



GREENBOOK
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THE IMPACT OF CLIMATE CHANGE ON GROUNDWATER AVAILABILITY

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Authors	Vuyelwa Mvandaba, Jean-Marc Mwenge Kahinda, Phumlani Nzuza and Philip Hobbs
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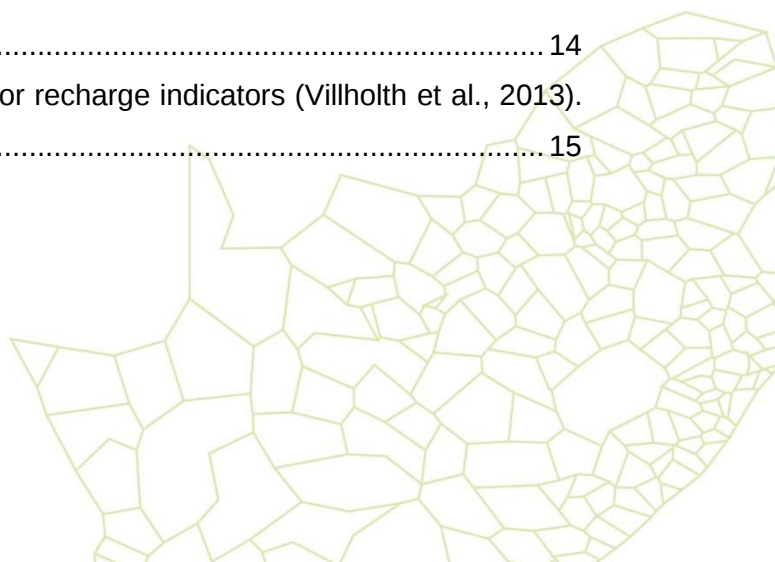


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1 INTRODUCTION

In South Africa, groundwater plays a key strategic role in supporting economic development and sustaining water security in several rural and urban settlements that are either entirely or partially dependent on groundwater supply. Groundwater is, however, a natural resource whose availability and distribution is highly influenced by climate variability and change. To meet the needs of current and future communities, it is therefore important to understand the impact of climate change on groundwater resources, identify potential 'at risk' areas, determine the resultant implications for these vulnerable areas and develop a practical set of guiding mitigation and adaptation strategies. In addressing this challenge an analysis of the impact of climate change on potential groundwater recharge is conducted for the period 2031 to 2050, following two Intergovernmental Panel on Climate Change (IPCC) scenarios based on the Fifth Assessment Report (AR5). Areas that are predicted to experience a low groundwater recharge potential included the western, western-interior and northern-most parts of the country; while the central interior and south-eastern coastline may experience an increase in groundwater recharge potential. The suggested adaptation strategy involves a local municipality-level integrated water resource management approach which prioritises the water needs and development plans of the local settlement.

2 BACKGROUND

Groundwater is the water found underground in the cracks and spaces in soil, sand and rock. It is stored in and moves slowly through geologic formations of soil, sand and rocks called aquifers. Groundwater is naturally recharged by rain, or other forms of precipitation, and is the source of water for aquifers, springs, boreholes and wells.

South Africa extends across varying physiographical and climatic terrains resulting in diverse hydrogeological characteristics that determine the occurrence of aquifers and therefore the occurrence, movement and distribution of groundwater within aquifers. An understanding of those hydrogeological characteristics is essential for successful groundwater resource management.

South African geohydrology is mainly characterised by six types of aquifers, namely the Dolomites, Table Mountain Group sandstones, coastal sand deposits, basement granites,

Karoo dolerites and alluvium along perennial rivers that have been broadly classified into karst, fissured, low permeability and unconsolidated intergranular deposits (Figure 1).

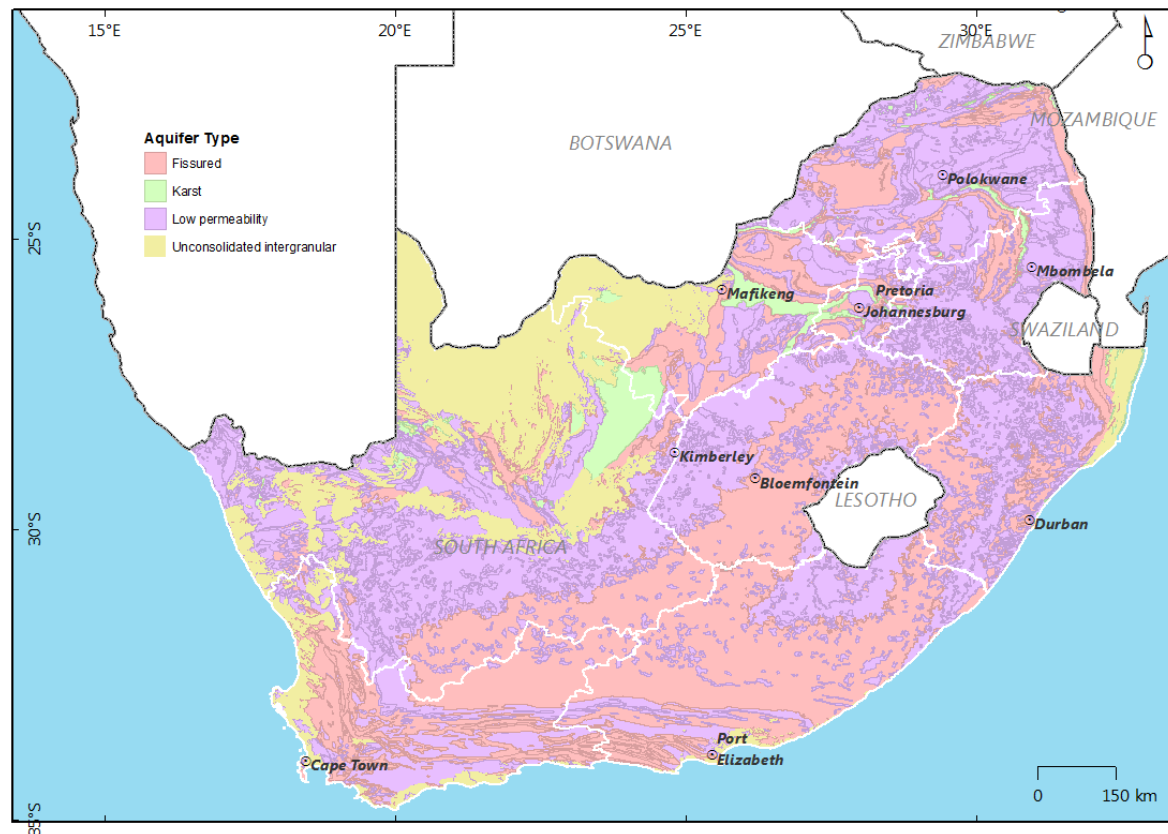


Figure 1: Distribution of aquifers across South Africa (SADC-HGM, 2010).

Over 80% of the country is underlain by moderate to low-yielding, shallow, weathered and/or fractured-rock aquifer systems (Woodford *et al.*, 2006). 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, respectively, as well as from a number of primary aquifers situated along the coastline (**Error! Reference source not found.**).

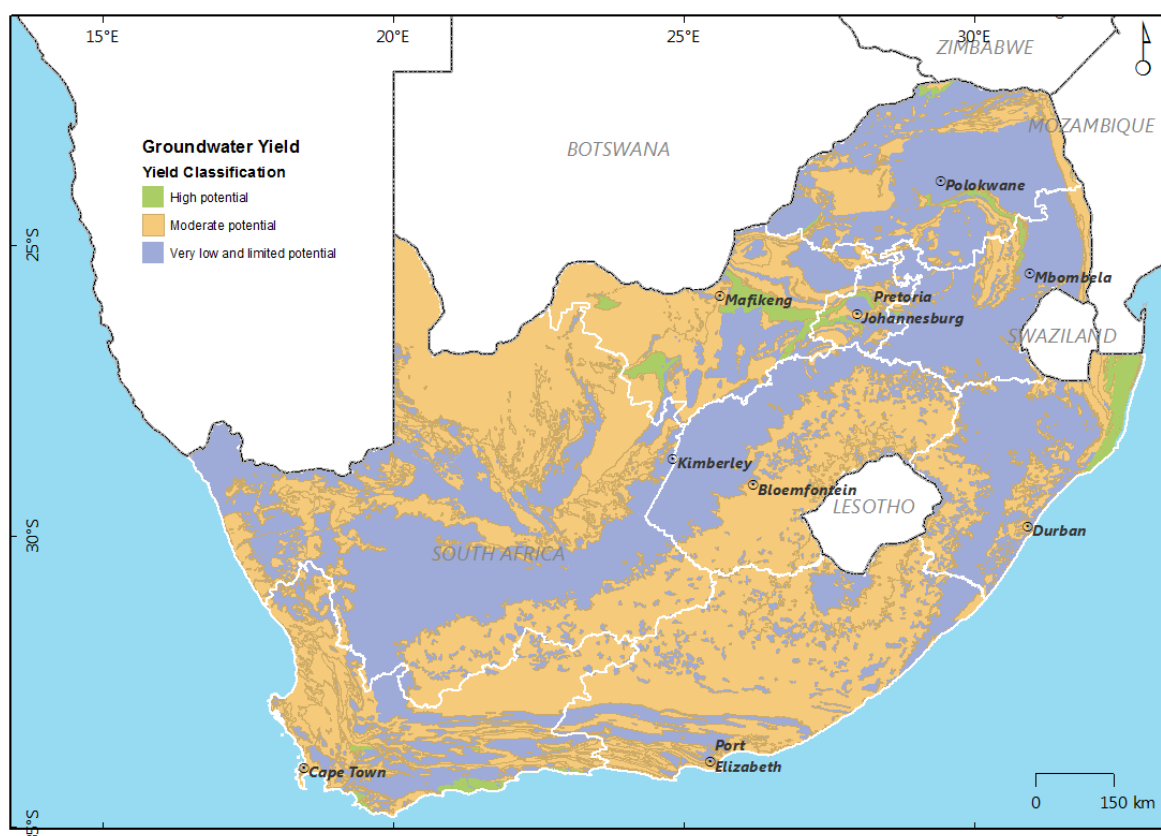


Figure 2: Groundwater yield classification associated with the distribution of aquifers across South Africa (SADC-HGM, 2010).

2.1 The importance of groundwater and its various uses in South Africa

Groundwater is a natural resource of significant social, environmental and economic importance, especially in water-scarce and predominantly semi-arid regions such as South Africa. The main water uses of groundwater in South Africa are domestic water supply (13%), irrigated agriculture (66%), mining (15%), livestock, industry (including power generation) and aquaculture (6%). Because of the increasing socioeconomic pressures on urban water resources, groundwater is increasingly being considered as an alternative resource for urban settlements (DWS, 2016).

Registered groundwater use in the Water Authorisation Registration Management System (WARMS) database amounts to 2,466 Mm³ (million cubic metres), which was predicted to increase by 39% in 7 years (Fourie, 2012). That is well below the 19,000 Mm³ of groundwater that could be abstracted on an annual basis. The bulk of groundwater abstraction occurs in

the so-called “large-scale groundwater abstraction areas” which generally overlap with strategic groundwater source areas (Figure 3).

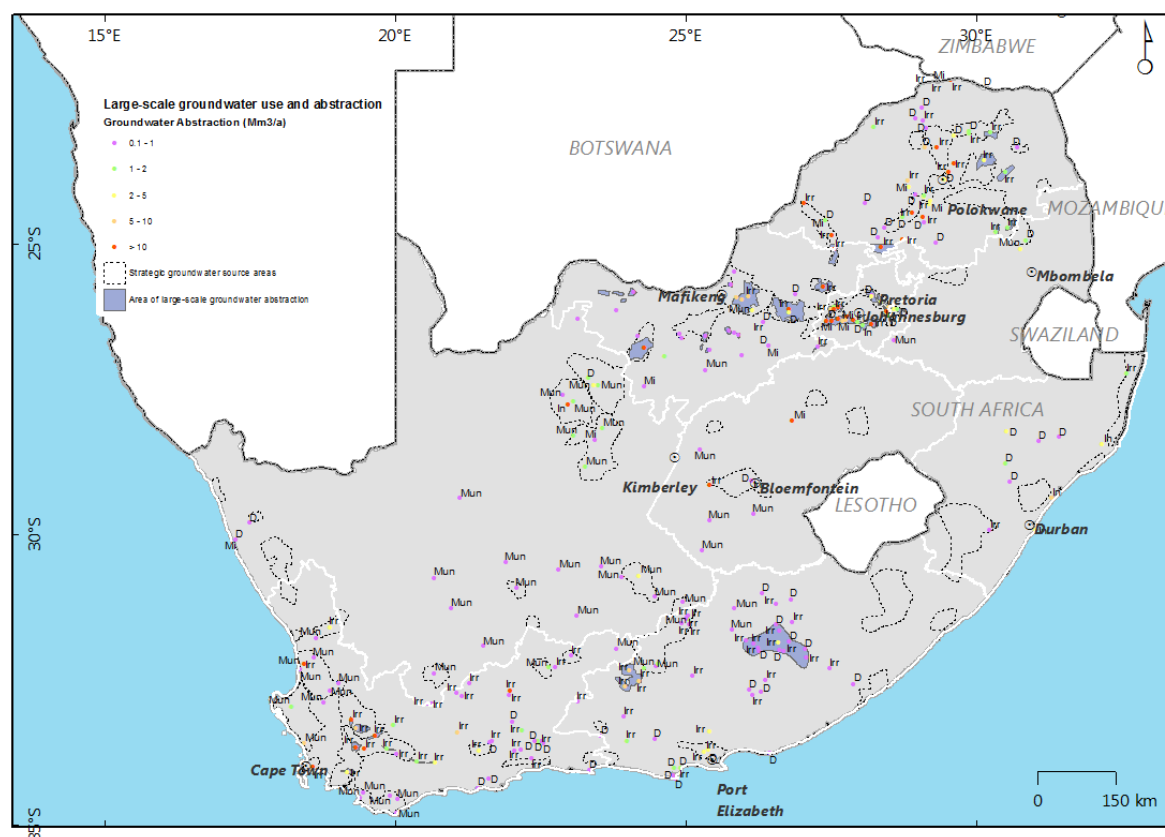


Figure 3: Nationwide distribution of strategic groundwater source areas, large-scale groundwater abstraction areas and their associated sectoral uses.

A strategic groundwater source area is defined as an area associated with high groundwater availability, where the groundwater forms a nationally important resource (Smith-Adao et al., 2016). Collated water use data from the All Towns Reconciliation Strategies studies (DWS, 2012) and the WARMS dataset indicate the percentage usage of surface water and groundwater in local municipalities (Figure 4). This information has been summarised as follows (Smith-Adao et al., 2016):

- 11% of the total population reside in settlements that only rely on groundwater for their water supply;
- The country's 11 metropolitan municipalities mostly rely on surface water supply (>50%);
- Settlements that rely solely on groundwater supply are mostly rural village clusters or small towns. 35% of these settlements fall within strategic groundwater source areas;

- Only 8% of these sole groundwater supply settlements are located within national strategic groundwater source areas.

Most groundwater dependent settlements source their water from minor aquifer regions (**Error! Reference source not found.**). A major aquifer region represents a high-yielding system of good water quality while minor and poor regions respectively represent moderately-yielding aquifer systems of variable water quality, and low to negligible yielding aquifer systems of moderate to poor water quality.

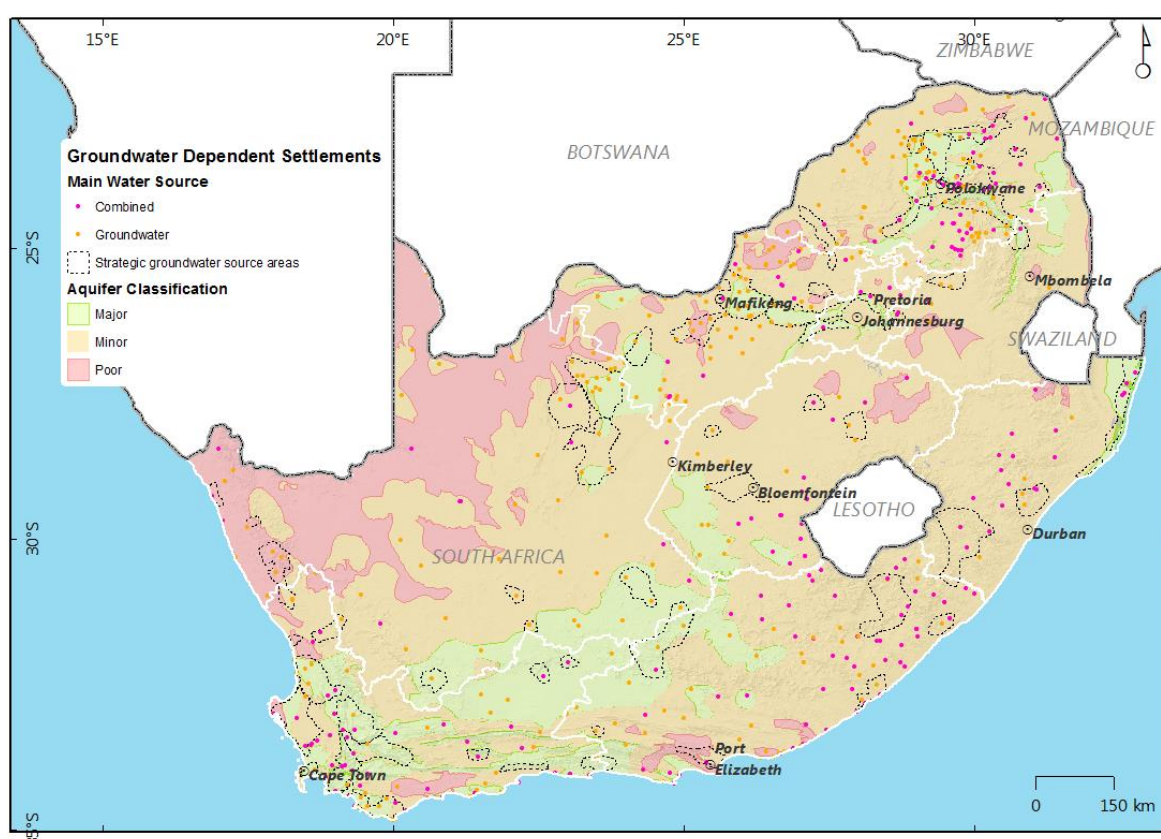


Figure 4: South African settlements that depend entirely on groundwater or on both surface and groundwater and the associated aquifer type (DWS, 2012).

Twenty years after the passing of the National Water Act (Act 36 of 1998), and following the development of the associated groundwater management guidelines for resource allocation, South Africa is still confronted by many obstacles to the achievement of the stated objectives of equity, efficiency and sustainability (Knüppe, 2011). Groundwater resources and associated goods and functions are still undervalued and are not being utilised to their full potential. The inadequate knowledge of groundwater management, especially at municipal level requires serious attention.



2.2 Groundwater and climate change

The strategic importance of groundwater for both water and food security is likely to intensify under climate change with more frequent and intense climate extremes (droughts and floods) and increased variability in precipitation, soil moisture and surface water. Increased variability in precipitation and more extreme weather events caused by climate change will most likely lead to longer periods of droughts and floods, which directly affects availability and dependency on groundwater. During long periods of droughts people in water-scarce areas increasingly depend on groundwater because of its buffer capacity, thus, there is a higher risk of depletion of aquifers.

In the context of climate change, groundwater resources are typically seen in quantitative terms as a volumetric change driven by rainfall trends as these influence recharge, the process whereby some portion of rainwater infiltrating through the subsurface reaches an aquifer. The sustainability of groundwater resources, however, is not determined by recharge alone (Vegter, 2000). Aquifers vary in their capacity to store and transmit water, depending on the hydrophysical nature of the host material.

The impact of climate change on groundwater, however, extends beyond volumetrically sustainable considerations. There is also a potential geotechnical impact associated with the risk that prevails in regard to land stability in dolomitic (karst) terranes. Over-abstraction of groundwater in these terranes can lead to the formation of sinkholes (DWS, 2010; Oosthuizen and Richardson, 2011). This impact is of particular relevance to areas of concentrated human habitation (including towns and cities) that are located on dolomitic formations. The geotechnical risk aspect is evaluated mainly at a sub-regional or local scale matched to the footprint of a proposed development on dolomitic land. This is informed by the publication endorsed by the South African Institute of Civil Engineering (SAICE – Geotechnical Division, 2010). The comparatively limited distribution of dolomitic strata in South Africa (carbonate strata cover ~15% of the country) restricts the incorporation of this impact assessment to a similarly delimited spatial footprint.

2.3 Purpose and aim of the study

The main objective of this study is to identify potential high-risk areas under a changing climate. In relation to groundwater recharge, these high-risk areas include areas predicted to



experience extensive low or high groundwater recharge potential values in response to changing temperatures, evaporation and precipitation. This information will be useful in guiding climate change adaptation strategies for settlements in South Africa.

3 BASELINE SCENARIO

The first GIS-based national hydrogeological mapping project, aptly entitled 'Groundwater Resources of South Africa (GRA1)' was produced in 1995 (Vegter, 1995a & b). It was subsequently updated into the Groundwater Harvest Potential map of the Republic of South Africa (Baron et al., 1998), a derivative of the GRA1 set of maps. It provides an estimate of the maximum volume of groundwater that may be abstracted per square kilometre per annum, without depleting the aquifers. In 2001, the Harvest Potential map was revised to take into consideration the highly variable permeability within and between the various aquifer systems (Haupt, 2001). Subsequently, a set of twenty-one 1:500,000 scale, national hydrogeological maps were completed, using new and updated sources of information (Jonck and Meyer, 2004). The maps provide the occurrence and distribution of groundwater resources on the basis of both aquifer type and successful borehole yield.

In late 2003, the Department of Water Affairs and Forestry (DWAF) initiated the Groundwater Phase 2 Project (DWAF, 2006) known as Groundwater Resources Assessment 2 (GRA2). The project produced a methodology for the quantification of the country's groundwater resources, which includes algorithms for the estimation of storage, recharge, baseflow and the impact on the reserve as well as present groundwater use.

A chronological summary of groundwater assessment in the country can be seen in Figure 5 in the form of a timeline from 1995 to the present day.

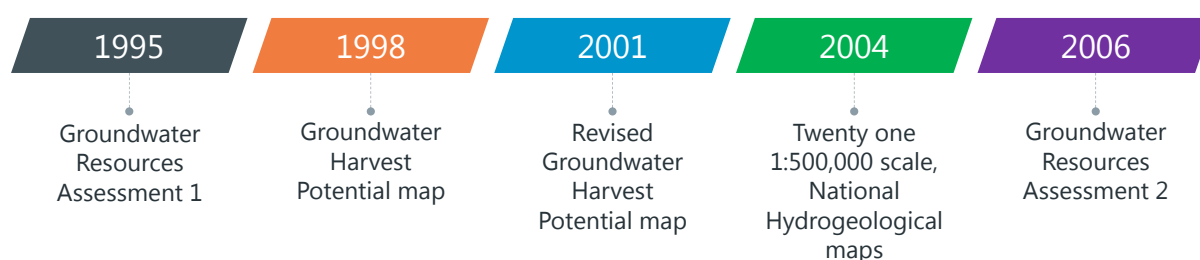


Figure 5: Timeline and groundwater resources assessments in South Africa

The main output of GRA2 is a comprehensive dataset of groundwater information and data, including spatial recharge estimates (Figure 6) that incorporate both climatic factors and hydrophysical factors.

The long-term annual groundwater recharge map (DWAF, 2006) is based on a commonly used method known as the chloride mass-balance method (Figure 6).

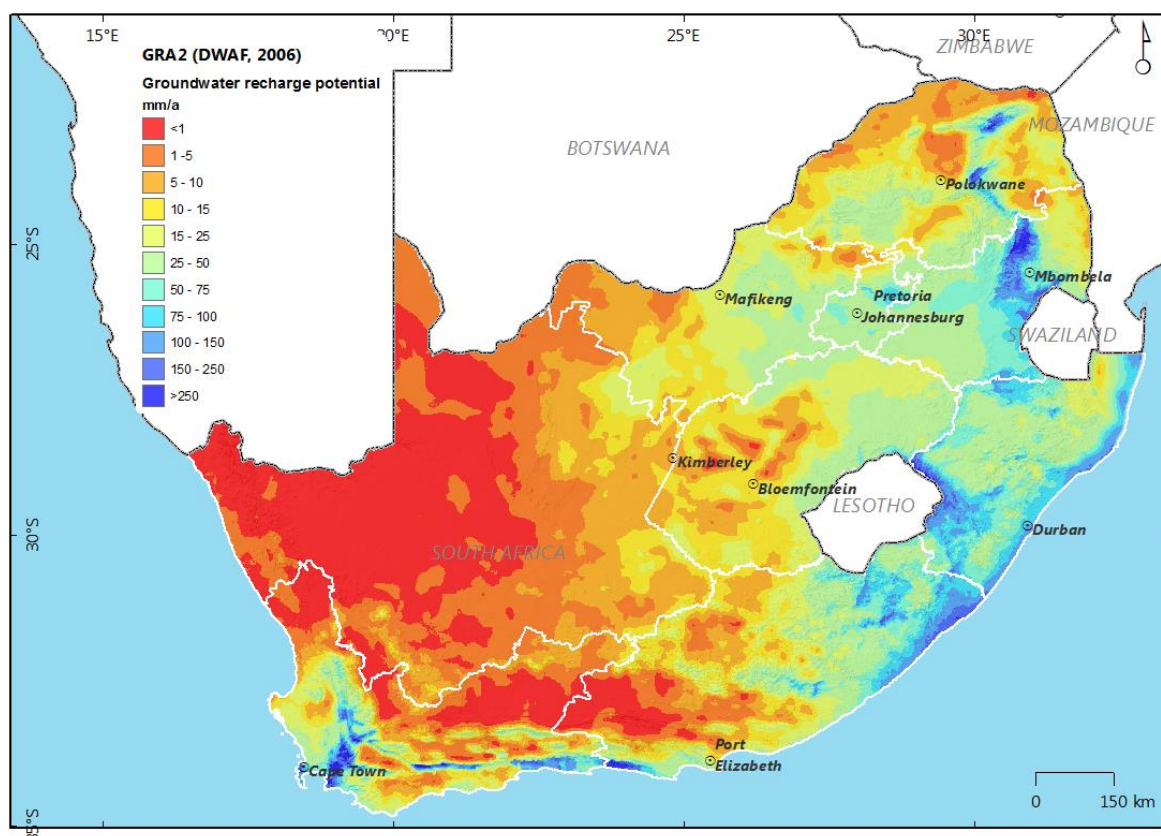


Figure 6: Annual groundwater recharge from rainfall estimated using the chloride-mass-balance method and a GIS-based modelling approach using various empirical rainfall versus recharge relationships (DWA, 2006).

Its reliability is hampered by an insufficient national coverage of chloride measurements in rainfall as well as errors inherent in the method. The map was reclassified and weighted following Villholth et al. (2013) to produce a potential recharge map (Figure 7). The reclassified and weighted map highlights more distinctive recharge potential zones and less severe groundwater conditions across the interior of the country.

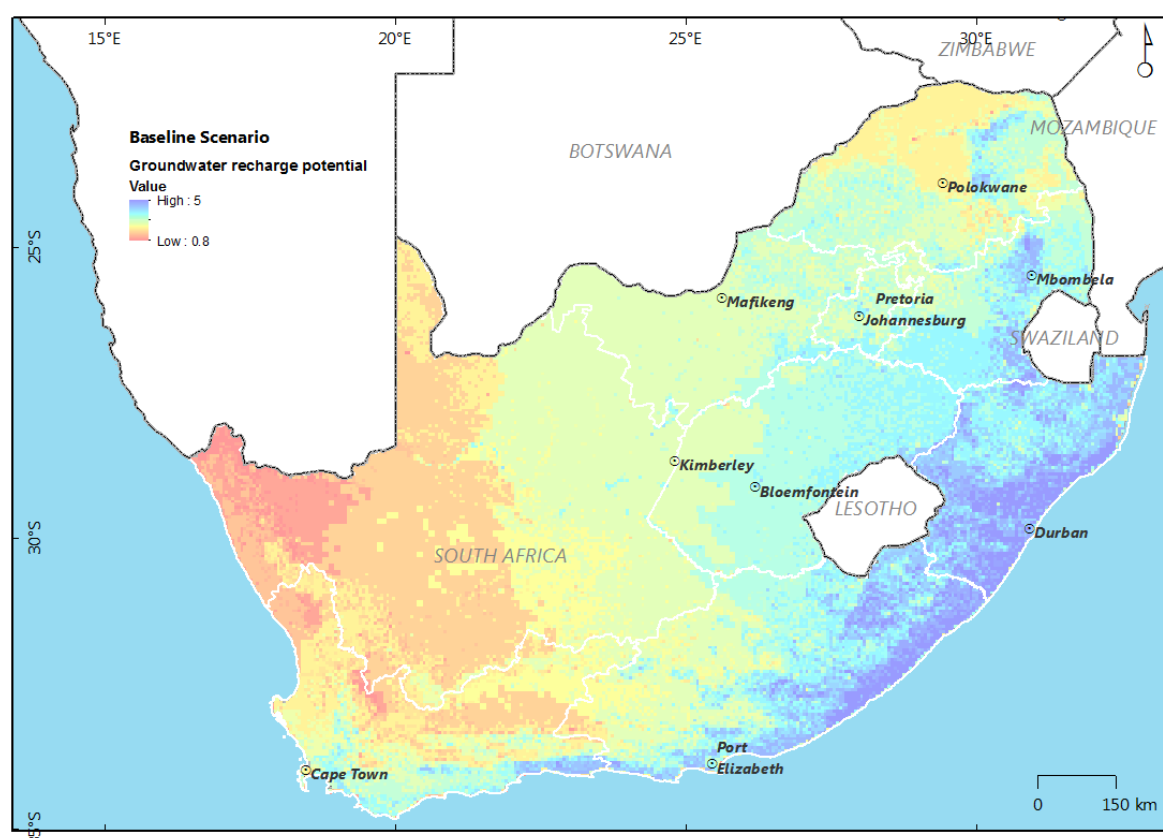


Figure 7: Reclassified and weighted annual groundwater recharge.

The base scenario of groundwater recharge potential indicates that while groundwater recharge potential is influenced by the distribution on aquifer systems across the country, the rainfall distribution of climate zones across the country may have a greater impact on recharge as it influences the amount of rainfall occurring. Low groundwater recharge potential zones correlate with high aridity regions, while wet and humid climates as experienced along the east coast correlate to higher recharge potential.

4 METHODOLOGY

The Villholth et al. (2013) GRiMMS (Groundwater Drought Risk Mapping and Management System) formulation, which implemented a composite mapping analysis technique to produce an explicit groundwater recharge drought risk map, was adapted to formulate a series potential groundwater recharge maps for the far-future across South Africa. The novelty in using this approach is that the widely used GRA2 groundwater recharge maps can be updated to reflect current base scenario conditions and near- and far-future recharge values can be determined where no studies have been carried out.

The parameters and variables that inform estimation of groundwater recharge potential were obtained from multiple sources (Table 1) including existing national groundwater assessments projects. Data collected comprised datasets and coverages for rainfall, vegetation and slope.

Table 1: Meta-data for data collected

Dataset	Description	Resolution	Reference period	Source
Historical rainfall	Long-term MAP ^a	8 km	1996-2008	USGS ^b
Projected rainfall		8 km	2031-2050	CSIR, 2017
Vegetation	Long-term mean NDVI ^c	8km	1983-2003	USGS ^b
Terrain slope	SRTM ^d DEM ^e	1 km	v4.1	CGIAR-CSI ^f

^aMAP Mean Annual Precipitation

^bUSGS United States Geological Services

^cNDVI Normalised Difference Vegetation Index

^dSRTM Shuttle Radar Topography Mission

^eDEM Digital Elevation Model

^fCGIAR-CSI Consultative Group on International Agricultural Research-Consortium for Spatial Information. Jarvis et al. (2008)

Following the output of groundwater drought risk maps by Villholth et al. (2013), the impact of climate change on groundwater resources is illustrated through a set of “change in recharge” (Δ recharge) maps reflecting, in qualitative terms, the response of groundwater systems to climate-induced recharge patterns. Three recharge parameter layers, namely precipitation, vegetation and slope, were combined using ArcGIS to produce a national map of relative groundwater recharge potential (Figure 8).

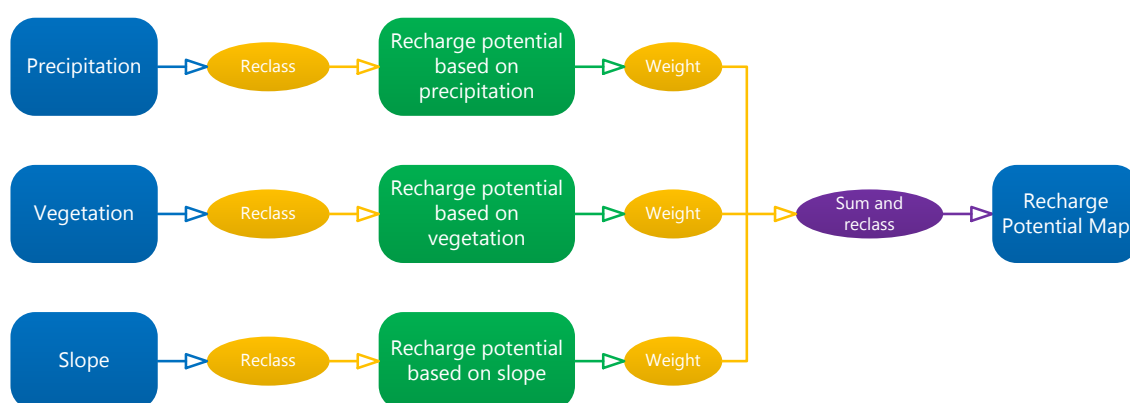


Figure 8: Workflow for mapping of national recharge potential

The map values of the three indicators (Figure 8) were reclassified to represent recharge potential on a zero-to-5 point scale. In each case, a value of 1 indicates low recharge potential and a value of 5 a high recharge potential, while a zero will indicate no recharge potential. Thereafter, each indicator was assigned a weight according to its perceived relative impact on



groundwater recharge (Table 2). Finally, the weighted maps were summarised to produce an aggregate map that incorporates the ratings from each map.

Table 2: Reclassification scheme and weights for recharge indicators (Villholth et al., 2013).

Recharge indicator	Reclassification		Weight
Precipitation [mm yr⁻¹]	0-100	0	0.5
	100-250	1	
	250-500	2	
	500-1000	3	
	1000-1500	4	
	>1500	5	
NDVI	< 0	0	0.35
	0 – 0.2	1	
	0.2 – 0.4	2	
	0.4 – 0.5	3	
	0.5 – 0.6	4	
	> 0.6	5	
Slope [degrees]	0 – 2.5	5	0.15
	2.5 - 5	4	
	5 – 7.5	3	
	7.5 - 10	2	
	> 10	1	

We compare the future period 2031 to 2050 with a historical period 1961 to 1990, following two Intergovernmental Panel on Climate Change (IPCC) scenarios based on the Fifth Assessment Report (AR5) and on the Representative Concentration Pathways (RCP): 4.5 and 8.5. RCPs are concentration pathways used in the IPCC AR5 scenarios. RCP4.5 describes future conditions where emissions are notably reduced, whereas the ‘business as usual’ model for RCP8.5 describes future conditions where there are no reductions in emissions.



5 RESULTS

The two RCPs are each respectively analysed at 10th, 50th (median) and 90th percentiles (Figure 9), the aim is to compare the changes in potential groundwater recharge in each of the six modelling scenarios and analyse the impact of climate change on groundwater recharge between 2031 and 2050. Along a distribution of projected changes (outcomes), the 50th percentile (median) illustrates the central estimate of the likely impact of climate on groundwater recharge, while the 10th and 90th percentiles respectively represent the low and high estimates of the projected future conditions.

Climate projections for South Africa predict slight to moderate rainfall increases over the central interior and south-eastern regions, despite general drier conditions over most of southern Africa under both RCP4.5 and RCP8.5 (Davis et al., 2017). These conditions correlate with the potential groundwater recharge that is projected for RCP4.5 and RCP8.5 conditions, in Figure 9. The groundwater recharge potential illustrated in Figure 9 represents the difference between projected groundwater recharge and baseline scenario conditions i.e. a high groundwater recharge potential represents favourable future changes for projected scenarios, hence more groundwater recharge for the region. When comparing the RCP4.5 and RCP8.5 scenarios, it is evident that lower groundwater recharge can be expected under RCP8.5 conditions. The western, western-interior and northern regions of the country are most affected by the predicted lower rainfall, hence lower groundwater recharge is consequently projected for those regions across the 10th, 50th and 90th percentiles. The spread and intensity of decreasing groundwater recharge potential is more evident under the 90th percentile thus it can be concluded that RCP8.5 90th percentile represents the worst possible impact of climate change on groundwater recharge availability in South Africa. Regions that are predicted to become more favourable for groundwater recharge include the central-interior and eastern coastline of South Africa, which is evidenced by the higher groundwater recharge potential under both RCP4.5 and RCP8.5 conditions.

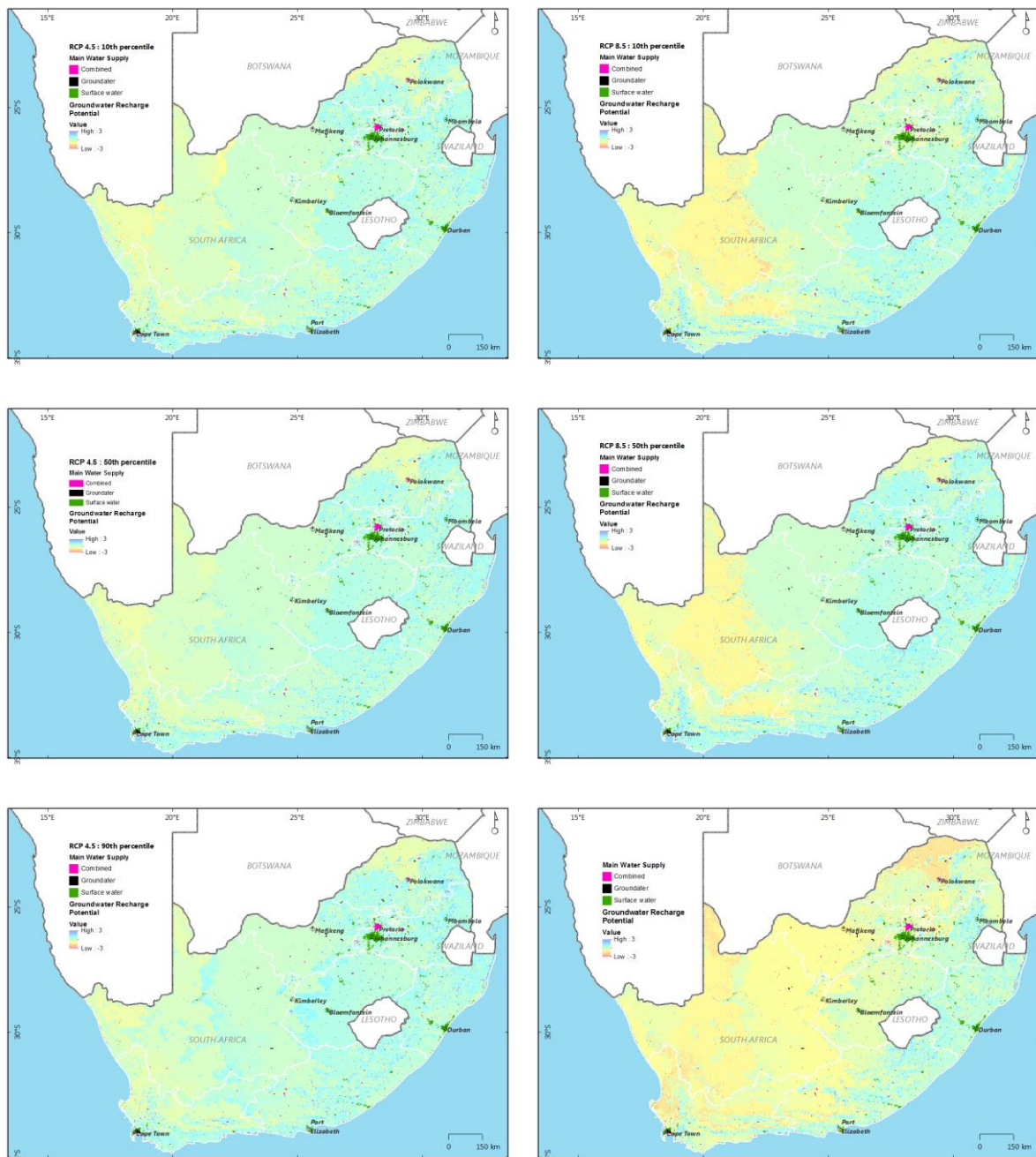


Figure 9: Conformal cubic atmospheric model CCAM projected change in potential groundwater recharge over South Africa (ensemble average of six downscaled global climate models (GCMs) between 2031 to 2050 respect to 1961 to 1990 for the 90th percentile (upper), the median (middle), the 10th percentile (lower) following RCP4.5 (left) and RCP8.5 (right).

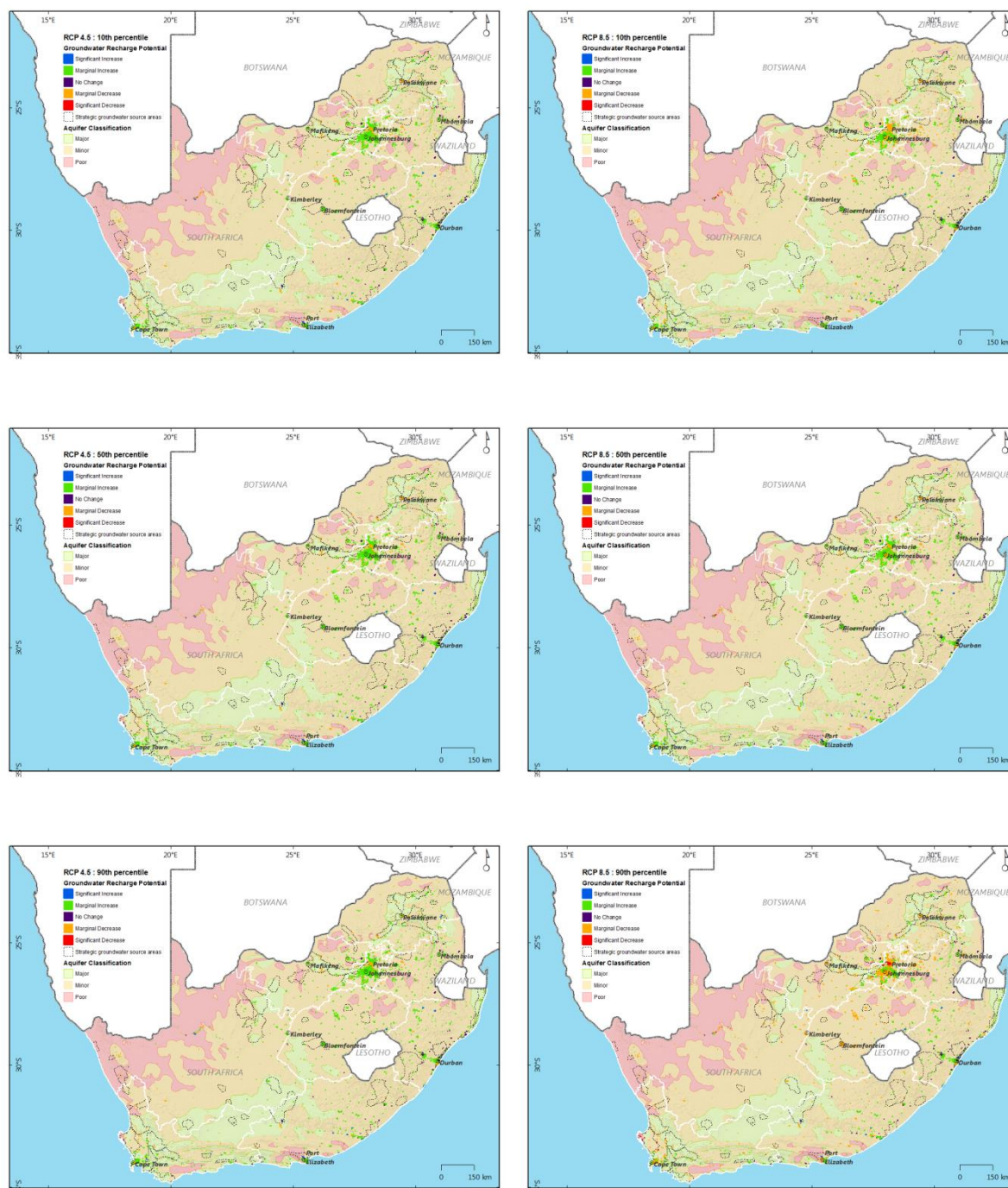


Figure 10: Projected nett (average) change in potential groundwater recharge over South Africa between 2031 to 2050 with respect to 1961 to 1990 for the 90th percentile (upper), the median (middle), the 10th percentile (lower) following RCP4.5 (left) and RCP8.5 (right).

A closer look at the projected nett groundwater recharge associated with the national distribution of settlements is presented in **Error! Reference source not found..** To acquire the nett groundwater recharge, projected groundwater recharge values were averaged for each individual settlement and differentiated into five classes depicting the change in groundwater namely: no change, moderate increase/decrease and significant increase/decrease. Although at a provincial scale the general trend observed in Figure 9 illustrates more favourable future conditions under RCP4.5 than RCP8.5 i.e higher groundwater recharge availability in RCP4.5 when compared to RCP8.5, while several of the settlements (e.g. Hazyview, Mpumalanga; Vereeniging, Gauteng) are predicted to experience an overall 'no change' in groundwater recharge under the conditions of both the RCP4.5 and 8.5 scenarios, at the median percentile. Other settlements including Beaufort West in the Western Cape, Howick in the KwaZulu-Natal and Kimberley in the Northern Cape confirm the trend observed in Figure 9: a marginal increase in groundwater recharge is observed under RCP4.5 conditions while the same settlement experiences marginal decrease in groundwater recharge under RCP8.5 conditions. This trend is observed across all the percentiles.

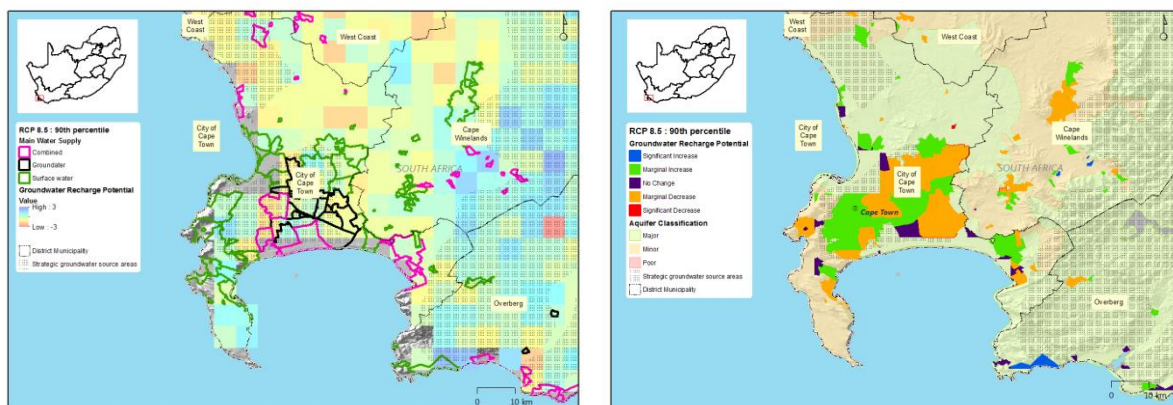


Figure 11: Projected potential groundwater recharge for the City of Cape Town Metropolitan Municipality and its surrounding district municipalities at the 90th percentile, under RCP8.5.

The City of Cape Town Metropolitan Municipality and its surrounding district municipalities (DM) i.e. Cape Winelands DM, Overberg DM, West Coast DM provides a clear picture of the likely variability in groundwater recharge potential between neighbouring settlements (Figure 11). As illustrated, the projected groundwater recharge potential is not uniform for all settlements in the region. The settlements of Muizenberg and Athlone are predicted to experience marginally decreased groundwater recharge, while greater groundwater recharge is projected for Durbanville and Khayelitsha.

In recent years, the City of Cape Town and surrounding towns experienced extensive demand and supply-related water shortages which called for Level 6B water restrictions (DWS, 2018;



Felix, 2018) to be administered. Similar to the 2004/2005 water restrictions (Geustyn et al., 2007), these recent water restrictions have also resulted in notable water savings. Other suggested mitigation and adaptation strategies in response to the water shortages include, and are not limited to rainwater harvesting, groundwater from local aquifers, desalination of seawater, re-use of municipal effluent and modification of catchment vegetation (Mukheibir and Ziervogel, 2007). All of these strategies fall in line with the municipality's integrated water management plan approach and are adaptable to climate change-related water management plans.

6 RECOMMENDATIONS

The impact of climate change on national water resources including groundwater is a major concern for the South African government. Consequently, national water strategies which seek to promote the protection and sustainable use of water resources have highlighted climate change as a key area for research. The National Groundwater Strategy (DWS, 2010; 2016) is one such advisory document and a few of its suggested actions for meeting future water supply and demand include:

- Conduct groundwater resource assessments and development programmes (including the rehabilitation of existing water supply boreholes) for towns threatened by surface water shortages as water demand increases;
- Update the GRA 2 figures on groundwater availability (groundwater recharge) and use as new data becomes available to (1) Resolve incorporation of privately held groundwater datasets into the National Groundwater Archive; (2) Provide an integrated groundwater information system to support water services provision at municipal level, and; (3) Improve the compatibility (and/or integration) of existing groundwater databases / information systems maintained by different institutions (including water quality databases and municipal groundwater asset registers);
- Develop and implement a Groundwater Monitoring Strategy to address the monitoring challenges at the national and regional level.

National-scale climate change adaptation measures have however been found to be inadequate at the municipal-scale as they do not consider the availability of resources and capacity required to ensure implementation and operation of these national adaptation plans, at a local level (Mukheibir and Ziervogel, 2007). Given that South Africa has a varied climate which ranges from a temperate to semi-arid interior, sub-tropical north-eastern coast and

Mediterranean south-western coast, it is essential to understand how climate change impacts local sectors within a municipality and which mitigation and adaptation measures can be prioritised to directly address the resultant local vulnerabilities.

In that regard, Mukheiber and Ziervogel (2007) have suggested the use of a ‘municipal adaptation plan’ for adapting local municipalities to future climate change impacts. The adaptation plan is provided as a general framework that can be adjusted to address a number of issues relating to climate change. In the context of this study, the municipality adaptation plan has been revised to address the availability of groundwater resources for settlements (Figure 12).

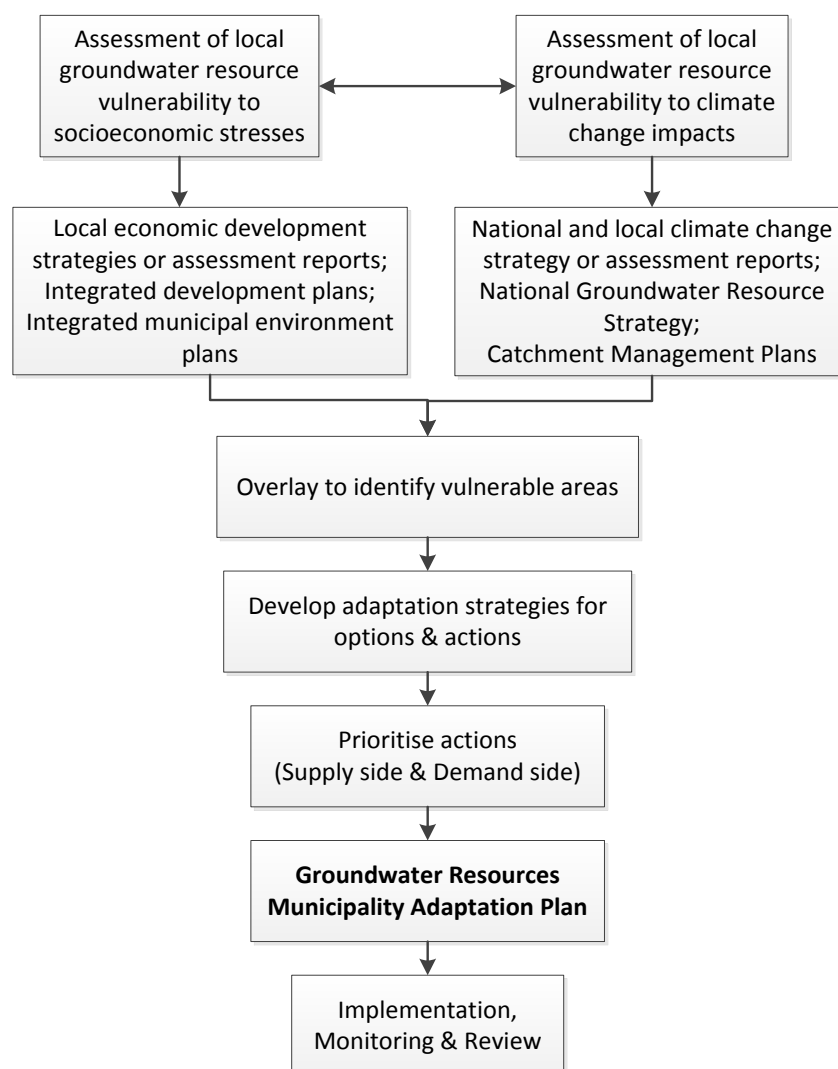


Figure 12: Framework for developing groundwater resources climate change adaptation plan for district/local municipalities (after Mukheiber and Ziervogel, 2007 and Mukheiber, 2008).



The adaptation plan highlights the need for an integrated analysis approach which takes into account the impact of socioeconomic stresses (e.g. economic development, water supply and demand etc.) and climate change impacts on municipality-level groundwater resources. Similar to the methodology applied in this study, the adaptation plan also recommends an overlay of multiple groundwater-related datasets to delineate high-risk areas and use that visualisation tool to develop a site-specific climate change adaptation plan.

Given the results of this study, the currently available groundwater-related datasets and national and municipal climate change mitigation and adaptation strategies in place, it is recommended that groundwater-dependent settlements develop and implement adaptation plans that take into consideration the following aspects of the settlement:

- Local hydrogeology – main productive aquifers, their maximum yield and the harvest potential;
- Local climate and predicted climate changes;
- Spatial relation between settlement, aquifers and nearest strategic groundwater source areas (conservation of groundwater source areas is highly advisable);
- The Consumptive rate of groundwater uses (domestic, industry, agricultural irrigation, mining etc., including large-scale abstractions);
- Predicted changes in recharge
 - low recharge areas may need to invest in artificial recharge operations which supplement groundwater supply with available surface water supply,
 - inter-catchment groundwater transfer schemes may need to be set up between high recharge and low recharge areas,
- Planned economic developments that will impact the availability of groundwater, and;
- Current availability of financial resources and human capacity that will support the implementation of the adaptation plans.

These components and any other additional factors need to be analysed within a holistic and integrated water resource management approach.

7 CONCLUSIONS

The response of groundwater recharge to future climate change impacts was explored for South Africa at a national scale, the aim is to identify potential high-risk areas that coincide



with the location of settlements. In relation to the effect of climate change on potential groundwater recharge, high-risk areas were characterised as settlements that are currently solely or partially dependent on groundwater for water supply and are predicted to experience significantly low or high groundwater recharge potential values in response to a changing climate. Several national-scale groundwater datasets including large-scale groundwater abstraction, and strategic groundwater source areas were employed to delineate these areas. To assess the impact of climate change on groundwater resources, a composite mapping analysis technique was adapted to formulate a series of six potential groundwater recharge maps depicting groundwater recharge scenarios across South Africa between 2031 and 2050. RCP4.5 and RCP8.5 were mapped at the 10th, 50th and 90th percentiles and compared to determine the probability of changes in groundwater recharge in each scenario. Modelling results suggest that the potential groundwater recharge under RCP4.5 is generally likely to be greater than under RCP8.5 conditions. The trend of decreasing groundwater recharge potential is observed across the 10th, 50th and 90th percentiles however, RCP8.5 90th percentile represents the worst possible impact of climate change on groundwater recharge availability. Areas that are predicted to experience a low groundwater recharge potential included the western, western-interior and northern-most parts of the country, while higher groundwater recharge potential is projected for the central interior and south-eastern coastline. A closer look at individual settlements has revealed that the nett groundwater recharge experienced by each town will vary spatially from no change in recharge to moderate or significant increases and decreases. This observation highlights the great uncertainty associated with modelling the impact of climate change on subsurface water resources.

Given the results of this study, it can be concluded that the impact of climate change on potential groundwater recharge will vary in magnitude and extent across the country. The variance in recharge values will depend on the regional climate conditions particularly the amount and intensity of rainfall that occurs. Several large-scale groundwater abstraction schemes and groundwater dependent settlements' water supply will be affected by predicted low recharge values. To ensure sustainable economic growth and continuity of water and food security for future generations, climate change mitigation and adaptation strategies need to be implemented.



8 REFERENCES

- Baron, J., Seward, P. and Seymour, A., 1998. The Groundwater Harvest Potential Map of the Republic of South Africa. Technical Report Gh 3917. Directorate Geohydrology, Department of Water Affairs and Forestry, Pretoria.
- Buttrick, D.B., Kleywegt, R.J., Shedden, E., Trollip, N.Y.G., Van Schalkwyk, A., Venter, I.S. and Venter, J.P., 2003. Guideline for engineering-geological characterisation and development of dolomitic land. Council for Geoscience (CGS) and South African Institute of Engineering and Environmental Geologists (SAIE&EG), Pretoria, RSA. 66 pp. ISBN 919908-45-5.
- Davis, C., Engelbrecht, F., Tadross, M., Wolski, P. and Archer van Garderen, E., 2017. Future Climate Change over Southern Africa. In: J. Mambo and K. Facer (eds.). *Understanding the Social & Environmental Implications of Global Change [Second edition of the South African Risk and Vulnerability Atlas]*. Stellenbosch: African Sun Media, 13-25.
- DWAF (Department of Water Affairs and Forestry), 2006. Groundwater Resource Assessment II – Task 3aE Recharge. Pretoria, South Africa.
- DWS (Department of Water and Sanitation), 2018, 7 March. Media Statement: Dam levels nationally improve slightly with concerns in some provinces. Pretoria, South Africa. Accessed on 3 July 2018 from <http://www.dwa.gov.za/Communications/PressReleases/2018/MS%20-%20Dam%20levels%20nationally%20improve%20slightly%20with%20concerns%20in%20some%20provinces.pdf>
- DWS (Department of Water and Sanitation), 2016. National Groundwater Strategy- Draft 3. Pretoria, South Africa.
- DWS (Department of Water and Sanitation), 2012. All Towns Reconciliation Strategy. Pretoria, South Africa.
- DWS (Department of Water and Sanitation), 2012. Aquifer Classification of South Africa. Pretoria, South Africa.
- DWS (Department of Water and Sanitation), 2010. National Groundwater Strategy-. Pretoria, South Africa.



- Felix, J., 2018, 1 February. #WaterCrisis: Welcome to Level 6B water restrictions. Accessed on 06 July 2018 from <https://www.iol.co.za/capeargus/news/watercrisis-welcome-to-level-6b-water-restrictions-13043675>
- Fourie, F., 2012. Groundwater Use: The Planning Perspective. Symposium on Groundwater and Municipalities, Potchefstroom, 15-16 October 2012.
- Geustyn, L., Jacobs, H.E., Du Plessis, J.A., Fair, K. and Daniels, J., 2007. Analysis of water savings - A case study during the 2004/2005 water restrictions in Cape Town: Technical Paper. Journal of the South African Institution of Civil Engineering, 49(3): 16-26.
- Haupt, C.J., 2001. Water resources situation assessment: Groundwater resources of South Africa. Department of Water Affairs and Forestry, Pretoria, South Africa.
- Jonck, F. and Meyer, S., 2004. Hydrogeological map series of the Republic of South Africa. Department of Water Affairs and Forestry.
- Knüppe, K., 2011. The challenges facing sustainable and adaptive groundwater management in South Africa. Water SA, 37(1), 67-80.
- Mukheibir, 2008. Water Resources Management Strategies for Adaptation to Climate-Induced Impacts in South Africa. Water Resources Management, 22: 1259-1276.
- Mukheibir, P. and Ziervogel, G., 2007. Developing a Municipal Adaptation Plan for climate change: the city of Cape Town. Environment and Urbanization, 19(1): 143-158.
- Oosthuizen, A.C. and Richardson, S., 2011. Sinkholes and subsidence in South Africa. Council for Geoscience Report 2011-0010. Bellville, Cape Town.
- SADC-HGM (Southern African Development Community- Hydrogeological Mapping), 2010.
- Smith-Adao, L., Seyler, H., Holland, M., Maherry, A., Nel, J., Le Maitre, D. and Witthuser, K., 2016. Enhancement of the method to identify and delineate South Africa's Water Source Areas (K5/2431): Conceptual Framework Report. CSIR Report No. K5/2431. Stellenbosch, South Africa.
- The South African Institution of Civil Engineering – Geotechnical Division. 2010. *Site Investigation Code of Practice*, 1st Edition. The South African Institution of Civil Engineering – Geotechnical Division, Midrand.
- Vilholth, K.G., Tottrup, C., Stendel, M. and Maherry, A., 2013. Integrated mapping of groundwater drought risk in the Southern African Development Community (SADC) region. Hydrogeology Journal, 21: 863-885.



Vegter, J.R., 2000. Groundwater development in South Africa and an introduction to the hydrogeology of groundwater regions. Water Research Commission, Pretoria, RSA, WRC Report TT134/00. 106 pp.

Vegter, J.R., 1995a. An Explanation of a set of National Groundwater Maps. Water Research Commission report TT 74/95, Pretoria, South Africa.

Vegter, J.R., 1995b. Groundwater Resources of the Republic of South Africa – Sheet 1 and Sheet 2. Maps published by the Water Research Commission, South Africa.

Woodford, A., Rosewarne, P. and Girman, J., 2006. 1 How much groundwater does South Africa Have?.SRK newsletter.
http://www.srk.co.za/files/File/newsletters/groundwater/PDFs/1_A_Woodford.pdf