Development of Decision-Support Guidelines for Groundwater Related Vulnerability Assessments

By

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Declaration

I declare that the dissertation hereby handed in for qualification MSc. Geohydrology at the University of the Free State, is my own independent work and that I have not previously submitted the same work for a qualification in another university or faculty.

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Phaello Rantlhomela

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Dedication

I dedicate this dissertation to brother, Ntlhome Rantlhomela who passed away beginning of this year. Thank you for always believing that I would get this far and encouraging me to study further.

Acknowledgements

"No man is an island" John Donne.

- I am greatly humbled by the grace of God that has carried me this far.
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- My parents, I owe you so much. You gave me everything that I could need, moral and financial support.
- Lastly my colleagues at IGS

Key words: Groundwater, climate change, vulnerability, adaptation

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List of Abbreviations

AIDS	Acquired Immunodeficiency Syndrome
ANC	African National Congress
BGS	British Geological Survey
CO_2	Carbon Dioxide
CCS	Carbon Capture and Storage
CTL	Coal-to-liquid
DEAT	Department of Environmental Affairs and Tourism
DEA	Department of Environmental Affairs
DME	Department of Minerals and Energy
EC	Electrical Conductivity
ERC	Energy Research Centre
GCM	General Circulation Model
GWC	Growth without constraints
HIV	Human Immunodeficiency Virus
LTMS	Long Term Mitigation Scenarios
NC	National Communication
NCCC	National Committee on Climate Change
NGA	National Groundwater Archive
NGO	Non- government organization
NWA	National Water Act (Act 36 of 1998)
IPCC	Intergovernmental Panel on Climate Change
RBS	Required by Science
SBT	Scenario Building Team
SRES	Special Report on Emissions Scenarios
SSA	Statistics South Africa
TDS	Total Dissolved Solids

TNA	Technology Needs Assessment
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
WfGD	Water for Growth and Development
WFP	World Food Programme
WMA	Water Management Agencies
WRC	Water Research Commission

List of Measurement Units

Gg	gigagram
km	kilometers
km^2	square kilometers
mamsl	meters above mean sea-level
mbgl	mbgl
mm	millimeters
m2/d	meter squared per day
Mm^3/a	million cubic meters per annum

1 Introduction

"There is not a single facet of life, not a single act by any person, not a place on earth and not a moment in time that does not inherently contain a degree of hazard."

Ron Kuban and Heather Mackenzie-Carey

1.1 Preamble

Climate change is major threat to our world particularly poor countries. Since the industrial revolution, our globe has been steering towards a warm period (Oliver-Smith, 2009).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). As our planet warms, rainfall patterns become erratic and extreme events such as droughts and floods become frequent.

Of particular concern presently, is the fact that the earth's climate warms at a rate faster than preceding climate changes the planet has experienced (Archer, 2010). Therefore, much strain will be placed on water resources especially in areas where water infrastructure does not exist, or where water delivery is difficult due to aridity (Pietersen, 2005). This study will examine the causes of climate change and explore the resulting effects on the environment, social and economic sectors.

1.2 Background to South Africa

South Africa covers an area of 1.2-million km^2 and has a population of approximately 50 million people (SSA, 2010).The country is well known for its wealth in natural resources such as diamonds, gold and coal. Despite its natural resources endowment, South Africa like any African country is still to encounter climate change impacts. South Africa is viewed as a water-stressed country with an average annual rainfall of 500mm and any climatic change could have adverse impacts on water resources of the country.

During the mid-1980s, the Water Research Commission (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 that almost deemed the research impossible. Nonetheless, the need to know more about climate change was more than it could be curtailed by limited technological advancements.

Building on the outcomes of the prior research of the WRC on climate change impacts on water resources, WRC initiated another 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 became the focus of research in the water sector and that led to the development of climate scenarios for future and present conditions (Lumsden *et al*., 2009). Certainly, the impacts of climate change have to be the main focus since South Africa is seen to be more at risk than other regions of the world due to high climatic variability and widespread poverty which all might limit its ability to cope with the present effects of climate change, and possibly impede the execution of adaptation strategies in future (Schulze, 2005).

In South Africa where women play a critical role in the rural economy, it is necessary to understand the diversity of their experiences in the context of changing climate and rural economy. With the anticipated climate change impacts, it is believed that men and women will be differently impacted and vulnerable to climatic changes (Babugura, 2010). There is now sufficient knowledge of the struggles of women to obtain fuel or water. For example, Banda and Mehlwana point out that rural women walk 7 km and spend 1 to 5 hours chopping, bundling and carrying wood. The effect this has on women's health includes neck, back and child bearing complications (Banda & Mehlwana, 2005). Therefore, addressing climate change as a threat to people particularly women must be a priority.

1.3 Aims

Increased temperatures and frequency of extreme events are a major threat to already stressed water resources of South Africa. Despite the uncertainty that comes with climate change, there are multiple challenges that groundwater resources are yet to encounter, chief amongst which alter the use and availability of groundwater resources of the country.

For that reason, it is the aim of this dissertation to present the methodology for the assessment of the impacts of climate change on groundwater to assist in the implementation of adaptation strategies. Hence it is essential to consider the following points in order to achieve the aim of this dissertation:

- Review the relevant literature related to climate change vulnerability with particular emphasis on South African groundwater resources.
- Identify key variables that are sensitive to climate change and are likely to have an effect on groundwater.
- Implement the main findings from the study to provide an indication of when adaptation strategies are necessary.

1.4 Dissertation structure

There are seven chapters in this dissertation and their organization is as follows:

- **Chapter one:** is forms the introduction, including the aims of this study
- **Chapter two:** focuses on the review of literature surrounding climate change and the work that has been completed in South Africa about climate change.
- **Chapter three:** discusses vulnerability assessments and adaptation requirements
- **Chapter four:** presents an overview of quantifying groundwater related impacts due to climate change impacts
- **Chapter five:** gives an overview of the study area, describing its climate, geology, geohydrology.
- **Chapter six:** discusses the methodologies applied and the results obtained
- **Chapter seven:** consists of the discussions, conclusions and recommendations for future study.

2 Climate change impacts

2.1 Introduction

In recent years, the concept of vulnerability assessment has risen within several research communities. Vulnerability assessment is an important way to guide adaptation policy to global environmental changes. In the light of increasing frequency of disasters and continuing environmental degradation, measuring vulnerability is a crucial task if science is to help support the transition to a more sustainable world (Birkmann, 2006).

2.2 Climate change

The Intergovernmental Panel on Climate Change (IPCC) defines climate change as a change in the state of climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer (IPCC, 2004). The climate system evolves in time under the influence of its own internal dynamics and due to changes in external factors that affect climate (IPCC, 2007). The factors that are responsible for climate change can either be natural or human induced.

Since the advent of the industrial revolution in the 18^{th} century, human society has been producing greenhouse gases in ever-increasing amounts and thus leading the earth's surface towards a warming trend (IPCC, 2001). The earth's atmosphere consists largely of nitrogen, oxygen and a small amount of greenhouse gases (Archer, 2010). The greenhouse gases act as a partial blanket for the longwave radiation coming from the surface (Figure 1). This blanketing is known as the natural greenhouse effect (IPCC, 2007). The greenhouse effect results in the earth being 33^{0} C warmer than it would be

(Clarke, 2008). Without it, life on earth would not exist. However, current concern to scientists is the increased concentration of greenhouse gases within the earth's atmosphere, which results in the warming of the lower atmosphere and thus changes present climate patterns (Clarke, 2008).

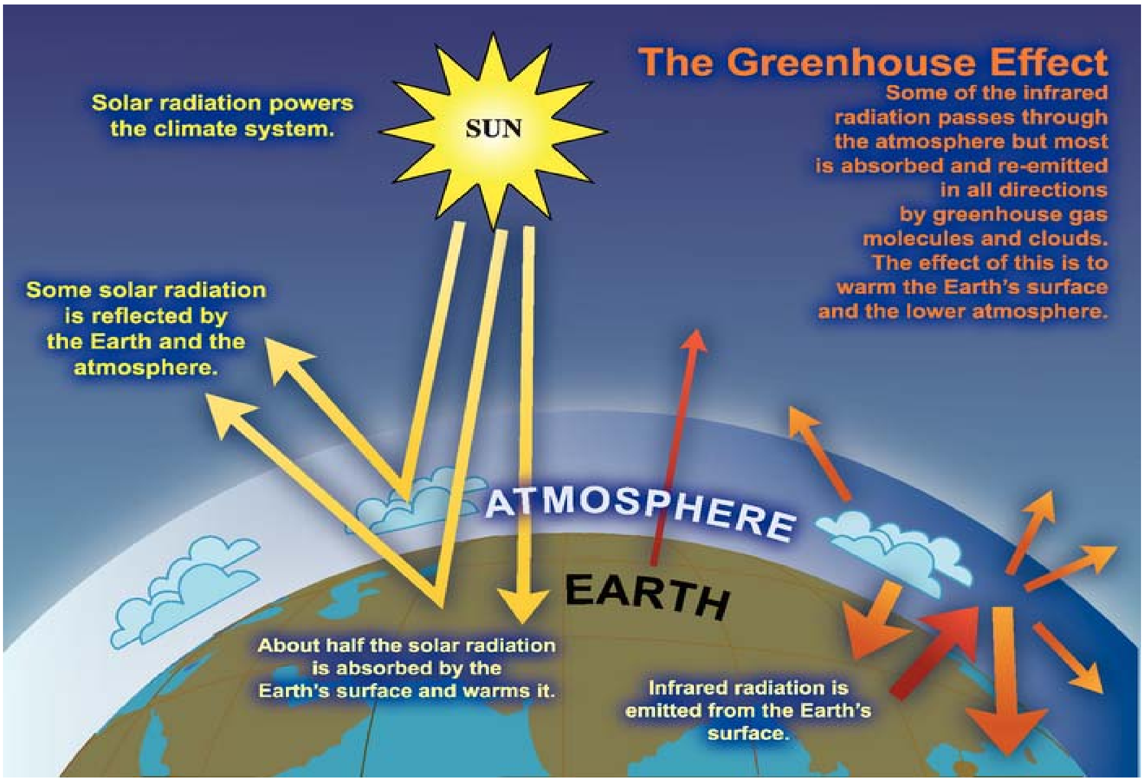

Figure 1: An idealized model of the natural greenhouse effect (Source: IPCC, 2007)

The effect can be briefly described as solar radiation passing through the atmosphere unimpeded. The atmosphere and earth's surface then reflect some solar radiation. While some is absorbed by the earth's surface and warms it. It is converted into heat, causing the emission of long-wave radiation back to the atmosphere. However, the long-wave terrestrial radiation emitted by the warm surface of the Earth is partially absorbed and then re-emitted by greenhouse gas molecules in the cooler atmosphere (UNEP/GRID-Arendal, 2000).

2.2.1 Natural causes

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

- *Solar variation*

Solar variations are the 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. A common example is a sunspot, where due to intensified magnetic energy one patch of the sun's surface becomes cooler than its surroundings, causing a relatively darkpspot (McDonald, 2009). When there is a large number sunspots on the sun it is suspected that the earth's climate will be slightly cooler.

- *Volcanic eruptions*

Explosive volcanic eruptions eject immense amount of dust and poisonous gases into the atmosphere. Of the gases emitted to the atmosphere, sulphur dioxide poses a significant threat. This gas is converted into sulphuric acid aerosols. These aerosols remain suspended in the atmosphere for several years (Burroughs, 2001) reflecting solar energy back into space. As a result there is a cooling at the surface which may oppose the greenhouse warming for a few years following an eruption (IPCC, 2007).

- *Ocean currents*

Ocean currents play a major role of transporting energy to high latitudes. However, significant changes in the transport pattern can have substantial climate implications (Burroughs, 2001). Interactions between the ocean and atmosphere can produce phenomena such as El Niño which occur every 2 to 6 years. Without this movement the poles would be colder and the equator warmer. The oceans play an important role in determining the atmospheric concentration of CO_2. Changes in ocean circulation may affect the climate through the movement of CO_2 into or out of the atmosphere (IPCC, 2001).

2.2.2 Anthropogenic causes

Human activities result in emissions of four principal greenhouse gases: carbon dioxide, methane, nitrous oxide and the halocarbons. These gases accumulate in the atmosphere, causing concentrations to increase with time (IPCC, 2007). Since the industrial era, human activities have contributed significantly to the greenhouse gases concentration (Figure 2).

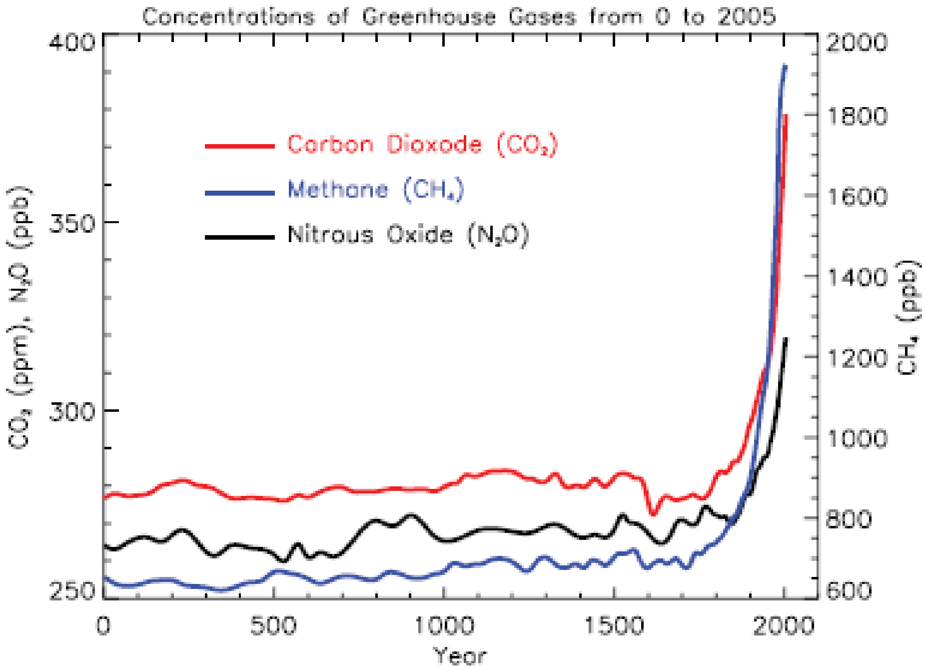

Figure 2: Concentrations of Greenhouse gases (Source: IPCC, 2007)

Below are the activities that humans carry out that are responsible for change (IPCC, 1995).

- *Fossil fuel burning*

  In Africa, less than 30% of all households have access to electricity, so that generally the hydrocarbons (coal and kerosene) are used in conjunction with biofuels fuels (wood fuel, crop waste, dung) (Banda & Mehlwana, 2005). Burning of fossil fuels releases carbon dioxide gas to the atmosphere. Carbon dioxide is one of the greenhouse gases. The greenhouse gases affect the climate by altering incoming solar radiation and outgoing infrared radiation that are part of earth's energy balance. Therefore changing the atmospheric abundance or properties of these gases and particles can lead to a warming or cooling of the climate system (IPCC, 2007).

- *Deforestation*

Deforestation is a process whereby forests are cut down faster than they can be replaced. Forests help to absorb carbon dioxide therefore lowering the greenhouse gas emission to the atmosphere. More deforestation means more carbon dioxide build up in the atmosphere.

- *Agriculture*

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 the intensified use of fertilizers. Another contributing factor is the biomass burning which is the burning of vegetation for land clearing prior to land use. Biomass burning is estimated to be 90% (Earth Observatory, 2010).

2.3 Climate change in South Africa

"Of the many complex challenges facing humanity today, climate change has been the issue that has had the most success in terms of using science to inform policy and action. Nevertheless, we need to be building on this foundation. Climate change is undoubtedly a foremost challenge of the 21st century. It is the only issue that consistently ranks high on the political agenda of all nations of the world, be they developing or developed, and also feature high on the agenda of multilateral forums such as the United Nations. As such, it is no surprise that the broader global scientific community is being challenged on a daily basis to step up to the plate and play an even bigger and more value-adding role in the fight against climate change."

Keynote Address by Director-General Phil Mjwara at the National Climate Change Policy Summit, 2009

2.3.1 Introduction

According to Mjwara (2009), the following aspects have to be taken into account when considering climate change impacts for South Africa:

- The complexity and scale of climate change require a very strong foundation in the fundamental earth sciences.
- The IPCC Fourth Assessment Report, particularly the report from working group 2, highlight that of all the continents, Africa is likely to be the most negatively impacted due to climate change and variability. Impacts will be wide-ranging and will be felt in the water sector, agriculture, fisheries as well as negative exposure to sea-level rise.
- Coping with climate change and variability demands good scientific understanding which is based on sufficient and reliable observations.
- There is an urgent need to substantially enhance efforts on the energy front. We have already put in place a number of platforms, initiatives and programs that assist in building the technological capabilities required to mitigate climate change.
- Solving the climate change challenge through an exclusive focus on hard technological fixes will not succeed. In terms of the nature of the challenge, more effort is required in terms of understanding and managing difficult issues in the area of human and social dynamics.

The temperature in South Africa is projected to increase by between 1 and 3 degrees, and the country's rainfall is projected to decrease by 5-10%. However, more importantly, is the way in which these will be experienced.

As well as average temperature increase, the daily maximum temperatures in summer and autumn in the western part of South Africa are likely to increase.

With regards to rainfall, the east of the country is projected to become wetter, but the distribution of rainfall within the rainfall season (summer) will also change, with the rainfall season beginning later and the annual average falling over fewer days with an increase in extreme events (which has implications for the growing season). The west of the country (the winter rainfall region) will become drier.

The change in temperature and rainfall will have implications for a number of sectors. Water resources are already under pressure in South Africa, and climate change will lead to a decline in the availability of surface and groundwater resources. This will happen at the same time, as socio-economic development will increase the demand for water.

2.3.2 Government's response to climate change

2.3.2.1 Internationally

The United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol were adopted because of worldwide concern over climate change. South Africa signed the UNFCCC in 1994 and endorsed it in 1997. In terms of its responsibilities under Article 12 of the convention, South Africa completed its Initial National Communication in 2004. This report documents South Africa's greenhouse gas inventory (as currently available) and indicates the contributions of different sectors to total greenhouse gas emissions.

The Kyoto Protocol was adopted on 10 December 1997. It aims to reduce the effects of climate change by reducing the emissions of six greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC), perfluorocarbons (PFC), and sulphur hexafluoride (SF_6). This protocol is an international agreement among industrialized countries as well as countries in transition to a market economy (mainly in Eastern Europe). Developed countries that are parties to the protocol are legally bound to reduce their collective emissions of greenhouse gases by at least 5% below 1990 levels during the treaty's 'first commitment period' (2008–2012).

South Africa acceded to the Kyoto Protocol in 2002 but, as a developing country, it is not currently required to reduce its greenhouse gas emissions. However, during the second commitment period, which begins in 2012, South Africa may need to make commitments to cut back.

2.3.2.2 Nationally

Numerous initiatives have been untaken by the South African government. These include:

- The establishment of a National Committee on Climate Change in 1994 to advise the relevant minister on climate change-related issues (ERC, 2009),
- The 1990 to 2000 national greenhouse gas inventories,
- The first and second National Communications to the United Nations Framework Convention on Climate Change (UNFCCC) in 2000 and 2009,
- The 2004 Climate Change Response Strategy,
- The 2005 Technology Needs Assessment which resulted in a Cabinet-endorsed prioritised list of environmentally sound technologies,
- The 2005 Climate Change Conference,
- The 2005 South African Country Study on Climate Change
- The African National Congress (ANC)'s 2007 Polokwane resolution on climate change,
- The Long Term Mitigation Scenarios (LTMS) process and the 2008 Cabinet Response,

- The March 2009 Climate Policy Summit Discussion Document and international commitments made at the 2009 Copenhagen Conference of the Parties to the Kyoto Protocol.

The most important of the above mentioned will be discussed in more detail in the following sections.

2.3.2.3 The National Committee on Climate Change

A National Committee on Climate Change (NCCC) consists of representatives from a number of affected sectors, government departments, and non-governmental organizations (NGOs). The purpose of the National Committee on Climate Change is to advise and consult the Minister of Environmental Affairs, on matters relating to national responsibilities with respect to climate change, and in particular in relation to the United Nations Framework Convention on Climate Change and the Kyoto protocol.

2.3.2.4 The 1990 to 2000 national greenhouse gas inventories

To fulfill its obligation under the UNFCCC, a number of projects related to climate change have since been undertaken by South Africa. These include the preparation of greenhouse gas (GHG) inventories, which comprises one of the inputs to the agreed National Communications (NC) to UNFCCC.

The total emissions for the 2000 inventory was 436,257 Gg CO_2e (or 437.3 million tonnes CO_2e). Four fifths (78.9%) were associated with energy supply and consumption, with smaller contributions from industrial processes (14.1%), agriculture (4.9%) and waste 2.1%) (See Table 0-4). These figures do not include emissions or sinks caused by agriculture, land use change and forestry activities. Activities in agriculture, land use and forestry contributed 40,772.94 Gg CO_2e as sources, but provided a sink of 20,279.43 Gg CO_2e, to provide a net source of emissions of 20,493.51 Gg CO_2e . If this is taken into account, the net emissions total from South Africa is reduced to 435 461.62 Gg CO_2e.

2.3.2.5 The first and second National Communications to the United Nations Framework Convention on Climate Change (UNFCCC) in 2000 and 2009

The results of the above-mentioned communications include:

- An urgent need exists for the establishment and maintenance of a greenhouse gas emissions inventory database. An independent verification system to ensure that only verified data is included in a national emissions database needs to be developed and maintained.
- Based on the results of the vulnerability and adaptation assessment undertaken as part of the South African Country Studies Programme, relevant government departments will be evaluating the financial and technical assistance that is required to undertake planning for adaptation.
- An integrated National Climate Change Response Strategy incorporating each vulnerable sector is being finalised.
- A national research policy is being developed to guide and consolidate research into climate change.
- Significant work needs to be undertaken to ensure that capacity is built in all sector of the society to deal with issues relating to climate change and to utilise the opportunities presented by the Convention in respect of adaptation and in particular the potential investment offered through the Clean Development Mechanism.
- The preliminary investigation into potential mitigation options needs to be extended to include more specific macro-economic modelling to evaluate the impact of different measures on the economy.
- Approaches to the evaluation of the measures need to be developed and implemented. Climate friendly technologies need to be incorporated into government's cleaner technology initiatives. Appropriate tools to model impacts and consequences of climate change need to be developed.

2.3.2.6 The 2004 Climate Change Response Strategy

A National Climate Change Response Strategy for South Africa was compiled in 2004, which aimed to address issues identified as priorities for dealing with climate change in the country. It also supports the policies and principles laid out in the government's White Paper on Integrated Pollution and Waste Management of 1998, as well as other national policies including those relating to energy, agriculture, and water.

The focus of the strategy is on the following areas: adapting to climate change; developing a sustainable energy programme; adopting an integrated response by the relevant government departments; compiling inventories of greenhouse gases; accessing and managing financial resources; and research, education, and training.

2.3.2.7 The 2005 Technology Needs Assessment

This report is the outcome of a stakeholder-driven Technology Needs Assessment (TNA) to identify and assess environmentally sound technologies that will, within national development objectives, reduce the impact of climate change and the rate of greenhouse gas emissions in South Africa. The process of conducting the TNA was initiated by the National Committee on Climate Change, which mandated the Department of Science and Technology to manage the process.

2.3.2.8 The 2005 South African Country Study on Climate Change

This report concludes that the key vulnerable areas such as water, agriculture, health and biodiversity, and as such should be mainstreamed into the current sustainable development initiatives. The identification of key stakeholders in this process will be crucial for the detection of adaptation project activities. These projects will aim to reduce poverty by building the adaptive capacity of the vulnerable, informing current developmental strategies and policies and establishing methodologies.

2.3.2.9 The African National Congress (ANC)'s 2007 Polokwane resolution on climate change

The resolution acknowledges the role of South Africa as a large developed country emitter, the impact of climate change on the poor, and the ANC's past and continuing commitment to a sustainable future. The resolution resolves to set a greenhouse gas mitigation target for the country in the future, and to diversify the energy mix away from its current coal focus with a strong emphasis on renewable energy, particularly wind and solar. Setting a price on carbon emissions, ambitious renewable energy targets and a mandatory energy efficiency programme comprise the main pillars of the path to achieve greenhouse gas reductions in the resolution. It speaks to the context of the employment creation imperative, and mobilising all stakeholders to respond to the climate change challenge. The fast-tracking of appropriate institutional mechanisms to support mitigation is directly identified.

2.3.2.10 The Long Term Mitigation Scenarios (LTMS)

The LTMS can be conceptually summarised in a set of graphs, depicting the baseline of business as usual emissions growth for South Africa from 2003 to 2050. The LTMS can be conceptually summarised in a set of graphs, depicting the baseline of business as usual emissions growth for South Africa from 2003 to 2050, *Growth without constraints* (GWC) against a *Required by science* (RBS) emissions trajectory, and a set of four strategic mitigation options which the country could take to take to respond to this challenge. The LTMS process modelled the country's emissions trajectory as if all existing mitigation policy was implemented. This trajectory, called *Current development plans*, includes the Energy Efficiency Strategy to achieve a final energy demand reduction of 12% by 2015 (DME, 2003), and the target of 10000 GWC renewable energy contribution to final energy consumption by 2013 (DME, 2003). This trajectory brings GWC down slightly, but not significantly compared to RBS. The LTMS process modelled the country's emissions trajectory as if all existing mitigation policy was implemented.

This trajectory, called Current development plans, includes the Energy Efficiency Strategy to achieve a final energy demand reduction of 12% by 2015 (DME, 2003), and the target of 10000 GWC renewable energy contribution to final energy consumption by 2013 (DME, 2003). This trajectory brings GWC down slightly, but not significantly compared to RBS.

The RBS scenario, indicates that South Africa's fair contribution to global greenhouse gas reduction is a reduction of between 30-40% from 2003 levels by 2050 (SBT, 2007). In the four strategic options: Start now, Scale up, Use the market and Reach for the goal, the main mitigation components which could get the country close to the RBS trajectory are identified, and packaged differently in each option. Start now includes accelerated energy and vehicle efficiency measures, passenger modal shift, and some nuclear and renewables for electricity generation. Scale up builds on Start now, incorporating extended renewables and nuclear for electricity generation, carbon capture and storage (CCS) technologies for synfuels, and electric vehicles. Use the market entails putting a price on carbon, together with subsidies for renewables, biofuels and solar water heaters. This option results in a carbon free electricity grid by 2050, with no new coal plants or coal-to-liquid (CTL) plants being built. But even under the Use the market option, which is modelled as resulting in the greatest reductions by 2050, emissions are still not brought down to the RBS level. The Reach for the goal scenario anticipates the use of new and as of yet unidentified technologies, and planning and behavioural change.

2.3.2.11 The March 2009 Climate Policy Summit Discussion Document

The process of developing policy to support Cabinet's mitigation vision was formally begun with the March 2009 Climate Change Policy Summit. A discussion document was circulated at the conference, and cited as an 'organising framework and starting point' (DEAT, 2009) for South African climate change mitigation policy going forward. The document uses the peak, plateau and decline trajectory as a basis, and elaborates that planned infrastructure projects (including coal-fired power stations and CTL plants) will be built.

2.3.2.12 Water for growth and development strategy

'Water is life – Securing the Nation's Needs Across Generations' WfGD vision

In 2001, the Department of Water Affairs and Forestry led a water sector support programme called Masibambane partnership. It is a partnership between Department of Provincial and Local Government, the South African Local Government Association, the European Union and its member states, the Swiss Government and the Ireland aid.
It was within the third phase of Masibambane programme that Water for Growth and Development theme was developed. The aim of Water for Growth and Development strategy is to (DWA, 2008)**:**

- Provide clear, accessible information to inform decision-making at all levels.
- To harness the productive potential of water at the same time limiting its destructive impacts in order to ensure that water is allocated equitably and sustainably as a resource which can leverage growth and development.

This strategy explores how water can be best managed and developed to promote economic growth and alleviate poverty, including rectifying past inequitable distribution of water and sanitation infrastructure by:

- Looking beyond eliminating service backlogs and providing services, to achieving sustainable economic and social developments that are environmentally friendly.
- Looking across the board constraints and opportunities for optimal water development and use from rainwater harvesting opportunities for local food security, to efficient use of water in our homes, farms and factories and to protect our health and environment.

- Building and supporting water institutions, human capacity and skills in the sector in order to ensure effective management of resources and delivery of services.

The WfGD represents an acknowledgement that water has a multiplicity of roles including:

- Supporting the economic activities that will be required to achieve the economic growth
- targets of South Africa
- Providing for domestic and social needs
- Maintaining the environment
- Improving the overall quality of life of people living in South Africa

Its intention is to place water at the heart of all planning that takes place in the country so that any decisions that rely on the steady supply of water adequately factor in water availability.

Climate change is an accepted threat to the sustainability of water supplies as highlighted by the Inter-Governmental Panel on Climate Change's technical report. What is uncertain is the quantification of the impact, and this complicates the planning required to ensure sufficient future water supplies. For this reason, it is vital that the department participates in, contributes to, and supports ongoing research and monitoring of the effects of climate change on the sub-region and continent.

The Department's potential impact on mitigation of climate change is relatively small, and probably lies most in leveraging other government departments that have a greater impact on carbon emissions. However, in terms of mitigation, the department should ensure that carbon accounting forms part of the planning process for all major projects.
The critical role of climate change in relation to DWA planning processes is in terms adaptation. All scenario planning must factor in the predicted future impacts of climate

change. This in turn requires research to be disseminated within the department, and water sector in general.

It is likely that the net effect of climate change will be to reduce availability of water, although these effects will be unevenly distributed, with the eastern coastal regions of the country possibly becoming wetter. In the interior and the western parts of the country climate change is likely to lead to more intense and prolonged periods of drought. In general, climate change is likely to lead to weather events that are more intense and variable than in the past, e.g. sudden high volumes of rain fall leading to flooding.

In addition to the general challenges to water security posed by the net drying effects of climate change in some areas, the increased variability of rainfall presents specific challenges. Even where average annual rainfall remains constant, increased variability in rainfall patterns will result in less reliable stream flows and consequent increases in the unit costs of water from dams. The effects of increased evaporation due to higher temperatures, particularly in relation to large, shallow dams, need to be considered in deciding upon new dam constructions versus enhancing groundwater resources. Coupled with more uneven and less predictable distribution patterns for rainfall, increased inconsistency of supply represents a challenge in resource management.

Periods of unusually low river flow present a problem in terms of the dilution of wastewater and effluent, with concomitant health risks. With this in mind, and bearing in mind the general challenges to the water resource, in some areas it may be necessary to reconsider priorities in terms of replacing dry sanitation with water-borne systems. Conversely, sudden flood events are also known vectors for the spread of waterborne disease, such as cholera – particularly in areas where urban drainage is not designed to cope with flooding. For these reasons, research into the impact of climate change on water quality and public health is needed to inform policy formulation.

Climate change also presents particular challenges to water infrastructure. Extreme wetting and drying cycles result in greater soil movement and make water and sewerage pipes more prone to cracking. Increases in intense rainfall events will place soil dams at risk and increase siltation of dams and estuaries. Coupled with higher temperatures, intense rainfall effects also cause problems with water quality in terms of colour and odour.

A critical threat to water for growth and development in South Africa is natural resource degradation. Invasive alien plant species tend to use more water than the indigenous plants that they displace, and decrease the mean annual runoff. Climate change could exacerbate the impact even further.

Climate change has become an increasingly important issue in water resource management. Research clearly identifies the resulting risks to the water resources of the country: higher temperatures and more extreme weather resulting in increased rainfall intensity in some parts of the country and longer and extreme drought periods in others. As a result of climate change, the reliability of supply to water users and the levels of risk of supplying users are likely to increase.

To address the potential risks and threats posed by climate change with respect to water security, the following actions should be seriously considered:

- Development of a water sector response strategy comprising of adaptation plans and
- mitigation measures;
- Stimulate shift in focus from climatic prediction and mitigation to response and adaptation
- options; and

- Focus on those WMAs or catchments likely to face the greatest risk of water shortages and develop an appropriate and reliable understanding so that risk and disaster management plans can be drawn up and implemented.

Provinces with large rural populations should consider development of small-scale projects, like rainwater harvesting, that conserve water, address issues of affordability and improve reliability of water services. The building of small communal dams and standalone schemes to support livestock should be an integral part of rural development.

Women should be thought of as strategic users of water. They manage the use of water for preparing food, for drinking, bathing and washing, for irrigating home gardens and watering livestock. Women know the location, reliability and quality of local water resources. They collect water, store it, and control its use and sanitation. They recycle water, using grey water for washing and irrigation. Their participation in all development programmes should be given priority.

2.3.2.13 Current situation

Currently, the climate change policy process is being led by the Department of Environmental Affairs (DEA), which may not have the necessary institutional strength to drive a policy position entailing a substantial transformation of the way in which the economy currently operates, given significant vested influence in maintenance of the status quo. The issue of climate change is included as something which the proposed Planning Commission (Presidency, 2009) will tackle, and if this Commission is established with high level political and stakeholder support, it could assist DEA in overcoming the challenges it is likely to face in policy development.

2.4 Anticipated climate change impacts

Figure 3 provides a summary of the climate change impacts found in Africa. This Section discusses the various impacts of climate change.

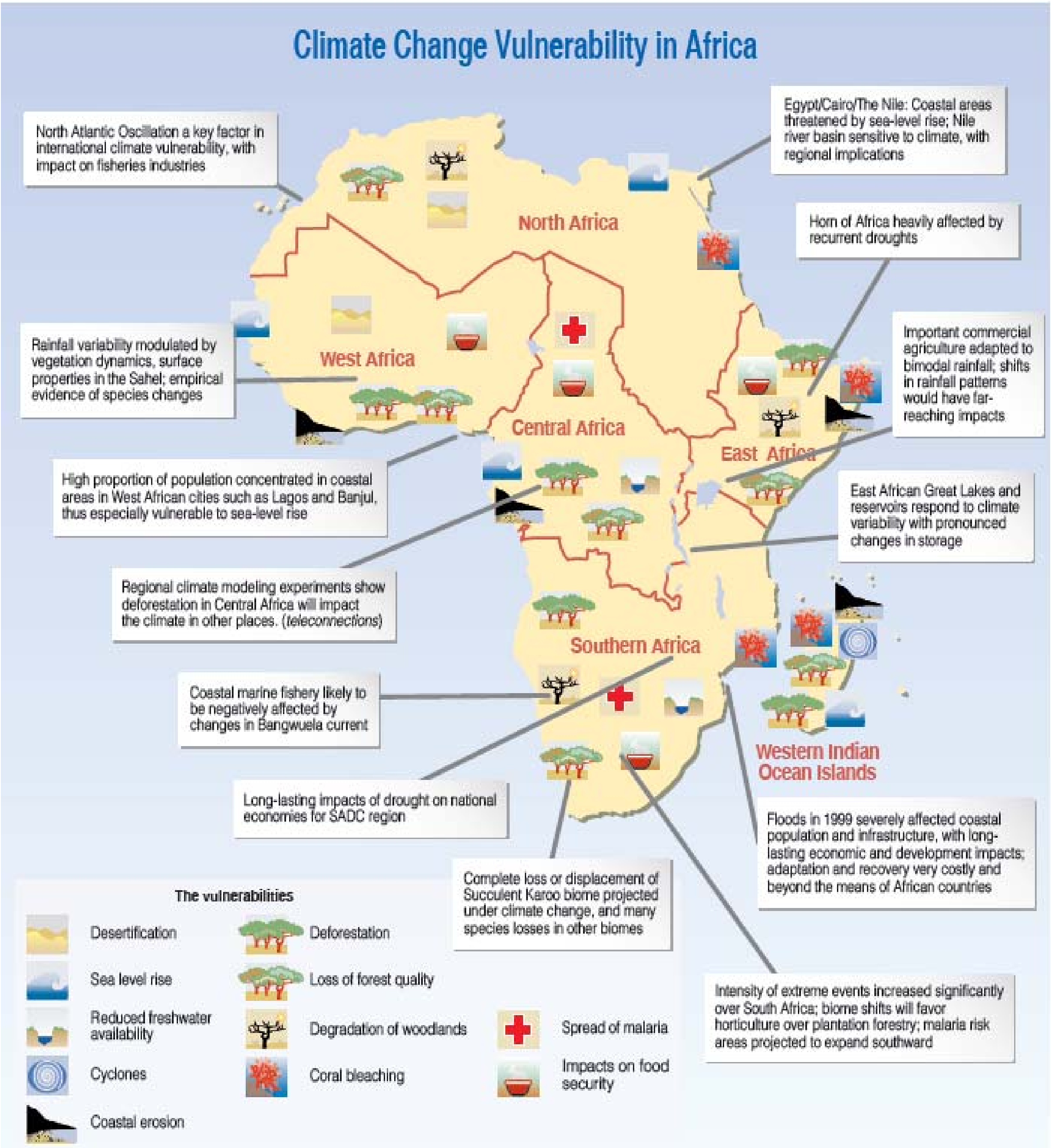

Figure 3: Climate change vulnerability in Africa (Source: UNEP/GRID Arendal Maps and Graphics Library, 2002)

2.4.1 Drought

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 has 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 localized 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 humid equatorial climate. These areas generally have more abundant water resources with perennial surface water (Braune and Xu, 2008).

In South Africa, rural water supply is already using groundwater extensively. Therefore, this makes rural areas to be more susceptible to drought as a result making access to rural water supplies even more vulnerable (Naidoo *et al*., 2009).

During droughts water restrictions have to be imposed on the 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. The result is an outbreak of waterborne diseases such as diarrhea and typhoid. Population migration is also common in search of better supply of food and water elsewhere.

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

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 and van Lanen, 2004).

Increased temperatures generally results in increased evaporation mainly because the water-holding capacity of air is increased. Evaporation from the land surface includes evaporation from surface water, soil, shallow groundwater and water stored on vegetation along with transpiration through plants. With higher temperatures and increased evaporation, the result is loss of soil moisture and groundwater recharge and greater exposure to desertification and soil erosion (BGR, 2008).

The effects of climate change on soil moisture do not vary with the degree of climate change but with soil characteristics. The capacity of the soil to hold water plays an essential role in the soil moisture deficits; the lower the capacity, the greater the sensitivity to climate change. Climate change may also affect soil characteristics, through changes in waterlogging or cracking, which in turn may affect soil moisture storage properties (Arnell & Liu, 2001).

Drought usually enhances the demand for water therefore leading to a higher pressure on groundwater and surface water resources (Tallaksen and van Lanen, 2004). When groundwater is used at rates greater than at which it is replenished by precipitation, the water level drops. This behavior is usually common during drought seasons. Lowering of the water levels reduces well yields and thus the cost of pumping increases.

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 the precipitation. Recharge water may reach the aquifer rapidly, through macro-pores or fissures (preferential pathway), or either slowly by infiltrating 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 a*l., 2007). Variations in aquifer recharge change the aquifer yield and modify groundwater flow network (Dragoni & Sukhija, 2008).

In South Africa, It is claimed that the rainfall may increase in some parts of the country, and decrease in other parts (Hogan, 2010). Any significant changes in the amount of recharge will alter recharge patterns and thus fluctuating water levels. In extreme cases of drought, water levels drop as well as the yield of boreholes.

Groundwater discharge is a loss of water from the 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, lake 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).

Groundwater storage is influenced by a change in recharge, discharge and extraction over a longer period. For example; recharge of 40mm per annum occurs over an area of $100km^2$ under the present climate, assuming steady state conditions of groundwater flow. If the recharge reduces to 10mm 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 $1.5 \times 10^6 m^3$ of water resources for the area each year (Cavé et. al, 2003).

Salt-water intrusion (Figure 4) 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).

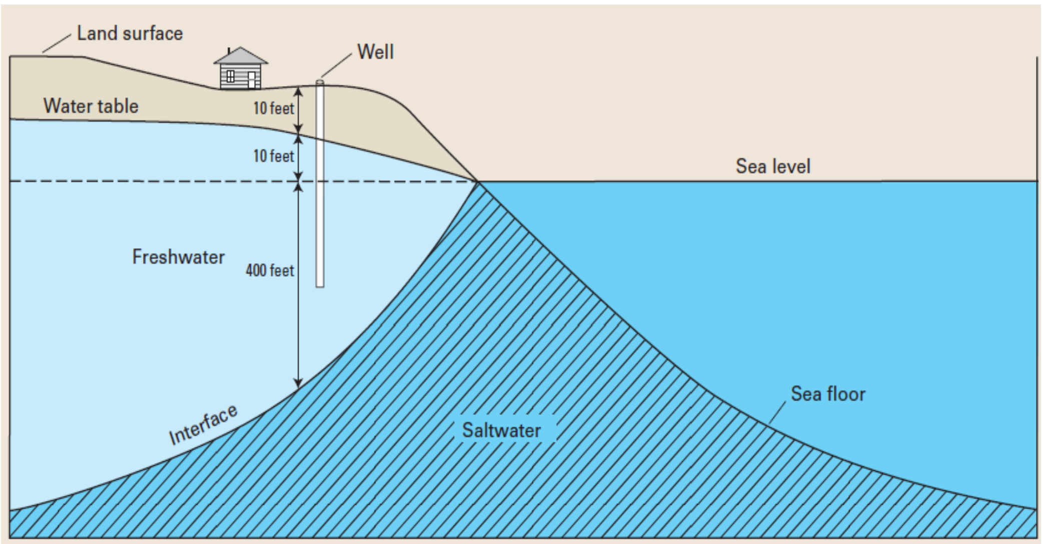

Figure 4 Simplified freshwater-saltwater interface (Taken from Barlow, 2003)

Salt water degrades the quality of water and harms the aquatic plants and animals that cannot tolerate high salinity. The amount of intrusion will however depend on the local groundwater gradient (IPCC, 2001).

2.4.2 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 period of time or snowmelt.

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 basins where most precipitation infiltrates the soil surface, flood response may be greatly modified by surface transmissivity (Smith and Ward, 1998).

When severe floods occur in areas occupied by humans, they can create natural disasters that can involve the loss of human life and property plus serious disruption to the ongoing activities of rural communities. The impacts of floods are discussed below.

Land erosion, combined with re-deposition of coarse sediments, can be major source of agricultural loss, especially where aggressive rivers excavate deep, unconsolidated material. Agricultural losses depend very much on the season of flooding and the type and state of the crop. In groundwater, floods increase the mobilization of pollutants due to increased water table.

Floods have a serious impact on arable land and therefore depriving people with 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 out-migration of younger, fitter members of the community.

Temporary stoppage of water, electricity supply, telecommunication and temporary shut down of schools and markets are some of the impacts that prevail during flood event. 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.

Some impacts of floods include physical damage to property, loss of human and animal lives, and ill health of flood victims. Water related diseases spread easily due to failure of sewage systems and the contamination of drinking water supplies by microbiological pollution after floods (Smith and Ward, 1998). Smith reports that women, children and the poor suffer the most.

In flood events, water levels are raised and the soil becomes over saturated and therefore cannot absorb any water. Water that cannot be absorbed flows on the surface and it is known as runoff. Runoff degrades the quality of water and causes soil erosion. Boreholes with excessive amounts of floodwater in the casing yields highly turbid, gray-brown water. Some wells and localized aquifer zones may yield lower TDS and EC values as well as elevated turbidity and bacterial contamination.

Sea level rise is the increase of the volume of ocean water due to thermal expansion of the ocean. It is among the most profound impacts of climate change. There is evidence mounting of the accelerating rate of sea-level rise because of greenhouse gases. Research shows that sea level rise is caused by a variety of factors.

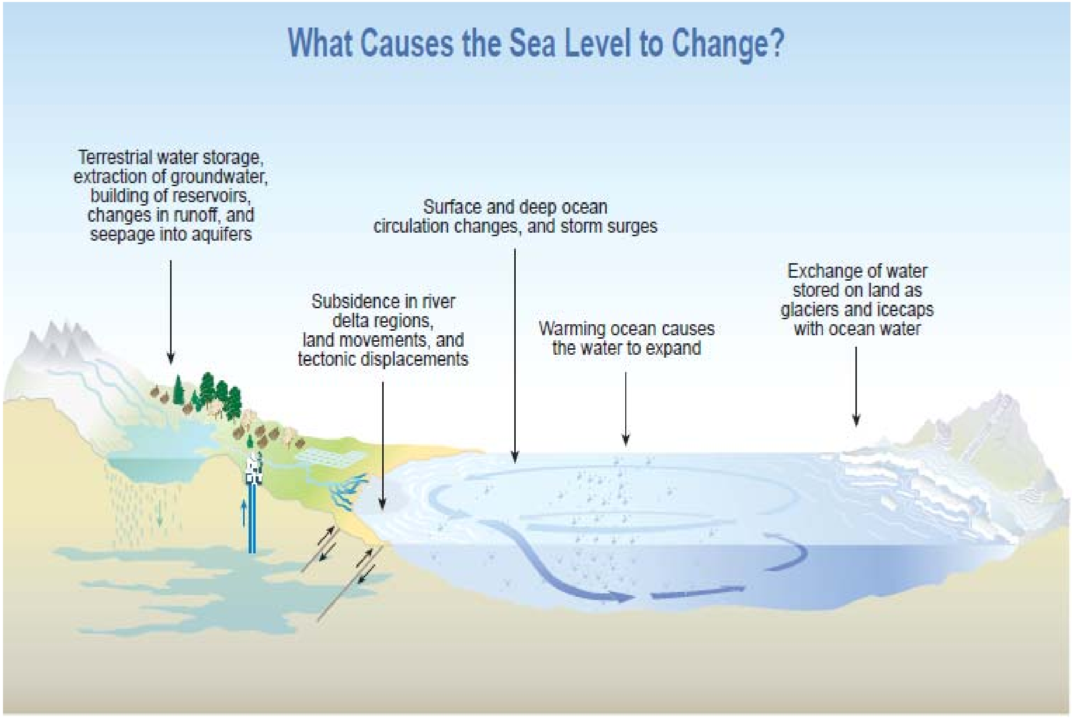

Figure 5: Causes of sea level change (Taken from UNEP/GRID Arendal Maps and Graphics Library, 2002)

Among the factors that contribute to sea level rise, temperature is the major one. As climate change increases ocean temperatures, initially at the surface and over centuries at depth, the water will expand, contributing to sea level rise due to thermal expansion. The seawater changes due salinity variations and therefore cause sea level changes (Cazenave *et al*., 2008). Over the 21st century, the IPCC's Fourth Assessment projected that thermal expansion will lead to sea level rise of about 17-28 cm (plus or minus about 50%).

Glaciers worldwide have made a larger contribution than the ice sheets recently, despite having only one percent of the total mass of ice on land. This is because they are in warmer climates, making them more sensitive to climate change. There is uncertainty in their contribution because there is a very large number of glaciers (over 100,000), of which scientists have monitored just a few hundred, and care is needed in treating these as representative. Nevertheless, there is reasonable agreement between observed and simulated changes in global glacier mass balance (Gregory, 2008). Changes in the volume of land ice results from mountain glaciers melting and change in the mass of ice sheet.

Terrestrial water storage includes water stored in subsurface saturated and unsaturated zones, in the snow pack and in surface water bodies. Anthropogenic activities have resulted in the partitioning of water between that stored on the continents and in the ocean, leading to changes in sea level. Human activities such as aquifer depletion and wetland drainage serve to divert water to the ocean that would have been otherwise stored in the continents (Sahagian and Vorosmarty, 2000).

Being a coastal country itself, South Africa has experienced several difficulties of sea level during the past million years (Cooper, 1995). Cooper further reports that sea level is expected to rise due to thermal expansion of the upper layers of the ocean, increased melting of alpine glaciers and possible melting of the Greenland and west Antarctic ice sheets. Like other vulnerabilities, sea-level rise will affect some areas than the other. However, the most likely impacts will be felt in the coastal regions.

Rising sea level affects the drainage of coastal wetlands, deforestation and reclamation, and enhance the discharge of fertilizers, sewage and contaminants in the coastal water. Additionally, rising sea level inundates wetlands and other low-lying lands, erode beaches, intensify flooding, and increase the salinity of rivers and bays. The shoreline would be threatened as communities, individual homes in low-lying zones became flooded, increasing sediment loading, and threatening submerged aquatic vegetation and shellfish (Wetlands watch, 2010).

There are several aspects of sea level rise that will affect the sustainability of coastal peoples and communities, but may or may not pressure people to move. It is well known that human activities cluster around coastal areas because of transport opportunities and proximity of seafood. Therefore, aspects such as salinization of groundwater and rising water table may seriously affect both residence and agricultural production (Oliver-Smith, 2009). However, even the modest sea level rise would have a substantial effect on human society (Darwin and Tol, 2001).

Dzhamalov (2006), states that these changes impair groundwater quality to the extent it does not meet water quality standards for use, thus partially or completely preventing specific types of consumption.

Groundwater pollution is directly related to the hydraulic parameters of the aquifer overburden. The deeper the groundwater level and the thicker the relatively impermeable beds overlying it, the lower will be the groundwater vulnerability to any types of pollutants (Dzhamalov, 2006). To some degree, groundwater vulnerability is determined by the contaminant attenuation.

Groundwater in rural areas is particularly vulnerable to pollution because of lack of knowledge of factors that cause pollution. The major sources of pollution in these areas include municipal, agricultural chemicals that seep into the groundwater system and mining activities.

The vulnerability of groundwater to pollution depends upon (Saayman and Sillilo, 2005):

- The time of travel of infiltrating water (and contaminants)
- The relative quantity of contaminants that can reach groundwater
- The contaminant attenuation capacity of the geological materials through which the water and contaminants travel.

Most pollutants are introduced in the environment as sewage, waste and accidental discharge. Open dumps are the oldest and the most common way of disposing of solid waste. In many cases, open dumps are located wherever land is available, without regard to safety, health hazard and aesthetic degradation. The waste is often piled as high as the equipment allows. In some cases, the refuse is allowed to burn while in some instances it is periodically leveled and compacted (Alshaebi et al., 2009). Furthermore, Alshaebi et al. reports that open dumps tend to be breeding ground for pests and therefore creating a health hazard, polluting the air, groundwater and surface water.

Municipal solid waste did not pose a significant problem until humans established settlements (Alshaebi et al., 2009) .Human settlements generate large quantities of waste. To manage this waste sewage networks are constructed. However, in rural communities there is lack of such networks, therefore resulting in the accumulation of waste and the pollution of water resources.

A great threat to groundwater quality in rural communities is the use of pit latrines because of the discharge of the waste before pre-treatment. Another source of groundwater pollution is the disposal of solid waste on land surface.

Cultivation of crops for food production and for economic benefit, and husbandry of livestock have long been dominant activities in human communities. Population growth and the increased food demand are the driving forces for expansion of agriculture. Fertilizers are therefore used to increase the agricultural productivity. The risk of groundwater pollution by nitrate depends on the interaction of the nitrogen loading and the vulnerability of the aquifer (BGS, 2009).

There are other sources of nitrate associated with farms and farming. Discharge of effluent from intensive livestock units and leachate from manure stores and leaking slurry pits, and slurry or manure spreading on land as organic fertilizer can all be sources of groundwater pollution (BGS, 2009).

In rural communities of South Africa, commercial agriculture is commonly practiced. Modern farming practices have increased the use of pesticides and fertilizers to meet the growing food demand and the rising population. Intensive use of chemical fertilizer on farms results in leaching of the residual nitrate causing high nitrate concentrations in groundwater (Kaur and Rosin, 2007).

South Africa is well known for being a leading supplier of variety of minerals and mineral products. Mines produce a variety of ores and potential contaminants depending on the ore deposit type. Typical mine pollutants include sulphate, salinity, acidity and metals, which may contribute to non-point pollution of surface water, groundwater (Figure 6) and atmospheric pollution (Heath et al., 2009). Mining pollution is related to water problems, largely associated with water quality deterioration due to oxidation of ferrous minerals (Usher and Vermeulen, 2006). Closed and abandoned mining operations in particular, appear to be the most significant threats in terms of potential groundwater contamination from the mining sector in South Africa, reports Heath *et al.*, 2009. Heath further states that the country is facing major problems with regard to the management and treatment of contaminated mine water.

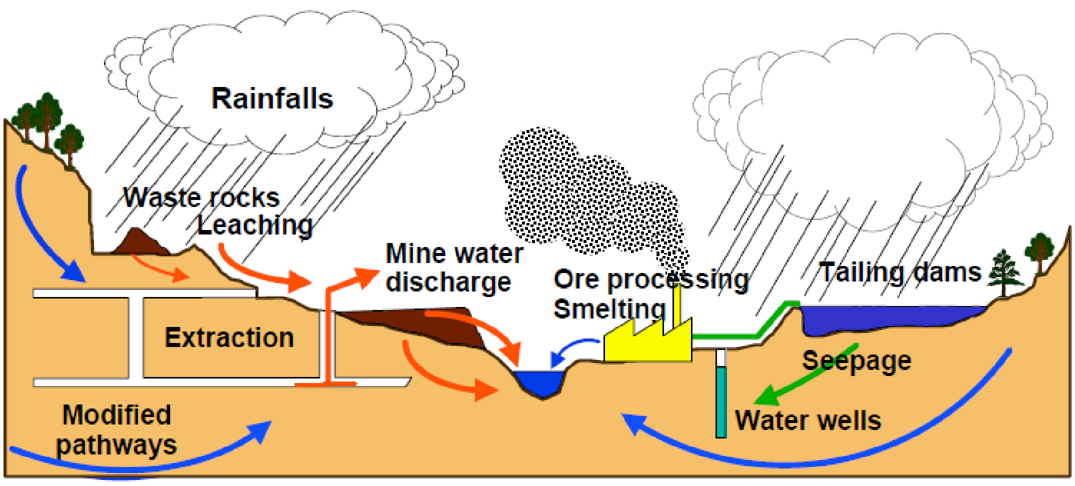

Figure 6: Global impacts of mining process on water (Taken from Cottard, 2001)

Other impacts associated with mining is the inappropriate placement of opencast and underground mining waste disposal facilities such as tailing dams and slurry ponds on surface or in open pits. These give rise to the seepage mounds, decrease water quality and change the rate and direction of groundwater movement (Ashton *et al*., 2001).

Social vulnerability refers to the inability of people, organizations, and societies to withstand adverse impacts from multiple stressors to which they are exposed. These impacts are due in part to characteristics inherent in social interactions, institutions, and systems of cultural values.

In a warmer world, there will be multiple impacts on human health. As a result of climate change, serious several diseases are likely to spread further. These would include vector-borne diseases like malaria, dengue and leishmaniasis, and water- borne diseases like cholera (Wakeford, 2008). In areas where public health infrastructure is weak or deteriorating, higher temperatures will cause expansion of malaria transmission zones to higher altitudes and possibly to higher latitudes (Smith, 2006). Lack of adequate health care will make many bad health- related situations even worse.

Poverty, which is already endemic in Africa, will be exacerbated by the stresses of changing climate (Wakeford, 2008). Variability in rainfall and temperature will cause variability in agricultural production and food security. Lower food security, because of reduced crop yields and increased impacts of extreme events on food supplies, is expected to increase malnutrition (Smith, 2006). In developing countries, the number of under-nourished people is currently estimated to be around 1.02 billion people (WFP, 2010).

Migration is a response of people whose livelihoods have been degraded by climate change. Shifting rainfall patterns and their impacts on water and food availability will force many people to migrate as climate change advances (Wakeford, 2008). Families that find it difficult to deal with environmental change resort to seasonal migration (The periodic movement of a population from one region or climate to another in accordance with the yearly cycle of weather and temperature changes). This practice is likely to become even more common, as is the practice of migrating from place to place in search ecosystems that can still support rural livelihoods (Adamo *et al*., 2009).

A study conducted by Adamo *et al*.(2009) on the impact of climate change on agriculture in Sahel shows that migration is a traditional coping mechanism in the region, representing a livelihood diversification strategy. However, in some areas these traditional patterns have changed in recent decades.

Combined social pressures may cause a competition over critical resources, especially water and food but also other forms of energy such as wood (Wakeford, 2008).

Competition: The arrival of environmental migrants can burden the economic and resource base of the receiving area, promoting native-migrant contest over resources. If the receiving area has fewer resources and property rights are underdeveloped, pressure is expected to rise with a number of migrants and residents (Reuveny, 2007).
Ethnic tension: Large-scale population displacement will redraw the ethnic map of many countries bringing previously separate groups into close proximity with each other. In the context of poor governance, poverty and easy access to small arms, these situations can easily turn violent (Brown, 2008).

Gender *inequality* is a situation where women and men have unequal conditions for realizing their full human rights and potential are unable to contribute equally to national political, economic, social and cultural development. (Banda & Mehlwana, 2005).

It is believed that both men and women will be faced with different vulnerabilities to climate change impacts due to existing inequalities such, as their role and position in society, access to resources and power relations that may affect the ability to respond to the effects of climate change (Babugura, 2010). However, the level of vulnerability to climate change for men and women will depend on their ability to cope with, to recover from or adapt to climate change and variability.

In Africa, women constitute 70 % of the workforce in the agricultural sector. This proves the dependence their on natural resources (Babugura, 2010). The effects of adverse impacts of climate change and environmental degradation on human health, such as waterborne diseases as a result of polluted water supplies, more extreme weather resulting in natural disasters, and changes in air quality and food quality, also have a particular impact on women in their role as principal caregivers (Agostino, 2010).

Women play a major role in the rural economies of both developed and developing countries. In most parts of the developing world, they participate in crop production and provide food and water for their families (UN, 2008). Despite all activities that women can carry out, they are still denied access and control over land and other productive resources. In South Africa, women constitute 51% of the total population (SSA, 2010) and they still face serious challenges in effectively carrying out multiple roles in their families and communities. Therefore, women and girls are the most vulnerable group in society.

Water collection is a major part of the work for women in rural areas. Scarcity of water increases the burden on women and girls of walking extended distances to get water, which put them at risk of gender based violence. Girls may miss the opportunity of attending school and women undertaking income-generating activities.

In some rural areas, land allocation remains a challenge to unmarried women and widows as preference is still given to men.

There are ways identified to influence the vulnerability of women to climate change (Banda & Mehlwana, 2005):

- Climate change could mean extra hardship for farming activities, which are often carried out by women.
- The task of supplying water and fuel for the family is typically the responsibility of women. This activity will also be affected by climate change with the many problems of accessing clean water supply.
- The increase in extreme events such as storms, floods and cyclones puts the burden of dealing with devastation and destruction on the women who keep the family together. During a time of catastrophe, the burden of nurturing the family, especially young children as well as providing the daily essentials is largely borne by women.
- Economic impacts of climate change will be much wider and more complex than the cost of relocating property, people, industry, agriculture and transport infrastructure from areas threatened by climate change (Brooks *et al*., 2006).

Any economic super structure and complex social organization cannot exist without a good foundation of producing enough food to feed its population. In most African countries, farming depends entirely on the quality of the rainy season (IPCC, 1998). Unfortunately, agriculture is the most vulnerable sector to climate change (Wakeford, 2008). A rise in mean winter temperature also would be detrimental to the production of winter wheat and fruits that need the winter chill (IPCC, 1998). It is expected that climate change will lower crop yields globally and thus lead to increased food prices.

Climate change impacts on industry vary widely by location and scale. The most vulnerable industries are those located on the coast or on the river floodplain and those who rely on climate sensitive resources.

In Africa, South Africa is known as the continent's industrial powerhouse, having long relied on the country's abundant coal reserves for cheap power. This historical advantage is now becoming a great challenge: how to lower the energy and carbon intensity of the economy. In any event, current projections are that South Africa will continue its coal dependence for decades, despite the contribution to global warming. The impact of this may have on trade with carbon-conscious countries is likely to be negative (Wakeford, 2008).

Climate is a major factor for tourists when choosing a destination. Tourism is one of Africa's fastest growing industries. It is based on wildlife, coastal resorts, nature reserves and an abundant water supply for recreation. Projected droughts and /or reduction in precipitation in the Sahel and eastern and southern Africa would devastate wildlife and reduce attractiveness of some nature reserves, thereby reducing income from current vast investments in tourism (IPCC, 1998). The likely impacts of climate change on tourism vary greatly according to location. Warmer climates open up the possibility of extending exotic environments, which could be considered by some tourists as positive but could lead to spatial extension and amplification of water and vector borne diseases (IPCC, 2007).

Coastal zones are characterised by a rich diversity of ecosystems and great number of socio-economic activities. The human population in these areas has been growing at double the national rate of population growth (IPCC, 1998). According to Smith, coastal areas will suffer additional impacts due to sea-level rise. Impacts will aggravate current pressures on coastal areas and ecosystems, with potentially disastrous effects in some locations (Smith, 2006).It is well noted that a growing number of large cities are located in coastal areas, which means that large amounts of infrastructure may be affected by climatic extremes (IPCC, 1998).

The coastal zone of east Africa will also be affected although this area experiences calm conditions through much of the year. However, sea level rise and climatic variation may reduce buffer effect of coral and patch reefs along the east coast, increasing potential for erosion. In South Africa, Cape Town could face very particular threats as many suburbs and settlements, as well as industrial sites, are situated on the low-lying Cape Flats. The worst-case scenarios could prove devastating for shipping infrastructure and hence international trade (Wakeford, 2008).

3 Vulnerability assessments and adaptation

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" (Doll, 2009).

3.1 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 the annual total rainfall, especially in semi-arid areas. An extended period of medium-intensity rainfall is more likely to lead to significant runoff and 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 runoff and recharge, depending on the daily rainfall distribution.

3.2 Vulnerability conceptual frameworks

Vulnerability conceptual frameworks are essential tools that assist in the development of methodology for measuring vulnerability (Birkmann, 2006). Vulnerability assessments show clear trends towards interdisciplinary analyses of the potential consequences of climate change; towards the integration of impact and adaptation assessments; and towards the integration of climate change with other stresses and concerns (Fussel and Klein, 2005).

This chapter presents reviews of vulnerability conceptual frameworks that are used in different fields to assess vulnerability to natural hazards which in the case of this study will be climate change.

3.2.1 Pressure and release model approach (PAR)

Pressure and release model (Figure 7) is a tool that underlines how disasters occur when natural hazards affect vulnerable people (Blaikie *et al.*, 1994). This model is primarily used to address social groups facing disaster events (Turner *et al.*, 2003). The basis for this model is that disaster is the intersection of two opposing forces: those processes generating vulnerability on one side, and the natural hazard event on the other (Blaikie *et al.*, 2004). It stresses the fact that vulnerability and the development of a potential disaster can be viewed as a process involving increasing pressure on the one hand and the opportunities to relieve the pressure on the other (Birkmann, 2006). Pressure and release model assumes that disasters are indirectly made possible by the power system of the society. It is based on the commonly used equation:

Risk= Hazard x Vulnerability

Within this model, vulnerability progresses in following three levels:

- **Root causes**: these are factors that determine access to and distribution of power in society. They include political system and economic infrastructure. Consequently, those at low economic levels tend to have less power over their sociopolitical and physical environment. Therefore, as a result vulnerability is greater for them (St.Cyr, 2005).
- **Dynamic pressure**: this level encompasses activities that transform and channel the effects of root causes into unsafe conditions. Examples include urbanization, epidemic diseases and violent conflict.
- **Unsafe conditions:** human vulnerability is revealed and it is expressed in temporal or spatial dimension. Examples are exposure of coastal dwellers to Tsunamis and lack of protection against diseases.

However, the shortcomings of this model are that it does not address the coupled human-environment system in the sense of considering the vulnerability of biophysical subsystems, it provides little detail on the structure of the hazard's causal sequence, including the nested scales of interactions; and it tends to underemphasize feedback beyond the system of analysis (Turner *et al.*, 2003).

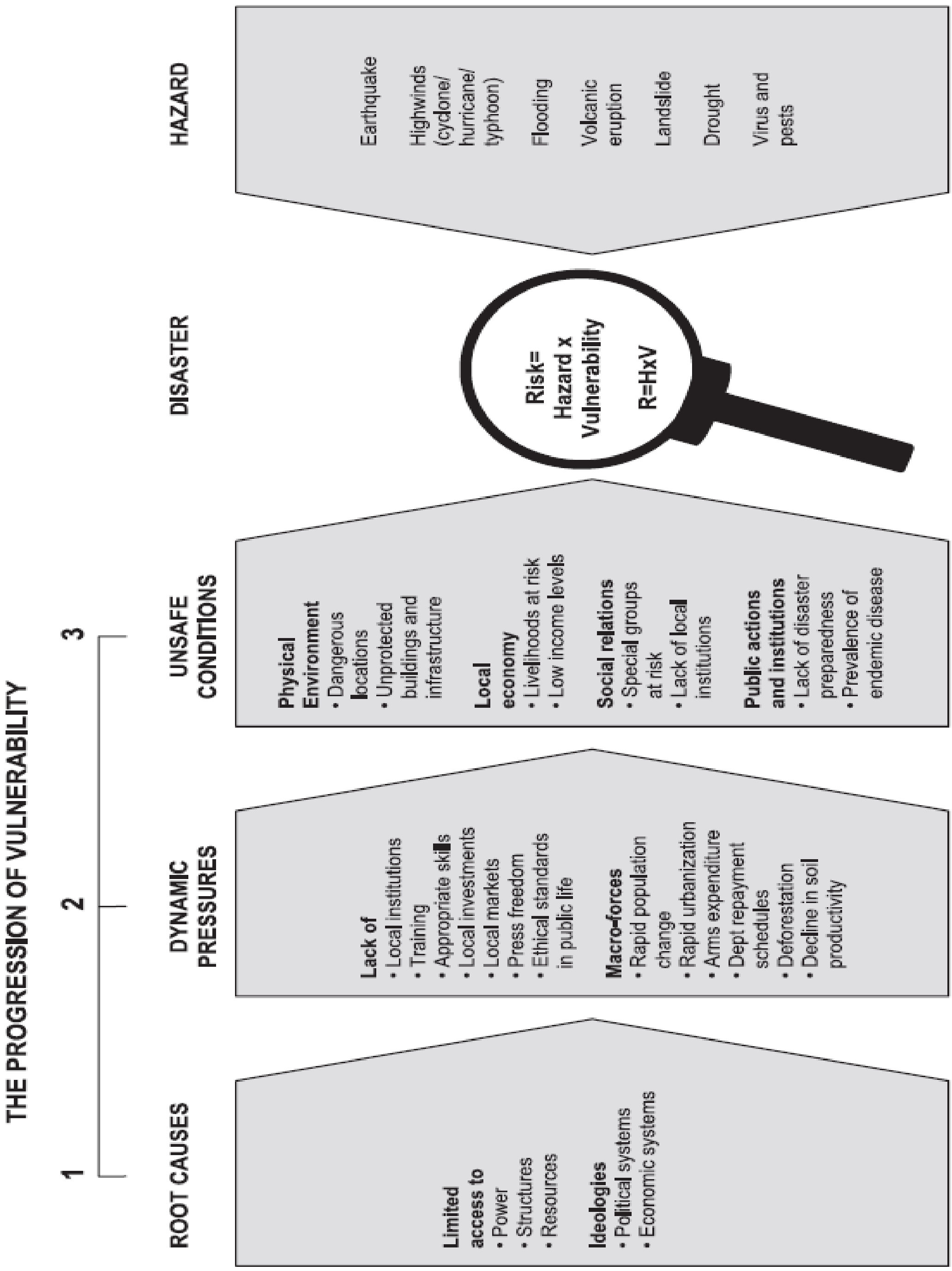

Figure 7: Pressure and release model (Taken from Birkmann, 2006)

3.2.2 Risk-hazard approach

The risk-hazard framework is applied to assess the risk to certain valued elements that arise from their exposure to specific hazards (Fussel, 2005). The framework assumes that hazard events are rare, and that the hazard is known and stationary. It distinguishes two factors that determine the risk to a particular system: the 'hazard', which is 'a potentially damaging physical event, phenomenon or human activity that is characterized by its location, intensity, frequency and probability' and 'vulnerability', which denotes the 'relationship between the severity of hazard and the degree of damage caused' (Fussel, 2006).

The framework is however difficult to apply to people whose exposure to hazards largely depends on their behaviour. Moreover, it does not treat the following: ways in which the systems in question amplify or attenuate the impacts of the hazard; the distinctions among exposed subsystems and components that lead to significant variations in the consequences of the hazards; and lastly the role of the political economy, especially social structures and institutions, in shaping differential exposure and consequences (Turner *et al.*, 2003).

3.2.3 Vulnerability analysis framework

This conceptual framework (Figure 8) was developed by Turner et al. (2003). Primarily this framework directs attention to coupled human-environment system. It clearly defines exposure, coping response, impact response and adaptation response as parts of vulnerability (Birkmann, 2006). Vulnerability analysis framework includes elements that are aimed at advancing sustainability. They are listed below (Turner *et al.*, 2003):

- Multiple interacting perturbations and stressors/stresses and the sequencing of them
- Exposure beyond the presence of a perturbation and stressor/stresses including the manner in which the coupled system experiences hazards
- Sensitivity of the coupled system to the exposure

- The system's capacities to cope or respond, including the consequences and attendant risks of slow recovery
- The system's restructuring after the response taken
- Nested scales and scalar dynamics of hazards, coupled systems and their responses.

This type of framework may be undertaken at any spatial or temporal scale suitable for the problem in question.

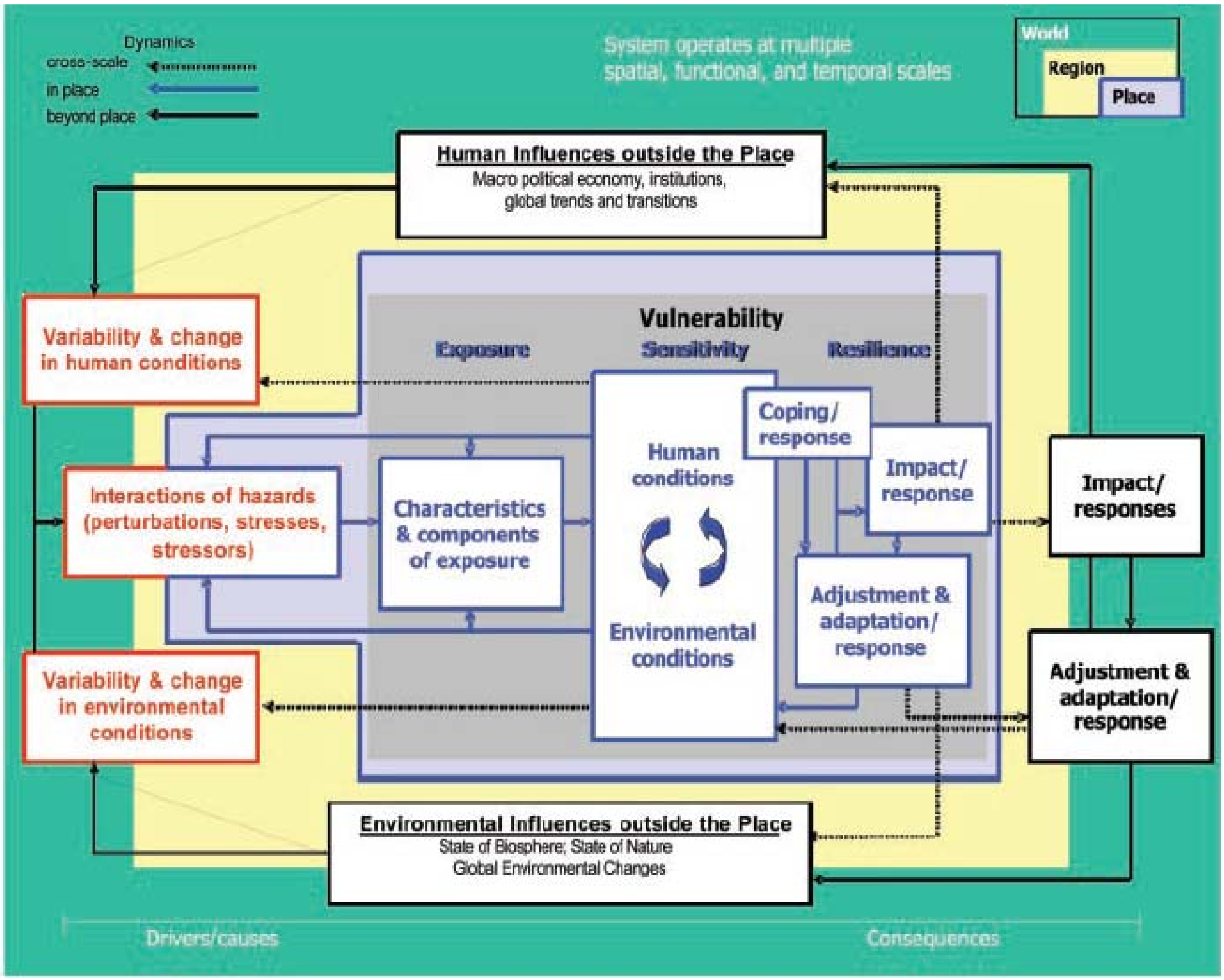

Figure 8: Vulnerability analysis framework (Taken from Turner et al., 2003)

3.2.4 Political-economy framework

The political-economy framework focuses its attention exclusively to people, seeking to analyze who is most vulnerable and why. It is based on an explanatory model of socio-economic vulnerability to a range of stresses and consequences (Fussel, 2005). According to this framework, vulnerability denotes the socioeconomic response capacity of individuals and groups to variety of stressors (Fussel, 2005). In its context, it defines vulnerability as *the state of individuals, groups or communities in terms of their ability to cope with and adapt to any external stress placed on their livelihoods and well-being*. It is determined by the availability of resources and, crucially by the entitlement of individuals and groups to all on these resources (Fussel, 2006). It is largely consistent with the starting-point interpretation of vulnerability.

3.2.5 BBC conceptual framework

BBC conceptual framework is linked to conceptual work done by Bogardi and Birkmann (2004) and Cardona (1999 & 2001), hence the name BBC. This framework is a combination of different elements of the above-mentioned frameworks (Birkmann, 2006). The BBC conceptual framework addresses various vulnerabilities in the social, economic and environmental sphere. It implies that the development of vulnerability indicators and the assessment of vulnerability should address on the one hand the susceptibility and exposure of different elements at risk in the economic, social and environmental sphere on the other it should also identify and assess coping capacities and potential intervention tools (UNU-EHS, 2006).

Moreover, the BBC conceptual framework (Figure 9) promotes a problem solving perspective, by analysing the probable losses and deficiencies of the various elements at risk and their coping capacities as well as the potential intervention measures, all within the three key thematic spheres. In this way, it shows the importance of being proactive in order to reduce vulnerability before an event strikes the society, economy or environment (Birkmann, 2006). Birkmann further points out that this framework stresses that the changes of vulnerability from one thematic dimension to another should be taken into account and viewed as a problem, since these shifts do not imply real vulnerability reduction.

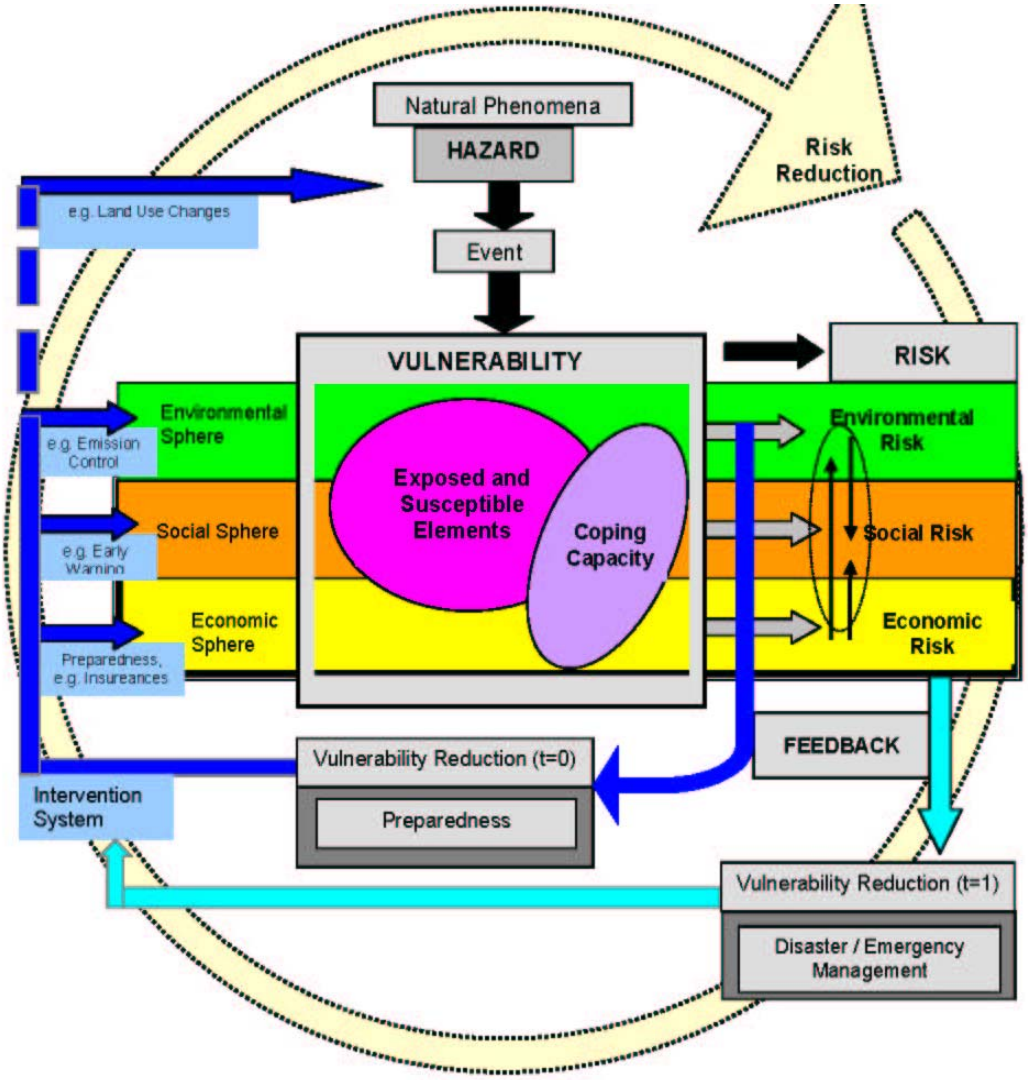

Figure 9: BBC Conceptual framework (Taken from UNU-EHS, 2006)

Vulnerability assessment is done to assist with the protection of water resources. The protection is done by allowing development planners to incorporate a specific consideration of water into their planning decisions (Saayman *et a*l., 2007).

In South Africa, it is physically and economically infeasible to protect all water resources to the same degree. Therefore, water resource protection will be prioritised according to (Saayman *et al*., 2007):

- The value of the resource
- The vulnerability of the resource
- The risk of adverse impacts on human health and ecosystems.

There are various models used to assess vulnerability including:

- Index models: These methods are based on combining maps of various physiographic attributes by assigning an index to each attribute. Index methods can assess vulnerability spatially over large areas and therefore can show vulnerability of the water resources in the region. With these methods, parameters depicting the physical properties of the system such as depth of water, river flow and lithology are mapped based on either existing data sets or field data. Subjective numerical values or ratings are then assigned to each parameter map. The rated maps are then combined to produce a relative indication of the vulnerability spatially over an area.

  The overlay method has evolved drastically because it makes use of parameter weighting system and GIS technology. These methods are however limited because of the subjective nature of the rating schemes, and because the hydrologic system is not explicitly represented. In addition, the index methods cannot differentiate between contaminants and hence are applicable to assessment of intrinsic vulnerability only.

- Statistical methods: With these methods, the response variable such as the frequency of the occurrence, concentration or probabilities are used. It based on the concept of uncertainty, which is described in terms of probability distributions for the variable of interest. These methods are typically used in places with diffuse sources of contamination, such as to detect nitrates over agricultural areas. Statistical methods begin by analysing and then mapping water quality from known sites such as wells or soil, the maps are then integrated into linear regression models in which the contaminant concentration is related to a series of factors such as geology, well depth or land use (Liggett and Talwar, 2009). The method has an advantage over index models in that it can be used when there is a specific interest for a particular contaminant over a large area and sufficient data of water quality exists.

- Process based simulation models: these methods use deterministic approaches to estimate time of travel, contaminant concentrations and the duration of contamination to quantify areas of high and low vulnerability. These approaches include analytical approaches and numerical computer models. To classify results into specific vulnerability categories, interpretation is required. With these methods, a representation of the flow system can be shown hence they are an ideal for determining the vulnerability of a source receptor such as a water well (Liggett and Talwar, 2009). On the contrary, these methods are data intensive and require extensive resources to develop. In addition, they are typically applied at local scales to determine well vulnerability, rather than at regional scales.

3.3 Adaptation

Adaptation to climate change is the adjustment of the system to moderate the impacts of climate change, to take advantages of new opportunities or to cope with the consequences (Adger *et al.*, 2003).

With such an overwhelming evidence of climate change, a serious effort on understanding of adaptation measures must be undertaken and adaptive capacity of most vulnerable societies must be enhanced.

It has been noted that in developing countries, adaptation may take a form of reducing dependence on vulnerable systems such as diversifying food production away from a limited number of drought prone crops while rural dwellers may migrate to urban areas in times of short water supply (Adger *et al.*, 2003).

3.3.1 Adaptation measures

3.3.1.1 Agricultural sector adaptation

Agricultural production remains the main source of income for most rural communities in the region, adaptation of the agricultural sector is imperative to protect the livelihoods of the poor and to ensure food security. A better understanding of farmers' perceptions of climate change, ongoing adaptation measures, and the decision-making process is important to inform policies aimed at promoting successful adaptation strategies for agricultural sector (Bryan *et al., 2009*).

Bryan *et al*. (2009) further reports that the most common adaptation strategies include:

- Use of different crop or crop varieties
- Planting trees
- Soil conservation
- Change planting dates and irrigation

3.3.1.2 Adaptation to sea level rise (Brooks et al., 2006)

- Improvements in physical infrastructure (including transport infrastructure)
- Watershed management that avoids deforestation

- Stabilization of slopes with vegetation
- The prevention of the encroachment of settlements onto floodplains and unstable slopes the provision of safe housing and agricultural land for the very poor and marginalized
- Policies that support rural livelihoods, thus reducing the growth of informal settlements in vulnerable areas at the periphery of cities, which often are situated in highly exposed coastal areas.

3.3.1.3 Community-based adaptation

According to Munasinghe and Swart (2005), attributes of adaptive capacity needed to incorporate climate change adaptation into community-based development include:

- Availability of information and skills: people can use information about vulnerability and the nature of climate change in devising new risk management and livelihood strategies. Skills are needed to use this information effectively in planning and facilitating community-level projects, and in adapting and applying technologies. Information and skills need to be supported by access to appropriate education and training.
- Effective institutions: communities benefit from access to support and services provided by well-organized institutions with flexible and appropriate policies in place in government, research, education, civil society and the private sector. Effective community-based organizations are key to informing and mobilizing local communities and assisting them in incorporating adaptation into development activities.
- Access to technology: many adaptation approaches involve use of technology, such as protective designs for building homes, flood control structures, early warning systems and crop breeding. Farmers may need new techniques for storing water, improving drainage and conserving soil. Capacity to develop and adapt technologies to local needs increases adaptation options and enable local enterprise development.
- Economic resources: increasing incomes and improving access to financial resources is likely to give poor people more options for coping with climate change impacts. Ability to adapt is therefore strengthened by, for example,

access to micro credit schemes, development of markets and local enterprise development to open new livelihood options that are resilient to climate impacts.

3.3.1.4 Gender inequality

It is highly essential to identify gender sensitive strategies for responding to the environmental and humanitarian crises caused by climate change. To enhance adaptation to climate change, it would be wise to provide access to basic services and infrastructure, improve access to markets and assisting them with resources to encourage agricultural production (Babugura, 2010).

Women are effective agents of change in relation to both mitigation and adaptation. They have a strong body of knowledge and expertise that can be utilized in climate change mitigation, disaster reduction and adaptation strategies. Therefore, their full knowledge and expertise must be taken into account.

4 Quantifying groundwater related climate change impacts

4.1 Introduction

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 technique.

4.2 General circulation models

Global GCMs have become the primary tools for the projection of climate change. Bates et al. (2008) describes a GCM's as numerical representations 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). GCM's are the basic tool used for modeling 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. GCM's depict the climate using a three dimensional grid over the globe as shown in Figure 10. The GCM's 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 on which typical groundwater studies are carried out.

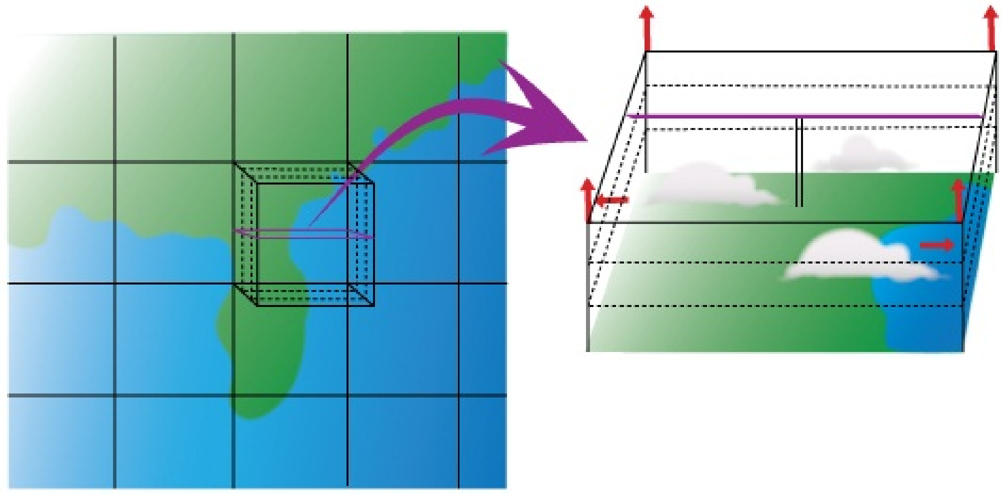

Figure 10: Graphical representation of a GCM (Adapted from Ucar, 2010)

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 observed climate change data 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.

4.3 Down scaling

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

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

Figure 11 shows a graphical representation of the downscaling concept.

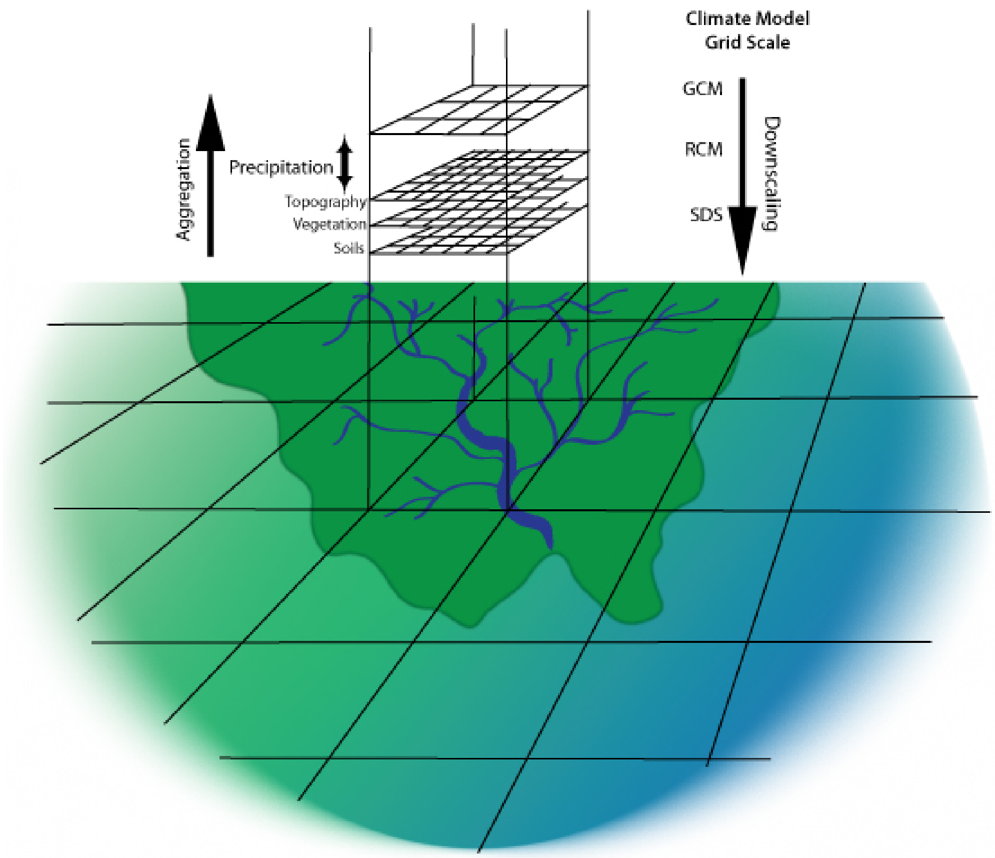

Figure 11: Graphical representation of the downscaling mechanism (Adapted from Wilby and Dawson, 2007)

Bates *et al.* (2008) distinguishes 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 variable with local/regional climate variables. The quality of the downscaled product depends on the quality of the driving model.

4.4 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 and Loaciga, 1993).

In Cavé *et. al* (2003) study, 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 impacts of future climate changes (Cave *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 impacts of climatic change on groundwater resources. Data was used from various studies, and then compared recharge rates as a function of annual rainfall for Southern Africa, found that for areas with an annual rainfall of less than 500mm/annum, large differences in recharge values were found. The observed rainfall-recharge relationship (Figure 12) to be used as a tool to examine possible groundwater trends if the projected changes in mean annual precipitation occurs as a response to human induced climate change. Groundwater recharge becomes negligible for rainfall lower than 400mm/a.

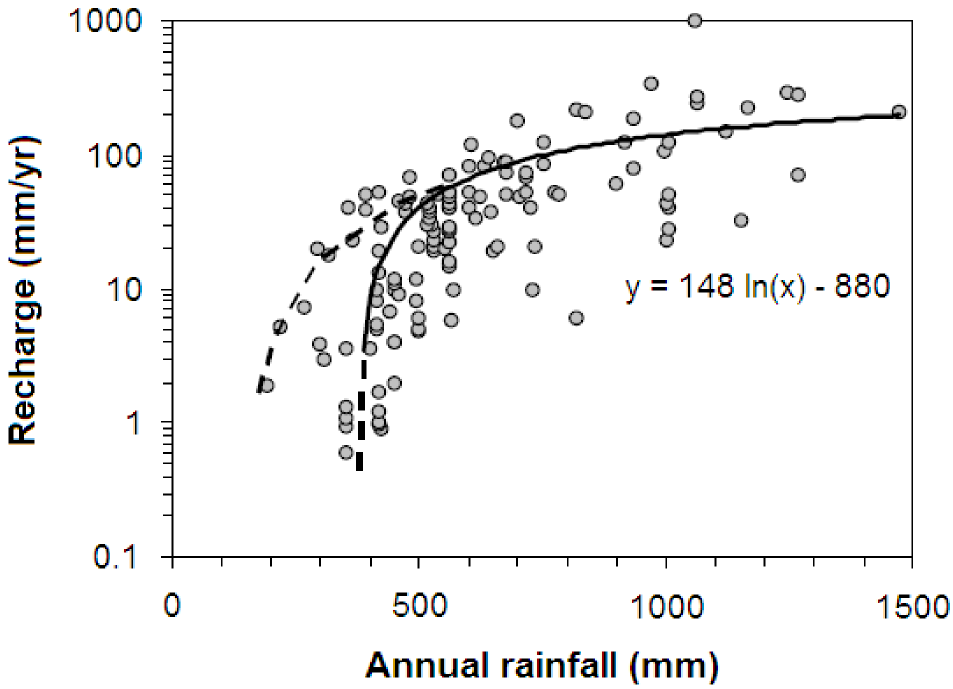

Figure 12: Recharge rates in South Africa (Taken from Cavé et. al, 2003)

Aquifer recharge and groundwater levels interact, and depend on climate and groundwater use; each aquifer has different properties and requires detailed characterization and eventually quantification (e.g., numerical modelling) of these processes and linking 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 of scale of project and availability of geohydrological and climatic datasets. However, this method requires intensive data.

Another method proposed by Van Tonder (2010) is to utilize 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 stream flow 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.

5 Description of the study area

5.1 Location

This study focuses its attention on South Africa as a whole. South Africa is a country on the southern tip of the African continent (Figure 13). It covers an area of 1.2 million square kilometers. On the eastern side, it is bordered by the Indian Ocean while the Atlantic Ocean borders it on the western side. Along the northern borders lies Namibia, Botswana, Zimbabwe whereas on the northeastern border lies Mozambique and Swaziland, with Lesotho being enclosed by South Africa.

Figure 13: Location

5.2 Climate

South Africa is often influenced by high-pressure systems of the subtropical high-pressure belt and therefore the climate is classified as subtropical climate. Due to the high-pressure system, the western half of South Africa has a semi-arid climate (DST, 2010). It is well noted that factors such as topography and the surrounding oceans control the climate of the country. The western, southern and the eastern escarpments lead to a high plateau of about 1250 mamsl. The plateau experiences hot summers and cold winters, but the oceans moderate the climate of the coastal plains, providing milder winters (Davis, 2010). The warm Agulhas current causes the eastern coastal areas to have a warm and humid, whilst the cold Benguela current along the west coast contributes to the arid climate of this region (DST, 2010).

South Africa experiences warm climate and much of the country has average annual temperatures of above 17^{o}C (Figure 14). The southern and eastern escarpments are the regions with the lowest temperatures, due to decrease in temperature with altitude (Engelbrecht & Landman, 2005).

The average annual rainfall is approximately 500mm (considerably less than the world average of 860mm). Most of the central and eastern parts of the country enjoy summer rainfall, whilst the western side of the country is the winter rainfall region.

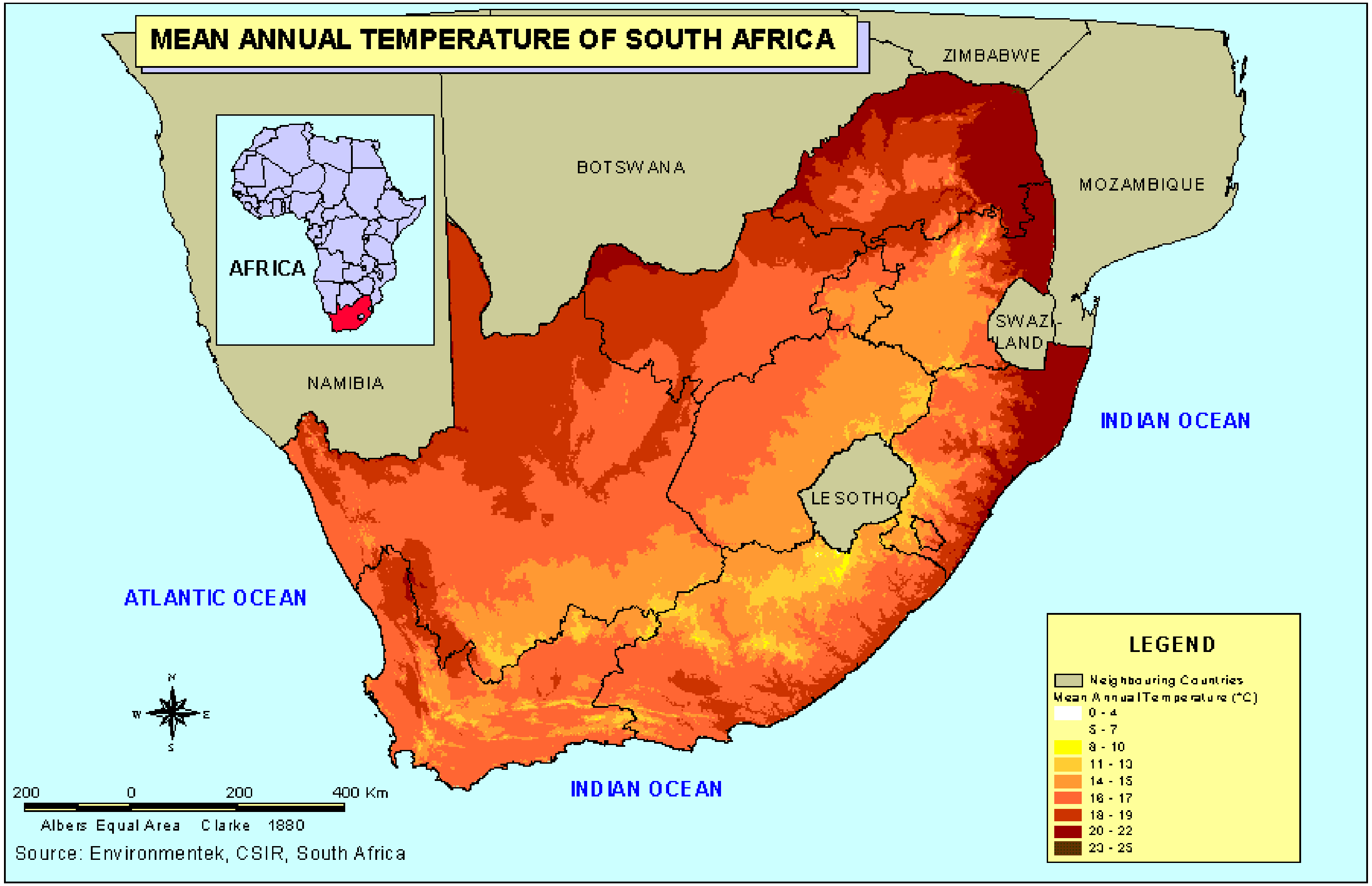

Figure 14: Mean temperature (Source: http://www.environment.gov.za)

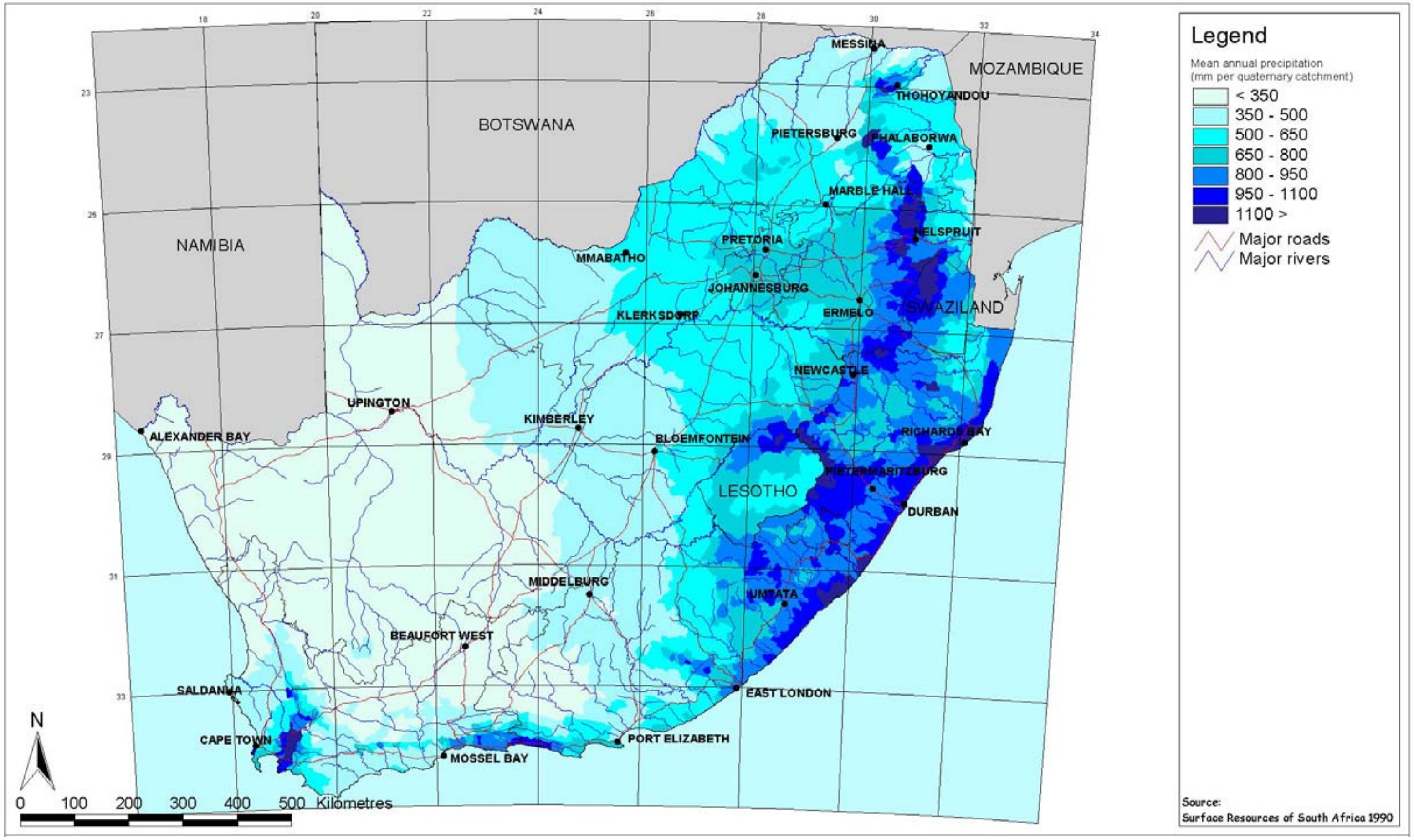

Figure 15: Mean annual precipitation (Source: http://www.environment.gov.za)

5.3 Geology

It was about 3500 million years ago when the earliest known rocks were being poured out over several large sections of South Africa. Through the following millions of years, geological shifts from tectonic arching, breaking and the formation of crevasses, the resulting eruptions of volcanoes, depressions, to the deposition of gravel and wind and water erosion were all hard at work shaping the country's geological profile as we know it today.

It is not uncommon to say that the geological history of South Africa is complex and its complexity is revealed in its stratigraphy. The South African stratigraphy is briefly outlined below.

5.3.1 Barberton Supergroup

The Barbeton supergroup is known to provide the first glimpse of the large scale geological process involved in forming the earth. This Supergroup comprises of two main components of layered pile of volcanic and sedimentary rocks perhaps 20 km thick. The originally horizontal volcanic and sedimentary rock pile has been folded on itself in the form of a trough and the layers now stand on edge (McCarthy & Rubige, 2005).

5.3.2 Witwatersrand Supergroup

The Witwatersrand Supergroup divided into two groups, the West Rand Group and the Central Rand Group. The West Rand Group is dominated by foredeep shales and sandstones while the Central Rand Group is composed largely of alluvial sandstones and auferous conglomerates (Jolley et al., 2003). Within this group also there is ripple marked quartzite and volcanic tuff.

5.3.3 Ventersdorp Supergroup

Overlying the central Rand Group of the Witwatersrand Supergroup is the Ventersdorp Supergroup. This Supergroup comprises of ultramafic and mafic lavas succeeded by the mixed mode volcanics and sediments.

5.3.4 Transvaal Supergroup

This Supergroup is characterised by two basins, the Transvaal basin and the Giqualandwest basin. The Transvaal basin has four groups which consist of quartzite, minor lava bands, conglomerate, shale, dolomite, banded iron formation. While the Griqualandwest basin comprises of three groups that are made up of quartzite, shale, dolomite, banded iron formation, diamictite, purple quartzite, schist and lava. (Lurie, 1994).

5.3.5 Bushveld Igneous Complex

This Supergroup comprises three different groups of igneous rocks. The oldest is a series of volcanic rocks, followed by basaltic magma that did not reach the surface. The intrusive basalt instead formed a large underground chamber, the largest known in the world, stretching 400 x 300 km across Limpopo, North West and Mpumalanga provinces and attaining a maximum thickness of 8 km. Finally, a very different magma was intruded above the older basaltic body and crystallized as granite (McCarthy & Rubige, 2005).

5.3.6 Karoo Supergroup

The Karoo Supergroup outcrops in an elliptical northeast to southwest area covering three-fourths of South Africa. Towards the southwestern part it rest conformably upon the Cape Supergroup. The supergroup is subdivided into four groups.

- The Dwyka group forms the base of the sequence and is encountered in all nine provinces. This group is dominated by the tillites.
- The Ecca group also occurs in all nine provinces. It consists of greenish-grey shale, sandstone, arkosic sandstone and coal seams.
- The Beaufort group is made up of mudstone with interbedded sandstone. Within its formations, coarse sandstone, shale and fine grained sandstone are encountered.
- The Drakensberg and Lebombo groups are dominated by basaltic lavas.

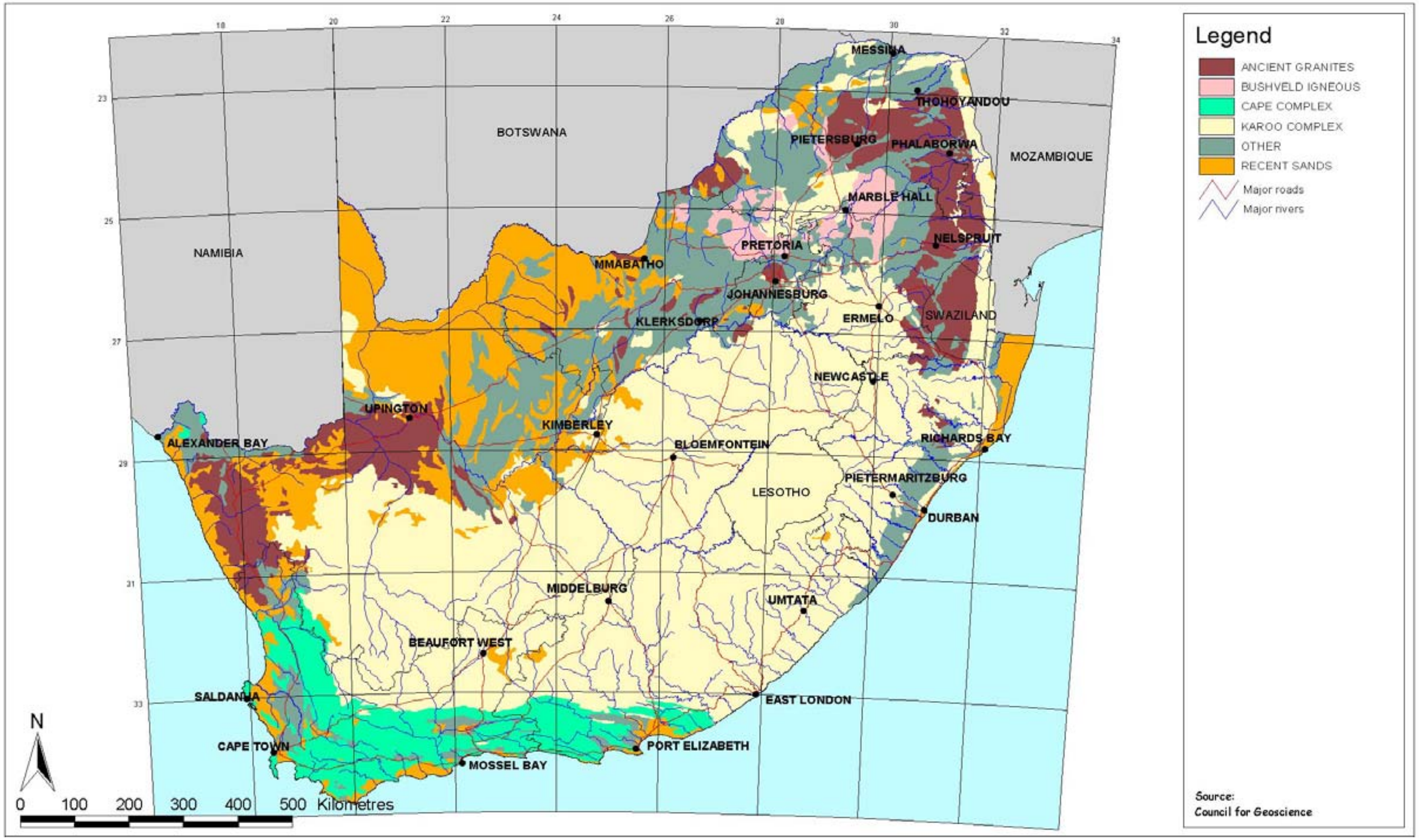

Figure 16: South African geology (Source: http://www.environment.gov.za)

5.4 Geohydrology

Geohydrology of South Africa is characterized by predominantly secondary aquifer conditions, with groundwater occurrences being controlled by geological settings and structural features such as faults and fractures (DWAF, 2006).

More than 80 % of South Africa is underlain by relatively low yielding, shallow, weathered and/or fractured- rock aquifer systems. By contrast, appreciable quantities of groundwater can be abstracted at relatively high rates from dolomitic and quartzitic aquifer systems located in the northern and southern parts of the country as well as from a number of primary aquifers situated along the coastline (Woodfood & Rosewarne, 2005).

Most exploitable groundwater occurs in the eastern and northeastern parts of the country and in the Western Cape, where aquifers are concentrated. Although the results of studies vary considerably as to the estimated quantity of groundwater in South Africa, the latest data indicate that of a total of 235 000 Mm^3/a that is stored, between 10 000 Mm^3/a and 16 000 Mm^3/a are available for use in an average rainfall year, and 7 000 Mm^3/a in a drought year (DEA, 2007).

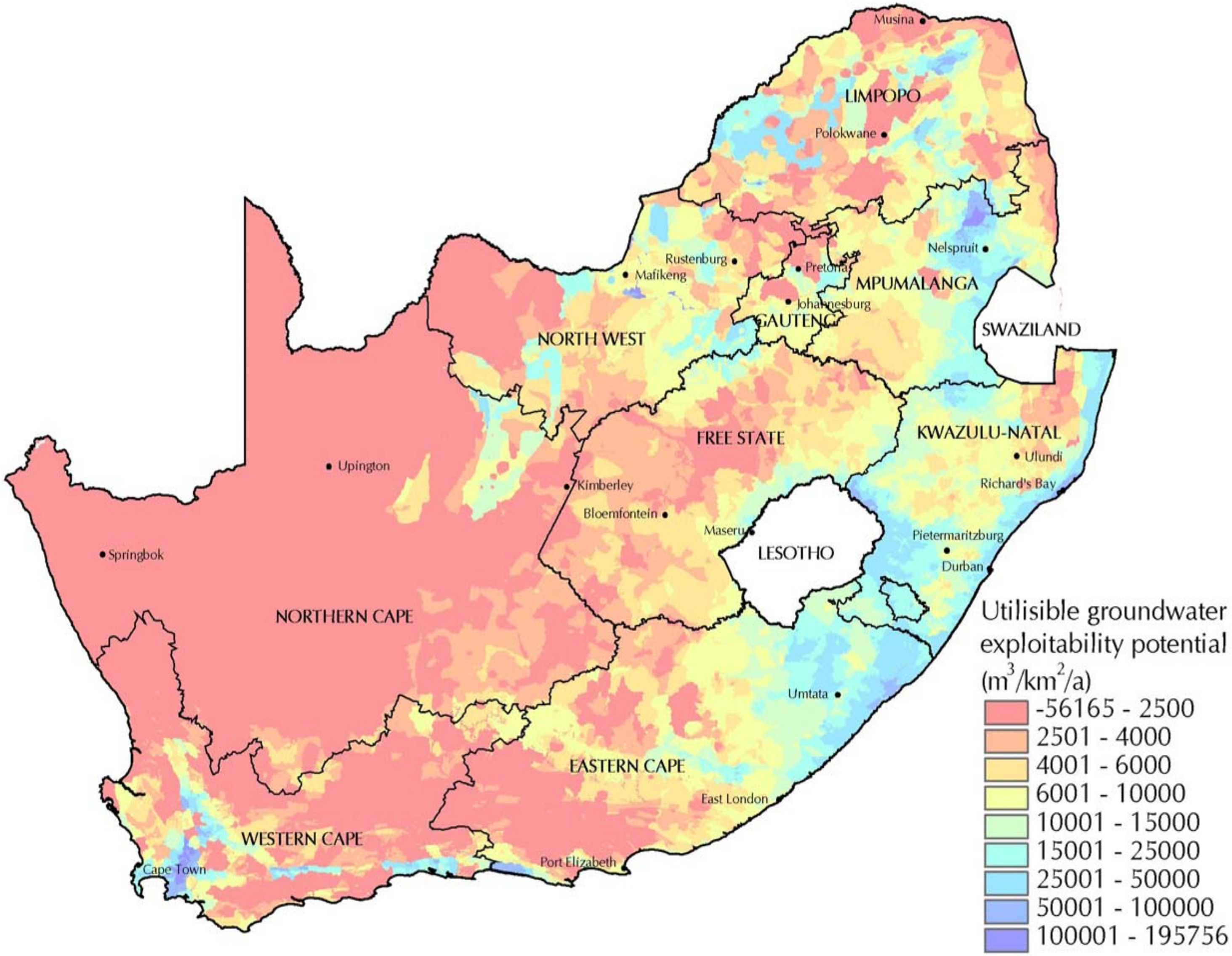

Figure 17: Groundwater potential (Source: DEA, 2007)

5.5 Social issues (taken from http://soer.deat.gov.za)

The settlement typology (Figure 18) for South Africa is defined as:

- large metropolitan areas (over 2 million people),
- large cities (500 000 to 2 million),
- medium sized cities/large towns (100 000–500 000), and
- medium sized towns (50 000–100 000).
- small towns (fewer than 50 000 people);
- displaced urban or dense rural settlements (fewer than 50 000);
- large rural villages (5 000–50 000 people); and
- small rural villages and scattered settlements (fewer than 5 000).

To understand South African settlement typology, geographic location and distribution also need to be considered. Settlements are defined by their relative location within and adjacent to urban cores, as well as in terms of their economic divisions, whether they are in the core of cities, or on the fringe or periphery, or at some distance from them. In addition to their spatial location, settlements can also be differentiated as planned and unplanned, formal and informal, and comprising a range of housing types.

Unplanned settlements evolved as people settled in areas that were closer to employment opportunities. They have occurred in various locations, these being within planned townships, on open land within an urban area, or in peri-urban areas. Peri-urban squatter settlements typically develop on farms or smallholdings situated on the outskirts of cities and towns.

Planned informal settlements have evolved through site-and-service schemes, where the identification and preparation of land before settlement takes place and includes the provision of basic infrastructural services. There has been wide in situ upgrading of existing informal settlements, which involves the provision of secure tenure and the service infrastructure required to promote the health and safety of people living and working there.

Access to potable water and sanitation are essential elements for the effective function of human settlements, and are integral to human health and well-being. Since 1994, there has been an improvement in access to clean water. In 2001, 9.5 million households (84.5%) had access to piped water, an increase of 2.4 million households since 1996. The lowest percentages of households with access to piped water occur in areas of the Eastern Cape and KwaZulu-Natal.

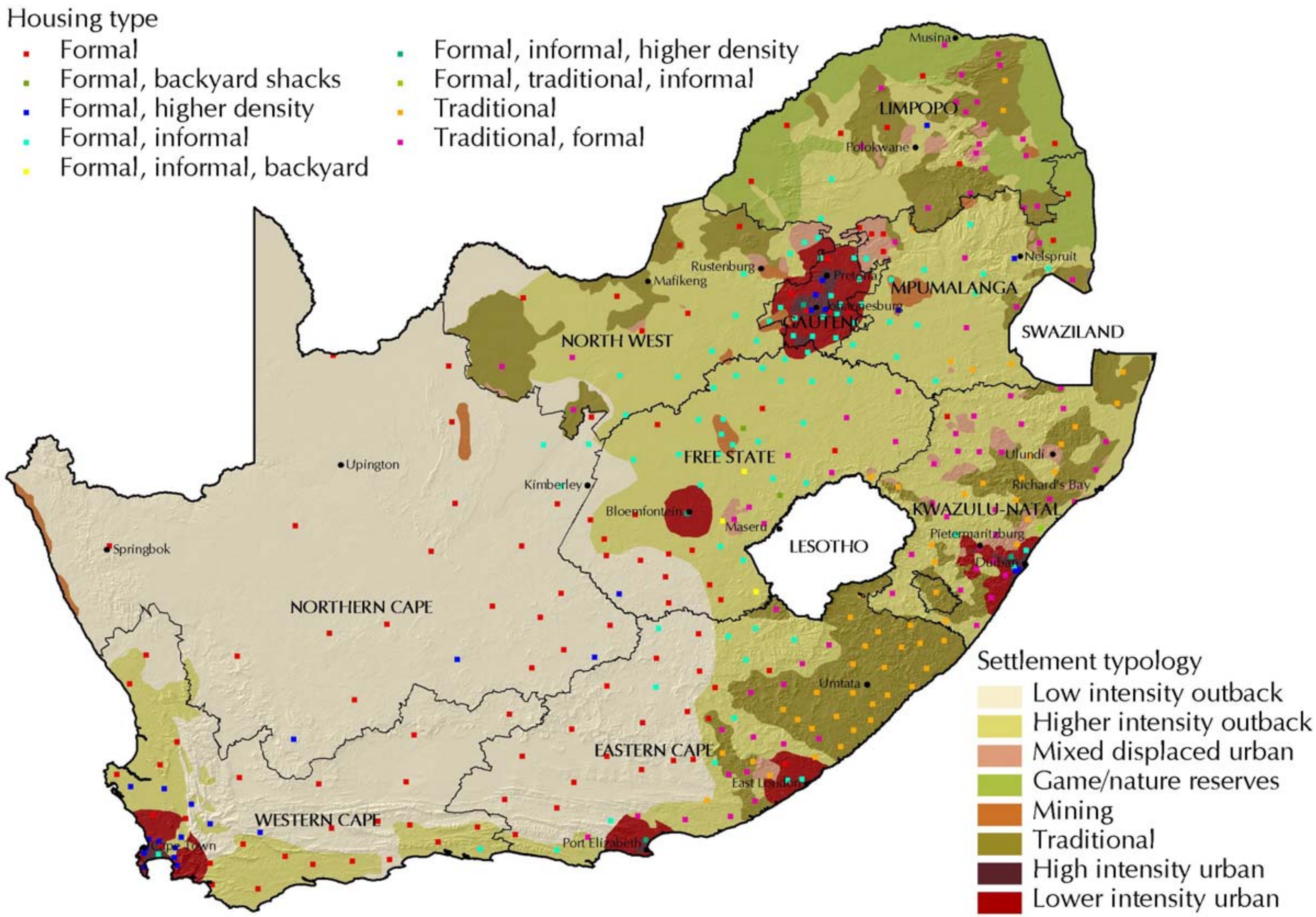

Figure 18: South African settlements (Source: http://soer.deat.gov.za)

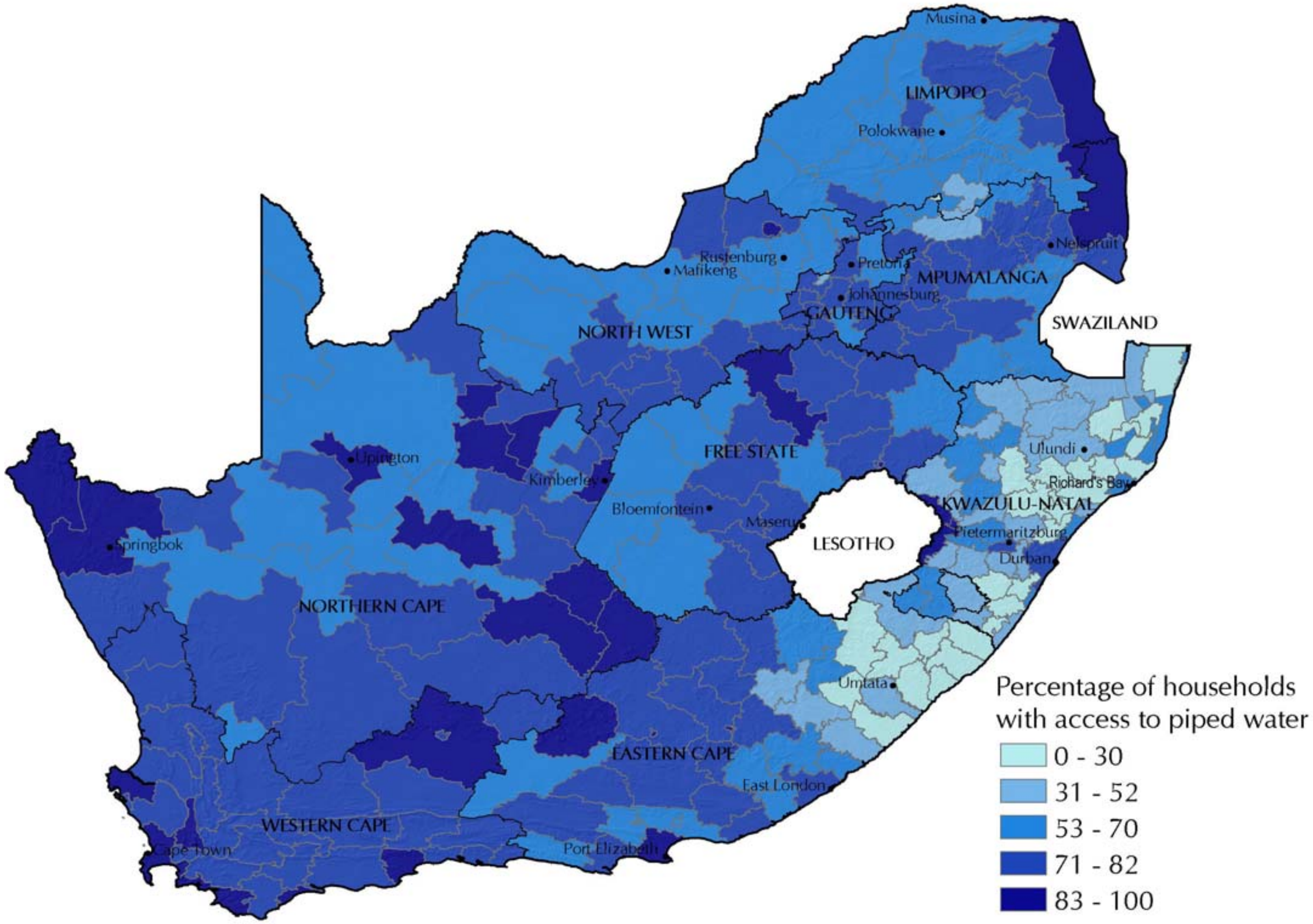

Figure 19: Households with access to piped water (Source: http://soer.deat.gov.za)

6 Methodology

6.1 Introduction

In 2001, the Department of Water Affairs and Forestry led a water sector support programme called Masibambane partnership. It is a partnership between Department of Provincial and Local Government, the South African Local Government Association, the European Union and its member states, the Swiss Government and the Ireland aid.

It was within the third phase of Masibambane programme that Water for Growth and Development theme was developed. Water for Growth and Development strategy aims to provide clear, accessible information to inform decision-making at all levels. To harness the productive potential of water at the same time limiting its destructive impacts in order to ensure that water is allocated equitably and sustainably as a resource which can leverage growth and development (DWA, 2008)**.** In pursuit of fulfilling the aims of the Water for Growth and Development this dissertation undertook a study to gain better understanding of the impacts of climate change on groundwater and develop a vulnerability index.

This chapter presents the study's selected methodology. As shall be seen, the methodology is analogous to the well known DRASTIC methodology of vulnerability assessment of groundwater to pollution.

The first step in our approach involves the creation of a climate change groundwater 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 the 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.

The next step is to access the potential human related impacts due to climate induced groundwater changes. Human vulnerability is defined as the interface between exposure to the physical threats to human well-being and the capacity of people and communities to cope with those threats. It is strongly linked to the complex make-up of society, including class, gender and age, past loss and misfortune, and susceptibility to future losses. It is outside the scope of this study to develop a detailed vulnerability methodology for this – however a basic qualitative methodology will be developed to provide an indication of when adaptation strategies should be considered.

6.2 DART Methodology

6.2.1 Introduction

In analogy with the DRASTIC methodology the DART methodology was developed. 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 focus more on typical parameters used in sustainability studies, but also indirectly accommodate the issue of quality due to the fact that the 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 the 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 Organization)
- CSIR0_MK3_5 (Commonwealth Scientific and Industrial Research Organization)
- 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.

6.2.2 Depth to water level change

The depth to water level was determined for the South African 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 20, allowing the use of a Bayesian approach for water level generation in areas where no water level data is available.

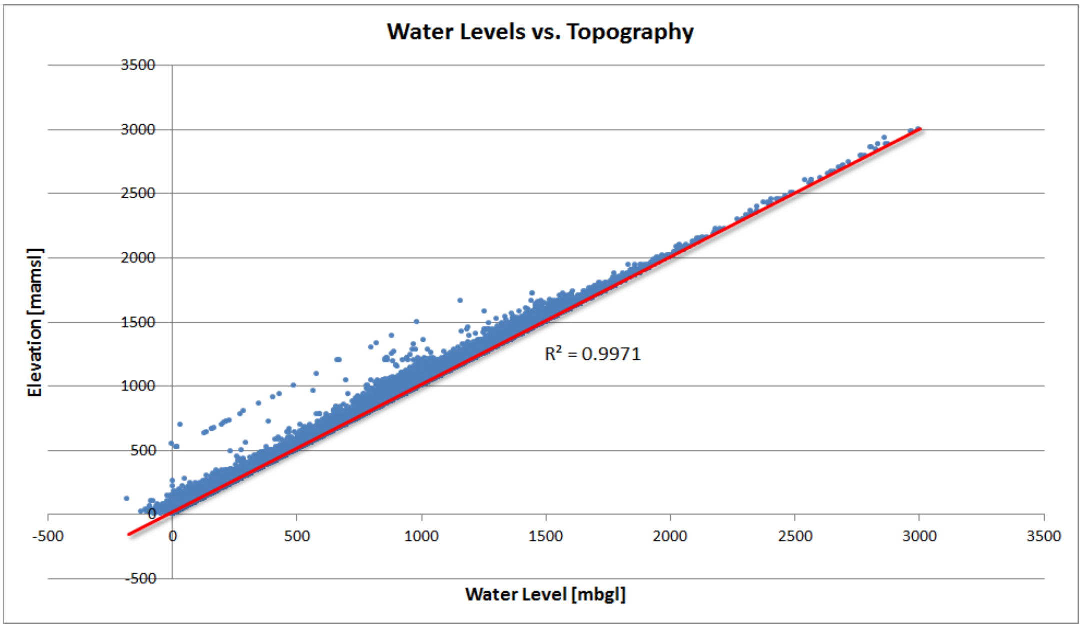

Figure 20: Water levels vs. topography

It is worth mentioning that the extremely high correlation value is obtained because such a wide range of values are considered. A map of the resultant water levels is shown in Figure 21. These water levels are used as the reference level for the current climate scenario.

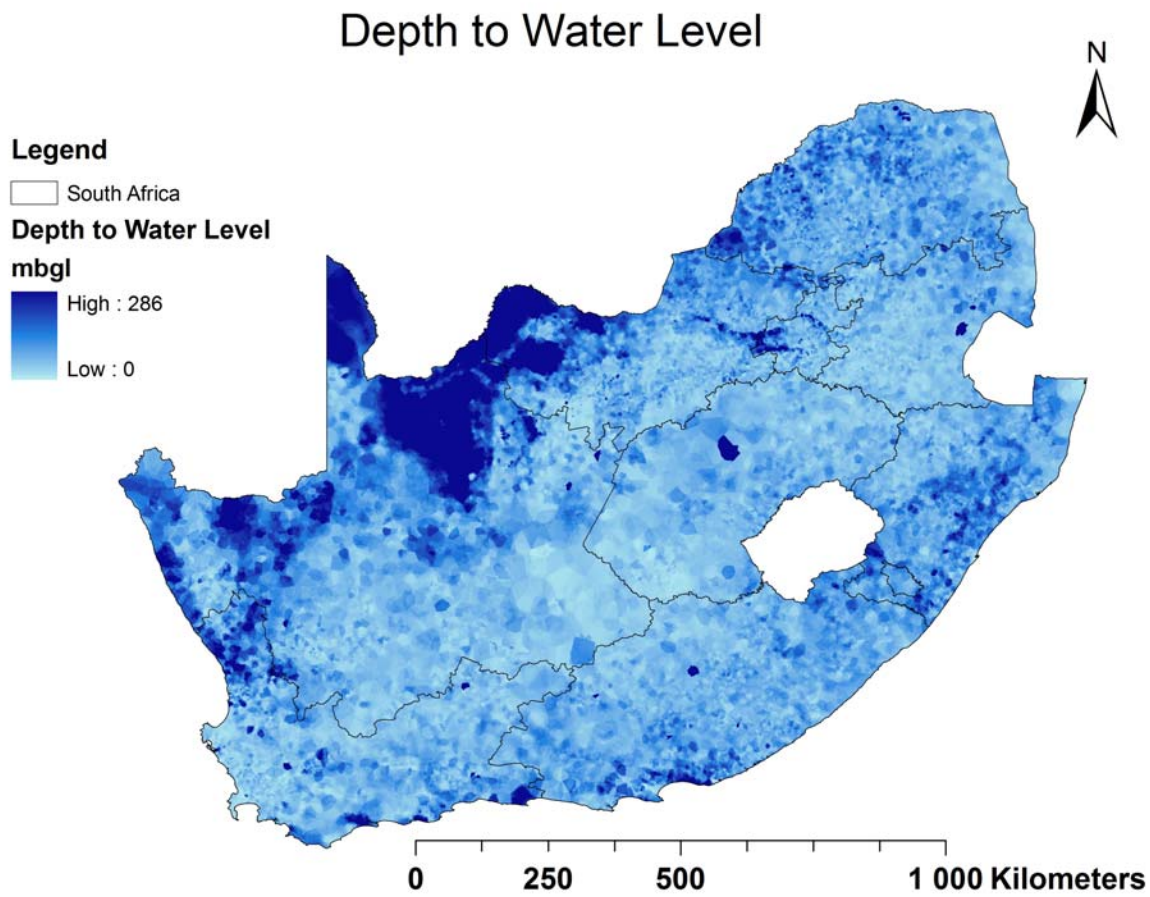

Figure 21: South African depth to water levels

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

$$\Delta Water\ Level = \frac{\Delta Recharge}{Storage\ Coefficient}$$

It is clear from the relationship that the 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 22 shows the monthly water level change between the current and future scenario.

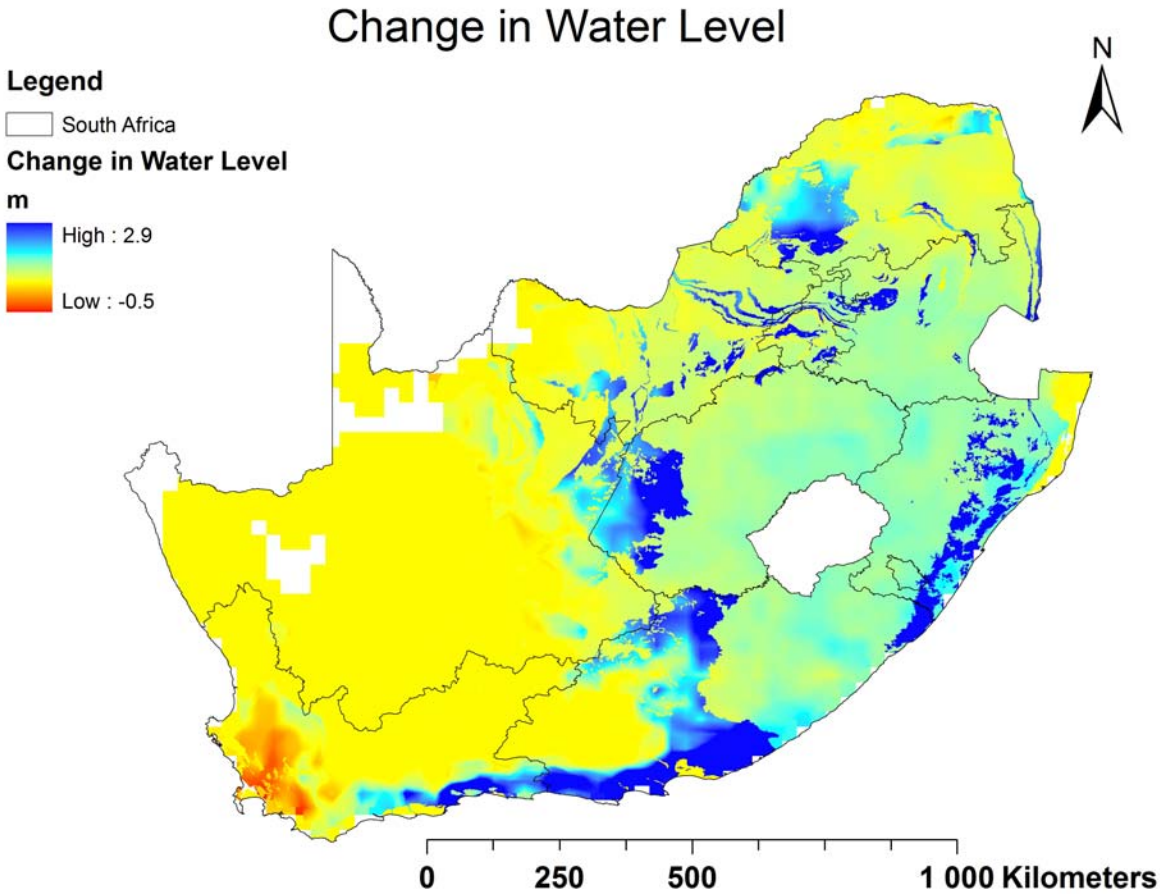

Figure 22: Water level change between current and future scenario

6.2.3 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 used in the Groundwater Decision Tool (Dennis, 2001). The resultant map of aquifer types are shown in Figure 23.

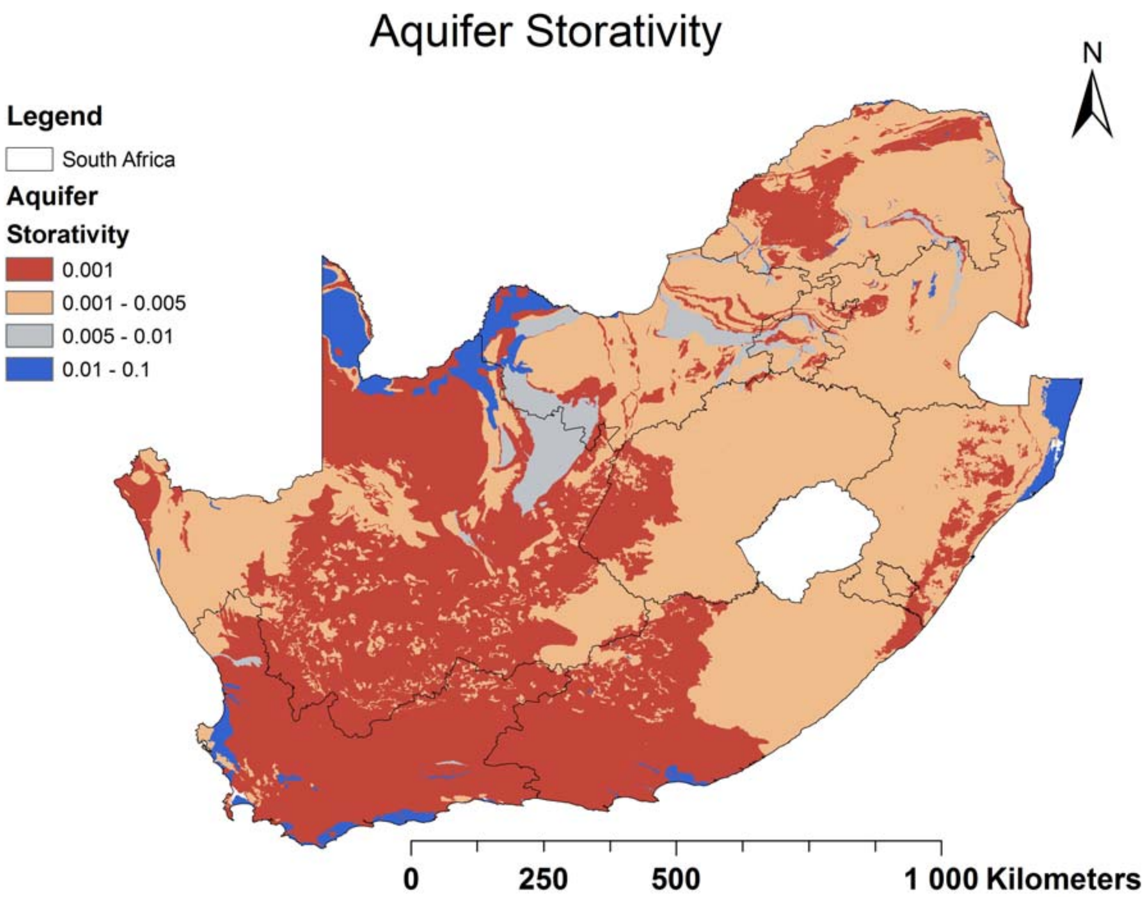

Figure 23: Aquifer type based on storativity

6.2.4 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.

6.2.4.1 Precipitation

The current and future annual precipitation distribution is shown in between the current and the future scenario as shown in Figure 24 and Figure 25 respectively. The difference between the current and future scenario is shown in Figure 26.

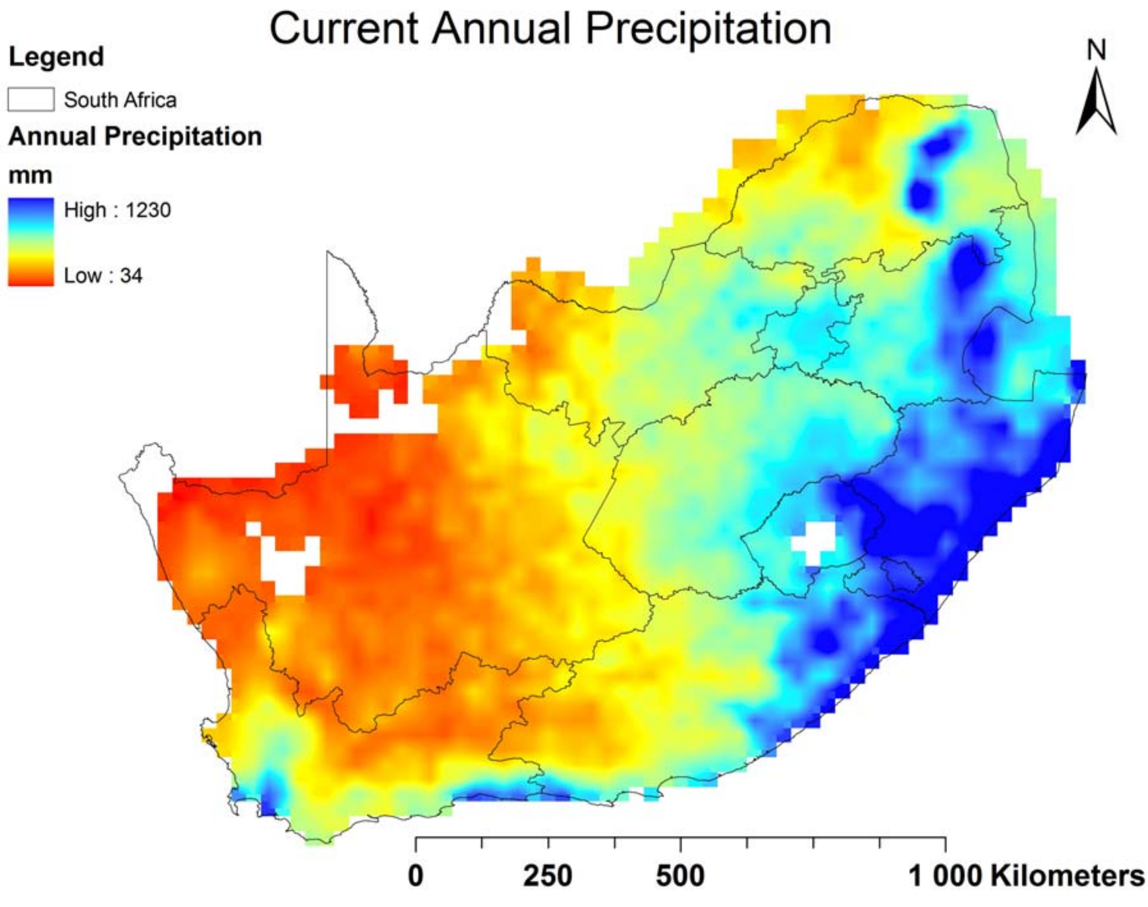

Figure 24: Future annual precipitation

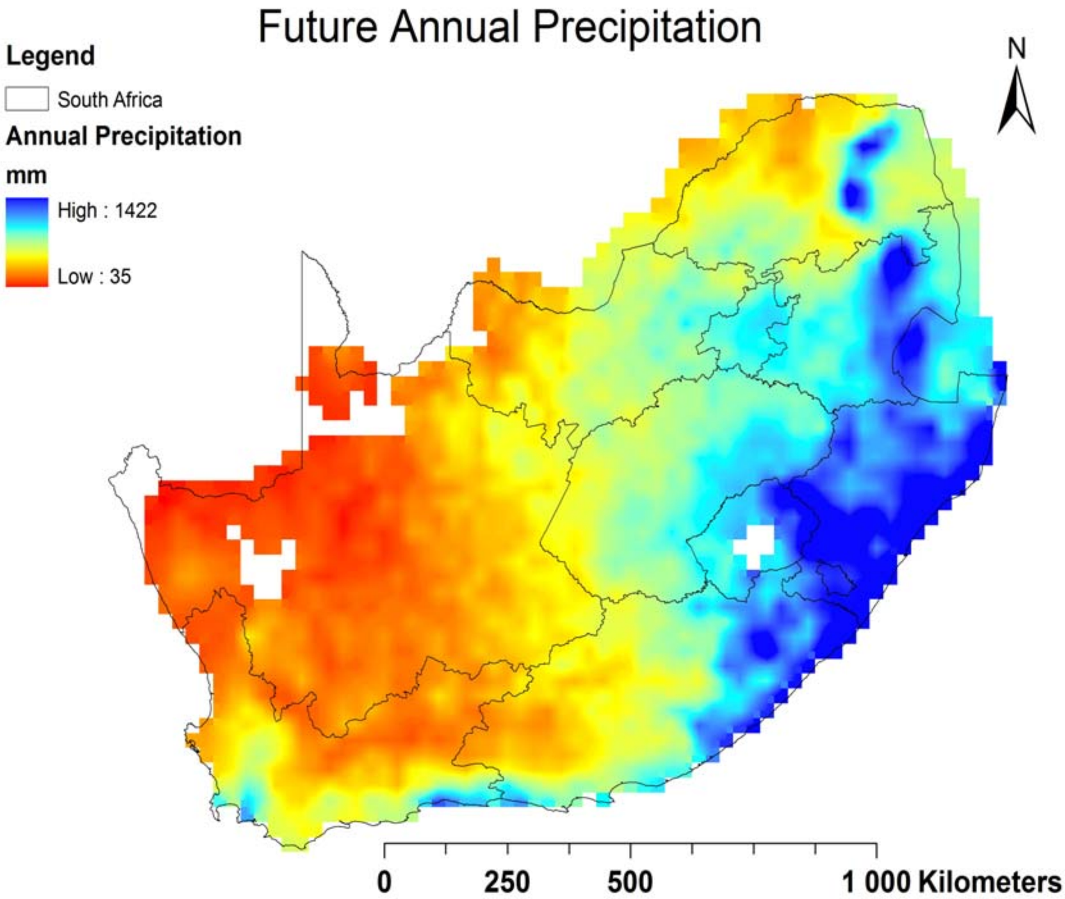

Figure 25: Future annual precipitation

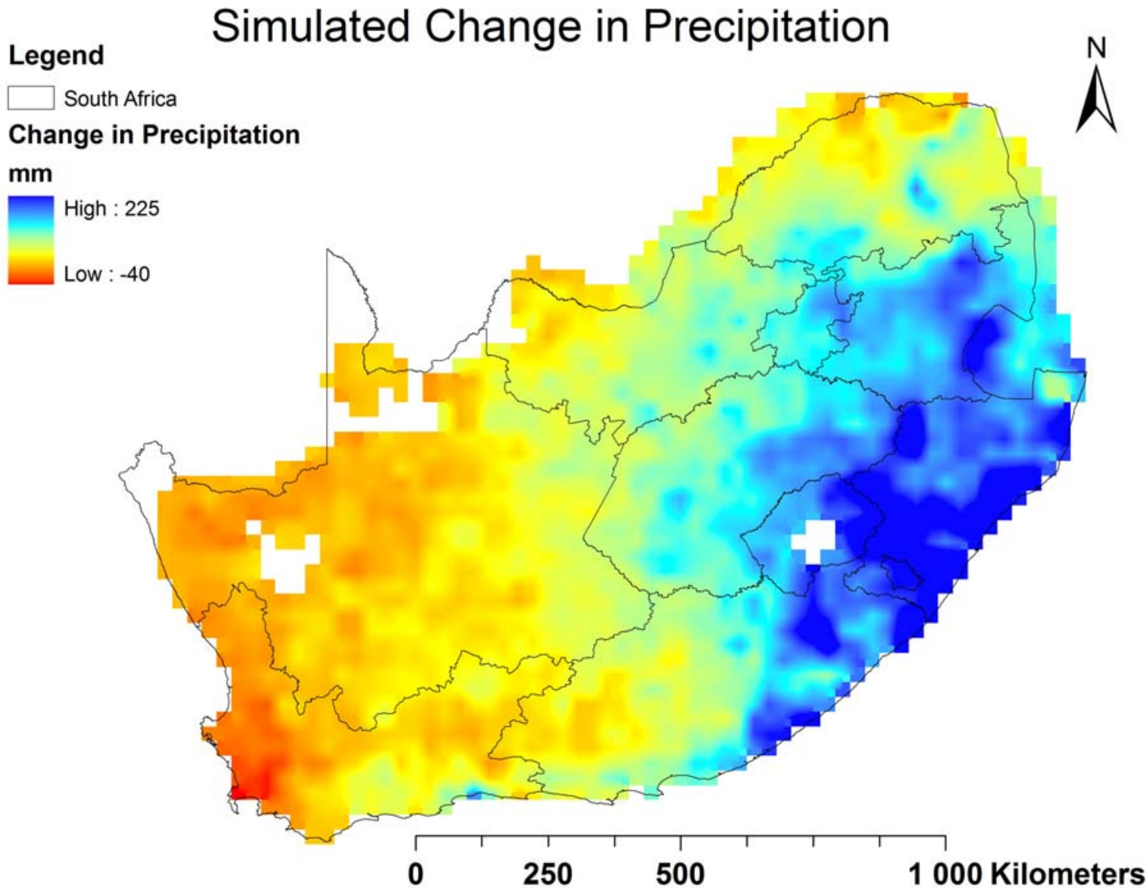

Figure 26: Change in precipitation between current and future scenario

6.2.4.2 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 1km x 1km is used. The slope is shown in Figure 27.

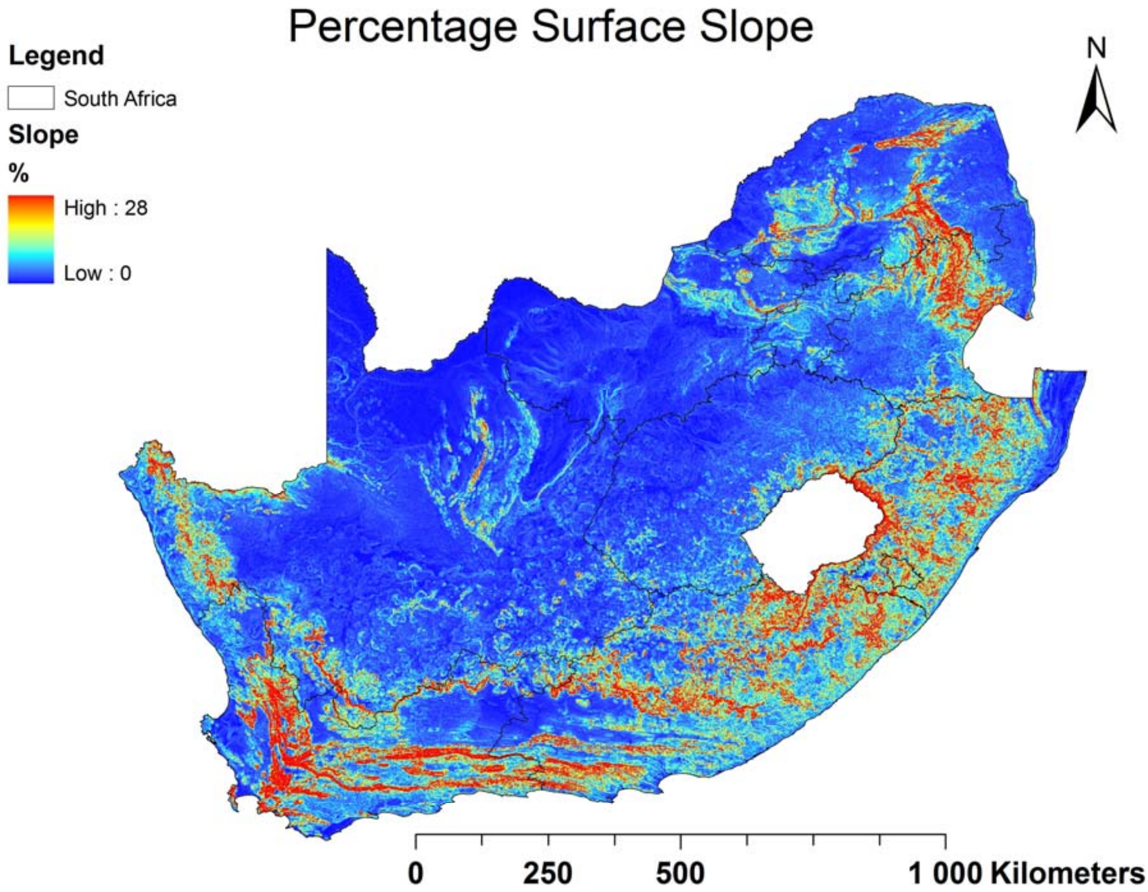

Figure 27: Slope distribution over South Africa

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:

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

The graphical representation of the aforementioned equation is shown in Figure 28.

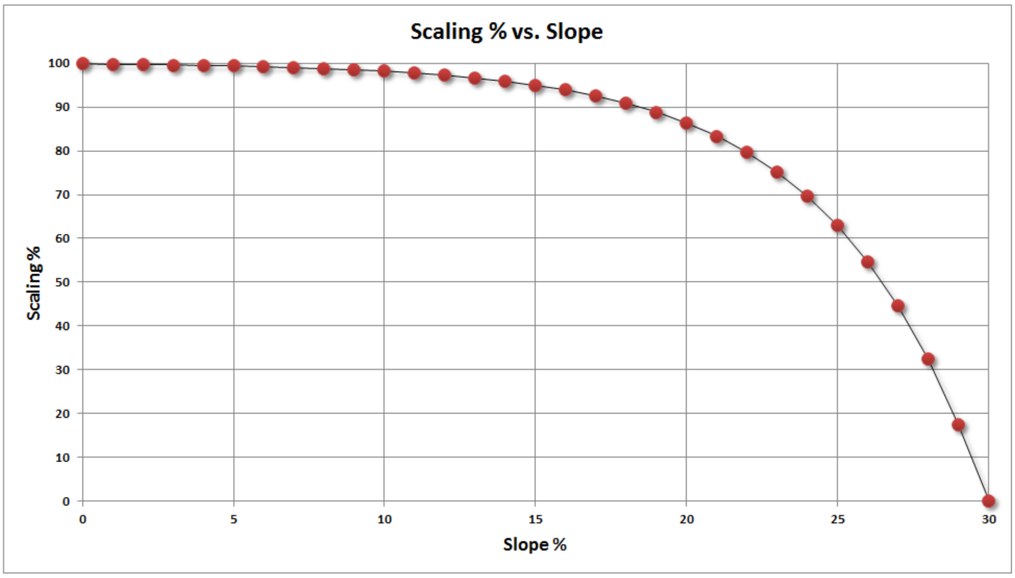

Figure 28: Recharge scaling factor based on slope (%)

6.2.4.3 Recharge model

The recharge model implemented is based on the relationship between precipitation and recharge (Figure 12) and the slope dependence (Figure 28). The recharge model formulation and output space is shown in Figure 28.

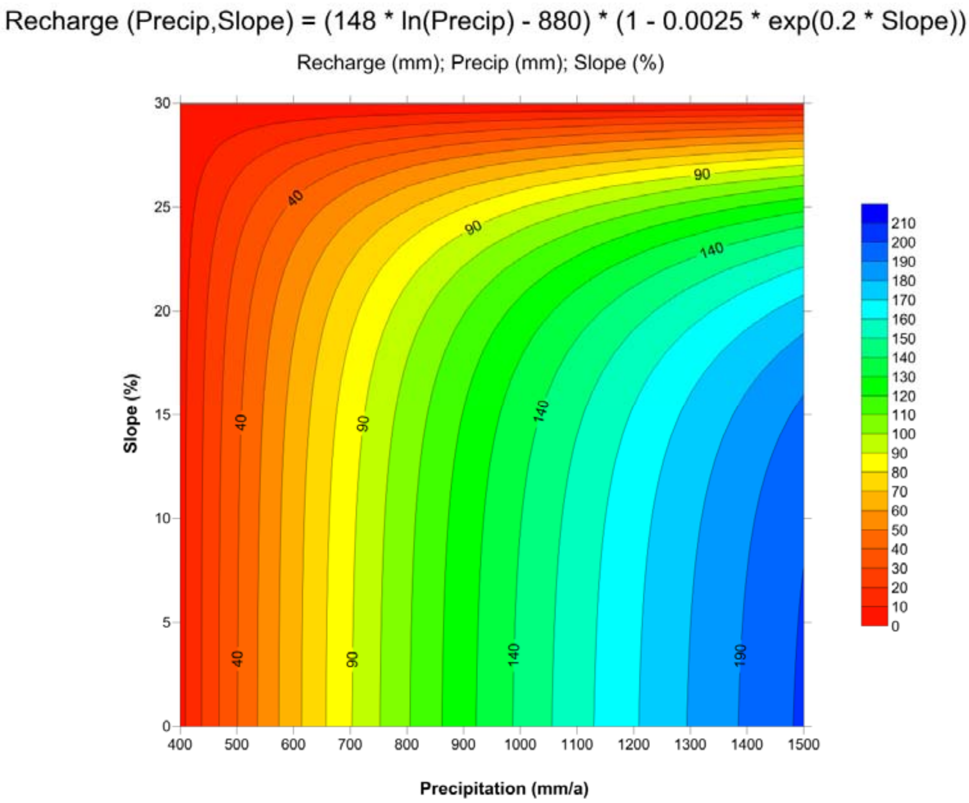

Figure 29: Recharge model annual output space

The current and future annual recharge distribution based on the model output is shown in Figure 30 and Figure 31 respectively.

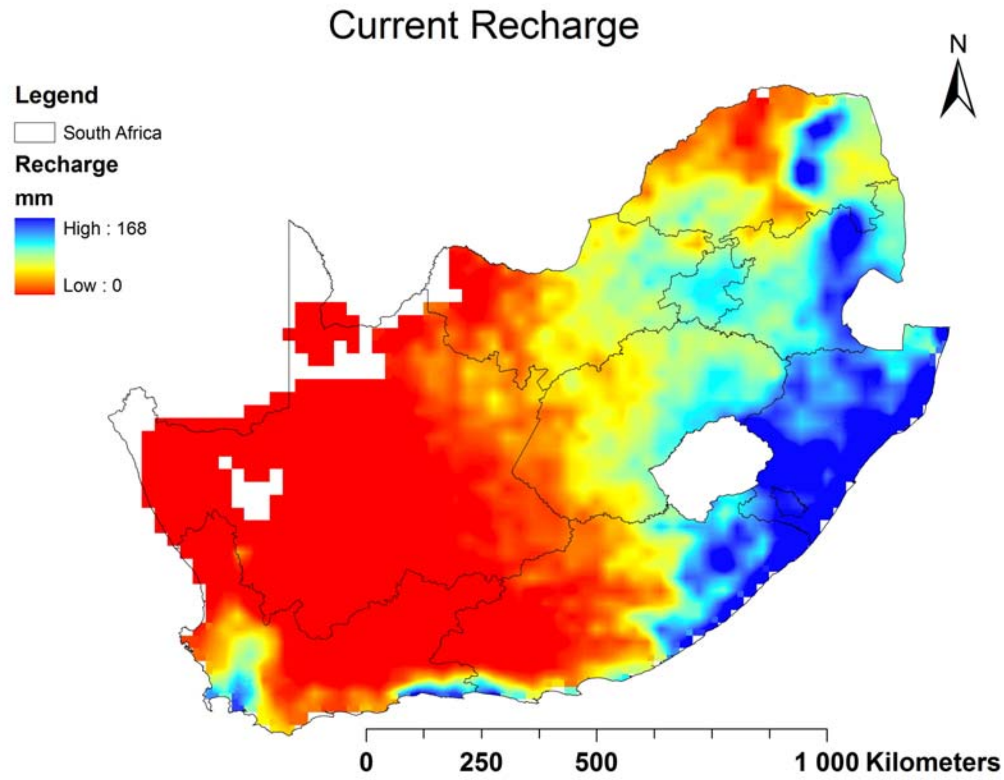

Figure 30: Current annual recharge

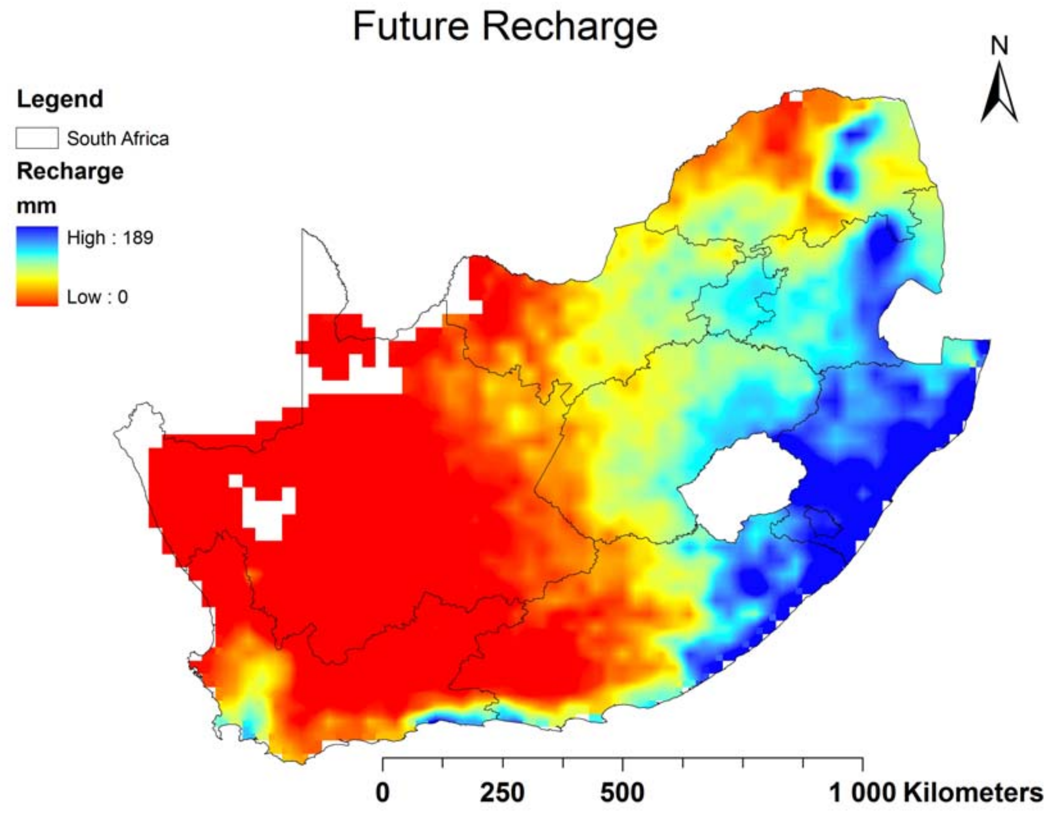

Figure 31: Future annual recharge

6.2.5 Transmissivity

The transmissivity map was also produced in 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 – 25 m^2/d. The resultant map is shown in Figure 32. Note that higher transmissivities can occur due to the fractured nature of formations.

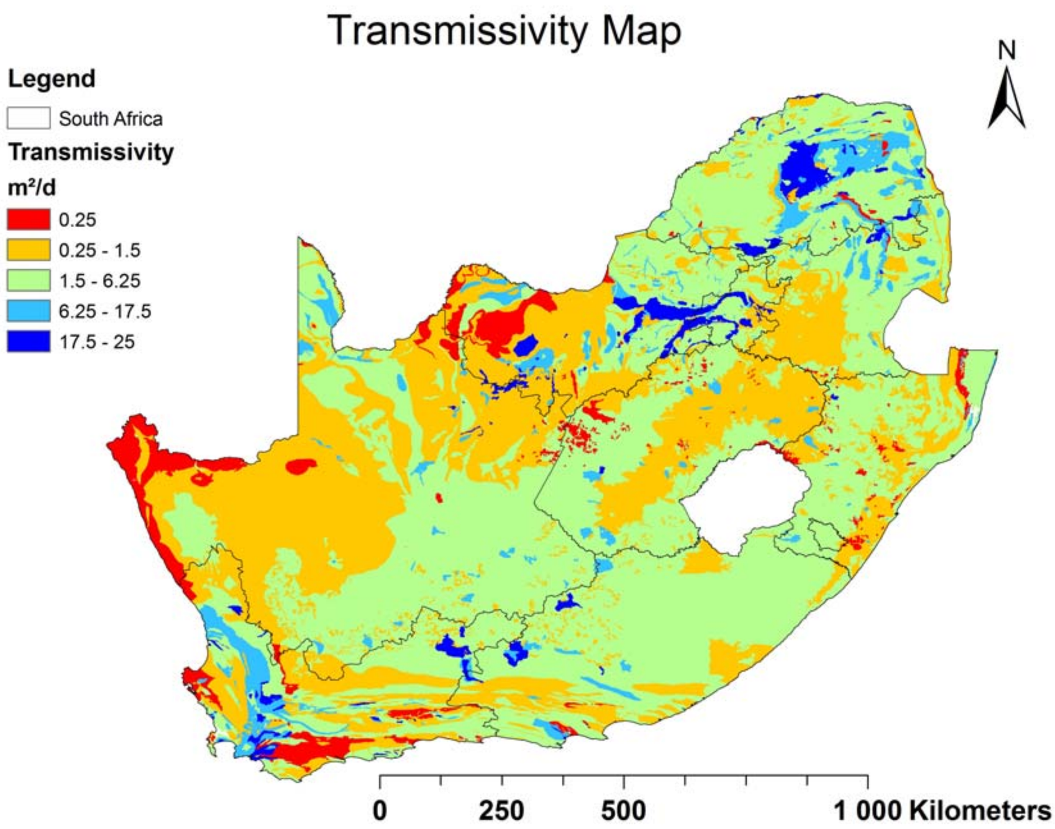

Figure 32: Transmissivity map

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 the 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 5m 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 10mm/month was selected based on the results shown in Figure 12 and Figure 33.

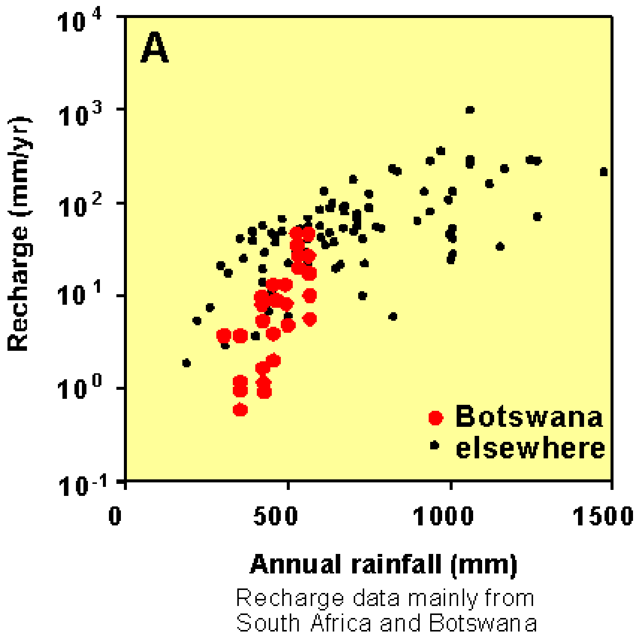

Figure 33: Rainfall vs. recharge in South Africa and Botswana

6.2.6 Results of assessment

Both the average current and future DART indices are shown in Figure 34 and Figure 35 respectively.

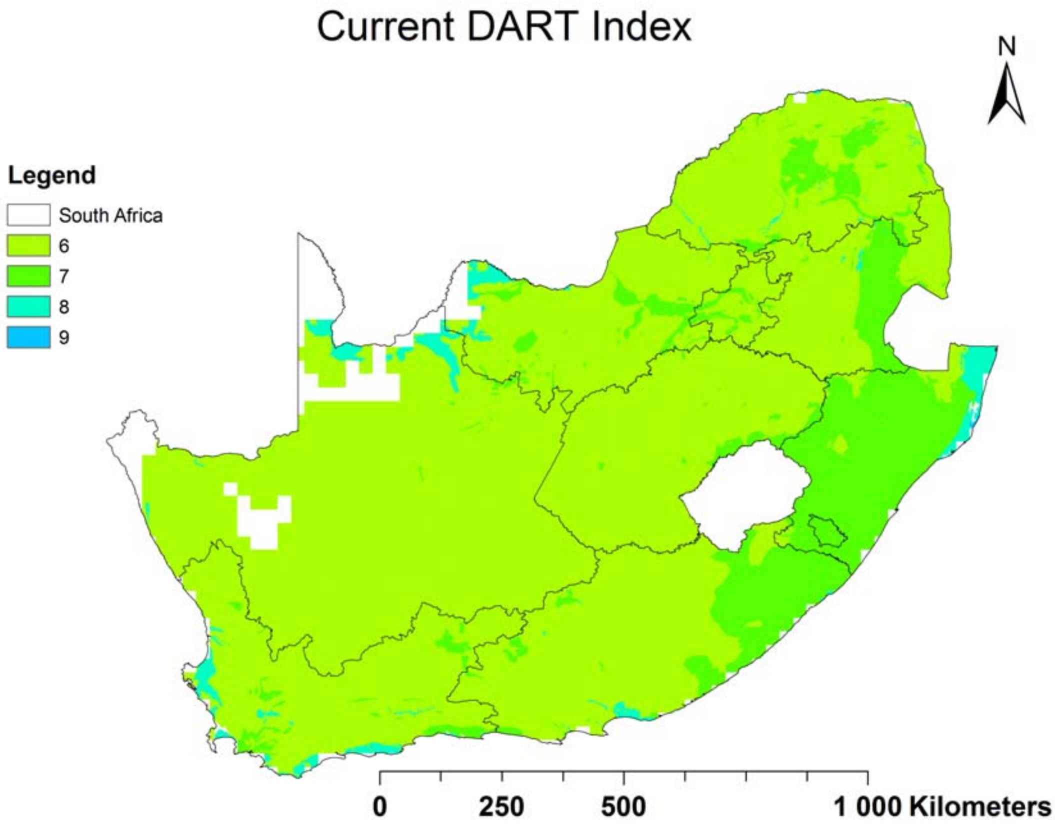

Figure 34: Current average DART index

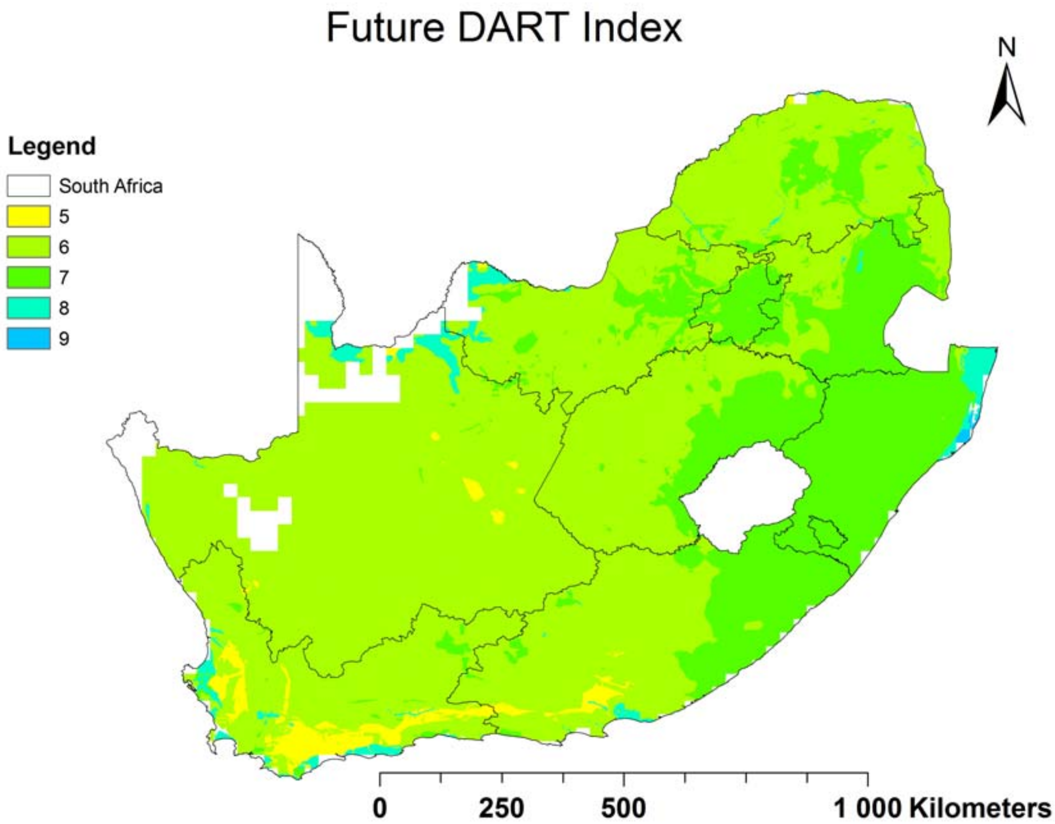

Figure 35: Future average DART index

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 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 this will result in a better index value than currently portrayed if the recharge is significant.

The average change in the DART index between the current and future scenario is shown in Figure 36. It is clear from the average change that only small areas will be affected negatively on average compared to bulk of the area refelecting no change with patches where the index increased with 10%.

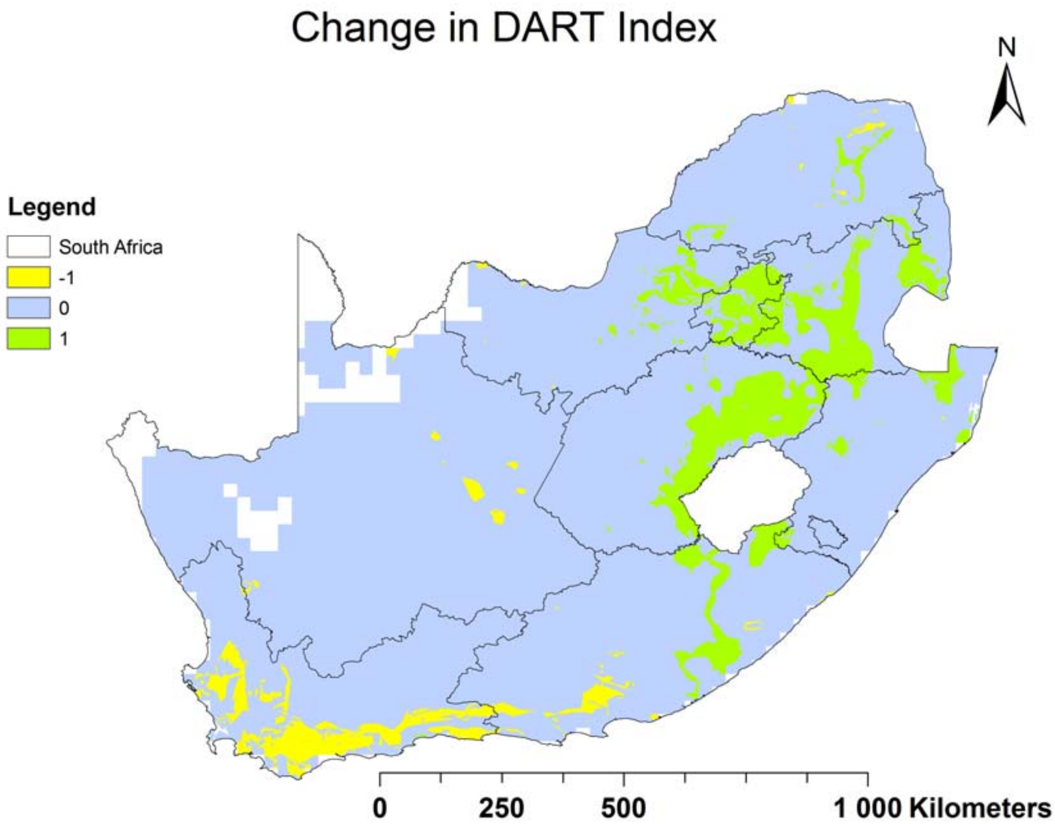

Figure 36: Change in average DART index between current and future scenario

6.3 Human vulnerability index

6.3.1 Index calculation

Vulnerability indices are developed to assess the impacts of global change at spatial scale to enhance the understanding of impacts on people, and develop the appropriate policies for adaptation. For the purpose of this study, a vulnerability index was developed to assess the impacts of climate change on groundwater resources of South Africa on rural communities. Figure 37 provides a vulnerability index for the identified indicators associated with groundwater impacts on communities. Vulnerability, here, was defined in terms of sensitivity and exposure. Indicators considered include health, loss of income, migration and conflict. These indicators were assigned weights and ratings. The weights (developed on a scale of 1 - 5) were assigned based on the sensitivity of the indicator to climate change, whereas the ratings (developed on the scale of 1 - 3) were allocated based on the level of risk a certain indicator is exposed to.

The vulnerability index is calculated according to the following formula:

Index= $(\Sigma R_i W_i)/i$

Where

R_i = rating of the indicator i

W_i = weight of the indicator i

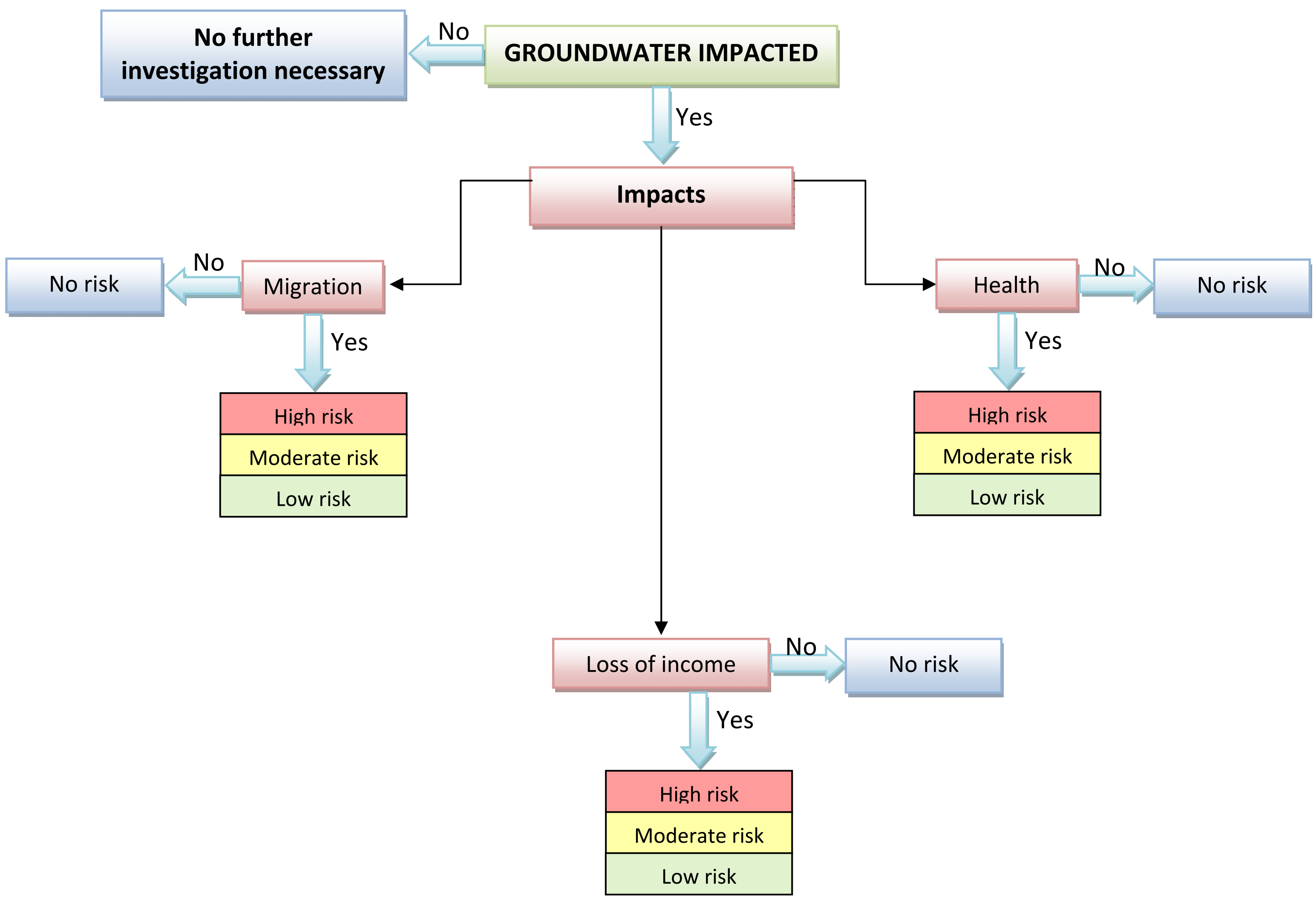

Figure 37: Methodology for assessing groundwater impacts on communities

Table 3 is a summary of the rating and weights used in the vulnerability calculations.

Table 3: Rating and weight

Indicator	Rating	Indicator	Weight
High risk	3	Health	5
Moderate risk	2	Loss of income	4
Low risk	1	Migration	3

6.3.2 Health

Tuberculosis (TB), HIV and AIDS, and malaria are significant threats to human health in South Africa. Furthermore, several diseases in South Africa have strong environmental links. Hepatitis and cholera are most often transmitted through contaminated water, whereas typhoid fever is often associated with lack of clean water supply and sanitation facilities, unplanned urbanization, and increased movement of migrant workers.

Water quality therefore plays a large role in the health of the community. The current national total dissolved solids (TDS) map (Figure 38) is used as an indicator of water quality. The health rating (shown in Table 4) is based on TDS concentrations derived from drinking water guidelines.

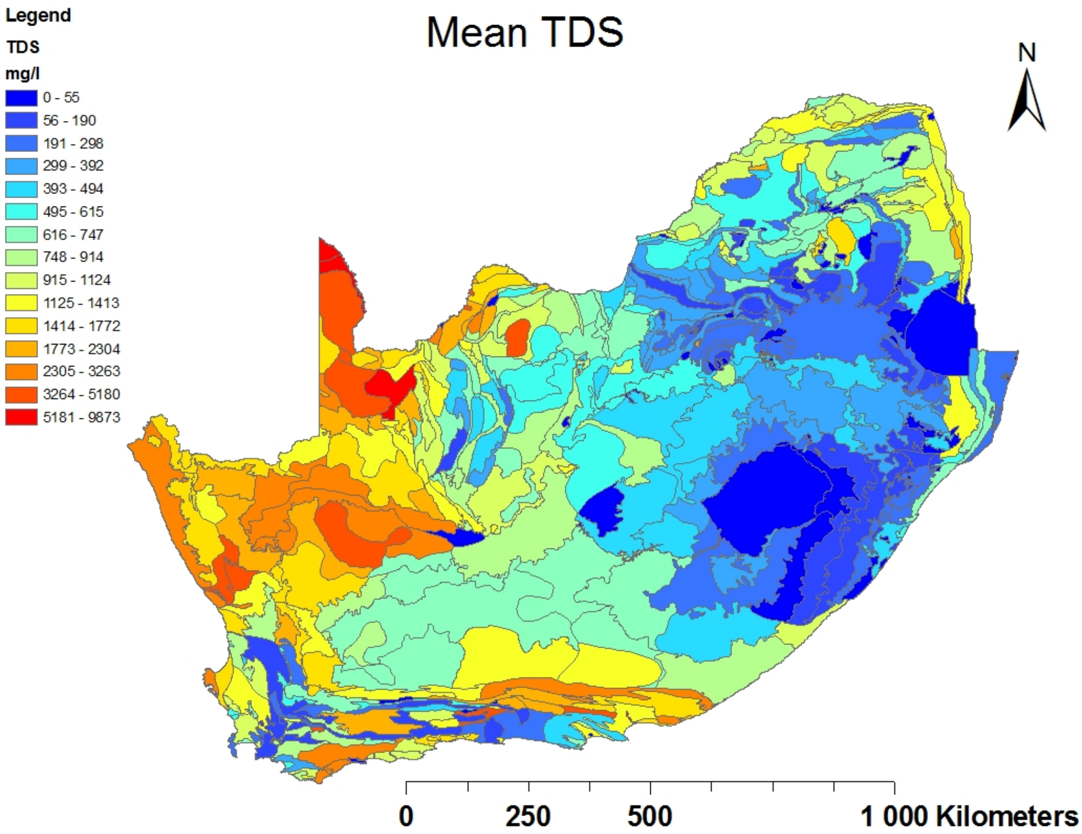

Figure 38: TDS in groundwater

Table 4: Rating for health

Indicator	TDS Concentration (mg/l)
High risk (3)	> 2400
Moderate risk (2)	1000 - 2400
Low risk (1)	450 – 1000
No risk (0)	<450

6.3.3 Loss of income

The largest proportion of rural South Africans is employed in elementary occupations in labour-intensive economic sectors, such as agriculture, which tend to be sensitive to water availability.

Land degradation are among the world’s and South Africa’s most critical environmental issues, intricately linked to food security, poverty, urbanization, climate change, and biodiversity.

Areas of severe degradation (that is, degradation of both soil and vegetation) in South Africa are perceived to correspond closely with the distribution of communal rangelands, specifically in the steeply sloping environments adjacent to the escarpment in Limpopo, KwaZulu-Natal, and the Eastern Cape. Many communal areas in the Limpopo, North West, Northern Cape, and Mpumalanga provinces are also severely degraded.

The commercial farming areas with the most severe degradation are located in the Western and Northern Cape provinces.

Degradation (Figure 39) is therefore used as an indicator for the loss of income.

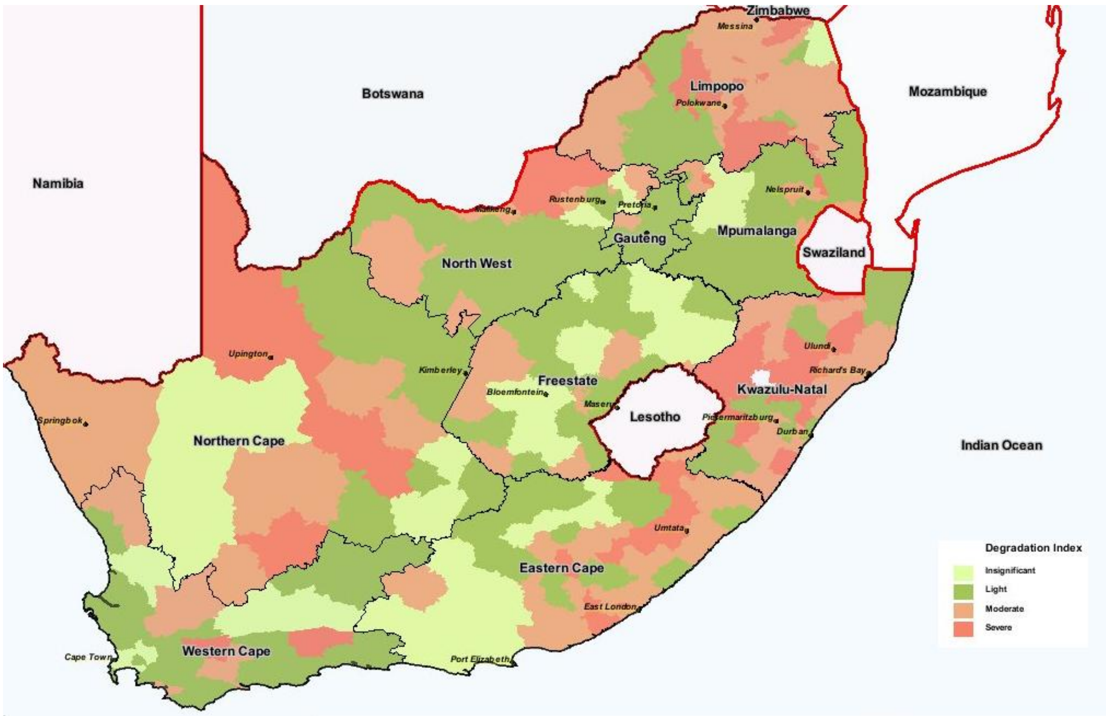

Figure 39: Land degradation (Source: http://soer.deat.gov.za)

The loss of income rating (shown in Table 5) is based on the degradation index as defined by the Department of Environmental Affairs.

Table 5: Rating for loss of income

Indicator	Degradation index
High risk (3)	Severe
Moderate risk (2)	Moderate
Low risk (1)	Light
No risk (0)	Insignificant

6.3.4 Migration

Migration of rural communities mostly to cities can increase due to climate change impacts. Therefore the current migration map (Figure 40) can be used as an indicator of the future trends.

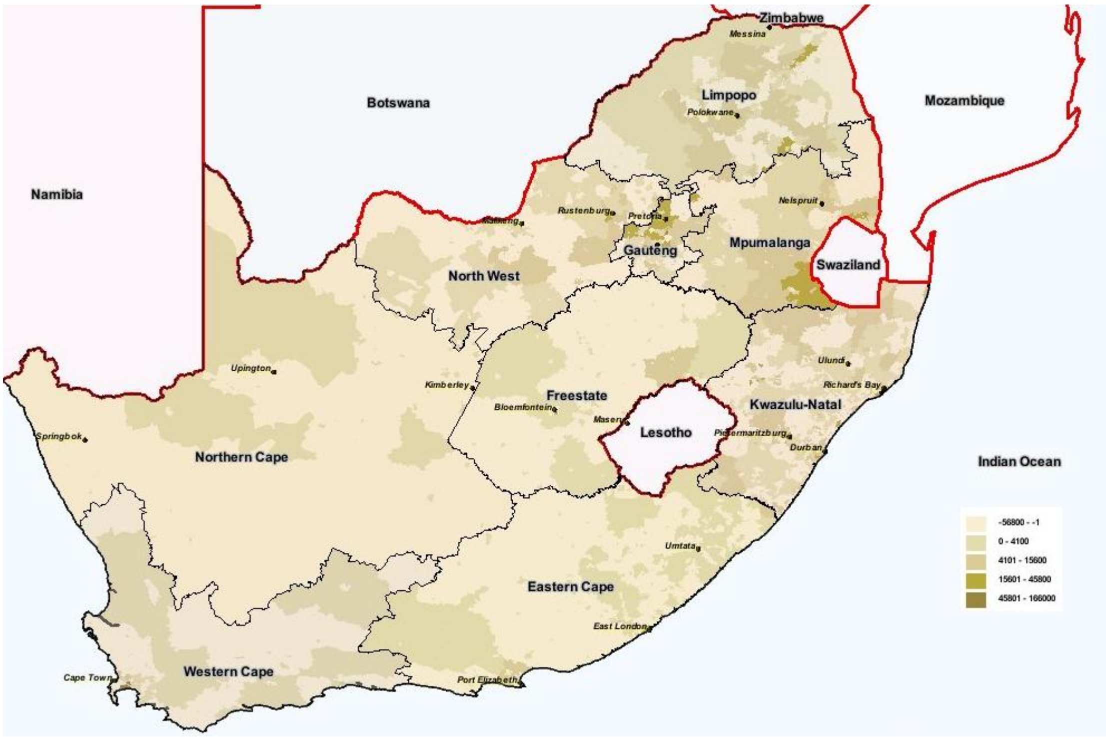

Figure 40: Current population migration trends (Source: http://soer.deat.gov.za)

The migration rating (shown in Table 6) is based on the current migration of populations as defined by the Department of Environmental Affairs.

Table 6: Rating for loss of income

Indicator	No of people migrating
High risk (3)	>45000
Moderate risk (2)	15000 – 45000
Low risk (1)	4000 -15000
No risk (0)	< 4000

6.3.5 Result of assessment

The results of the assessment are shown in Figure 41. These results indicate pockets of high social vulnerability.

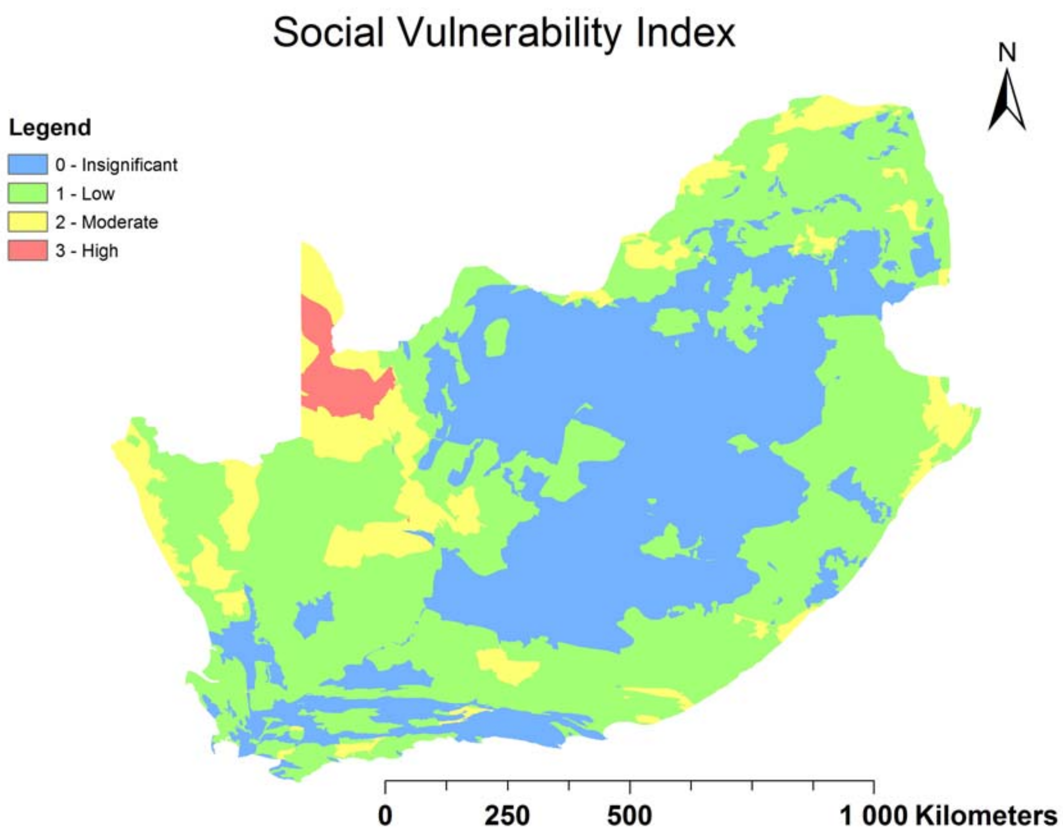

Figure 41: Results of social assessment

7 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 Chapter 6 demonstrate a method for mapping vulnerability that can be used to assess climate impacts in the context of a 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 are not 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, 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 and spatial 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 endeavors. Adequate data are crucial to understanding observed changes and to improve models, which 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 riverbank infiltration and spreading methods.

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9 Summary

Climate change is major threat to our world particularly poor countries. 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). Much strain will be placed on water resources especially in areas where water infrastructure does not exist, or where water delivery is difficult due to aridity (Pietersen, 2005). This dissertation examines the causes of climate change and explores the resulting effects on the environment, social and economic sectors.

This study focuses its attention on South Africa as a whole. 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 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. 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 first step in the approach involves the creation of a climate change groundwater vulnerability profile. In analogy with the DRASTIC methodology the DART methodology was developed. 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 DART methodology focus more on typical parameters used in sustainability studies, but also indirectly accommodate the issue of quality due to the fact that the

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 the current precipitation patterns and the future scenario is representative of the predicted scenario based on the selected GCM.

Vulnerability indices are developed to assess the impacts of global change at spatial scale to enhance the understanding of impacts on people, and develop the appropriate policies for adaptation. For the purpose of this study, a vulnerability index was developed to assess the impacts of climate change on groundwater resources of South Africa on rural communities.

At first glance, the results indicate there is not a significant difference between the current and future average indices, which indicates that climate change impacts on groundwater have very little impact on communities and therefore few adaptation requirements are necessary for community impacts due to groundwater impacts based on climate change.