Climate change vulnerability index for South African aquifers

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Abstract

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 surface hydrology for Africa and Southern Africa have received considerable attention from hydrologists during the past 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. To assess these impacts a climate change vulnerability index was developed. This vulnerability-index method is known as the DART index. The parameters considered in the DART method are as follows: depth to water-level change, aquifer type (storativity), recharge and transmissivity. The DART index is used as a regional screening tool to identify areas that could experience possible changes in their groundwater resources as a result of climate change. The current DART index does not account for adaptation and migration occurrences.

Keywords: groundwater, climate change, vulnerability index, South Africa, DART

Introduction

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

South Africa is viewed as a water-stressed country with an average annual rainfall of 500 mm (the world average annual rainfall is 860 mm) with decreasing precipitation from east to west. Total groundwater use is estimated at 15% over 65% of the surface area of South Africa.

Any climatic change could have adverse impacts on the water resources of a water-stressed country like South Africa. The potential impacts of climate change on water resources and surface hydrology for Africa and Southern Africa have received considerable attention from hydrologists during the past decade (e.g. Lumsden et al., 2009; IPCC, 2008), but very little research has been conducted on the future impact of climate change on groundwater resources in South Africa. Climate change can affect groundwater levels, recharge and groundwater contribution to baseflow. The question of the likely impact of climate change on renewable groundwater resources is highly relevant, but under-researched (Kundzewicz et al., 2008). This paper serves as a first step in assessing the impact of climate change on South Africa's aquifers on a regional scale.

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What is climate change?

The earth's climate system is governed by the energy that it continuously receives from the sun. About 70% of all solar energy is absorbed by the earth through the oceans, continents and the atmosphere whereas the remaining 30% is reflected back to space. The absorbed heat is later re-emitted in the form of infrared radiation or transferred by heat fluxes. However, certain gases in the troposphere and stratosphere absorb most of the outgoing infrared radiation before it can escape into space, thereby warming the atmosphere before the heat is once again re-emitted. These are referred to as greenhouse gases (IPCC, 2007).

This greenhouse effect results in the earth being warmer than it would be. Without it, life on earth would not be able to exist. However, of current concern to scientists is the increased concentration of greenhouse gases (for example, due to the burning of fossil fuels and deforestation) within the earth's atmosphere, which results in the warming of the lower atmosphere and appears to be changing present climate patterns. A shift in the earth's climatic regimes and changes in the nature of weather events are commonly referred to as climate change.

Climate change in South Africa

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

South Africa is a water-limited country with a changing water-management structure and priorities. It is situated in a region with increasing levels of water scarcity and water-quality problems, compounded by population growth and issues of social and economic development. The introduction of additional stresses on water resources arising from potential climate change can intensify these problems over much of the country.

Predicted climatic changes for South Africa include a general warming across the country of higher average

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temperatures in sub-humid areas. Mukheibir (2008) suggests that the temperature is expected to increase by approximately 1.5°C along the coast and 2°C to 3°C inland of the coastal mountains by 2050. Cavé et al. (2003) stated that the Western Cape is likely to experience an extended summer.

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

Schulze (2000) has demonstrated clear runoff reductions in the already dry western part of Southern Africa. Turpie et al. (2002) suggest that the country's main rivers are likely to have reduced runoff or become less predictable. Arnell (1999) too predicts a substantial reduction in runoff in the Limpopo (−30%) and Orange (−5%) catchments as well as decreases in the volumes of low flows in these 2 rivers.

An increase in the occurrence of extreme events (floods and droughts), depending on the region and the time of year, may occur due to the projected increases in rainfall and rainfall intensity that cause flooding. According to predictions, a rise in sea levels in coastal zones as well as seasonal changes (i.e. shifts in the annual timing of rainfall and temperature) can be expected.

It is clear from this discussion that climate change is a reality and is therefore an important consideration in the field of geohydrology. Despite its relatively small contribution to bulk water supply, more than 60% of South Africa's population is dependent on groundwater (Braune and Xu, 2008).

Quantifying climate-change impacts

Preamble

Global General Circulation Models (GCMs) have become the primary tools for the projection of climate change. Bates et al. (2008) describes a GCM as a numerical representation of the climate system, based on the physical, chemical and biological properties of its components, their interactions and feedback processes. GCMs depict the climate using a 3D grid over the globe. The horizontal resolution of these grids can vary between 250 km and 600 km which is considered coarse when compared to the scale at which typical geohydrological are carried out. Projections of future climate change through GCMs may provide insight into potential broad-scale changes in the atmosphere and ocean. These changes include shifts in the major circulation zones and the degree of sea-level rise.

It is evident from GCMs that rising concentrations of greenhouse gases may have a significant impact on the global climate. It is not clear, however, to what extent local-scale meteorological processes will be affected. The gap between what climate modellers are able to provide and what impact assessors require, is bridged by means of so-called 'downscaling' techniques (Wilby and Wigley, 1997). The term 'downscaling' refers to the development of regional-scale projections based on global models. This introduces an uncertainty that limits confidence in the magnitude of the projected change, although the pattern of change can be interpreted with greater certainty (Mukheibir and Ziervogel, 2006).

Aspects to consider when evaluating 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. Cavé et al. (2003) propose that rainfall–recharge relationships may be used in a first attempt to assess the impacts of climatic change on groundwater resources. Data from various studies were compiled, and recharge rates were compared to annual rainfall for Southern Africa. Large differences in recharge values were identified for areas with an annual rainfall of less than 500 mm. The observed rainfall–recharge relationship can be used as a tool to examine possible groundwater trends if the projected changes in mean annual precipitation occur as a response to human-induced climate change.

Aquifer recharge and groundwater levels interact, and depend on climate and groundwater use. Each aquifer has different properties and requires detailed characterisation and eventually quantification (e.g. numerical modelling) of these processes and linking of the recharge model to an appropriate climate model (York et al., 2002). In practice, any aquifer that has an existing and verified conceptual model, together with a calibrated numerical model, can be assessed for climate-change impacts through scenario simulations. The accuracy of predictions depends largely on scale of the project and availability of geohydrological and climatic datasets.

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

Quantifying climate-change impacts on groundwater

In analogy with the DRASTIC vulnerability index (Lynch et al., 1994), 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 vulnerability index was developed to express aquifer vulnerability with reference to the threat of pollution. The DART methodology focuses more on typical parameters used in sustainability studies, but also indirectly accommodates the issue of quality due to the fact that the water quality is likely to deteriorate with a drop in water level over time as the salt load will concentrate. The availability of regional data to support the DART index was a major consideration in the selection of parameters.

Two scenarios are considered in the calculation of the DART index; current and future. The current scenario is representative of the current precipitation patterns and represents the time period between 1961 and 2000. The future scenario is a

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prediction based on the selected GCM scenario and represents the time period between 2046 and 2065.

The most probable future scenario, in terms of atmospheric carbon dioxide concentration, is currently uncertain. What is known, however, is that even if emissions were to be cut today, the earth is still committed to a certain degree of climatic change (Davis, 2010). For the purpose of this article the Meteorological Research Institute Coupled General Circulation Model was chosen with a future A2 SRES (Special Report on *Emissions Scenarios)* emissions scenario.

The A2 storyline and scenario describes a very heterogeneous world, assuming a moderate to high growth in greenhouse-gas concentration. The observed CO_2 emissions compared to the A2 story line are shown in Fig. 1. The downscaled datasets were made available by the Climate System Analysis Group at the University of Cape Town.

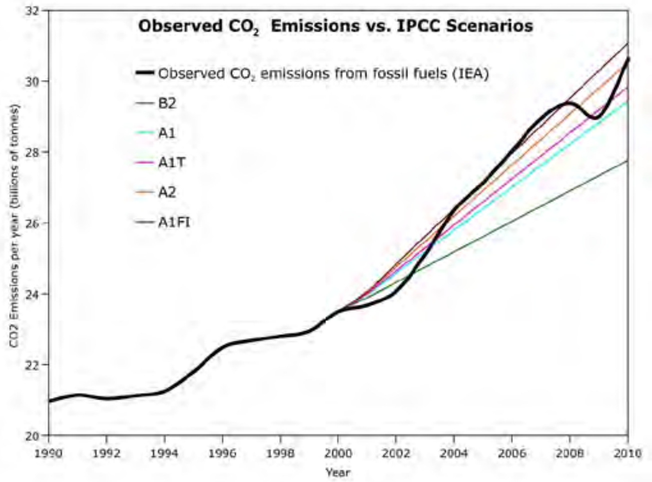

Figure 1
Observed CO2 emissions vs. IPCC scenarios (IPCC, 2000)

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. The resultant map of aquifer types is shown in Fig. 2. The aquifer type is considered a static variable in the DART index and will only change with updates to the geohydrological maps of South Africa.

Table 1
Aquifer type

Aquifer type	Storage coefficient
Fractured	0.001
Fractured and intergranular	0.005
Karst	0.01
Intergranular	0.1

Recharge

Recharge is a function of both precipitation and slope and an attempt was made to formulate a recharge function based on the aforementioned parameters to accommodate monthly recharge figures based on monthly precipitation.

The slope of the area 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

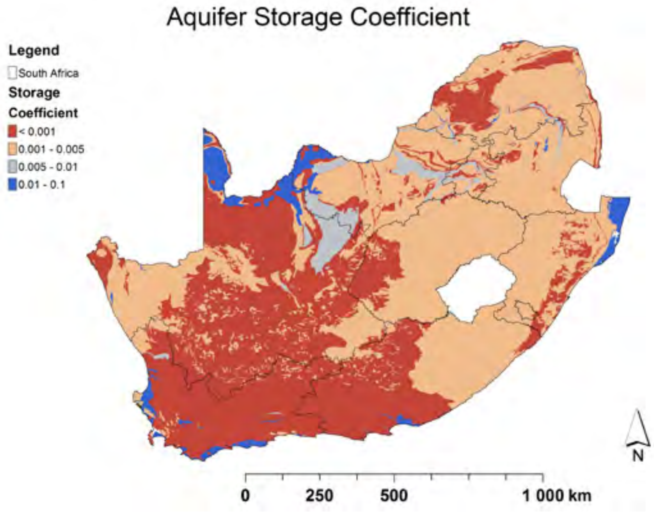

Figure 2
Aquifer type based on storage coefficient

topographical grid of 1 km x 1 km is used as shown in Fig. 3. A maximum slope of 30% was chosen as an absolute maximum and the following exponential scaling relationship was assumed for the recharge:

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

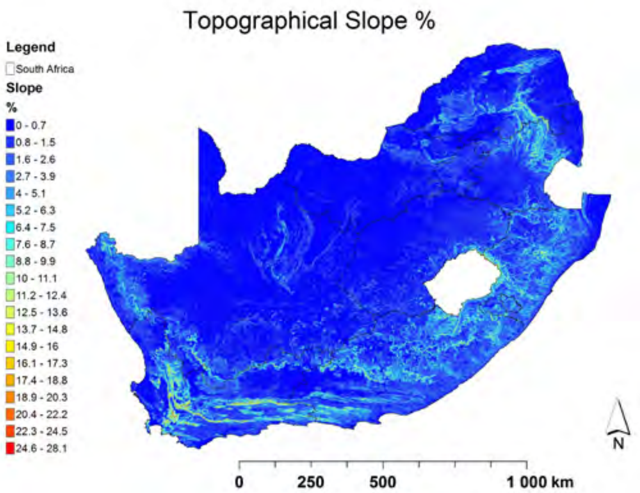

Figure 3
Topographical slope percentage

The second parameter defining the recharge function is the precipitation. The current precipitation scenario for South Africa is shown in Fig. 4. The grid structure of Fig. 4 is the grid on which the climate-change scenarios used are presented, hence the results of the DART index will also be based on the extent of this particular grid.

Cavé et al. (2003) established a rainfall-recharge relationship based on multiple observations as shown in Fig. 5. This relationship was proposed as a tool to examine possible groundwater trends in response to human-induced climate change:

$$Recharge\ (mm)=148*\ln\ (Precipitation)\ -\ 880$$

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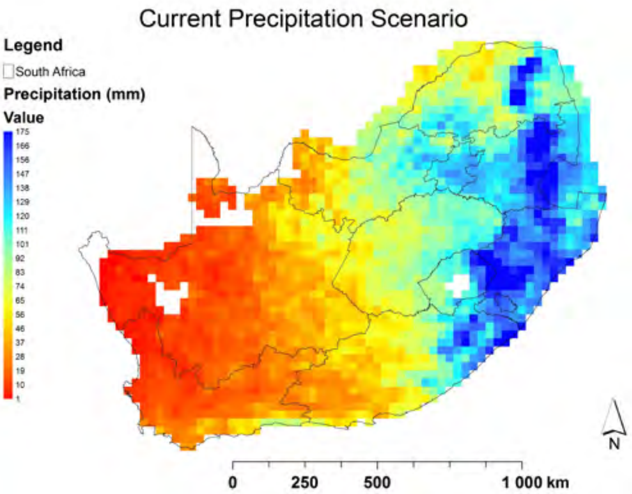

Figure 4
Current annual precipitation scenario

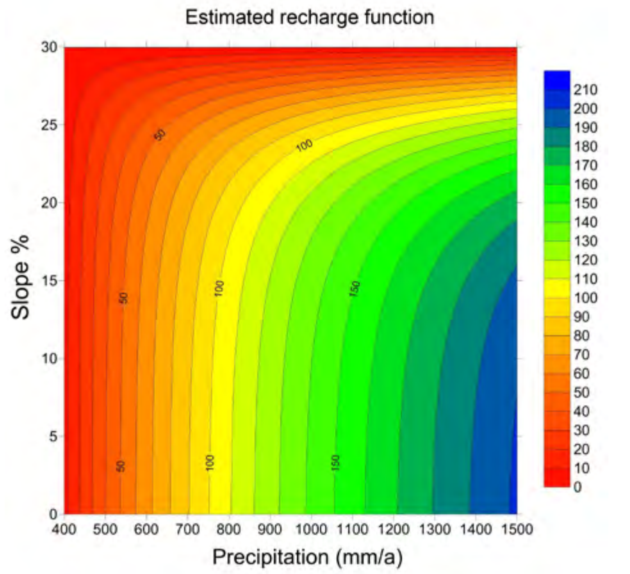

Figure 6
Recharge function based on precipitation and slope percentage. The current recharge and change in future recharge based on the recharge function are shown in Fig. 7 and Fig. 8, respectively.

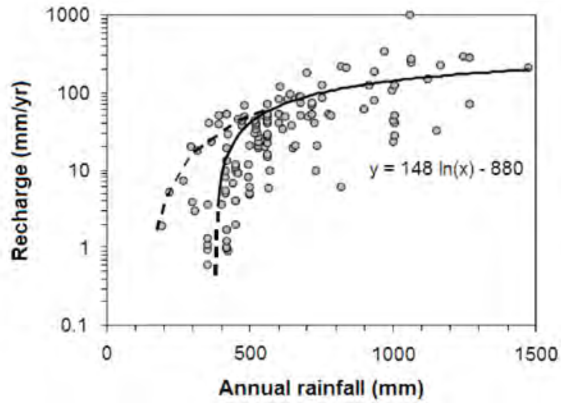

Figure 5
Recharge relationship determined by multiple observations (Cavé et al., 2003)

In the above recharge relationship, recharge becomes negligible for rainfall lower than 400 mm/a (Cavé et al., 2003).

The recharge function formulated for the purpose of this study is a combination of the recharge-rainfall relationship defined by Cavé et al. (2003) and the slope dependency assumed for the recharge. The formulated recharge function is presented below and the graphical representation is shown in Fig. 6.

$$\textit{Recharge}\ (mm) = (148 \times \ln(\textit{Precipitation}) - 880) \times (1 - 0.0025e^{0.2*\textit{Slope}})$$

The resultant recharge formulation allowed for recharge to be calculated as a function of the precipitation and slope over the area. National recharge datasets, e.g. GRA2 (Groundwater Resources Assessment Phase2) reports recharge percentages on quaternary catchment level which would not be suited for the GIS procedure utilised in this study as quaternary boundaries would appear to create artefacts.

The purpose of the aforementioned recharge function is to determine a smooth recharge cover over the whole of South Africa. Research on groundwater recharge is an ongoing field of study. Governing mechanisms like episodic recharge are not yet fully understood and cannot be modelled. The DART methodology should be updated accordingly as new recharge models become available.

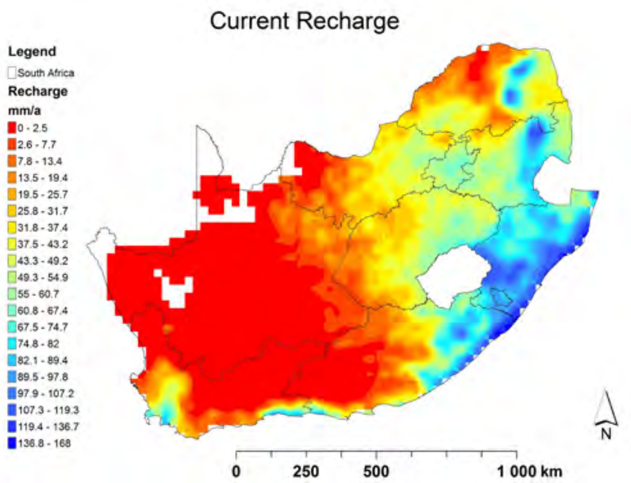

Figure 7
Current annual recharge

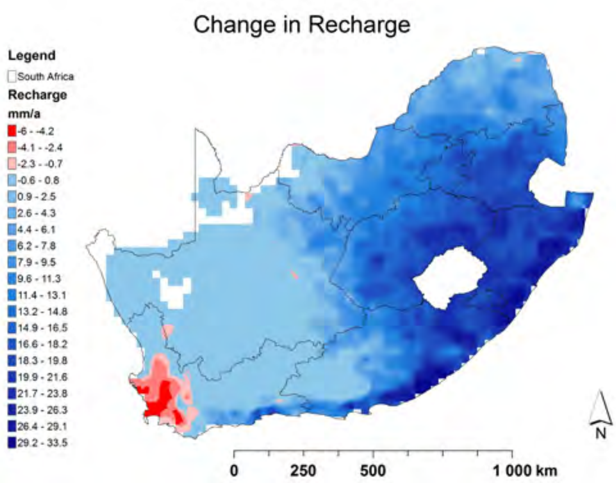

Figure 8
Change in annual recharge between current and future scenario

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Depth to water level change

The depth to water level was determined by using the average water level for each borehole on the NGA (National Groundwater Archive) and then performing Bayesian interpolation to exploit the correlation between water level and topography. A total of 244 733 boreholes were used and the borehole distribution is shown in Fig. 9. A map of the resultant water levels in metres below ground level (m bgl) is shown in Fig. 10. These water levels are used as the reference level for the current climate scenario.

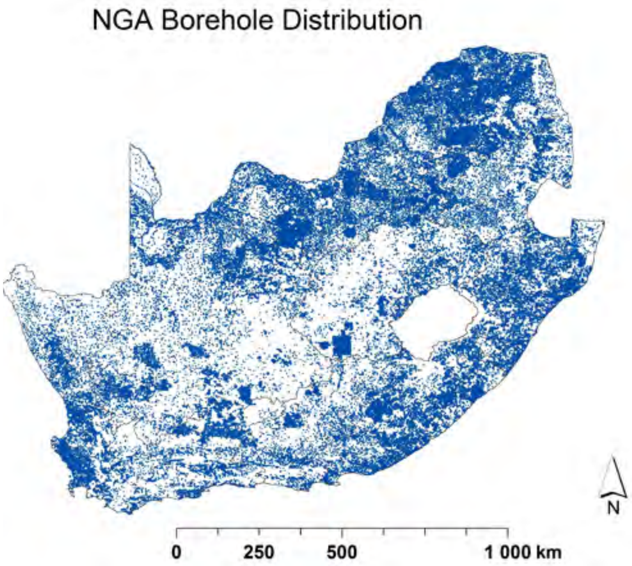

Figure 9
NGA borehole distribution

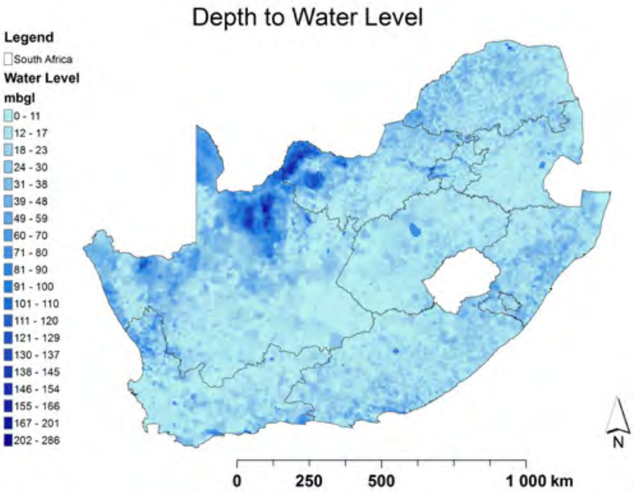

Figure 10
South African depth to water levels

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 Fig. 11 show the monthly water-level change between the current and future scenario.

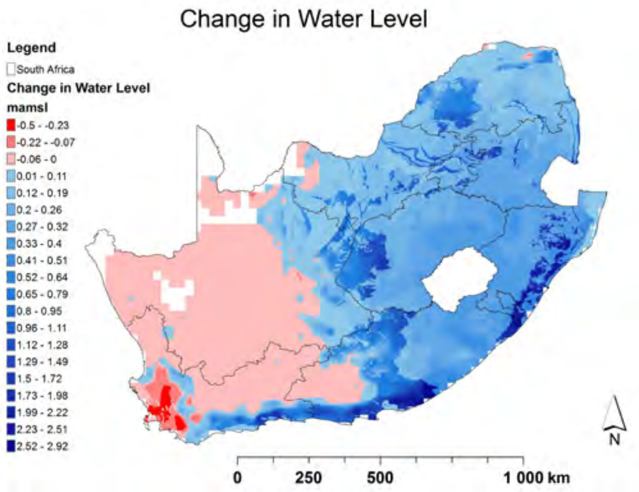

Figure 11
Water-level change between current and future scenario

Transmissivity

The transmissivity map was also produced through using the geohydrological maps of South Africa and translating the yield values to transmissivity values using a factor of 5. Traditionally a factor 10 was used for this purpose as a rule of thumb, but has been revised to a factor 5 as more information became available over time (Van Tonder, 2010).

The resultant transmissivities lie in the range of 0.25 m²/d to 25 m²/d. The transmissivity map is shown in Fig. 12. Note that higher transmissivities can occur due to the fractured nature of formations.

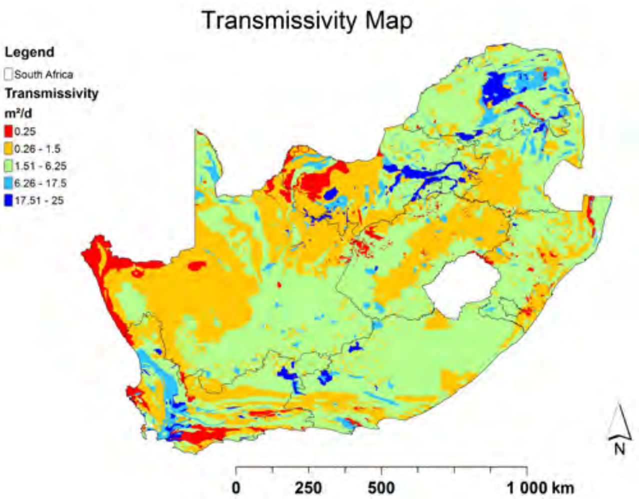

Figure 12
Transmissivity map

DART index calculation

With datasets produced for each parameter used in the DART index the calculation is done according to the ranges, classification and associated weights presented in Table 2. The DART index has a maximum score of 10 where higher

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Table 2 DART index calculation							
Depth to water-level change (m bgl)		**Aquifer type (storage coefficient)**		**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*	

values represent more resilience to the climate-change impacts driven by the change in rainfall.

Results of assessment

The results of the DART index are presented in Figs 13 to 16, which represent the monthly results for a complete hydrological year. The results are presented as the current DART index and the effective change the future scenario will have for each of the months. A negative value in the change of the DART index indicates deterioration in the index compared to the current scenario. It is important to keep in mind that the DART index is

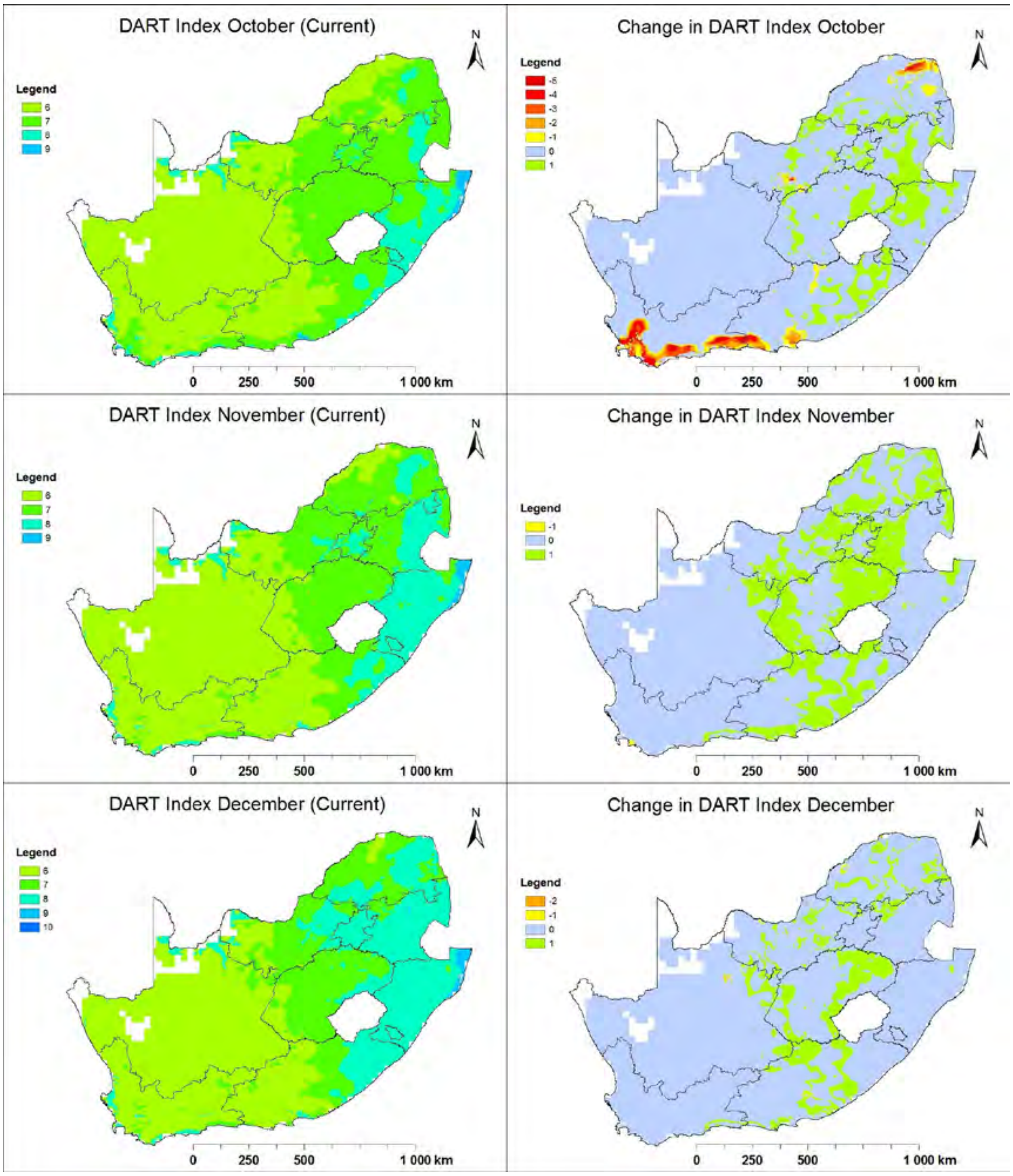

Figure 13
Change in average DART index between current and future scenario (October to December)

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a regional index and that it should be used to identify areas that will be negatively impacted by climate change with respect to groundwater.

The average change in the DART index over a hydrological year is shown in Fig. 17. Note that for the majority of the country the DART index remains unchanged. Areas that will experience an average degradation in their current DART index are mainly situated in the Western Cape. These areas are characterised mainly by a high slope percentage and low transmissivity values.

Conclusions and recommendations

The DART index is used as a regional screening tool to identify areas that could experience possible changes in their groundwater resources as a result of climate change.

The monthly DART index calculations indicate a strong spatial and temporal dependency of the index with a maximum negative index change of 6 and a maximum positive index change of 2 over the simulated hydrological year. A negative index change represents areas which will experience more

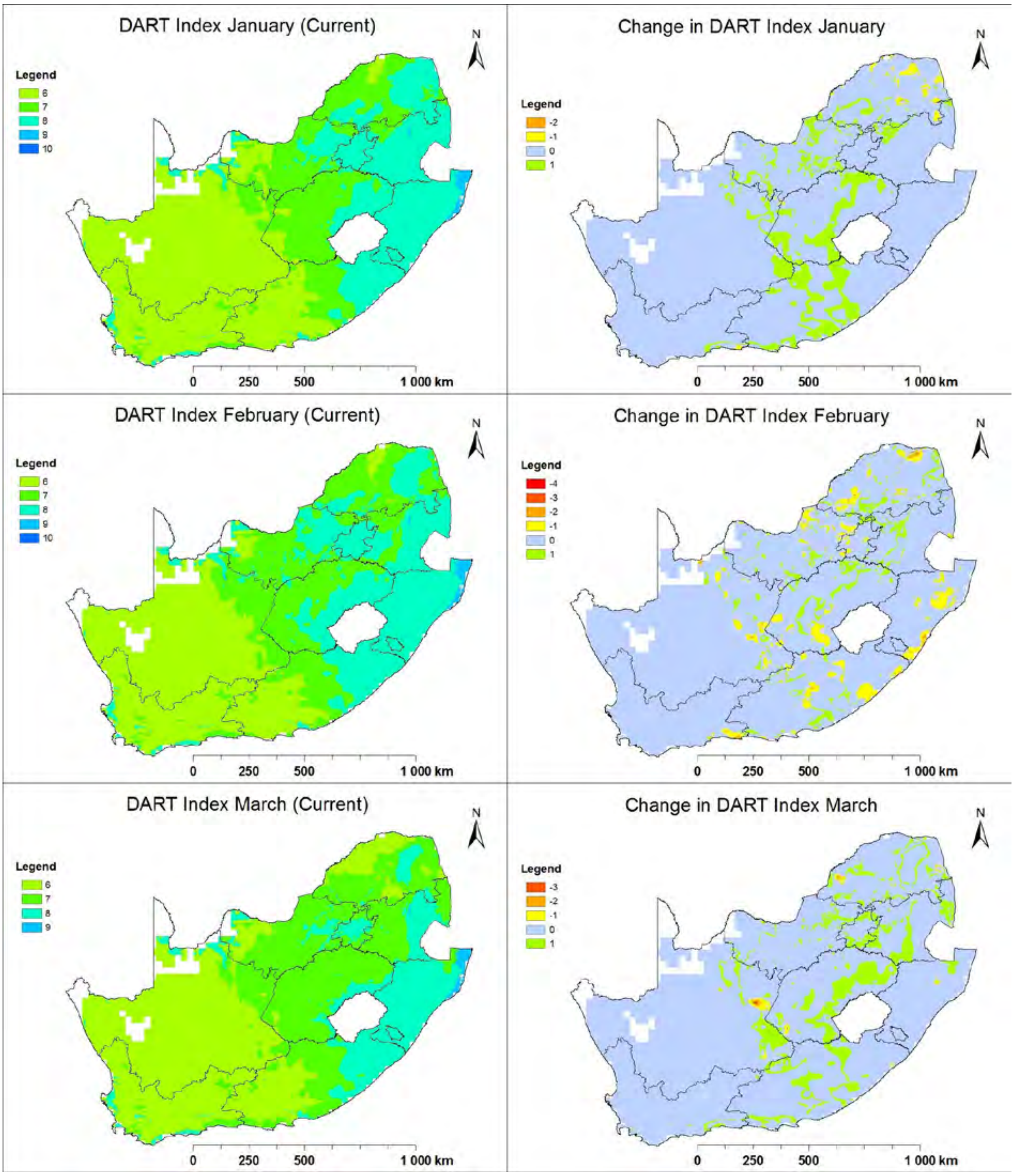

Figure 14
Change in average DART index between current and future scenario (January to March)

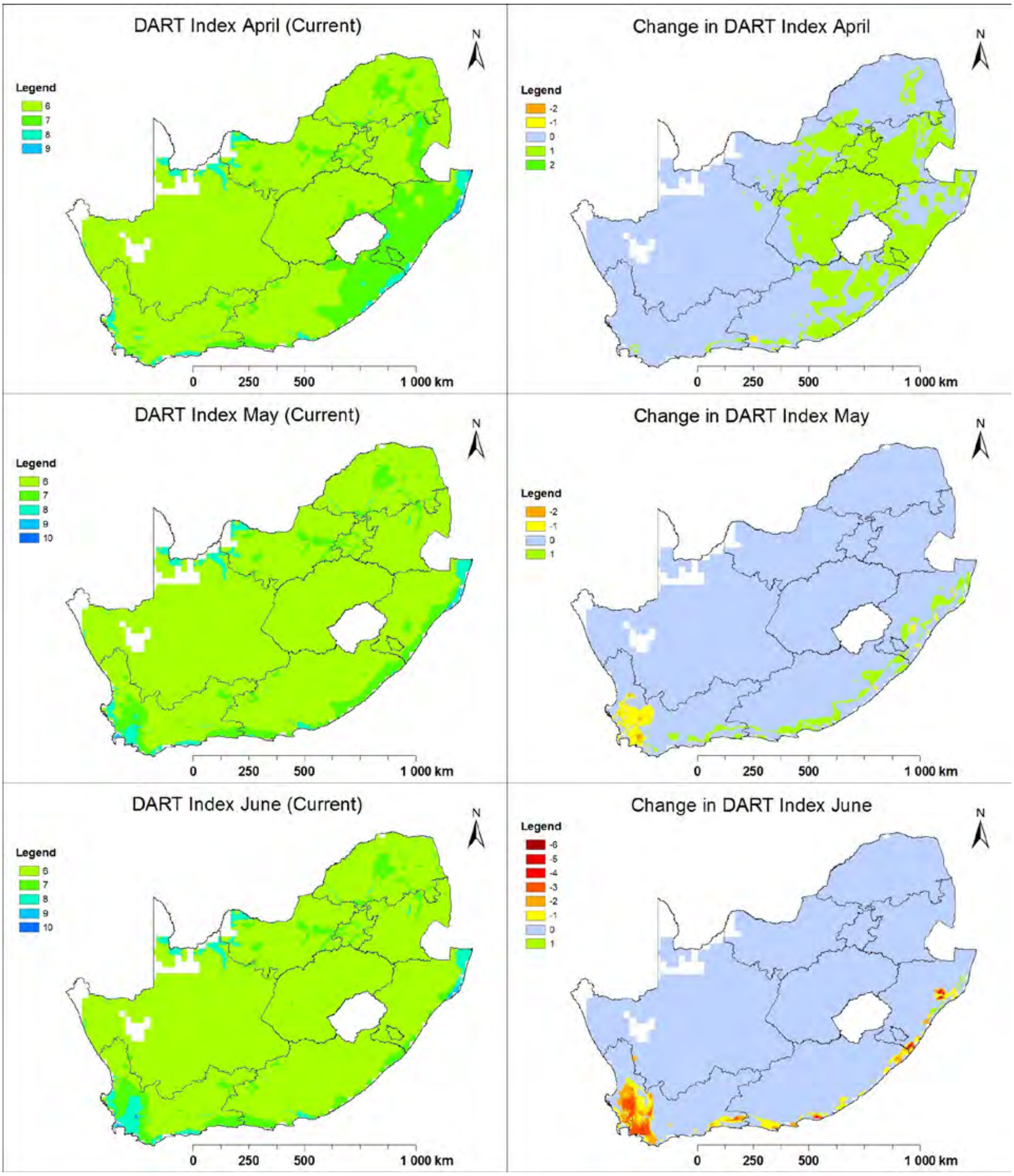

Figure 15
Change in average DART index between current and future scenario (April to June)

stress on their groundwater resources with respect to their current groundwater conditions.

The temporal nature of the DART index is also scale-dependent. This is evident from the average change in the DART index. On average, the majority of the country will maintain its current DART index. Note that, due to the selected recharge model, large portions of western South Africa do not experience a change in recharge, which in turn implies no change in water level. These low-precipitation areas are prone to episodic recharge events.

Areas subject to average degradation of their current DART index are mainly situated in the Western Cape and are characterised mainly by a high slope percentage and low transmissivity values.

Two scenarios manifest themselves in areas which are subject to the same negative change in the DART index:

- Areas not experiencing stress in their current groundwater resources might experience possible stress in their future groundwater resources for certain months of the year.

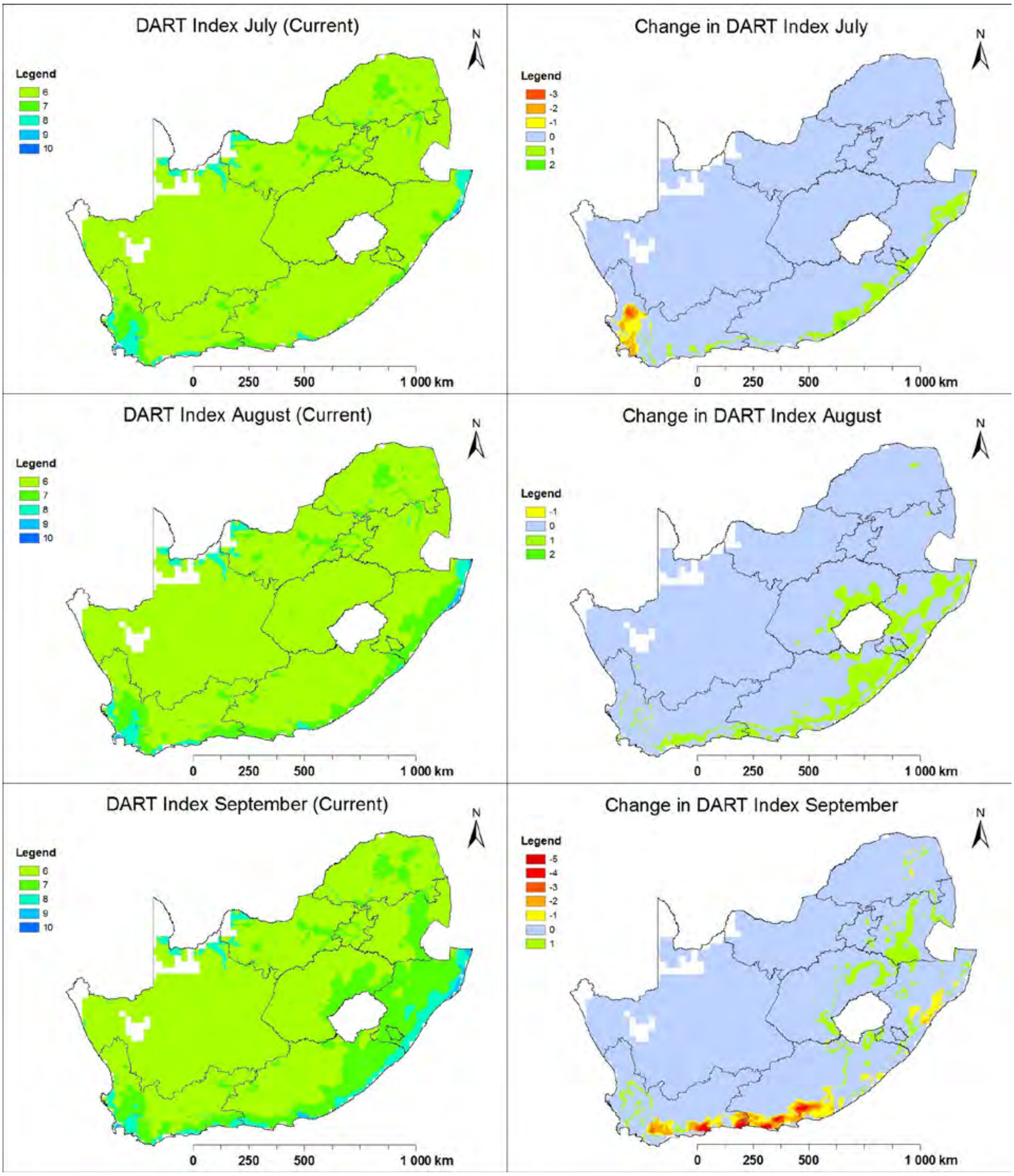

Figure 16
Change in average DART index between current and future scenario (July to September)

- Areas currently experiencing stress in their groundwater resources might experience failure of their groundwater resources in future for certain months of the year.

The question is how effectively these possible changes can be managed and will people be able to adapt? Detailed local-scale studies should be conducted to quantify the actual impacts in areas highlighted by the DART index. The current DART methodology does not account for the effect of adaptation and migration.

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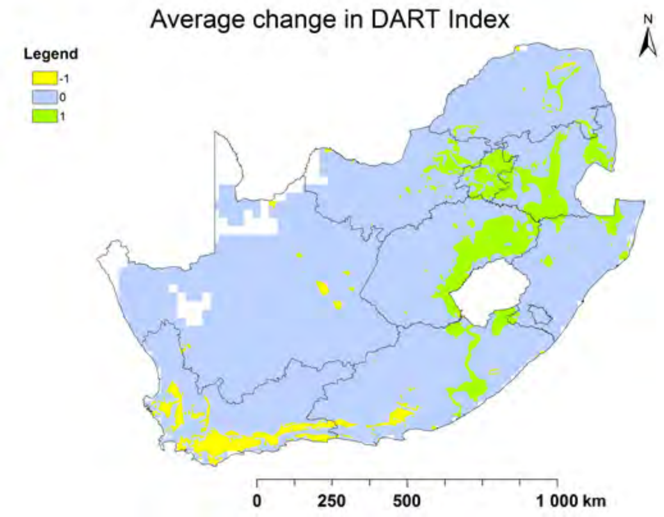

Figure 17
Average change in DART index

The project team values the inputs made by Prof. Gerrit van Tonder.

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