Potential Climate Change Impacts on Karoo Aquifers

Report to the
Water Research Commission

by

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Executive Summary

South Africa is viewed as a water-stressed country with an average annual rainfall of 500 mm, and any climatic change could have adverse impacts on the water resources of the country. The potential impacts of climate change on water resources and hydrology for Africa and Southern Africa have received considerable attention from hydrologists during the last decade. However, very little research has been conducted on the future impact of climate change on groundwater resources in South Africa. Climate change can affect groundwater levels, recharge and groundwater contribution to baseflow. This document serves as a first step in assessing the impact of climate change on South African Karoo aquifers.

Approximately 50% of South Africa is underlain by the so-called Karoo Supergroup of geological formations. A major characteristic of the Karoo Supergroup, which consists mainly of sandstone, mudstone, shale and siltstone, is their low permeability. The majority of boreholes drilled in Karoo formations therefore have very low immediate yields (<1 ℓ/s), however, these aquifers supply numerous towns and rural communities.

Climate change impacts can play a large role in the sustainability of Karoo aquifers. Typical impacts include:

- The sensitivity of groundwater to drought depends on the amount of recharge. The western part of South Africa is semi-arid and has a low recharge rate. This makes these rural areas more susceptible to drought and makes access to rural water supplies even more vulnerable.
- The greatest effects of drought are felt in agriculture and related sectors due to the reliance of these sectors on water resources.
- Drought events typically serve to extend existing environmental problems such as soil erosion and desertification.
- Floods occur because of heavy rains falling over unusually long periods of time. In arid or semi-arid areas, when the ground surface is baked hard during dry conditions, extensive areas may be flooded by heavy rainfall ponding on the surface.
- Floods increase the mobilisation of pollutants in groundwater, due to the increased water table. Floods have a serious impact on arable land and thereby deprive people of proper nutrition. People with low nutritional status cannot work and there is a subsequent loss of income and further deprivation. In turn, this can lead to famine, together with the emigration of younger, fitter members of the community.

- Flooding can increase vulnerability of groundwater to pollution. The major sources of pollution in these areas include municipal wastewater, agricultural chemicals that seep into the groundwater system and mining (especially coal mining) and other industrial activities.
- After floods, water-related diseases spread easily due to failure of sewage systems and the contamination of drinking water supplies by microbiological pollution (Smith &Ward, 1998). Smith and Ward report that women, children and the poor suffer the most in such situations.

The first step in our approach involves the creation of a climate change vulnerability profile. The DART methodology was developed by analogy with the DRASTIC methodology. The parameters considered in the DART methodology are as follows:

D – Depth of water level change
A – Aquifer type (storativity)
R – Recharge
T – Transmissivity

The DRASTIC methodology was developed to express aquifer vulnerability with reference to the threat of pollution. The DART methodology focuses more on typical parameters used in sustainability studies, but also indirectly accommodates the issue of quality due to the fact that water quality is likely to deteriorate with a drop in water level over time, as the salt load will concentrate.

Two scenarios are considered: current and future. The current scenario is representative of current precipitation patterns and the future scenario is representative of a predicted scenario based on the selected GCM.

At first glance, the results indicate that there is not a significant difference between current and future average indices, which indicate that the change in climate does not alter the average water level (i.e. the recharge) that much. There seems to be very little change in the indices of the dry months, due to the fact that the recharge model shows very little recharge over similar months. This is a worst-case scenario, as episodic recharge events will take place and, if the recharge is significant, this will result in a better index value than currently portrayed.

The results presented in this document demonstrate a method for mapping vulnerability that can be used to assess the impacts of climate change on both a regional and national scale. In developing a new approach for climate vulnerability mapping, we contribute to a growing body of literature on vulnerability science. However, it is important to recognise both the limitations and strengths of the method. The major limitation of this approach is that the total water balance is not considered as a whole.

Coupled surface-groundwater models are required for local scale assessment of possible climate change impacts based on GCM scenarios. These coupled models require extensive data sets to accurately describe the study area. The advantage of this approach is that the water balance is considered as a whole.

Despite current levels of uncertainty concerning the impacts of climate change on groundwater in South Africa, much can be achieved by preparing for the worst and ensuring that adequate data and a plan of action are available for appropriate resource management decision-making. From the analysis presented, the following recommendations can be made for future work:

- Drought impact studies, in which impacts on groundwater withdrawal and quality are assessed.
- Among the urgent research needs are those that may lead to reducing uncertainty, both to better understand how climate change might affect groundwater and to assist water managers who need to adapt to climate change. Research should be focused on: reducing uncertainties in under-standing; observations and projections of climate change and its impacts; and vulnerabilities.
- It is necessary to evaluate social and economic costs and benefits (in the sense of avoided damage) of adaptation, at several time scales.
- On the modelling side, climate change modelling and impact modelling have to be better integrated and this requires solving a range of difficult problems related to scale mismatch and uncertainty.
- To take advantage of the natural storage capacity provided by aquifers, the artificial recharge of groundwater is an option that should be further explored. Methods include well injections, recharge dams, induced river bank infiltration and spreading methods.

Abbreviations

CO_2	Carbon dioxide
CSIR	Council for Scientific and Industrial Research
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DKRZ	Deutsches Klimarechenzentrum GmbH
DWA	Department of Water Affairs
ECHAM4	Fourth-generation Atmospheric General Circulation Model
GCM	General Circulation Model
IHP	International Hydrological Programme
IPCC	Intergovernmental Panel on Climate Change
NGA	National Groundwater Archive
SNG	Synthetic Natural Gas
SSA	Statistics South Africa
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UV	Ultraviolet
WGII	Working Group 2
WRC	Water Research Commission

Units of Measurement

a	annum
cm	centimetre
d	day
km^2	square kilometre
ℓ	litre
m	metre
m^2	square metre
m^3	cubic metre
mamsl	metres above mean sea level
mbgl	metres below ground level
mbs	metres below sea level
mm	millimetre
s	second

Glossary

ABSORPTION OF RADIATION[1]: The uptake of radiation by a solid body, liquid or gas. The absorbed energy may be transferred or re-emitted.

ABSTRACTION: The removal of water from a resource, e.g. the pumping of groundwater from an aquifer.

AEROSOL[1]**:** Particulate matter, solid or liquid, larger than a molecule, but small enough to remain suspended in the atmosphere. Natural sources include salt particles from sea spray, dust and clay particles as a result of weathering of rocks, both of which are carried upward by the wind. Aerosols can also originate as a result of human activities and are often considered pollutants. Aerosols are important in the atmosphere as nuclei for the condensation of water droplets and ice crystals, as participants in various chemical cycles, and as absorbers and scatters of solar radiation, thereby influencing the radiation budget of the Earth's climate system.

AFFORESTATION[1]: Planting of new forests on lands that have not been recently forested.

AIR POLLUTION[1]: One or more chemicals or substances in high enough concentrations in the air to harm humans, other animals, vegetation, or materials. Such chemical or physical conditions (such as excess heat or noise) are called air pollutants.

ALLUVIAL: Sediments deposited by flowing water.

ALLUVIAL AQUIFER: An aquifer formed of unconsolidated material deposited by water, typically occurring adjacent to river channels and in buried or palaeochannels.

ALLUVIUM: A general term for unconsolidated deposits of inorganic materials (clay, silt, sand, gravel, boulders) deposited by flowing water.

ANISOTROPIC: Having some physical property that varies with direction.

ANTHROPOGENIC[1]: Human made. In the context of greenhouse gases, emissions that are produced as the result of human activities.

AQUATIC: Associated with and dependent on water, e.g. aquatic vegetation.

AQUATIC ECOSYSTEMS: The abiotic (physical and chemical) and biotic components, habitats and ecological processes contained within rivers and their riparian zones and reservoirs, lakes, wetlands and their fringing vegetation.

[1] United Nations Framework Convention on Climate Change, 2010.

AQUIFER: A geological formation that has structures or textures that hold water or permit appreciable water movement through them [from National Water Act (Act No. 36 of 1998)].

AQUITARD: A saturated geological unit with a relatively low permeability that retards and restricts the movement of water, but does not prevent the movement of water; while it may not readily yield water to boreholes and springs, it may act as a storage unit.

ATMOSPHERE[1]: The mixture of gases surrounding the Earth. The Earth's atmosphere consists of about 79.1% nitrogen (by volume), 20.9% oxygen, 0.036% carbon dioxide and trace amounts of other gases. The atmosphere can be divided into a number of layers according to its mixing or chemical characteristics, generally determined by its thermal properties (temperature). The layer nearest the Earth is the *troposphere*, which reaches up to an altitude of about 8 kilometres (about 5 miles) in the polar regions and up to 17 kilometres (nearly 11 miles) above the equator. The *stratosphere*, which reaches to an altitude of about 50 kilometres (31 miles) lies atop the troposphere. The *mesosphere*, which extends from 80 to 90 kilometres atop the stratosphere, and finally, the *thermosphere*, or *ionosphere*, gradually diminishes and forms a fuzzy border with outer space. There is relatively little mixing of gases between layers.

AVAILABLE DRAWDOWN: The height of water above the depth at which the pump is set in a borehole at the time of water level measurement (m).

BANK STORAGE: Water that percolates laterally from a river in flood into the adjacent geological material, some of which may flow back into the river during low-flow conditions.

BASEFLOW: Sustained low flow in a river during dry or fair weather conditions, but not necessarily all contributed by groundwater; includes contributions from delayed interflow and groundwater discharge.

BOREHOLE: Includes a well, excavation, or any other artificially constructed or improved groundwater cavity which can be used for the purpose of intercepting, collecting or storing water from an aquifer; observing or collecting data and information on water in an aquifer; or recharging an aquifer [from National Water Act (Act No. 36 of 1998)].

CARBON DIOXIDE[1]: A colourless, odourless, non-poisonous gas that is a normal part of the ambient air. Carbon dioxide is a product of fossil fuel combustion. Although carbon dioxide does not directly impair human health, it is a greenhouse gas that traps terrestrial (i.e. infrared) radiation and contributes to the potential for global warming.

CATCHMENT: The area from which any rainfall will drain into the watercourse, contributing to the runoff at a particular point in a river system; synonymous with the term *river basin*.

CHANGE OF CLIMATE[1]: This is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.

CLIMATE SYSTEM (OR EARTH SYSTEM)[1]: The atmosphere, the oceans, the biosphere, the cryosphere, and the geosphere, together make up the climate system.

COAL GASIFICATION[1]: Conversion of solid coal to synthetic natural gas (SNG) or a gaseous mixture that can be burned as a fuel.

CONCENTRATION[1]: Amount of a chemical in a particular volume or weight of air, water, soil, or other medium.

CONFINED AQUIFER: An aquifer overlain by a confining layer of significantly lower hydraulic conductivity in which groundwater is under greater pressure than that of the atmosphere; also known as an artesian aquifer.

CONTAMINATION: The introduction of any substance into the environment by the action of man.

DEFORESTATION[1]: Those practices or processes that result in the conversion of forested lands for non-forest uses. This is often cited as one of the major causes of the enhanced greenhouse effect for two reasons: 1) the burning or decomposition of the wood releases carbon dioxide; and 2) trees that once removed carbon dioxide from the atmosphere in the process of photosynthesis are no longer present.

DISCHARGE AREA: An area in which subsurface water, including water in the unsaturated and saturated zones, is discharged at the land surface.

ECONOMY[1]: System of production, distribution, and consumption of economic goods.

ECOSYSTEM: An organic community of plants, animals and bacteria and the physical and chemical environment they inhabit.

EMISSIONS[1]: Releases of gases into the atmosphere (e.g., the release of carbon dioxide during fuel combustion). Emissions can be either intended or unintended releases.

ENERGY[1]: The capacity for doing work as measured by the capability of doing work (potential energy) or the conversion of this capability to motion (kinetic energy). Energy has several forms, some of which are easily convertible and can be changed to another form for useful work. Most of the world's convertible energy comes from fossil fuels that are burned to produce heat that is then used as a transfer medium to mechanical or other means in order to accomplish tasks.

ENHANCED GREENHOUSE EFFECT[1]: The concept that the natural greenhouse effect has been enhanced by anthropogenic emissions of greenhouse gases. Increased concentrations of carbon dioxide, methane, and nitrous oxide, CFCs, HFCs, PFCs, SF_6, NF_3, and other photochemically important gases caused by human activities such as fossil fuel consumption, trap more infra-red radiation, thereby exerting a warming influence on the climate.

EVAPOTRANSPIRATION: The loss of moisture from the combined effects of direct evaporation from land and sea and transpiration from vegetation.

FERTILISER[1]: Substance that adds inorganic or organic plant nutrients to soil and improves its ability to grow crops, trees, or other vegetation.

FORMATION: A general term used to describe a sequence of rock layers.

FOSSIL FUEL[1]: A general term for buried combustible geologic deposits of organic materials, formed from decayed plants and animals that have been converted to crude oil, coal, natural gas, or heavy oils by exposure to heat and pressure in the earth's crust over hundreds of millions of years.

FOSSIL FUEL COMBUSTION[1]: Burning of coal, oil (including gasoline), or natural gas. The burning needed to generate energy releases carbon dioxide by-products that can include unburned hydrocarbons, methane, and carbon monoxide. Carbon monoxide, methane, and many of the unburned hydrocarbons slowly oxidise into carbon dioxide in the atmosphere. Major sources of fossil fuel combustion include cars and electrical utilities.

FRACTURE: A crack, joint or break in the rock that can enhance water movement.

FRACTURED AQUIFER: An aquifer that owes its water-bearing properties to fracturing caused by folding and faulting.

GEOHYDROLOGY: The study of the properties, circulation and distribution of groundwater; in practice used interchangeably with hydrogeology; but in theory hydrogeology is the study of geology from the perspective of its role and influence in hydrology, while geohydrology is the study of hydrology from the perspective of its influence on geology.

GLOBAL WARMING[1]: The progressive gradual rise of the earth's surface temperature thought to be caused by the greenhouse effect and responsible for changes in global climate patterns.

GREENHOUSE EFFECT[1]: Trapping and build-up of heat in the atmosphere (troposphere) near the earth's surface. Some of the heat flowing back toward space from the earth's surface is absorbed by water vapour, carbon dioxide, ozone, and several other gases in the atmosphere and then reradiated back toward the earth's surface. If the atmospheric concentrations of these greenhouse gases rise, the average temperature of the lower atmosphere will gradually increase.

GROUNDWATER: Water found in the subsurface in the saturated zone below the water table or piezometric surface, i.e. the water table marks the upper surface of groundwater systems.

GROUNDWATER CONTRIBUTION TO BASEFLOW OR RIVER FLOW: That groundwater that discharges into effluent streams and sustains baseflow.

GROUNDWATER FLOW: The movement of water through openings and pore spaces in rocks below the water table, i.e. in the saturated zone.

HEAT[1]: A form of kinetic energy that flows from one body to another when there is a temperature difference between the two bodies. Heat always flows spontaneously from a hot sample of matter to a colder sample of matter. This is one way of stating the second law of thermodynamics.

HYDRAULIC CONDUCTIVITY: A measure of the ease with which water will pass through earth material; defined as the rate of flow through a cross-section of one square metre under a unit hydraulic gradient at right angles to the direction of flow (in m/d).

HYDRAULIC GRADIENT: The slope of the water table or piezometric surface. It is a ratio of the change of hydraulic head divided by the distance between the two points of measurement.

HYDRAULIC HEAD: The height of a column of water above a reference plane.

HYDROGRAPH: A graphical plot of hydrological measurements over a period of time, e.g. water level, flow, discharge.

HYDROLOGICAL CYCLE: The continuous circulation of water between oceans, the atmosphere and land. The sun is the energy source that raises water by evapotranspiration from the oceans and land into the atmosphere, while the forces of gravity influence the movement of both surface and subsurface water.

HYDROLOGY: The study of the properties, circulation and distribution of water.

OZONE[1]: A colourless gas with a pungent odour, having the molecular form of O_3, found in two layers of the atmosphere, the stratosphere and the troposphere. Ozone is a form of oxygen found naturally in the stratosphere that provides a protective layer shielding the earth from ultraviolet radiation's harmful health effects on humans and the environment. In the troposphere, ozone is a chemical oxidant and major component of photochemical smog. Ozone can seriously affect the human respiratory system.

PIEZOMETRIC LEVEL: The elevation to which groundwater levels rise in boreholes that penetrate confined or semi-confined aquifers.

POLLUTION: The introduction into the environment of any substance by the action of man that is, or results in, significant harmful effects to man or the environment.

RADIATION[1]: Energy emitted in the form of electromagnetic waves. Radiation has differing characteristics depending upon the wavelength. Because the radiation from the sun is relatively energetic, it has a short wavelength (e.g. ultraviolet, visible, and near infrared) while energy re-radiated from the earth's surface and the atmosphere has a longer wavelength (e.g., infrared radiation), because the earth is cooler than the sun.

RECHARGE: The addition of water to the zone of saturation, either by the downward percolation of precipitation or surface water and/or the lateral migration of groundwater from adjacent aquifers.

RIPARIAN: Area of land directly adjacent to a stream or river, influenced by stream-induced or related processes.

RIVER: A physical channel in which runoff will flow; generally larger than a stream, but often used interchangeably.

RUNOFF: All surface and subsurface flow from a catchment, but in practice this refers to the flow in a river, i.e. it excludes groundwater not discharged into a river.

SALINE INTRUSION: Replacement of freshwater by saline water in an aquifer, usually as a result of groundwater abstraction.

SATURATED ZONE: The subsurface zone below the water table, where interstices are filled with water under pressure greater than that of the atmosphere.

SOLAR ENERGY[1]: Direct radiant energy from the sun. It also includes indirect forms of energy such as wind, falling or flowing water (hydropower), ocean thermal gradients, and biomass, which are produced when direct solar energy interacts with the earth.

SOLAR RADIATION[1]: Energy from the sun. Also referred to as short-wave radiation. Of importance to the climate system, solar radiation includes ultra-violet radiation, visible radiation, and infrared radiation.

STORAGE COEFFICIENT: The volume of water that an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

SURFACE RUNOFF: That part of the total runoff that travels over the ground surface to reach a stream or river channel.

SURFACE WATER: Bodies of water, snow or ice on or above the surface of the earth (such as glaciers, lakes, streams, ponds, wetlands, etc.).

TEMPERATURE[1]: A measure of the average speed of motion of the atoms or molecules in a substance or combination of substances at a given moment.

TOTAL RUNOFF: The total volume of water that flows into a stream, including contributions from channel precipitation, quickflow, interflow and the groundwater contribution to river flow.

TRANSMISSIVITY: The rate at which a volume of water is transmitted through a unit width of aquifer under a unit hydraulic head (m^2/d); product of the thickness and average hydraulic conductivity of an aquifer.

UNCONFINED AQUIFER: An aquifer with no confining layer between the water table and the ground surface, where the water table is free to fluctuate.

ULTRAVIOLET RADIATION[1] (UV): A portion of the electromagnetic spectrum with wavelengths shorter than visible light. The sun produces UV, which is commonly split into three bands of decreasing wavelength. Shorter wavelength radiation has a greater potential to cause biological damage to living organisms.

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1 Introduction

1.1 Preamble

Climate change is one of the major challenges of our time and adds considerable stress to our societies and to the environment. From shifting weather patterns that threaten food production, to rising sea levels that increase the risk of catastrophic flooding, the impacts of climate change are global in scope and unprecedented in scale. Without drastic action today, adapting to these impacts in the future will be more difficult and costly (UNEP, 2010).

Climate change is driven by changes in the atmospheric concentrations of greenhouse gases and aerosols. These gases affect the absorption, scattering and emission of radiation within the atmosphere and the earth's surface, thus resulting in changes in the energy balance (IPCC, 2007). Since the mid-19th century, our globe has been moving towards a warm period (Oliver-Smith, 2009). As the planet warms, rainfall patterns become erratic and extreme events such as droughts and floods become more frequent.

Over the past years, many studies around the world have been conducted to observe changes in climate. Although it is a natural phenomenon for climate around the world to change over decades, there is a well-founded concern that human activities over the past two centuries have caused climate changes above the expected natural variation.

South Africa covers an area of 1.2-million square kilometres and has a population of about 50 million people (SSA, 2010). The country is well known for its wealth in natural resources such as diamonds, gold and coal. Like any African country, South Africa is still to encounter climate change impacts, despite its endowment of natural resources.

South Africa is viewed as a water-stressed country with an average annual rainfall of 500 mm, and any climatic change could have adverse impacts on the water resources of the country. The potential impacts of climate change on water resources and hydrology for Africa and Southern Africa have received considerable attention from hydrologists during the past decade (e.g. O'Brien, 2009), but very little research has been conducted on the future impact of climate change on groundwater resources in South Africa. Climate change can affect groundwater levels, recharge and groundwater contribution to baseflow. The question of the likely impact of climate change on renewable groundwater resources is highly relevant, but under-researched (Kundzewicz *et al.*, 2008). This document serves as a first step in assessing the impact of climate change on Southern Africa's Karoo aquifers.

1.2 Climate change

The earth's climate system is driven by the energy that is continuously received from the sun. About 30% of incoming solar energy is reflected back to space by clouds and the earth's surface. About 70% of solar energy is absorbed by the oceans, continents and the atmosphere. The absorbed heat is later re-emitted in the form of infrared radiation, or transferred by sensible and latent heat fluxes. However, certain gases in the troposphere and stratosphere absorb most of the outgoing infrared radiation before it can escape into space, thereby warming the atmosphere before the heat is once again re-emitted. These are referred to as greenhouse gases (IPCC, 2007). This greenhouse effect results in the earth being 33°C warmer than it would be (Clarke, 2008). Without it, life on earth would not be able to exist. However, of current concern to scientists is the increased concentration of greenhouse gases (due to the burning of fossil fuels and deforestation, for example) within the earth's atmosphere, which results in the warming of the lower atmosphere and appears to be changing present climate patterns (Clarke, 2008). A shift in the earth's climatic regimes and changes in the nature of weather events are commonly referred to as climate change.

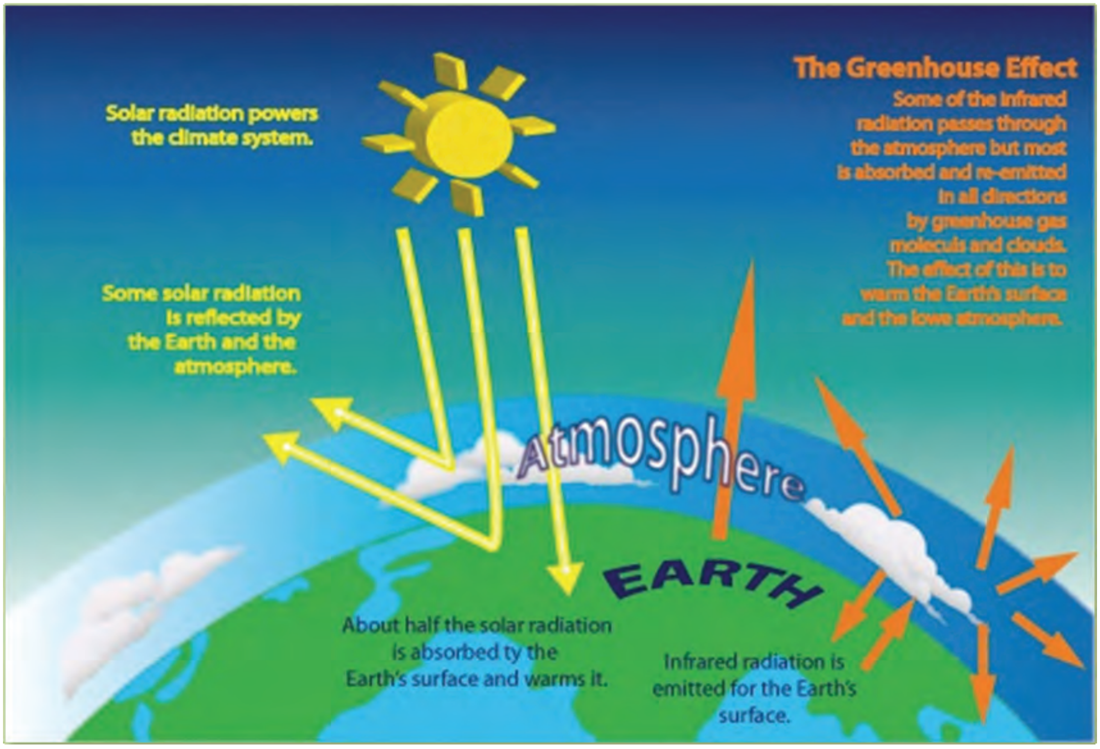


Figure 1: An idealised model of the natural greenhouse effect (Taken from IPCC, 2007)

There are several natural factors that are capable of changing the climate. These include the following:

- Solar variations are events where the sun's energy changes. If there is a variation over time in the amount of energy emitted by the sun, there is bound to be an effect on the earth's climate (McDonald, 2009).
- Explosive volcanic eruptions eject immense amounts of dust and poisonous gases into the atmosphere, causing sulphuric acid aerosols that reflect solar energy back into space (IPCC, 2007).
- Changes in ocean circulation may affect the climate through the movement of CO_2 into or out of the atmosphere (IPCC, 2001).

Human activities are also changing the atmospheric concentration and distribution of greenhouse gases. Below are a few of the activities that humans carry out that are responsible for such change (IPCC, 1996):

- The burning of fossil fuels releases carbon dioxide and other gases into the atmosphere. These greenhouse gases affect the climate by altering incoming solar radiation and outgoing infrared radiation.
- Deforestation is the process whereby forests are cut down faster than they can be replaced. Forests help to absorb carbon dioxide, thereby lowering greenhouse gas emissions to the atmosphere.
- Agriculture produces significant effects on climate change, primarily through the production and release of greenhouse gases such as carbon dioxide, methane, and nitrous oxide through intensified use of fertilisers and the digestive processes of cattle and other livestock.

Groundwater flow in shallow aquifers is part of the hydrological cycle and is affected by climate variability, as well as by human interventions in many locations (Petheram *et al.*, 2001). Climate change affects groundwater recharge and depths of groundwater tables. However, knowledge of current recharge and levels in both developed and developing countries is poor, and there has been very little research on the future impact of climate change on groundwater, or groundwater–surface water interactions. Information on other factors that need to be taken into account when considering the effects of climate change on groundwater is discussed below:

- ***Recharge***

  Any significant changes in the amount of recharge will alter recharge patterns and result in fluctuating water levels. Water levels drop in extreme cases of drought, as does the yield of boreholes.

  Dragoni and Sukhija (2008) define aquifer recharge as the residual flux of water added to the saturated zone resulting from the evaporative, transpirative and runoff losses of precipitation.

Recharge water may reach the aquifer both rapidly, through macro-pores or fissures (preferential pathways), or slowly, by filtering through soils and permeable rocks overlying the aquifer (diffuse infiltration). Aquifer recharge is dependent on factors such as climate, geology, geomorphology, vegetation, soil conditions and antecedent soil moisture (Saayman *et al.*, 2007). Variations in aquifer recharge change the aquifer yield and modify the groundwater flow network (Dragoni & Sukhija, 2008).

Increased precipitation variability may decrease groundwater recharge in humid areas because more frequent precipitation events may result in the infiltration capacity of the soil being exceeded more often. In semi-arid and arid areas, increased precipitation variability may increase groundwater recharge, because only high-intensity rainfalls are able to infiltrate fast enough before evaporating, and alluvial aquifers are recharged mainly by inundations due to floods.

According to the results of a global hydrological model, groundwater recharge, when averaged globally, increases less than total runoff (by 2% as compared with 9% until the 2050s) (Döll & Flörke, 2005).

- ***Discharge***

  Groundwater discharge is a loss of water from aquifers to surface water to the atmosphere, and abstraction for human needs (Dragoni & Sukhija, 2008). Under natural conditions, groundwater discharge sustains baseflow in streams, wetlands and springs (Crosbie, 2007). Groundwater discharge is a key factor controlling water table conditions, surface and groundwater quality, dam levels, baseflow of rivers and streams, and terrestrial and aquatic ecosystems. Climate change affects groundwater discharge in indirect ways through alterations in recharge (UNESCO IHP, 2006).

- ***Storage***

  Groundwater storage is influenced by a change in recharge, discharge and extraction over a longer period. For example; recharge of 40 mm per annum occurs over an area of 100 km^2 under the present climate, assuming steady-state conditions of groundwater flow. If the recharge reduces to 10 mm per annum, under a significantly warmer, drier climate, the volume of groundwater taken into storage annually will be reduced by 3×10^6 m^3. If it is assumed that a maximum of 50% of the annual recharge can be sustainably abstracted, the change in groundwater storage represents a loss of 1.5×10^6 m^3 of water resources for the area each year (Cavé *et al.*, 2003).

- ***Saltwater intrusion***

  Saltwater intrusion is the movement of saline water into freshwater aquifers (Barlow, 2003). Excessive groundwater withdrawals in coastal areas cause saltwater to move into areas of use in coastal and some inland areas and decrease the volume of freshwater available (Alley *et al.*, 2002). Saltwater degrades the quality of water and harms aquatic plants and animals that cannot tolerate high salinity. The amount of intrusion will, however, depend on the local groundwater gradient (IPCC, 2001). Salinisation can also occur inland, due to a reduction in recharge.

- ***Floods***

  Floods are related to climate change. Floods mostly occur on floodplains as a result of flow exceeding the capacity of the stream channels and over-spilling the natural banks or artificial embankments. Floods occur because of heavy rains, falling over unusually long periods of time.

  In arid or semi-arid areas, when the ground surface is baked hard during dry conditions, extensive areas may be flooded by heavy rainfall ponding on the surface. Water storage in the soil and deeper subsurface layers may affect both the timing and magnitude of flood response to precipitation. Low storage often results in rapid and intensified flooding. In catchments where most precipitation infiltrates the soil surface, flood response may be greatly modified by surface transmissivity (Smith & Ward, 1998).

1.3 Climate change in South Africa

Africa is one of the most vulnerable continents to climate variability and change because of multiple stresses and low adaptive capacity. The livelihoods of people in Africa, including South Africa, are often directly linked to the climate of the area (CSIR, 2010).

South Africa is a water-limited country with a changing water-management structure and priorities. It is situated in a region with increasing levels of water scarcity and water quality problems, compounded by population growth and issues of social and economic development. Additional stresses on water resources arising from potential climate change can exacerbate these problems over much of the country. Heightened water stress can lead to (CSIR, 2010):

- Possible southward expansion of the transmission zone of malaria.
- Climate changes may favour horticulture over plantation forestry in certain areas.
- Fynbos and Succulent Karoo are likely to be the most vulnerable ecosystems, while the savannah is argued to be more resilient.

- Coastal marine fisheries are likely to be negatively affected by changes in the Benguela current.
- Increase in the occurrence of international water conflicts.
- Decrease in water quality due to run-off, erosion salt water intrusion and concentrated nutrients/contaminants due to increased drought periods.
- Decrease in agricultural development and profits due to droughts.
- Salinisation can also affect inland aquifers due to a reduction in groundwater recharge.

Predicted climatic changes for South Africa include a general warming across the country of higher average temperatures in sub-humid areas. Mukheibir (2008) suggests that the temperature is expected to increase by approximately 1.5°C along the coast and 2 to 3°C inland of the coastal mountains by 2050. Cavé *et al.* (2003) state that the Western Cape is likely to experience an extended summer.

Numerous organisations such as the CSIRO and the DKRZ (using the ECHAM4 scenario) indicate fairly consistent projected changes in precipitation under climate change in South Africa.

Decreases in rainfall for the Western and Northern Cape Provinces and disrupted rainfall patterns for other areas can be expected. Eastern and Southern Africa, on the other hand, can expect higher average annual rainfall patterns. Hewitson *et al.* (2005) indicate a wetter escarpment in the east, a shorter winter season in the south-west, a slight increase in intensity of precipitation, and drying in the far west.

A low rainfall, compounded by forestry and agricultural land use, means that only 9% of precipitation reaches South African rivers, compared to the world average of around 30% (Scott & Joubert, 2008). Schulze (2000) has demonstrated clear runoff reductions in the already dry western part of Southern Africa. Turpie *et al.* (2002) suggest that the country's main rivers are likely to have reduced runoff or become less predictable. Projections based on two major catchments studies (namely the Orange River catchment in the north-west and the Mgeni River catchment in the east) indicate a decrease in outflow of 12 to 20% by 2050. Arnell (1999) too predicts a substantial reduction in runoff in the Limpopo (−30%) and Orange (−5%) catchments, as well as decreases in the volumes of low flows in these two rivers.

An increase in the occurrence of extreme events (floods and droughts), depending on the region and the time of year, may occur due to the projected increases in rainfall and rainfall intensity that cause flooding.

According to predictions, a rise in sea levels in coastal zones as well as seasonal changes (i.e. shifts in the annual timing of rainfall and temperature) can be expected.

It is clear from this discussion that climate change is a reality and is therefore an important consideration in the field of geohydrology, as despite its relatively small contribution to bulk water supply (13%), rainfall represents an important and strategic water resource in South Africa, since it services between 52 and 82% of community water-supply schemes in the Eastern Cape, Limpopo, Northern Cape, North West and KwaZulu-Natal (DWA, 2009).

Most climate change mitigation research accentuates the 2050–2100 period, since it is believed to be an adequate timescale for response and adaptation to climate changes that might happen in the future due to past emissions.

1.4 Aim

During the mid-1980s, the WRC initiated a research on the potential impacts of atmospheric carbon dioxide induced climate change on water resources of South Africa. At that time, computational resources were not as advanced as they are presently, and this made the research exceedingly difficult. Nonetheless, the need to know more about climate change was not to be curtailed by limited technological advancements. Building on the outcomes of prior research by the WRC on climate change impacts on water resources, the WRC initiated further research in 2002 to gain a better understanding of the magnitude of climate change impacts on water resources and adaptation needs (Green, 2008). Since then, climate change impacts on water resources have become the focus area in the water sector and this has led to the development of climate scenarios for future and present conditions (Lumsden *et al.*, 2007). As a result, a number of questions arise in this context, when thinking about groundwater:

- What is likely to be the impact of climate change on rainfall, other water balance components and groundwater recharge?
- What will be the likely future increase in demand for groundwater due to population growth?
- How might demographic changes in turn affect the water balance, and groundwater recharge in particular?
- In terms of future research and action, where should our priorities lie?

The aim of this research is to provide a foundation for understanding the possible effects of climate change on the Karoo Aquifer system and to address some of the questions that have been raised. In this regard, existing datasets and current research in the field of climate change in this area will be used to develop a broad overview of possible impacts. To achieve this aim, the following steps are considered:

- The first step in completing this investigation will be an extensive international literature review of past and current research that has been done in the field of climate change and its impacts on groundwater. Applicable research will be identified from the literature review to be used in the proposed study.
- Secondly, key variables need to be identified to determine the requirements or risk factors that will impact on the analysis of aquifers during climate change.
- Lastly, a climate change vulnerability index will be developed for Karoo aquifers.

The impact of climate change on aquifers is a key concern, as groundwater is an integral part of the water cycle and represents over 95% of the freshwater resources available globally. The output of this project should also form the basis for future research in the field of climate change impacts on South African groundwater resources.

2 Karoo aquifers

We expect that reliable surface water availability will decrease, or only marginally increase, in most regions of the world, due to lower long-term average total runoff and/or higher temporal flow variations that stem from increased precipitation variability and reduced summer low flows in snow-dominated basins. Given the higher storage capacity of groundwater as compared to surface water in rivers, we hypothesize that use of groundwater could ease freshwater stress under climate change (Kundzewicz *et al.*, 2007)

2.1 General (summarised from Woodford and Chevallier, 2002)

Approximately 50% of South Africa is underlain by the so-called Karoo Supergroup of geological formations (Figure 2). A major characteristic of the Karoo Supergroup, which consists mainly of sandstone, mudstone, shale and siltstone, is their low permeability. The majority of boreholes drilled in Karoo formations therefore have very low immediate yields (<1 ℓ/s). Indeed, the common view is that Karoo aquifers do not contain large quantities of groundwater, hence the name Karoo, which is the Hottentot word for dry. However, large volumes of groundwater are pumped from wellfields supplying towns, mines and the basements of buildings on a daily basis in areas underlain by the Karoo formations, which is not what one would expect from aquifers with a limited yield. The Main Karoo Basin encompasses an area of approximately 630 000 km^2, including the greater part of the central plateau region of South Africa. The surface altitude ranges between 800 and 3 650 mamsl, with the exception of a narrow belt along the south and the south-eastern coastal zone, and the Tankwa Basin in the west (see Figure 2). Altitudes are highest in the east, decreasing gradually as the surface slopes down to the west. The generally flat relief is broken by the up-warped plateau edges and the escarpment, which are most prominent in the Drakensberg region around the KwaZulu-Natal/Lesotho border. A prominent feature of the Karoo landscape is flat-topped hills, which are often capped by the more resistant dolerite sills or sandstone beds. Outcrops are rare between the hills, because of the superficial cover of calcrete, windblown sand, alluvium, colluvium and soil.

The river flow is highest in the east due to increased rainfall in these areas. The major drainage features are the Orange River and its perennial tributaries, the Vaal and Caledon Rivers. Other drainage is mostly peripheral, with the high-gradient rivers flowing from the escarpment to the coast. In the central and western Karoo Basin the rivers are mainly ephemeral, flowing only for short periods of time following heavy rainfall. A number of perennial easterly draining rivers occur along the eastern edge of the Basin.

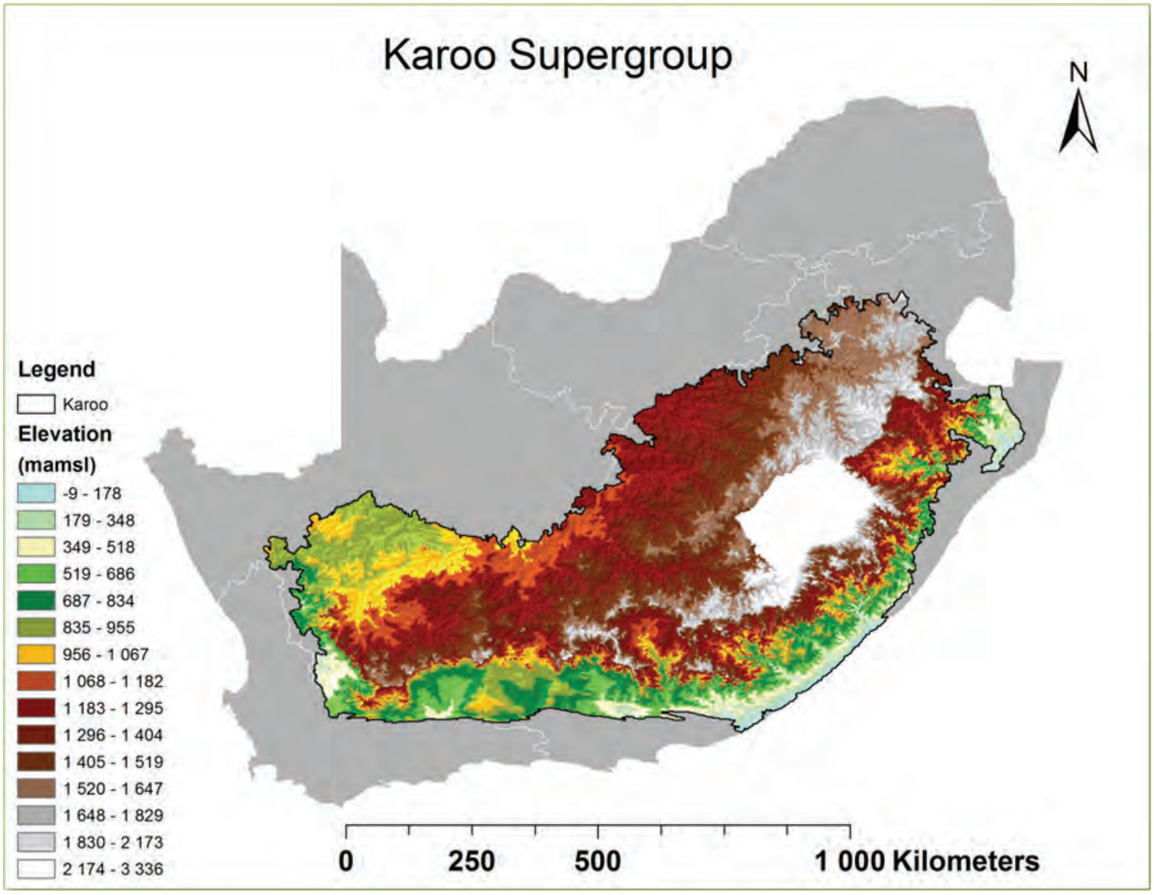


Figure 2: Location of Karoo Supergroup

Climate change impacts play a large role in Karoo groundwater related issues as discussed in the sections below.

2.1.1 Drought conditions

Drought exists when the actual water supply is below the minimum normal operation and reflects a deficit in the water balance (Hazelton *et al.*, 2009). It is essentially endemic and presents a major challenge to the achievement of sustainable development. The occurrence of drought is one of the climatic extremes which have both long- and short-term effects on the groundwater availability.

The sensitivity of groundwater to drought depends on the amount of recharge. The western part of South Africa is semi-arid and has a lower recharge rate. Therefore, in these areas groundwater recharge may be limited and probably largely localised to line or point sources such as streambeds and dam basins. In contrast, the eastern and northern part of the country may be characterised by a humid equatorial climate. In South Africa, rural water supply already uses groundwater extensively. This therefore makes rural areas more susceptible to drought, and as a result makes access to rural water supplies even more vulnerable (Naidoo *et al.*, 2009).

During droughts, water restrictions have to be imposed on residents in order to conserve water supplies. Water supplies dry up, therefore necessitating even longer distances to collect water from other alternatives. This results in conflicts among water users. Furthermore, bathing or hand-washing may be reduced. Water that is not potable may be used for drinking, with the result that there is an outbreak of waterborne diseases such as diarrhoea and typhoid. Population migration in search of better supply of food and water elsewhere also becomes more common.

The greatest effect is felt in agriculture and related sectors due to the reliance of these sectors on water resources. There is therefore a loss in agricultural production, which may in turn decrease national income and increase food prices and unemployment. In addition, drought affects the economy through reduced navigability of rivers and recreation activities (Tallaksen & Van Lanen, 2004) and damage to the tourism sector due to reduced water supplies.

Moreover, there is loss in public and local management revenue because of reduction of taxes, economic damage to industries struck by hydroelectric energy reduction and there is pressure on financial institutions (Rossi *et al.*, 2007).

Drought events typically serve to extend existing environmental problems such as soil erosion and desertification. In South Africa, where the natural veld is overstocked by approximately 50 to 60%, widespread land degradation has occurred (Wilhite, 2000). The natural vegetation dries up and wild animals suffer. Concentration of most components increases and thus stresses aquatic communities and degrades the water quality for domestic use (Tallaksen & Van Lanen, 2004).

2.1.2 Flooding

Agricultural losses depend very much on the season of flooding and the type and state of the crop. Losses can be high in rural areas where most of the damage is sustained by crops, livestock and the agricultural infrastructure, such as irrigation systems, levees, walls and fences. In groundwater, floods increase the mobilisation of pollutants due to increased water table. Floods have a serious impact on arable land, thereby depriving people of proper nutrition. People with low nutritional status cannot work and there is a subsequent loss of income and further deprivation. In turn, this can lead to famine together with the emigration of younger, fitter members of the community.

Flooding can increase the vulnerability of groundwater to pollution. The major sources of pollution in these areas include municipal wastewater, agricultural chemicals that seep into the groundwater system and mining (especially coal mining) and other industrial activities.

After floods, water related diseases spread easily due to failure of sewage systems and the pollution of drinking water supplies by microbiological pollution. It is reported that women, children and the poor suffer the most in such situations (Smith & Ward, 1998).

2.2 Geology and geohydrology (taken from Woodford and Chevallier, 2002)

The formation of the Karoo Basin was controlled by four major geological events:

1. Deposition of the Karoo sediments and the uplift of the Cape Fold Belt.
2. Intrusion of Karoo basalt and dolerite, and the break-up of Gondwanaland.
3. Intrusion of kimberlite and localised mantle up-welling.
4. Modern geomorphology, deposition of recent sediments, uplift, and cessation of regional tectonism.

The major lithostratigraphic units of the Karoo Supergroup are shown in Figure 3. Each Group corresponds to progressively changing depositional environments and will be discussed in more detail below.

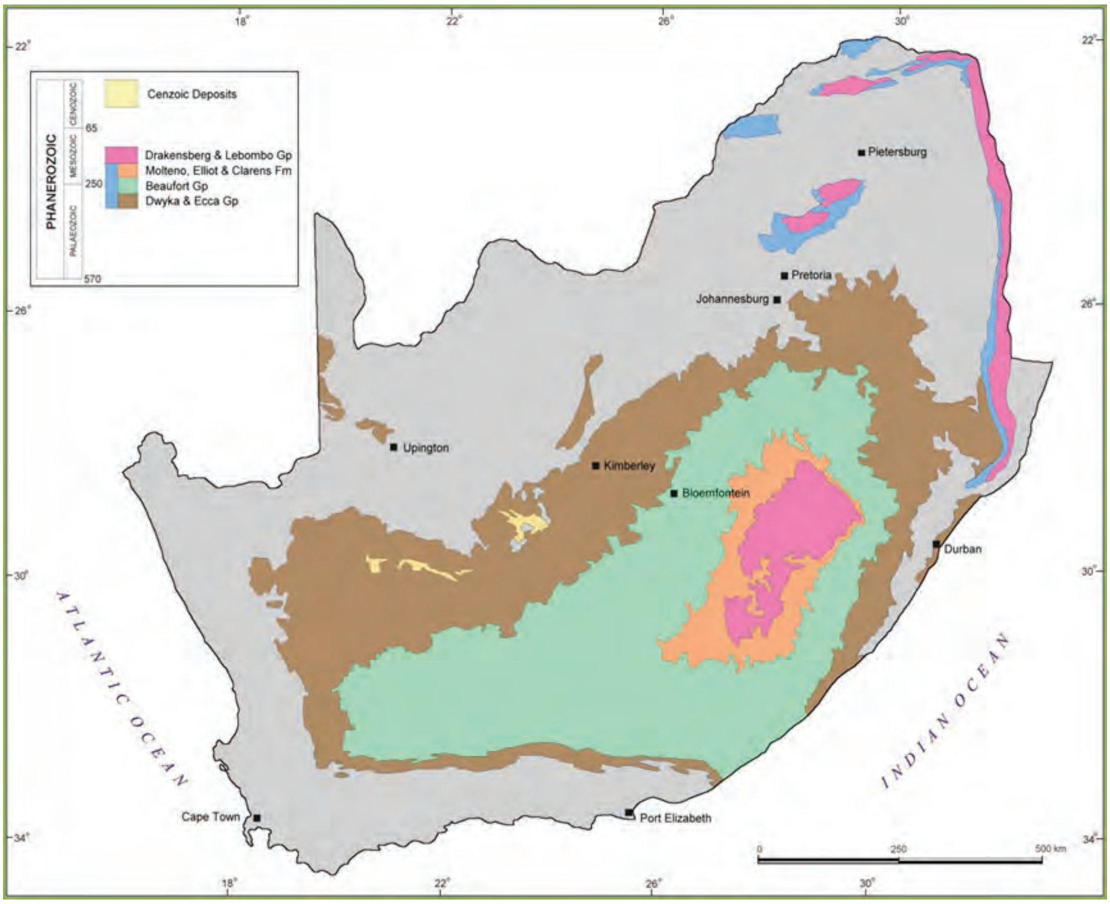


Figure 3: Simplified geology of the Karoo Supergroup in South Africa (after Woodford & Chevallier, 2002)

2.2.1 Dwyka Group

Geology

The Dwyka sediments consist mainly of diamictite (tillite), which is generally massive with little jointing, but may be stratified in places. Subordinate rock types are conglomerate, sandstone, rhythmite and mudrock (both with and without dropstones).

The *northern valley/inlet facies* were deposited within several southward-trending, glacially-excavated palaeo-valleys, where sub-glacial lodgement, supra-glacial ablation tills, marginal moraines, debris-rain sediments and outwash sands and gravels have been recognised. The *southern platform facies* extends southwards from the foot of a prominent east-west trending palaeo-escarpment with a diamictite-dominated assemblage, which was deposited as sub-glacial tills of grounded ice, sub-aqueous rain-out from floating ice-sheets and re-worked deposits in the form of debris flows.

Geohydrology

The Dwyka diamictite and shales have very low hydraulic conductivities, and virtually no primary voids. The Dwyka Group constitutes a very low-yielding fractured aquifer and water is confined within narrow discontinuities like jointing and fracturing. They therefore tend to form aquitards rather than aquifers. The few sandstone bodies deposited in the glacial valleys of the northern facies are very limited in extent, and sealed off by the diamictite or mudrock. Since the Dwyka sediments were deposited mainly under marine conditions, the water in these aquifers tends to be saline.

2.2.2 Ecca Group

Geology

The Permian-aged Ecca Group comprises a total of 16 formations, reflecting the lateral facies changes that characterise this succession:

- The Prince Albert Formation is confined to the south-western half of the Karoo Basin. Towards the north-east, it thins and locally pinches out against the basement or merges with the Vryheid and/or Pietermaritzburg Formations. Along the western and southern outcrop belt, its thickness is highly variable (40–150 m). The northern facies is characterised by the predominance of greyish to olive green, micaceous shale and grey, silty shale, as well as a pronounced transition from the underlying glacial deposits. Dark grey to black carbonaceous shale and fine- to medium-grained feldspathic arenite and wacke are also present. The southern facies is characterised by the predominance of dark grey, pyrite-bearing, splintery shale, siltstone and the presence of dark coloured chert and phosphatic nodules and lenses.

- The Whitehill Formation consists of white, weathered mudrocks. In fresh outcrops and in the subsurface, the predominant facies is black, carbonaceous, pyrite-bearing shale. The black, organic-rich shales are thought to represent suspension-settling of mud under reducing conditions. The Whitehill Formation loses its distinctive lithological character towards the north-east, with its lower part containing siltstone and very fine-grained sandstone.
- Outcrops of the Collingham Formation are confined to the southern and western margins of the Main Karoo Basin. The formation is generally between 30 and 70 m thick and comprises a rhythmic alternation of thin, continuous beds of hard, dark grey, siliceous mudrock and very thin beds of softer yellowish tuff. In the western part of the area, minor sandstone and siltstone units occur in the upper half of the formation, while the distinctive Matjiesfontein Chert Bed is present in the lower half.
- The predominantly argillaceous Vischkuil Formation overlies the Collingham Formation in the south-western part of the basin. The Vischkuil Formation becomes more arenaceous towards the east and grades into the Ripon Formation. A western cut-off is located where the overlying Laingsburg Formation pinches out. The formation varies in thickness between 200 and 400 m. The Vischkuil Formation consists essentially of dark shale, alternating with subordinate fine-grained sandstone, siltstone and minor yellowish tuff layers.
- The Laingsburg Formation usually comprises four sandstone-rich units separated by shale units and is approximately 400 m thick in its type area. It wedges out towards the west and north. A vertical cut-off is located in the east, where the underlying Vischkuil Formation merges with the Ripon Formation. The four sandstone-rich units represent arenaceous submarine fan systems, which are separated by basin-plain shale units.
- The Ripon Formation is generally 600 to 700 m thick, but is over 1 000 m in the eastern part of its outcrop area. It consists of poorly sorted, fine- to very fine-grained lithofeldspathic sandstone, alternating with dark grey, clastic rhythmite and mudrock. The sandstones have been interpreted as turbidites deposited within a submarine fan environment, while the mudrocks are thought to represent basin-plain suspension and distal turbidites.
- The Fort Brown Formation consists of rhythmite and mudrock with minor sandstone intercalations and displays an overall coarsening upward tendency. At certain localities, one or more fairly prominent sandstone units occur some distance below the upper contact. Individual sand/silt and silt/clay layers comprising rhythmite units of similar thickness, ranging from a few millimetres to a few centimetres, are laterally persistent. The sand/silt layers display a general upward increase in thickness within the formation.

- The arenaceous Waterford Formation overlies the Fort Brown Formation to the west of longitude 26ºE, where its thickness generally varies between 200 and 800 m. The formation comprises alternating very fine-grained, lithofeldspathic sandstone and mudrock or clastic rhythmite units. The Britskraal Shale Member in the upper part of the Waterford Formation in the eastern outcrop area averages 100 m in thickness and consists essentially of dark grey mudrock and rhythmite. Well-developed oscillation ripples and ball-and-pillow and related deformation structures are characteristic features of the Waterford Formation. Thin mud-flake conglomerate layers are occasionally present. Brown weathering calcareous concretionary bodies occur in both the sandstones and the argillaceous rocks.
- The Tierberg Formation is a predominantly argillaceous succession which reaches a maximum thickness of approximately 700 m along the western margin of the basin, thinning to about 350 m towards the north-east. The bulk of the Tierberg Formation comprises well laminated, dark grey to black shale. Some yellowish tuffaceous beds up to 10 cm thick occur in the lower part of the succession along the western and northern margins of the Basin. Calcareous concretions are common towards the top of the formation. Clastic rhythmites occur at various levels in the sequence.
- The Skoorsteenberg Formation is a lenticular, arenaceous unit located between the Tierberg and Kookfontein Formations in the south-western part of the basin. It attains a maximum thickness of approximately 200 m at its type locality, where it comprises five sandstone-rich units with shale units separating them.
- The Kookfontein Formation overlies the Skoorsteenberg Formation with a sharp contact and grades upwards into the Waterford Formation. It is a lateral equivalent of the upper part of the Tierberg Formation and is approximately 300 m thick at its type locality. The lower part of the formation comprises horizontally laminated dark grey shales alternating with clastic rhythmites, which form minor upward thickening cycles.
- The Waterford Formation, formerly the known as the Koedoesberg Formation, outcrops along the western flank of the Basin and overlies the Kookfontein and Tierberg Formations with a gradational contact. The contact with the overlying Abrahamskraal Formation is relatively sharp. The major rock types are fine- to medium-grained sandstone, siltstone, shale and rhythmite. The lower part of the formation is characterised by upward coarsening cycles of sediments, which are capped by extensive sheet like sandstones and alternating chaotic, slump and slide deposits. The Waterford Formation, formerly named the Carnarvon Formation, outcrops along the north-western margin of the Basin and is up to 250 m thick in the vicinity of Carnarvon. The sediments consist of fine- to very fine-grained tabular sandstones that are up to 8 m thick, siltstone, shale and rhythmite. Brown-weathering, calcareous concretions are present in all the rock types. Wavy bedding, including hummocky cross-bedding and symmetrical ripples, are predominant, as well as slump structures, ball-and-pillow structures and load-casts.

- The Pietermaritzburg Formation comprises dark, upward coarsening, silty mudrock, which is heavily bioturbated. Pene-contemporaneously deformed sandy and silty beds appear near the top of the formation. Outcrops of the Pietermaritzburg Formation are confined to the eastern margin of the basin, but extensive drilling has shown that it underlies the Vryheid Formation over much of the north-eastern part of the basin.
- The Vryheid Formation thins towards the north, west and south from a maximum of approximately 500 m in the Vryheid–Nongoma area. The uneven pre-Karoo topography in the vicinity of the northern and north-western margins of the basin, where the Vryheid Formation rests directly on pre-Karoo rocks or the Dwyka Group, gives rise to marked variations in thickness. The Vryheid Formation comprises mudrock, rhythmite, siltstone and fine- to coarse-grained sandstone (pebbly in places). The Formation contains up to five (mineable) coal seams. The different lithofacies are mainly arranged in upward coarsening deltaic cycles (up to 80 m thick in the south-east).
- The Volksrust Formation is a predominantly argillaceous unit, which interfingers with the overlying Beaufort Group and underlying Vryheid Formation. The Formation consists of grey to black, silty shale with thin, usually bioturbated, siltstone or sandstone lenses and beds, particularly towards its upper and lower boundaries. Thin phosphate and carbonate beds and concretions are relatively common.

Geohydrology

The Ecca Group consists mainly of shales, which are very dense, and are often overlooked as significant sources of groundwater. The deltaic sandstones represent a facies of the Ecca sediments in which one would expect to find high-yielding boreholes. Unfortunately, these permeabilities are usually very low. The main reason for this is that the sandstones are usually poorly sorted, and that their primary porosities have been lowered considerably by diagenesis.

2.2.3 Beaufort Group

Geology

- In the southern and central parts of the Basin, the Adelaide Subgroup consists of alternating bluish-grey, greenish-grey or greyish-red mudrock and grey, very fine- to medium-grained, lithofeldspathic sandstone. In the northern part of the Basin, coarse to very coarse sandstone, or even granulestone, are also common in the Normandien Formation. Sandstone generally constitutes 20 to 30% of the total thickness, but in certain areas may be as little as 10%, while some sandstone-rich intervals may in places contain up to 60% sandstone.

- The early Triassic Tarkastad Subgroup is characterised by a greater abundance of both sandstone and red mudstone when compared with the Adelaide Subgroup. The boundary between these two subgroups is the only one in the Beaufort Group that can be traced with certainty throughout the Main Karoo Basin. In the south, the Tarkastad Subgroup comprises a lower, sandstone-rich Katberg Formation and an upper, mudstone-rich Burgersdorp Formation. The Katberg Formation sandstones are light brownish grey to greenish grey, fine- to medium-grained and contain scattered pebbles. The Burgersdorp Formation sandstones are greenish grey to light brownish grey and are fine-grained.

Geohydrology

The main sediment source area for the Beaufort rocks lay along the high-lying, southern margin of the Basin. The coarser grained rocks are, therefore, found near the Cape Fold Belt (alluvial fan and braided stream environments), while mudstone, shale and fine-grained sandstones dominate the more distal central and northern portion (meandering river and floodplain environment) of the Basin. The sedimentary units in the Group therefore usually have very low primary permeabilities. The geometry of these aquifers is complicated by the lateral migration of meandering streams over a floodplain. Aquifers in the Beaufort Group will thus not only be multi-layered, but also multi-porous, with variable thicknesses. The contact plane between two different sedimentary layers will cause a discontinuity in the hydraulic properties of the composite aquifer. The complex behaviour of aquifers in the Beaufort Group is further complicated by the fact that many of the coarser, and thus more permeable, sedimentary bodies are lens-shaped. The life-span of a high-yielding borehole in the Beaufort Group may therefore be limited if the aquifer is not recharged frequently.

2.2.4 Molteno, Elliot and Clarens Formations

Geology

- The late Triassic Molteno Formation attains a maximum thickness of close to 600 m in its southern outcrop area. It is less than 10 m thick in the extreme north. The Formation comprises alternating medium- to coarse-grained, "glittering" sandstones and grey mudrocks, with well-preserved plant fossils and sporadic coal seams.
- The late Triassic to early Jurassic Elliot Formation comprises an alternating sequence of mudrock and subordinate fine- to medium-grained sandstone. It attains a maximum thickness of about 500 m in the south, thinning to ~100 m in the north. Contacts with the underlying Molteno and the overlying Clarens Formations are gradational. The maroon and green-grey mudrock units typically range in thickness between 25 and 100 m in the type area and contain vertebrate (mainly dinosaur) fossils. The sandstone layers are yellowish grey to pale red and are up to 22 m thick.

- The early to middle Jurassic Clarens Formation represents the final phase of the Karoo sedimentation and consists mainly of wind-blown, fine-grained sandstone and siltstone. Channel-filled wadi sandstones and horizontally-laminated sheet-flood sandstone are also present. Minor interbedded sandstone, siltstone and mudstone represent localised playa lake deposits. The northern Clarens Formation is usually in the order of 100 m thick, but it is up to 300 m thick in the south.

Geohydrology

The characteristics and depositional history of the *Molteno Formation* indicate that the Formation should form an "ideal" aquifer. This applies not only to the pebble conglomerates and coarse-grained sandstones at the base of the Formation, but also to the other sedimentary bodies. The largest part of the *Elliot Formation* consists of red mudstone. The Formation thus represents more of an aquitard than an aquifer. The *Clarens Formation* consists almost entirely of well-sorted, medium- to fine-grained sandstones, deposited as thick consistent layers. It is thus the most homogeneous Formation in the Karoo Supergroup. With this type of geometry, the Formation should be an ideal aquifer. Although the Formation has a relatively high and uniform porosity (average 8.5%), it is poorly fractured and has a very low permeability. The Formation may therefore be able to store large volumes of water, but is unable to release it quickly.

3 *Quantifying climate change impacts*

Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems (IPCC, 2008).

One of the most significant anticipated consequences of global climate change is the change in frequency of hydrological extremes. Predictions of climate change impacts on the regime of hydrological extremes have traditionally been conducted by a top-down approach that involves a high degree of uncertainty associated with the temporal and spatial characteristics of general circulation model outputs and the choice of downscaling techniques.

3.1 General circulation models

Global general circulation models (GCMs) have become the primary tools for the projection of climate change. Bates *et al.* (2008) describes a GCM as a numerical representation of the climate system, based on the physical, chemical and biological properties of its components, their interactions and feedback processes. It is further stated that climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal and inter-annual climate predictions (Bates *et al.*, 2008). GCMs are the basic tool used for modelling climate change, with 30 modelling groups around the world investigating the potential impact on the climate.

Projections of future climate change by GCMs may provide insight into potential broad-scale changes in the atmosphere and ocean, such as shifts in the major circulation zones and the magnitude of sea-level rise. GCMs depict the climate using a three-dimensional grid over the globe, as shown in Figure 4. GCMs typically have a horizontal resolution of between 250 and 600 km, 10 to 20 vertical layers in the atmosphere and sometimes as many as 30 layers in the oceans (IPCC, 2009). The GCM resolution is considered coarse compared to the scale at which typical groundwater studies are carried out.

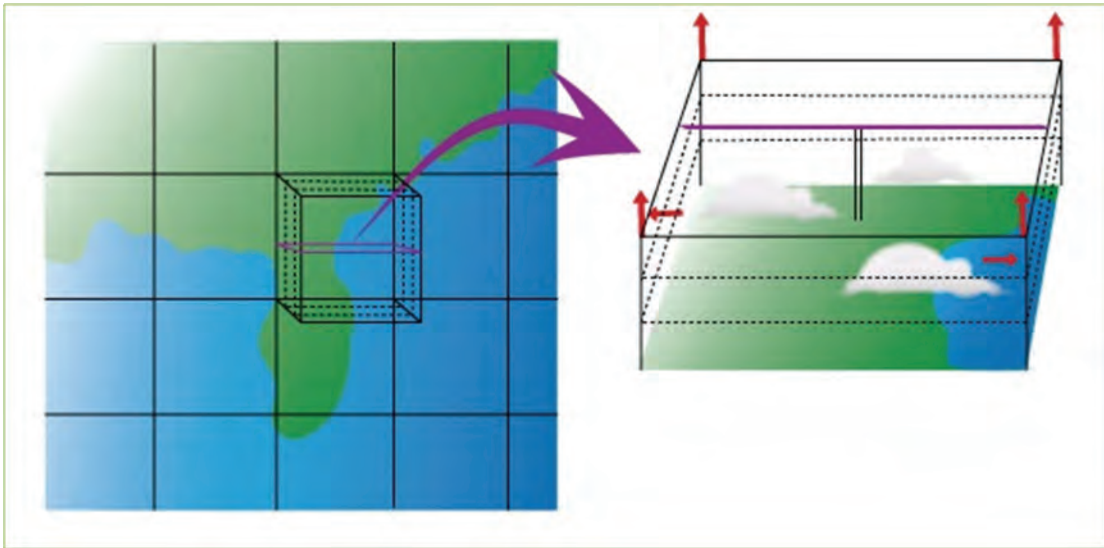


Figure 4: Graphical representation of a GCM (Adapted from Ucar, 2010)

Future projections of climate variables are calculated by models that are run under various scenarios. To estimate climatic changes in the future, variations in continental and regional rainfall and average temperatures during each season are obtained using climate change data observed over the last 100 years. These are used to project possible temperature and rainfall variations in the next 100 years (CSIR, 2010). Climate models are able to effectively represent many important climate features, such as the large-scale distributions of atmospheric temperature, precipitation, radiation and wind, and of oceanic temperatures, currents and sea ice cover (IPCC 2007). Models still show significant errors, however, which generally occur at the regional scale.

3.2 Downscaling

GCMs suggest that rising concentrations of greenhouse gases may have significant consequences for the global climate. It is not clear, however, to what extent local-scale meteorological processes will be affected. The gap between what climate modellers are able to provide and what impact assessors require, is bridged by means of so-called "downscaling" techniques (Wilby & Wigley, 1997).

The term *downscaling* refers to the development of regional-scale projections of change based on global models. This introduces an uncertainty that limits confidence in the magnitude of the projected change, although the pattern of change can be interpreted with greater certainty (Mukheibir & Ziervogel, 2006).

Figure 5 gives a graphical representation of the downscaling concept.

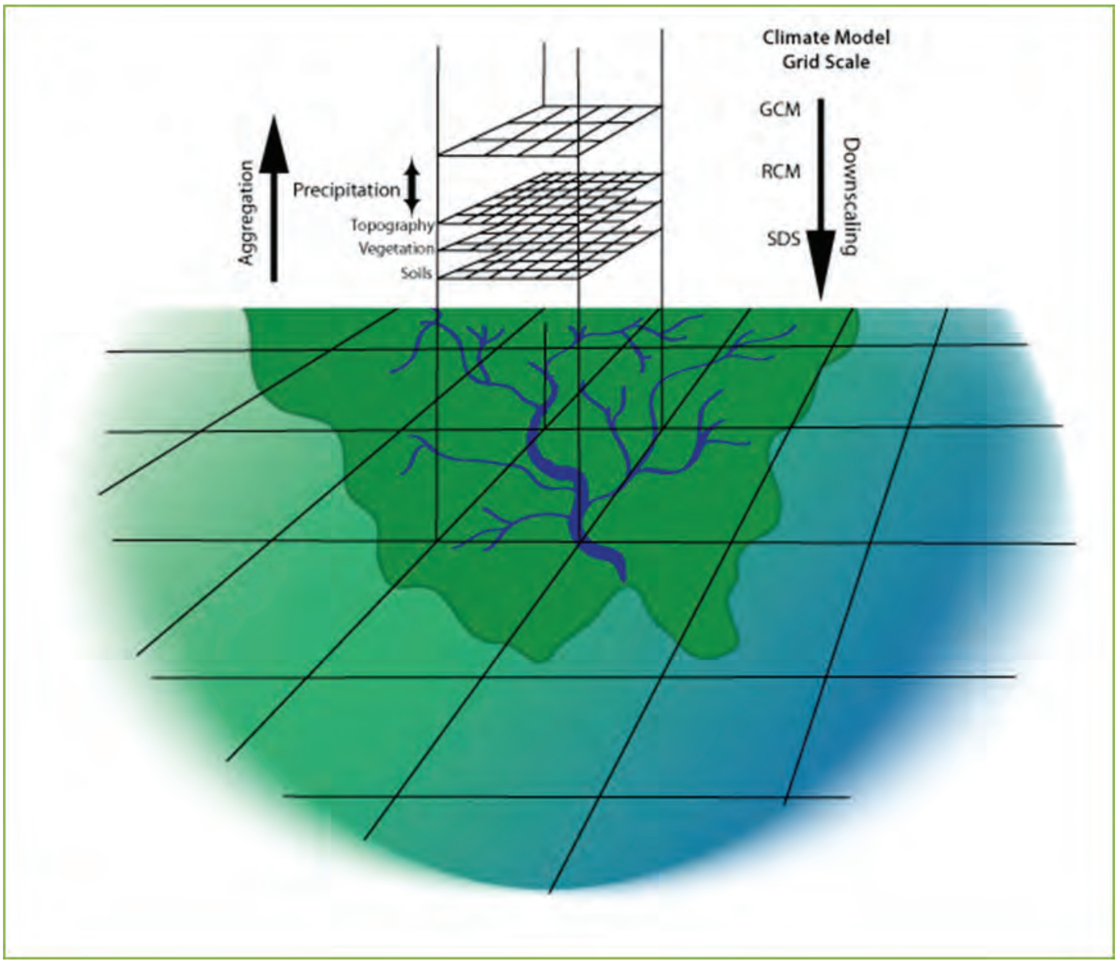


Figure 5: Graphical representation of the downscaling mechanism (Adapted from Wilby & Dawson, 2007)

Bates *et al.* (2008) distinguish between two main methods: *dynamical downscaling* and *empirical/ statistical downscaling.* The dynamical method uses the output of regional climate models, global models with variable spatial resolution or high resolution global models, while the empirical/statistical methods develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. The quality of the downscaled product depends on the quality of the driving model.

For the purpose of illustration, the empirical/statistical approach is used. The scenario of greenhouse gasses increasing by 1% per annum is selected. Data for the selected scenario were obtained from the IPCC Data Distribution Centre. The following data sets were used:

- 1961–1990 mean monthly values.
- 2010–2039 mean monthly change fields.
- 2040–2069 mean monthly change fields.
- 2070–2099 mean monthly change fields.

The correlation between the scenario data and the local data for both precipitation and temperature are shown in Figure 6 and Figure 7 respectively.

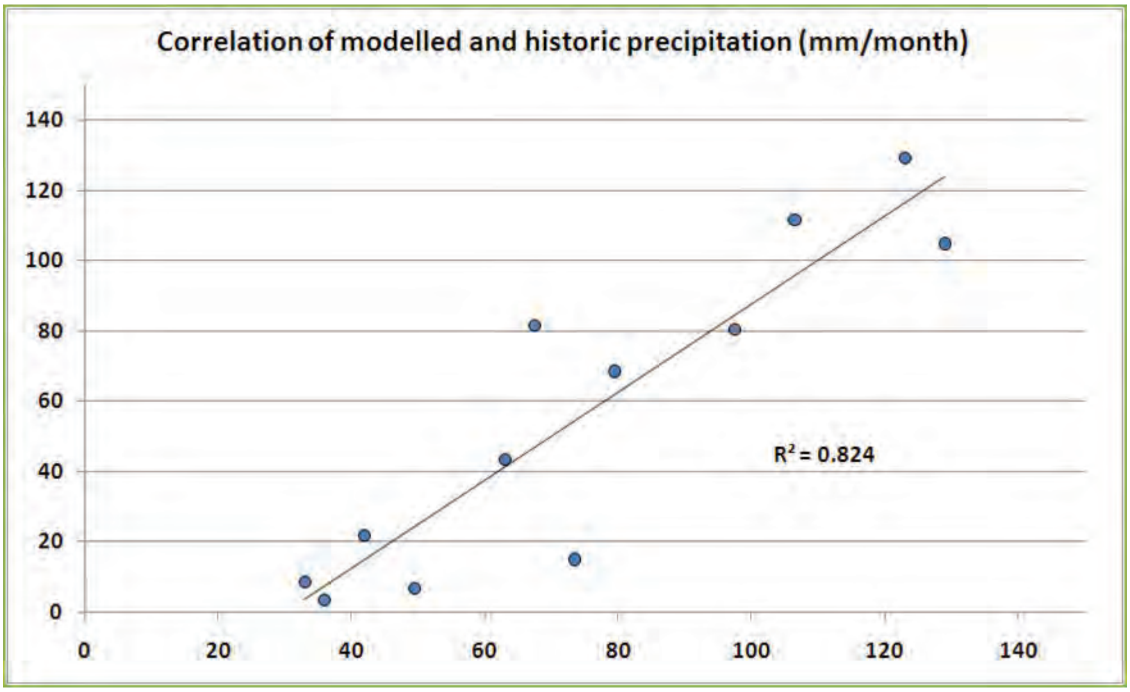


Figure 6: Correlation of modelled and historic precipitation data

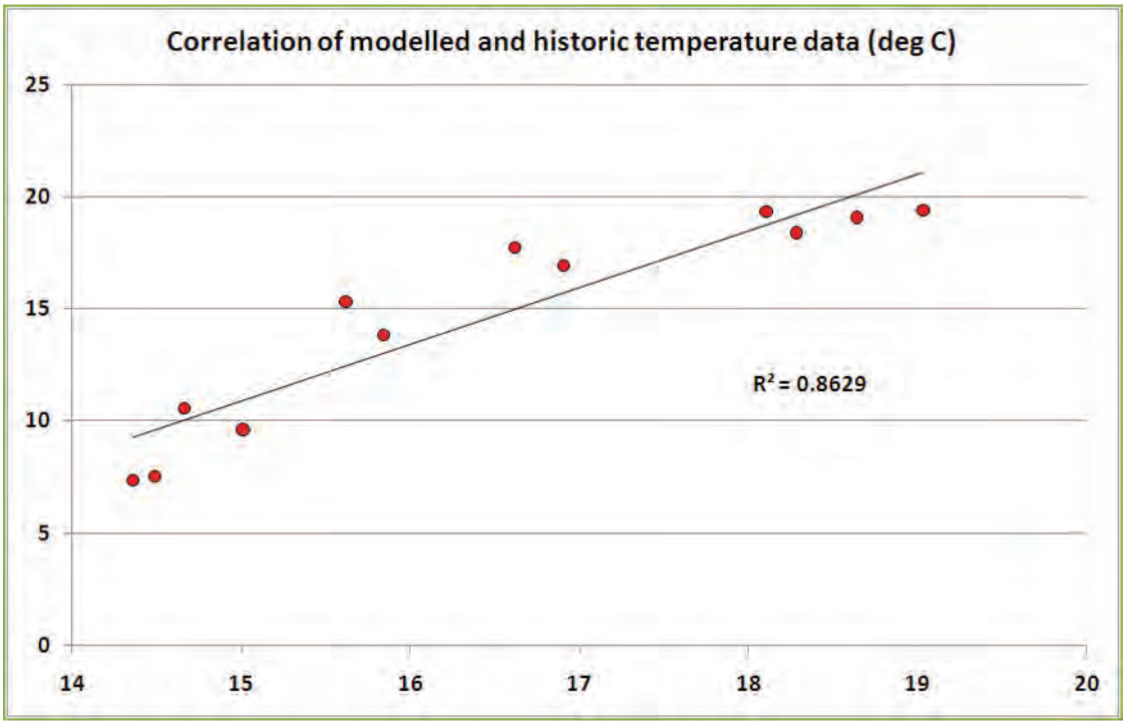


Figure 7: Correlation of modelled and historic precipitation data

Good correlation exists between the modelled and historical data (82% for precipitation and 86% for temperature). These correlations are used to produce the downscaled time series data required on a local scale.

The scenario data for both precipitation and temperature for a selected study area in the Karoo sequence are shown in Figure 8.

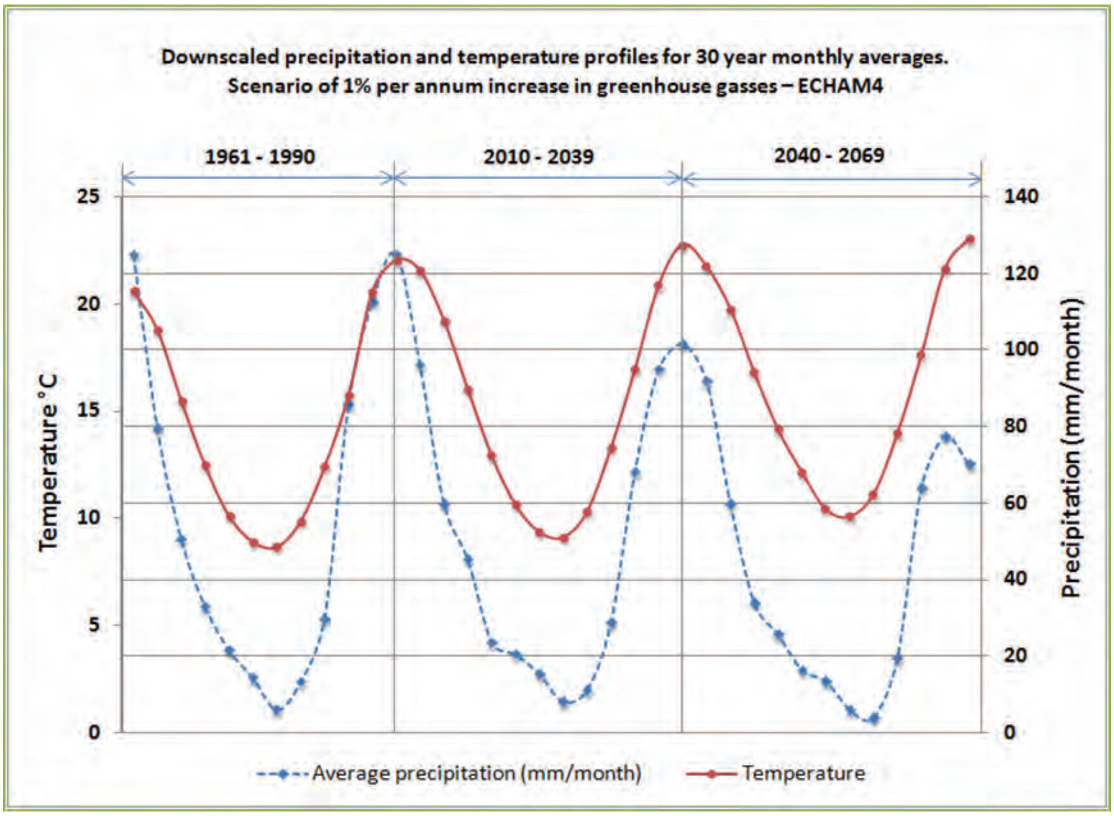


Figure 8: Downscaled precipitation and temperature data to local scale

3.3 Quantifying groundwater related climate change impacts

The main reason for studying the interactions between aquifers and the atmosphere is to determine how groundwater resources are affected by climate variability and climate change. It is expected that changes in temperature and precipitation will alter groundwater recharge to aquifers, causing shifts in water table levels in unconfined aquifers as a first response to climate trends (Changnon *et al.*, 1988; Zektser & Loaciga, 1993).

In the study by Cavé *et al.* (2003), various approaches were considered to evaluate the impact of climate change on water resources. One such approach was the adoption of climate change analogues from palaeoclimatic-historical climate research for application in water resources management, since groundwater resources generally contain rich archives of past states and fluxes. By analysing these archives, insight into the changing conditions of climate can be obtained and hence used in forecasting the impacts of future climate changes (Cavé *et al.*, 2003). Unfortunately, this approach is very difficult to apply in southern Africa, since there are very few locations where records of climate and groundwater have been kept in sufficient detail to allow such detailed analysis.

Cavé *et al.* (2003) propose that rainfall–recharge relationships may be used in a first attempt to assess the impacts of climatic change on groundwater resources. Data was used from various studies, and recharge rates were compared as a function of annual rainfall for Southern Africa, which found large differences in recharge values for areas with an annual rainfall of less than 500 mm/a. The observed rainfall–recharge relationship (Figure 9) can be used as a tool to examine possible groundwater trends if the projected changes in mean annual precipitation occur as a response to human induced climate change. Groundwater recharge becomes negligible for rainfall lower than 400 mm/a.

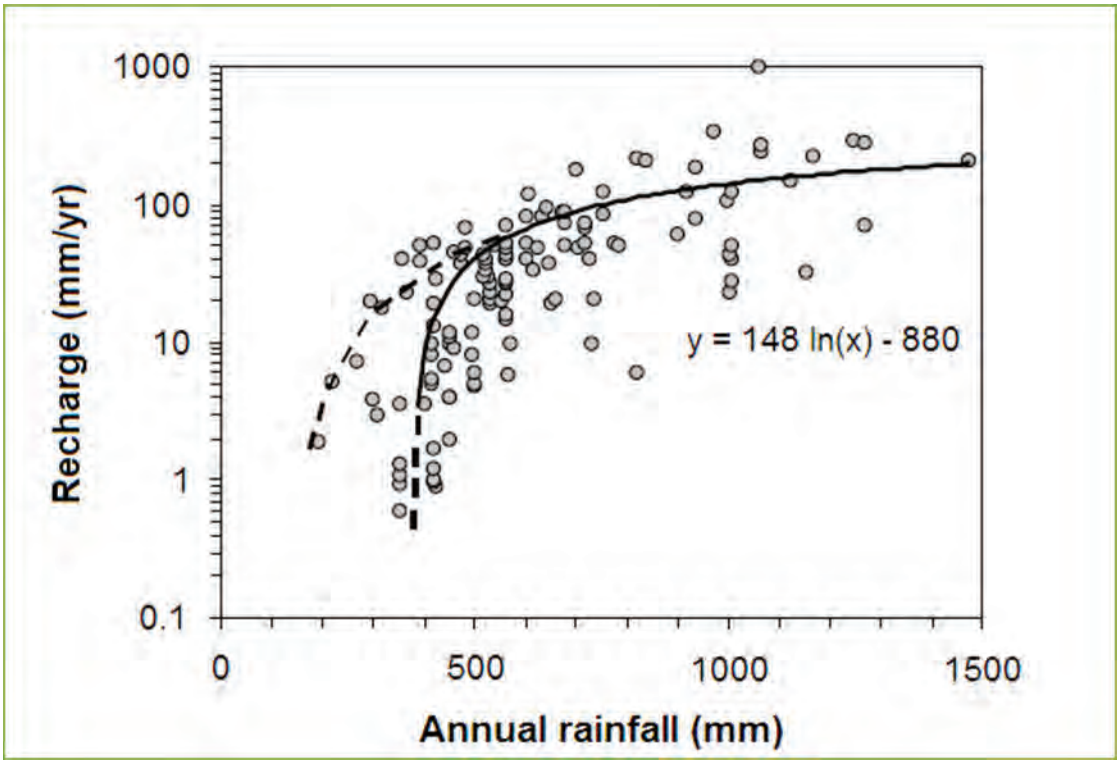


Figure 9: Recharge rates in South Africa (taken from Cavé *et al.*, 2003)

Aquifer recharge and groundwater levels interact, and depend on climate and groundwater use; each aquifer has different properties and requires detailed characterisation and eventually quantification (e.g. numerical modelling) of these processes and linking of the recharge model to climate model predictions (York *et al.*, 2002). In practice, any aquifer that has an existing and verified conceptual model, together with a calibrated numerical model, can be assessed for climate change impacts through scenario simulations. The accuracy of predictions depends largely on scale of project and availability of geohydrological and climatic datasets. An example of such a case study for Karoo aquifers is shown in Appendix A. However, this method requires intensive data. These data sets are sparse for the Karoo aquifers.

Another method proposed by Van Tonder (2010) is to utilise recession curves on projected stream-flow to obtain the change in groundwater contribution to baseflow. He proposes the method developed by Moore (1997) where the recession curve is the specific part of the flood hydrograph after the crest (and the rainfall event) where streamflow diminishes. The slope of the recession curve flattens over time from its initial steepness as the quickflow component passes and baseflow becomes dominant. A *recession period* lasts until streamflow begins to increase again due to subsequent rainfall. Hence, recession curves are the parts of the hydrograph that are dominated by the release of water from natural storages, typically assumed to be groundwater discharge.

4 *Methodology to quantify climate change impacts for Karoo aquifers*

Vulnerability to climate change 'is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change ...' and is 'a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity' (Döll, 2009).

4.1 Introduction

The first step in our approach involves the creation of a climate change vulnerability profile. It is already known (e.g. Rushton *et al.*, 2006; Eilers *et al.*, 2007) that annual runoff and recharge totals are more sensitive to short-term rainfall distribution than to annual total rainfall, especially in semi-arid areas. An extended period of medium-intensity rainfall is more likely to lead to significant recharge than either a period of high-intensity rainfall (which will lead to increased runoff) or a period of low-intensity rainfall (most of which will evaporate). Two years with the same annual rainfall may give very different values of recharge, depending on the daily rainfall distribution.

Climate change affects groundwater mainly due to changes in groundwater recharge (and the resulting water table changes). Where groundwater recharge decreases in semi-arid and coastal regions, groundwater salinity may increase.

4.2 DART Methodology

4.2.1 Introduction

The DART methodology was developed by analogy with the DRASTIC methodology. The parameters considered in the DART methodology are as follows:

D – Depth to water level change

A – Aquifer type (storativity)

R – Recharge

T – Transmissivity

The DRASTIC methodology was developed to express aquifer vulnerability with reference to the threat of pollution. The DART methodology focuses more on typical parameters used in sustainability studies, but also indirectly accommodates the issue of quality due to the fact that water quality is likely to deteriorate with a drop in water level over time, as the salt load will concentrate.

Two scenarios are considered: current and future. The current scenario is representative of current precipitation patterns and the future scenario is representative of the predicted scenario based on the selected GCM.

Future precipitation projections from ten statistically downscaled GCMs are available:

- IPSL_CM4
- GFDL_CM2_0 (Geophysical Fluid Dynamics Laboratory)
- CCMA_CGCM3_1 (The Third Generation Coupled Global Climate Model)
- MRI_CGCM2_3_2A (Meteorological Research Institute Coupled General Circulation Model)
- CSIR0_MK3_0 (Commonwealth Scientific and Industrial Research Organisation)
- CSIR0_MK3_5 (Commonwealth Scientific and Industrial Research Organisation)
- MPI_ECHAM5 (European Centre Hamburg Model)
- GISS_MODEL_E_R (Goddard Institute for Space Studies)
- CNRM_CM3 (Centre National de Recherche Meteorologique)
- MIUB_ECHO_G

These downscaled models were made available by the Climate System Analysis Group at the University of Cape Town (Davies, 2010).

The most probable future scenario, in terms of atmospheric carbon dioxide concentration, is currently uncertain. What is known, however, is that even were emissions to be cut today, the earth is still committed to a certain degree of climatic change (Davies, 2010). For the purpose of this document, the Meteorological Research Institute Coupled General Circulation Model was chosen with a future A2 SRES emissions scenario. The A2 storyline and scenario describes a very heterogeneous world, assuming a moderate to high growth in greenhouse gas concentration.

4.2.2 Depth to Water Level Change

The depth to water level was determined for the Karoo aquifers using the average water level for each borehole on the NGA (National Groundwater Archive). A strong correlation exists between the water levels and topography over the study area, as shown in Figure 10, allowing the use of a Bayesian approach for water level generation in areas where no water level data is available.

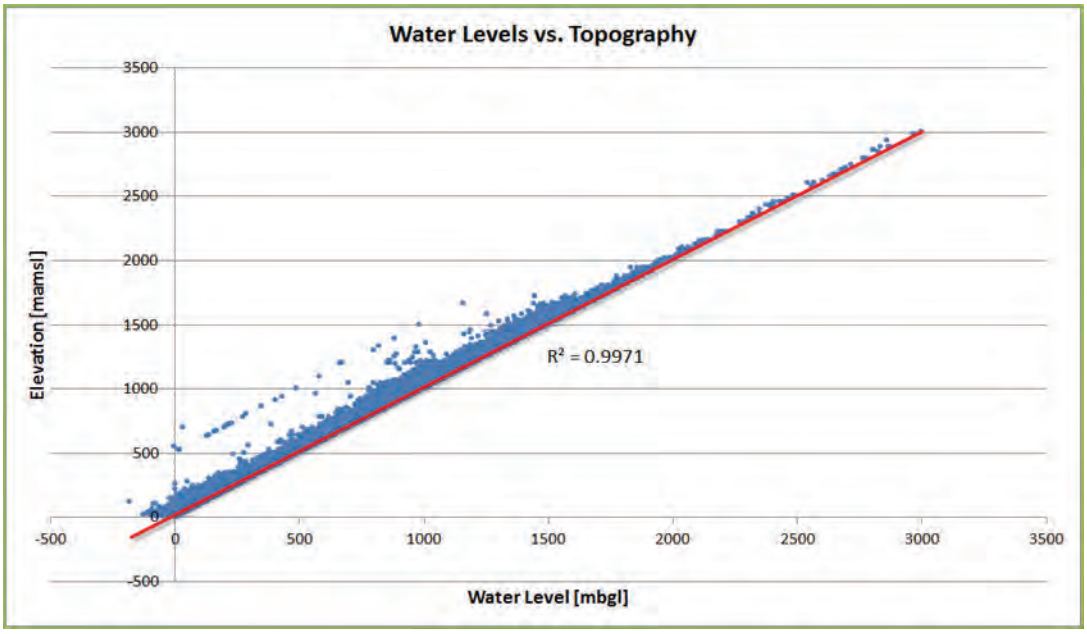


Figure 10: Karoo water levels *versus* topography

It is worth mentioning that the extremely high correlation value is obtained because such a wide range of values is considered. A map of the resultant water levels is shown in Figure 11. These water levels are used as the reference level for the current climate scenario.

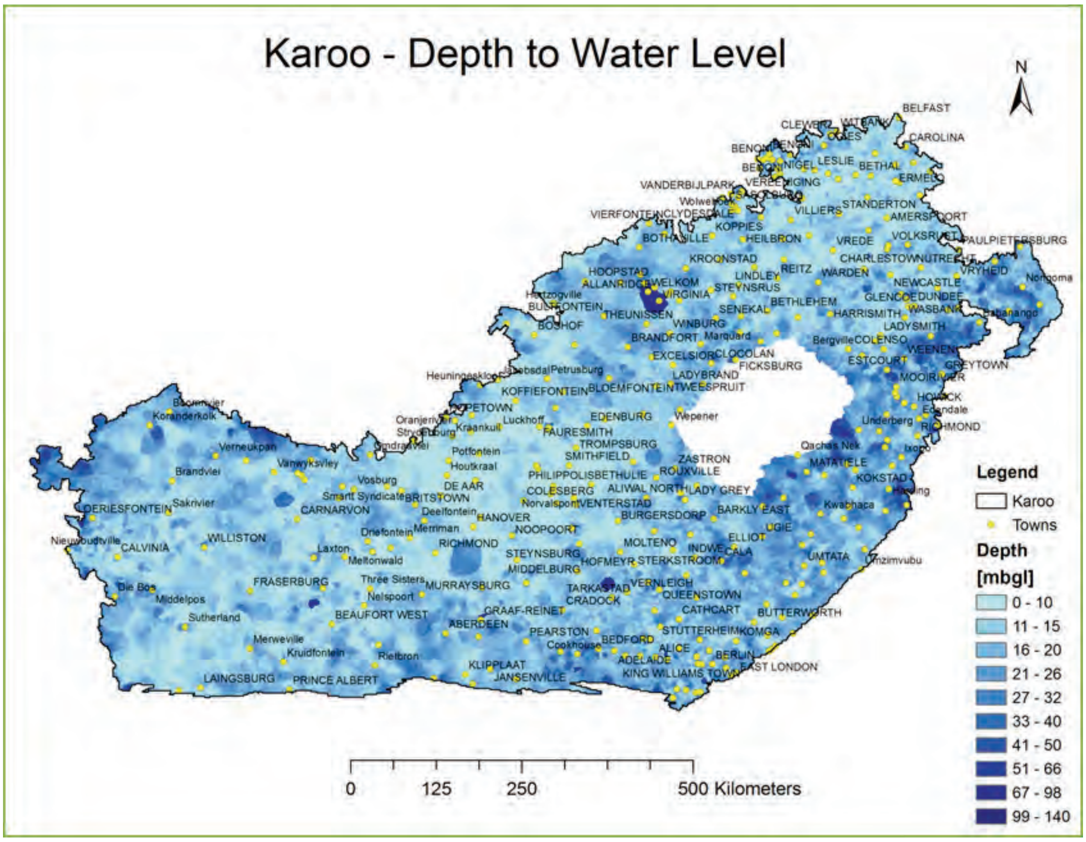
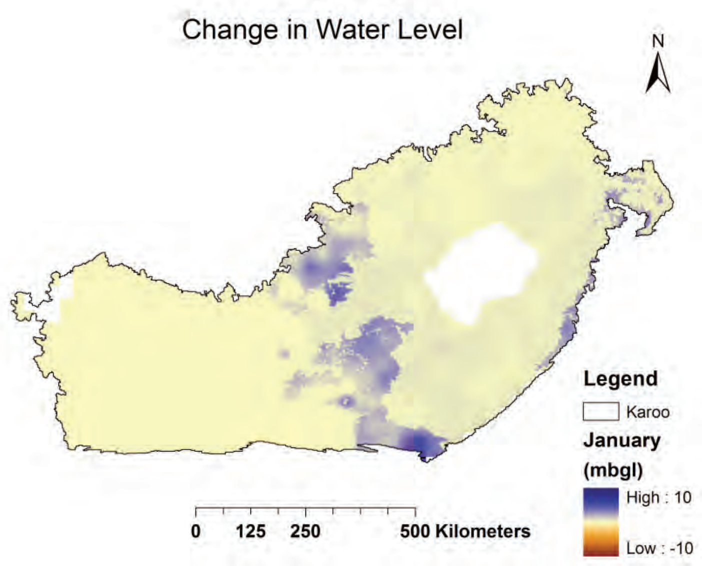


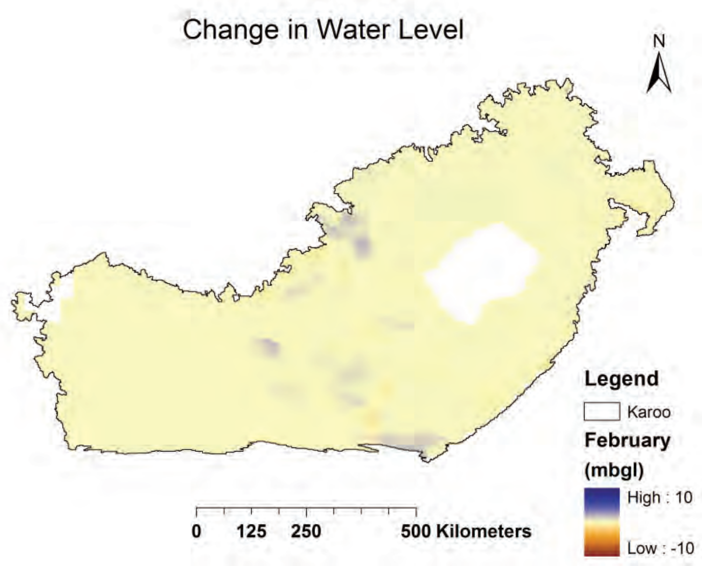
Figure 11: Karoo water levels

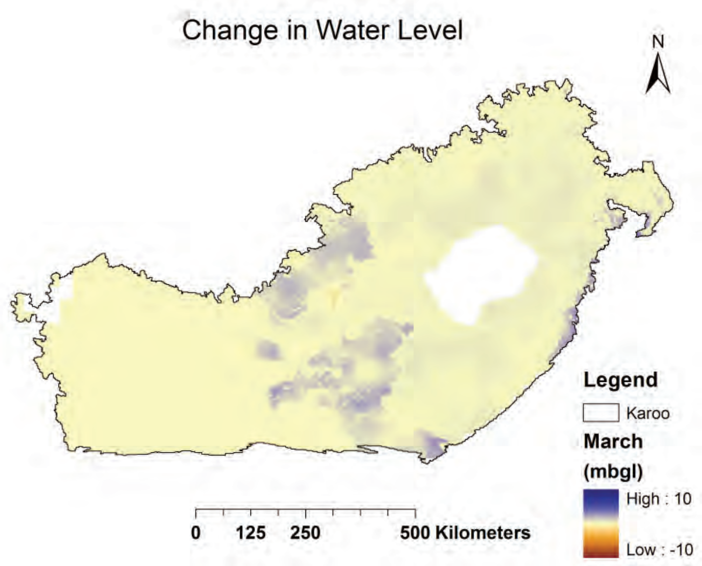
The change in water level per month for both current and future scenarios was determined using the following relationship between water level, recharge and storage coefficient:

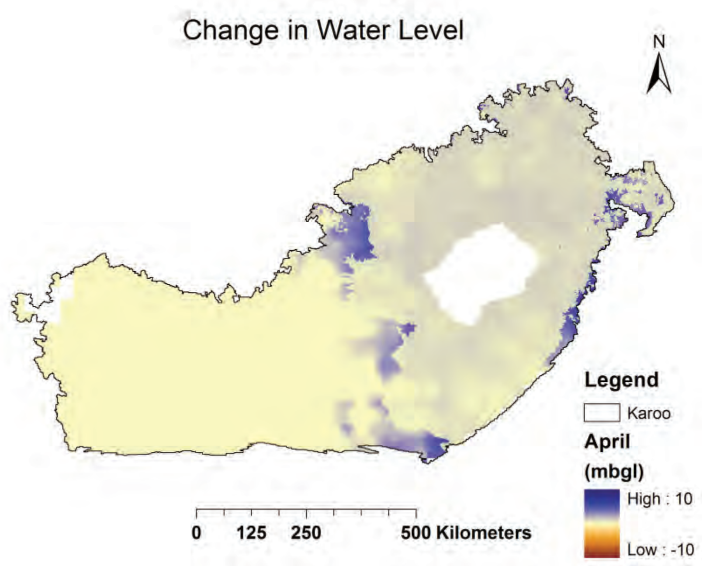
$$\frac{Recharge}{Storage\ Coefficient}$$

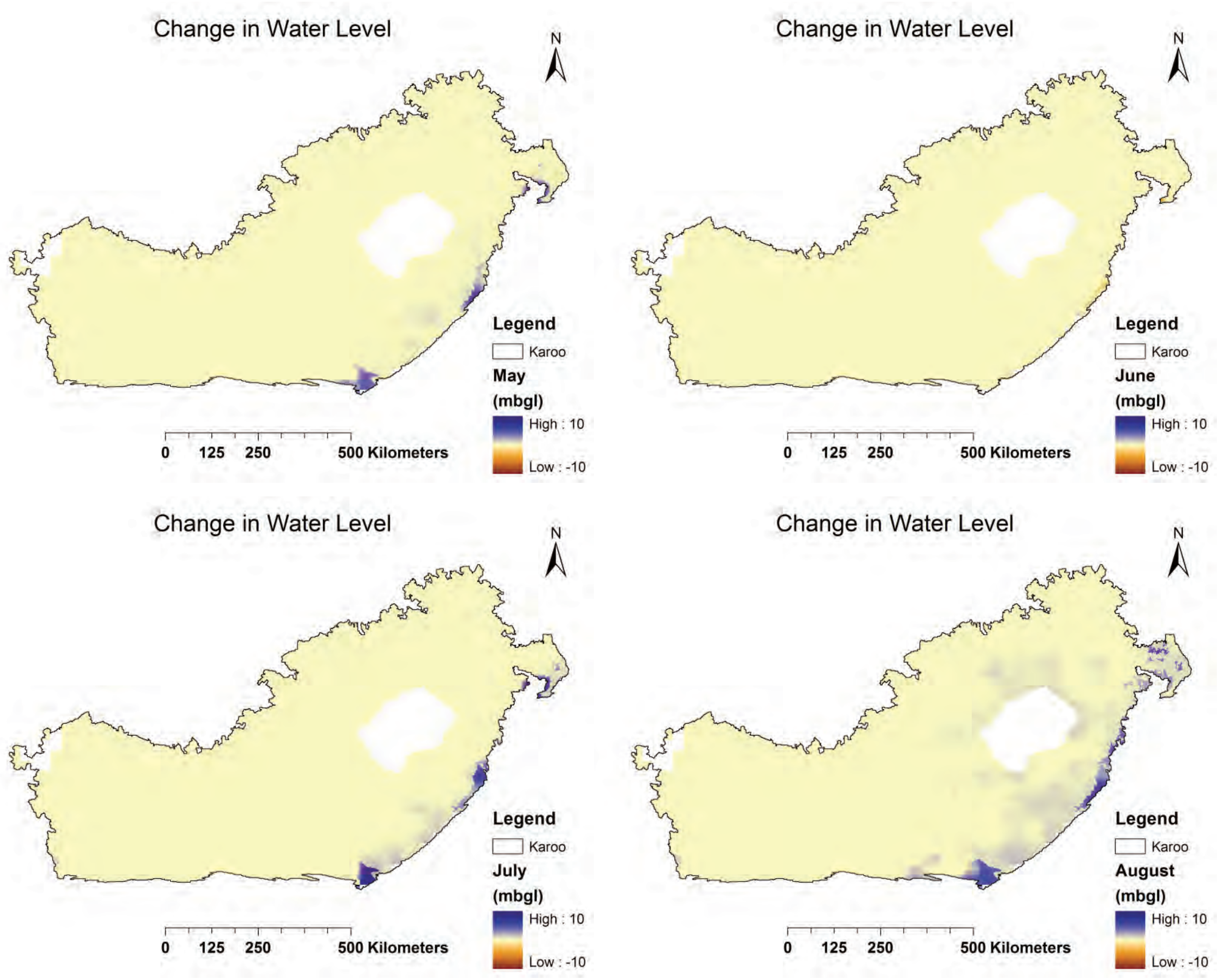
It is clear from the relationship that recharge is the driving force of the water level since the storage coefficient is a static parameter. The following set of maps presented in Figure 12 shows the monthly water level change between the current and future scenarios.


Change in Water Level
N
Legend
Karoo
January
(mbgl)
High : 10
Low : -10
0
125
250
500 Kilometers


Change in Water Level
N
Legend
Karoo
February
(mbgl)
High : 10
Low : -10
0
125
250
500 Kilometers


Change in Water Level
N
Legend
Karoo
March
(mbgl)
High : 10
Low : -10
0
125
250
500 Kilometers


Change in Water Level
N
Legend
Karoo
April
(mbgl)
High : 10
Low : -10
0
125
250
500 Kilometers



Change in Water Level
N
Legend
Karoo
May
(mbgl)
High : 10
Low : -10
0 125 250 500 Kilometers
Change in Water Level
N
Legend
Karoo
June
(mbgl)
High : 10
Low : -10
0 125 250 500 Kilometers
Change in Water Level
N
Legend
Karoo
July
(mbgl)
High : 10
Low : -10
0 125 250 500 Kilometers
Change in Water Level
N
Legend
Karoo
August
(mbgl)
High : 10
Low : -10
0 125 250 500 Kilometers

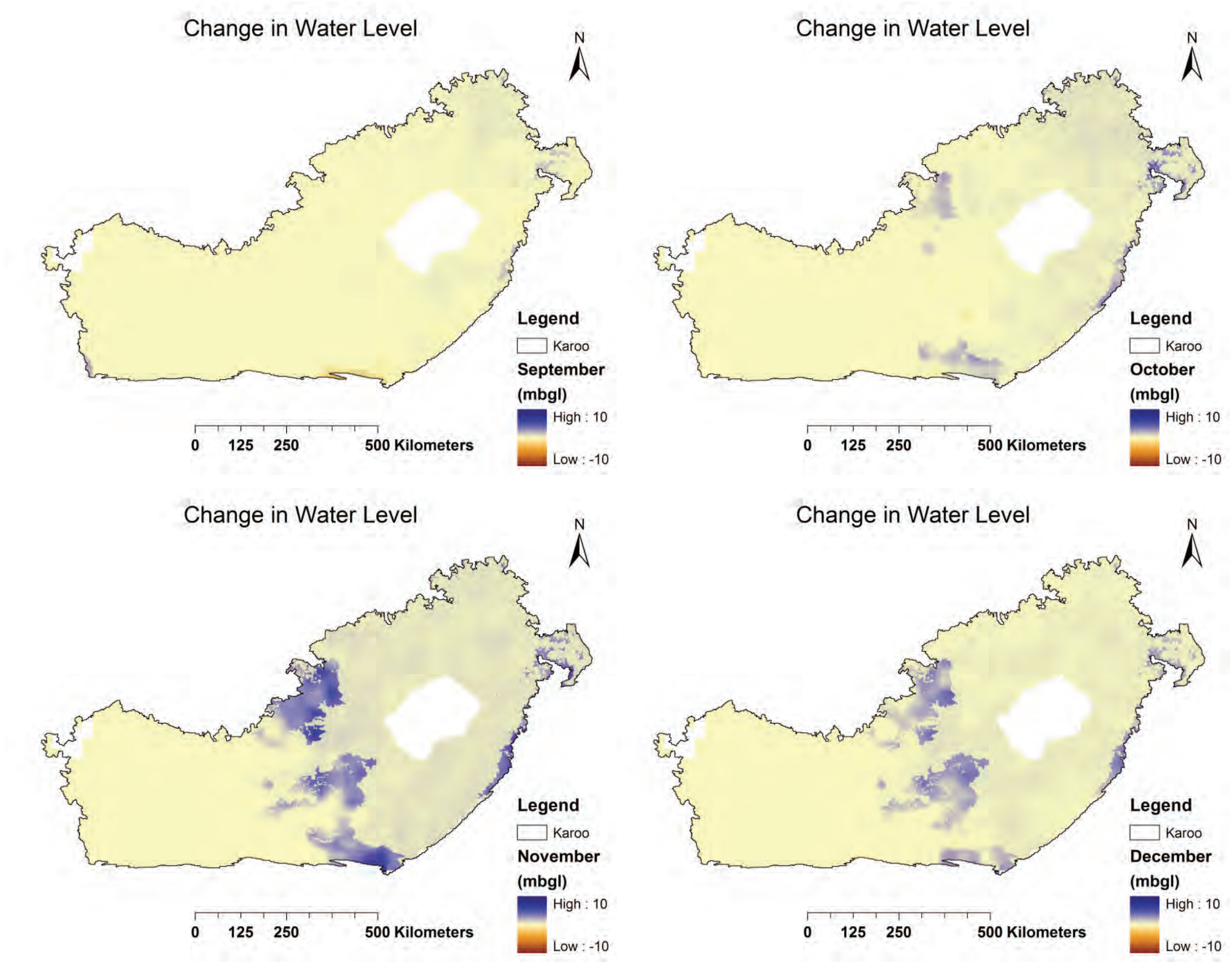


Figure 12: Water level change between current and future scenarios

4.2.3 Aquifer Type

The aquifer type was derived using the geohydrological maps of South Africa in conjunction with the classification of aquifer type given in Table 1.

Table 1: Aquifer type

Aquifer Type	Storativity
Fractured	0.001
Fractured and Intergranular	0.005
Karst	0.01
Intergranular	0.1

A similar classification was used in the sustainability risk calculation to that used in the Groundwater Decision Tool (Dennis, 2001). The resultant map of aquifer types is shown in Figure 13.

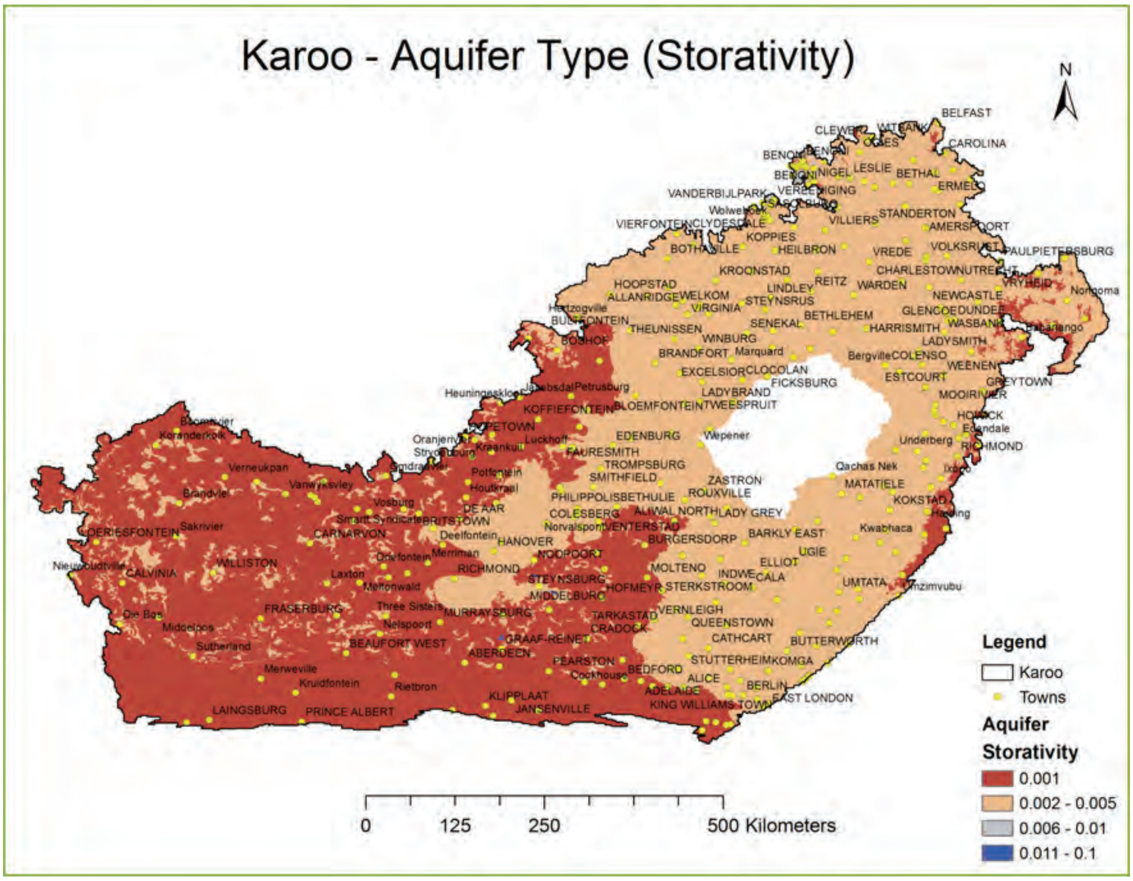


Figure 13: Karoo aquifer type based on storativity

4.2.4 Recharge

Recharge is a function of both precipitation and slope and an attempt was made to formulate a recharge model based on the aforementioned parameters to accommodate monthly recharge figures based on monthly precipitation. It is a known fact that although recharge varies with precipitation, major recharge takes place through episodic rainfall events.

Episodic recharge is a common occurrence, which has the effect that the percentage recharge will vary according to the type of daily rainfall event that takes place. Recent research has indicated a one-in-five-year return period for episodic recharge associated with certain rainfall patterns (Van Wyk, 2010). This is not an easy phenomenon to model and on-going research is conducted in this field, hence episodic recharge is not taken into account in this report. By not taking into account episodic recharge events, a worst-case scenario is considered in the analysis.

4.2.4.1 Precipitation

The current and future annual precipitation distribution is shown in Figure 14 and Figure 15, respectively.

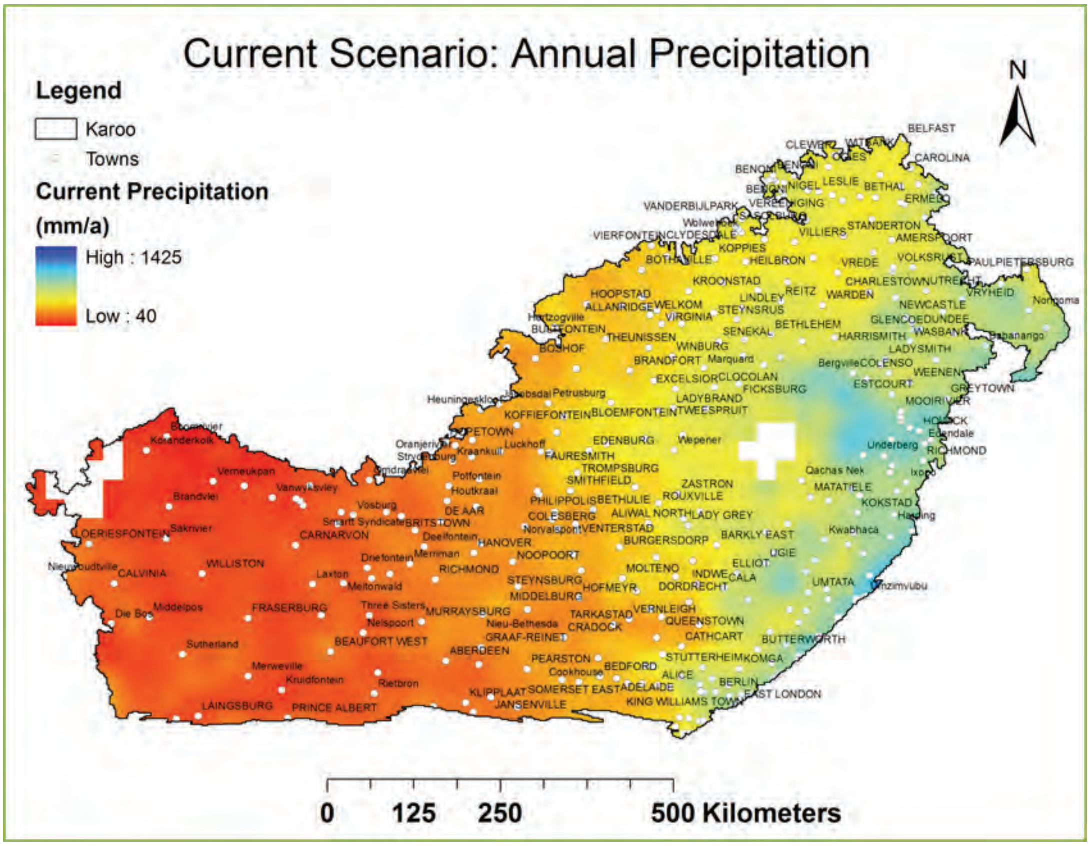


Figure 14: Current annual precipitation

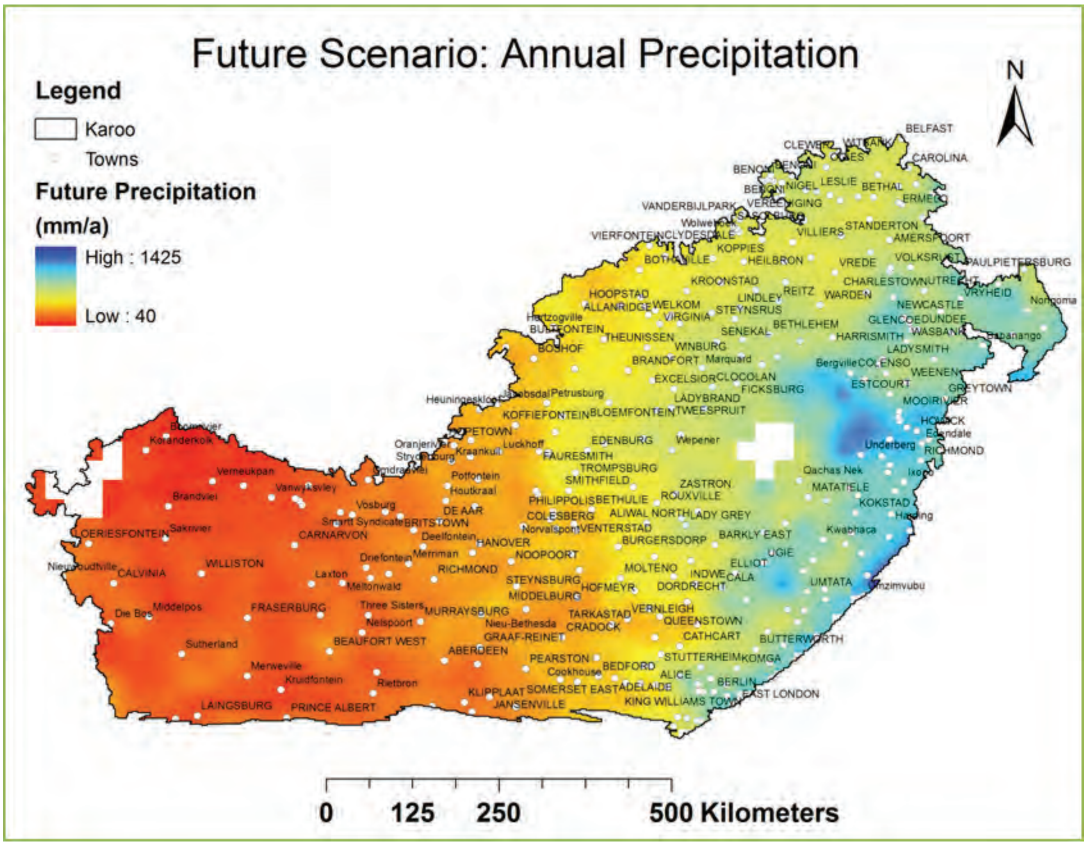


Figure 15: Future annual precipitation

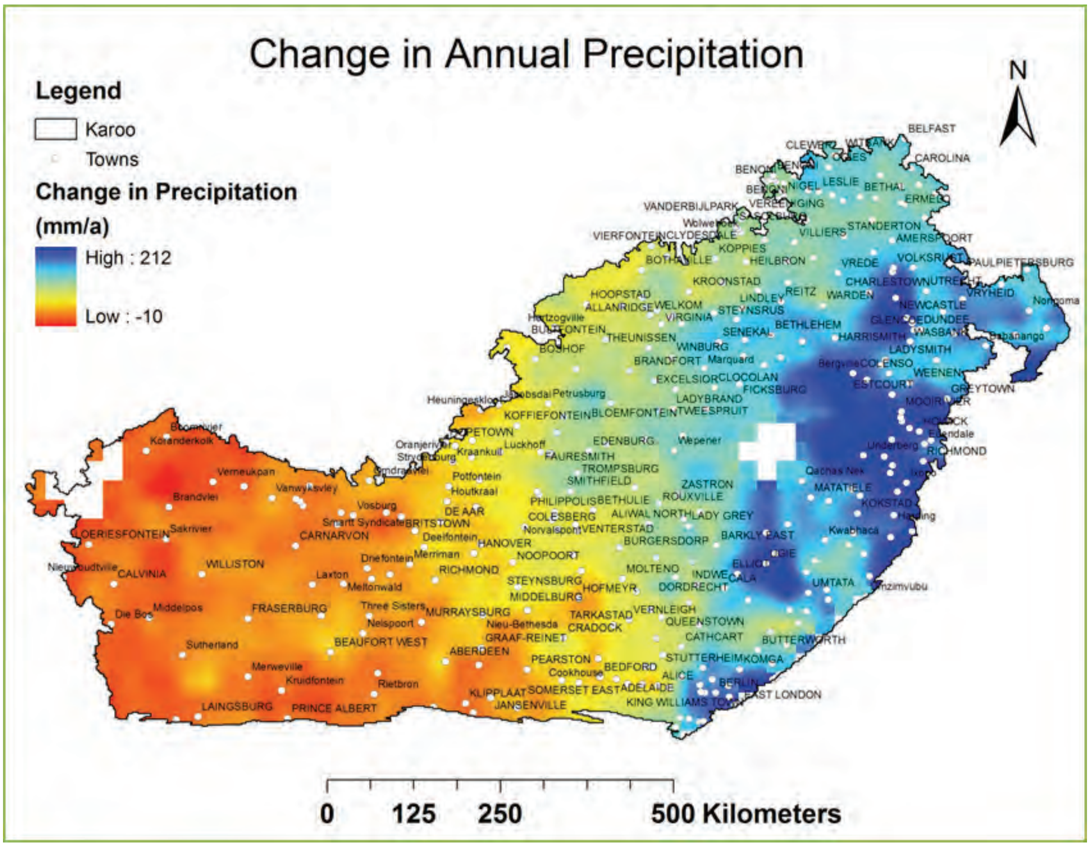
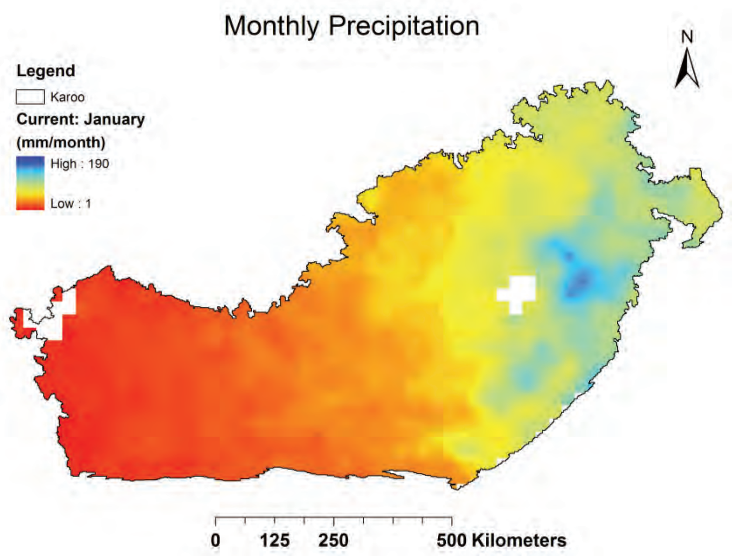
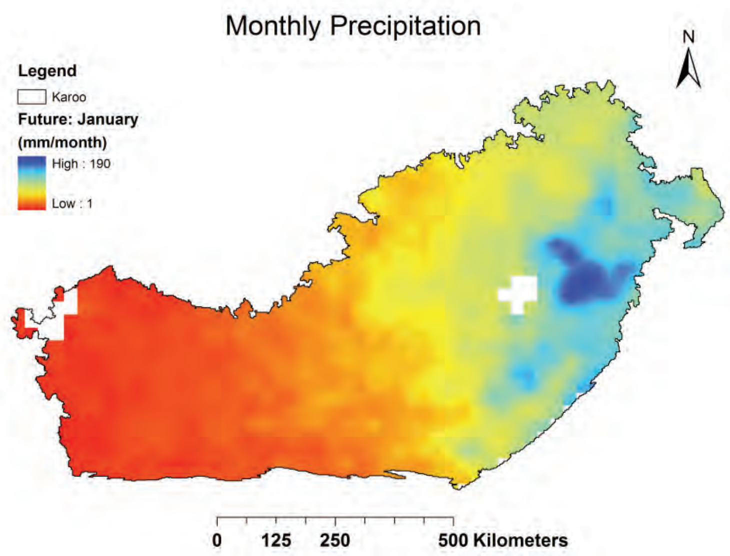
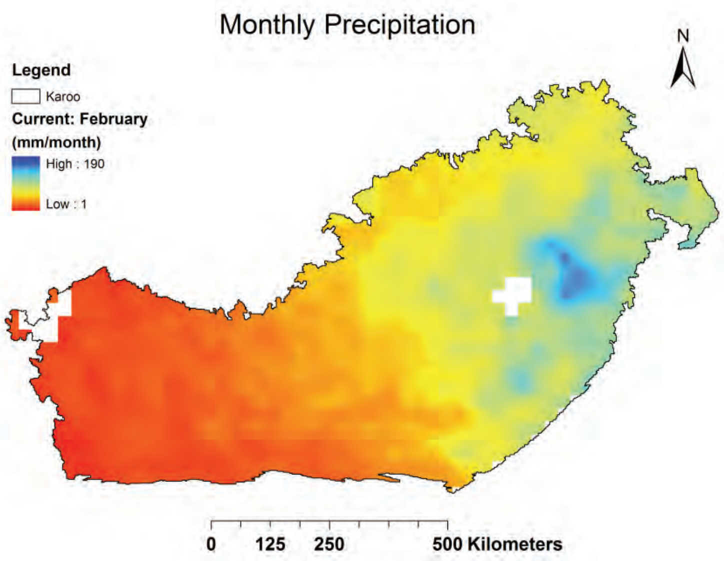


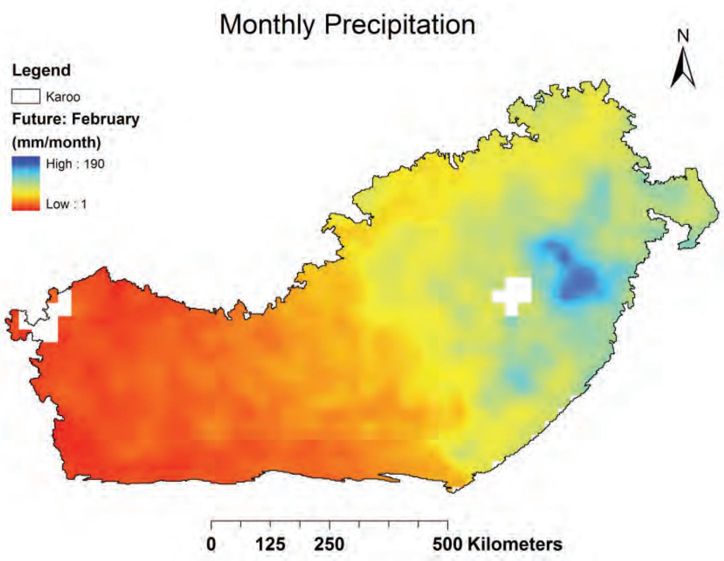
Figure 16: Change in precipitation between current and future scenarios

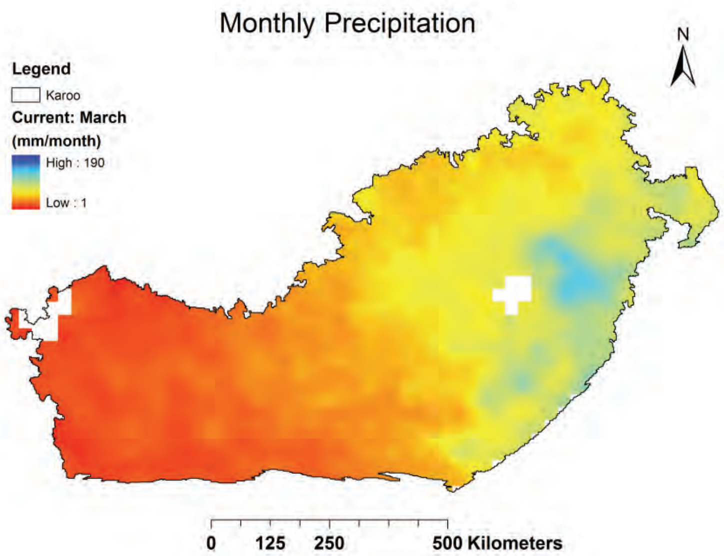
The monthly precipitation for both the current and future scenarios is shown in below in the sequence of maps (Figure 17). Precipitation is an important factor in the analysis as water level change is governed by recharge, which in turn is governed by precipitation, as shown in Section 4.2.2.

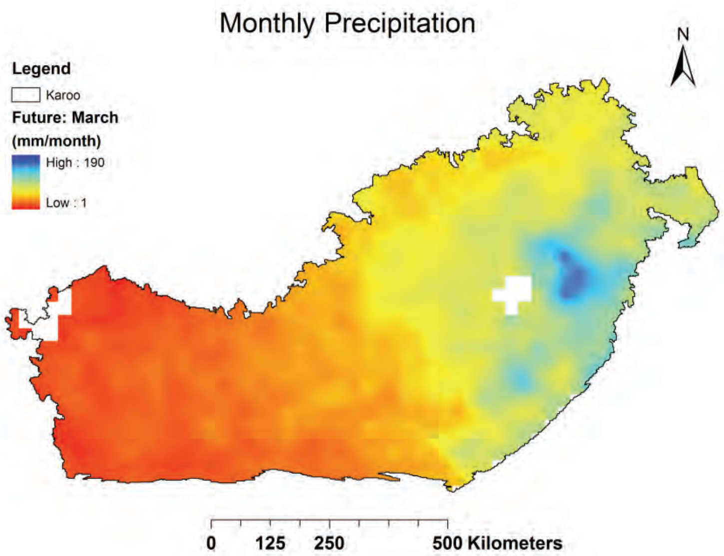


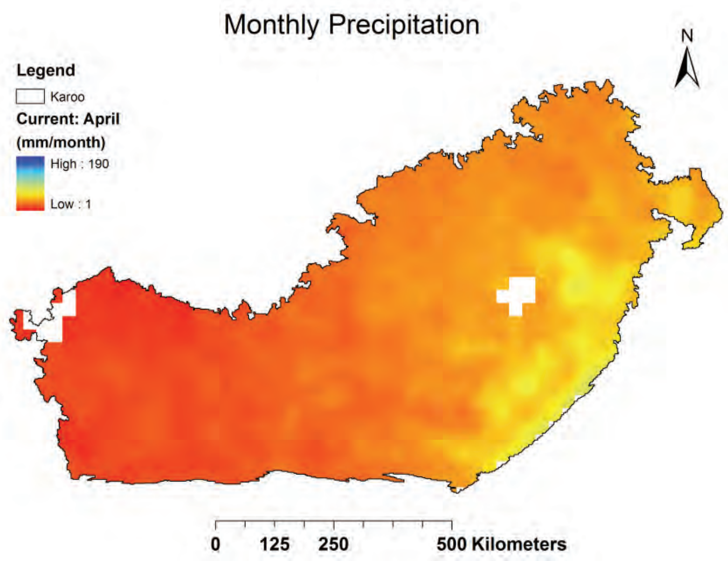


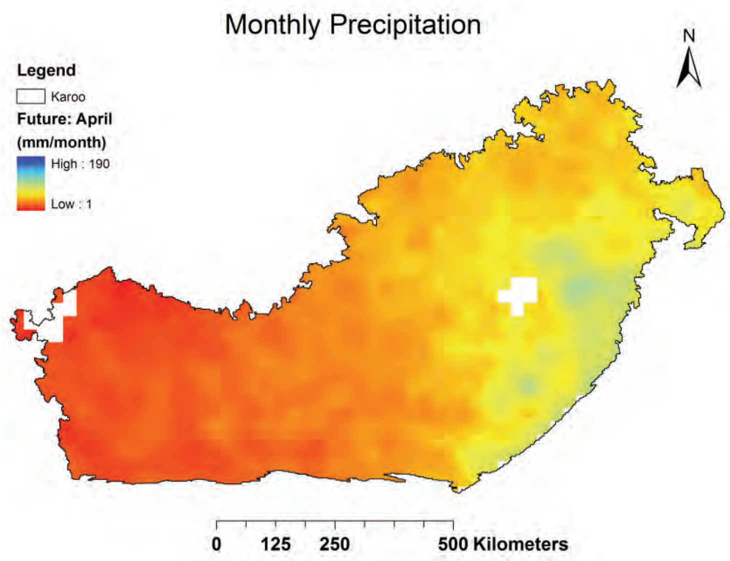

Monthly Precipitation
N
Legend
Karoo
Current: February
(mm/month)
High : 190
Low : 1
0
125
250
500 Kilometers

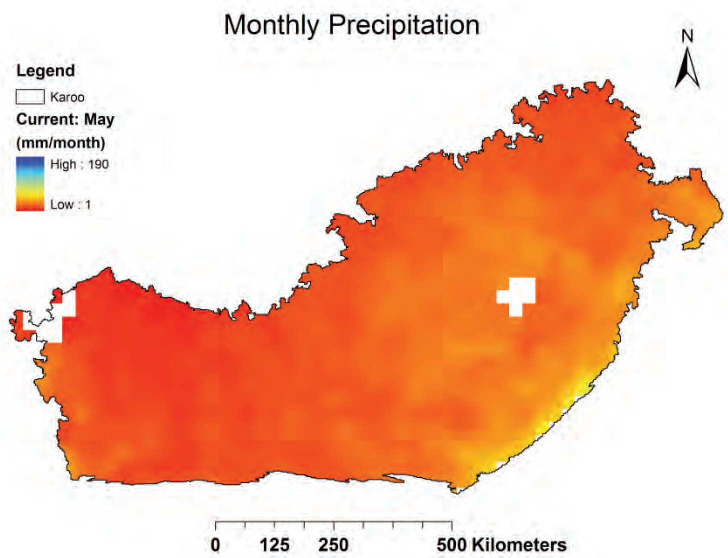

Monthly Precipitation
N
Legend
Karoo
Future: February
(mm/month)
High : 190
Low : 1
0
125
250
500 Kilometers

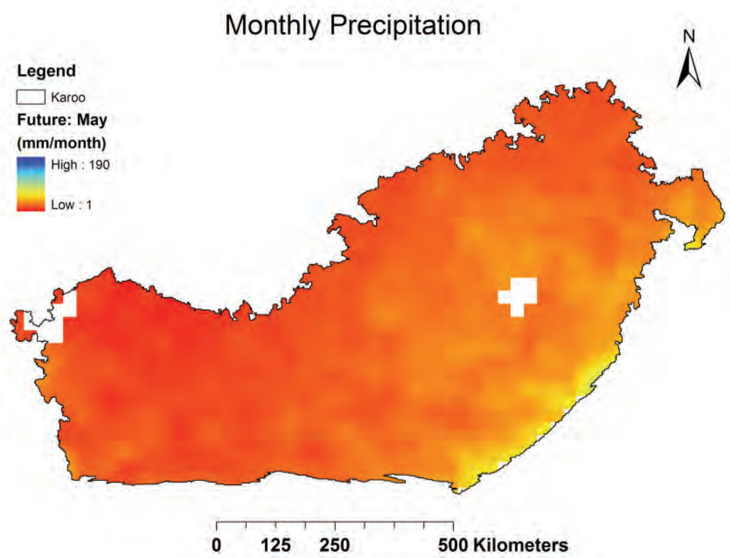

Monthly Precipitation
N
Legend
Karoo
Current: March
(mm/month)
High : 190
Low : 1
0
125
250
500 Kilometers

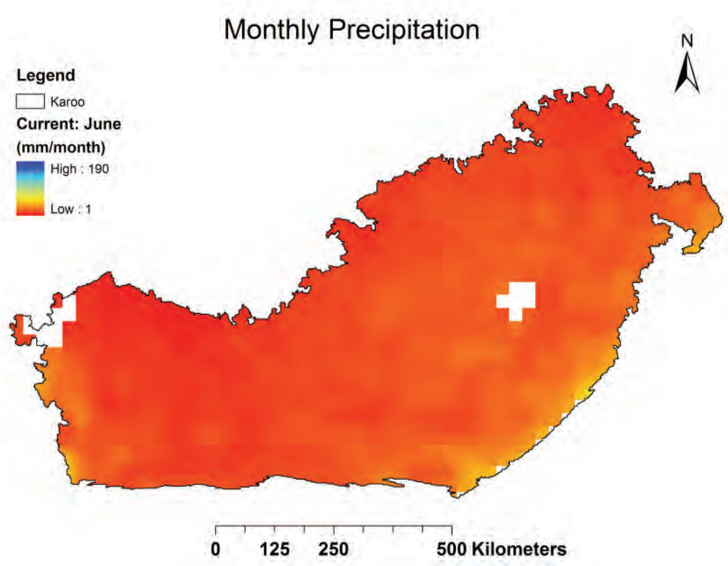

Monthly Precipitation
N
Legend
Karoo
Future: March
(mm/month)
High : 190
Low : 1
0
125
250
500 Kilometers

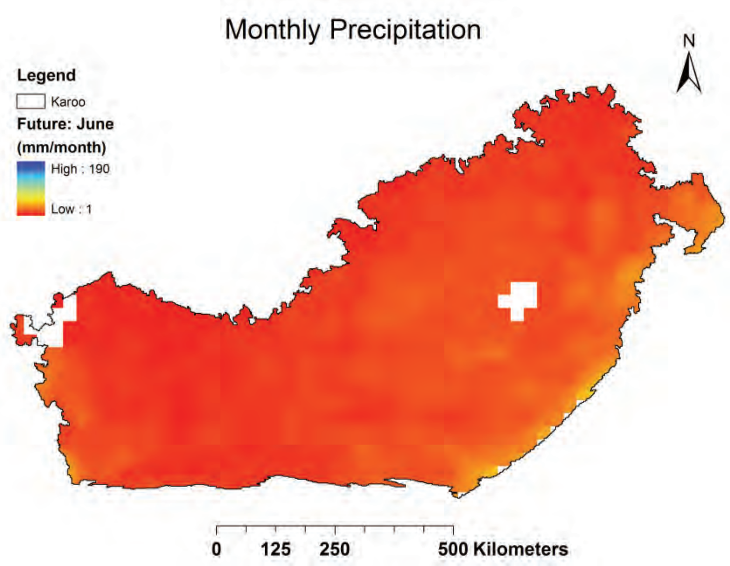

Monthly Precipitation
Legend
Karoo
Current: April
(mm/month)
High : 190
Low : 1
N
0
125
250
500 Kilometers

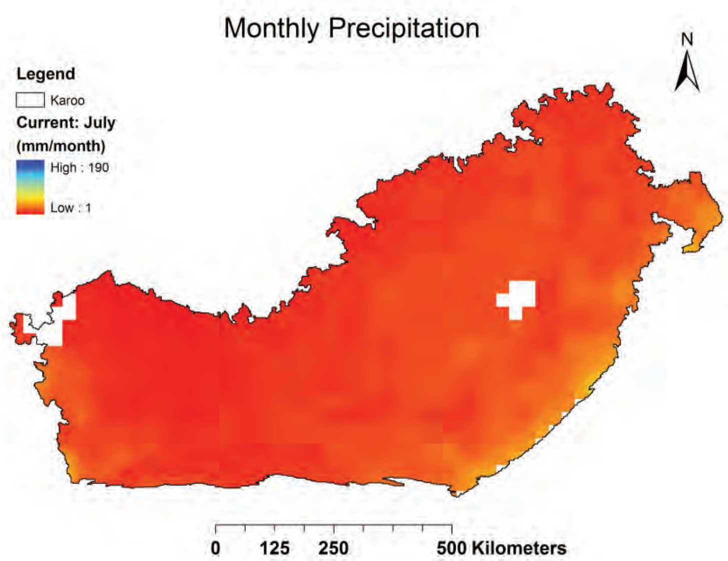

Monthly Precipitation
Legend
Karoo
Future: April
(mm/month)
High : 190
Low : 1
N
0
125
250
500 Kilometers

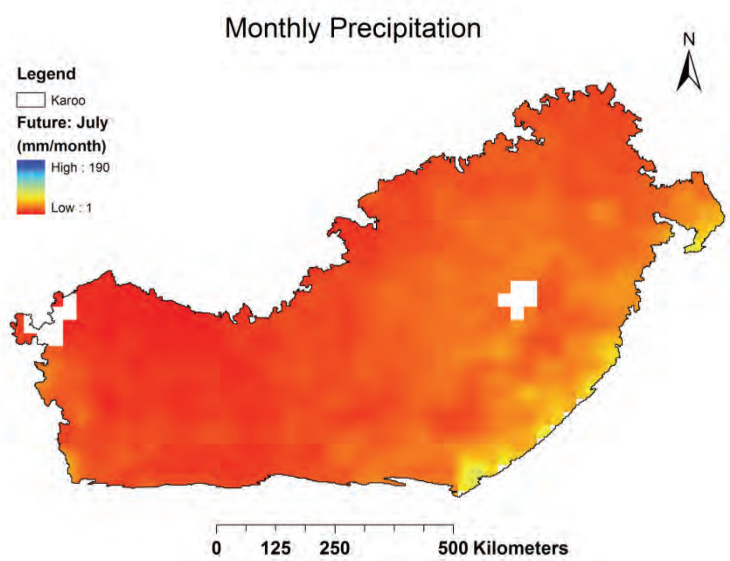

Monthly Precipitation
Legend
Karoo
Current: May
(mm/month)
High : 190
Low : 1
N
0
125
250
500 Kilometers

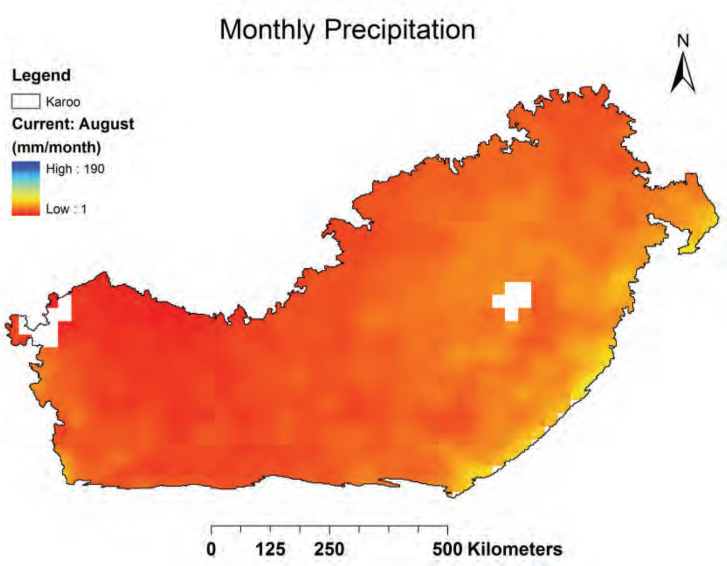

Monthly Precipitation
Legend
Karoo
Future: May
(mm/month)
High : 190
Low : 1
N
0
125
250
500 Kilometers

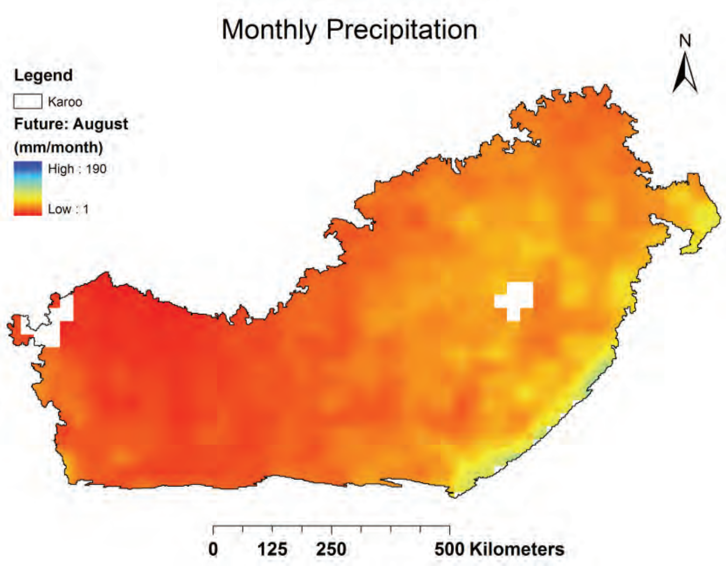

Monthly Precipitation
Legend
Karoo
Current: June
(mm/month)
High : 190
Low : 1
N
0
125
250
500 Kilometers

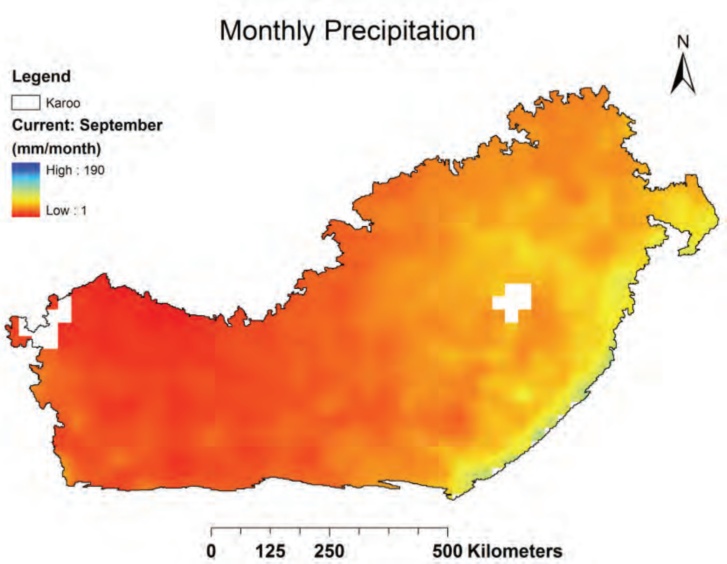

Monthly Precipitation
Legend
Karoo
Future: June
(mm/month)
High : 190
Low : 1
N
0
125
250
500 Kilometers

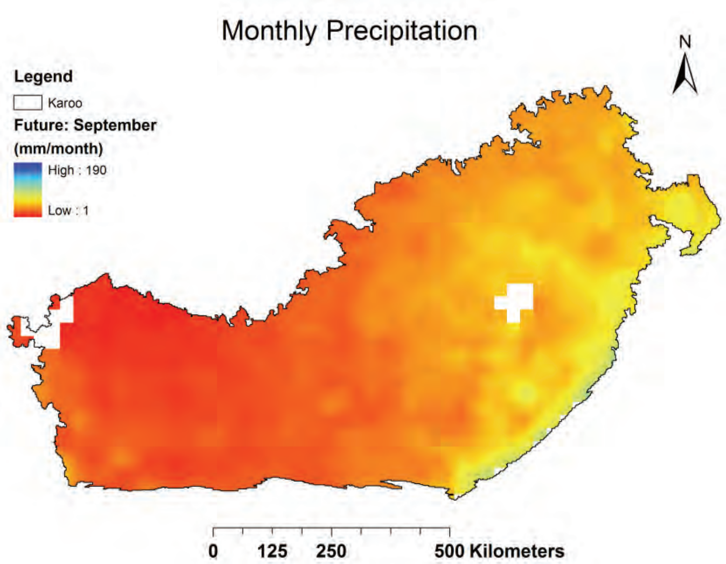

Monthly Precipitation
Legend
Karoo
Current: July
(mm/month)
High : 190
Low : 1
N
0
125
250
500 Kilometers

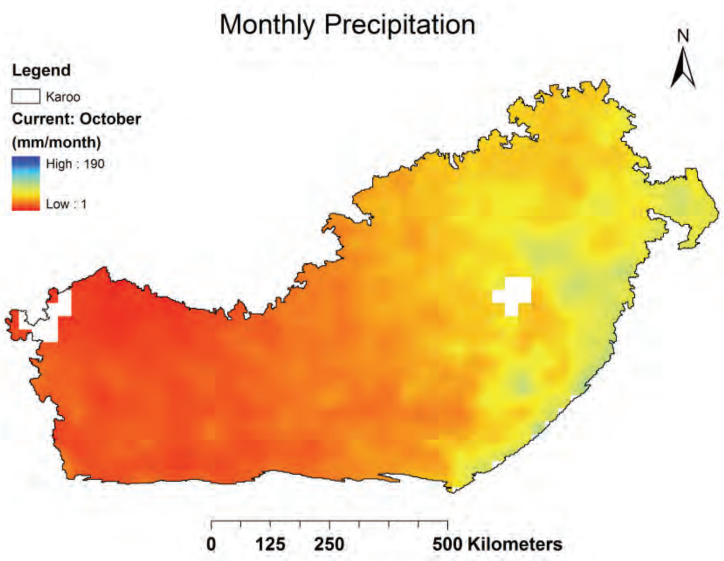

Monthly Precipitation
Legend
Karoo
Future: July
(mm/month)
High : 190
Low : 1
N
0
125
250
500 Kilometers

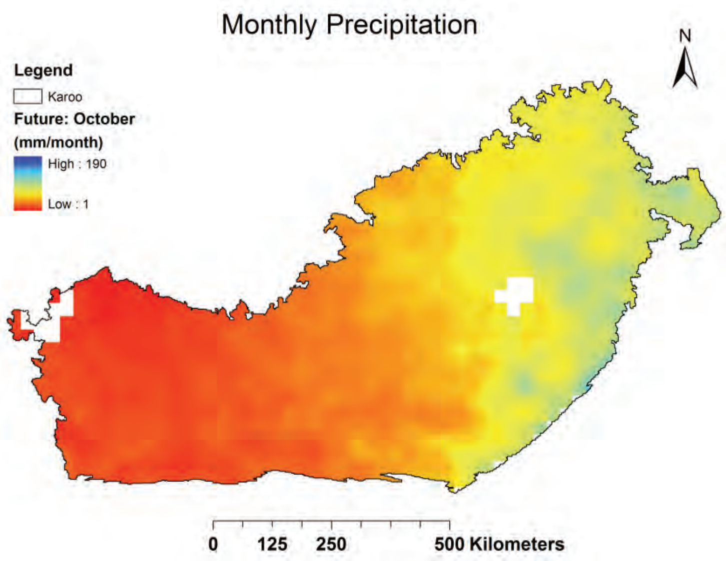

Monthly Precipitation
Legend
Karoo
Current: August
(mm/month)
High : 190
Low : 1
N
0
125
250
500 Kilometers

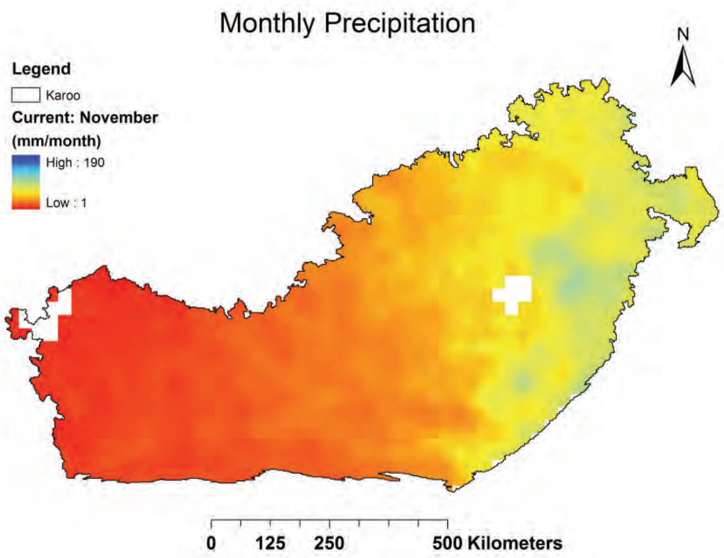

Monthly Precipitation
Legend
Karoo
Future: August
(mm/month)
High : 190
Low : 1
N
0
125
250
500 Kilometers

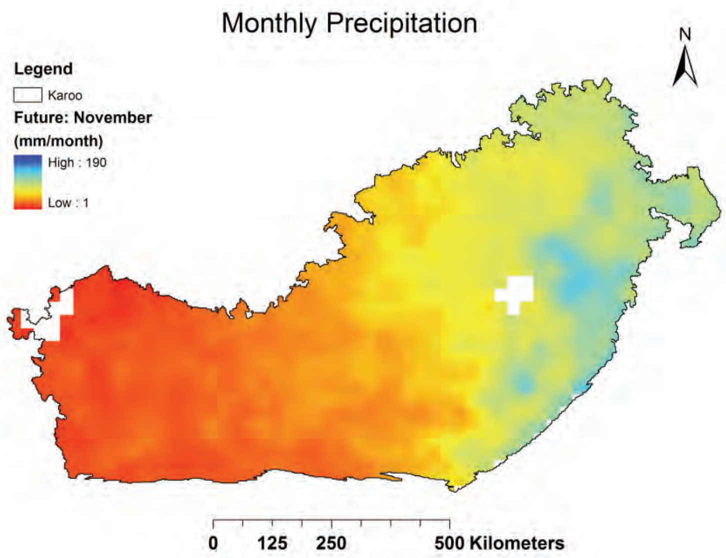

Monthly Precipitation
Legend
Karoo
Current: September
(mm/month)
High : 190
Low : 1
N
0
125
250
500 Kilometers


Monthly Precipitation
Legend
Karoo
Future: September
(mm/month)
High : 190
Low : 1
N
0
125
250
500 Kilometers


Monthly Precipitation
Legend
Karoo
Current: October
(mm/month)
High : 190
Low : 1
N
0 125 250 500 Kilometers


Monthly Precipitation
Legend
Karoo
Future: October
(mm/month)
High : 190
Low : 1
N
0 125 250 500 Kilometers


Monthly Precipitation
Legend
Karoo
Current: November
(mm/month)
High : 190
Low : 1
N
0 125 250 500 Kilometers


Monthly Precipitation
Legend
Karoo
Future: November
(mm/month)
High : 190
Low : 1
N
0 125 250 500 Kilometers

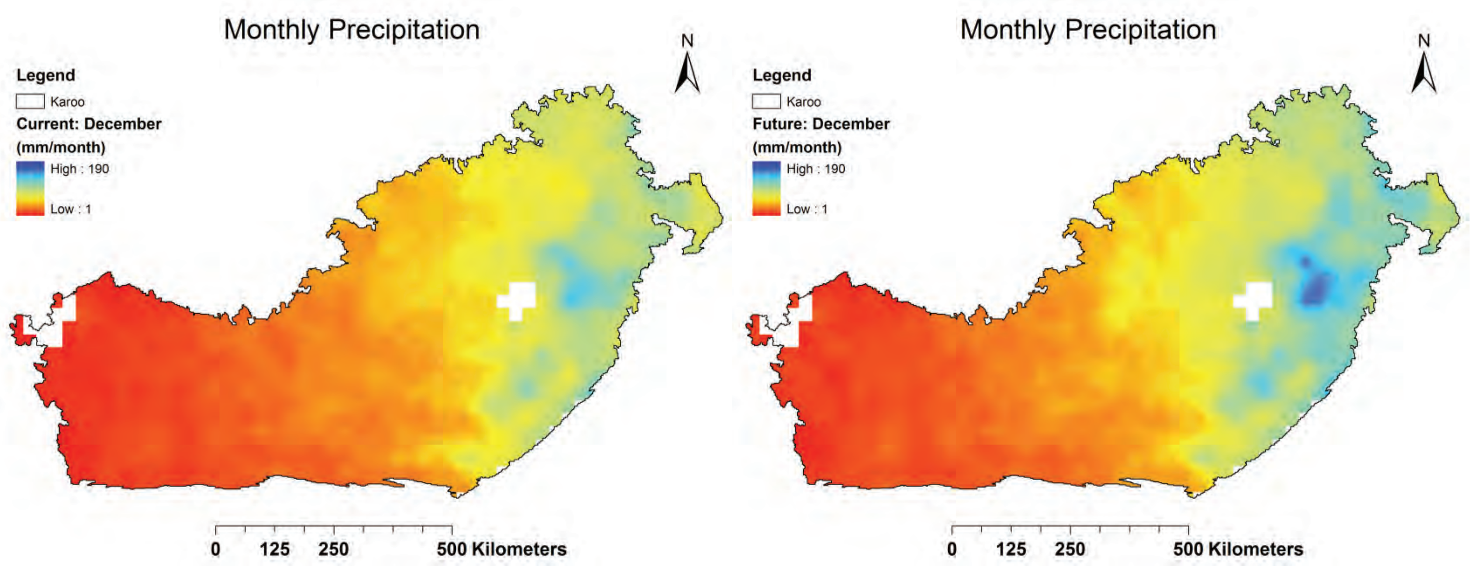


Figure 17: Precipitation comparison for current and future scenarios (MRI_CGCM2_3_2A)

4.2.4.2 Slope

The slope of the area also influences recharge in the sense that the higher the slope the more runoff will occur, leading to reduced recharge in these areas. A maximum slope of 28% is detected over the whole extent of South Africa if a topographical grid of 1 km × 1 km is used. Likewise, a maximum slope of 25% is detected over the Karoo Supergroup, as shown in Figure 18.

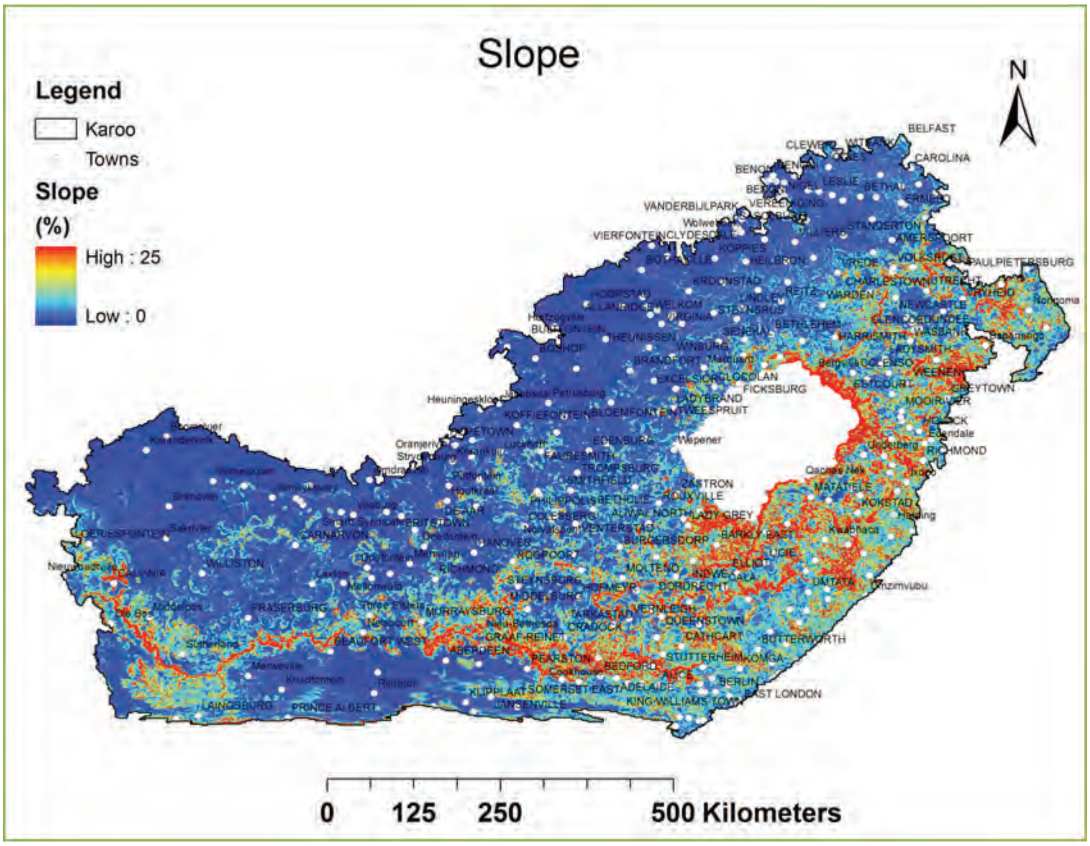


Figure 18: Slope distribution over the Karoo

A maximum slope of 30% was chosen as an absolute maximum and the following exponential relationship was defined as the percentage the recharge must be scaled according to slope:

$$Scaling(\%) = 100 - 0.25e^{0.2 \cdot Slope}$$

The graphical representation of the aforementioned equation is shown in Figure 19.

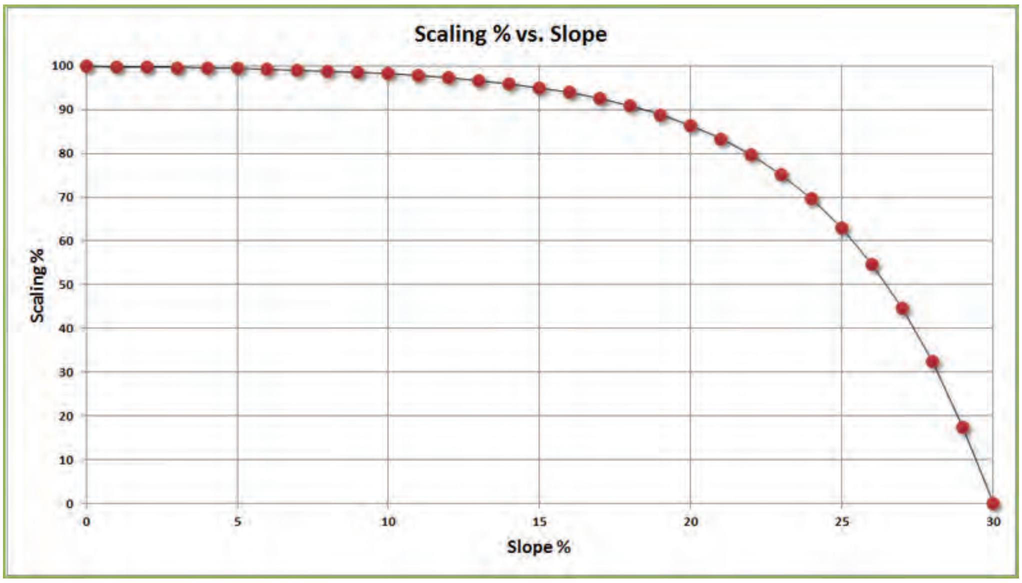


Figure 19: Recharge scaling factor based on slope (%)

4.2.4.3 Recharge Model

The recharge model implemented is based on the relationship between precipitation and recharge (Figure 9) and slope dependence (Figure 19). The recharge model formulation and output space is shown in Figure 20.

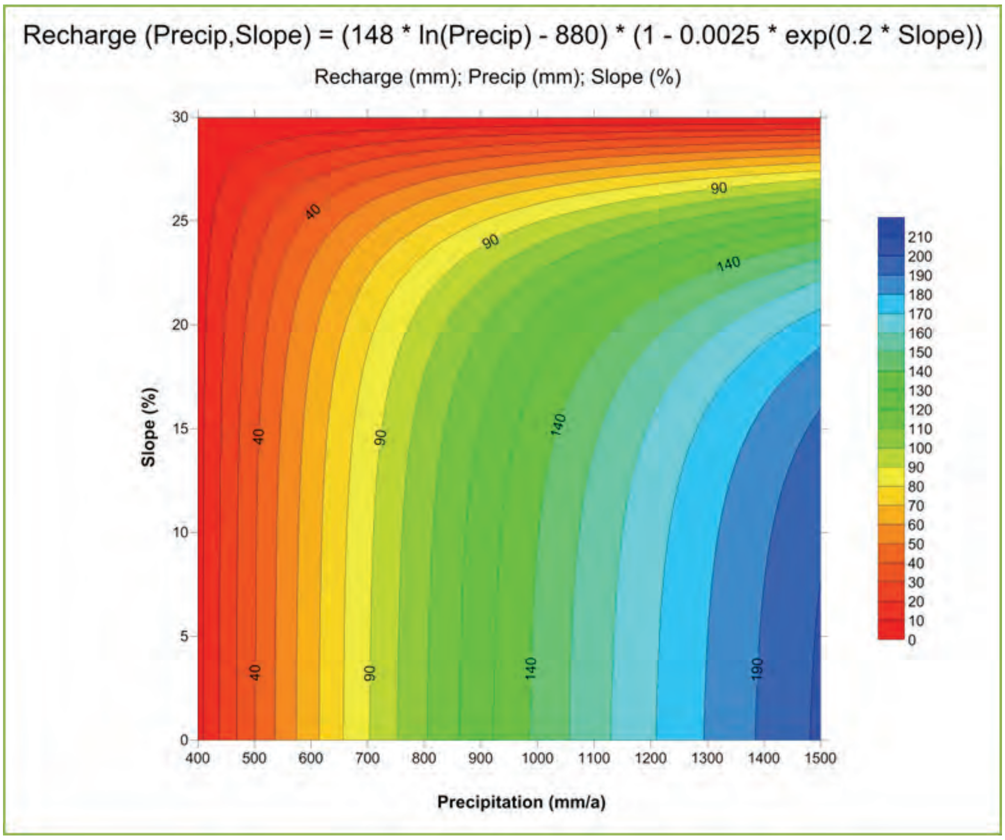


Figure 20: Recharge model annual output space

The current and future annual recharge distribution based on the model output is shown in Figure 21 and Figure 22, respectively.

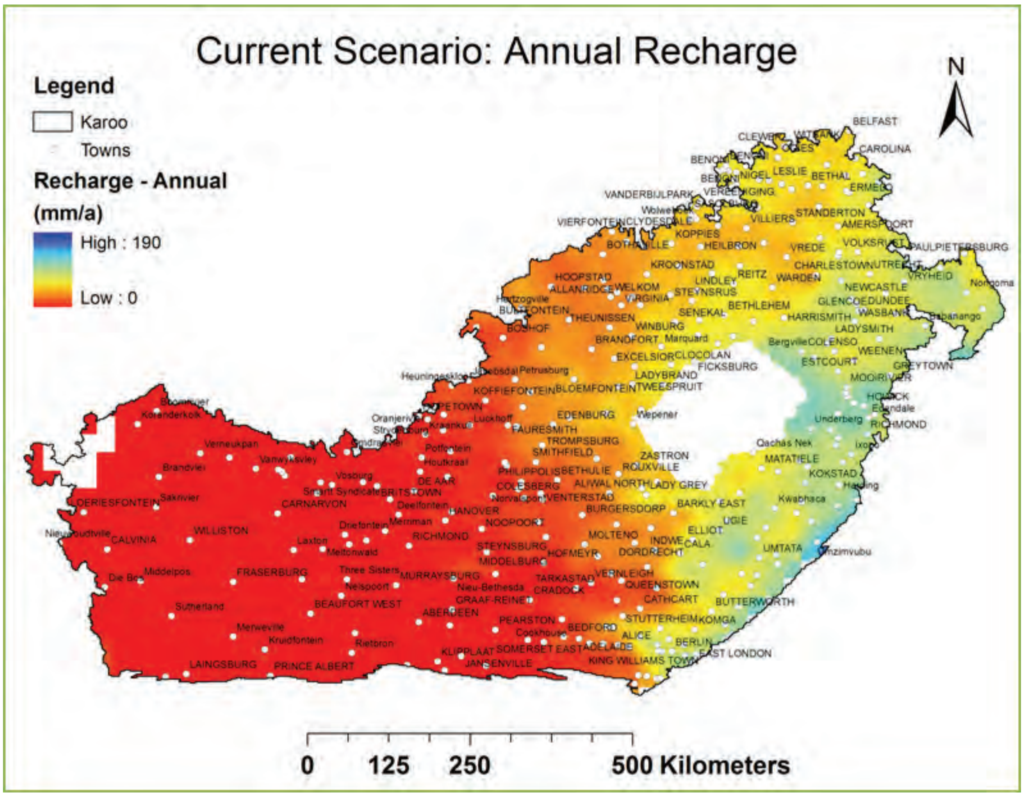


Figure 21: Current annual recharge

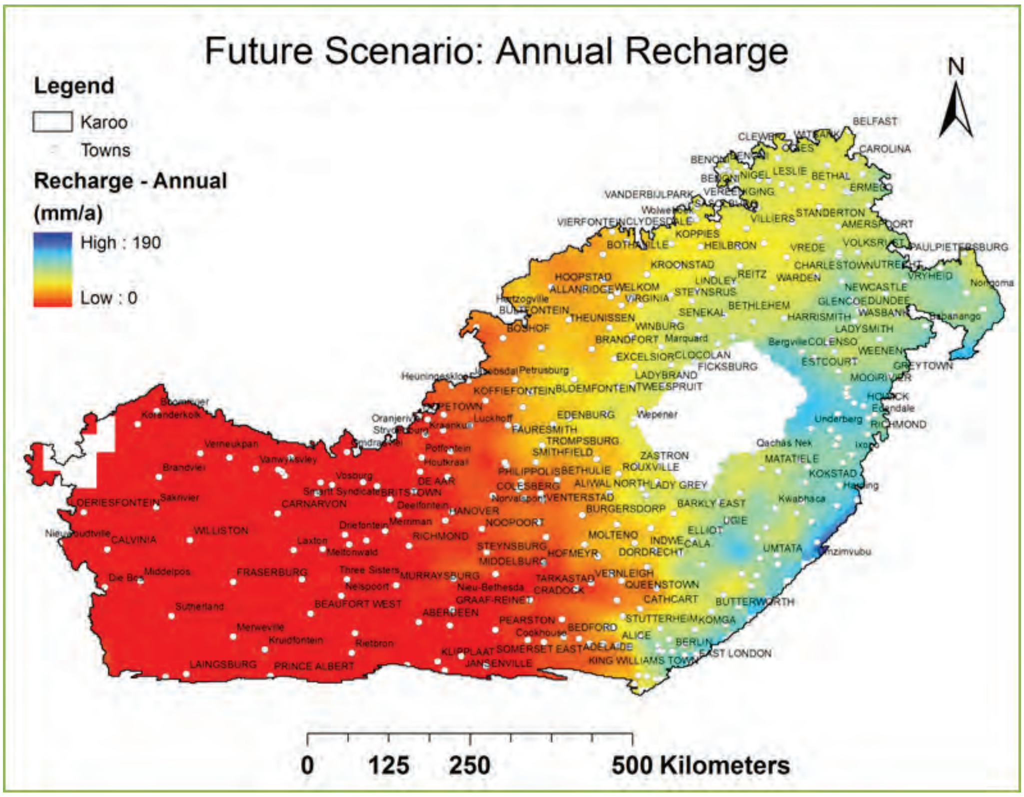


Figure 22: Future annual recharge

The change in recharge between the current and the future scenarios is shown in Figure 23.

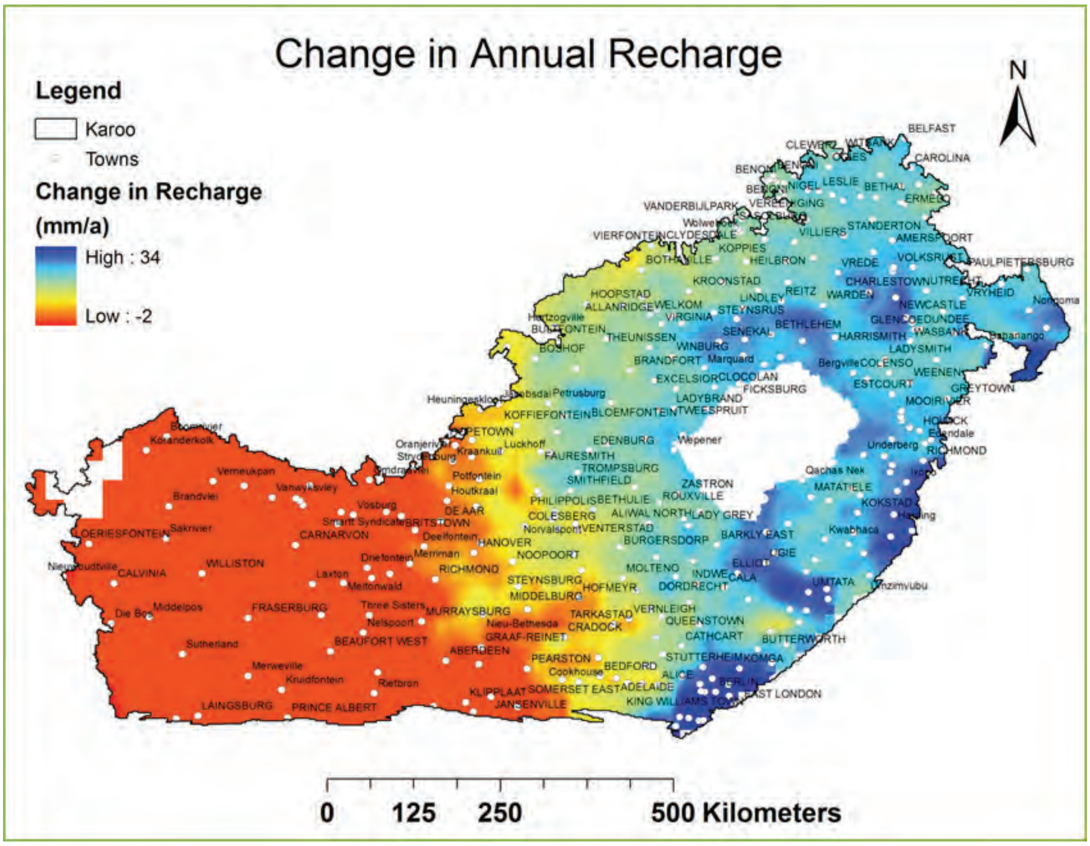
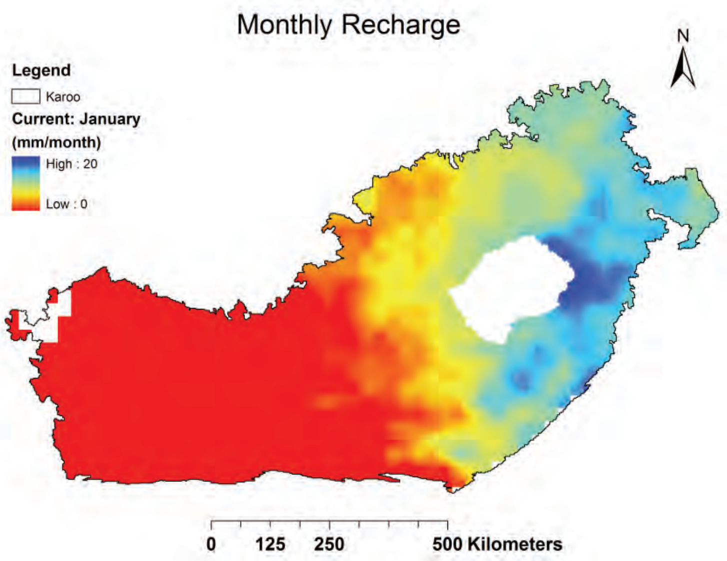
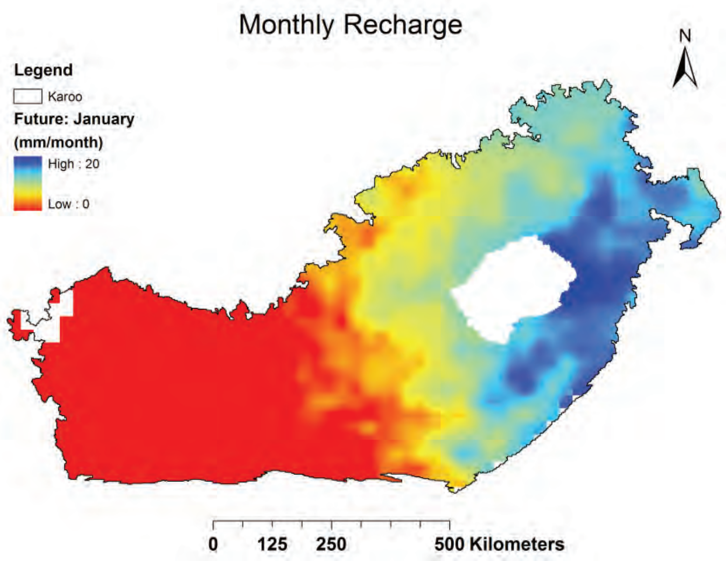
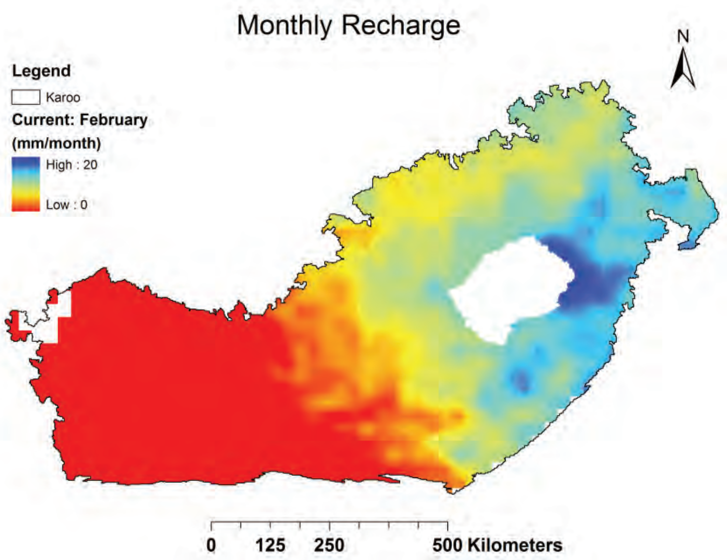


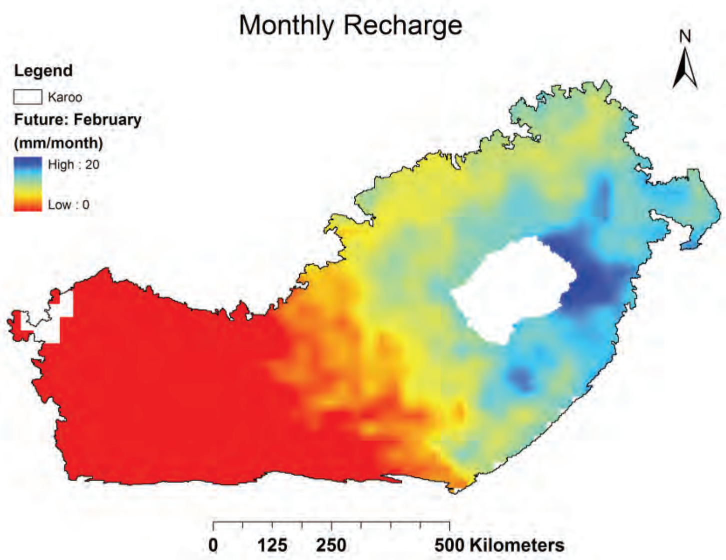
Figure 23: Change in precipitation between current and future scenarios

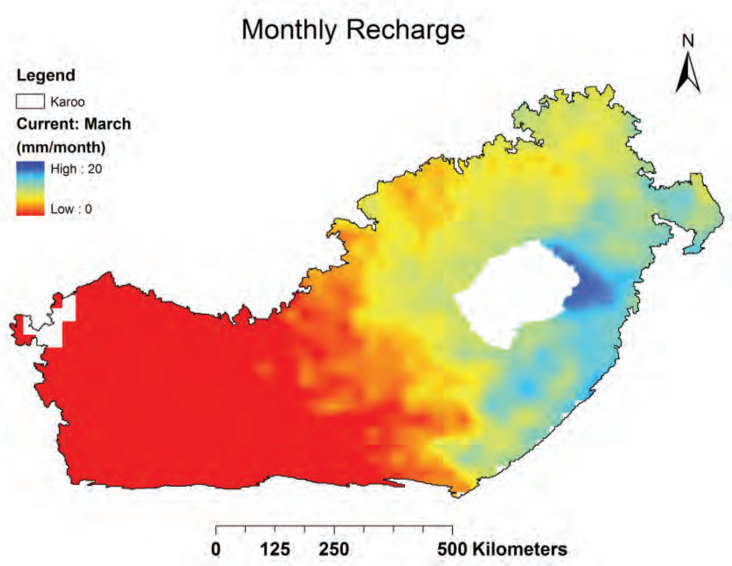
The monthly recharge figures for both the current and future scenarios are shown in Figure 24 for comparison purposes. These variations in recharge are important as they drive the changes in water level between the scenarios.

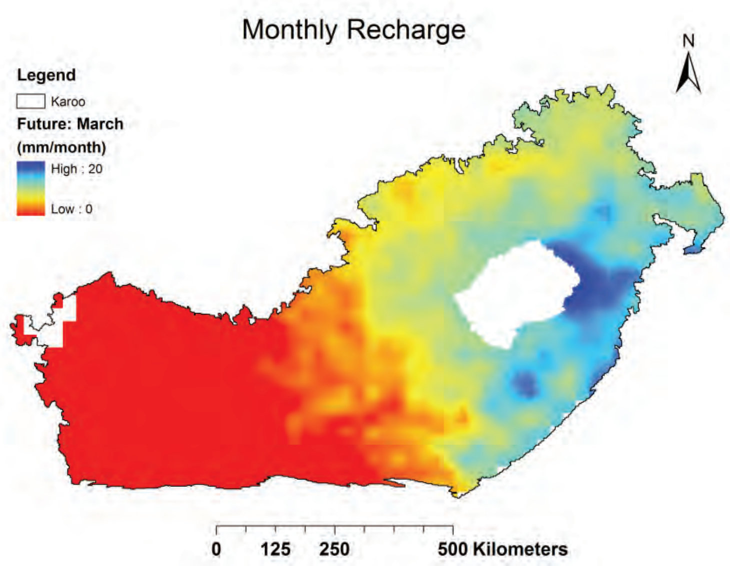

Monthly Recharge
N
Legend
Karoo
Current: January
(mm/month)
High : 20
Low : 0
0 125 250 500 Kilometers

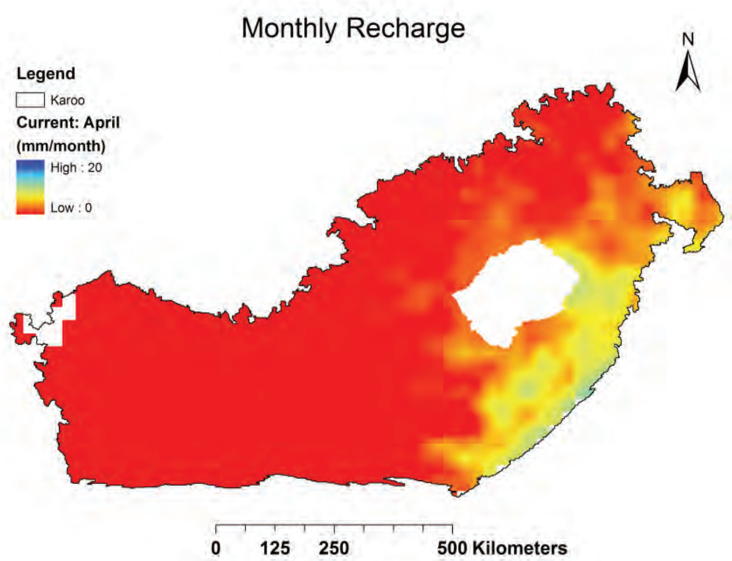

Monthly Recharge
N
Legend
Karoo
Future: January
(mm/month)
High : 20
Low : 0
0 125 250 500 Kilometers

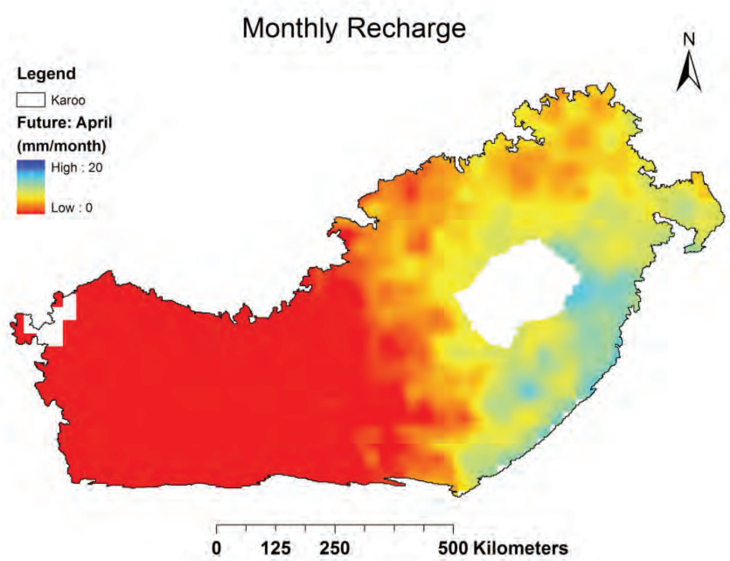

Monthly Recharge
N
Legend
Karoo
Current: February
(mm/month)
High : 20
Low : 0
0 125 250 500 Kilometers

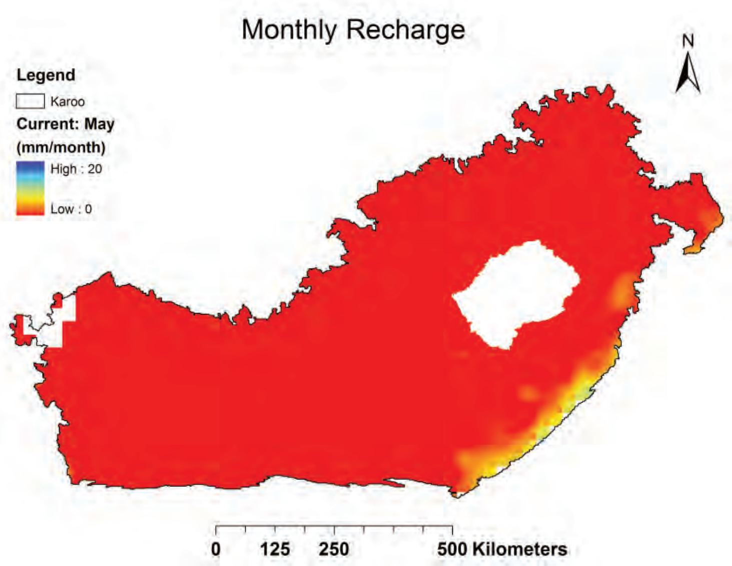

Monthly Recharge
N
Legend
Karoo
Future: February
(mm/month)
High : 20
Low : 0
0 125 250 500 Kilometers

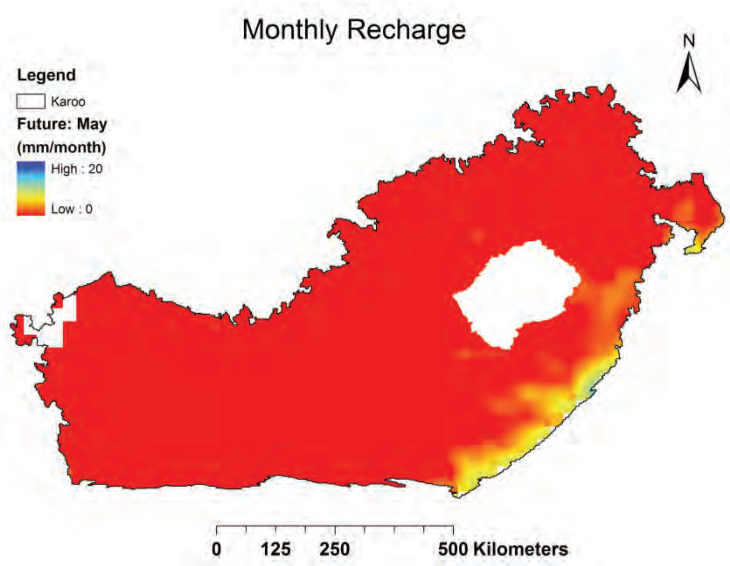

Monthly Recharge
Legend
Karoo
Current: March
(mm/month)
High : 20
Low : 0
N
0
125
250
500 Kilometers

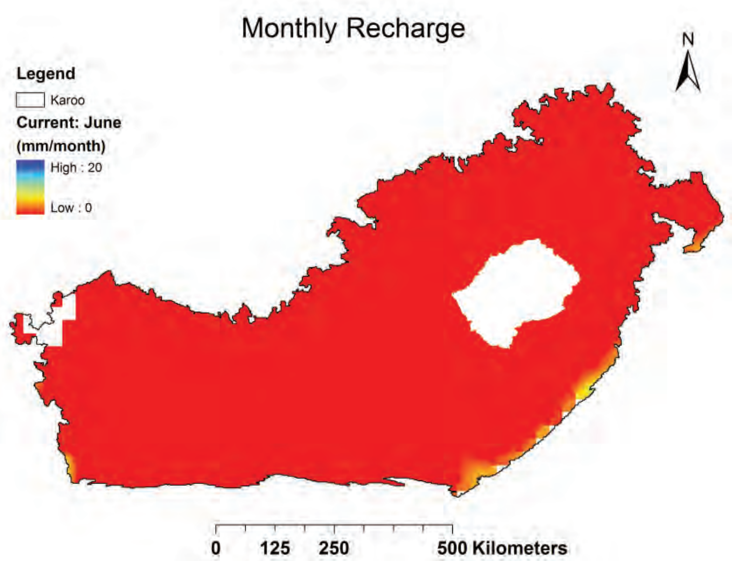

Monthly Recharge
Legend
Karoo
Future: March
(mm/month)
High : 20
Low : 0
N
0
125
250
500 Kilometers

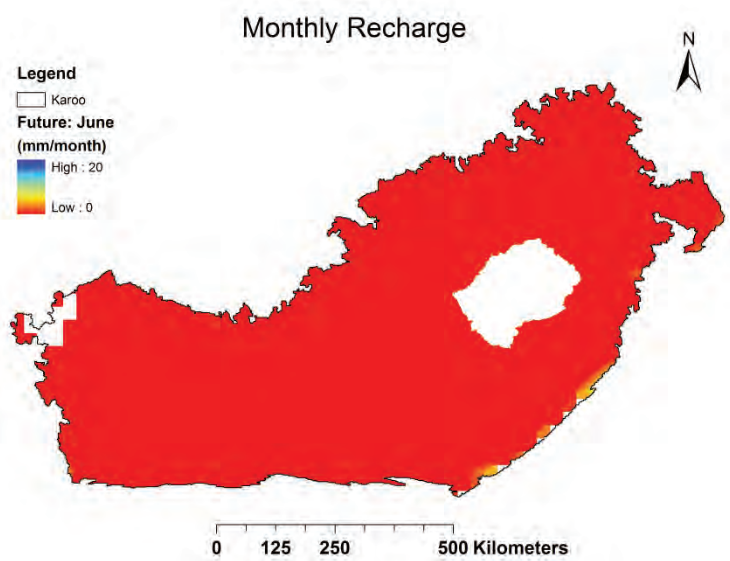

Monthly Recharge
Legend
Karoo
Current: April
(mm/month)
High : 20
Low : 0
N
0
125
250
500 Kilometers

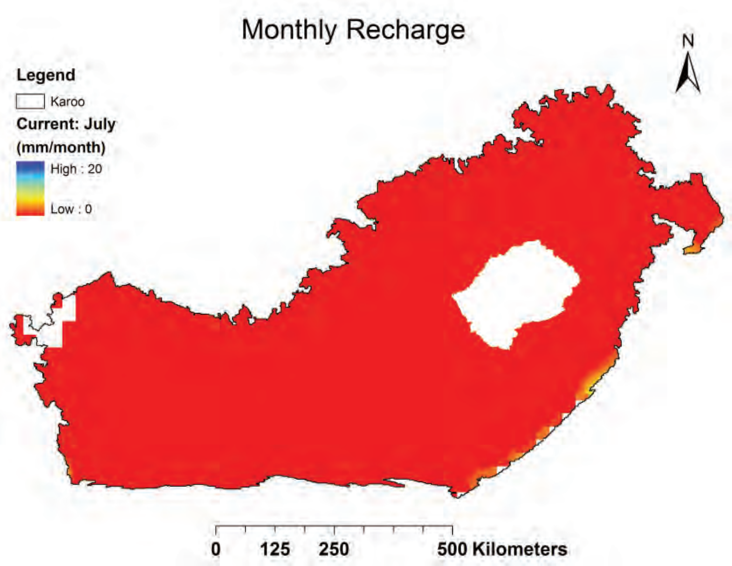

Monthly Recharge
Legend
Karoo
Future: April
(mm/month)
High : 20
Low : 0
N
0
125
250
500 Kilometers

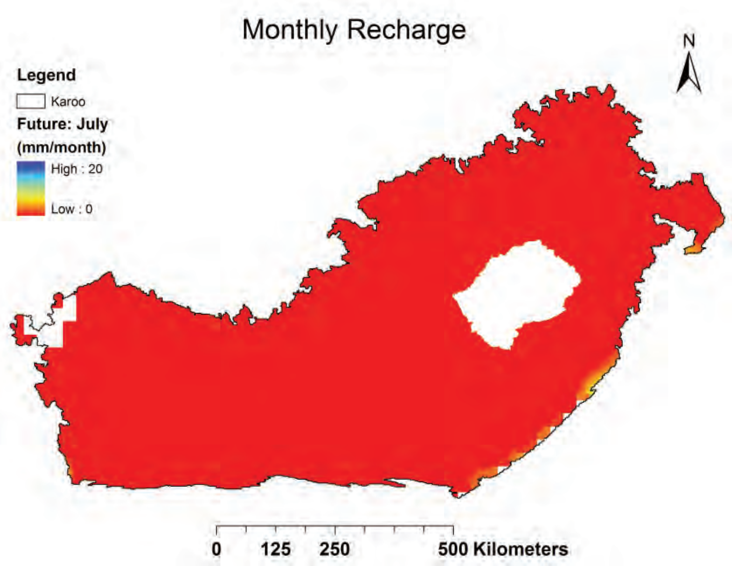

Monthly Recharge
Legend
Karoo
Current: May
(mm/month)
High : 20
Low : 0
N
0
125
250
500 Kilometers

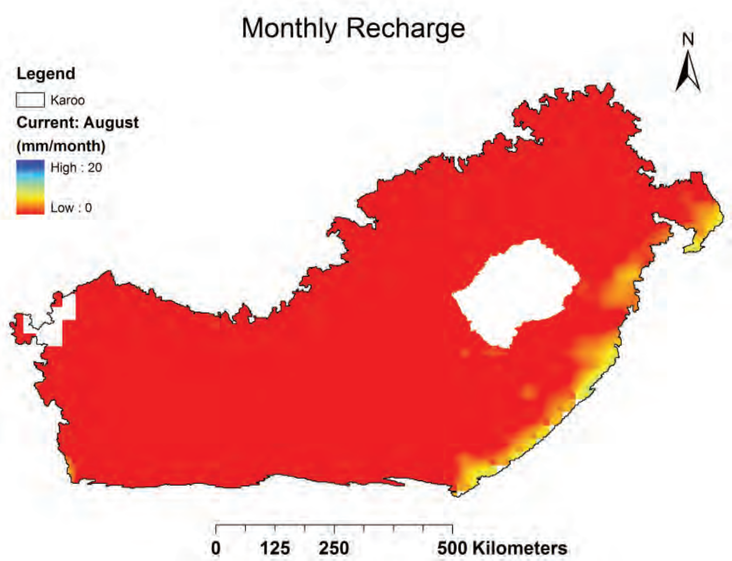

Monthly Recharge
Legend
Karoo
Future: May
(mm/month)
High : 20
Low : 0
N
0
125
250
500 Kilometers

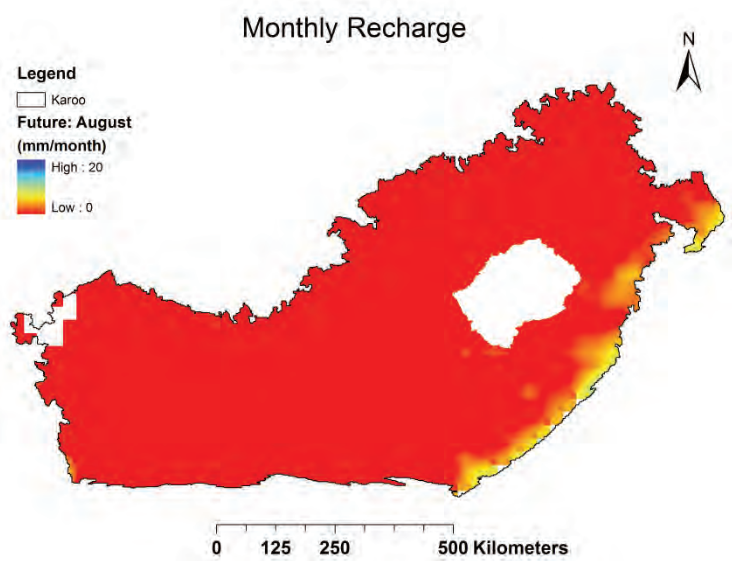

Monthly Recharge
Legend
Karoo
Current: June
(mm/month)
High : 20
Low : 0
N
0
125
250
500 Kilometers

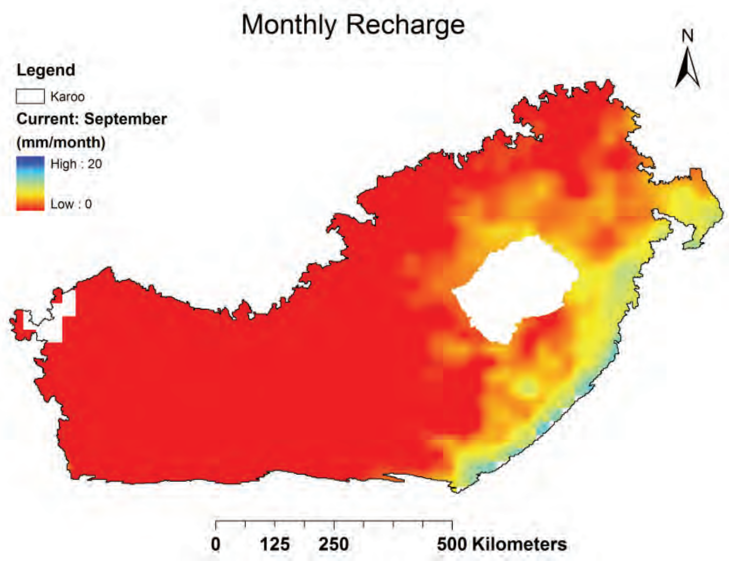

Monthly Recharge
Legend
Karoo
Future: June
(mm/month)
High : 20
Low : 0
N
0
125
250
500 Kilometers

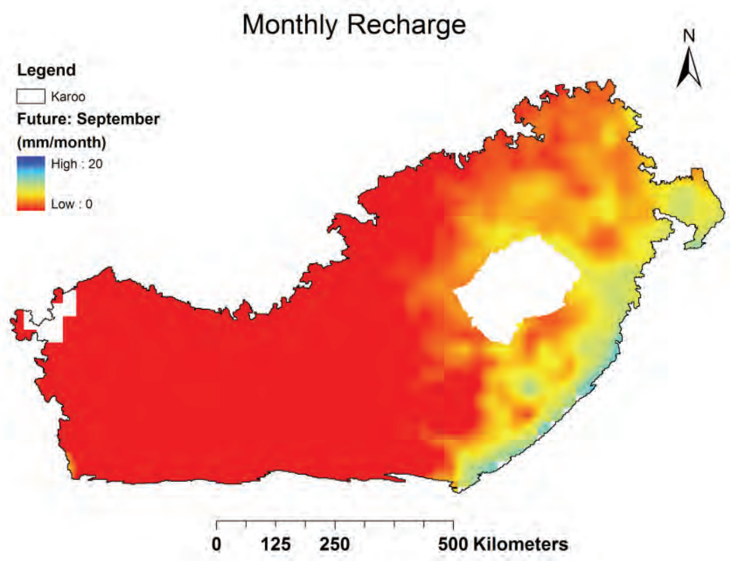

Monthly Recharge
Legend
Karoo
Current: July
(mm/month)
High : 20
Low : 0
N
0
125
250
500 Kilometers

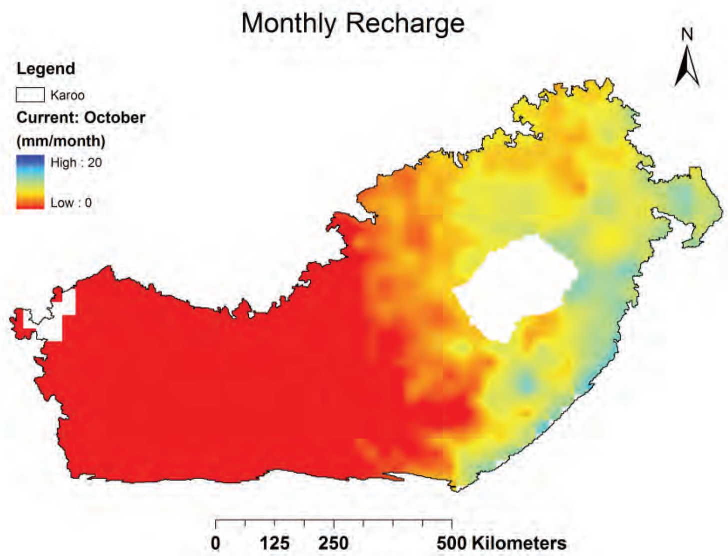

Monthly Recharge
Legend
Karoo
Future: July
(mm/month)
High : 20
Low : 0
N
0
125
250
500 Kilometers

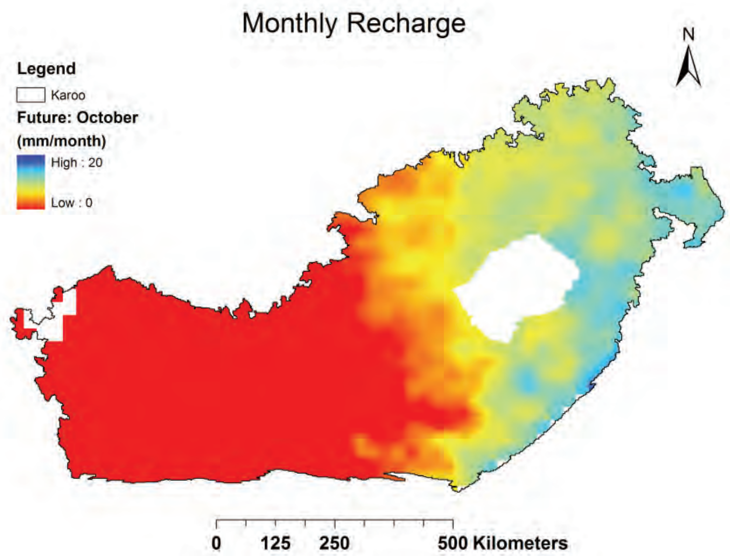

Monthly Recharge
Legend
Karoo
Current: August
(mm/month)
High : 20
Low : 0
N
0
125
250
500 Kilometers


Monthly Recharge
Legend
Karoo
Future: August
(mm/month)
High : 20
Low : 0
N
0
125
250
500 Kilometers


Monthly Recharge
Legend
Karoo
Current: September
(mm/month)
High : 20
Low : 0
N
0 125 250 500 Kilometers


Monthly Recharge
Legend
Karoo
Future: September
(mm/month)
High : 20
Low : 0
N
0 125 250 500 Kilometers


Monthly Recharge
Legend
Karoo
Current: October
(mm/month)
High : 20
Low : 0
N
0 125 250 500 Kilometers


Monthly Recharge
Legend
Karoo
Future: October
(mm/month)
High : 20
Low : 0
N
0 125 250 500 Kilometers

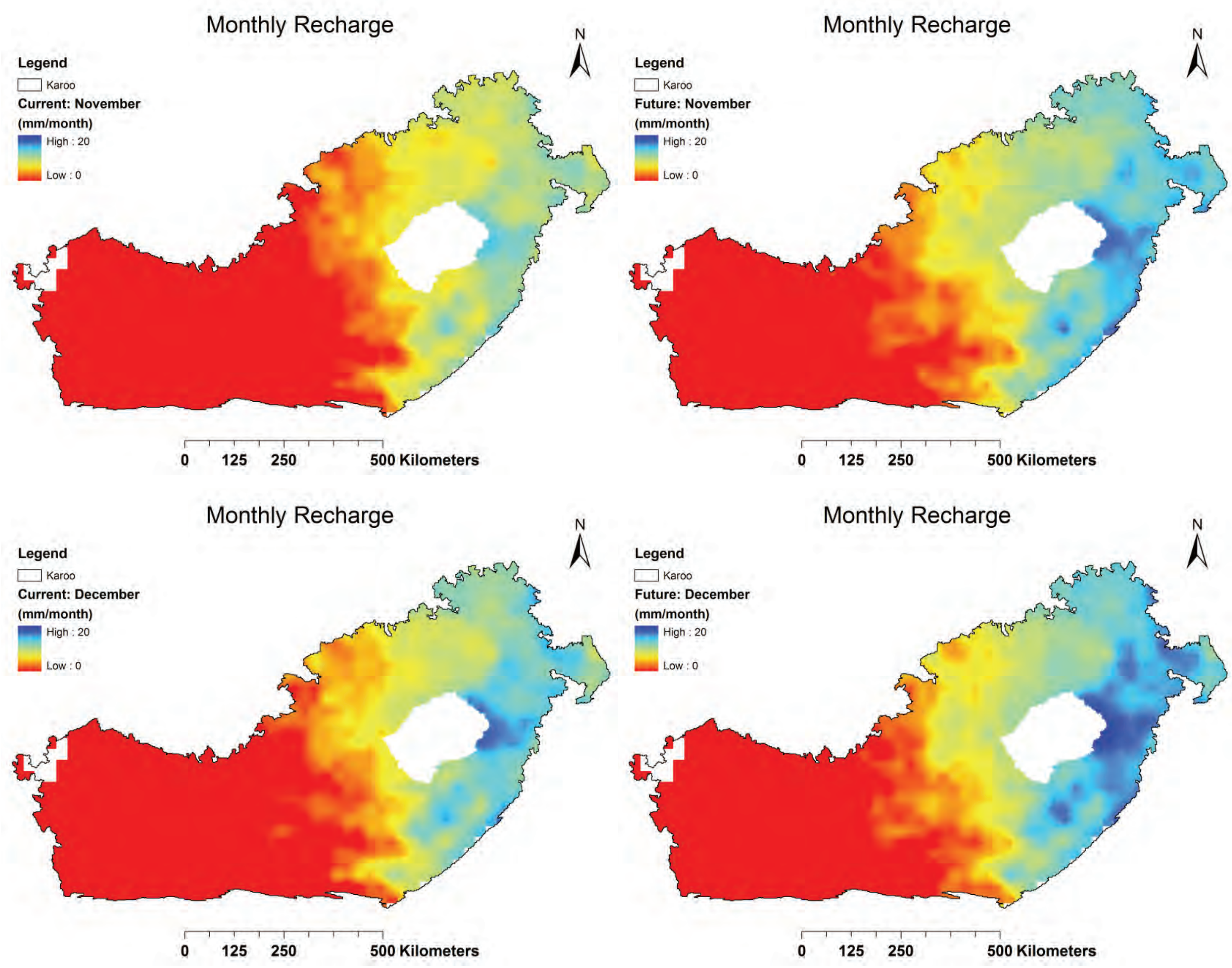


Figure 24: Current and predicted recharge trends (MRI_CGCM2_3_2A)

4.2.5 *Transmissivity*

A transmissivity map was also produced, using the geohydrological maps of South Africa and translating the yield values to transmissivity values using a factor of 5. This led to transmissivities in the range of 0.25 to 25 m^2/d. The resultant map is shown in Figure 25. Note that higher transmissivities can occur due to the fractured nature of the Karoo formations.

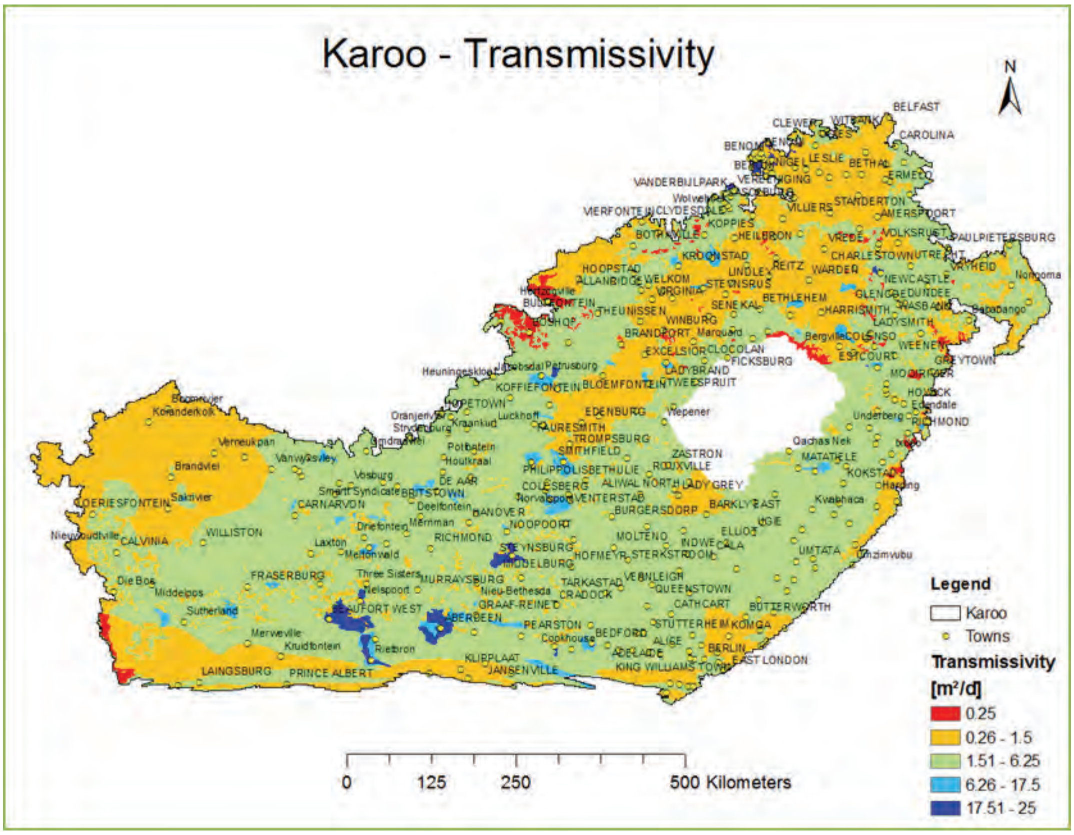


Figure 25: Karoo transmissivity map

Index Calculation Table 2 shows the resulting ranges, classification and associated weights to calculate the DART index with a maximum score of 10. Higher values will represent more resilience to climate change impacts driven by the change in rainfall.

Table 2: DART index calculation

Depth to Water Level Change (mbgl)		Aquifer Type (storativity)		Recharge (mm)		Transmissivity (m^2/d)	
65%		15%		15%		5%	
Range	Rating	Range	Rating	Range	Rating	Range	Rating
−5-0	0-10	0-0.1	0-10	0-10	0-10	0-25	0-10
*Rating = (2*Range) + 10*		*Rating = 100*Range*		*Rating = Range*		*Rating = 0.4*Range*	

A conservative change in water level of 5 m was selected as being the maximum tolerable change in any water level that will be allowed for the future scenario. A favourable recharge figure of 10 mm/month was selected based on the results shown in Figure 9 and Figure 26.

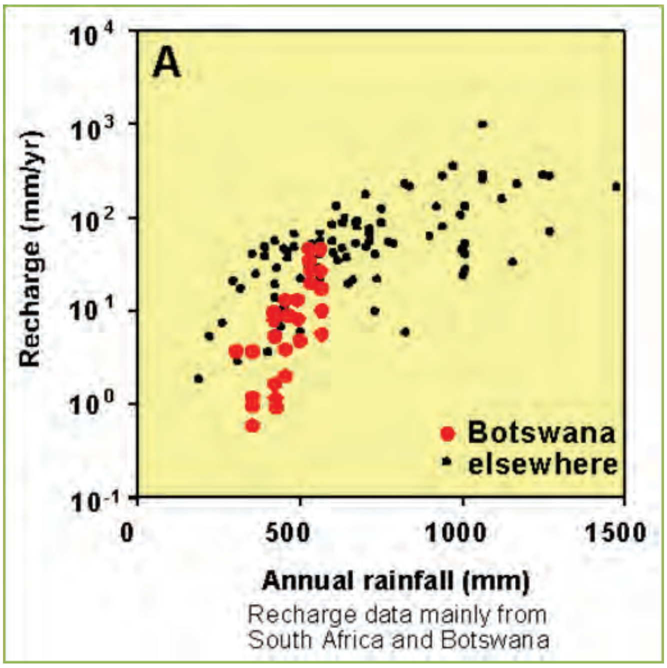


Figure 26: Rainfall vs. recharge in South Africa and Botswana

5 *Results of Assessment*

Both the average current and future DART indices are shown in Figure 27 and Figure 28, respectively. The monthly comparison of the DART indices is shown in Figure 29. It is assumed that the average water level fluctuation for the current scenario is negligible.

At first glance, there is not a significant difference between the current and future average indices, which indicates that the change in climate does not alter the average water level (i.e. the recharge) that much. There seems to be very little difference between the indices of the dry months due to the fact that the recharge model shows very little recharge over similar months. This is a worst-case scenario, as episodic recharge events will take place and, if the recharge is significant, this will result in a better index value than currently portrayed.

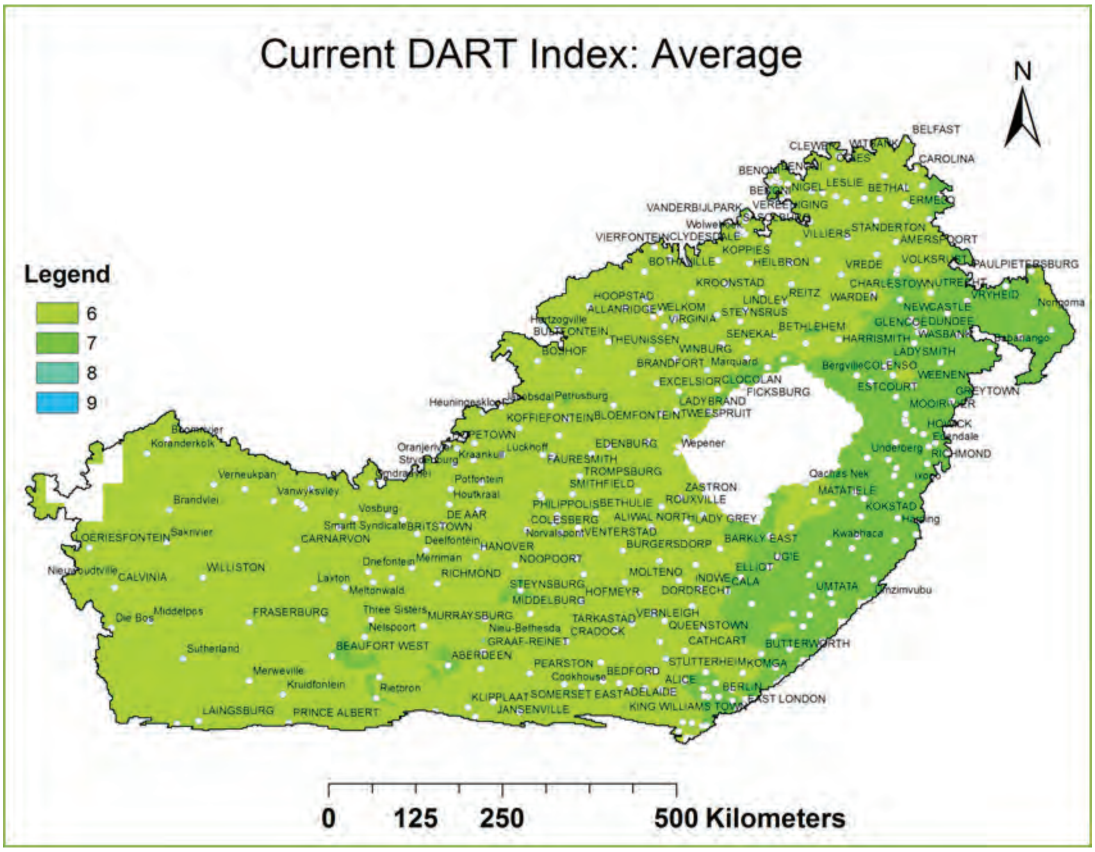


Figure 27: Current average DART index

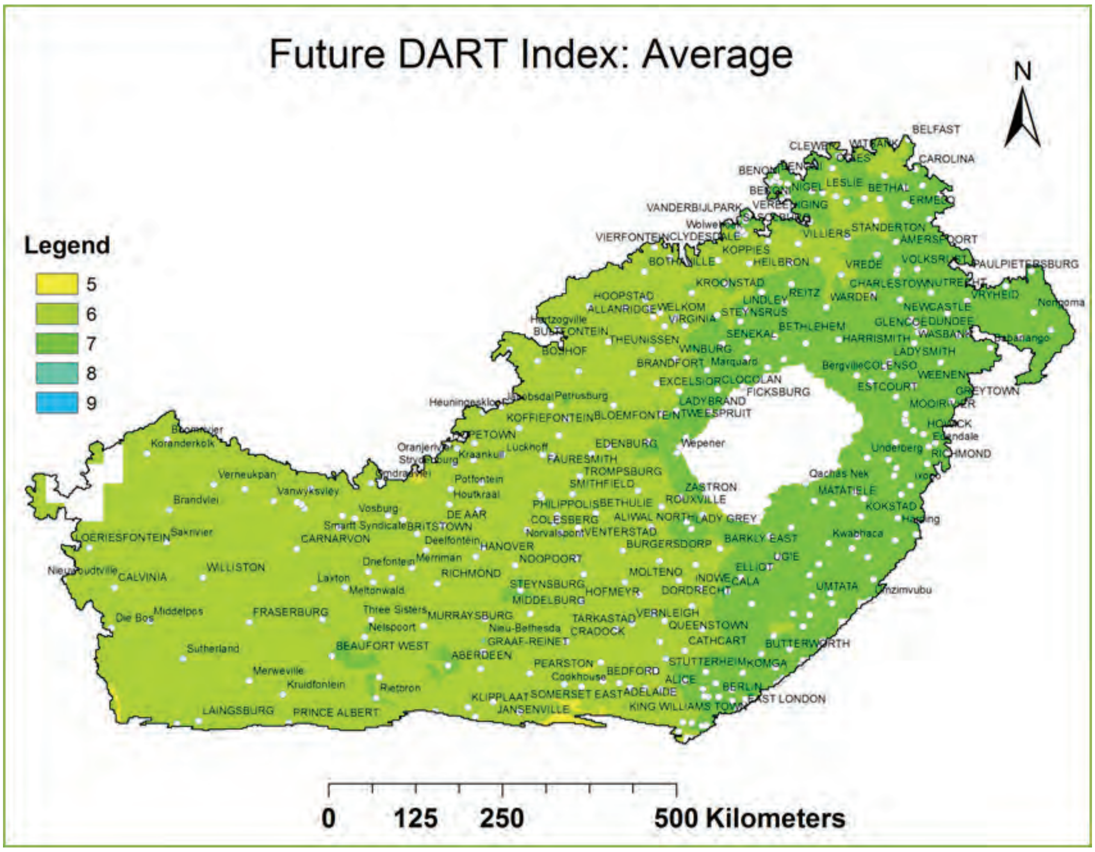
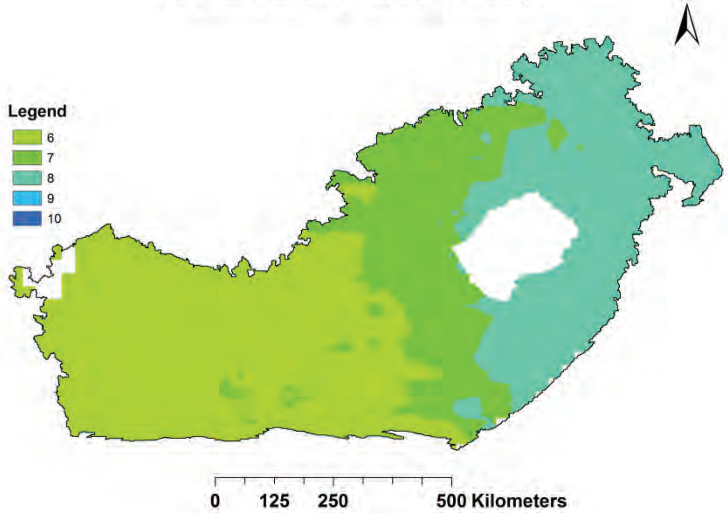
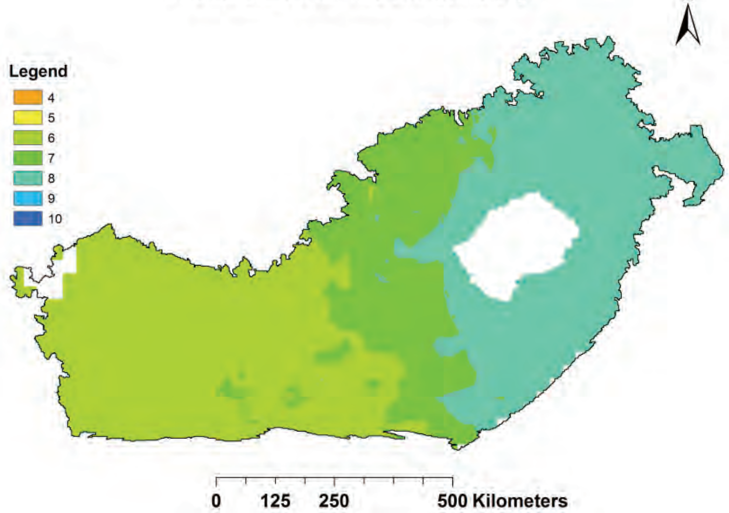


Figure 28: Future average DART index

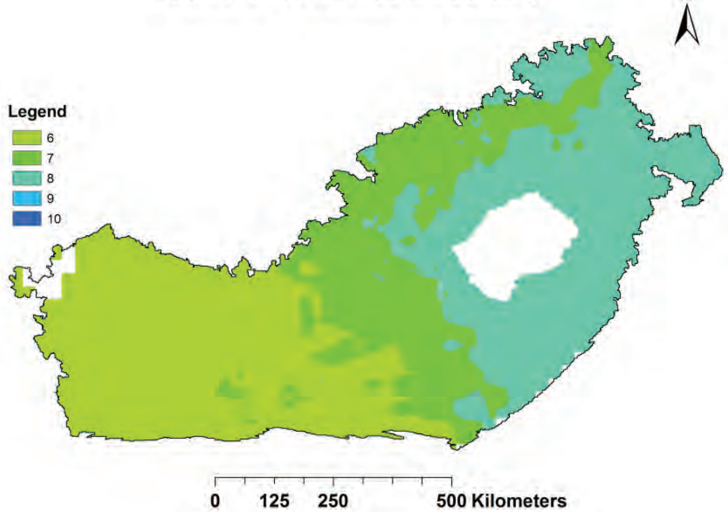
Current DART Index: January



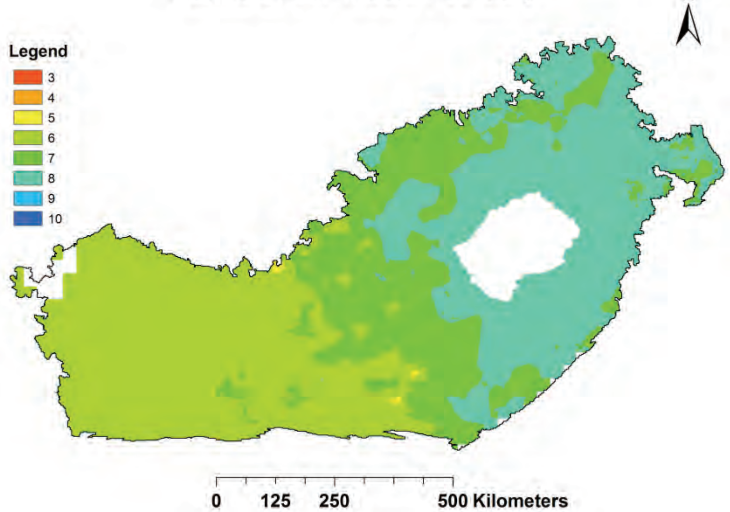
Future DART Index: January

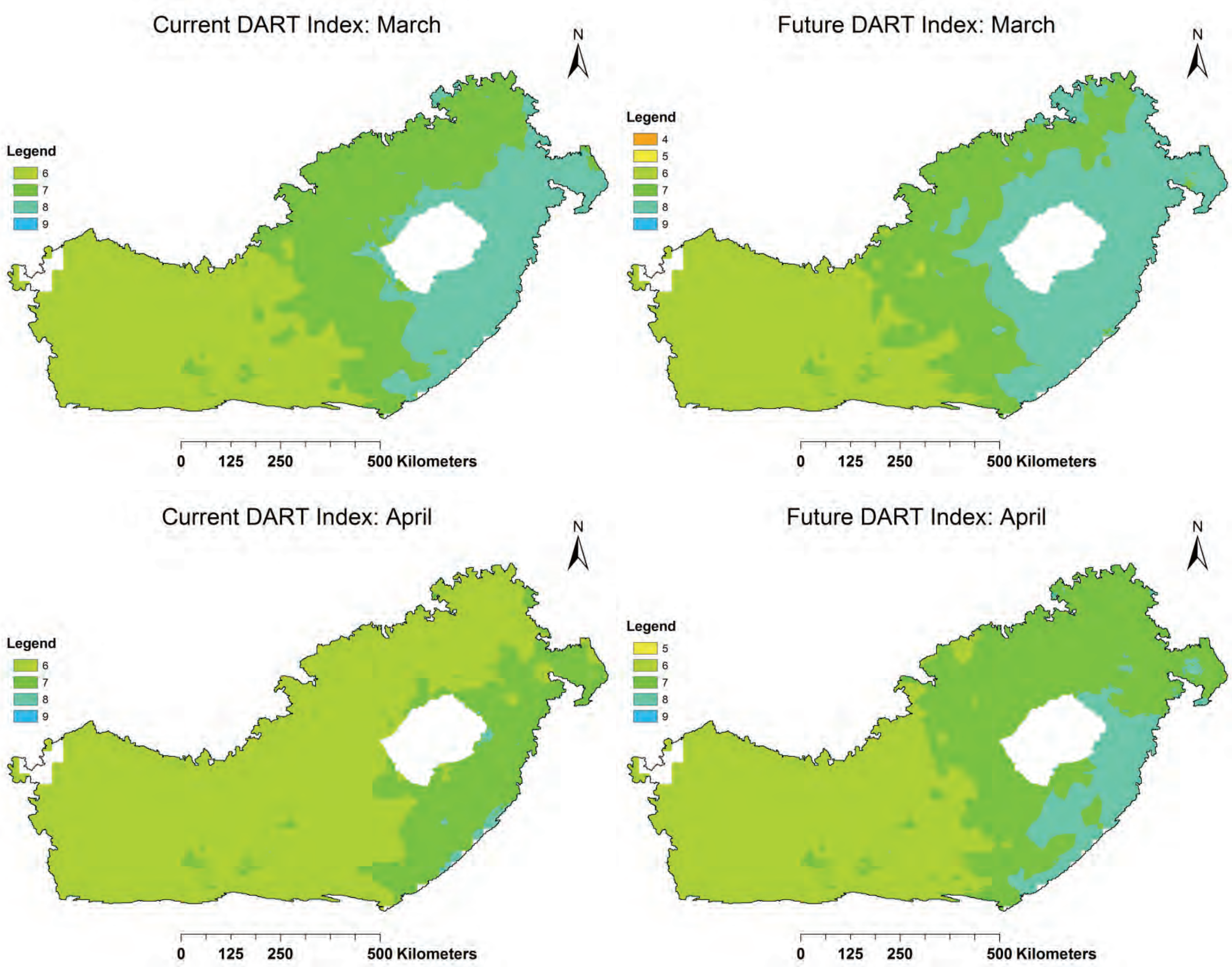


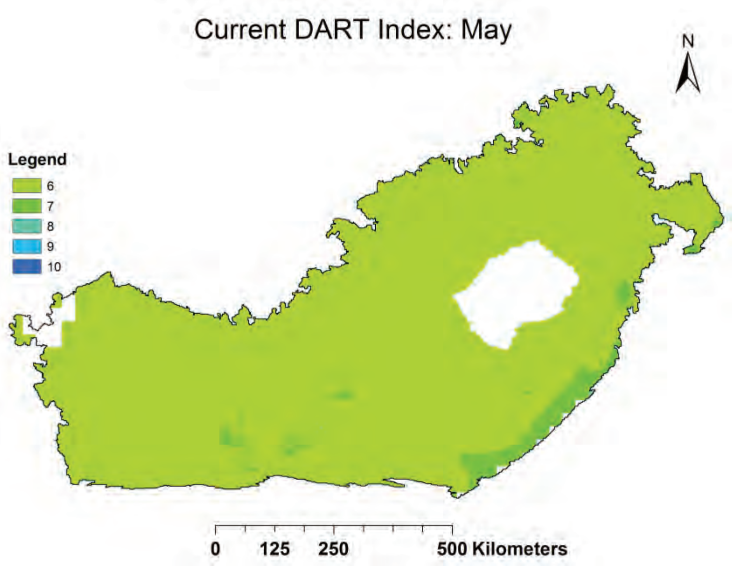
Current DART Index: February

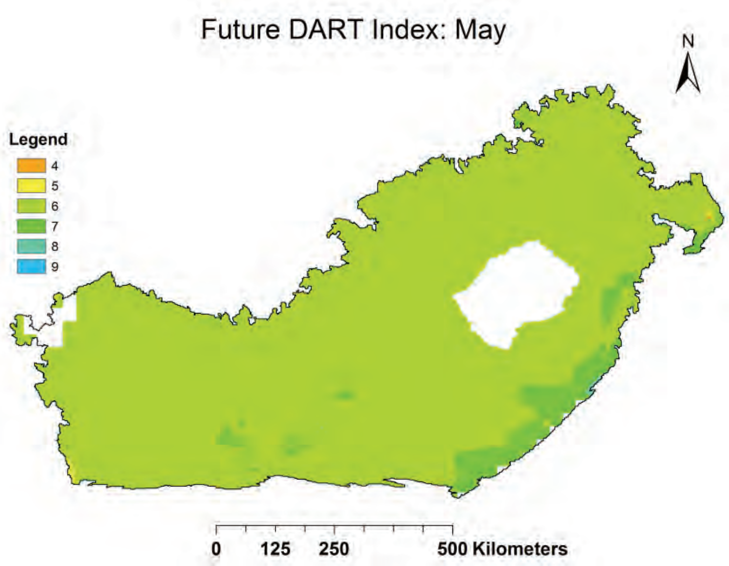


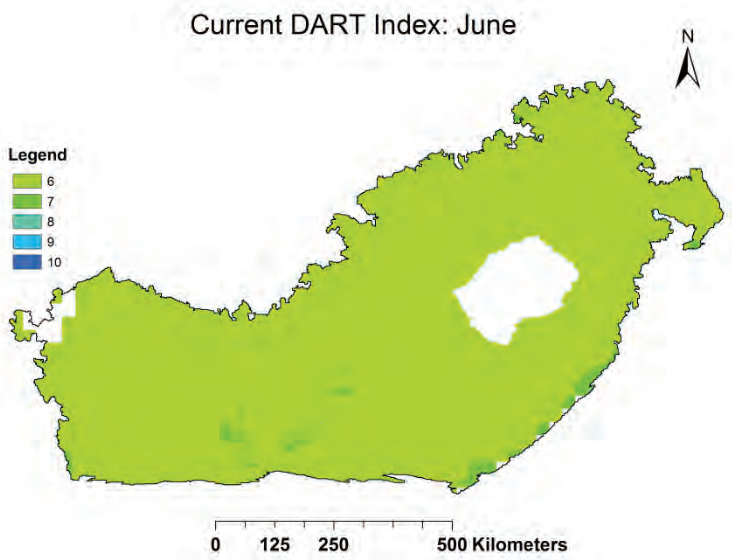
Future DART Index: February

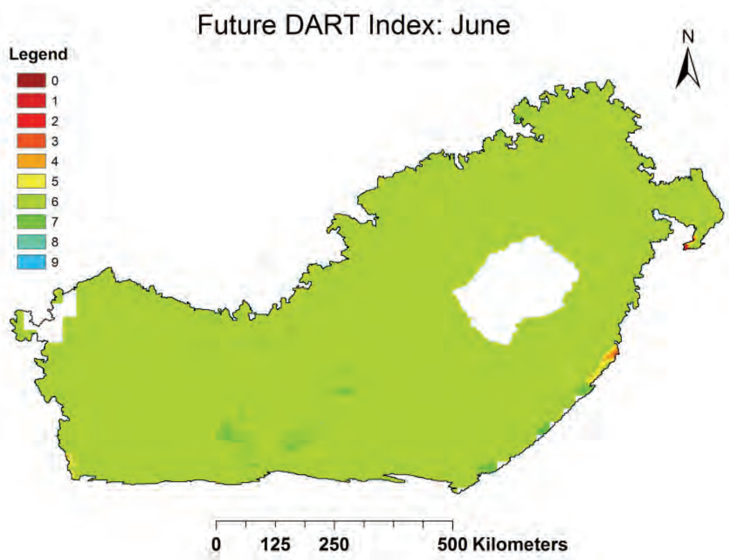


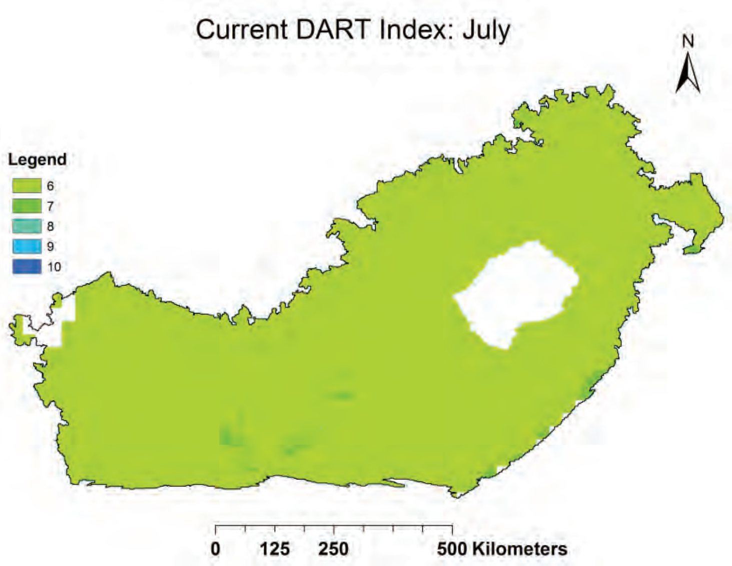

Current DART Index: March
Legend
6
7
8
9
N
0 125 250 500 Kilometers
Future DART Index: March
Legend
4
5
6
7
8
9
N
0 125 250 500 Kilometers
Current DART Index: April
Legend
6
7
8
9
N
0 125 250 500 Kilometers
Future DART Index: April
Legend
5
6
7
8
9
N
0 125 250 500 Kilometers

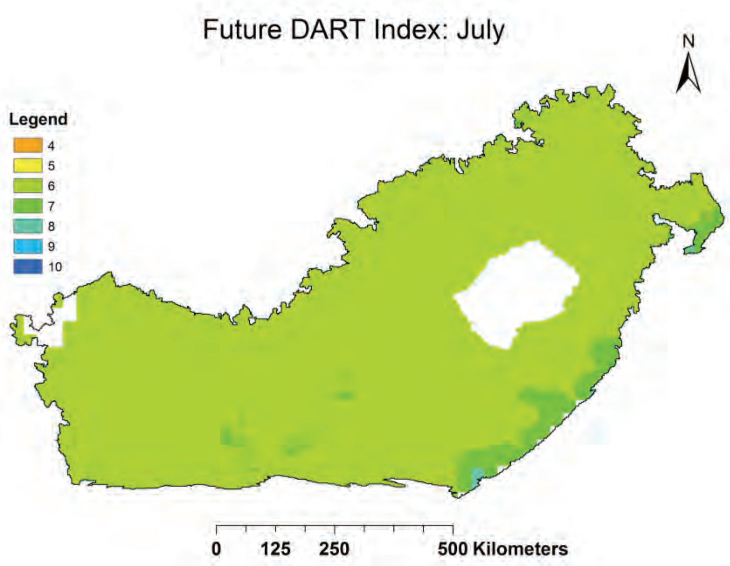

Current DART Index: May
N
Legend
6
7
8
9
10
0
125
250
500 Kilometers

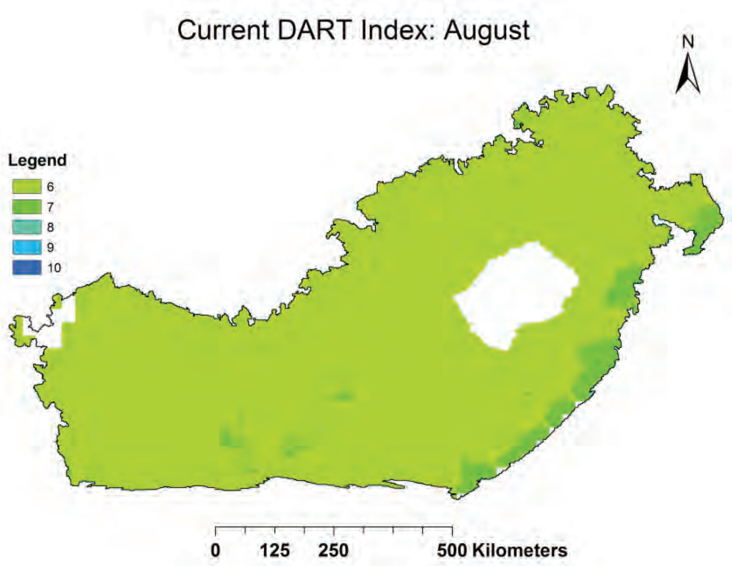

Future DART Index: May
N
Legend
4
5
6
7
8
9
0
125
250
500 Kilometers

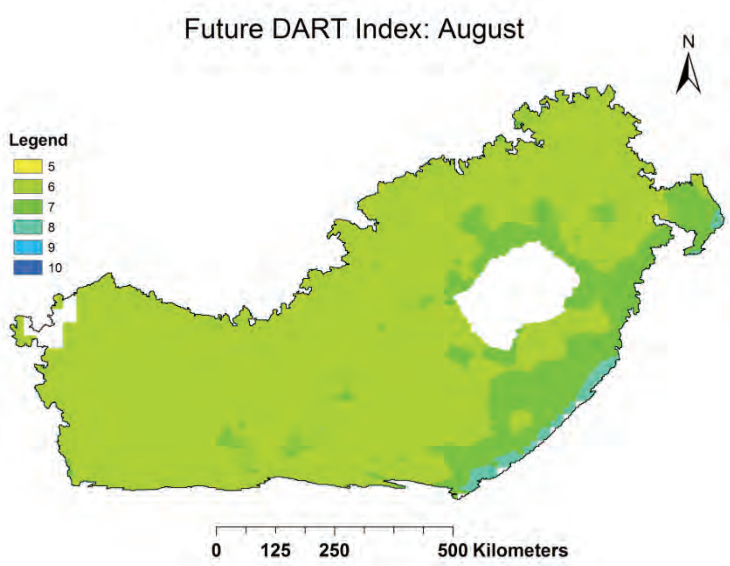

Current DART Index: June
N
Legend
6
7
8
9
10
0
125
250
500 Kilometers

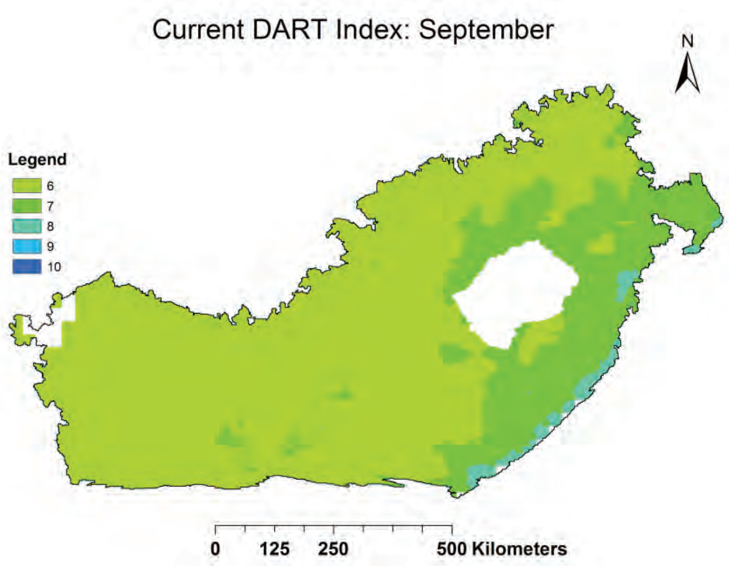

Future DART Index: June
N
Legend
0
1
2
3
4
5
6
7
8
9
0
125
250
500 Kilometers

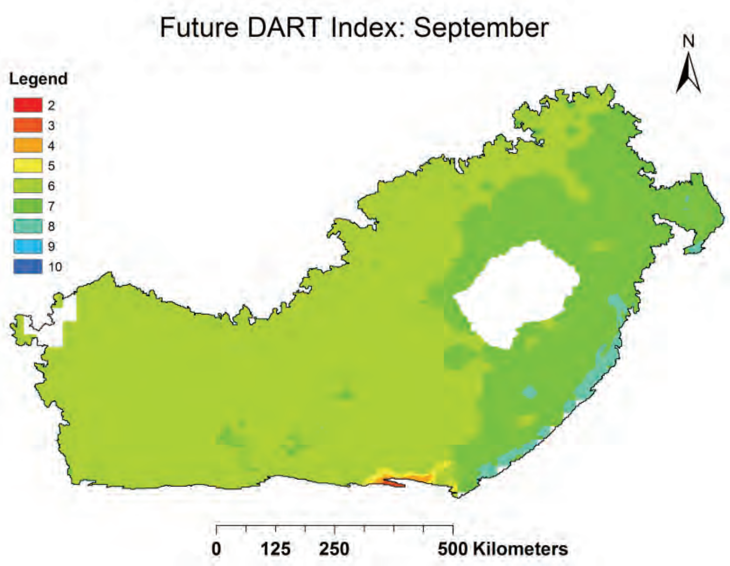

Current DART Index: July
N
Legend
6
7
8
9
10
0
125
250
500 Kilometers

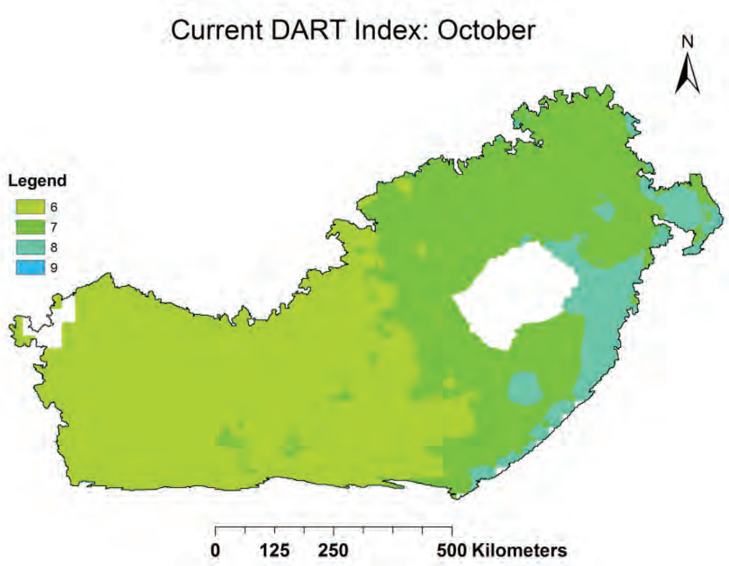

Future DART Index: July
N
Legend
4
5
6
7
8
9
10
0
125
250
500 Kilometers

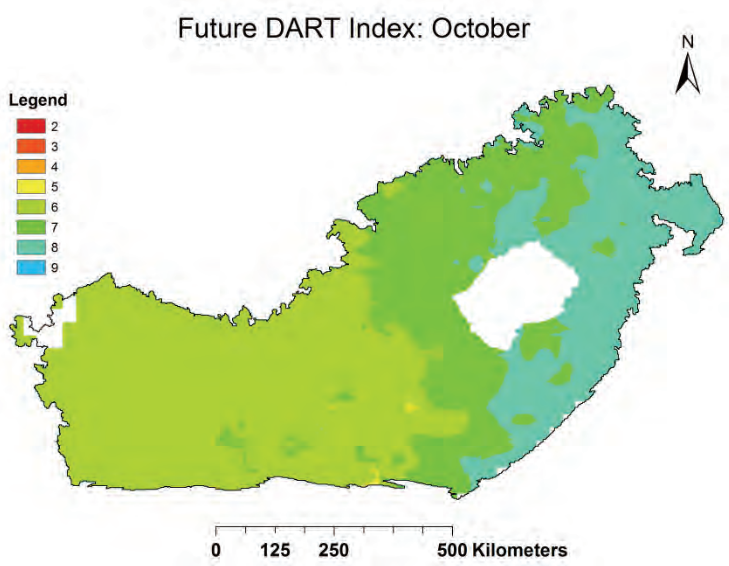

Current DART Index: August
N
Legend
6
7
8
9
10
0
125
250
500 Kilometers


Future DART Index: August
N
Legend
5
6
7
8
9
10
0
125
250
500 Kilometers


Current DART Index: September
N
Legend
6
7
8
9
10
0
125
250
500 Kilometers


Future DART Index: September
N
Legend
2
3
4
5
6
7
8
9
10
0
125
250
500 Kilometers


Current DART Index: October
N
Legend
6
7
8
9
0
125
250
500 Kilometers


Future DART Index: October
N
Legend
2
3
4
5
6
7
8
9
0
125
250
500 Kilometers

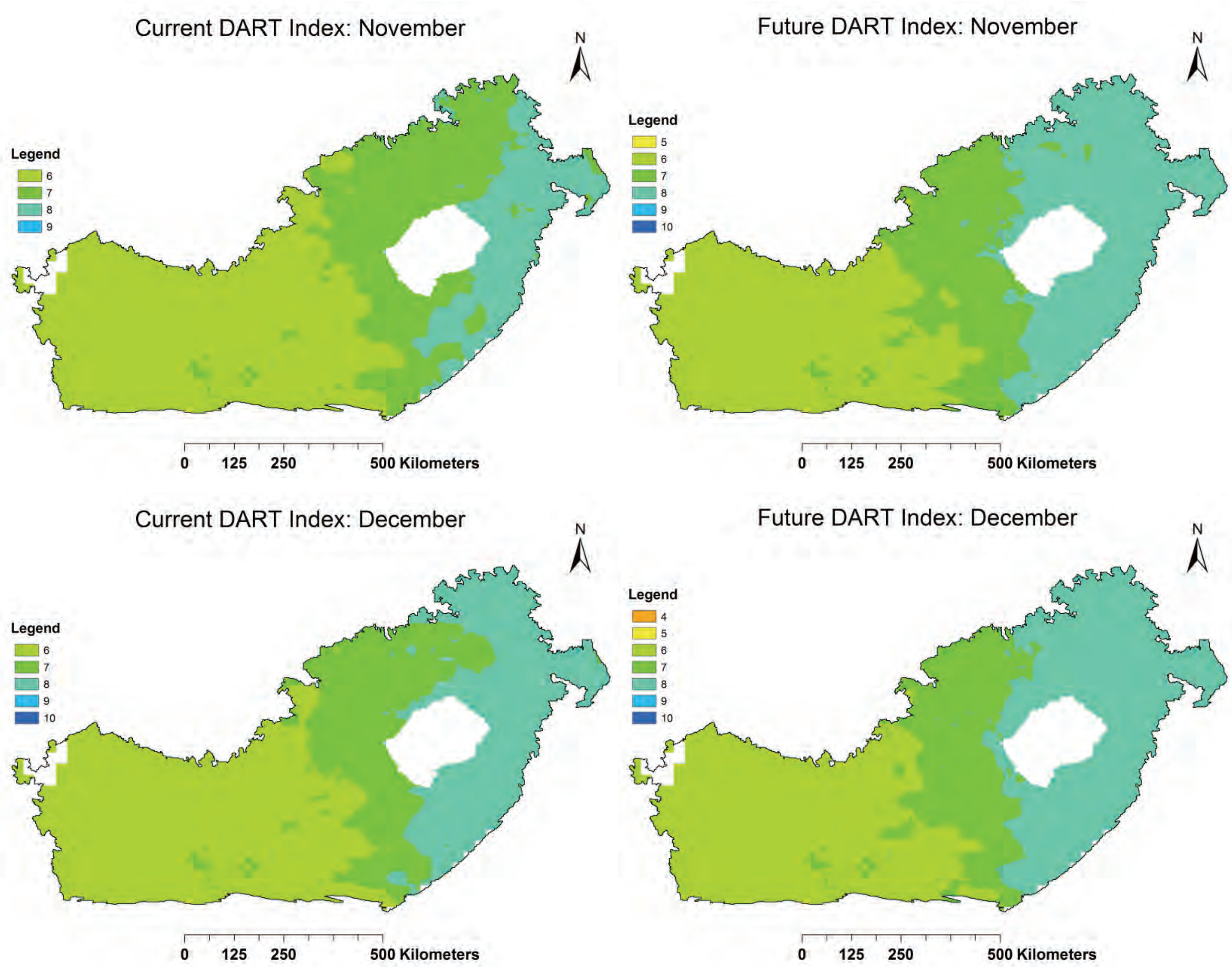


Figure 29: Monthly comparison between current and future DART index

The average change in the DART index between the current and future scenarios is shown in Figure 30. It is clear from the average change that only small areas will be affected negatively on average, compared to the bulk of the area reflecting no change, with patches in the eastern part of the Karoo where the index increases by 10%.

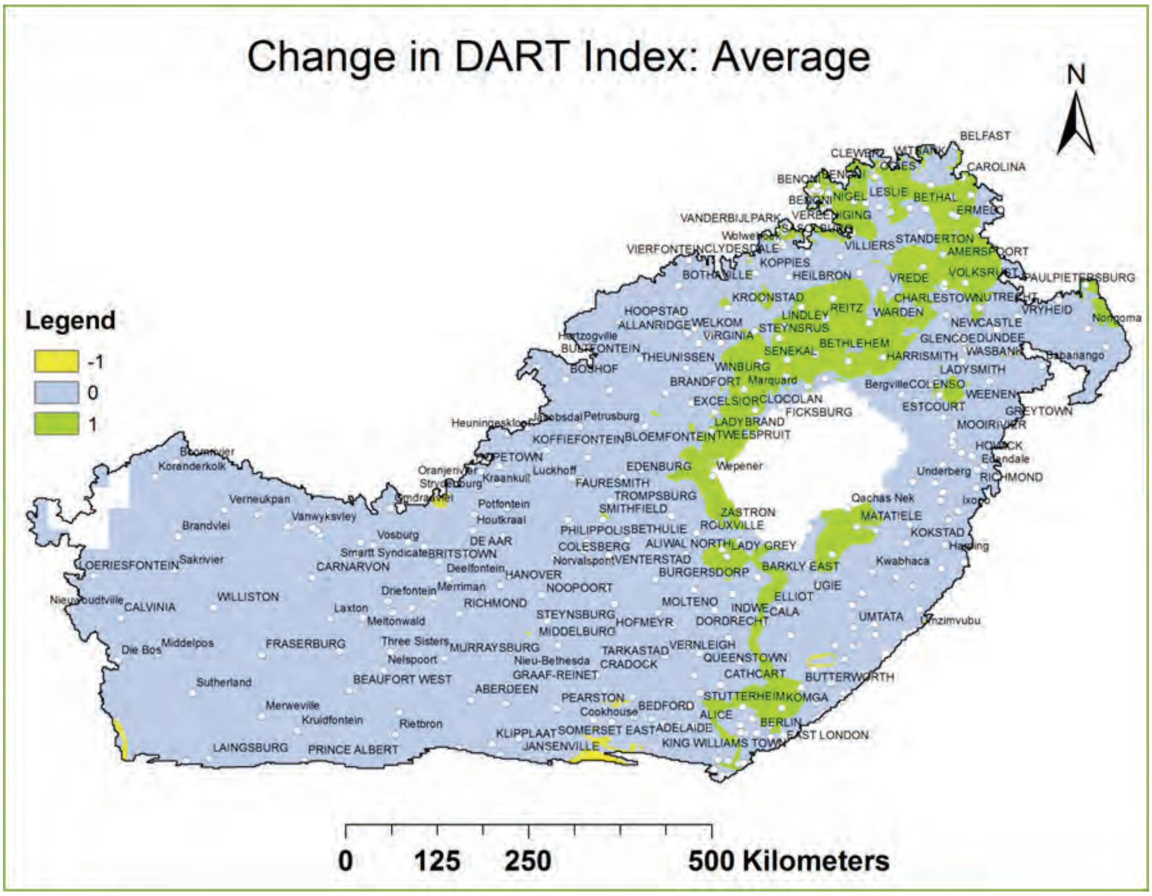
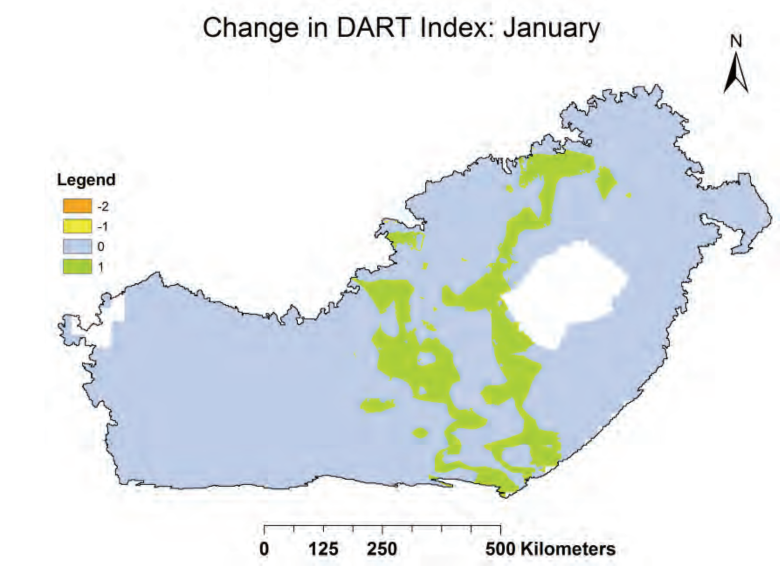


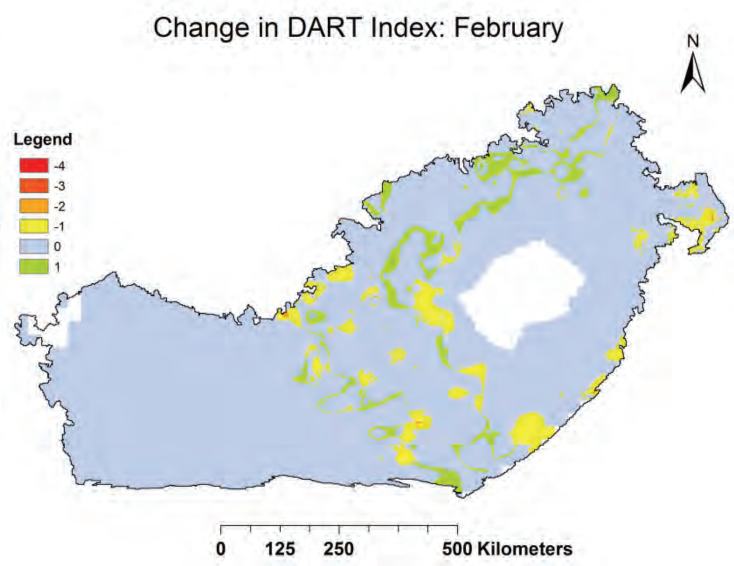
Figure 30: Change in average DART index between current and future scenarios

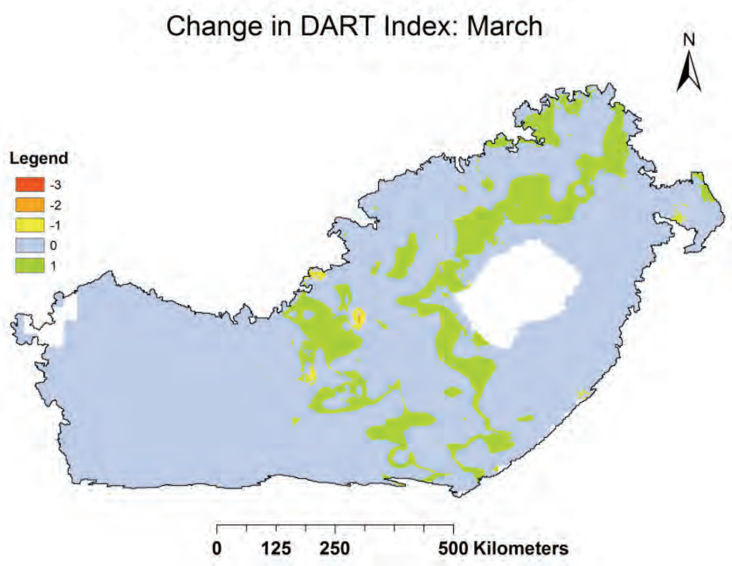
The monthly comparison of the change in DART index is shown in the following sequence of maps (Figure 31). The areas of change are more clearly visible in this comparison and it is clear that more areas will benefit from the future scenario than experience a negative influence.

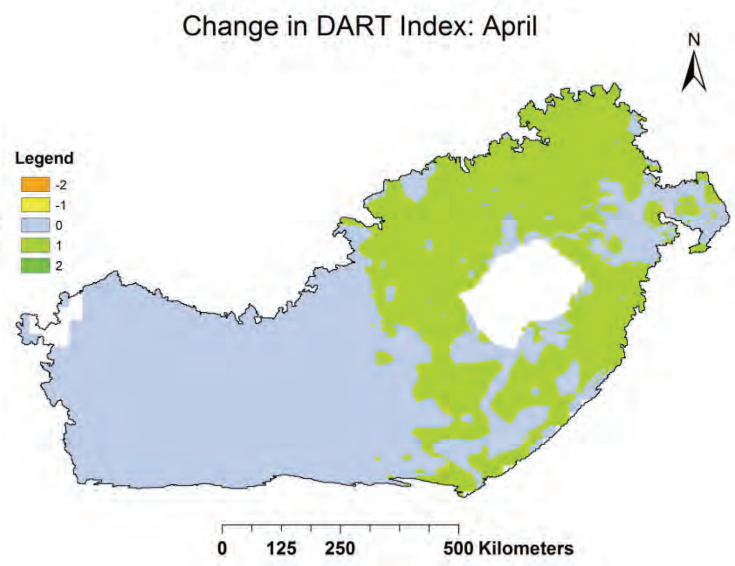
It is important to keep in mind that even if only small areas are impacted negatively, this could lead to a crisis if these areas are already under significant stress.

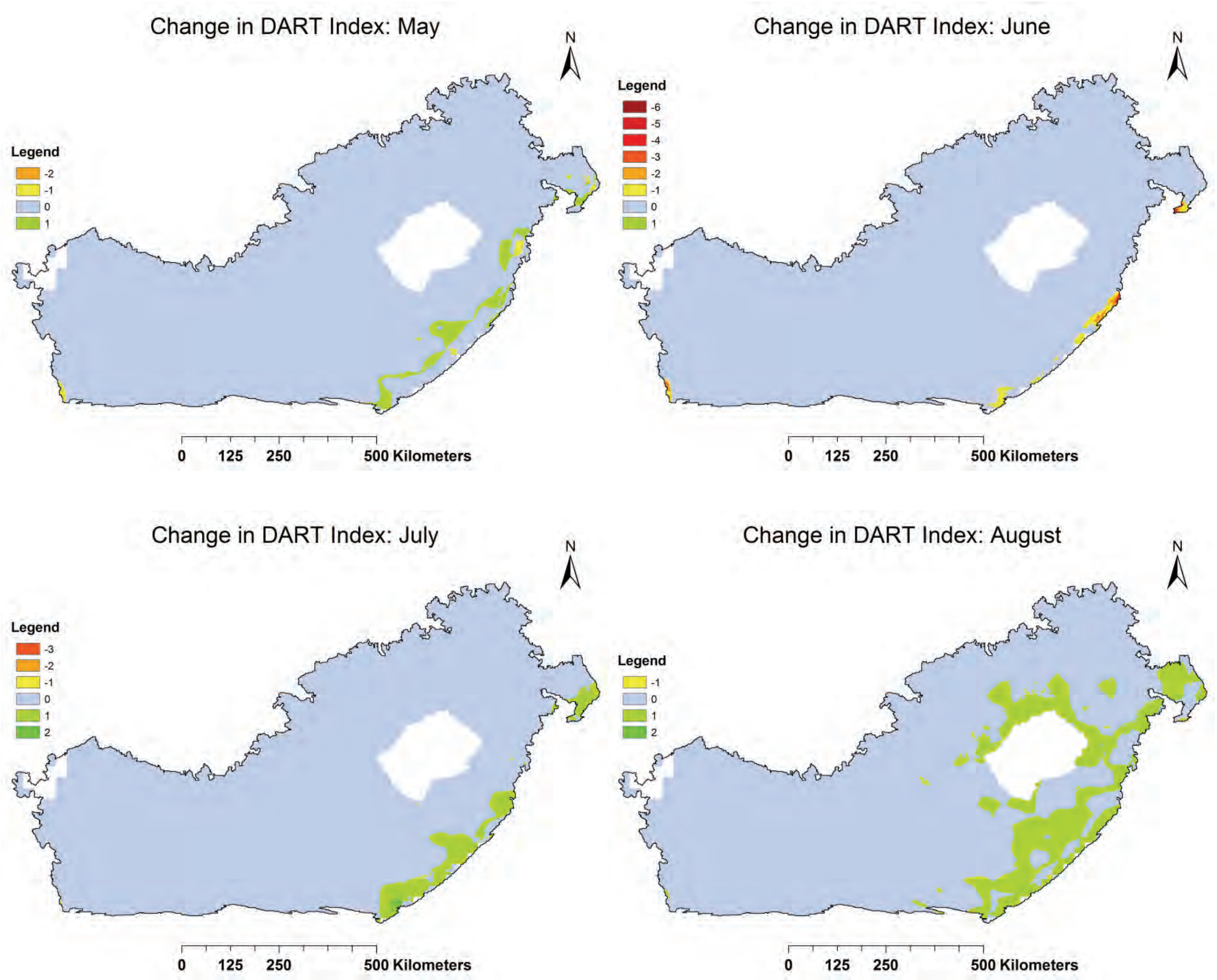
The DART index only takes into account the change in precipitation, and factors like population growth, population migration and the stress on surface water resources are not taken into account.


Change in DART Index: January
N
Legend
-2
-1
0
1
0
125
250
500 Kilometers


Change in DART Index: February
N
Legend
-4
-3
-2
-1
0
1
0
125
250
500 Kilometers


Change in DART Index: March
N
Legend
-3
-2
-1
0
1
0
125
250
500 Kilometers


Change in DART Index: April
N
Legend
-2
-1
0
1
2
0
125
250
500 Kilometers


Change in DART Index: May
N
Legend
-2
-1
0
1
0
125
250
500 Kilometers
Change in DART Index: June
N
Legend
-6
-5
-4
-3
-2
-1
0
1
0
125
250
500 Kilometers
Change in DART Index: July
N
Legend
-3
-2
-1
0
1
2
0
125
250
500 Kilometers
Change in DART Index: August
N
Legend
-1
0
1
2
0
125
250
500 Kilometers

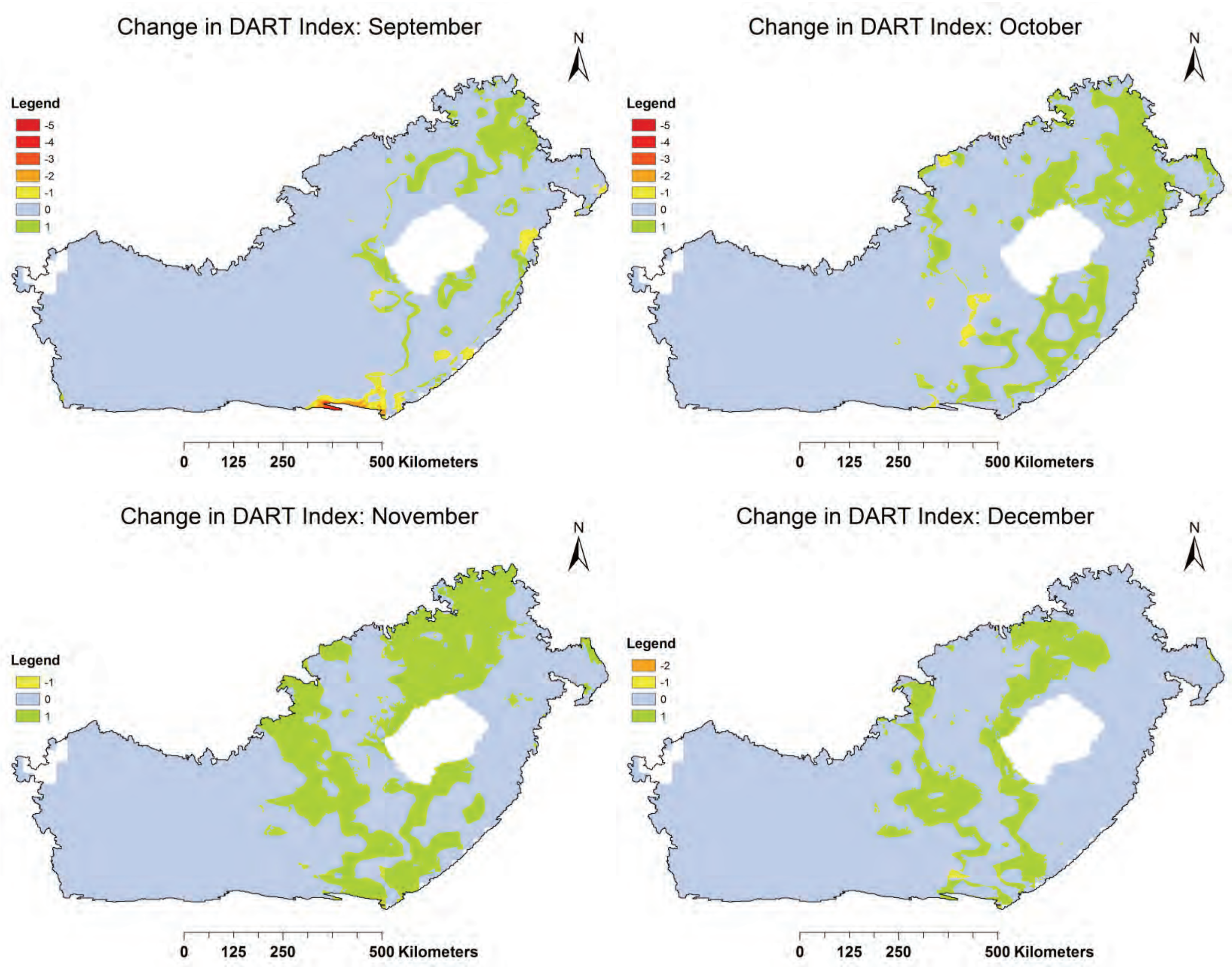


Figure 31: Monthly comparison of change in DART index

6 Conclusions and Recommendations

The amount of water available for withdrawal is a function of runoff, groundwater recharge, aquifer conditions (e.g. degree of confinement, depth, thickness and boundaries), water quality and water supply infrastructure (e.g. reservoirs, pumping wells and distribution networks). Safe access to drinking water depends more on the level of water supply infrastructure than on the quantity of runoff. However, the goal of improved safe access to drinking water will be harder to achieve in regions where runoff and/or groundwater recharge decreases as a result of climate change. In addition, climate change leads to additional costs for the water supply sector, e.g., due to changing water levels affecting water supply infrastructure, which might hamper the extension of water supply services to more people. This leads, in turn, to higher socio-economic impacts and follow-up costs, especially in areas where the prevalence of water stress has also increased as a result of climate change.

Groundwater withdrawals as a fraction of total human water withdrawals are likely to increase where surface water becomes scarcer, due either to increased surface water withdrawals, or to less reliable surface water supply caused by climate change and increasing variability of precipitation and river flow. However, increased groundwater withdrawals are not sustainable if quantities are not much less than groundwater recharge to avoid (i) harmful reductions in baseflow to surface water bodies and (ii) large drawdowns of the groundwater table.

The results presented in Section 5 demonstrate a method for mapping vulnerability that can be used to assess climate impacts in the context of regional to national scale. In developing a new approach for climate vulnerability mapping, we contribute to a growing body of literature on vulnerability science. However it is important to recognise both the limitations and strengths of the method. The major limitation of this approach is that the total water balance is not considered as a whole.

Coupled surface-groundwater models are required for local scale assessment of possible climate change impacts based on GCM scenarios. These coupled models require extensive data sets to accurately describe the study area. The advantage of this approach is that the water balance is considered as a whole.

The likelihood of deleterious impacts, as well as the cost and difficulty of adaptation, are expected to increase with magnitude and speed of the global climate change (Stern, 2006). Hence, effective mitigation of climate change (IPCC, 2007) is necessary to reduce the adverse impacts of climate change on water resources. Climate change will affect current water management practices and the operation of existing water infrastructures, which are very likely to be inadequate to overcome the negative impacts of climate change on water supply reliability.

Despite current levels of uncertainty concerning the impacts of climate change on groundwater in South Africa, much can be achieved by preparing for the worst and ensuring that adequate data and a plan of action are available for appropriate resource management decision-making. From the analysis presented, the following recommendations can be made for future work:

- Drought impact studies, in which impacts on groundwater withdrawal and quality are assessed.
- Among the urgent research needs are those that may lead to reducing uncertainty, both to better understand how climate change might affect groundwater and to assist water managers who need to adapt to climate change. Research should be focused on: reducing uncertainties in understanding; observations and projections of climate change and its impacts; and vulnerabilities.
- It is necessary to evaluate social and economic costs and benefits (in the sense of avoided damage) of adaptation, at several time scales. Estimation, in quantitative terms, of future climate change impacts on freshwater resources and their management, should be improved. Progress in understanding is conditioned by adequate availability of observation data, which calls for enhancement of monitoring endeavours. Adequate data are crucial to understanding observed changes and to improve models that can be used for future projections.
- On the modelling side, climate change modelling and impact modelling have to be better integrated and this requires solving a range of difficult problems related to scale mismatch and uncertainty.
- To take advantage of the natural storage capacity provided by aquifers, the artificial recharge of groundwater is an option that should be further explored. Methods include well injections, recharge dams, induced river bank infiltration and spreading methods.

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Kundzewicz ZW, Mata LJ, Arnell N, Döll P, Jiménez B, Miller K, Oki T, Şen Z & Shiklomanov I (2007) *Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

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8 *Appendix A: Case Study*

The downscaled climate data discussed in Section 3.2 are used as input in the Integrated Ground-Water Surface-Water Flow Model. A model representative of both surface and groundwater has to be set up for the study area.

GSFLOW is an integrated hydrologic basin-scale model to simulate coupled groundwater and surface water resources, as depicted in Figure 32. The GSFLOW model is based on the integration of the US Geological Survey Precipitation Runoff Modelling System (PRMS) and the Modular Groundwater Flow Model (MODFLOW-2005) (Markstrom *et al.*, 2008).

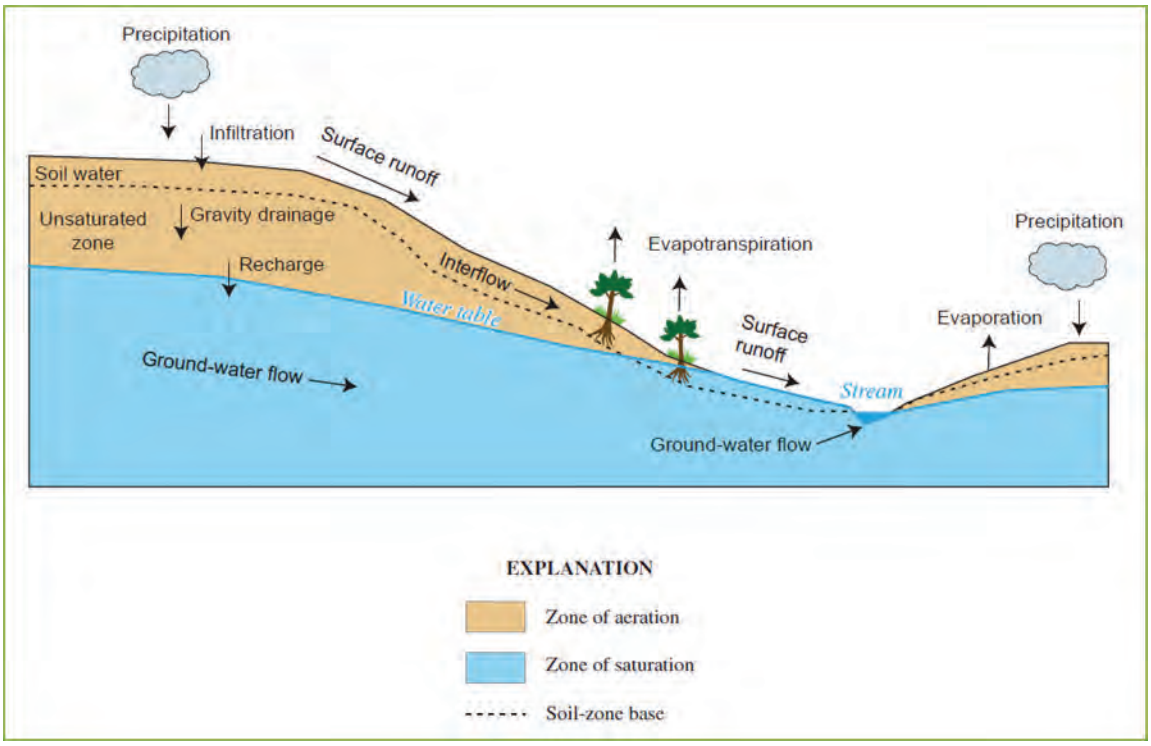

Figure 32: Distribution, flow, and interaction of water on the land and in the subsurface (Markstrom *et al.*, 2008)

GSFLOW consists of three regions, simulating flow within and among these regions. The first region is bounded on top by the plant canopy and on the bottom by the lower limit of the soil zone; the second region consists of all streams and lakes; and the third region is the subsurface zone beneath the soil zone (Figure 33) (Markstrom *et al.*, 2008).

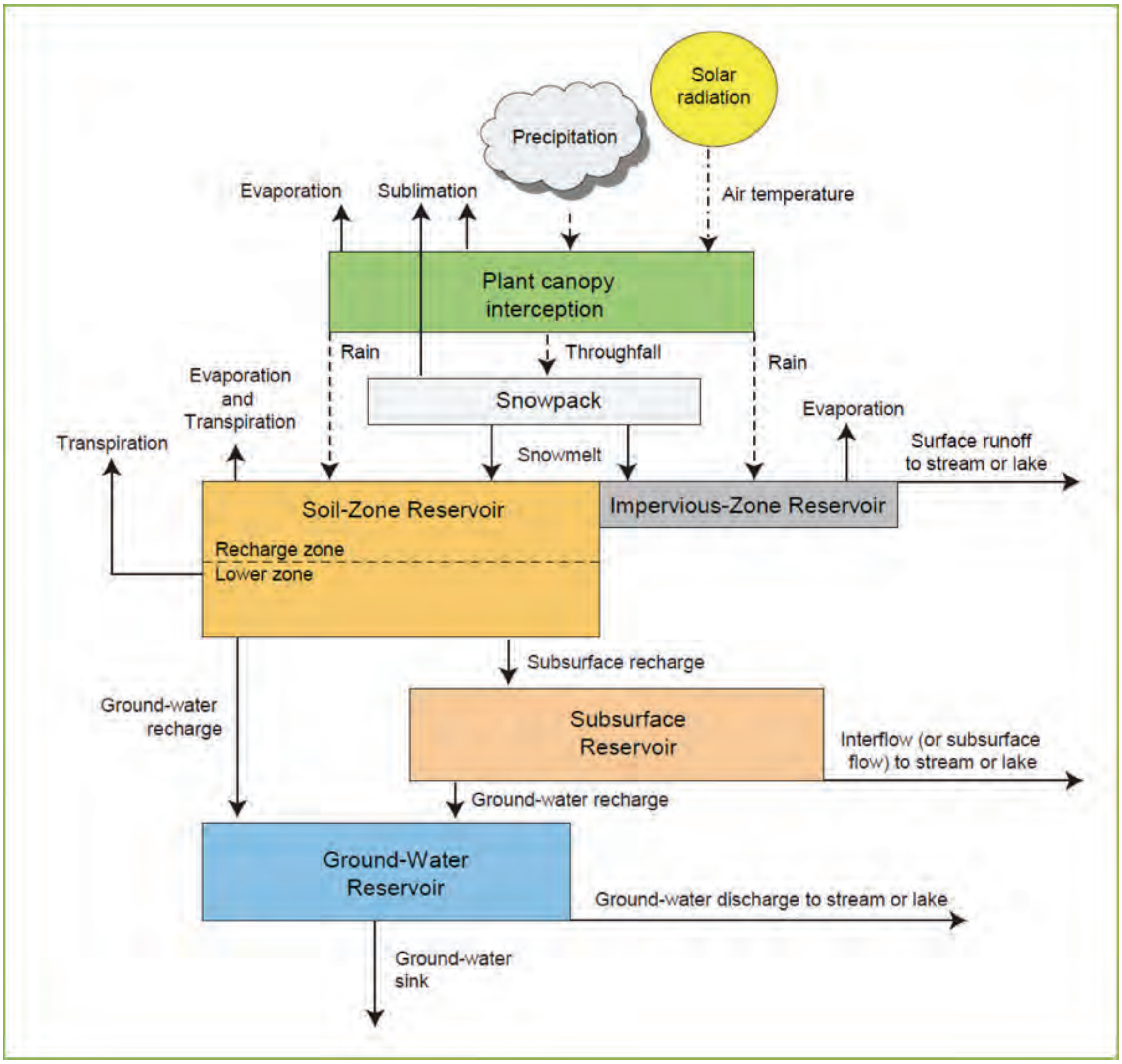

Figure 33: Schematic diagram of a watershed and its climate inputs (precipitation, air temperature, and solar radiation) simulated by PRMS (Markstrom *et al.*, 2008)

Flow is exchanged on the basis of interdependent equations that calculate flow and storage of water throughout the simulated hydrological system, as shown in Figure 34. The first region is simulated with PRMS modules, while the second and third regions are simulated with MODFLOW-2005 packages (Markstrom *et al.*, 2008).

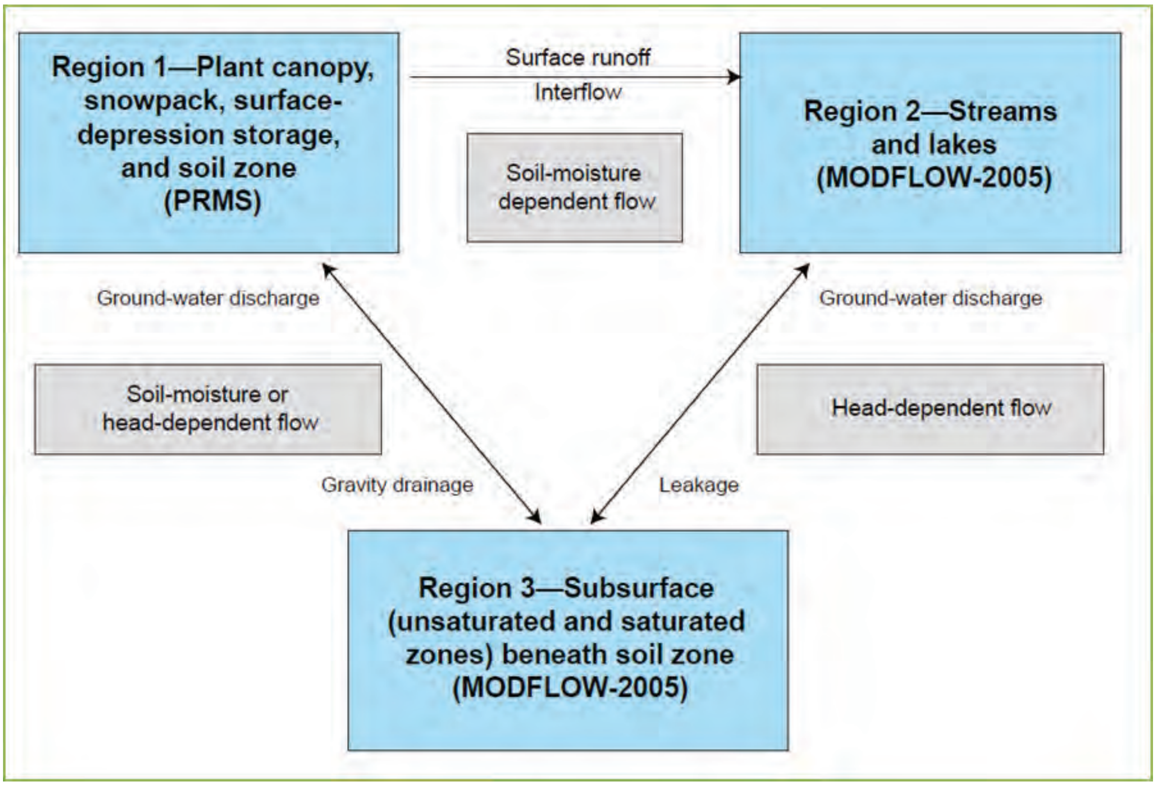

Figure 34: Schematic diagram of the exchange of flow among the three regions in GSFLOW (Markstrom *et al.*, 2008)

The model inputs used for the study area are daily precipitation, and maximum and minimum air temperatures. Precipitation, air temperature and solar radiation data are the driving forces used to compute evaporation, transpiration, sublimation, surface runoff and infiltration in the simulations (Markstrom *et al.*, 2008). The optional solar radiation input was kept constant in the PRMS simulations for the purpose of this study.

As an example, consider the impact of climate change on the groundwater contribution to baseflow in the case study presented in the next section.

CASE STUDY

The study area is in the Mpumalanga Province of South Africa as shown in Figure 35.

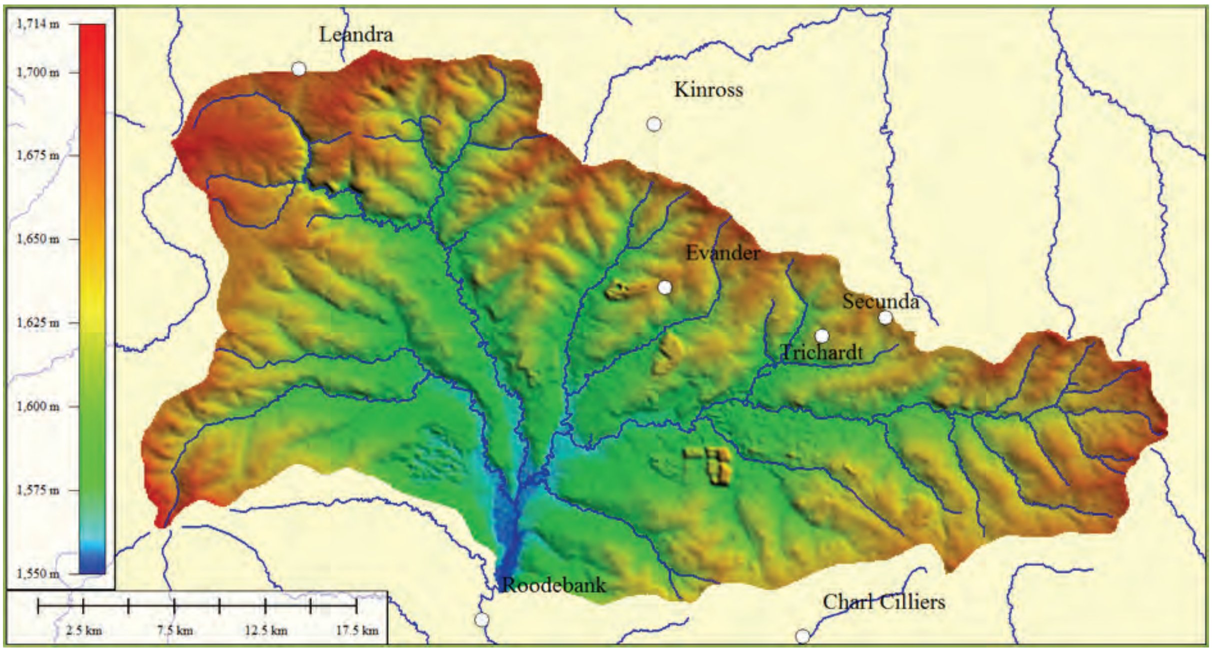

Figure 35: General case study area

The downscaled precipitation and temperature data for the study area is presented in Figure 36.

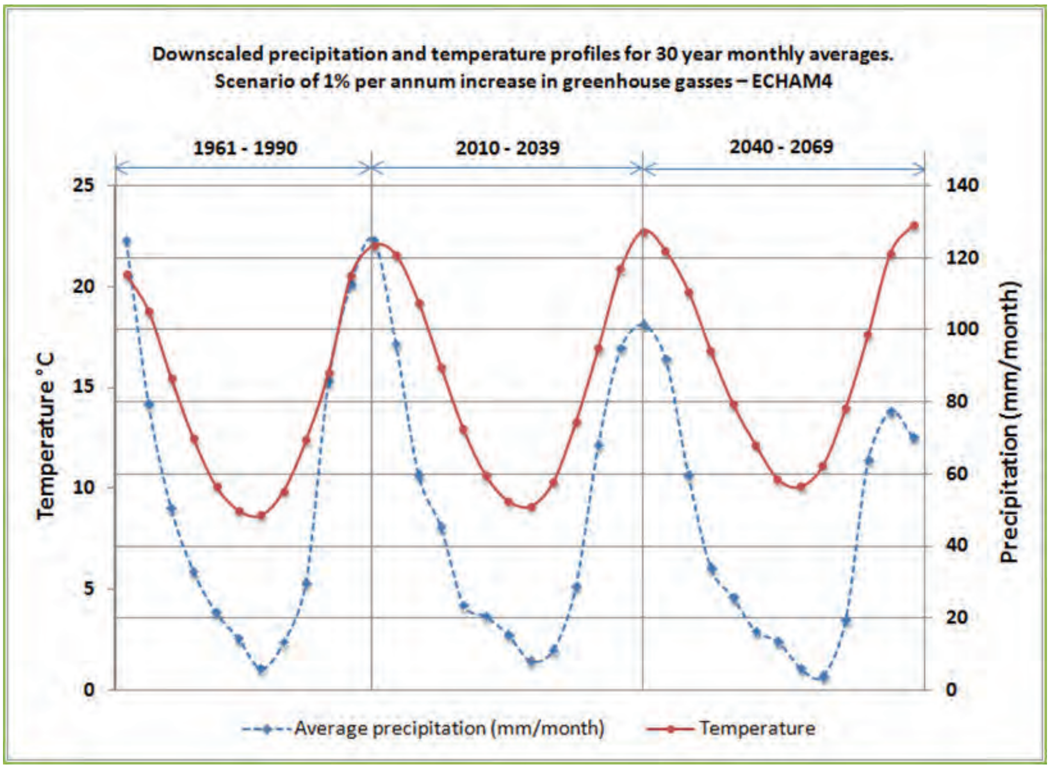

Figure 36: Downscaled precipitation and temperature data to local scale for the study area

The climate change scenarios of a 1% per annum increase in greenhouse gasses is applied to the study area in question.

The results of simulated groundwater contribution to baseflow are shown in Figure 37. A definite decrease in the downscaled precipitation data is visible. Only a slight decrease in groundwater contribution to baseflow is visible.

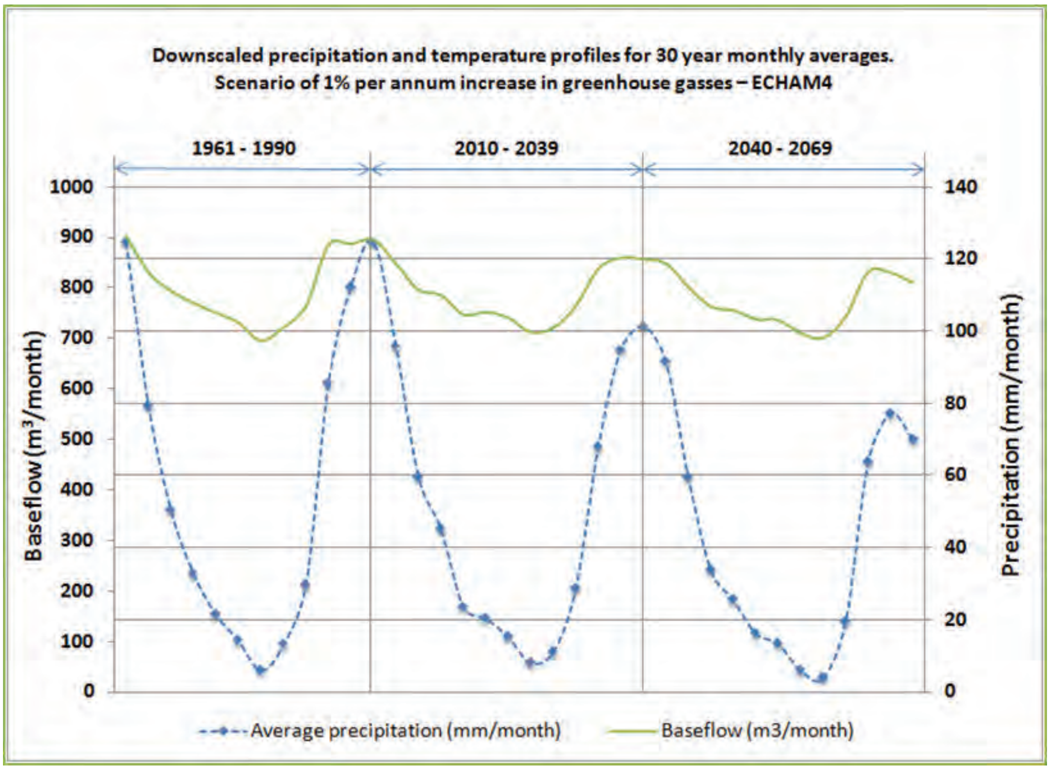

Figure 37: Simulated groundwater contribution to baseflow

Various scenarios can be applied to the model that represents the study area, to determine the impact on a whole array of parameters. Various systems subject to the same scenario will respond differently, according to their unique environment.