the region. Urban land uses (in combination) constitute 11.3% of the surface area, but contributed 15% to the cumulative water used, with industrial use being the main consumer (12.6%). These urban water use records were taken directly from the WARMS database and require cross-validation with the City of Cape Town's records.

RF and CART analyses were used to identify the VILs for evapotranspiration in the Cape area. The results are presented in Tables 3.9 and 3.10. The relatively high accuracies (70% to 73%) of the classifications suggest that the machine learning models were able to establish a strong relationship between water use and the various predictor variables. It also suggests that the water use categories (as determined by natural breaks) are representative. According to the VILs, the main driver of water use is land cover/use (100% importance for both algorithms). Soil depth and elevation were also highlighted as having an influence on water use, but at a much-reduced level (45% and 30%) compared to land cover.

TABLE 3.9

Variable importance list for the Classification and Regression Tree Analysis (CART) of water use in the Cape study area.

Spatial data set	Percentage importance (%)
Land cover/use groups	100
Average soil depth	45.18
Slope	36.66
Average soil clay content	34.59
Elevation	28.76

TABLE 3.10

Variable importance list for the Random Forest (RF) classification of water use in the Cape study area.

Spatial data set	Percentage importance (%)
Land cover/use groups	100
Elevation	29.96
Average soil depth	24.75
Average soil clay content	21.72
Slope	15.46

3.4.4 Case study analysis: Inkomati

Figure 3.14 shows ET derived from ETLook for the 2014/15 season. The zonal statistics is presented in Table 3.11. When the water use data are analysed geographically, it is clear that most of the water is being used in the central and south-eastern parts of the study area (Figure 3.14). Most of the area (73.6%) is covered by natural vegetation, while cultivation makes up 22.2% of the land use. Forestry (plantations) is by far the largest individual land user (13.6%) and contributes to 21% (4,062 $Mm^3 a^{-1}$) of the overall water use in the area (Table 3.11). Perennial crops, plantations, indigenous forests and cultivated cane are the largest users of water per unit area (more than 1,000 mm a^{-1} each). The contribution of evaporation from water bodies (1%) is much lower compared to the Cape Town area, partly because a smaller proportion of the area (0.3%) is covered by water bodies and because the climate is less dry (especially during the warm summer season).

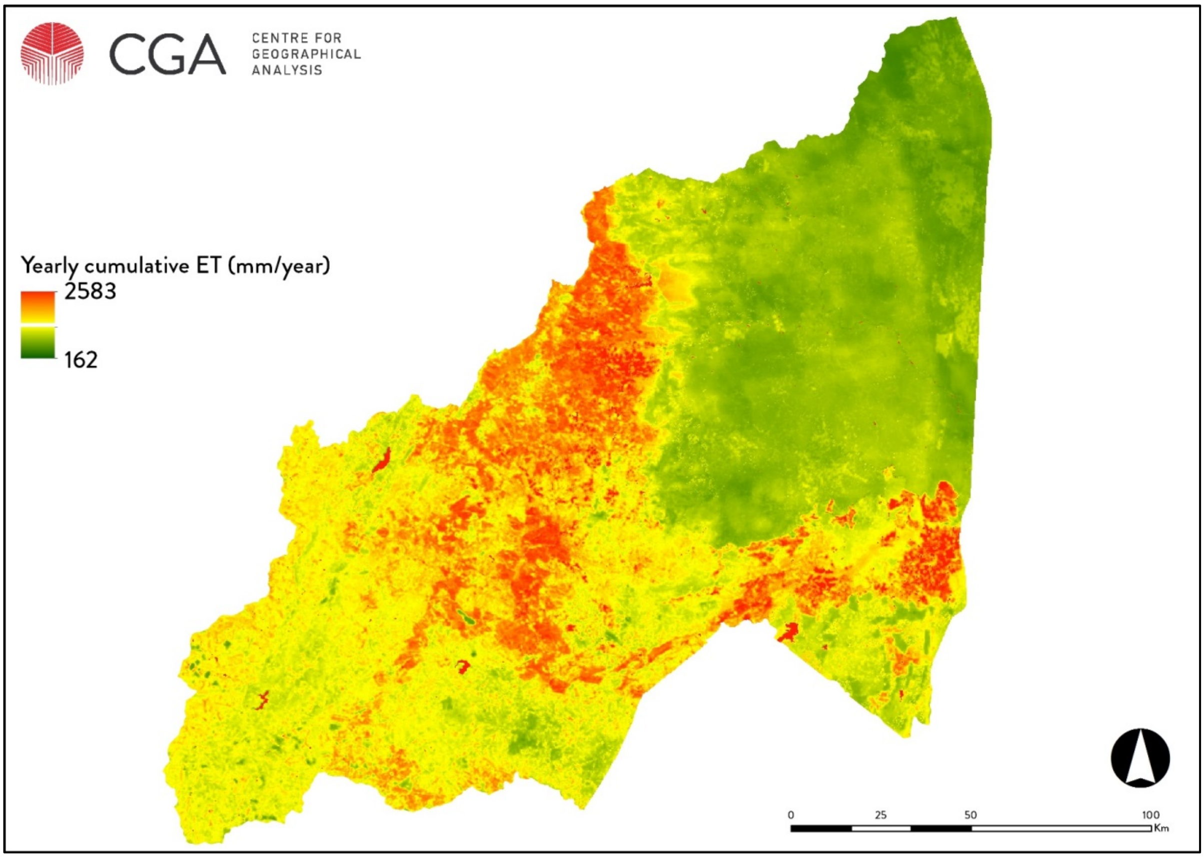


Figure 3.14

ETLook evapotranspiration ET (mm a^{-1}) of the Inkomati study area for the 2014/15 period.

TABLE 3.11
Evapotranspiration for each land cover/use group for the year 2014/15 in the Inkomati study area (in descending order according to average ET).

Land cover class grouping	Area (ha)	Evapotranspiration (ET)					
		Average ET (mm a^{-1})	Total water consumption (x 10^6 m^3 a^{-1})	Maximum ET (mm a^{-1})	Minimum ET (mm a^{-1})	Median ET (mm a^{-1})	Standard deviation (mm a^{-1})
Waterbodies	9550	1557	185	2583	232	1939	677
Cultivated perennial	40360	1093	448	2424	353	1068	292
Cultivated cane	23260	1022	636	2378	159	1032	233
Indigenous Forest	658670	1013	242	2409	467	1041	159
Plantations / Woodlots	691020	1009	4062	2478	297	1043	198
Wetlands	679590	774	305	2448	271	756	192
Cultivated commercial annuals	8940	727	784	2382	276	711	121
Urban sport and recreation	110250	703	8.77	1205	301	707	226
Bare none vegetated	41900	640	26.4	2583	210	591	338
Grassland	30960	629	4416	2518	141	650	158
Thicket/Dense bush	61650	613	4031	2583	139	612	206
Cultivated subsistence	389330	594	184	2463	160	595	141
Urban industrial	4340	587	6.87	1788	324	548	178
Urban residential	4470	572	34.5	1957	278	556	101
Low shrubland	930	546	48.9	2489	165	547	198
Urban others	1260	485	379	2396	258	464	126
Mines	9900	473	19.7	2468	232	454	159
Urban commercial	6200	468	4.23	1080	258	454	113
Urban informal	1240	465	44	2284	295	444	95
Woodland/Open bush	81680	420	2795	2583	149	404	146
TOTAL	2855500	-	18660	2583	139	-	-

CART and RF analyses identified the VILs for the Inkomati study area (Tables 3.12 and 3.13). The overall accuracies (81%) are higher than those of the wider Cape study site and suggest that the models and classifications are a good representation of water use. As with the wider Cape results, land cover/use dominated the VILs (100% importance), showing that it is by far the most important driver of water use in the Inkomati area. The climatic variables, particularly rainfall and temperature, played a more important role in Inkomati than in the wider Cape study site. The size of the Inkomati region and the associated variations in climate may have been the main factors contributing to this finding.

TABLE 3.12 Variable importance list for the Classification and Regression Tree Analysis (CART) of water use in the Inkomati study area.	
Spatial data set	**Percentage importance (%)**
Land cover/use groups	100
Average soil depth	45.18
Slope	36.66
Average soil clay content	34.59
Elevation	28.76

TABLE 3.13 Variable importance list for the Random Forest (RF) classification of water use in the Inkomati study area.	
Spatial data set	**Percentage importance (%)**
Land cover/use groups	100
Elevation	29.96
Average soil depth	24.75
Average soil clay content	21.72
Slope	15.46

3.5 Comparison of MOD16 ET and ETLook ET

In the previous Sections, evapotranspiration data derived from MOD16 (Section 3.3) and ETLook (Section 3.4) were processed and interpreted. Although MOD16 yearly ET was estimated for 2012 and ETLook data refer to 2014/15 and the two algorithms produce ET at different resolutions (250 m for ETLook and ~1 km for MOD16), it was deemed worth to compare the results from two different satellite-based ET products.

Spatial representations of ET with MOD16 (Figure 3.10 for the wider Cape and Figure 3.11 for the Inkomati catchment) were compared with ETLook maps (Figure 3.13 for the wider Cape and Figure 3.14 for the Inkomati). The similarity in spatial patterns is evident in the maps. Both ET estimation methods appear to be suitable to indicate areas of low ET and hotspots of high ET. They generally provide realistic spatial patterns that can be interpreted based on the land uses.

At national scale, the following observations were made:

- Indigenous forests exhibited high average ET values for both products and they were comparable: 801 mm a^{-1} for MOD16 and 848 mm a^{-1} for ETLook.
- Water bodies were the highest water consumer with ETLook (1,463 mm a^{-1}). MOD16 estimation of evaporation from water bodies is known to have shortcomings.
- Plantations/woodlots feature high on the water consumption list for both products, however higher ET was estimated with ETLook (837 mm a^{-1}) compared to MOD16 (557 mm a^{-1}). Similar results were obtained for land cultivated with perennial crops.
- ET from annual crops obtained with ETLook (520 mm a^{-1}) was higher compared to MOD16 (350 mm a^{-1}). However, the opposite was recorded for cultivated subsistence land.
- In general, ETLook estimated higher ET for wetlands, thicket/dense bush, woodlands/open bush and grasslands compared to MOD16. These land uses are in the middle of the list of water consumers.
- MOD16 estimated higher ET from urban land compared to ETLook.
- Estimates of ET with the two products were close in the low range of ET (mines, fynbos shrubland and low shrubland).
- Bare soil produced higher ET for MOD16 (234 mm a^{-1}) compared to ETLook (49 mm a^{-1}).
- In general, given the principles driving the underlying algorithms, the range of ET values estimated with ETLook were much wider than those estimated with MOD16. This is evident from the maximum and minimum values, although the standard deviations were in the same range for most land covers.

For the wider Cape study site, the following was observed:

- The total areas considered were not much different: 5,755 km^2 for MOD16 and 6,493 km^2 for ETLook.
- Total water consumption was 2,464 Mm^3 a^{-1} for MOD16 and 2,459 Mm^3 a^{-1} for ETLook, which is very similar.
- With the exception of water bodies, indigenous forests exhibited the highest average ET values for both products, 828 mm a^{-1} with MOD16 and 682 mm a^{-1} with ETLook.
- ET from annual crops obtained with ETLook (335 mm a^{-1}) was lower compared to MOD16 (386 mm a^{-1}). However, the opposite was recorded for cultivated perennials (584 mm a^{-1} with ETLook and 446 mm a^{-1} with MOD16).

- For other vegetated areas, MOD16 generally estimated higher ET than ETLook, but the values were not dramatically different.
- MOD16 also estimated higher ET from urban land and mines compared to ETLook.

For the Inkomati catchment, the following observations were made:

- The total areas considered were very similar: 28,249 km^2 for MOD16 and 28,555 km^2 for ETLook.
- Total water consumption was 18,776 Mm^3 a^{-1} for MOD16 and 18,660 Mm^3 a^{-1} for ETLook, which is very similar.
- With the exception of water bodies, cultivated perennials exhibited the highest average ET values with ETLook (1,093 mm a^{-1}), and plantations/woodlots with MOD16 (1,010 mm a^{-1}).
- ET from crops (annual, perennial, subsistence and cane) obtained with ETLook were all higher compared to MOD16.
- For other land uses, MOD16 and ETLook did not show substantial differences in terms of average ET values.

4 HISTORIC LAND USE AND WATER USE

4.1 Approach

The main purpose of this Chapter was to quantify the relationships between each land cover/use group and water use based on historic data (Objective 2 of the project). The historic relationships of water use and land use are presented using primarily WARMS data (updated up to August 2016), the NLC2013/14 and NLC1990 maps, satellite-derived air temperature, VPD and MOD16 ET data (2000-2012) as well as rainfall data from the SAWS and Schulze (2006). Data were analysed at National, provincial and case study site scales (Inkomati and wider Cape area). Primary observations and findings are discussed in the Sections below. More detailed analyses can be found in Deliverables 5 and 7 associated to this WRC project.

4.2 WARMS and Municipality databases

For the purpose of the historic analyses of WARMS water uses (registrations) at national and provincial scales, data for taking water from a water resource were used for each Province/Regional Office/Catchment Management Agency. In order to get an overview of the historic trends, registration data were sorted by year to include all active registrations for each year from 2000 until 2016.

In order to analyse water uses at the case study scales (Wider Cape and Inkomati), Municipality data of water use per suburb were acquired from the City of Cape Town and the City of Mbombela. The water use for the City of Cape Town was determined by using a combination of MOD16 ET (natural and agricultural land) and water use data from the City of Cape Town (urban areas). The water use for Inkomati was determined using MOD16 ET data solely because the study site is dominated by natural vegetation and agricultural activities. Satellite-derived MOD16 evapotranspiration therefore provided a good coverage of spatial water use in the Inkomati catchment.

4.2.1 National scale analysis

The historic water uses countrywide per water sector are represented in graphical format in Figure 4.1. The following findings are highlighted from the data presented in Figure 4.1:

- Water use registrations have been increasing fairly steadily in South Africa since 2000. The increase was sharp in the period 2000-2003 due to registrations of existing users being entered into the system, followed by a period of small and steady increase.

- Water use registrations for irrigation were the highest countrywide since 2000, followed by water supply services, urban industry and mining.
- In the last four years, water use registrations for non-urban industry overtook the mining sector. The remaining water sectors use substantially less water according to the WARMS registrations.

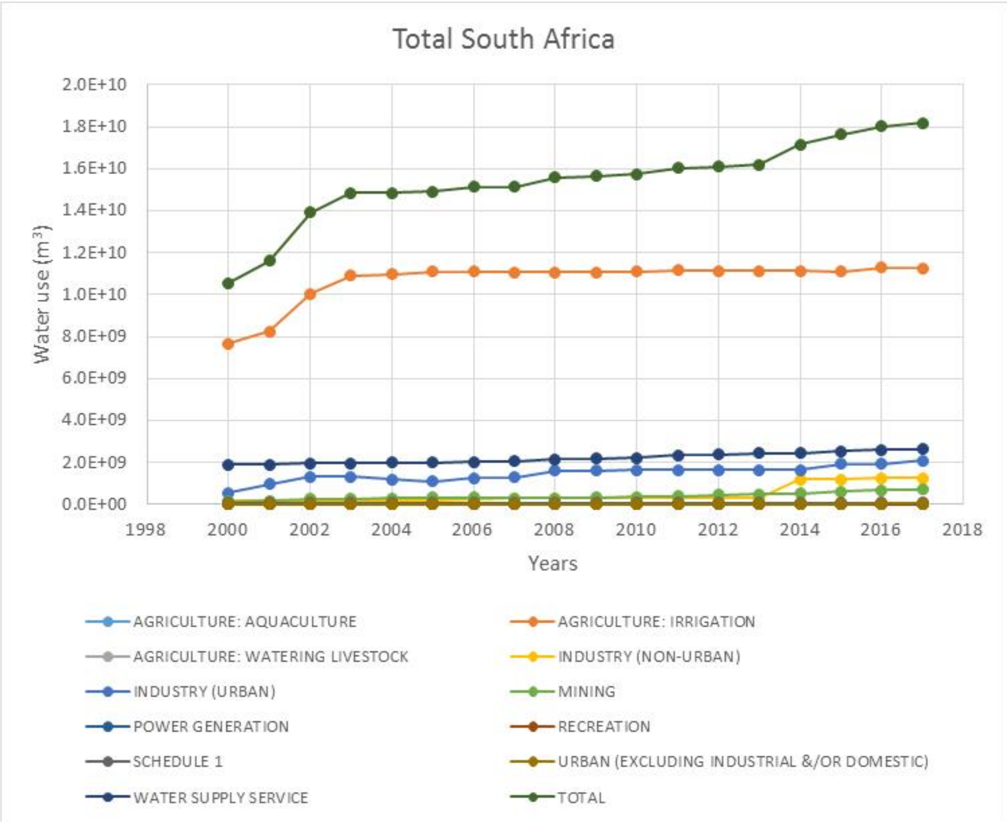


Figure 4.1

Yearly water volumes (m^3 a^{-1}) registered in the WARMS database countrywide per water sector for taking water from a water resource.

4.2.2 Provincial scale analysis

The historic water uses per Province/Regional Office/Catchment Management Agency and per water sector are represented in graphical format in Figure 4.2 (a and b). The following observations were made from the data presented in Figure 4.2 (a and b):

- Total water use registrations increased steadily in all provinces since 2000, with a few exceptions. Water use registrations for irrigations were generally on the increase since 2000 in all provinces.

- Sharp increases were observed in the period 2000-2003 for Breede-Gouritz, Gauteng, Inkomati-Usuthu, Lower Orange, Lower Vaal, Mpumalanga, North West and Western Cape (possibly due to registrations of new users).
- From 2003 on, water use registrations for irrigation slightly decreased in Gauteng, Inkomati-Usuthu, Limpopo and North West.
- Irrigation was the highest water user in all provinces, except in Gauteng where urban industry is the highest user of water. Considerable water use registrations for urban industry were also recorded for Inkomati-Usuthu, North West and Western Cape. All provinces had also relatively high water uses registered for water supply services, although this depends on the type of water supply in place. Water use registrations for other sectors were generally less.
- In Breede-Gouritz, irrigation was by far the major water user, followed by water supply services and urban industry.
- In the Eastern Cape, irrigation was followed by water supply services. The volumes displayed a rise in 2011 for water supply services when some new districts were registered in the database.
- A slight increase in all sectors was generally recorded for Free State.
- In Gauteng, water use registrations by industry (urban) decreased in 2004 and 2005 due to closing date of registrations of some Eskom plants. However, this increased sharply in 2008 with a large water use registration for Sasol, and in 2015 with some new Eskom registrations.
- In Inkomati-Usuthu, the urban industry water use increased in 2005 and 2006 following the registration of the Inkomati and Usuthu sub-systems.
- In KwaZulu-Natal, new registrations and expiry of water use licenses have been common during the studied period. In particular, the number of expired registration was large in 2015 when the registered water volumes decreased for that year.
- The registration of water use by non-urban industry has also been substantial in KwaZulu-Natal, increasing slightly but steadily.
- In Limpopo, water use registrations by the irrigation sector have been slightly decreasing over the years, whilst water supply services and mining have been on the increase.
- In the Lower Orange and Lower Vaal, there has been a sharp increase in registered water volumes for irrigation in 2003.

- In Mpumalanga and North West, water use registrations for irrigation have been rather steady since 2002. However, registrations for industry and mining water users have been increasing.
- In the Western Cape, the registrations of irrigation users have been increasing steadily causing an increase in total water use. Water uses in other sectors were rather constant since 2002.

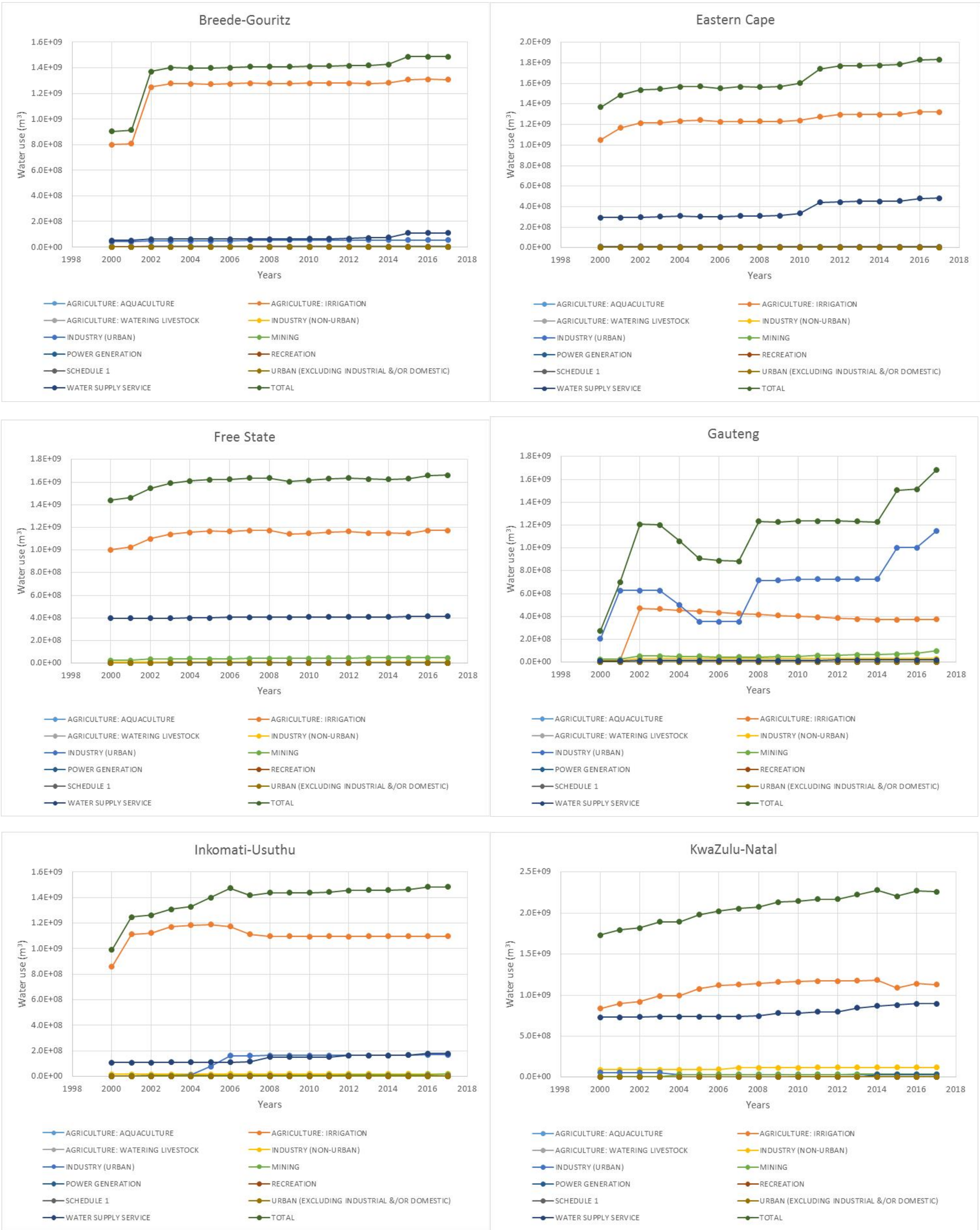


Figure 4.2a

Yearly water volumes (m^3 a^{-1}) registered in the WARMS database per Province/Regional Office/Catchment Management Agency and per water sector for taking water from a water resource.

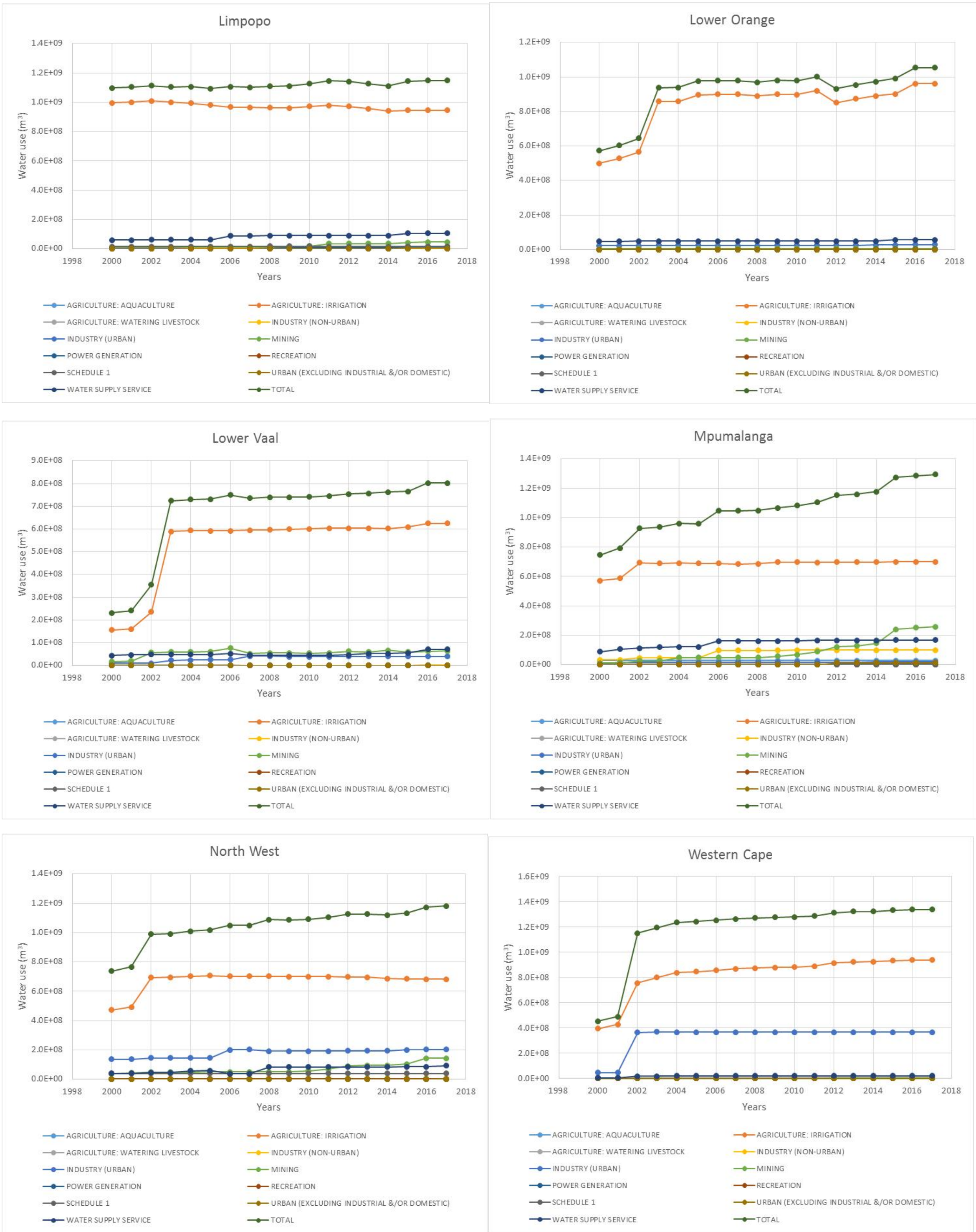


Figure 4.2b

Yearly water volumes (m^3 a^{-1}) registered in the WARMS database per Province/Regional Office/Catchment Management Agency and per water sector for taking water from a water resource.

4.2.3 Case study analysis: Wider Cape

The bulk monthly water uses obtained from the City of Cape Town were processed and Figure 4.3 presents the yearly water uses in kL per user category (period July 2005-June 2017). It is evident from Figure 4.3 that the total water use steadily increased from 210 x 10^6 m^3 a^{-1} in 2005/06 to 240 x 10^6 m^3 a^{-1} in 2014/15, in particular due to the domestic water use increase from 144 to 173 x 10^6 m^3 a^{-1}. It is also very evident how the water use dropped in the last two years to 197 x 10^6 m^3 a^{-1}, since water restrictions have been introduced by the City of Cape Town to mitigate drought.

The GIS files of Cape Town suburbs with the average daily annual demand per suburb for the period May 2016 – April 2017 (residential and industrial) are shown in Figure 4.4. It is evident from Figure 4.4 that water use is the highest in the urban suburbs where residential areas and industrial activities are the densest and large volumes of water are distributed through the water supply system. The suburbs that used the most water were Philippi (3.8 x 10^6 m^3 a^{-1}), Gugulethu (2.1 x 10^6 m^3 a^{-1}) and Parklands (1.5 x 10^6 m^3 a^{-1}), primarily due to their size and population density. Areas on the peninsula, along the West Coast, the Philippi agricultural area, the stretch of the Cape Flats between the airport and the Helderberg as well as the Hottentot-Holland reserve (eastern parts) are not populated and they exhibit low water use. These areas are under natural vegetation where the dominant water use is evapotranspiration. It was thereby suggested that the urban suburb data obtained from the City of Cape Town are a good representation of water use for residential/industrial areas, whilst MOD16 evapotranspiration data would represent better areas under natural vegetation. This resulted in the compilation of water use maps that combined City of Cape Town water use data (urban areas) and MOD16 ET (natural and cultivated areas) for years 2005-2012.

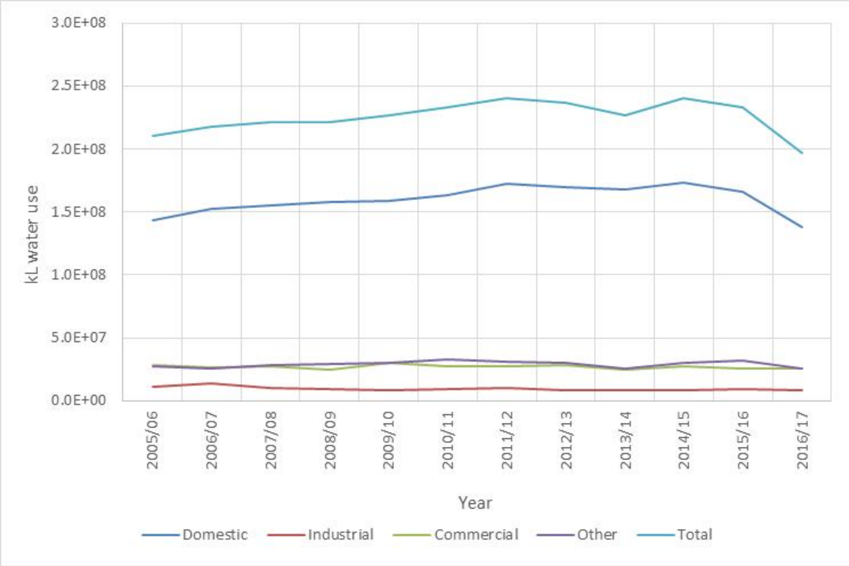


Figure 4.3

Annual water use in the City of Cape Town per user category.

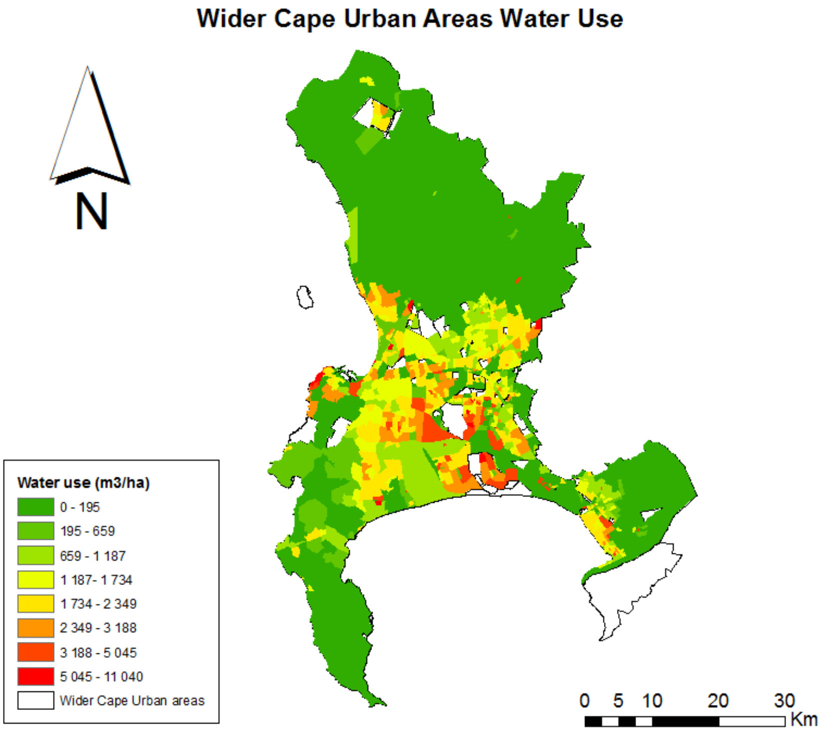


Figure 4.4

Water use (residential and industrial) in Cape Town suburbs for the period May 2016 – April 2017 based on City of Cape Town information.

The City of Cape Town suburb water use data was attributed to the corresponding suburb shapefiles using the *join* tool in ArcGIS. The following step was to calculate the area of each suburb in the shapefiles, and to do this the *zonal geometry as table tool* in ArcGIS was used. The cell size for both the suburb shapefiles and MOD16 ET satellite image were re-sampled to 30 m x 30 m cell size. MOD16 ET and suburb water use were then overlaid. MOD16 ET does not provide data for urban areas (blank pixels with data out of range). For the areas not provided by MOD16, the City of Cape Town water use data were retained. For pixels where both MOD16 and City of Cape Town suburb data were available, MOD16 was used (City of Cape Town suburb data were covered). These pixels were located outside the urban areas with low population density and they exhibited low suburb water use (peninsula, along the West Coast, the Philippi agricultural area, the stretch of the Cape Flats between the airport and the Helderberg as well as the Hottentot-Holland reserve). The last step involved converting all water use data in $m^3\ ha^{-1}\ a^{-1}$. Examples of water use maps are shown in Figure 4.5 for years 2005, 2008 and 2011.

According to MOD16, the ET range ($m^3\ ha^{-1}\ a^{-1}$) was from ~2,500 to ~12,800 in the year 2005, 2,500-13,000 in 2008 and 2,500-12,000 in 2011. According to the City of Cape Town suburb water use data, the ranges ($m^3\ ha^{-1}\ a^{-1}$) were as follows: 0-11,000 in the year 2005, 0-11,900 in 2008 and 0-13,000 in 2011. It appeared that MOD16 ET from natural vegetation varied depending on climatic conditions, in particular rainfall, whereas the water use in urban suburbs increased during the period 2005-2012.

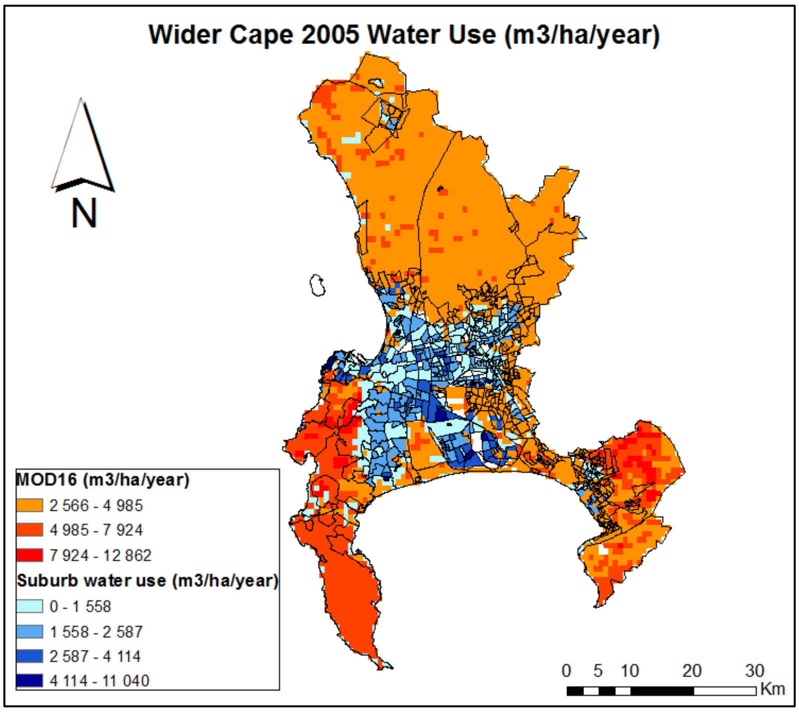


Figure 4.5a

Combined water use ($m^3\ ha^{-1}\ a^{-1}$) in the Wider Cape study site (2005). Light blue to dark blue colour ramp represents suburb water use data obtained from the City of Cape Town, while red to orange represents water use data extracted from MOD16 satellite image.

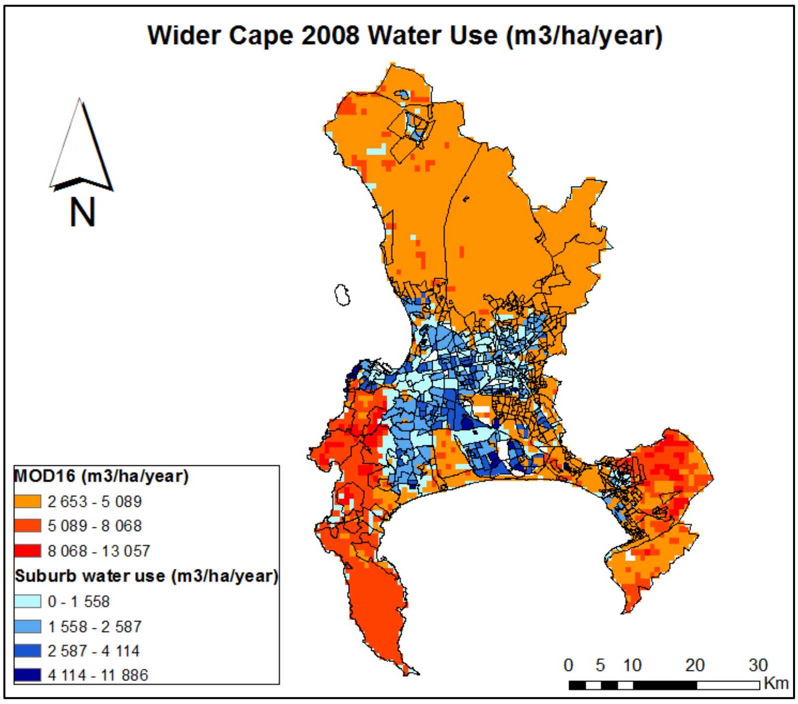


Figure 4.5b

Combined water use ($m^3\ ha^{-1}\ a^{-1}$) in the Wider Cape study site (2008). Light blue to dark blue colour ramp represents suburb water use data obtained from the City of Cape Town, while red to orange represents water use data extracted from MOD16 satellite image.

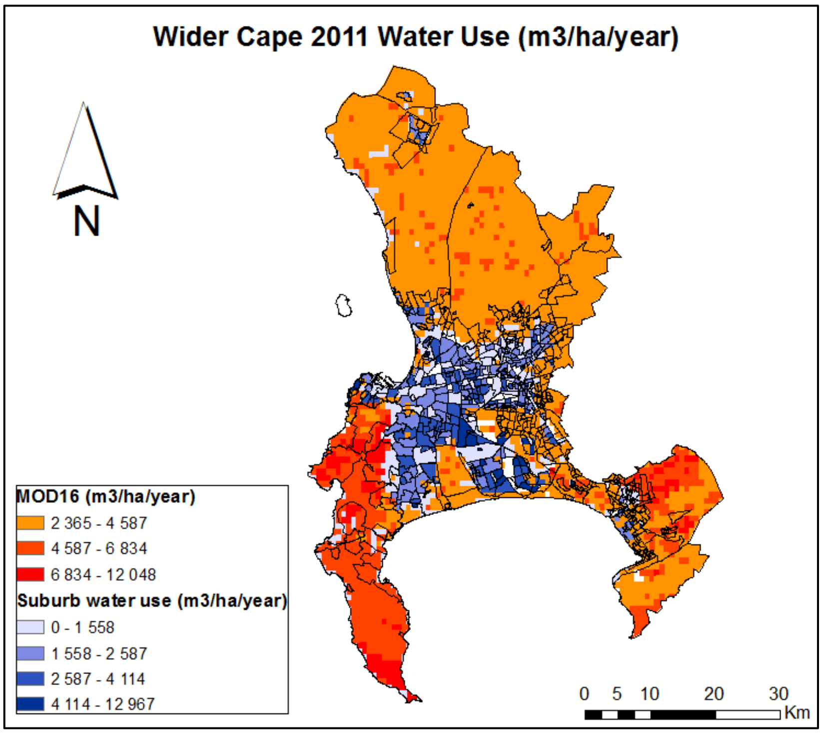


Figure 4.5c

Combined water use (m^3 ha^{-1} a^{-1}) in the Wider Cape study site (2011). Light blue to dark blue colour ramp represents suburb water use data obtained from the City of Cape Town, while red to orange represents water use data extracted from MOD16 satellite image.

4.2.4 Case study analysis: Inkomati

The Inkomati study site is much larger in extent compared to the wider Cape area. It is predominantly covered by natural and cultivated vegetation. The urban areas are small and they cover a much smaller percentage in the Inkomati area compared to the wider Cape. Many villages practice subsistence agriculture. Although data of urban water use were obtained for Mbombela (major urban area in the Inkomati case study site), satellite-derived MOD16 evapotranspiration provided a better coverage of spatial water use in the Inkomati catchment compared to the Cape. The maps in Figure 4.6 show water consumption in m^3 ha^{-1} a^{-1} for years 2005, 2008 and 2011. According to the results, MOD16 ET ranged between ~2,200 and ~15,250 in the year 2005, 2,600-16,400 in 2008 and lastly 2,600-16,000 in 2011.

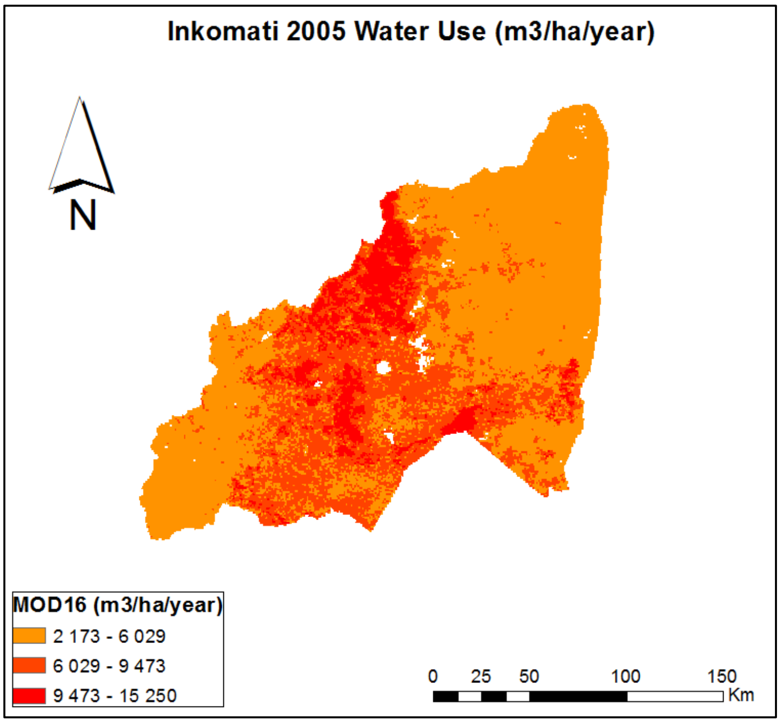


Figure 4.6a

Water use (m^3 ha^{-1} a^{-1}) estimated with MOD16 in the Inkomati study site (2005).

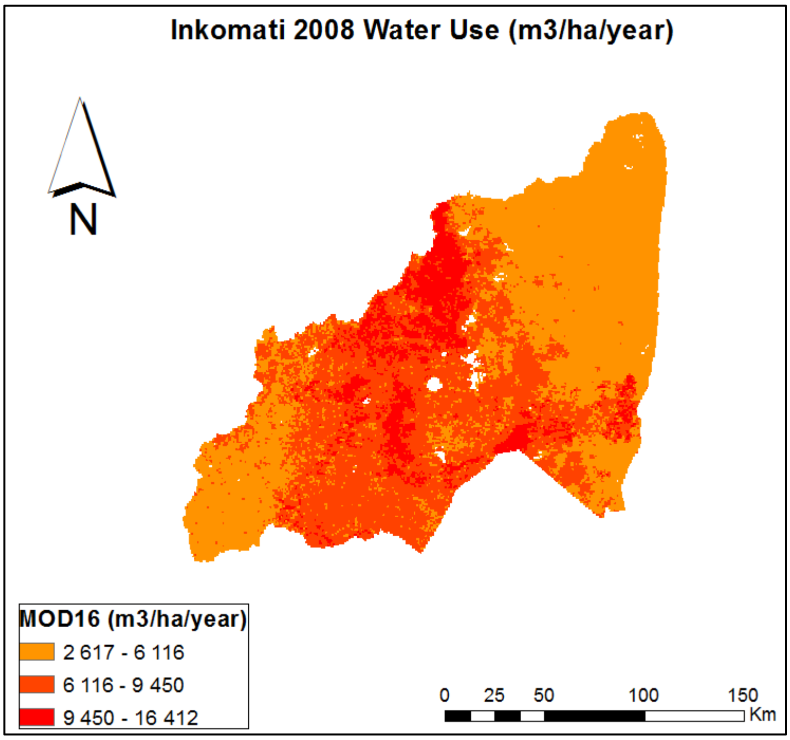


Figure 4.6b

Water use (m^3 ha^{-1} a^{-1}) estimated with MOD16 in the Inkomati study site (2008).

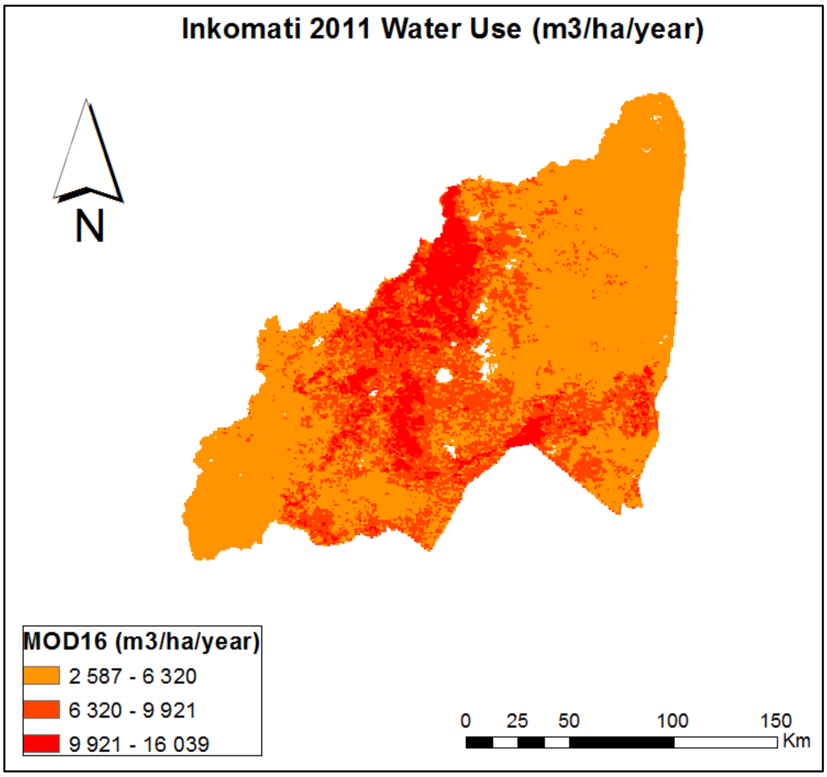


Figure 4.6c

Water use (m^3 ha^{-1} a^{-1}) estimated with MOD16 in the Inkomati study site (2011).

4.3 Areas of no change

The Areas-of-No-Change (AoNC) analysis was done to determine land cover/use groups which have remained persistent or unchanged from the start to the end of the studied period. Two existing land cover datasets, derived from digital Landsat imagery that describe the landscape in 1990 (GeoTerraImage 2016) and 2013/14 (Thompson 2014; GeoTerraImage 2015), were used. A geographic *World Geodetic System (WGS) 1984* coordinate system was used for both NLC1990 and NLC2013/14. The NLC1990 and NLC2013/14 maps were compared to identify the land cover/use groups that have not changed. The areas of no-change were extracted by doing a simple per-pixel change analysis (30 x 30 m) between the 1990 and 2013/14 NLC maps. Groups which did not occur in the NLC1990 were assimilated to other existing classes in the NLC2013/14. Sugarcane cultivation is an example of a land cover which was not classified in the NLC1990 and therefore assimilated to the cultivated perennial group in the NLC2013/14 map. Urban land cover/use groups and waterbodies were not included in the analysis because ET from these land covers is not adequately estimated with the MOD16 satellite product.

The AoNC map is shown in Figure 4.7. The overall accuracy of the change map varied between 58 and 70%. A comprehensive accuracy assessment and AoNC analysis of the NLC1990 and NLC2013/14 maps can be found in Deliverable 5a of this project. Amongst the provinces, the Northern Cape showed the largest area of change, but the least in terms of percentage (24%). The largest percentage change was observed in Limpopo (48%). Amongst land cover/use groups, thicket/dense bush (+), woodland/open bush (+), grasslands (-) and low shrubland (-) showed the largest changes.

Table 4.1 shows the area of each land cover/use group in 1990 and 2013-14 and the percentage change as a positive or negative value based on total area for South Africa. The largest areas of the country are covered by low shrubland (281,646 km^2) and grassland (195,144 km^2). Changes in land cover were recorded between 1990 and 2013/14 with increases in woodland/open bush (+1.746%) and thicket/dense bush (+1.349%), whilst bare non-vegetated land (-0.724%) and grassland (-0.661%) decreased. More profitable perennial crops (+0.424%) increased at the expense of annuals (-0.637%). Urban areas increased by +0.129%. A concern is the decrease of areas under wetlands (-0.400%) and fynbos (-1.095%). Appendix C reports equivalent tables per province.

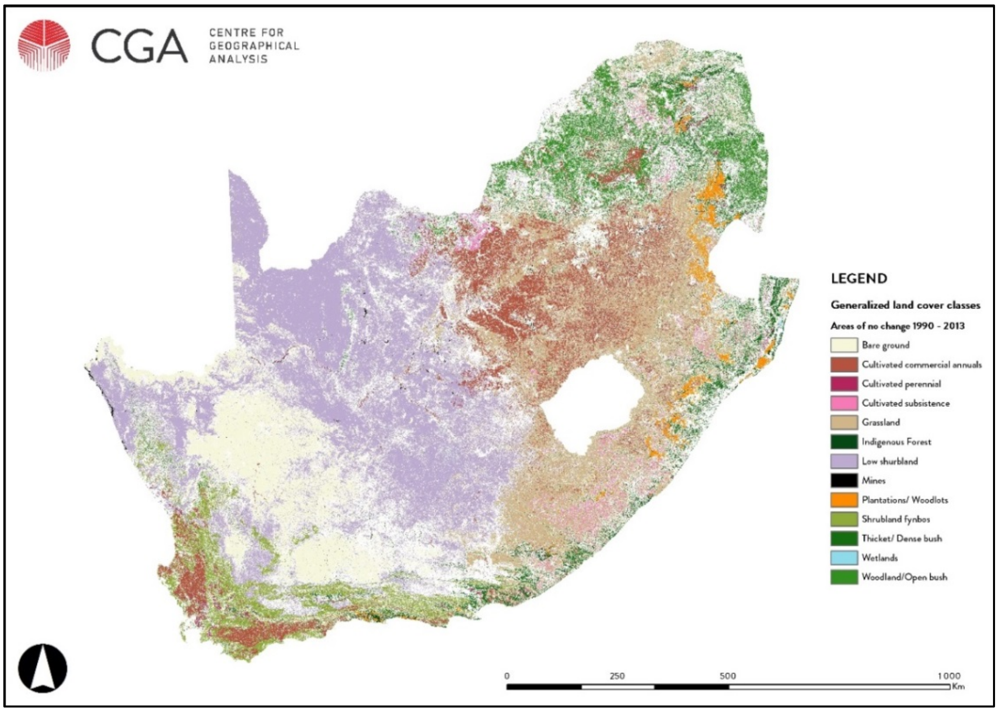


Figure 4.7

Land cover/use groups map showing Areas of No-Change (AoNC) determined by comparing NLC1990 and NLC2013/14 maps.

TABLE 4.1 Areas of each land cover/use group and percentage changes from 1990 to 2013/14 in South Africa.			
Class	**1990 Area (km^2)**	**2013/14 Area (km^2)**	**Change (%)**
WTB	16,900	15,730	-0.124
WTL	11,511	7,737	-0.400
INF	2,872	3,261	0.041
TDB	49,848	62,559	1.349
WOB	75,092	91,543	1.746
GRS	201,374	195,144	-0.661
LSB	282,515	281,646	-0.092
MNS	2,168	2,460	0.031
BNV	106,414	99,588	-0.724
PWD	14,392	14,018	-0.040
CCA	88,172	82,170	-0.637
CPE	3,639	7,630	0.424
CSU	14,889	15,399	0.054
SHF	51,898	41,581	-1.095
Urban	20,619	21,835	0.129
TOTAL	942,302	942,302	0

4.4 Spatial data extraction

The model builder function in ArcGIS (version 10.4) was used to extract monthly data derived from MODIS satellite images for 2000-2012 (MOD16 ET, average air temperature and VPD) to a resolution of 30 x 30 m consistent with the NLC land cover maps. The AoNC data file containing no-change land cover data between 1990 and 2013/14 was used as the extractor feature in the model. The basic function of the process was to take a value raster as an input and thereafter to calculate for each of the cells a statistics (e.g. mean or median) using the value of the individual cells belonging to the same zone. The *Zonal Statistics* spatial algorithm from ESRI's ArcMap creates data and summarizes them in a table format. Tables were produced for each of the months in the entire observation period (2000-2012) and they were then combined to produce time series data for trend analysis.

In order to extract monthly rainfall from the average annual rainfall of Schulze (2006), the following steps were undertaken:

- **Step 1:** The long-term monthly rainfall data (mm a^{-1}) (Schulze 2006) was divided by 12 to get a monthly mean rainfall raster in mm $month^{-1}$ (ScMM). Monthly mean rainfall values were extracted to each SAWS weather station point.
- **Step 2:** For each respective area, a monthly mean difference value (MMD) was calculated for each month by averaging the difference between the SAWS rainfall values for that month and the long-term rainfall value. This led to a MMD value for each month (156 MMD values per area)
- **Step3:** Each MMD was then added to the ScMM to produce the respective month's rainfall raster.

This method was undertaken in order to generate spatial layers of monthly rainfall consistent with monthly MOD16 ET data.

4.5 MOD16 evapotranspiration

The analysis of the historic relationship between water use and land use employed MOD16 ET data (2000-2012), air temperature and VPD derived from the NASA/GMAO MERRA as well as rainfall data from SAWS and Schulze (2006). The purpose was to determine multiple regression equations (empirical formulae) of ET as a function of rainfall, air temperature and VPD for each land use at national, provincial and case study scales. It is recognized that a certain degree of auto-correlation exists between ET and air temperature and VPD. Air temperature and VPD derived from the NASA/GMAO MERRA are inputs into the MOD16 ET algorithm and they are all derived from observations with the same satellite (MODIS). This was, however, deemed not too critical for the purpose of deriving multiple regression equations and for running future scenarios. Data of rainfall were sourced from entirely independent datasets (ground measurements of SAWS and Schulze (2006)).

4.5.1 Provincial scale analysis

Climatic variables and evapotranspiration statistical data (medians) were extracted per province at a monthly temporal scale for the entire historic data period (2000-2012) and for each land cover/use group. The provincial map containing land cover/use groups of no-change per province was used in the extraction process. The model builder tool in ArcGIS (version 10.4) was used to extract data from satellite images from 2000-2012, at a 30 x 30 m resolution. The data extracted for this period were monthly data (13 years x 12 months = 156 observations per variable) for the following variables: evapotranspiration (mm month^{-1}) as the dependent variable, average air temperature (ºC) and vapour pressure deficit (kPa), as independent variables. Monthly rainfall data were generated using ground stations of SAWS and the map of Schulze (2006), as described in the previous section.

Historic trends of monthly rainfall data were plotted for all provinces in Figure 4.8. The values provide a realistic representation of rainfall averaged for the different sub-regions of each province. The overall average did not indicate any visually-detectable trends over the study period. The highest rainfall was generally recorded in KwaZulu-Natal, with high peaks visible during particularly wet years in Gauteng and Limpopo (2000 and 2010/11).

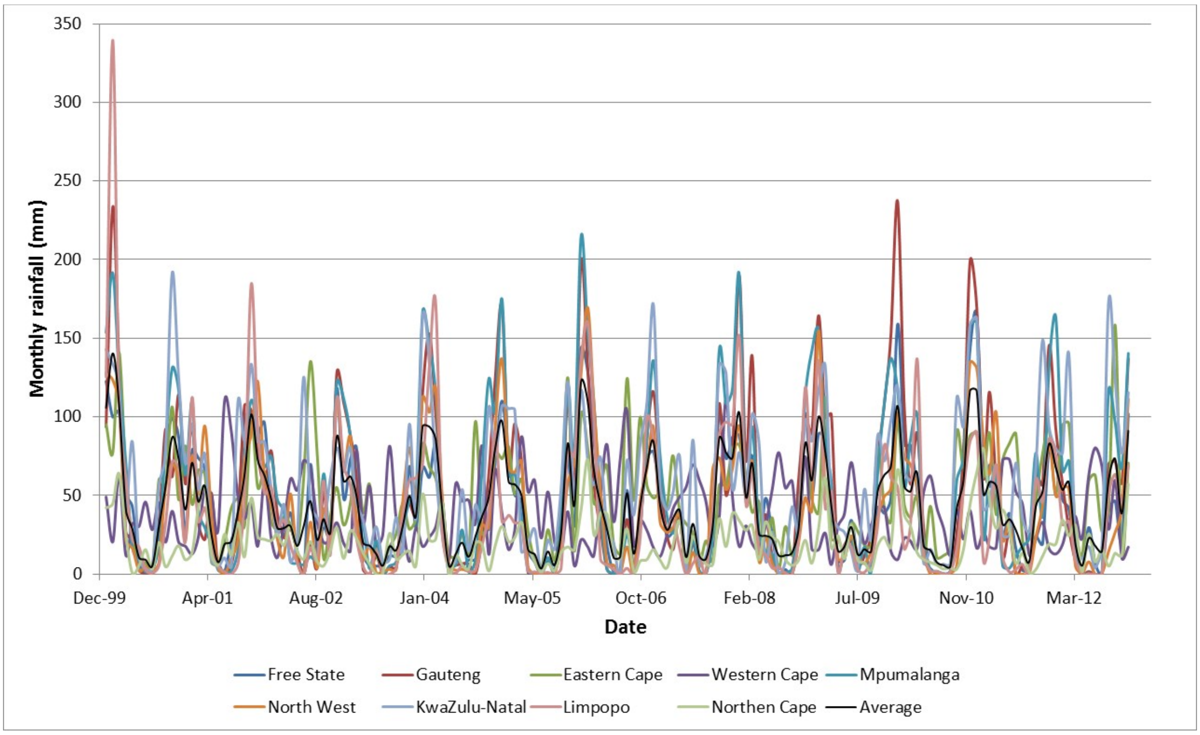


Figure 4.8

Monthly rainfall per province (average of SAWS ground weather stations).

Figure 4.9 presents another representation of the data with actual monthly rainfall recorded at the selected weather stations in Gauteng (summer rainfall, small area) and the Western Cape (winter rainfall, large and heterogeneous area). The seasonality of rainfall is very evident for Gauteng, with peaks up to 350 mm month^{-1} (Johannesburg Botanical Gardens) and with relatively small differences in monthly rainfall recorded at different stations. This is due to the proximity of the weather stations in a province of relatively small surface area. In the Western Cape, the variability in rainfall between stations and years is much more pronounced. The weather station locations are much sparser in the large provinces and represent much more heterogeneous landscapes. Peaks in rainfall were recorded up to > 450 mm month^{-1} in particular on the southern coast. The complete dataset of monthly rainfall for all provinces can be found in Deliverable 5a of this project.

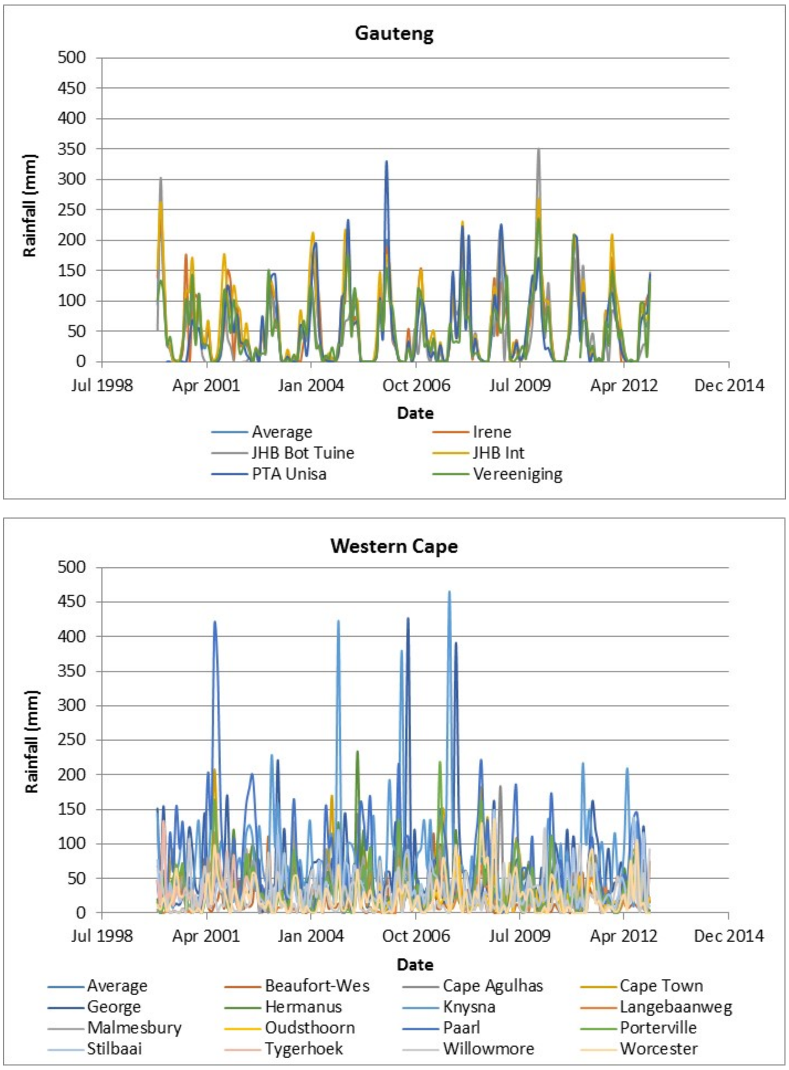


Figure 4.9

Monthly rainfall in Gauteng and Western Cape for the weather stations considered.

Monthly air temperatures were averaged for different land covers. An example is shown in Figure 4.10. In Gauteng, monthly temperatures ranged from about 10°C to about 25°C, with small differences between land covers. The highest air temperatures were generally recorded in woodland/open bush and the lowest in cultivated subsistence. In the Western Cape, the temperature range was similar as in Gauteng, however larger differences were recorded between land uses covering wider areas. Cultivated subsistence and low shrubland generally exhibited the widest range in air temperature. The complete dataset of monthly air temperatures for all provinces and land covers can be found in Deliverable 5a of the project.

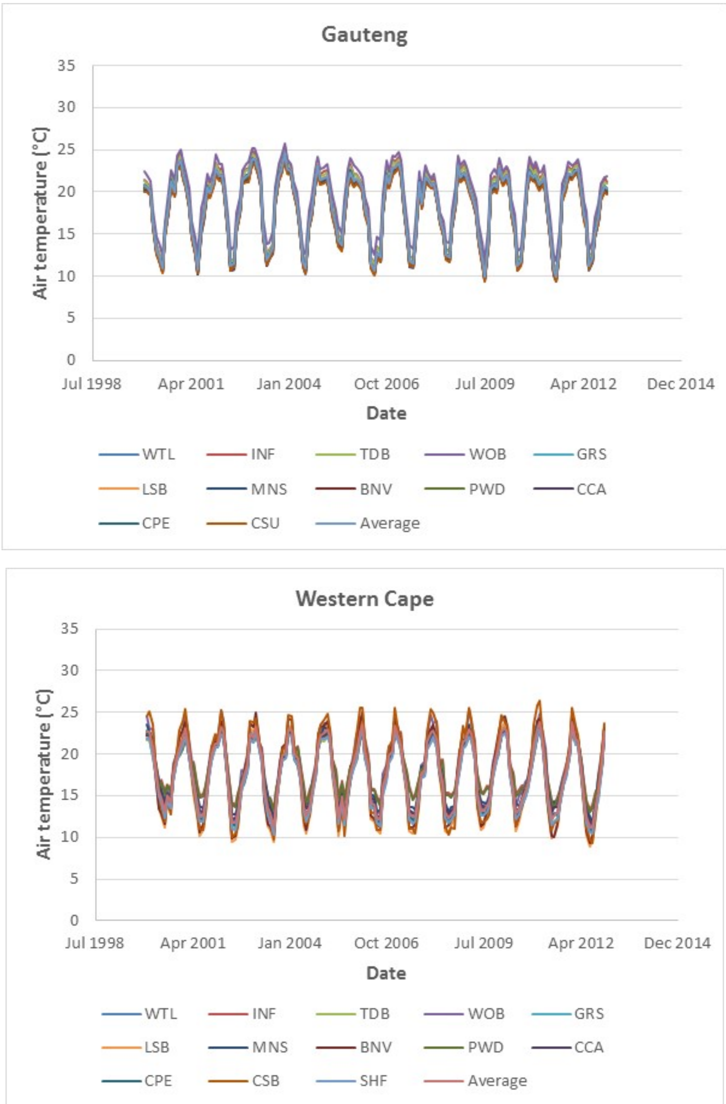


Figure 4.10

Monthly average air temperature in Gauteng and Western Cape for different land covers.

Similar observations as for air temperature can be made for VPD (Figure 4.11). Vapour pressure deficit ranged between about 0.8 and 2.8 kPa in Gauteng with very small differences between land covers. In the Western Cape, VPD ranged between about 0.5 and 3.0 kPa. The highest VPD was generally recorded from bare soil, and the lowest in cultivated land and wetlands. The complete dataset of monthly VPD for all provinces and land covers can be found in Deliverable 5a of the project.

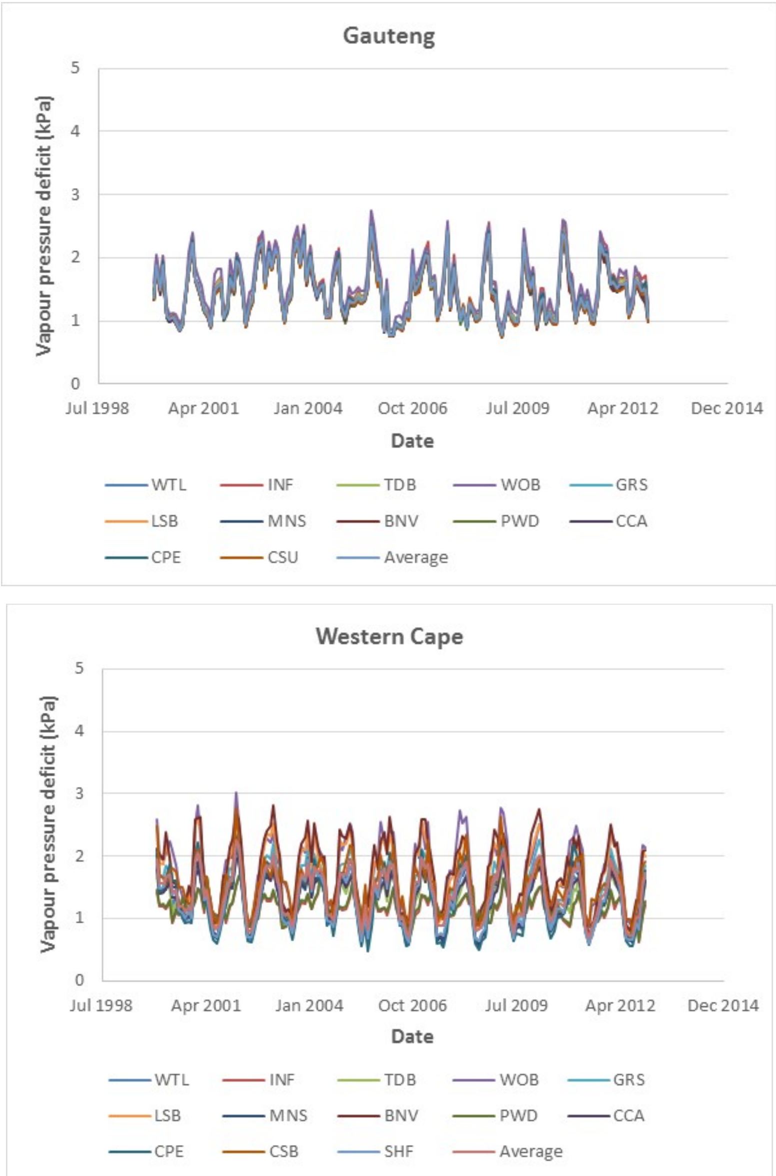


Figure 4.11

Monthly average vapour pressure deficit in Gauteng and Western Cape for different land covers.

Monthly MOD16 ET was plotted in Figure 4.12 averaged over different land cover/use groups in Gauteng and the Western Cape. In Gauteng, monthly MOD16 ET varied consistently between about 10 and 90 mm month^{-1} with small differences between land covers and very pronounced seasonality. In the Western Cape, differences in MOD16 ET were very pronounced for different land covers, with peak ET values >150 mm month^{-1} occurring from indigenous forests and peaks >100 mm month^{-1} occurring from plantations/woodlots. The complete dataset of monthly MOD16 ET for all provinces and land covers can be found in Deliverable 5a of the project.

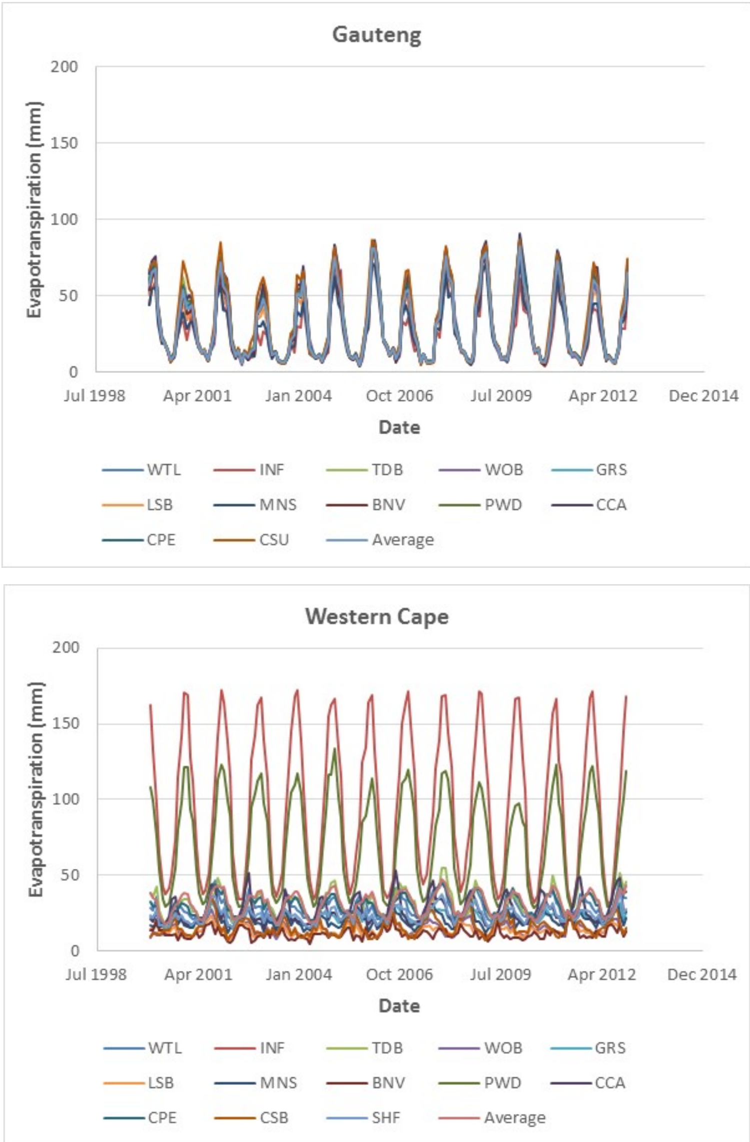


Figure 4.12

Monthly average MOD16 evapotranspiration in Gauteng and the Western Cape for different land covers.

4.5.2 Case study analysis: Wider Cape

The graphs in Figures 4.13-4.16 show the seasonal variability of climatic variables (evapotranspiration, air temperature, vapour pressure deficit and rainfall) in various land cover/use groups of the wider Cape area. Evapotranspiration values in the wider Cape area ranged from approximately 10 to 70 mm month^{-1} for most land cover/use groups as a result of seasonal fluctuations, while indigenous forests had a different range (30-40 mm month^{-1}) compared to the other land cover/use groups (Figure 4.13). Indigenous forests, plantations/woodlots and thicket dense bush recorded the highest ET and mines recorded the lowest (Figure 4.13).

Median air temperatures ranged from approximately 10 to 25 ºC during the 2000-2012 period; during this period, strong seasonal fluctuations were displayed. There was little variation in air temperature for different land cover/use groups (Figure 4.14). Grasslands, mines and cultivated commercial annuals recorded the highest median temperatures.

Vapour pressure deficit values ranged from 0.5 to 2.5 kPa. Strong seasonal fluctuations were pronounced (Figure 4.15).

Strong seasonal fluctuations in rainfall were observed in the wider Cape area. Rainfall ranges were approximately 0-150 mm month^{-1} with peak rainfall occurring around the months of June and July (Figure 4.16). The highest rainfall was in plantations/woodlots, bare ground and thicket dense bush.

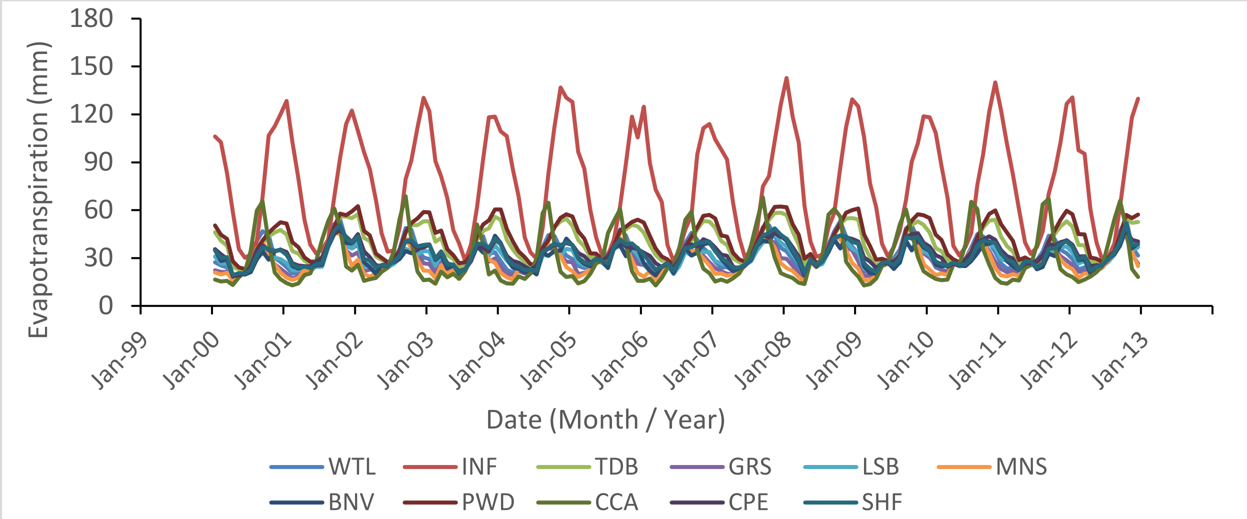


Figure 4.13

Monthly median evapotranspiration in various land cover/use groups in the wider Cape area (2000-2012).

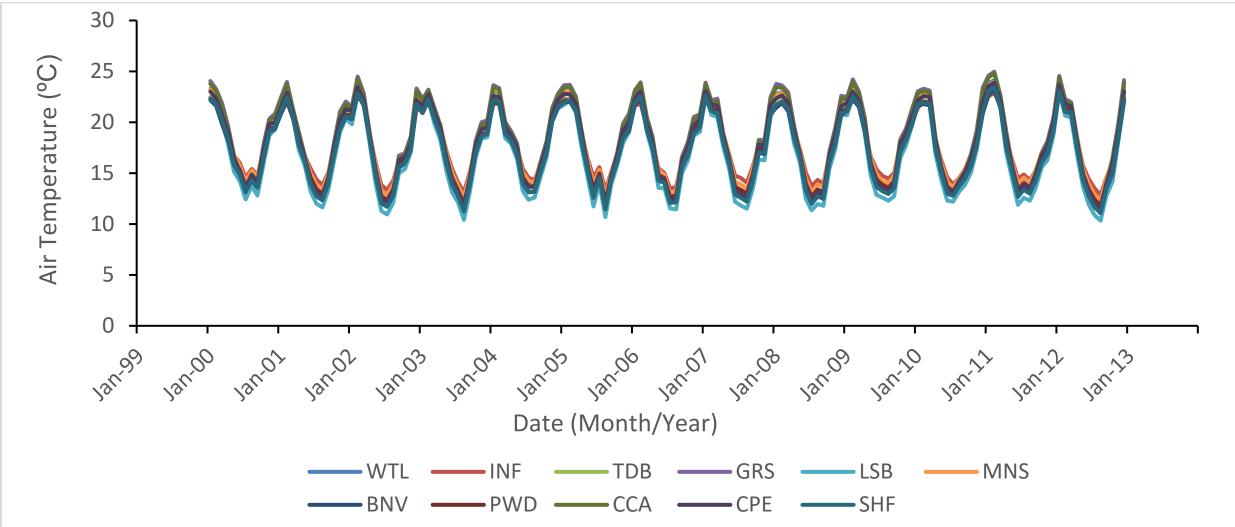


Figure 4.14

Monthly median air temperature in various land cover/use groups in the wider Cape area (2000-2012).

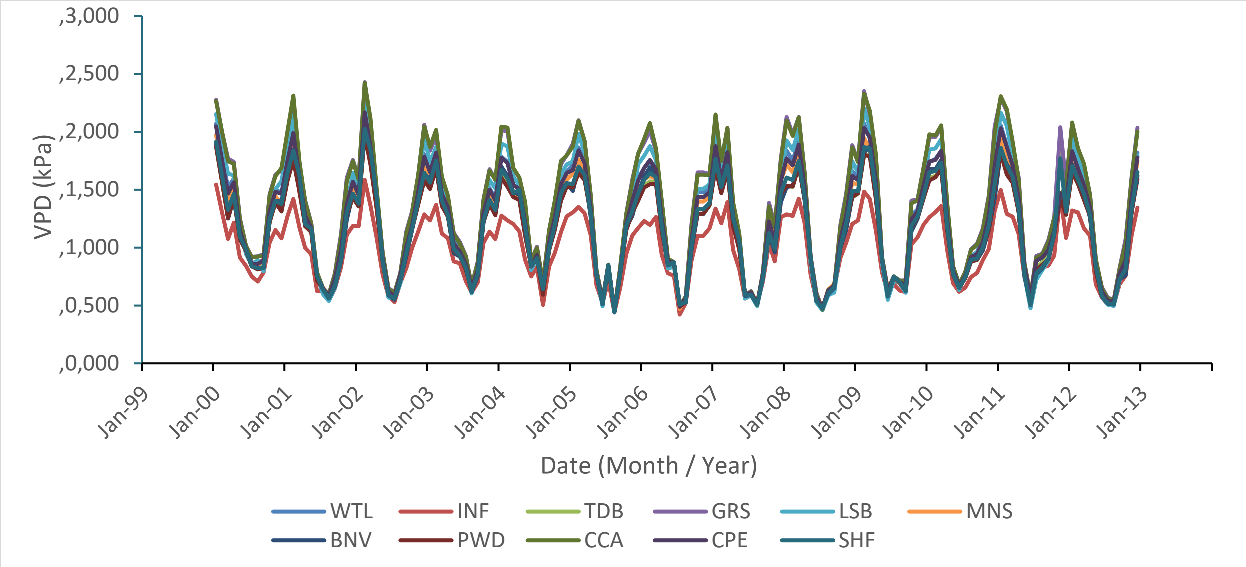


Figure 4.15

Monthly median vapour pressure deficit in various land cover/use groups in the wider Cape area (2000-2012).

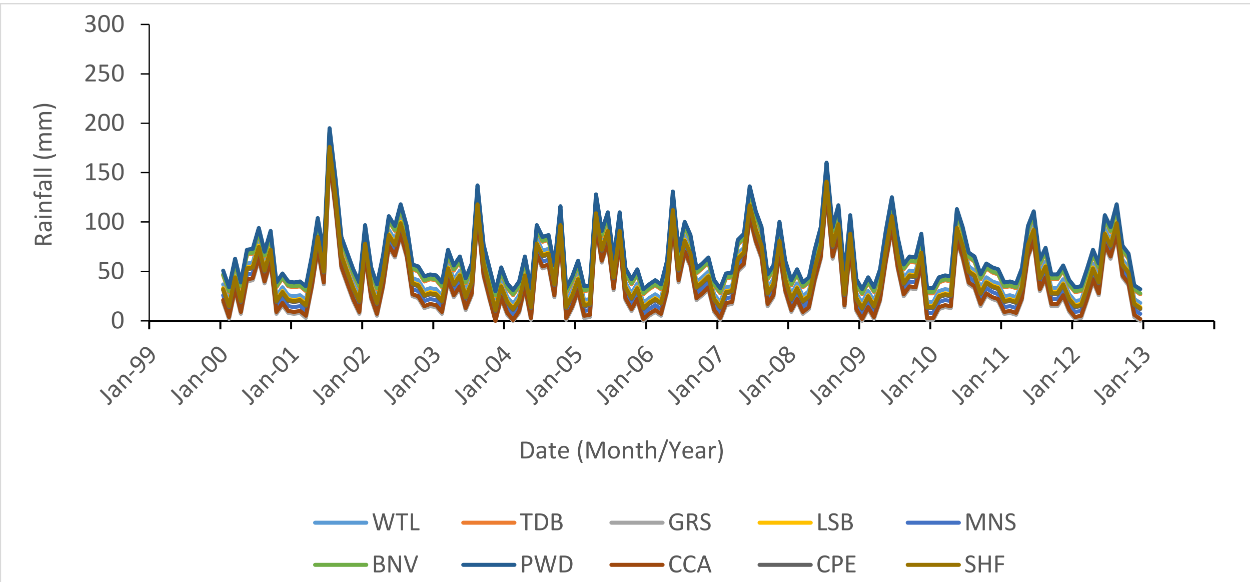


Figure 4.16

Monthly median rainfall in various land cover/use groups in the wider Cape area (2000-2012).

4.5.3 Case study analysis: Inkomati

The graphs in Figures 4.17-4.20 show the seasonal variability of climatic variables (evapotranspiration, air temperature, vapour pressure deficit and rainfall) in various land cover/use groups in the Inkomati study area. Evapotranspiration values in the Inkomati ranged from approximately 10 to 150 mm month^{-1} for most land cover/use groups as a result of strong seasonal fluctuations (Figure 4.17). The highest monthly median evapotranspiration recorded was in indigenous forests, followed by plantations/woodlots and cultivated perennials. The least recorded median ET was in mines.

Median air temperatures varied from approximately 10 to 25 ºC during the 2000-2012 period with strong seasonal fluctuations and variations among land cover/use groups (Figure 4.18). The highest median air temperatures were recorded in the woodlands/open bush land cover, followed by cultivated subsistence and thicket dense bush.

Vapour pressure deficit values in the Inkomati ranged from 0.5 to 2.5 kPa with high random fluctuations and variations among land cover/use groups (Figure 4.19).

Rainfall range in the Inkomati area was 0-230 mm month^{-1} with strong seasonal fluctuations and peaks occurring during the month of January (Figure 4.20). The highest rainfall occurred in indigenous forests, plantations/woodlots and cultivated perennial land covers.

Historic climatic data (rainfall, air temperature, vapour pressure deficit) and MOD16 ET generally displayed larger variability in the Inkomati catchment (larger and more heterogeneous area) compared to the wider Cape.

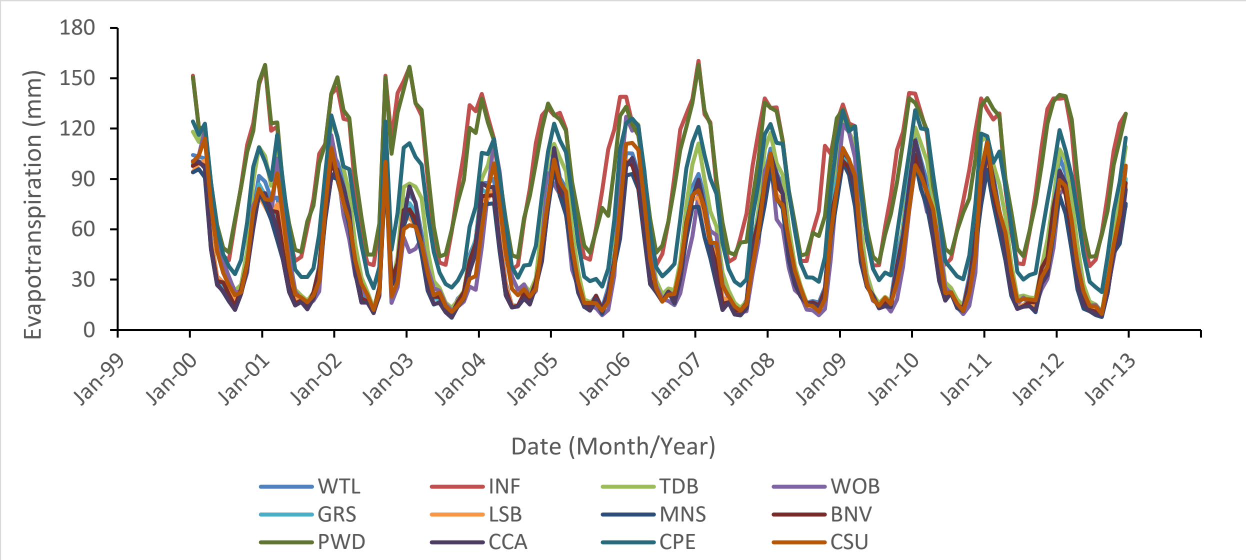


Figure 4.17

Monthly median evapotranspiration in various land cover/use groups in the Inkomati area (2000-2012).

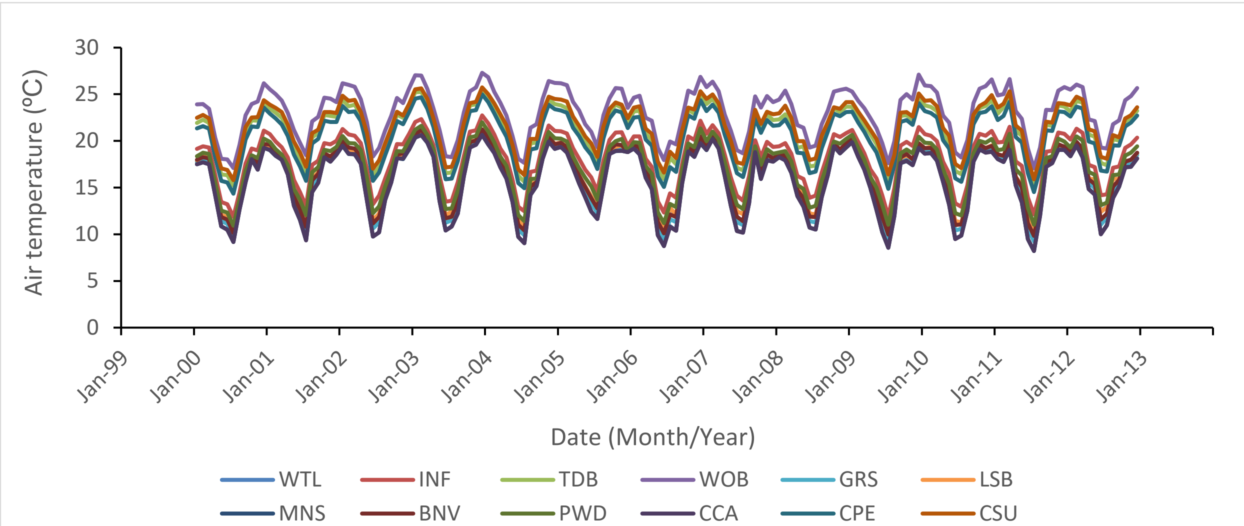


Figure 4.18

Monthly median air temperature in various land cover/use groups in the Inkomati area (2000-2012).

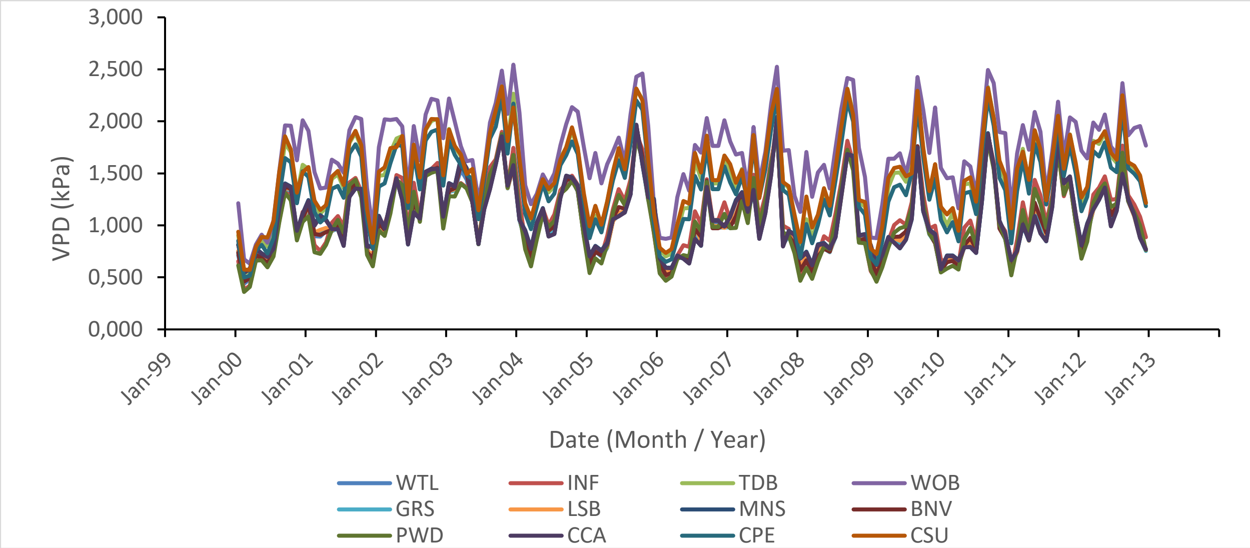


Figure 4.19

Monthly median vapour pressure deficit in various land cover/use groups in the Inkomati area (2000-2012).

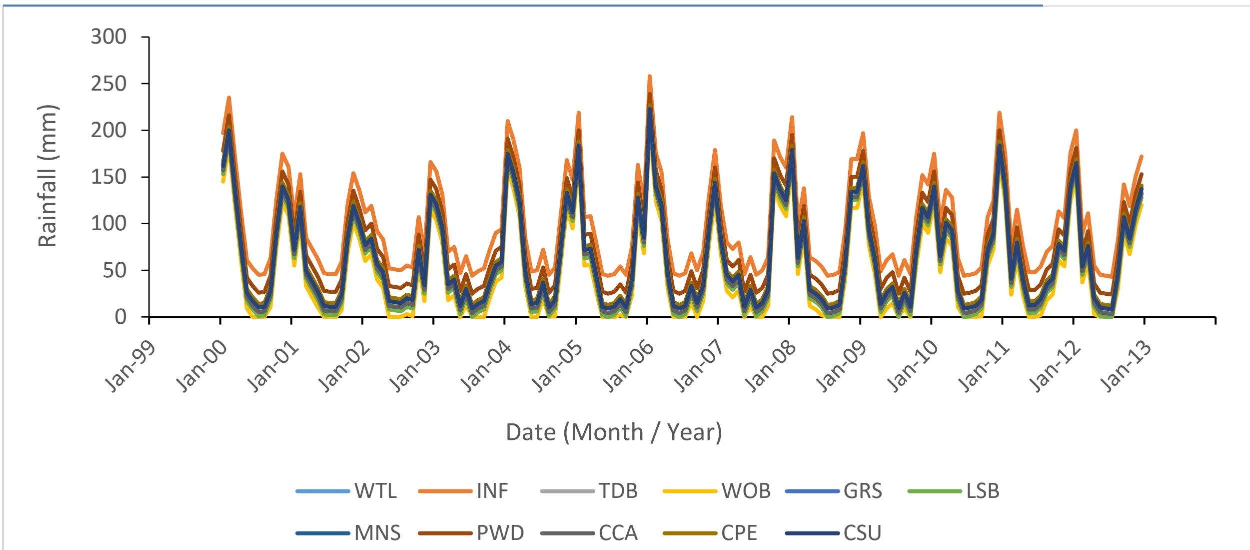


Figure 4.20

Monthly median rainfall in various land cover/use groups in the Inkomati area (2000-2012).

4.5.4 Multiple regression analysis (MRA)

The aim of multiple regression analysis (MRA) was to understand the relationships between monthly evapotranspiration as dependent variable and climatic variables as independent variables (temperature, vapour pressure deficit and rainfall) over a 13 year period (2000-2012) for each land cover in each province/case study area. To understand these relationships, a multiple regression analysis test was used. R-studio (Version 1.0.143), an open source software, was used to determine multiple regression equations. Median values for each of the variables (mean total in the case of rainfall) were used in the multiple regression analysis calculations. The multiple regression equations were generated in the format:

ET = a * rainfall + b * air temperature + c * VPD + intercept

where a, b and c are coefficients of the multiple regression equations for each independent variable. The main outputs of the software were:
(1) Coefficients for each of the independent variables (rainfall, temperature and vapour pressure) describing the change in the dependent (y) variable expected as a result of a unit change in the independent (x) variable.
(2) Coefficient of determination (R^2) value for the overall regression analysis, used to describe the proportion of variability in the dependent variable which can be described by changes in the independent variables.
(3) Significance level (p-value) determining the significance of each independent variable in explaining the variability in the dependent variable. The output also provides the overall significance of the regression test, combining all independent variables.

Table 4.2 summarizes the values of intercept and coefficients for the independent variables (rainfall, air temperature, VPD) for all provinces and land covers. These empirical formulae derived from multiple regression analyses can be used to calculate ET as a function of climatic variables. They can also be used to project ET for future climatic conditions. The combined coefficients of determination of the multiple regressions (R^2) were also reported in Table 4.2. Historic climatic data (rainfall, air temperature, vapour pressure deficit) and MOD16 ET displayed larger variability over large and heterogeneous areas, and smaller variability in small provinces with homogeneous landscapes. The R^2 values varied for different land covers and provinces, indicating that the relationship between MOD16 ET and climatic variables is strong in some instances and weak in others. The highest correlations (R^2) of multiple regression functions were generally obtained in wetter climates and associated land covers, and the lowest in drier areas and associated land covers. However, the relationships were statistically significant in all cases ($p<0.05$). The Eastern Cape and KwaZulu-Natal Provinces have the highest coefficient of determination values (R^2) compared to the other provinces. The Northern Cape and the Western Cape are the only provinces which have R^2 below 0.5. The highest correlations (R^2) of multiple regression functions were generally obtained in wetter climates (e.g. KwaZulu-Natal) and associated land covers (e.g. indigenous forests), and the lowest in drier areas (e.g. Northern Cape) and associated land covers (e.g. shrubland fynbos). The highest R^2 value (0.95) was observed for cultivated subsistence in the Eastern Cape, and the lowest value (0.22) for wetlands in the Western Cape. By comparing R^2 for different land covers, the highest average R^2 (0.82) was observed for indigenous forests and the lowest for shrubland fynbos (0.63). By province, the highest average R^2 (0.87) was recorded for KwaZulu-Natal, and the lowest for the Northern Cape (0.60). Rainfall (positive correlation) and vapour pressure deficit (negative correlation) are generally the two main climatic drivers of ET.

Table 4.2 also summarizes the values of intercept and coefficients for the independent variables (rainfall, air temperature, VPD) for all land covers at the two case study sites (wider Cape and Inkomati). MOD16 ET is generally positively correlated to air temperature and negatively correlated to vapour pressure deficit. MOD16 ET was negatively correlated to rainfall in the wider Cape, and positively correlated in the Inkomati. Negative intercepts were recorded in all land cover/use groups except in the grasslands and mines in the Inkomati, while in the wider Cape area all intercepts recorded were positive. In the Inkomati, air temperature coefficients were found to be positive for all land cover/use groups while in the wider Cape air temperature coefficients in mines and cultivated commercial annuals had a negative coefficient. However, these two results were reported to be statistically insignificant due to p-values > 0.05 in both land cover/use groups. Vapour pressure deficit coefficients were found to be negative for all land cover/use groups in the Inkomati and wider Cape study sites. This confirms that there is a negative correlation between ET and VPD. Coefficients of VPD in the Inkomati were much higher than those in the wider Cape. Rainfall coefficients were found to be the smallest among the independent variables used in the analysis; in both catchments, rainfall coefficients ranged from 0.01 to 0.55. By combining three independent variables, there was a strong correlation for the Inkomati and weak in the wider Cape area, which can be observed from the adjusted R^2 values obtained in the multiple regression analyses (Table 4.2). In the Inkomati, the adjusted R^2 values ranged from 0.71 to 0.88 in the various land covers. However in the wider Cape area, adjusted R^2 values were between 0.10 and 0.47.

TABLE 4.2

Coefficients of multiple regressions between MOD16 evapotranspiration and air temperature (T), vapour pressure deficit (VPD) and rainfall per land cover for all provinces and two case study sites (Inkomati and wider Cape). Intercepts and coefficients of correlations (R^2) of the multiple regressions are shown.

Land cover	Coefficients	Gauteng	Western Cape	KwaZulu-Natal	Limpopo	Free State	North-West	Northern Cape	Eastern Cape	Mpumalanga	Inkomati	Wider Cape
LSB	Intercept	2.37	15.43	-1.14	4.22	5.14	7.81	10.99	10.01	-3.25	-9.47	15.03
	Air T	3.25	0.11	4.95	2.28	2.44	0.37	-0.35	2.11	4.09	6.59	2.62
	VPD	-27.89	-3.73	-43.39	-20.56	-21.24	-4.55	-0.14	-20.14	-32.28	-54.89	-21.78
	Rainfall	0.15	0.07	0.10	0.18	0.03	0.13	0.16	0.04	0.20	0.07	-0.04
	R^2	0.79	0.67	0.86	0.65	0.73	0.51	0.65	0.81	0.83	0.88	0.13
GRS	Intercept	-1.25	17.56	-27.15	8.80	-2.44	4.22	3.16	-5.17	-2.63	21.01	36.09
	Air T	3.79	0.93	7.30	2.37	4.98	1.87	0.19	5.93	4.82	5.98	0.59
	VPD	-30.39	-9.26	-48.56	-23.96	-39.68	-15.62	-1.19	-46.21	-39.84	-68.8	-12.14
	Rainfall	0.16	0.03	0.10	1.91	0.06	0.25	0.30	0.04	0.20	0.01	-0.06
	R^2	0.79	0.28	0.87	0.69	0.85	0.75	0.59	0.94	0.86	0.71	0.16
PWD	Intercept	-1.97	-56.86	-63.25	-40.18	9.85	3.53	10.61	-37.81	-19.23	-46.40	3.59
	Air T	3.94	11.23	9.90	8.89	1.55	2.32	-0.08	10.62	8.11	10.00	3.66
	VPD	-30.93	-61.45	-20.52	-26.43	-13.64	-18.87	-1.51	-62.83	-46.48	-33.89	-18.23
	Rainfall	0.16	-0.15	0.12	0.04	0.23	0.25	0.24	-0.03	0.10	0.02	-0.075
	R^2	0.81	0.73	0.91	0.85	0.83	0.76	0.62	0.92	0.85	0.83	0.38
TDB	Intercept	-5.30	6.48	-121.16	-13.24	-0.69	1.27	10.23	-41.64	-35.36	-48.44	12.91
	Air T	4.06	3.19	11.32	5.12	4.10	2.37	-0.21	9.64	7.00	9.36	2.65
	VPD	-30.71	-24.94	-46.36	-37.82	-31.48	-18.41	-0.50	-70.37	-45.76	-62.68	-14.24
	Rainfall	0.16	0.03	0.17	0.20	0.06	0.30	0.20	-0.02	0.20	0.02	-0.06
	R^2	0.79	0.63	0.88	0.75	0.85	0.75	0.58	0.86	0.82	0.85	0.24
WOB	Intercept	-3.94	22.50	-58.21	-2.64	-4.28	5.98	23.60	-15.52	-0.31	-37.06	-
	Air T	3.67	0.03	8.47	3.77	4.42	1.84	-0.19	7.05	4.39	8.38	-
	VPD	-28.77	-5.72	-47.49	-30.96	-33.10	-16.86	-4.43	-54.06	-40.75	-64.46	-
	Rainfall	0.16	0.04	0.14	0.19	0.06	0.31	0.06	0.01	0.22	0.17	-

TABLE 4.2
Coefficients of multiple regressions between MOD16 evapotranspiration and air temperature (T), vapour pressure deficit (VPD) and rainfall per land cover for all provinces and two case study sites (Inkomati and wider Cape). Intercepts and coefficients of correlations (R^2) of the multiple regressions are shown.

Land cover	Coefficients	Gauteng	Western Cape	KwaZulu-Natal	Limpopo	Free State	North-West	Northern Cape	Eastern Cape	Mpumalanga	Inkomati	Wider Cape
	R^2	0.78	0.71	0.85	0.72	0.83	0.72	0.66	0.90	0.70	0.81	-
INF	Intercept	8.77	-91.68	-189.97	-81.93	-2.50	3.25	-	-63.51	-91.20	-88.98	-
	Air T	2.70	16.18	13.58	10.27	4.41	2.38	-	13.20	10.58	10.94	-
	VPD	-26.57	-86.37	-30.32	-23.71	-32.33	-19.55	-	-67.89	-17.93	-21.44	-
	Rainfall	0.12	-0.27	0.17	0.06	0.07	0.23	-	-0.05	0.12	0.08	-
	R^2	0.73	0.69	0.89	0.87	0.85	0.80	-	0.81	0.90	0.87	-
MNS	Intercept	7.56	29.67	-10.48	11.25	3.03	9.38	7.82	0.66	7.75	2.45	50.10
	Air T	2.62	0.22	5.34	2.11	2.66	0.65	0.08	3.97	2.87	5.82	-0.51
	VPD	-25.57	-10.29	-39.44	-22.61	-22.98	-7.96	-1.90	-33.56	-28.50	-52.84	-9.42
	Rainfall	0.14	0.01	0.09	0.18	0.03	0.20	0.19	0.06	0.18	0.07	-0.55
	R^2	0.81	0.51	0.85	0.74	0.82	0.69	0.62	0.92	0.86	0.86	0.32
BNV	Intercept	2.24	10.27	-30.21	-1.60	5.86	7.00	18.58	12.86	-1.29	-	7.58
	Air T	3.39	0.31	6.49	3.46	1.82	0.69	-0.69	1.23	4.48	-	3.61
	VPD	-29.46	-4.13	-42.89	-28.60	-16.44	-7.17	-0.60	-13.98	-38.00	-	-31.34
	Rainfall	0.16	0.08	0.13	0.19	0.03	0.17	0.12	0.06	0.19	-	-0.04
	R^2	0.79	0.57	0.89	0.78	0.72	0.66	0.80	0.85	0.86	-	0.21
WTL	Intercept	-5.18	20.21	-33.85	-15.55	-3.73	-0.89	10.48	0.86	-5.02	-21.37	42.96
	Air T	4.15	1.84	8.84	4.80	5.12	2.68	0.00	4.97	5.06	7.87	0.80
	VPD	-31.16	-18.56	-60.66	-33.14	-40.68	-19.85	-2.41	-40.00	-41.24	-59.37	-16.96
	Rainfall	0.17	0.00	0.10	0.19	0.08	0.27	0.24	0.04	0.20	0.06	-0.08
	R^2	0.80	0.22	0.88	0.76	0.87	0.79	0.61	0.92	0.85	0.88	0.12
CSU	Intercept	-9.49	31.11	-34.56	7.27	5.23	10.58	32.10	-17.65	2.21	-31.55	-
	Air T	4.37	-0.38	6.87	2.67	2.30	0.63	-0.30	7.48	4.05	7.54	-
	VPD	-29.78	-6.23	-40.42	-25.83	-21.20	-8.16	-7.57	-58.19	-35.74	-56.49	-
	Rainfall	0.18	0.03	0.13	0.15	0.11	0.19	0.04	0.02	0.20	0.02	-

TABLE 4.2

Coefficients of multiple regressions between MOD16 evapotranspiration and air temperature (T), vapour pressure deficit (VPD) and rainfall per land cover for all provinces and two case study sites (Inkomati and wider Cape). Intercepts and coefficients of correlations (R^2) of the multiple regressions are shown.

Land cover	Coefficients	Gauteng	Western Cape	KwaZulu-Natal	Limpopo	Free State	North-West	Northern Cape	Eastern Cape	Mpumalanga	Inkomati	Wider Cape
	R^2	0.79	0.66	0.87	0.77	0.68	0.59	0.52	0.95	0.82	0.86	-
CPE	Intercept	-2.95	9.65	-104.30	-5.87	-2.85	0.01	1.13	-19.63	-36.87	-67.78	15.46
	Air T	3.97	2.04	10.09	5.44	4.12	2.92	0.65	7.55	7.80	9.95	2.57
	VPD	-31.13	-11.93	-43.54	-39.81	-29.44	-22.30	-1.16	-55.45	-44.17	-55.63	-20.93
	Rainfall	0.16	0.01	0.15	0.19	0.10	0.26	0.17	0.00	0.16	0.01	-0.05
	R^2	0.78	0.28	0.89	0.78	0.85	0.82	0.60	0.85	0.84	0.87	0.12
CCA	Intercept	-2.31	48.15	-34.36	-3.56	-5.77	7.16	14.76	-1.21	-5.77	-64.75	83.62
	Air T	4.08	0.10	8.41	3.51	5.05	1.06	0.18	5.29	4.60	8.06	-1.59
	VPD	-32.85	-17.47	-54.18	-27.85	-39.17	-10.02	-2.72	-43.33	-35.12	-56.61	-14.86
	Rainfall	0.17	-0.04	0.11	0.16	0.00	0.20	0.13	0.06	0.21	0.10	-0.16
	R^2	0.77	0.40	0.84	0.72	0.79	0.57	0.24	0.91	0.77	0.83	0.47
SHF	Intercept	-	16.03	-	-	-	-	26.67	-8.65	-	-	20.01
	Air T	-	1.37	-	-	-	-	-0.40	5.14	-	-	2.30
	VPD	-	-13.10	-	-	-	-	-4.02	-43.60	-	-	-21.20
	Rainfall	-	0.05	-	-	-	-	0.06	0.03	-	-	-0.05
	R^2	-	0.34	-	-	-	-	0.71	0.83	-	-	0.10

Figure 4.21 shows an example comparing the MOD16 ET time series and ET calculated using the multiple regression formulae for wetlands in the Western Cape and cultivated subsistence in the Eastern Cape. These land covers respectively exhibited the lowest and the highest R^2 in the MRA. Wetlands in the Western Cape had ET generally ranging between 20 and 40 mm $month^{-1}$. ET modelled with MRA was within the range of MOD16 ET, however it did not capture the seasonality of ET values. Monthly MOD16 ET and ET modelled with MRA displayed very similar values for cultivated subsistence in the Eastern Cape throughout the study period. The comparisons of MOD16 ET and ET calculated using the multiple regression formulae can be found in Deliverable 5a of the project.

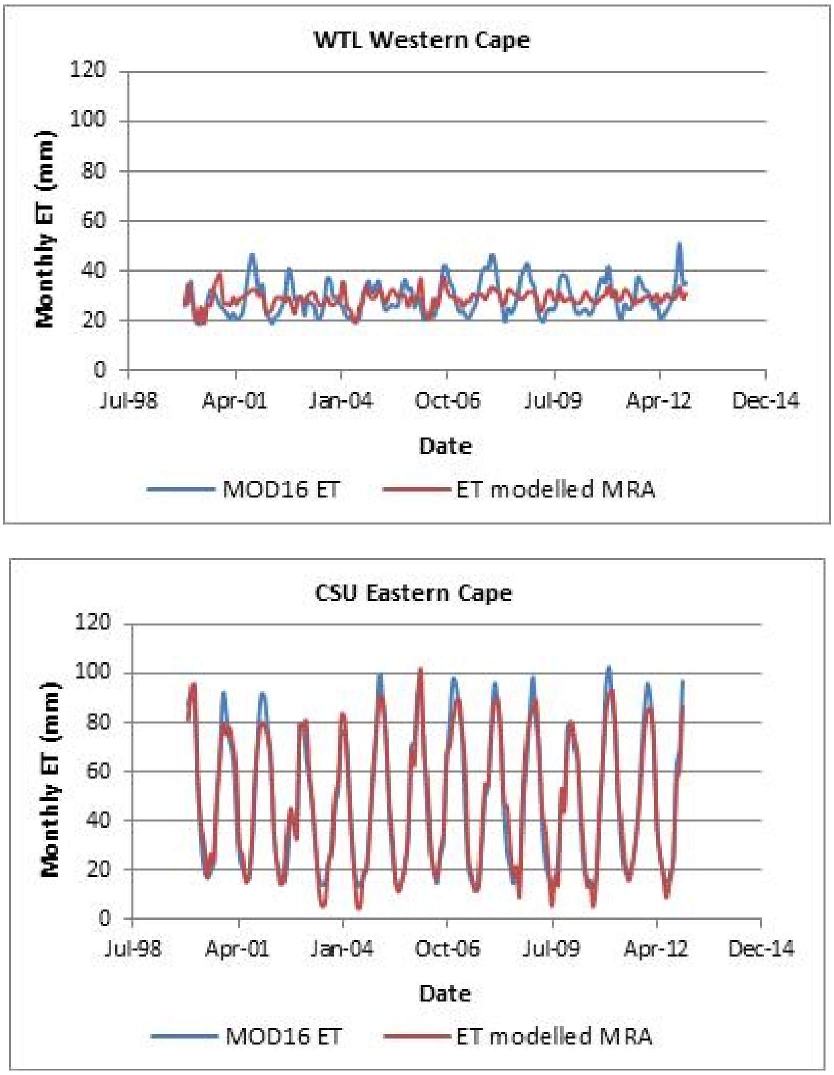


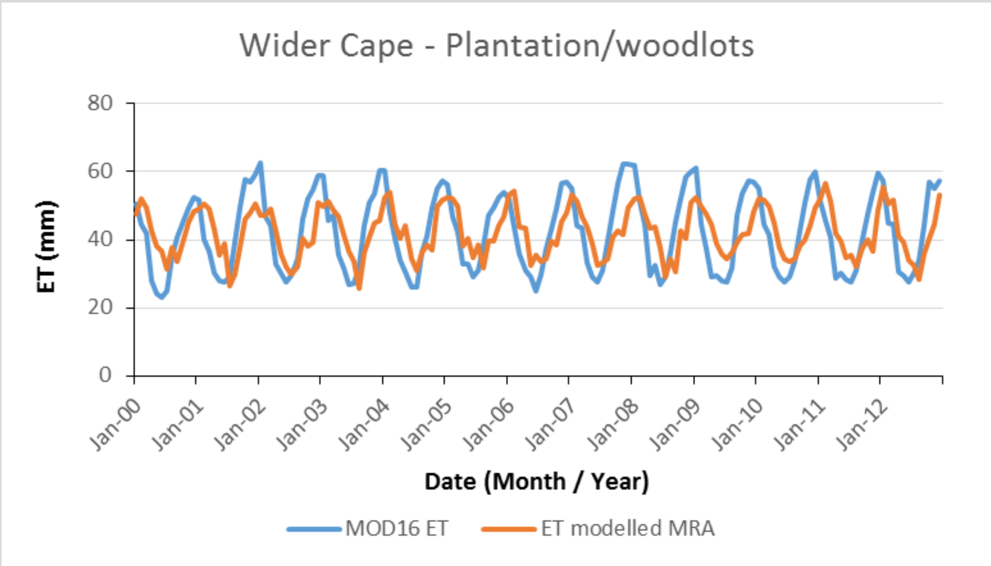
Figure 4.21

Monthly MOD16 evapotranspiration (ET) and ET calculated with multiple regression analysis (MRA) formulae for wetlands in the Western Cape and cultivated subsistence in the Eastern Cape.

Figure 4.22 compares the MOD16 ET time series and ET calculated using the multiple regression formulae for plantation/woodlots and shrubland fynbos in the wider Cape area. These are two characteristic land covers at the study site. For plantation/woodlots, the seasonal amplitude of MOD16 ET was between 20 and 60 mm $month^{-1}$, whereas ET calculated with MRA varied in a narrower range from 30 to 50 mm $month^{-1}$ (R^2 = 0.38). For fynbos, MOD16 ET varied seasonally from 20 to 50 mm $month^{-1}$, whereas ET calculated with MRA was stable around 30 mm $month^{-1}$ with an R^2 of 0.10, indicating that climatic variables explain little of the fynbos ET and that other factors such as the soil depth and water availability, root depth and plant adaptation may play a significant role.

For the Inkomati, the relation between ET and climatic variables was stronger than in the wider Cape (higher R^2 values) (Table 4.2). Examples for characteristic land uses in Inkomati (indigenous forests and grasslands) are shown in Figure 4.23. The seasonal amplitude of MOD16 ET for indigenous forests was between 30 and 150 mm $month^{-1}$. This was matched well by ET modelled with MRA (R^2 = 0.87). A good prediction of ET by MRA was also obtained for grasslands with ET generally ranging from 10 to 90 mm $month^{-1}$ (R^2 = 0.71).

The comparisons of MOD16 ET and ET calculated using the multiple regression formulae can be found in Deliverable 7 of the project for all land covers, provinces and two case study sites.



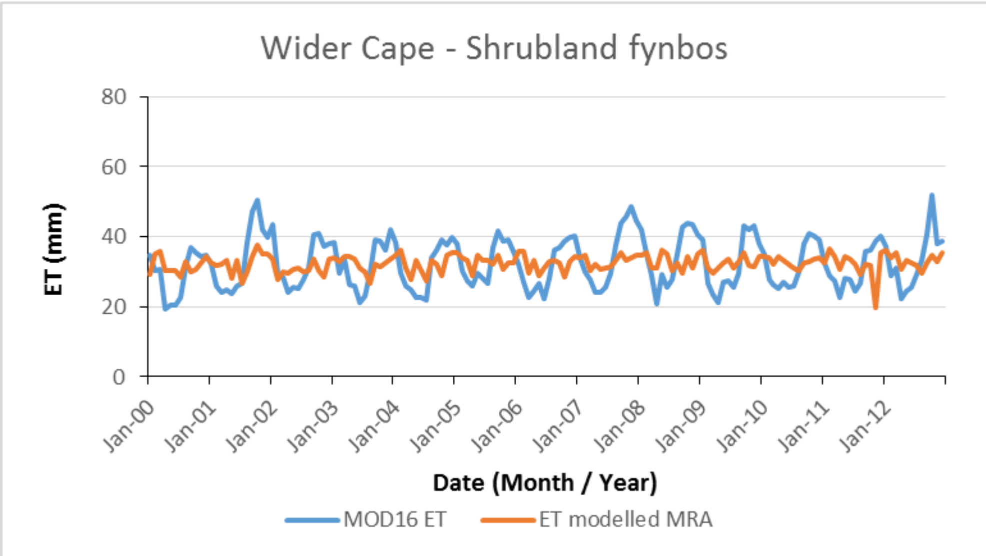
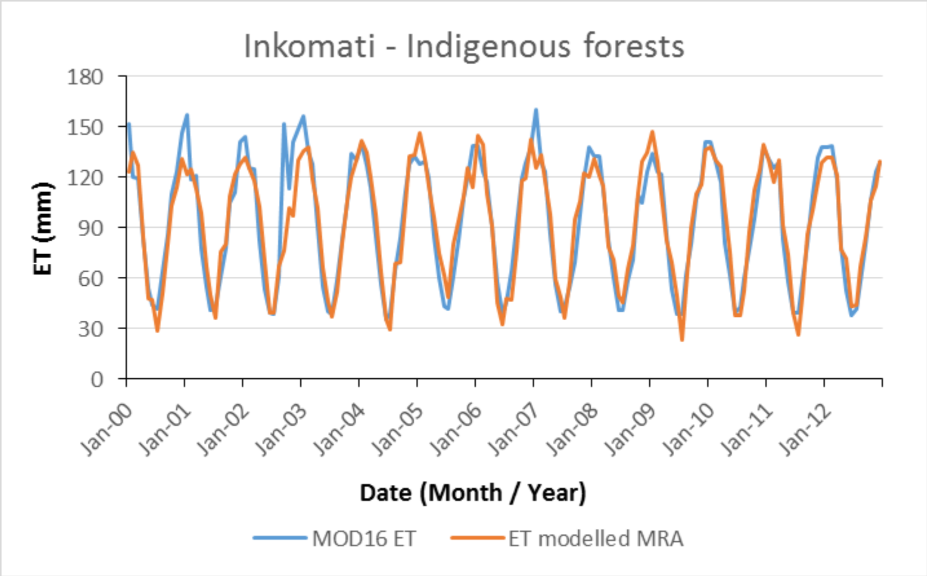


Figure 4.22

Monthly MOD16 evapotranspiration (MOD16 ET) and evapotranspiration modelled with multiple regression analysis (MRA) for plantation/woodlots and fynbos in the wider Cape area (2000-2012).



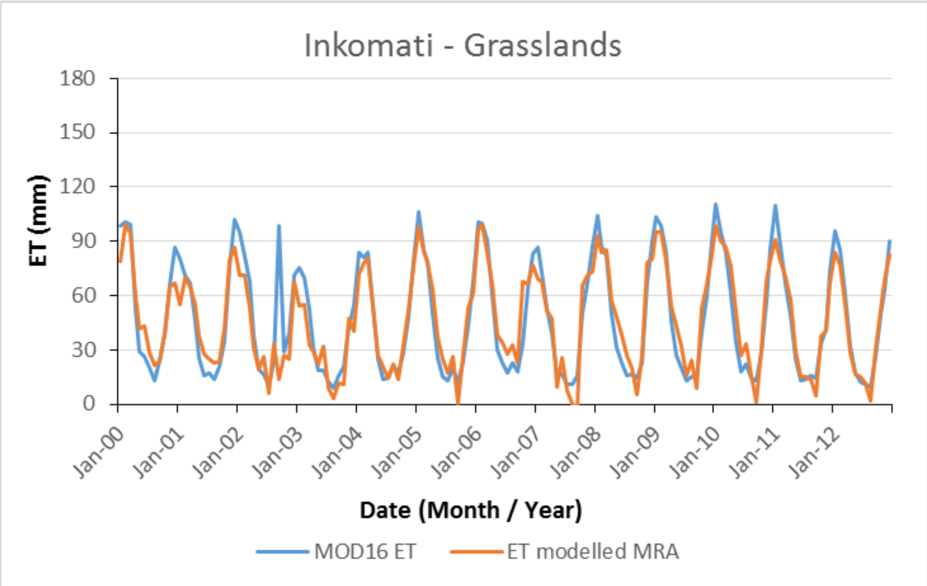


Figure 4.23

Monthly MOD16 evapotranspiration (MOD16 ET) and evapotranspiration modelled with multiple regression analysis (MRA) for indigenous forests and grasslands in the Inkomati area (2000-2012).

4.5.5 Auto-regressive and moving-average (ARIMA) analysis

Patterns in time series data can be used to predict future outcomes for the time series. An integrated autoregressive and moving-average (ARIMA) model was used to predict future outcomes for each variable per province and case study site, and per land cover/use group. In time series analyses, it is vital that the time series is stationary, which means that it should have a constant mean (no decreasing or increasing trend), variance and co-variance. This means that all seasonal trends should be removed from the data in order to model only the residuals. The ARIMA model applies a principle known as "differencing" to the data, which helps to describe certain types of non-stationary series. The non-stationarity of a time series is therefore taken into account when using an ARIMA model. The ARIMA process takes the auto-regressive (p), number of differences (d) and moving average (q) terms as input and is known as the process of order (PO) (Chatfield, 2004). A process of hyper-parameter optimization (grid search) was implemented.

This process systematically evaluated and ranked the outcome of an ARIMA model using a variable amount of PO combinations. All possible combinations of p, d, and q in the range of 0 to 6 where tested (i.e. 216 combinations). Each ARIMA output is ranked according to the model's combined Akaike's Information Criterion (AIC) and Bayesian Information Criterion (BIC) values. The PO that produced the best combined AIC and BIC criterion was then implemented to the time series data to predict possible future outcomes, up to the year 2030. This process was automated using Python software together with the StatsModels library (Seabold and Perktold, 2010). The approach of hyper-parameter optimization is not always successful as some time series models require a PO with higher p and q terms (higher than 6). Increasing the number of the PO combinations increases the processing time and intensity exponentially (e.g. increasing the range of possible PO combinations to 12 will result in 1728 iterations). The analyses resulted in a prediction of future outcomes for each variable per province and case study site, and per land cover/use group, together with a root mean square error (RMSE) based on the comparison between the actual and predicted 'in-sample' values. Apart from the AIC and BIC values, no accuracy estimation of the 'out-of-sample' prediction is presented, thus the results should be interpreted with caution. Further refinement of this method could include an improved accuracy estimation method and a more extensive hyper-parameter optimization approach.

Figures 4.24-4-26 show some examples of ARIMA forecasts applied to MOD16 monthly ET time series for selected land cover/use groups that exhibited different trends. In the Western Cape, no real trend in the water use was observed for cultivated commercial annual crops from 2000 until 2012, but seasonal fluctuations are clearly noticeable (Figure 4.24). Water use spikes in the months of August, September and October are apparent with a "higher than average" water use for the year of 2012. The forecast of monthly ET of cultivated commercial annual crops up to the year 2030 indicates no major change (Figure 4.14).

Figure 4.25 shows that seasonal fluctuations occur in the water use of cultivated perennial crops in the Western Cape from 2000 to 2012. The water use from April to July is relatively low with a dramatic increase in water use in October. The forecast of ET of cultivated perennial crops up to the year 2030 indicates a significant upwards trend.

Figure 4.26 shows that there is no clear trend in the water use of cultivated perennials in Mpumalanga from 2000 to 2012, but that seasonal fluctuation is strong. The highest water use is in January, February and March, with a clear underlying relationship between ET and rainfall. Figure 4.26 shows the forecast of ET of cultivated annual crops until the year 2030. It indicates no significant trends in mean water use, however a reduction in the seasonal amplitude of ET.

ARIMA analyses for all provinces, case study sites and land covers are available in Deliverables 5a and 7a of this project. Although the ARIMA analysis did produce a few noteworthy projections (e.g. Figure 4.25), the overwhelming majority of the projections indicated no significant change and, additionally, a large amount of projections completely failed. This is likely due to the fact that using only 13 years of climate data is not enough information to confidently model future climatic change. It is recommended that a much larger time frame be used when trying to predict changes in these climatic drivers with an ARIMA approach. It was therefore decided not to include any trends identified by ARIMA in any future climate change scenarios when using the MRA, the mean responses (across the 13 years) were rather used.

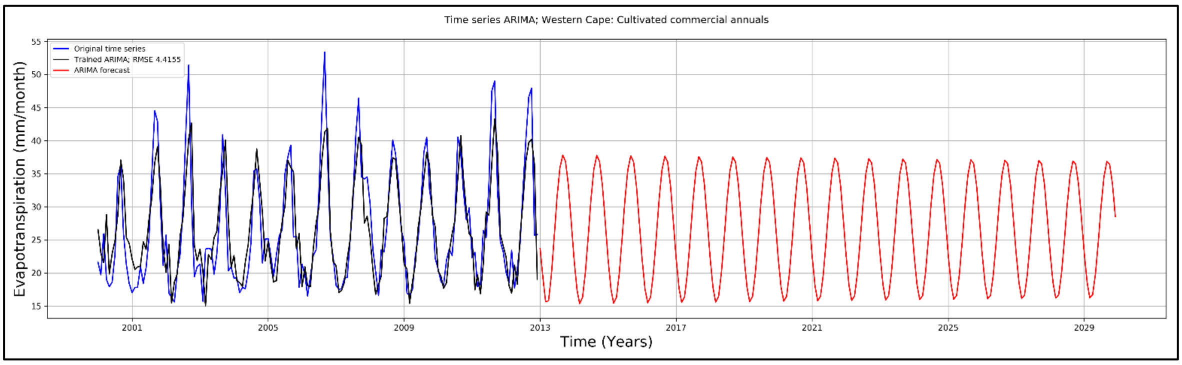


Figure 4.24

ARIMA forecast of monthly ET for cultivated commercial annual crops in the Western Cape. Years 2000-2012: Historic monthly MOD16 ET data (blue line) and ARIMA trained time series (black line). Years 2013-2030: ARIMA forecast (red line).

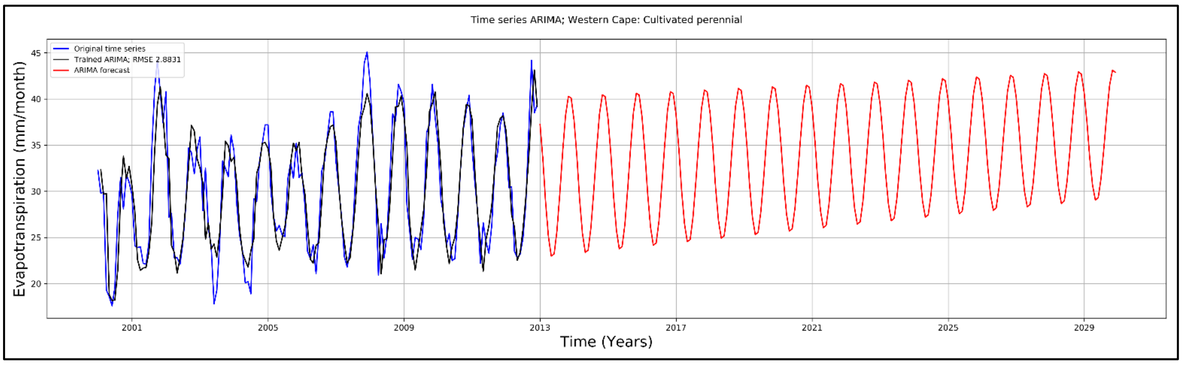


Figure 4.25

ARIMA forecast of monthly ET for cultivated commercial perennial crops in the Western Cape. Years 2000-2012: Historic MOD16 monthly ET data (blue line) and ARIMA trained time series (black line). Years 2013-2030: ARIMA forecast (red line).

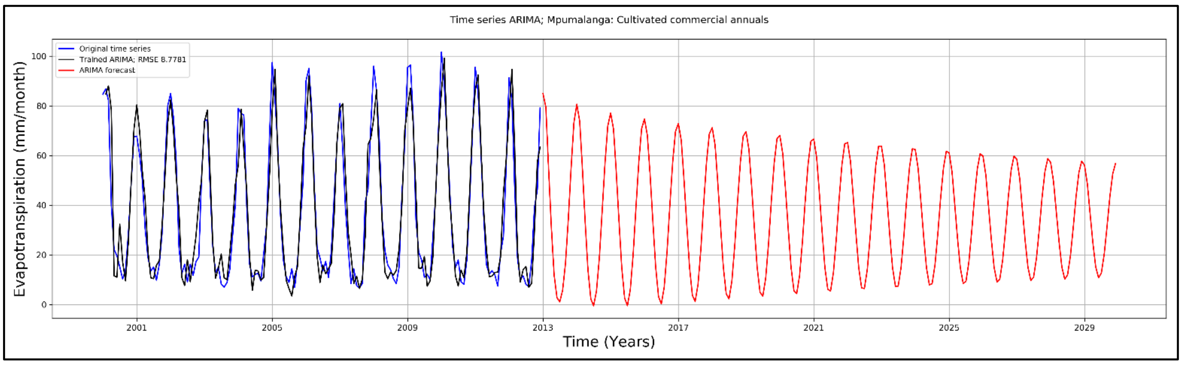


Figure 4.26

ARIMA forecast of monthly ET for cultivated commercial annual crops in Mpumalanga. Years 2000-2012: Historic MOD16 monthly ET data (blue line) and ARIMA trained time series (black line). Years 2013-2030: ARIMA forecast (red line).

5 PROJECTED SCENARIOS OF LAND USE AND WATER USE

5.1 Approach

The historical data described in Chapter 4 were used to develop multiple regression equations to link water consumption (evapotranspiration) to land uses and climatic data for all of South Africa, per province and per case study site. In this Chapter 5, multiple regression equations were used to project future water use changes as a function of land use and climatic changes (objective 3 of the project). For this purpose, plausible and realistic scenarios of future land and water use had to be established for the two case study sites, namely the wider Cape Town area and the Inkomati area. A web application (Water Use Scenario Builder or Water USB) was developed for the two cases study sites. The Water USB was then demonstrated through a few examples to estimate changes in water use as a function of changes in land cover and climatic variables.

5.2 Stakeholder engagement

The scenarios were drafted with key stakeholders (City of Cape Town, Inkomati-Usuthu Catchment Management Agency, Department of Water and Sanitation) at a workshop that was held on 8 November 2017 at Philippi Horticultural Association (PHA) in Schaapkraal, Cape Town.

The workshop was entitled “Decision Support Systems for Water Resources in South Africa”. The main purpose of the workshop was i) to solicit inputs from potential users and get feedback from stakeholders for further development, and iii) to design future scenarios of water and land use for the two case study sites, in cooperation with the City of Cape Town and the Inkomati-Usuthu Catchment Management Agency. The idea was based on making practical use of the wealth of information that exists in databases and monitoring systems for water resources management, in particular remote sensing observations that provide the opportunity for spatial and temporal representation of the water cycle variables.

5.3 Scenario design

Two interactive/group sessions were organized during the course of the workshop. The first session was aimed at soliciting answers from the participants to the following questions:

- What water-related decisions do you make in your institution, e.g. how can we optimize the use of water in the catchment?
- What tools do you currently use in your respective domains for decision making?

The group session and feedback demonstrated that there is a large amount of different types of decisions being made in the respective fields/institutions. It also highlighted issues of time scale and scale with respect to area being considered. A large number of tools is used within different institutions to aid/inform their decision-making.

The second interactive session was aimed at developing scenarios of land use and water use. Two groups were formed and each group was asked to design realistic future scenarios and their impacts on water use for the Inkomati and wider Cape areas. It was suggested to consider, for example, future changes in land use, changes in climate (temperature and rainfall) and population changes. The group developing scenarios for the wider Cape area compiled a table to show the type of scenario, the expected change for that scenario, and then the expected effect on the water resources (Table 5.1). The Inkomati group focused on changes in land use, changes in climate and population changes. Four activities related to changes in land use were deemed relevant, namely agricultural, stream flow reduction activities (SFRA), domestic, and mining and industry. The feedback from the Inkomati group is summarized in Table 5.2.

The workshop was successful in achieving the set objectives. The attendees participated meaningfully to the workshop and they contributed hands-on to the outputs. The feedback from the attendees was taken into consideration in the development of Water USB, and water use/land use scenario modelling were based on the draft suggested by the workshop participants. The full proceedings of the workshop are available in Deliverable 8 of this project.

TABLE 5.1

Future scenarios for the wider Cape area compiled during the stakeholder workshop.

Scenario	Expected change	Effect on water
Change in land use	Infilling of the Central Business District (CBD), densification, expanding of urban edge	Decreased groundwater recharge Increase in water demand and sanitation needs
	Formalization of informal settlements	Water use/demand impacts Decrease in water pollution
	Increase in agricultural land use (e.g. vineyards) which may result in less natural vegetation	Increased water demand and decline in water quality
	More mining and industry	Decreased available groundwater resources Increased pollution and salinity
	Landfill expansion and new sites	Pollution due to leaching of waste
	Urban area greening/Water Sensitive Urban Design (WSUD)	Improved water quality Increase in surface and groundwater availability
Climate change-linked scenarios	Rainfall intensity increased Temperature intensity increased Both within a shorter time period	Under current infrastructure: Decline in available water Decrease in water quality Flash flood potential Erosion increased
	Shifting seasons – effect on Mediterranean climate Increased wind speed	Increased evapotranspiration Increased water demand
Population increase	Increased residential area	Increase in water demand and sanitation
	Increase in construction	Increase in water demand
	Alternative water sources	Increased water supply
	Cost of water	Decrease of water consumption
	Informal settlements	Decrease in water wastage Decrease in water quality
Citizen behaviour changes	Improved water use and increased conservation awareness Installations of saving devices	Decrease in water demand Increase in water reuse Changes in water quality
Legislation changes	Smart metering Informed decision-making By-laws changed for development	

TABLE 5.2 Future scenarios for the Inkomati area compiled during the stakeholder workshop.	
Scenario	**Expected change**
Land use change from agricultural to urban	A large influx of immigrants occurred recently in the water management area from surrounding areas. People often settle. This has an impact on the size of settlements, as well as the population numbers that require water services.
Land use change from agricultural to mining	Much mine prospecting is currently taking place in the water management area.
Change of crop types	Traditionally, the dominant crop in the area has been sugarcane; however, there is a drive to establish tree plantations (e.g. macadamia nuts) in the area. Water use is expected to change as a result.
Climate change-linked scenarios	High seasonal variability with storm events and flood events is becoming more frequent. This is also likely to result in land use changes along the riparian zones of rivers that flood their banks during storm events, as lodges and luxury accommodation which were previously established along water courses now have to move beyond the newly defined floodlines for the area. With additional flood events, possible construction of dams may occur to capture excess flood waters for storage for times when water is needed.
Population increase	Population is expected to increase above the normal rate of natural population increase (number of births). This is due to the large influx of people from surrounding provinces and countries who settle in the area. This is likely to have an impact on water quality, it will increase the demand for water, and it will have a definite impact on sewer capacity due to larger waste streams, with risks of construction within the floodline as population numbers increase and space becomes limited.

5.4 Development of the Water Use Scenario Builder

The Water Use Scenario Builder (Water USB) is an interactive tool for projecting future water use changes as a function of land cover change and designed scenarios of climatic variability. Background data used in the tool included: multiple regression equations of ET and weather variables (rainfall, temperature and vapour pressure deficit), mean monthly ET and monthly standard deviations for each land cover class in each study area. The tool estimates mean water consumptive use (mm) and cumulative water use (Mm^{-3}) for each land cover and for each month of the year based on the historical 13-year monthly dataset analysed. Monthly estimates are then summed to give an estimate of annual totals. Impacts of land cover changes on water use can be estimated by changing the area of each land cover. Impacts of climatic variability are estimated from increases/decreases in vapour pressure deficit, air temperature and rainfall. The software is available from: https://csirwateruse.firebaseapp.com/ (it can be run from Google Chrome).

When launching the scenario tool, the landing page (Figure 5.1) shows the total area and the 13-year average annual water use in each case study site, namely Inkomati and the wider Cape area. The cumulative water use is calculated as a function of the mean evapotranspiration and the total area covered by each land group. The total area covered in the Inkomati is 27,844 km^2 and 6,265 km^2 in the wider Cape (Cape Town area).

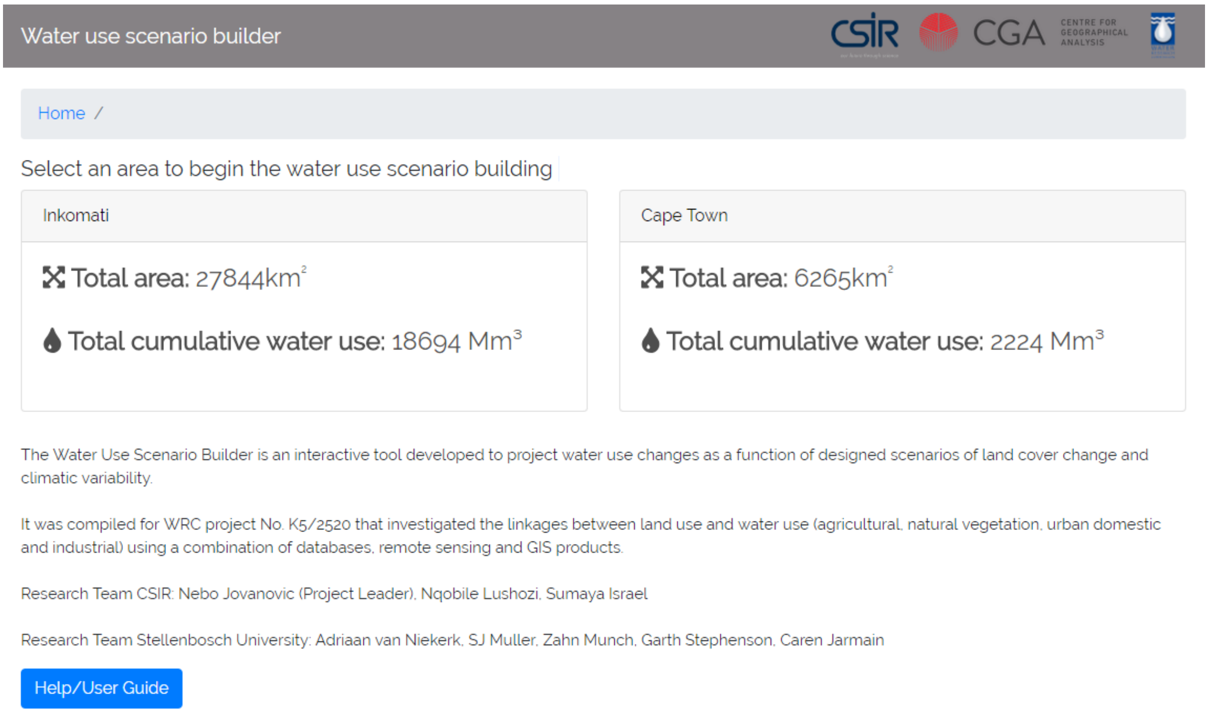
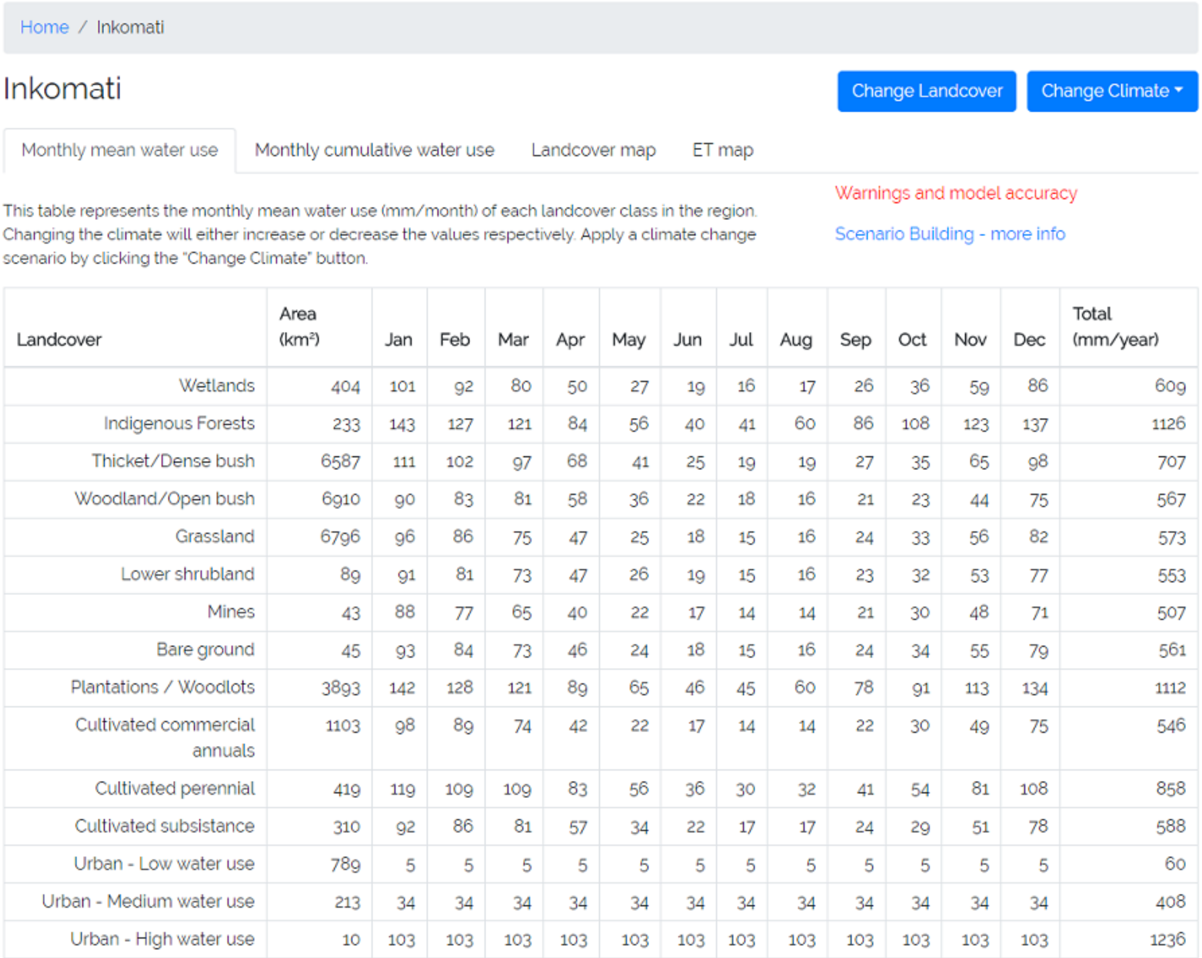


Figure 5.1

Screen capture of the Water Use Scenario Builder landing page.

Once the specific sub-catchment is selected, detailed information showing current water use is displayed; this includes average monthly water use, monthly cumulative water use, the land cover map and an ET map. The *"Monthly mean water use"* tab shows water use of each land cover/use group (mm month^{-1}) obtained from satellite-derived MOD16 data (Figure 5.2). Urban water use data (High, Medium, Low) were estimated from historic urban water use metered by the City of Cape Town and City of Mbombela.



Home / Inkomati

Inkomati

Change Landcover | Change Climate

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

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.

Warnings and model accuracy

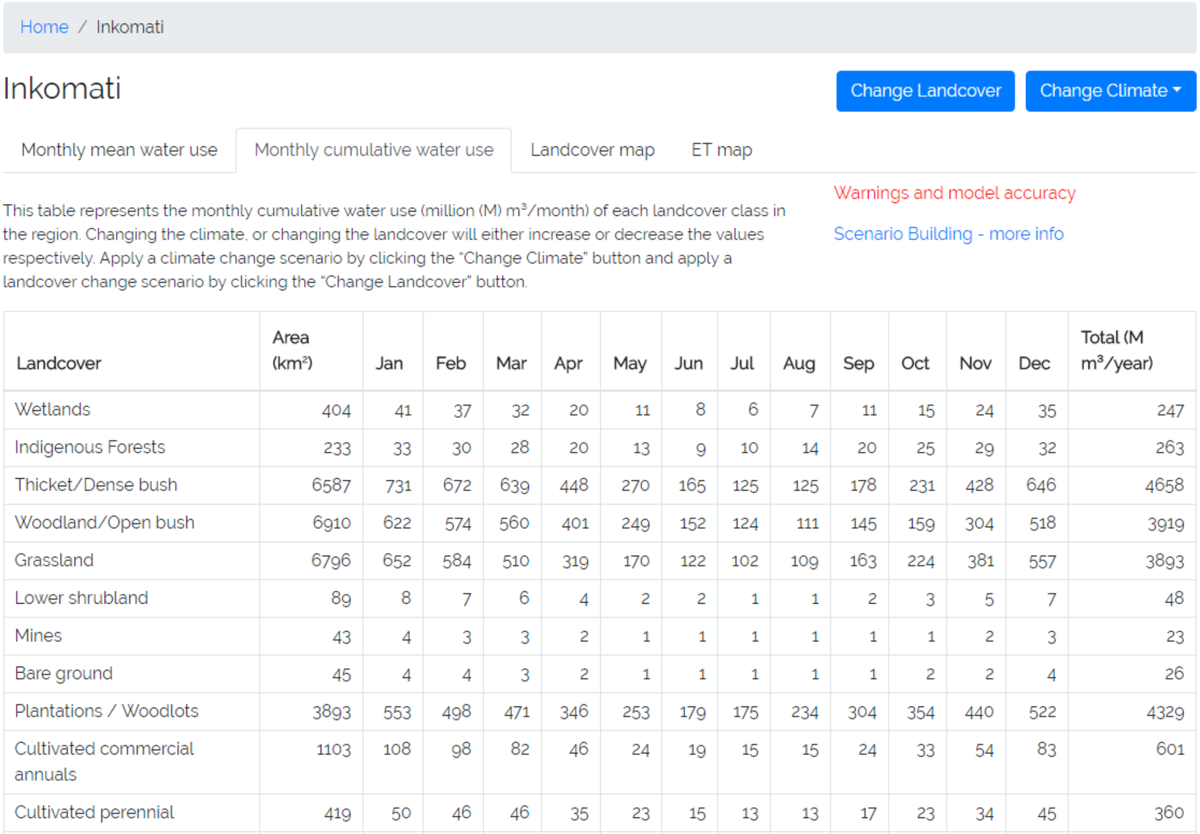
Scenario Building - more info

Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (mm/year)
Wetlands	404	101	92	80	50	27	19	16	17	26	36	59	86	609
Indigenous Forests	233	143	127	121	84	56	40	41	60	86	108	123	137	1126
Thicket/Dense bush	6587	111	102	97	68	41	25	19	19	27	35	65	98	707
Woodland/Open bush	6910	90	83	81	58	36	22	18	16	21	23	44	75	567
Grassland	6796	96	86	75	47	25	18	15	16	24	33	56	82	573
Lower shrubland	89	91	81	73	47	26	19	15	16	23	32	53	77	553
Mines	43	88	77	65	40	22	17	14	14	21	30	48	71	507
Bare ground	45	93	84	73	46	24	18	15	16	24	34	55	79	561
Plantations / Woodlots	3893	142	128	121	89	65	46	45	60	78	91	113	134	1112
Cultivated commercial annuals	1103	98	89	74	42	22	17	14	14	22	30	49	75	546
Cultivated perennial	419	119	109	109	83	56	36	30	32	41	54	81	108	858
Cultivated subsistance	310	92	86	81	57	34	22	17	17	24	29	51	78	588
Urban - Low water use	789	5	5	5	5	5	5	5	5	5	5	5	5	60
Urban - Medium water use	213	34	34	34	34	34	34	34	34	34	34	34	34	408
Urban - High water use	10	103	103	103	103	103	103	103	103	103	103	103	103	1236

Figure 5.2

Screen capture of the Water Use Scenario Builder page showing mean monthly water use estimations (mm month^{-1}).

The second tab shows the *"Monthly cumulative water use"* (Mm^3 month^{-1}) calculated based on the land cover area of each group (Figure 5.3). The monthly cumulative water use of each land cover/use group is calculated using the mean water use of each month (mm month^{-1}) and the total area of each land cover class (km^2). The third tab provides the *"Landcover map"* to show the spatial distribution of the various land cover/use groups. The fourth tab shows an *"ET map"* obtained from the MOD16 product (Figure 5.3).



Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (M m³/year)
Wetlands	404	41	37	32	20	11	8	6	7	11	15	24	35	247
Indigenous Forests	233	33	30	28	20	13	9	10	14	20	25	29	32	263
Thicket/Dense bush	6587	731	672	639	448	270	165	125	125	178	231	428	646	4658
Woodland/Open bush	6910	622	574	560	401	249	152	124	111	145	159	304	518	3919
Grassland	6796	652	584	510	319	170	122	102	109	163	224	381	557	3893
Lower shrubland	89	8	7	6	4	2	2	1	1	2	3	5	7	48
Mines	43	4	3	3	2	1	1	1	1	1	1	2	3	23
Bare ground	45	4	4	3	2	1	1	1	1	1	2	2	4	26
Plantations / Woodlots	3893	553	498	471	346	253	179	175	234	304	354	440	522	4329
Cultivated commercial annuals	1103	108	98	82	46	24	19	15	15	24	33	54	83	601
Cultivated perennial	419	50	46	46	35	23	15	13	13	17	23	34	45	360

Figure 5.3

Screen capture of the Water Use Scenario Builder page showing monthly cumulative water use estimations (Mm^3 $month^{-1}$).

Scenarios can be built by clicking on the blue buttons (Change Landcover and Change Climate). Three possible scenario cases can be run.

Scenario Case One (change in land cover area)

The user in this scenario case is able to change the area of each land cover/use group and, in changing the area, the cumulative water use changes (Figure 5.4). The "*Change Landcover*" button is used to either increase or decrease the area of any land cover/use group. To ensure the total area remains consistent, the user is prompted to balance the increase/decrease in a particular land cover by altering the area of another one. For example, a 10 km^2 loss in Grassland area should be added to one or more other land cover/use groups. As an example in Figure 5.5 for Inkomati, 10 km^2 was removed from Indigenous forest and expanded Thicket/Dense bush. The red/green highlights show the change (decrease/increase) in the total water use of the land cover/use group.

Home / Inkomati

Inkomati

Change Landcover | Change Climate

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

Increased Decreased

Warnings and model accuracy

Scenario Building - more info

This table represents the monthly cumulative water use (million (M) m³/month) of each landcover class in the region. Changing the climate, or changing the landcover will either increase or decrease the values respectively. Apply a climate change scenario by clicking the "Change Climate" button and apply a landcover change scenario by clicking the "Change Landcover" button.

Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (M m³/year)
Wetlands	404	41	37	32	20	11	8	6	7	11	15	24	35	247
Indigenous Forests	223	32	28	27	19	12	9	9	13	19	24	27	31	250
Thicket/Dense bush	6597	732	673	640	449	270	165	125	125	178	231	429	647	4664
Woodland/Open bush	6910	622	574	560	401	249	152	124	111	145	159	304	518	3919

Figure 5.4

Screen capture of the Water Use Scenario Builder page showing an example of output with increase/decrease in cumulative water use estimations (Mm^3 a^{-1}) of land covers as a function of increase/decrease in land cover areas in the Inkomati study area.

Scenario Case Two (climate change)

The user in this scenario case is able to select eight combinations (scenarios) of climate change: higher/lower rainfall, temperature and vapour pressure deficit during the rainy season (wet months) or the dry season (dry months). The mean of the climatic variable represents no change. Increased/decreased values of climatic variables are represented by the mean +/- standard deviations calculated from historic data. By selecting one of eight climatic scenarios, the mean evapotranspiration of each land cover/use group is altered and ultimately the cumulative water use changes. As an example, in Figure 5.5, scenario 7 was selected for dry months – *increased rainfall, while VPD and air temperature remain the same (average)*. Increased mean ET values were calculated as a result of the increase in rainfall while the other climatic drivers remain the same (green cells in Figure 5.5).

Home / Inkomati

Inkomati

Change Landcover | Change Climate

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

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.

Scenario 7 (dry months)
Increased Decreased
Warnings and model accuracy
Scenario Building - more info

Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (mm/year)
Wetlands	404	101	92	80	52	29	20	17	19	28	36	59	86	619
Indigenous Forests	233	143	127	121	88	60	44	45	64	90	108	123	137	1150
Thicket/Dense bush	6587	111	102	97	68	41	26	20	20	28	35	65	98	711
Woodland/Open bush	6910	90	83	81	58	36	23	18	16	21	23	44	75	568
Grassland	6796	96	86	75	48	26	19	16	17	25	33	56	82	579
Lower shrubland	89	91	81	73	47	26	19	15	16	23	32	53	77	553
Mines	43	88	77	65	40	22	17	14	15	21	30	48	71	508
Bare ground	45	93	84	73	46	24	18	15	16	24	34	55	79	561
Plantations / Woodlots	3893	142	128	121	90	66	47	46	61	79	91	113	134	1118
Cultivated commercial annuals	1103	98	89	74	43	23	18	15	15	23	30	49	75	552
Cultivated perennial	419	119	109	109	83	56	36	31	32	41	54	81	108	859

Figure 5.5

Screen capture of the Water Use Scenario Builder page showing an example of output with increase in evapotranspiration (mm a^{-1}) of land covers as a function of climate change (Scenario 7 – increased rainfall, while VPD and air temperature remain the same during dry months) in the Inkomati study area.

Scenario Case Three (combination of land cover change and climate change)

In this scenario case, the user can change both the areas of land cover/use groups and alter the climatic parameters by selecting one of the provided climatic scenarios in dry/wet months. As a result, both mean evapotranspiration of each land cover/use group and the cumulative water use change. The user is therefore able to run countless scenarios with different combinations of changes in land use with climate scenarios, and by combining climate scenarios for dry and wet months.

A comprehensive user-friendly manual is accessible from the interface to facilitate step-by-step operation ("Help/User Guide" button; Figure 5.1). To help guide the user in making interpretations and decisions, a *Warnings and model accuracy* feature (Figure 5.5) was added to the tool to assess the performance of multiple regression model predictions against satellite-derived ET for each month per land cover. Where the model accuracy was considered low

(low R^2 and RMSE>20%), the multiple linear regression estimations of ET require to be treated with caution, and the cells are highlighted in red.

The multiple linear regression models in the Inkomati area showed higher confidence compared to the wider Cape area. The R^2 range in the Inkomati was 0.82 to 0.89 (Table 4.2). RMSE were mostly < 20% during the wet months (January, February, March, October, November and December) compared to dry months when RMSE were mostly > 20%. The multiple regression R^2 values were very low for most land covers in the wider Cape area (Table 4.2), ranging from 0.1 to 0.6. RMSE of ET was generally >20% of the monthly mean water use. Taking into consideration the low R^2 and high RMSE values, this stresses the need to be cautious when interpreting the results of the Water USB for the wider Cape.

5.5 Examples of scenario results

The scenarios designed in Section 5.2 were applied in the Water USB to calculate changes in water use as a function of changes in land use and climate. Selected results of the scenarios are presented in the form of screen printouts of the Water USB in the following sections. The results are discussed and interpreted in terms of increase/decrease in water use.

5.5.1 Wider Cape

Conversion of peri-urban areas into urban areas

Figure 5.6 shows the initial (default condition) of water use in the wider Cape. It should be noted that default values of monthly and total Urban – High water use are approximately 0 because of the small area (7 km^2) compared to the other land uses. The user can choose to display values up to three decimals. Selected results of scenarios are presented where peri-urban areas (Grassland) are converted into urban areas (Low and High water use) (Figures 5.7 and 5.8). Changes highlighted in green indicate an increase in water use, whilst red cells indicate a decrease in water use. Figure 5.7 indicates that converting 10 km^2 grassland into urban areas with low water use would decrease the total water use by 4 $Mm^3\ a^{-1}$, in particular during the months of February, March, April and December. However, if Grassland is converted into High water use Urban areas, there would be an increase in water use by 8 $Mm^3\ a^{-1}$, particularly in the months from May to November, and January (Figure 5.8). This indicates the importance of implementing measures for low water use in urban areas.

Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (M m³/year)
Wetlands	183	5	4	4	4	5	5	5	7	9	9	7	6	70
Indigenous Forest	5	1	1	0	0	0	0	0	0	0	0	1	1	4
Thicket/ Dense bush	586	29	23	21	16	16	15	16	21	25	29	30	31	272
Grassland	365	9	8	8	8	9	9	10	12	15	14	12	11	125
Low shrubland	99	3	3	3	2	2	2	2	3	4	4	4	3	35
Mines	12	0	0	0	0	0	0	0	0	0	0	0	0	0
Bare ground	32	1	1	1	1	1	1	1	1	1	1	1	1	12
Plantations/ Woodlots	131	7	6	6	4	4	4	4	5	6	7	7	8	68
Cultivated commercial annuals	1361	24	20	22	23	30	34	49	73	86	57	33	26	477
Cultivated perennial	710	27	23	21	17	18	18	20	24	28	29	28	28	281
Shrubland fynbos	2047	76	59	57	49	53	51	53	68	82	86	82	80	796
Urban - Low water use	624	5	5	5	5	5	5	5	5	5	5	5	5	60
Urban - Medium water use	103	2	2	2	2	2	2	2	2	2	2	2	2	24
Urban - High water use	7	0	0	0	0	0	0	0	0	0	0	0	0	0
Total (M m³/month)		189	155	150	131	145	146	167	221	263	243	212	202	2224

Figure 5.6

Default (initial condition) water use in the wider Cape.

Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (M m³/year)
Wetlands	183	5	4	4	4	5	5	5	7	9	9	7	6	70
Indigenous Forest	5	1	1	0	0	0	0	0	0	0	0	1	1	4
Thicket/ Dense bush	586	29	23	21	16	16	15	16	21	25	29	30	31	272
Grassland	355	9	7	7	7	9	9	10	12	15	14	12	10	121
Low shrubland	99	3	3	3	2	2	2	2	3	4	4	4	3	35
Mines	12	0	0	0	0	0	0	0	0	0	0	0	0	0
Bare ground	32	1	1	1	1	1	1	1	1	1	1	1	1	12
Plantations/ Woodlots	131	7	6	6	4	4	4	4	5	6	7	7	8	68
Cultivated commercial annuals	1361	24	20	22	23	30	34	49	73	86	57	33	26	477
Cultivated perennial	710	27	23	21	17	18	18	20	24	28	29	28	28	281
Shrubland fynbos	2047	76	59	57	49	53	51	53	68	82	86	82	80	796
Urban - Low water use	634	5	5	5	5	5	5	5	5	5	5	5	5	60
Urban - Medium water use	103	2	2	2	2	2	2	2	2	2	2	2	2	24
Urban - High water use	7	0	0	0	0	0	0	0	0	0	0	0	0	0
Total (M m³/month)		189	154	149	130	145	146	167	221	263	243	212	201	2220

Figure 5.7

Projected water use when 10 km^2 Grassland is converted into Urban areas (Low water use) in the wider Cape. Green cells – Increase in water use; Red cells – Decrease in water use.

Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (M m³/year)
Wetlands	183	5	4	4	4	5	5	5	7	9	9	7	6	70
Indigenous Forest	5	1	1	0	0	0	0	0	0	0	0	1	1	4
Thicket/ Dense bush	586	29	23	21	16	16	15	16	21	25	29	30	31	272
Grassland	355	9	7	7	7	9	9	10	12	15	14	12	10	121
Low shrubland	99	3	3	3	2	2	2	2	3	4	4	4	3	35
Mines	12	0	0	0	0	0	0	0	0	0	0	0	0	0
Bare ground	32	1	1	1	1	1	1	1	1	1	1	1	1	12
Plantations/ Woodlots	131	7	6	6	4	4	4	4	5	6	7	7	8	68
Cultivated commercial annuals	1361	24	20	22	23	30	34	49	73	86	57	33	26	477
Cultivated perennial	710	27	23	21	17	18	18	20	24	28	29	28	28	281
Shrubland fynbos	2047	76	59	57	49	53	51	53	68	82	86	82	80	796
Urban - Low water use	624	5	5	5	5	5	5	5	5	5	5	5	5	60
Urban - Medium water use	103	2	2	2	2	2	2	2	2	2	2	2	2	24
Urban - High water use	17	1	1	1	1	1	1	1	1	1	1	1	1	12
Total (M m³/month)		190	155	150	131	146	147	168	222	264	244	213	202	2232

Figure 5.8

Projected water use when 10 km^2 of Grassland are converted into Urban areas (High water use) in the wider Cape. Green cells – Increase in water use; Red cells – Decrease in water use.

Conversion of natural land into intensive commercial agricultural production

This scenario implied the conversion of land cover/use groups such as Thicket/Dense bush and Shrubland fynbos into intensive, irrigated Cultivated perennial crops (e.g. vineyards, orchards). The results are displayed in Figure 5.9 and 5.10. Increases in water use were generally observed (green cells) in particular in intensive crop growth periods such as in spring (September to December), up to 5 Mm^3 a^{-1} per 10 km^2 area for conversion from Thicket/Dense bush.

Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (M m³/year)
Wetlands	183	5	4	4	4	5	5	5	7	9	9	7	6	70
Indigenous Forest	5	1	1	0	0	0	0	0	0	0	0	1	1	4
Thicket/ Dense bush	576	29	23	21	16	16	15	16	20	25	29	30	31	271
Grassland	365	9	8	8	8	9	9	10	12	15	14	12	11	125
Low shrubland	99	3	3	3	2	2	2	2	3	4	4	4	3	35
Mines	12	0	0	0	0	0	0	0	0	0	0	0	0	0
Bare ground	32	1	1	1	1	1	1	1	1	1	1	1	1	12
Plantations/ Woodlots	131	7	6	6	4	4	4	4	5	6	7	7	8	68
Cultivated commercial annuals	1361	24	20	22	23	30	34	49	73	86	57	33	26	477
Cultivated perennial	720	27	23	22	17	19	18	20	24	29	30	29	29	287
Shrubland fynbos	2047	76	59	57	49	53	51	53	68	82	86	82	80	796
Urban - Low water use	624	5	5	5	5	5	5	5	5	5	5	5	5	60
Urban - Medium water use	103	2	2	2	2	2	2	2	2	2	2	2	2	24
Urban - High water use	7	0	0	0	0	0	0	0	0	0	0	0	0	0
Total (M m³/month)		189	155	151	131	146	146	167	220	264	244	213	203	2229

Figure 5.9

Projected water use when 10 km² of Ticket/Dense bush are converted into Cultivated perennial crops in the wider Cape. Green cells – Increase in water use; Red cells – Decrease in water use.

Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (M m³/year)
Wetlands	183	5	4	4	4	5	5	5	7	9	9	7	6	70
Indigenous Forest	5	1	1	0	0	0	0	0	0	0	0	1	1	4
Thicket/ Dense bush	586	29	23	21	16	16	15	16	21	25	29	30	31	272
Grassland	365	9	8	8	8	9	9	10	12	15	14	12	11	125
Low shrubland	99	3	3	3	2	2	2	2	3	4	4	4	3	35
Mines	12	0	0	0	0	0	0	0	0	0	0	0	0	0
Bare ground	32	1	1	1	1	1	1	1	1	1	1	1	1	12
Plantations/ Woodlots	131	7	6	6	4	4	4	4	5	6	7	7	8	68
Cultivated commercial annuals	1361	24	20	22	23	30	34	49	73	86	57	33	26	477
Cultivated perennial	720	27	23	22	17	19	18	20	24	29	30	29	29	287
Shrubland fynbos	2037	75	59	57	49	53	51	53	67	81	86	81	79	791
Urban - Low water use	624	5	5	5	5	5	5	5	5	5	5	5	5	60
Urban - Medium water use	103	2	2	2	2	2	2	2	2	2	2	2	2	24
Urban - High water use	7	0	0	0	0	0	0	0	0	0	0	0	0	0
Total (M m³/month)		188	155	151	131	146	146	167	220	263	244	212	202	2225

Figure 5.10

Projected water use when 10 km² of Shrubland fynbos are converted into Cultivated perennial crops in the wider Cape. Green cells – Increase in water use; Red cells – Decrease in water use.

Climate change scenarios

Eight designed climate change scenarios were run with different combinations of increased/decreased rainfall, temperature and vapour pressure deficit for dry and rainy seasons (months). Selected results are shown in Figures 5.11 and 5.12. The ET results are expressed in mm month^{-1} and mm a^{-1}. Urban water uses that are derived from water-metered data do not change in the climate change scenarios.

The response in ET from different land covers depends on the combination of the climatic factors, based on the multiple regression equations and +/- standard deviations of the means. Some patterns are interesting to note. For example, ET in Indigenous forests responds more to air temperature changes than to rainfall (Figure 5.11) because they are represented by a small area located on mountain slopes that are likely to receive high rainfall. An increase in air temperature projects an increase in ET by as much as 500 mm a^{-1}. Vice versa, a decrease in air temperature could decrease ET by about 100 mm a^{-1}. On the other hand, Grasslands, Low shrubland, Wetlands, Cultivated commercial annuals, which are composed mainly of temperate species, generally exhibit a higher ET at lower temperatures compared to higher temperatures. This is also the case of Mines.

Evapotranspiration of some land covers (e.g. Thicket/Dense bush, Cultivated perennial, Shrubland fynbos) increases with decreasing rainfall and vice versa (Figure 5.12). This is because, in the Mediterranean climatic region, rainfall is associated with overcast conditions and low ET during the rainy season. On the other hand, when less rainfall occurs, climatic conditions are more conducive to higher ET. This behaviour of the system results from the multiple regression equations derived from historic monthly satellite-derived observations of ET. Irregular response patterns were observed from Bare ground and Plantations/Woodlots possibly due to variations within these land covers.

Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (mm/year)
Wetlands	183	57	52	49	42	39	34	38	45	58	64	58	58	594
Indigenous Forest	5	102	82	69	50	33	26	27	39	62	82	99	108	779
Thicket/ Dense bush	586	70	60	56	42	33	23	26	32	46	59	66	70	583
Grassland	365	33	28	28	24	26	24	26	33	42	42	37	34	377
Low shrubland	99	60	55	54	38	25	10	12	19	31	43	51	56	454
Mines	12	33	31	30	28	31	30	33	40	47	46	41	35	425
Bare ground	32	62	55	50	35	27	16	18	24	34	43	52	59	475
Plantations/ Woodlots	131	75	65	60	40	27	15	18	25	39	54	64	72	554
Cultivated commercial annuals	1361	37	35	34	33	37	39	50	68	77	58	41	38	547
Cultivated perennial	710	56	51	47	34	27	20	24	30	41	47	51	55	483
Shrubland fynbos	2047	68	62	59	45	35	25	27	34	46	57	61	66	585

Figure 5.11

Projected changes in evapotranspiration in the wider Cape area for climate scenario when rainfall, vapour pressure deficit and air temperature decrease. Green cells – Increase in water use; Red cells – Decrease in water use.

Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (mm/year)
Wetlands	183	18	11	13	18	28	33	36	45	52	46	32	24	356
Indigenous Forest	5	140	120	102	76	49	38	40	50	75	104	129	140	1063
Thicket/ Dense bush	586	48	36	34	33	41	47	47	54	59	59	56	54	568
Grassland	365	20	14	15	17	23	25	27	34	40	37	29	23	304
Low shrubland	99	6	0	0	9	27	39	38	45	43	32	22	15	276
Mines	12	14	11	12	15	22	23	26	34	39	35	27	18	276
Bare ground	32	23	12	12	21	36	46	44	52	51	41	36	32	406
Plantations/ Woodlots	131	52	40	37	36	46	54	54	60	64	63	61	59	626
Cultivated commercial annuals	1361	9	6	8	12	19	21	33	51	59	37	18	11	284
Cultivated perennial	710	29	22	22	24	34	39	41	48	50	44	39	34	426
Shrubland fynbos	2047	23	13	14	19	33	43	43	50	52	44	36	30	400

Figure 5.12

Projected changes in evapotranspiration in the wider Cape area for climate scenario when rainfall decreases, vapour pressure deficit and air temperature increase. Green cells – Increase in water use; Red cells – Decrease in water use.

5.5.2 Inkomati

Conversion of agricultural areas into urban areas

Figure 5.13 shows the initial (default condition) of water use in the Inkomati area. The scenario implied the conversion of agricultural land cover (Subsistence agriculture) into Urban areas (Low and High water use). This is projected due to the large influx of immigrants from surrounding regions. The generic Low and High Urban water use may be chosen depending on the size of settlements, as well as the population numbers that require water services. The results are presented in Figures 5.14 and 5.15. Conversion from subsistence agriculture to low urban water use decreases the total water use by 7 $Mm^3 a^{-1}$ for a 10 km^2 area of change, especially during the summer period (Figure 5.14). However, land use change from subsistence agriculture to more water-intensive urban settlements increases total water use by 5 $Mm^3 a^{-1}$ for a 10 km^2 area of change, especially during the winter-spring period (Figure 5.15).

Landcover	Area (km^2)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (M m^3/year)
Wetlands	404	41	37	32	20	11	8	6	7	11	15	24	35	247
Indigenous Forests	233	33	30	28	20	13	9	10	14	20	25	29	32	263
Thicket/Dense bush	6587	731	672	639	448	270	165	125	125	178	231	428	646	4658
Woodland/Open bush	6910	622	574	560	401	249	152	124	111	145	159	304	518	3919
Grassland	6796	652	584	510	319	170	122	102	109	163	224	381	557	3893
Lower shrubland	89	8	7	6	4	2	2	1	1	2	3	5	7	48
Mines	43	4	3	3	2	1	1	1	1	1	1	2	3	23
Bare ground	45	4	4	3	2	1	1	1	1	1	2	2	4	26
Plantations / Woodlots	3893	553	498	471	346	253	179	175	234	304	354	440	522	4329
Cultivated commercial annuals	1103	108	98	82	46	24	19	15	15	24	33	54	83	601
Cultivated perennial	419	50	46	46	35	23	15	13	13	17	23	34	45	360
Cultivated subsistance	310	29	27	25	18	11	7	5	5	7	9	16	24	183
Urban - Low water use	789	4	4	4	4	4	4	4	4	4	4	4	4	48
Urban - Medium water use	213	7	7	7	7	7	7	7	7	7	7	7	7	84
Urban - High water use	10	1	1	1	1	1	1	1	1	1	1	1	1	12
Total (M m^3/month)		2847	2592	2417	1673	1040	692	590	648	885	1091	1731	2488	18694

Figure 5.13

Default (initial condition) water use in the Inkomati area.

Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (M m³/year)
Wetlands	404	41	37	32	20	11	8	6	7	11	15	24	35	247
Indigenous Forests	233	33	30	28	20	13	9	10	14	20	25	29	32	263
Thicket/Dense bush	6587	731	672	639	448	270	165	125	125	178	231	428	646	4658
Woodland/Open bush	6910	622	574	560	401	249	152	124	111	145	159	304	518	3919
Grassland	6796	652	584	510	319	170	122	102	109	163	224	381	557	3893
Lower shrubland	89	8	7	6	4	2	2	1	1	2	3	5	7	48
Mines	43	4	3	3	2	1	1	1	1	1	1	2	3	23
Bare ground	45	4	4	3	2	1	1	1	1	1	2	2	4	26
Plantations / Woodlots	3893	553	498	471	346	253	179	175	234	304	354	440	522	4329
Cultivated commercial annuals	1103	108	98	82	46	24	19	15	15	24	33	54	83	601
Cultivated perennial	419	50	46	46	35	23	15	13	13	17	23	34	45	360
Cultivated subsistance	300	28	26	24	17	10	7	5	5	7	9	15	23	176
Urban - Low water use	799	4	4	4	4	4	4	4	4	4	4	4	4	48
Urban - Medium water use	213	7	7	7	7	7	7	7	7	7	7	7	7	84
Urban - High water use	10	1	1	1	1	1	1	1	1	1	1	1	1	12
Total (M m³/month)		2846	2591	2416	1672	1039	692	590	648	885	1091	1730	2487	18687

Figure 5.14

Projected water use when 10 km^2 of Cultivated subsistence farming are converted into Urban areas (Low water use) in the Inkomati area. Green cells – Increase in water use; Red cells – Decrease in water use.

Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (M m³/year)
Wetlands	404	41	37	32	20	11	8	6	7	11	15	24	35	247
Indigenous Forests	233	33	30	28	20	13	9	10	14	20	25	29	32	263
Thicket/Dense bush	6587	731	672	639	448	270	165	125	125	178	231	428	646	4658
Woodland/Open bush	6910	622	574	560	401	249	152	124	111	145	159	304	518	3919
Grassland	6796	652	584	510	319	170	122	102	109	163	224	381	557	3893
Lower shrubland	89	8	7	6	4	2	2	1	1	2	3	5	7	48
Mines	43	4	3	3	2	1	1	1	1	1	1	2	3	23
Bare ground	45	4	4	3	2	1	1	1	1	1	2	2	4	26
Plantations / Woodlots	3893	553	498	471	346	253	179	175	234	304	354	440	522	4329
Cultivated commercial annuals	1103	108	98	82	46	24	19	15	15	24	33	54	83	601
Cultivated perennial	419	50	46	46	35	23	15	13	13	17	23	34	45	360
Cultivated subsistance	300	28	26	24	17	10	7	5	5	7	9	15	23	176
Urban - Low water use	789	4	4	4	4	4	4	4	4	4	4	4	4	48
Urban - Medium water use	213	7	7	7	7	7	7	7	7	7	7	7	7	84
Urban - High water use	20	2	2	2	2	2	2	2	2	2	2	2	2	24
Total (M m³/month)		2847	2592	2417	1673	1040	693	591	649	886	1092	1731	2488	18699

Figure 5.15

Projected water use when 10 km^2 Cultivated subsistence farming are converted into Urban areas (High water use) in the Inkomati area. Green cells – Increase in water use; Red cells – Decrease in water use.

Conversion of agricultural areas into mining

This scenario implied the conversion of agricultural land groups (Cultivated commercial annuals, Cultivated perennial) into Mines (water used through ET only). This is projected due to prospecting that is currently taking place in the water management area. Cultivated perennials are more intensive water users than Cultivated commercial annuals. The conversion from Cultivated commercial annuals would increase the water use by 1 Mm^3 a^{-1} (in spring) (Figure 5.16), whilst the conversion from Cultivated perennial to Mines would decrease water use by 3 Mm^3 a^{-1} per 10 km^2 (mainly during fall) (Figure 5.17).

Landcover	Area (km^2)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (M m^3/year)
Wetlands	404	41	37	32	20	11	8	6	7	11	15	24	35	247
Indigenous Forests	233	33	30	28	20	13	9	10	14	20	25	29	32	263
Thicket/Dense bush	6587	731	672	639	448	270	165	125	125	178	231	428	646	4658
Woodland/Open bush	6910	622	574	560	401	249	152	124	111	145	159	304	518	3919
Grassland	6796	652	584	510	319	170	122	102	109	163	224	381	557	3893
Lower shrubland	89	8	7	6	4	2	2	1	1	2	3	5	7	48
Mines	53	5	4	3	2	1	1	1	1	1	2	3	4	28
Bare ground	45	4	4	3	2	1	1	1	1	1	2	2	4	26
Plantations / Woodlots	3893	553	498	471	346	253	179	175	234	304	354	440	522	4329
Cultivated commercial annuals	1093	107	97	81	46	24	19	15	15	24	33	54	82	597
Cultivated perennial	419	50	46	46	35	23	15	13	13	17	23	34	45	360
Cultivated subsistance	310	29	27	25	18	11	7	5	5	7	9	16	24	183
Urban - Low water use	789	4	4	4	4	4	4	4	4	4	4	4	4	48
Urban - Medium water use	213	7	7	7	7	7	7	7	7	7	7	7	7	84
Urban - High water use	10	1	1	1	1	1	1	1	1	1	1	1	1	12
Total (M m^3/month)		2847	2592	2416	1673	1040	692	590	648	885	1092	1732	2488	18695

Figure 5.16

Projected water use when 10 km^2 of Cultivated commercial annual crops are converted into Mines in the Inkomati area. Green cells – Increase in water use; Red cells – Decrease in water use.

Landcover	Area (km^2)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (M m^3/year)
Wetlands	404	41	37	32	20	11	8	6	7	11	15	24	35	247
Indigenous Forests	233	33	30	28	20	13	9	10	14	20	25	29	32	263
Thicket/Dense bush	6587	731	672	639	448	270	165	125	125	178	231	428	646	4658
Woodland/Open bush	6910	622	574	560	401	249	152	124	111	145	159	304	518	3919
Grassland	6796	652	584	510	319	170	122	102	109	163	224	381	557	3893
Lower shrubland	89	8	7	6	4	2	2	1	1	2	3	5	7	48
Mines	53	5	4	3	2	1	1	1	1	1	2	3	4	28
Bare ground	45	4	4	3	2	1	1	1	1	1	2	2	4	26
Plantations / Woodlots	3893	553	498	471	346	253	179	175	234	304	354	440	522	4329
Cultivated commercial annuals	1103	108	98	82	46	24	19	15	15	24	33	54	83	601
Cultivated perennial	409	49	45	45	34	23	15	12	13	17	22	33	44	352
Cultivated subsistance	310	29	27	25	18	11	7	5	5	7	9	16	24	183
Urban - Low water use	789	4	4	4	4	4	4	4	4	4	4	4	4	48
Urban - Medium water use	213	7	7	7	7	7	7	7	7	7	7	7	7	84
Urban - High water use	10	1	1	1	1	1	1	1	1	1	1	1	1	12
Total (M m^3/month)		2847	2592	2416	1672	1040	692	589	648	885	1091	1731	2488	18691

Figure 5.17

Projected water use when 10 km^2 of Cultivated perennial crops are converted into Mines in the Inkomati area. Green cells – Increase in water use; Red cells – Decrease in water use.

Change of crop types

This scenario implied the conversion of agricultural land groups from less water-intensive (Cultivated commercial annuals) to more water-intensive land uses (Cultivated perennial). On average, cultivated perennials use 5 Mm^3 a^{-1} more than commercial annuals per 10 km^2 in the Inkomati-Usuthu water management area, especially during the winter-spring period of the year (Figure 5.18).

Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (M m³/year)
Wetlands	404	41	37	32	20	11	8	6	7	11	15	24	35	247
Indigenous Forests	233	33	30	28	20	13	9	10	14	20	25	29	32	263
Thicket/Dense bush	6587	731	672	639	448	270	165	125	125	178	231	428	646	4658
Woodland/Open bush	6910	622	574	560	401	249	152	124	111	145	159	304	518	3919
Grassland	6796	652	584	510	319	170	122	102	109	163	224	381	557	3893
Lower shrubland	89	8	7	6	4	2	2	1	1	2	3	5	7	48
Mines	43	4	3	3	2	1	1	1	1	1	1	2	3	23
Bare ground	45	4	4	3	2	1	1	1	1	1	2	2	4	26
Plantations / Woodlots	3893	553	498	471	346	253	179	175	234	304	354	440	522	4329
Cultivated commercial annuals	1093	107	97	81	46	24	19	15	15	24	33	54	82	597
Cultivated perennial	429	51	47	47	36	24	15	13	14	18	23	35	46	369
Cultivated subsistance	310	29	27	25	18	11	7	5	5	7	9	16	24	183
Urban - Low water use	789	4	4	4	4	4	4	4	4	4	4	4	4	48
Urban - Medium water use	213	7	7	7	7	7	7	7	7	7	7	7	7	84
Urban - High water use	10	1	1	1	1	1	1	1	1	1	1	1	1	12
Total (M m³/month)		2847	2592	2417	1674	1041	692	590	649	886	1091	1732	2488	18699

Figure 5.18

Projected water use when 10 km² of Cultivated commercial annual crops are converted into Cultivated perennial crops in the Inkomati area. Green cells – Increase in water use; Red cells – Decrease in water use.

Climate change scenarios

The results of selected climate change scenarios for Inkomati are shown in Figures 5.19 and 5.20. In the predominantly tropical and wet climate of Inkomati, ET of all land covers depends mainly on air temperature. A decrease in air temperature results in a decrease in ET and vice versa (Figure 5.19). Contrary to the typical climatic conditions in the wider Cape, rainfall in the Inkomati-Usuthu is mainly in the form of convective showers with extensive sunshine time spells on rainy days. Increase in ET is therefore associated with increase in rainfall (Figure 5.20). Variations in ET due to climatic change compared to initial conditions can be up to about +/-300 mm a^{-1} for Indigenous forests and about +/- 200 mm a^{-1} for Plantations/Woodlots.

Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (mm/year)
Wetlands	404	98	87	73	41	14	3	0	7	19	32	54	83	511
Indigenous Forests	233	119	104	96	59	28	11	12	34	62	84	100	114	823
Thicket/Dense bush	6587	107	97	86	55	25	5	0	5	16	29	60	96	581
Woodland/Open bush	6910	95	87	80	57	30	15	9	11	17	24	49	82	556
Grassland	6796	96	85	71	41	16	7	4	9	19	32	55	83	518
Lower shrubland	89	89	78	65	37	12	1	0	5	15	31	52	79	464
Mines	43	83	72	59	32	15	8	5	10	17	29	46	69	445
Bare ground	45	92	81	68	38	16	6	3	10	20	33	53	79	499
Plantations / Woodlots	3893	127	112	105	71	44	24	23	42	62	76	98	120	904
Cultivated commercial annuals	1103	97	87	71	36	14	7	5	9	18	29	46	74	493
Cultivated perennial	419	112	101	97	69	40	18	11	18	30	46	73	102	717
Cultivated subsistance	310	92	85	74	48	23	8	3	8	17	26	49	78	511

Figure 5.19

Projected changes in evapotranspiration in the Inkomati area for climate scenario when rainfall, vapour pressure deficit and air temperature decrease. Green cells – Increase in water use; Red cells – Decrease in water use.

Landcover	Area (km²)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (mm/year)
Wetlands	404	105	96	86	60	40	35	31	28	34	40	65	88	708
Indigenous Forests	233	166	151	145	109	85	69	71	87	110	131	146	160	1430
Thicket/Dense bush	6587	116	107	108	81	57	45	40	33	38	40	70	101	836
Woodland/Open bush	6910	86	79	82	59	42	30	26	21	25	21	40	69	580
Grassland	6796	96	86	78	52	34	29	26	23	28	34	58	81	625
Lower shrubland	89	93	84	81	58	40	36	34	27	31	33	54	76	647
Mines	43	92	83	72	48	28	26	23	19	25	31	51	72	570
Bare ground	45	95	86	78	54	33	30	27	23	29	35	57	79	626
Plantations / Woodlots	3893	158	144	138	107	85	69	67	79	94	106	129	149	1325
Cultivated commercial annuals	1103	99	91	77	47	30	26	23	20	26	32	53	75	599
Cultivated perennial	419	126	116	120	96	72	55	50	46	52	61	89	115	998
Cultivated subsistance	310	93	87	87	66	45	35	32	26	31	32	54	77	665

Figure 5.20

Projected changes in evapotranspiration in the Inkomati area for climate scenario when rainfall, vapour pressure deficit and air temperature increase. Green cells – Increase in water use; Red cells – Decrease in water use.

6 CONCLUSIONS

This project succeeded in providing best estimates of current and historic land and water uses and their linkages at different spatial scales (national, provincial and case studies), by using primary sources of nationwide data such as WARMS, land cover maps and satellite-derived ET (MOD16 and ETLook). Multiple regression formulae were generated from historic land cover data, MOD16 and climatic variables per province and per land cover/use group. The multiple regression formulae were used to inform the Water Use Scenario Builder, a user-friendly web application for calculating changes in water use (mm and Mm^3) as a result of changes in land use and climate. The data processed and results obtained in this project were overwhelming given the volume of spatial data at national scale, and the most salient outcomes are difficult to outline and single out, as the relevant outcomes will depend on specific applications and users. The specific findings of the project were listed in the various chapters of this report. However, it is worth highlighting some general conclusions.

Current status of water and land use

Based on WARMS data (updated at August 2016), the highest water use volumes are registered at national level for taking water and storing water. The third highest water use is disposal of wastewater. By water resource types, water abstraction takes place primarily from water schemes, rivers/streams, boreholes and dams. The highest water withdrawals per sector are from agricultural irrigation (64.8% of the total), water supply services (14.7%), urban industry (13.3%), mining (4.3%) and non-urban industry (1.6%). Total water uses in each region (province) depend mainly on the economic activities and associated land uses. High water withdrawals are associated with urban regions, whilst high water storages are associated with high rainfall areas. Large scale irrigation with wastewater is limited to Breede-Gouritz (0.15 billion $m^3\ a^{-1}$) and Eastern Cape (0.07 billion $m^3\ a^{-1}$). It appears that such practice is under-used in arid and semi-arid regions, especially Lower Orange, Lower Vaal or North West. Discharging wastewater is associated with urban areas and industry. Removing underground water is mainly associated with dewatering mines. In all regions, the largest water use is from agricultural irrigation, except Gauteng. Industrial water use is the highest in Gauteng, KwaZulu-Natal, Mpumalanga and the Western Cape, which are the most industrialized regions. A large portion of industrial water use in KwaZulu-Natal and Mpumalanga is from non-urban industries. Water use for mining is the highest in Mpumalanga, followed by North West, Lower Vaal, Gauteng and Free State.

Satellite-derived ET (MOD16 and ETLook) provided quantified values of consumptive water use from natural and cultivated land. Apart from waterbodies, land covers under natural forests, plantations, cultivated cane and perennial crops contribute the most to water use per unit area (mm a^{-1}) at national scale. In many regions, cultivated annual crops consume less water per unit area than grasslands and low shrublands. In absolute terms (Mm^{-3} a^{-1}), grasslands and low shrublands use the most water at national scale because they cover the largest areas. One should, however, interpret these values with caution as there are large variations attributed to climatic conditions because land covers are spread over diverse regions and they are heterogeneous. The resolution of the satellite-derived ET data may also play a significant role. The median of ET is often below the average, indicating that most of the data are spread in the lower range of ET with some extreme high values for each land cover. By province, Mpumalanga uses the most water per unit area, most likely because it receives a high rainfall and is characterized by vegetation types and land uses that consume more water. Conversely, the Northern Cape uses the least water per unit area. The Eastern Cape is the largest user of water (in Mm^3 a^{-1}), even though it is relatively small (14%). The Limpopo and Free State are also large users of water. In terms of size, they are comparable with the Western Cape (10%), but consume more than double the water. Based on machine learning models, land cover and mean annual rainfall have the most significant influence on ET. Average soil clay content ranks third by importance because it determines water available to plants for ET. In the wider Cape area, soil depth and elevation are stronger drivers of ET than rainfall.

The volume of water registered in WARMS for sector agriculture – irrigation is far less than the volume of water consumed from cultivated land, as estimated with satellite-derived ET countrywide. Irrigation is in most cases used to supplement rainfall and it therefore contributes only a fraction of ET. It should be considered that not all irrigators are registered countrywide, and especially that satellite coverage includes both irrigated and rainfed land. Satellite-derived products give the opportunity to perform large scale water use validation, bearing in mind there are uncertainties in the estimates. The volume of water evaporating from non-agricultural vegetated land outweighs by far the agricultural water consumption estimated with satellite products and the volume of water registered in WARMS for agriculture. The non-agricultural vegetated land includes woodlands/open bush, wetlands, thicket/dense bush, plantations, low shrublands, indigenous forests, grasslands and fynbos. There may be therefore a case for better planning of these lands in terms of water resources management, although this is influenced by many environmental, social and economic factors, and local conditions. At national level, the total volume of water that evaporates from urban areas is more than double the water supplied to industry and domestic users. This is particularly the case in high rainfall areas. There may, therefore, be a case for capturing some of the rainwater before it reaches the ground and evaporates in urban areas (e.g. rainwater harvesting).

MOD16 and ETLook compared relatively well in terms of spatial representation of ET, considering that the two products provide ET at different resolutions and use different models. Both ET estimation methods appear to be suitable to indicate areas of low ET and hotspots of high ET. They generally provide realistic and similar spatial patterns of ET, although in absolute terms ETLook appears to provide a wider range of values compared to MOD16 (higher ET in the high range and lower ET in the low range) due to the principles and mechanisms adopted in the algorithms. This was evident from the maximum and minimum values, although the standard deviations of ET were in the same range for both MOD16 and ETLook, for most land covers.

Historical water and land use

Historically, water use registrations in WARMS have been increasing steadily in South Africa, especially since bulk registrations took place in the years 2000-2003. A rise in WARMS registrations also occurred in the last two years when intensive updating of the WARMS database took place. Water use registrations for irrigation were the highest countrywide, followed by water supply services, urban industry and mining. Water use registrations for non-urban industry overtook the mining sector in the last four years. Irrigation was the highest water user in all provinces, except in Gauteng where urban industry is the highest user of water.

Amongst the provinces, the Northern Cape showed the largest area of change by comparing NLC1990 and NLC2013/14, but the least in terms of percentage (24%). The largest percentage change was observed in Limpopo (48%). Amongst land covers, thicket/dense bush and woodland/open bush showed the largest increase in area nationally, whilst grasslands and low shrubland displayed the largest decrease. Urban areas increased, whilst a concern is the shrinking of wetlands and fynbos. More profitable perennial crops increased at the expense of annuals.

Urban water use data from the City of Cape Town indicated a steady increase from 2005/06 to 2014/15, in particular due to the domestic water use increase. Total water use dropped in the last two years (197 $Mm^3\ a^{-1}$) since water restrictions have been introduced by the City of Cape Town to mitigate drought. In the wider Cape, indigenous forests, plantation woodlots and thicket dense bush recorded the highest ET and mines recorded the lowest per unit area. Shrubland fynbos and wetlands are somewhere in the mid-range of water consumption per unit area. In absolute terms, the largest water consumers in the Cape are shrubland fynbos, cultivated commercial annuals and cultivated perennials because they cover the largest areas. The total volume of water that evaporates from the Cape urban areas is less than half the water supplied to industry and domestic users. This is due to rainfall occurring predominantly in winter when ET is low, low ET during the dry summer, and large water demand. There may be therefore a case for re-use of some of the water in urban areas. By combining MOD16 ET data from natural vegetation and suburb water use data obtained from the City of Cape Town (2005-2012), it was interesting to observe that ET from natural vegetation ranged between ~2,500 and ~13,000 m^3 ha^{-1} a^{-1}, whereas water use in urban areas was between 0 and ~13,000 m^3 ha^{-1} a^{-1}. It appeared that MOD16 ET from natural vegetation varied depending on climatic conditions, in particular rainfall, whereas the water use in urban suburbs increased during this period.

In the Inkomati, MOD16 ET water consumption ranged between ~2,200 and ~16,400 m^3 ha^{-1} a^{-1} (2005-2012). High ET values per unit area occurred mainly along the escarpment (plantations/woodlots to the central west), in the Lowveld (cultivated perennial crops to the north) and in the southern parts of the catchment (sugarcane cultivation). The south-western (Highveld) and north-eastern (Kruger Park) parts of the catchment show generally low ET. The least recorded median ET was in mines. By far the highest water consumers in the Inkomati (expressed in Mm^3 a^{-1}) were thicket/dense bush, woodlands/open bush, grassland and plantations/woodlots, and the lowest were low shrublands and urban area. The total volume of water that evaporates from urban areas is nearly double the water supplied to industry and domestic users. There may be therefore a case for capturing some of the rainwater before it reaches the ground and evaporates in urban areas (e.g. rainwater harvesting).

Historic climatic data (rainfall, air temperature, vapour pressure deficit) and MOD16 ET displayed larger variability over large and heterogeneous areas, and smaller variability in small provinces with homogeneous landscapes. The highest correlations (R^2) of multiple regression functions were generally obtained in wetter climates (e.g. KwaZulu-Natal) and associated land covers (e.g. indigenous forests), and the lowest in drier areas (e.g. Northern Cape) and associated land covers (e.g. shrubland fynbos). Rainfall (positive correlation) and vapour pressure deficit (negative correlation) are generally the two main climatic drivers of ET nationally.

The Inkomati covers a larger and more heterogeneous area compared to the wider Cape. As a result, historic rainfall, air temperature, vapour pressure deficit and MOD16 ET generally displayed larger variability than the Cape. Based on the multiple regression analysis, MOD16 ET was generally positively correlated to air temperature and negatively correlated to vapour pressure deficit both in the Cape and Inkomati. MOD16 ET was negatively correlated to rainfall in the Cape, and positively correlated in the Inkomati. In the Inkomati, the adjusted R^2 values ranged from 0.71 to 0.88 in the various land cover classes (correlations between MOD16 ET and climatic variables). In the wider Cape area, adjusted R^2 values were lower, between 0.10 and 0.47, due to drier climate and more heterogeneous land cover distribution compared to Inkomati.

Projections of water and land use

The multiple regression equations formulated from historic data of MOD16 ET and climatic variables (rainfall, air temperature and VPD) were built into the Water Use Scenario Builder, a user-friendly web application for estimating changes in water use (mm and Mm^3) as a result of changes in land use and climate. The Water USB developed in this project can be used by provinces and other local government organs and institutions in order to plan land and water use, as demonstrated for the two case study sites, wider Cape and Inkomati. It is envisaged that numerous applications of this tool are possible. The tool was developed primarily in response to the needs of the two case study areas voiced by the City of Cape Town and the Inkomati-Usuthu Catchment Management Agency during the November 2017 stakeholder workshop. For example, the tool can facilitate the City of Cape Town in projecting and planning water use changes as a result of densification and population increase, expansion of urban edge, formalization of informal settlements, increase in agricultural land use, behavioural changes of the population and changes in legislation. In the Inkomati-Usuthu Water Management Area, the tool can facilitate projecting and planning water use changes as a result of immigration and population changes, formalization of informal settlements, mineral exploration and mining, as well as changes in crop types (e.g. establishment of tree plantations). The main target users are therefore water managers and planners in the two case study site areas (Municipalities, Catchment Management Agencies, Department of Water and Sanitation). The Water USB enables users to answer practical questions on the relation between land use and water use, such as:

- How will ET change with increased or decreased air temperature and humidity (vapour pressure deficit)?
- How will ET change with increased or decreased rainfall?
- How will water use change in a region if a certain land cover is expanded/reduced?
- What will the effect of climate variability be on water use?
- How can water allocation be planned for different land covers in future?
- Which land uses will provide leverage to manage water in catchments?
- What are the recommended land uses for conserving water in future?

The multiple regression equations used in the Water USB tool are specific for the land cover at the two case study sites. However, the tool can be expanded fairly easily to other geographical regions (e.g. all nine South African provinces), because the background data already exist and they have been processed to generate multiple regression equations for each land cover in each province. It is recommended that the Water USB be run by the research team using plausible scenarios designed by target users, in order to facilitate the interpretation of data and results.

The outputs produced in this project were not meant to answer all practical questions that water managers may have at specific sites due to the large number of possible applications. However, they highlighted the innumerable opportunities that combining remote sensing and GIS could provide in solving water management problems, with a view on future climate and integrated land and water management. Examples of site-specific problems that can be investigated with this approach are:

- What are the major water users (agriculture, natural vegetation, domestic supply, industry etc.)?
- Where are the hotspots of high water use?
- What is the difference in water use between different land use/covers (e.g. flood plains, agriculture, natural vegetation)?
- What is the effect of climate variability on water use?
- Where are the sensitive areas in terms of drought and flood risks?
- How does the WARMS database compare with satellite-derived water use estimates?
- How can remote sensing support water licensing and allocation?
- Which land uses provide leverage to manage water in catchments?
- What are the recommended land uses for conserving water?

General guidelines and recommendations for the case studies (Cape and Inkomati), each province and at national level were provided in the format of mini-posters, and they are presented in the following Chapter.

7 RECOMMENDATIONS

The information processed and interpreted during the course of the project was synthesized and packaged in the form of mini-posters. The mini-posters, including graphical and tabular summaries, present an overview of the state of land and water use, as well as guidelines and recommendations for integrated land and water use. Because the state of land and water use is highly location-specific, mini-posters were produced for each province, two case study sites (Inkomati and wider Cape area) and the national scale. The mini-posters (A1 format) are available as Appendixes in Deliverable 11 of the project. An example of the national scale mini-poster is shown in Figure 7.1.

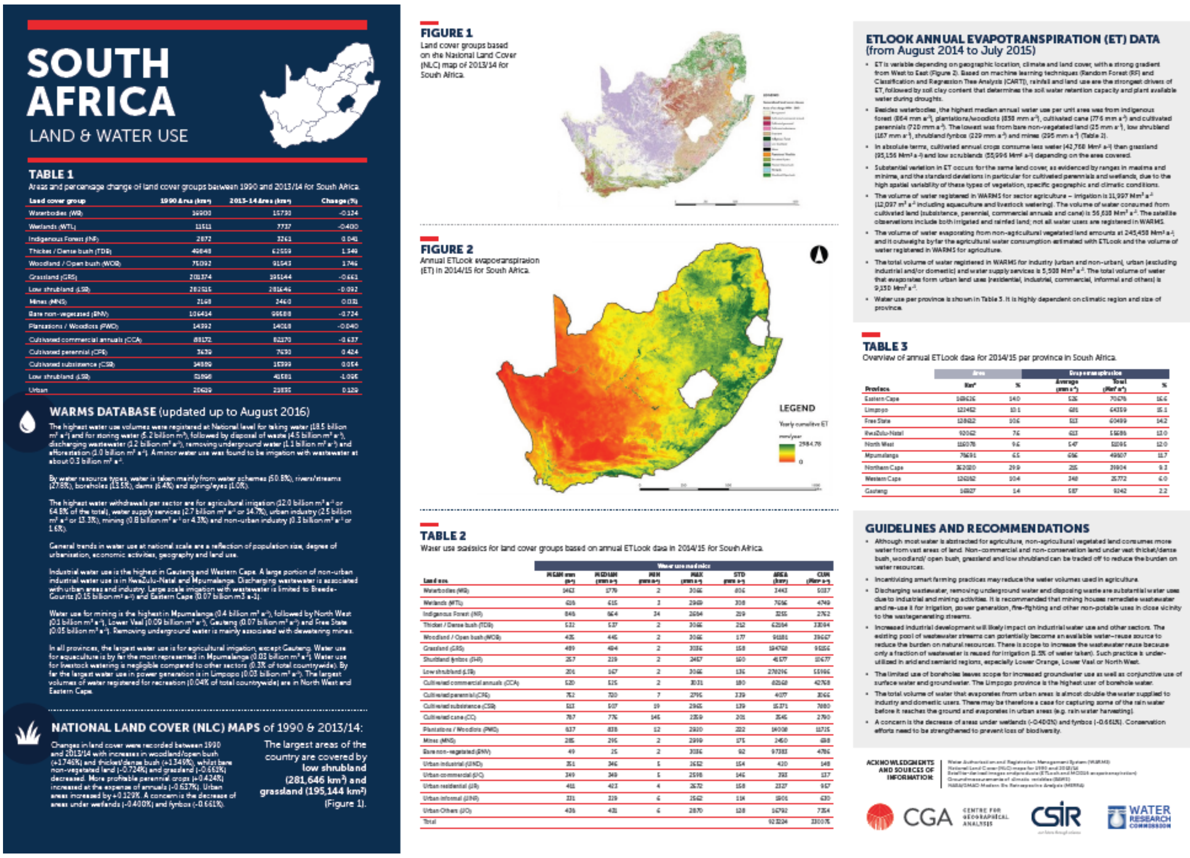


Figure 7.1

Example of mini-poster (A1 format) with overview of water and land uses, and guidelines and recommendations for South Africa.

The information and mini-posters are targeted mainly to decision-makers (e.g. provincial authorities), but also to the public in general. The reader can use the information provided in numerous ways for making tailor-made decisions. For example, Table 1 in Figure 7.1 can be used to support policy and strategic decisions on land use planning for a given geographic region. Table 2 in Figure 7.1 can be used to calculate trade-offs in land and water use changes. It should be considered that the information given in Tables 1 and 2 represents averages over large areas. The average values of water use for broadly defined land cover/use groups represent excellent information, however this should be used in the context of geographic and climatic variabilities (standard deviations are given for each land cover/use group). Specific environmental and socio-economic conditions may also have to be considered in decision-making.

Some general recommendations are given below based on the findings of the project and the content of the mini-posters.

- The WARMS database, at this stage, is in the process of being updated and verified, however, the analyses presented in this report gave us an indication of the extent to which water is being used in different geographical regions and sectors, and which resource types are being used. With respect to the data, the general trends in water use on a national scale is most likely a good reflection of population size, degree of urbanisation, and dominant land use practices in a particular province or Water Management Area. The identified trends are likely to be representative of the current situation.
- Verification and validation project findings showed that, while WARMS indicated a total of approximately 16,000 registered users in the KwaZulu-Natal province, an additional 6,000 potential water users, mostly unregistered, were identified (Kapangaziwiri et al., 2016). This shows that the totals per water use sector from WARMS may be somewhat underestimated in the database updated at August 2016, however, it is believed that the general trends are likely to hold as they are related to the factors mentioned above.
- The general land use types and population density, taking into account the expected growth rates, are likely to remain more or less the same across the country in the short term. The more rural unregistered users may impact the results more than urban activities as these may have never been accounted for. Increased industrial development (with certain areas being labelled industrial development zones such as in the Eastern Cape, Limpopo, Mpumalanga, Western Cape), or a push towards industrial water use in cities and areas on the outskirts of more urbanized cities may increase in the long term. These activities are likely to impact on industrial water use as well as scheme or water supply water sectors. An increase in urban areas is also accompanied by an increase in marginal land.

- Agriculture is the dominant user of water resources in 11 out of the 12 areas for which data were analysed, with the exception of Gauteng. Encouraging or incentivizing more efficient farming practices in future may reduce the volumes used in agriculture and hence reduce the burden on water resources.
- The current trend of water restrictions and water shedding in certain provinces is partly due to improper planning of water resources and reduced rainfall events. The WARMS data show that there is an existing pool of wastewater streams which is in essence an available water-reuse source for South Africa that could potentially reduce the burden on water resources.
- There is scope to increase the wastewater reuse because only a fraction of wastewater is reused for irrigation (1.5% of water taken). Such practice is under-utilized in arid and semi-arid regions, especially Lower Orange, Lower Vaal or North West.
- With quality of wastewater not always registered in the WARMS database, one cannot gauge the extent to which wastewater is re-usable from the volume data alone. However, treatment to the level where corrosion, scaling, biofouling and water quality parameters are acceptable will render more wastewater usable in generating power in the provinces which are currently not utilizing or re-using their wastewater. Water quality concerns associated with hydropower plants include dissolved oxygen, total dissolved gas, sedimentation, and downstream water temperature effects (http://www.hydroworld.com/environmental/waterquality.html, accessed on 25 September 2016). The costs of construction of dams and accompanying infrastructure could be compared to current costs of generating electricity. Alternatively, micro-power generation (household/village or area scale) could be something to consider for the elimination of large scale infrastructure costs.
- Better sewerage treatment methods may avail large volumes of water for re-use. Non-potable water can be used for alternative uses such as fire-fighting or water features, and possibly gardening depending on the quality.
- Mining houses could consider using practices where water requirements are reduced or re-using their own wastewater to reduce the use of fresh water, or alternatively using water from dewatering (where underground mining techniques are used in areas with low water tables) in mining processes, if this practice is not already in place.
- The limited use of boreholes countrywide leaves scope for increased groundwater use (or conjunctive surface and groundwater use) in nearly all provinces. The Limpopo Province is the highest user of borehole water at present. While there may be a large number of unregistered users falling into this category, the validation and verification

process countrywide may yield a better understanding of the extent of this resource's use.

- Gauteng and Mpumalanga are the biggest disposers of wastewater (due to the presence of mines), while they are among the negligible re-users of wastewater. It is recommended that mining houses try and remediate wastewater and re-use it for irrigation, power generation or fire-fighting in close vicinity to the waste-generating streams.
- The presence of lakes and wetlands being used as water resources raises some concerns for the environment. However, this represents less than 1% of the total water use in South Africa.
- Conservation efforts need to be strengthened to prevent loss of biodiversity countrywide, in particular shrubland fynbos (Eastern Cape, Northern Cape, Western Cape), wetlands and indigenous vegetation, and to reduce desertification (Free State, Northern Cape, North-West).
- Non-commercial and non-conservation land can be traded off to reduce encroachment and water use. Specific examples are:
    - Low shrubland is mainly replaced by grassland, possibly for agriculture – Eastern Cape.
    - Indigenous grassland needs to be conserved at the expense of encroaching low shrubland, woodland/open bush and desertification – Free State, North-West.
    - Urban development is a logical trade-off for grassland and informal settlements – Gauteng, Western Cape.
    - Encroachment by ticket/dense bush needs to be limited – KwaZulu-Natal.
    - Replacement of annual crops with more profitable perennial crops with smart water use reduction measures – KwaZulu-Natal, Limpopo, Mpumalanga.
    - Forestry is an important industry in some regions, but a large consumer of water that requires smart water use reduction measures – KwaZulu-Natal, Limpopo, Mpumalanga, Western Cape.
    - Vast areas of woodland/open bush and low shrubland encroaching grassland can be traded-off in support of development – Limpopo.
    - Vast areas of thicket/dense bush encroaching grassland and woodland/open bush can be traded-off in support of development – Mpumalanga.
    - Vast thicket/dense bush, woodland/open bush, grassland and low shrubland can be traded off to reduce water use – Western Cape and overall in the country.

- A strong decline of bare non-vegetated land was recorded in some regions, however this puts more pressure on water resources – Western Cape.
- Shrubland fynbos and wetlands may consume less than thicket/dense bush and woodland/open bush (often alien vegetation), which gives the opportunity for development trade-offs and improved land management and restoration – Western Cape.

The objectives and outcomes of this project should be linked with government priorities as per the National Development Plan – 2030 (https://www.gov.za/issues/national-development-plan-2030, accessed on 8 March 2019). During the MTEF (Medium Term Expenditure Framework) period, government aims to promote food security through provision of assistance to subsistence and smallholder producers (farmers) to produce their own food by ensuring that 1 million hectares of land are used for production by 2030. This may put further pressure on water resources and the following research studies are therefore urgently required:

- Analysis of water requirements in respect of water already allocated versus the determination of the reserve and actual water use in the area under the jurisdiction of water management institutions (irrigation boards and water user associations) to allow allocation to subsistence and smallholder producers including determination of the available source of water (dams, river, groundwater etc.) in the water management areas.
- Determination of water consumption by different forestry species.
- A number of specific sites require urgent attention for detailed investigation, such as the City of Tshwane where water demand growth is very high.

8 CAPACITY BUILDING AND TECHNOLOGY TRANSFER

Two MSc students worked on this project:

1) Mr Nqobile Lushozi was funded through a CSIR studentship and registered for an MSc in Geoinformatics at the Department of Geography and Environmental Studies, Stellenbosch University. The title of his thesis was “Examining (historical) changes in water use in relation to climate variability and land use changes: a case study in the Inkomati Basin and Wider Cape Town catchment”.
2) Mr Dwayne Brecht was funded through the WRC and DST Water RDI Roadmap, and registered at the Institute for Water Studies, University of the Western Cape, for the MSc in Environmental and Water Science. The title of his dissertation is “Comparing

water use to the ecological reserve set for the Crocodile-east & Komati River, as a case study."

Ms Zahn Munch, lecturer at the Department of Geography and Environmental Studies, Stellenbosch University, is currently registered for a PhD in Geoinformatics and contributed to the project as part of her research.

A stakeholder workshop was held on 8 November 2017 at the Philippi Horticultural Association in Cape Town. The workshop was entitled "Decision Support Systems for Water Resources in South Africa" and it was attended by 28 participants (Department of Water and Sanitation, City of Cape Town, Inkomati-Usuthu Catchment Management Agency for support, Hex Valley Water User Association and University of the Western Cape). The main purpose of the workshop was to showcase the progress of the project and the broader development of a multi-criteria decision support system (MCDSS) for water resources management and planning, to solicit inputs from potential users of the system and get feedback from stakeholders for further development, and to design future scenarios of water and land use for the two case study sites, namely the City of Cape Town and the Inkomati-Usuthu Catchment Management Agency. The workshop included both presentations and interactive/working group sessions. The main output of the workshop relevant to the project was the scenarios that have been used in Chapter 5 of this report. The full proceedings of the workshop can be found in Deliverable 8 of the project.

The main outputs produced during the project are:

- The Water Use Scenario Builder (web application) for calculating changes in water use as a function of projected land use and climatic changes for two case study sites (Inkomati catchment and wider Cape Town area).
- 12 mini-posters (national, 9 provinces and two case study sites) that summarize the data processed during the course of the project in tabular and graphical formats, and provide guidelines and recommendations for water planning, allocation and management.

These outputs are ready for distribution and dissemination at workshops, conferences and through personal interactions with local and national stakeholders.

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APPENDIX A: LAND COVER GENERALIZATION OF THE NLC2013/14 LAND COVER CLASSES

TABLE A1

Land cover classes in NLC (2013/14) (72, left column), groupings of land cover classes (21 groups in the middle column) and acronyms for each land cover/use group.

Original NLC (2013-2014)	Land cover/use groups	Acronym
Water seasonal	Waterbodies	WTB
Water permanent		
Wetlands	Wetlands	WTL
Indigenous Forest	Indigenous Forest	INF
Thicket /Dense bush	Thicket /Dense bush	TDB
Woodland/Open bush	Woodland/Open bush	WOB
Grassland	Grassland	GRS
Shrubland fynbos	Shrubland fynbos	SHF
Low shrubland	Low shrubland	LSB
Cultivated commercial fields (high)	Cultivated commercial annuals	CCA
Cultivated commercial fields (med)		
Cultivated commercial fields (low)		
Cultivated commercial pivots (high)		
Cultivated commercial pivots (med)		
Cultivated commercial pivots (low)		
Cultivated orchards (high)	Cultivated perennial	CPE
Cultivated orchards (med)		
Cultivated orchards (low)		
Cultivated vines (high)		
Cultivated vines (med)		
Cultivated vines (low)		
Cultivated permanent pineapple		
Cultivated subsistence (high)	Cultivated subsistence	CSU
Cultivated subsistence (med)		
Cultivated subsistence (low)		
Cultivated cane pivot – crop	Cultivated cane	CCN
Cultivated cane pivot – fallow		
Cultivated cane commercial – crop		
Cultivated cane commercial – fallow		
Cultivated cane emerging – crop		
Cultivated cane emerging – fallow		
Plantations / Woodlots mature	Plantations / Woodlots	PWD
Plantation / Woodlots young		
Plantation / Woodlots clearfelled		
Mines 1 bare	Mines	MNS
Mines 2 semi-bare		
Mines water seasonal		
Mines water permanent		
Mine buildings		
Erosion (donga)	Bare none vegetated	BNV
Bare none vegetated		
Urban commercial	Urban commercial	UCM
Urban industrial	Urban industrial	UIN
Urban informal (dense trees / bush)	Urban informal	UIF

TABLE A1 Land cover classes in NLC (2013/14) (72, left column), groupings of land cover classes (21 groups in the middle column) and acronyms for each land cover/use group.		
Urban informal (open trees / bush)		
Urban informal (low veg / grass)		
Urban informal (bare)		
Urban township (dense trees / bush)		
Urban township (open trees / bush)		
Urban township (low veg / grass)		
Urban township (bare)		
Urban residential (dense trees / bush)	Urban residential	URS
Urban residential (open trees / bush)		
Urban residential (low veg / grass)		
Urban residential (bare)		
Urban school and sports ground	Urban sport and recreation	USR
Urban sports and golf (dense tree / bush)		
Urban sports and golf (open tree / bush)		
Urban sports and golf (low veg / grass)		
Urban sports and golf (bare)		
Urban smallholding (dense trees / bush)	Urban others	UOT
Urban smallholding (open trees / bush)		
Urban smallholding (low veg / grass)		
Urban smallholding (bare)		
Urban village (dense trees / bush)		
Urban village (open trees / bush)		
Urban village (low veg / grass)		
Urban village (bare)		
Urban built-up (dense trees / bush)		
Urban built-up (open trees / bush)		
Urban built-up (low veg / grass)		
Urban built-up (bare)		

APPENDIX B: SUMMARY SHEETS OF MOD16 EVAPOTRANSPIRATION (ET) STATISTICS PER LAND COVER AND PER PROVINCE

EASTERN CAPE

	Baresoil	Cultivated Comm Annuals	Cultivated Perennial	Cultivated Subsistence	Thicket/Dense bush	Grasslands	Indigenous forests	Low shrublands	Fynbos shrublands	Mines	Open bush	Plantations	Urban commercial	Urban industrial	Urban informal	Urban residential	Urban others	Water bodies	Wetlands
Avg	370	482	698	670	530	477	920	490	323	441	482	694	627	774	605	600	676	487	480
Min	105	123	176	175	105	105	257	200	105	126	105	109	190	195	274	145	146	105	113
Max	1590	1727	1565	1844	1844	1844	1844	1727	1648	1291	1799	1572	1348	1324	1250	1333	1827	1590	1648
Median	291	426	678	672	489	426	878	453	279	396	438	684	611	729	566	573	677	439	450
St dev	213	250	235	204	257	245	241	204	150	226	242	249	194	259	217	243	212	255	231

FREE STATE

	Baresoil	Cultivated Comm Annuals	Cultivated Perennial	Cultivated Subsistence	Thicket/Dense bush	Grasslands	Indigenous forests	Low shrublands	Fynbos shrublands	Mines	Open bush	Plantations	Urban commercial	Urban industrial	Urban informal	Urban residential	Urban others	Water bodies	Wetlands
Avg	240	267	273	216	263	247	341	200		224	255	285	262	252	242	260	248	282	293
Min	59	68	87	141	55	55	129	55		55	55	66	80	77	92	83	89	59	55
Max	869	811	706	546	1065	1065	625	869		645	1065	1065	591	534	516	591	574	811	773
Median	207	251	256	194	245	221	322	180		198	234	273	232	215	207	244	209	268	284
St dev	122	102	122	70	105	110	89	92		102	112	104	111	104	101	95	101	106	108

GAUTENG

	Baresoil	Cultivated Comm Annuals	Cultivated Perennial	Cultivated Subsistence	Thicket/Dense bush	Grasslands	Indigenous forests	Low shrublands	Fynbos shrublands	Mines	Open bush	Plantations	Urban commercial	Urban industrial	Urban informal	Urban residential	Urban others	Water bodies	Wetlands
Avg	372	390	401	326	382	378	398	355		349	378	388	332	371	311	369	368	397	389
Min	181	170	249	186	170	170	398	166		181	166	181	166	170	166	179	166	190	177
Max	874	879	597	572	879	879	398	874		663	879	879	583	845	563	596	845	758	874
Median	367	384	398	302	378	372	398	351		345	374	382	331	371	300	364	366	394	384
St dev	71	67	58	78	68	68	0	64		62	68	66	78	71	73	69	73	70	68

KZN

	Baresoil	Cultivated Comm Annuals	Cultivated Perennial	Cultivated Subsistence	Thicket/Dense bush	Grasslands	Indigenous forests	Low shrublands	Fynbos shrublands	Mines	Open bush	Plantations	Urban commercial	Urban industrial	Urban informal	Urban residential	Urban others	Water bodies	Wetlands
Avg	630	666	907	725	740	719	861	614		611	721	834	737	760	747	814	731	699	733
Min	288	288	395	317	288	288	329	301		301	288	323	331	331	348	335	317	288	288
Max	1718	1567	1513	1596	2365	1647	1840	1548		1469	1647	2365	1410	1422	1276	1548	1706	1647	1840
Median	576	288	395	317	288	288	329	301		301	288	323	331	331	348	335	317	288	288
St dev	196	187	240	201	220	217	260	178		203	214	254	204	207	162	234	203	210	228

LIMPOPO

	Baresoil	Cultivated Comm Annuals	Cultivated Perennial	Cultivated Subsistence	Thicket/Dense bush	Grasslands	Indigenous forests	Low shrublands	Fynbos shrublands	Mines	Open bush	Plantations	Urban commercial	Urban industrial	Urban informal	Urban residential	Urban others	Water bodies	Wetlands
Avg	340	341	537	324	361	321	731	313		315	329	631	332	350	286	378	333	390	423
Min	40	73	90	99	66	46	167	46		40	46	112	171	50	138	116	100	69	73
Max	1417	1432	1432	1385	1446	1440	1446	1440		1339	1440	1446	1105	1266	531	1363	1410	1429	1424
Median	319	314	482	305	334	297	660	299		308	304	510	314	337	266	358	312	352	383
St dev	138	147	273	115	157	139	343	118		105	143	371	113	180	93	153	122	189	180

MPUMALANGA

	Baresoil	Cultivated Comm Annuals	Cultivated Perennial	Cultivated Subsistence	Thicket/Dense bush	Grasslands	Indigenous forests	Low shrublands	Fynbos shrublands	Mines	Open bush	Plantations	Urban commercial	Urban industrial	Urban informal	Urban residential	Urban others	Water bodies	Wetlands
Avg	511	493	782	551	565	550	887	501		434	564	681	471	517	481	504	494	545	555
Min	143	200	326	200	143	143	359	143		210	143	206	260	224	263	226	209	143	143
Max	1389	1405	1442	1294	1600	1600	1423	1600		1369	1600	1645	1335	1346	1114	1359	1376	1421	1412
Median	482	474	745	562	529	509	824	476		417	524	594	449	467	449	469	484	496	510
St dev	190	173	223	144	150	73	271	163		118	134	325	133	177	155	143	152	194	253

NORTH WEST

	Baresoil	Cultivated Comm Annuals	Cultivated Perennial	Cultivated Subsistence	Thicket/Dense bush	Grasslands	Indigenous forests	Low shrublands	Fynbos shrublands	Mines	Open bush	Plantations	Urban commercial	Urban industrial	Urban informal	Urban residential	Urban others	Water bodies	Wetlands
Avg	234	207	325	181	246	194	346	172		188	194	250	240	257	198	260	201	246	282
Min	32	43	78	45	31	31	233	30		31	31	39	70	83	69	70	38	42	42
Max	888	888	661	614	888	888	547	888		554	888	708	597	624	449	604	626	888	888
Median	233	189	343	164	244	175	343	151		173	176	238	233	250	181	254	199	234	277
St dev	86	95	111	72	85	54	66	47		77	68	88	89	83	72	96	85	106	83

NORTHERN CAPE

	Baresoil	Cultivated Comm Annuals	Cultivated Perennial	Cultivated Subsistence	Thicket/Dense bush	Grasslands	Indigenous forests	Low shrublands	Fynbos shrublands	Mines	Open bush	Plantations	Urban commercial	Urban industrial	Urban informal	Urban residential	Urban others	Water bodies	Wetlands
Avg	100	170	213	247	122	109		99	167	122	111	148	129	119	103	141	108	143	141
Min	25	40	49	87	25	25		25	58	25	25	39	37	45	45	37	32	27	42
Max	854	1007	686	475	1007	1007		1007	717	668	1007	878	780	564	294	597	597	799	765
Median	92	153	165	203	118	100		89	156	100	100	127	120	104	100	129	100	130	136
St dev	45	95	124	93	63	50		50	48	76	59	83	73	69	37	73	47	80	48

WESTERN CAPE

	Baresoil	Cultivated Comm Annuals	Cultivated Perennial	Cultivated Subsistence	Thicket/Dense bush	Grasslands	Indigenous forests	Low shrublands	Fynbos shrublands	Mines	Open bush	Plantations	Urban commercial	Urban industrial	Urban informal	Urban residential	Urban others	Water bodies	Wetlands
Avg	237	360	364	224	329	296	959	229	327	297	297	519	444	463	405	470	448	361	351
Min	117	120	129	163	117	120	325	117	121	124	117	120	148	145	151	140	140	118	117
Max	1297	1305	1290	385	1309	1304	1309	1264	1309	1290	1309	1309	1296	1290	1152	1296	1295	1295	1297
Median	193	347	342	196	300	271	1063	198	297	277	260	438	407	420	372	428	407	341	332
St dev	121	139	147	59	177	139	243	91	153	136	155	252	155	180	153	190	188	158	144

APPENDIX C: AREAS AND PERCENTAGE LAND COVER CHANGE BETWEEN 1990 AND 2013/14 PER PROVINCE

TABLE C1
Areas of each land cover/use group and percentage changes between 1990 and 2013/14 in the Eastern Cape.

Class	1990 Area (km^2)	2013/14 Area (km^2)	Change (%)
WTB	487	474	-0.010
WTL	1,699	1,185	-0.390
INF	868	1,020	0.116
TDB	9,444	16,947	5.690
WOB	1,651	4,417	2.097
GRS	49,414	54,633	3.957
LSB	33,640	27,072	-4.980
MNS	59	33	-0.020
BNV	12,039	4,451	-5.754
PWD	1,195	1,207	0.009
CCA	4,331	4,221	-0.084
CPE	460	376	-0.063
CSU	5,597	5,958	0.274
SHF	6,083	5,113	-0.735
Urban	4,915	4,774	-0.107
TOTAL	487	474	0

TABLE C2
Areas of each land cover/use group and percentage changes between 1990 and 2013/14 in the Free State.

Class	1990 Area (km^2)	2013/14 Area (km^2)	Change (%)
WTB	1,196	726	-0.481
WTL	2,802	1,687	-1.141
INF	46	51	0.005
TDB	885	1,130	0.251
WOB	968	851	-0.119
GRS	43,546	37,728	-5.950
LSB	18,025	25,180	7.316
MNS	182	180	-0.002
BNV	282	627	0.353
PWD	395	382	-0.013
CCA	28,635	28,228	-0.416
CPE	18	26	0.008
CSU	143	224	0.083
SHF	0	0	0.000
Urban	674	777	0.106
TOTAL	97,796	97,796	0

TABLE C3 Areas of each land cover/use group and percentage changes between 1990 and 2013/14 in Gauteng.			
Class	**1990 Area (km²)**	**2013/14 Area (km²)**	**Change (%)**
WTB	74	74	-0.002
WTL	465	396	-0.520
INF	0	0	0.000
TDB	725	804	0.584
WOB	1,197	1,431	1.750
GRS	4,852	4,639	-1.593
LSB	182	91	-0.677
MNS	181	154	-0.205
BNV	9	18	0.068
PWD	330	214	-0.867
CCA	3,008	2,966	-0.315
CPE	8	12	0.033
CSU	20	9	-0.085
SHF	0	0	0.000
Urban	2,339	2,584	1.830
TOTAL	13,391	13,391	0

TABLE C4 Areas of each land cover/use group and percentage changes between 1990 and 2013/14 in KwaZulu-Natal.			
Class	**1990 Area (km²)**	**2013/14 Area (km²)**	**Change (%)**
WTB	1,590	1,491	-0.139
WTL	1,392	1,118	-0.384
INF	1,054	1,173	0.168
TDB	12,298	14,631	3.280
WOB	3,725	4,492	1.078
GRS	29,926	25,112	-6.767
LSB	539	469	-0.098
MNS	40	42	0.002
BNV	254	521	0.375
PWD	5,181	5,361	0.254
CCA	5,590	3,501	-2.935
CPE	186	3,280	4.348
CSU	3,079	4,013	1.312
SHF	0	0	0.000
Urban	6,296	5,945	-0.494
TOTAL	71,149	71,149	0

TABLE C5 Areas of each land cover/use group and percentage changes between 1990 and 2013/14 in Limpopo.			
Class	**1990 Area (km^2)**	**2013/14 Area (km^2)**	**Change (%)**
WTB	114	143	0.031
WTL	578	342	-0.260
INF	285	332	0.052
TDB	12,242	12,628	0.423
WOB	38,796	45,238	7.083
GRS	23,562	14,295	-10.189
LSB	2,130	4,306	2.393
MNS	206	210	0.004
BNV	69	520	0.496
PWD	740	564	-0.194
CCA	5,746	5,359	-0.426
CPE	562	789	0.249
CSU	3,365	2,928	-0.481
SHF	0	0	0.000
Urban	2,558	3,302	0.818
TOTAL	90,955	90,955	0

TABLE C6 Areas of each land cover/use group and percentage changes between 1990 and 2013/14 in Mpumalanga.			
Class	**1990 Area (km^2)**	**2013/14 Area (km^2)**	**Change (%)**
WTB	301	336	0.062
WTL	1,750	1,503	-0.439
INF	170	228	0.103
TDB	4,623	6,313	3.005
WOB	9,874	9,411	-0.824
GRS	21,157	20,671	-0.863
LSB	567	305	-0.466
MNS	342	572	0.408
BNV	54	181	0.226
PWD	5,452	5,521	0.123
CCA	9,746	8,382	-2.426
CPE	231	766	0.950
CSU	672	490	-0.324
SHF	0	0	0.000
Urban	1,309	1,570	0.464
TOTAL	56,248	56,248	0

TABLE C7 Areas of each land cover/use group and percentage changes between 1990 and 2013/14 in the Northern Cape.			
Class	**1990 Area (km²)**	**2013/14 Area (km²)**	**Change (%)**
WTB	1,000	404	-0.210
WTL	948	351	-0.211
INF	2,277	1,778	-0.176
TDB	5,450	8,338	1.020
WOB	5,991	15,087	3.211
GRS	183,582	172,829	-3.797
LSB	773	758	-0.005
MNS	70,183	73,564	1.194
BNV	11	7	-0.001
PWD	1,613	1,745	0.047
CCA	263	298	0.012
CPE	33	30	-0.001
CSU	10,745	7,620	-1.103
SHF	0	0	0.000
Urban	340	401	0.022
TOTAL	283,210	283,210	0

TABLE C8 Areas of each land cover/use group and percentage changes between 1990 and 2013/14 in the North-West Province.			
Class	**1990 Area (km²)**	**2013/14 Area (km²)**	**Change (%)**
WTB	233	181	-0.067
WTL	670	253	-0.539
INF	5	7	0.002
TDB	2,265	1,677	-0.760
WOB	11,849	12,827	1.264
GRS	21,867	18,547	-4.291
LSB	20,518	25,316	6.201
MNS	327	430	0.133
BNV	14	325	0.402
PWD	128	108	-0.026
CCA	16,119	14,389	-2.236
CPE	39	39	0.000
CSU	1,972	1,713	-0.335
SHF	0	0	0.000
Urban	1,369	1,563	0.251
TOTAL	77,374	77,374	0

TABLE C9 Areas of each land cover/use group and percentage changes between 1990 and 2013/14 in the Western Cape.			
Class	**1990 Area (km²)**	**2013/14 Area (km²)**	**Change (%)**
WTB	433	439	0.006
WTL	1,128	849	-0.274
INF	439	444	0.005
TDB	4,653	6,268	1.584
WOB	1,327	4,169	2.786
GRS	552	4,046	3.425
LSB	20,066	22,726	2.608
MNS	48	73	0.024
BNV	21,260	17,166	-4.014
PWD	950	643	-0.302
CCA	13,384	13,377	-0.007
CPE	1,871	2,035	0.161
CSU	8	6	-0.002
SHF	35,069	28,845	-6.102
Urban	814	917	0.101
TOTAL	102,002	102,002	0

TABLE C10 Areas of each land cover/use group and percentage changes between 1990 and 2013/14 in the Inkomati study area.			
Class	**1990 Area (km²)**	**2013/14 Area (km²)**	**Change (%)**
WTB	50	70	0.097
WTL	329	296	-0.154
INF	127	172	0.214
TDB	3,369	4,846	7.037
WOB	6,350	5,058	-6.153
GRS	5,153	4,998	-0.737
LSB	147	66	-0.388
MNS	29	32	0.015
BNV	16	33	0.081
PWD	3,011	2,861	-0.715
CCA	1,165	812	-1.679
CPE	227	759	2.535
CSU	397	237	-0.761
SHF	0	0	0.000
Urban	618	746	0.609
TOTAL	20,987	20,987	0

TABLE C11 Areas of each land cover/use group and percentage changes between 1990 and 2013/14 in the wider Cape study area.			
Class	**1990 Area (km^2)**	**2013/14 Area (km^2)**	**Change (%)**
WTB	86	102	0.306
WTL	169	145	-0.465
INF	3	4	0.014
TDB	326	467	2.724
WOB	0	81	1.573
GRS	13	291	5.379
LSB	71	79	0.146
MNS	8	10	0.038
BNV	28	26	-0.040
PWD	195	104	-1.760
CCA	1,128	1,081	-0.919
CPE	559	564	0.100
CSU	0	0	0.000
SHF	2,065	1,632	-8.374
Urban	518	584	1.276
TOTAL	5,169	5,169	0