Consulting Services for Regional Groundwater Drought Management Support in SADC (Sub-component 2.1)

SADC Regional Groundwater Drought Vulnerability Mapping

Final Report

October, 2011

Preface

This report is the final report and details the progress towards implementation of the Southern African Development Community Groundwater Drought Vulnerability Mapping (SADC- GWDVM) component.

The important role of groundwater in drought protection and management has been increasingly recognized in the SADC as part of larger scale initiatives to collaborate on water management across the region, particularly manifested in the Regional Strategic Action Plan on Integrated Water Resources Development and Management (RSAP-IWRM) from 1998 and housed within the SADC Water Division.

However, proper drought protection and management and climate change adaptation in the region is hampered by lack of coordinated data and tools to support best practices and to facilitate better integration of groundwater, as an overriding and strategic resource, into planning and management of water resources in the region. The present project aims to contribute to the development of such shared and integrated tools.

As part of the larger strategy of RSAP-IWRM, a dedicated programme on groundwater was developed, entitled Groundwater Management Programme in SADC, encompassing various components. To support the data and knowledge base on groundwater, one component focussed on the compilation of a regional hydrogeological map and atlas (HGMA) for the SADC (European Union and GTZ, 2009a, b). The present sub-component, entitled Regional Groundwater Vulnerability Mapping under the project Groundwater and Drought Management in SADC, which is also a priority project under the Groundwater Management Programme initiated in 2005, further develops the regional groundwater mapping tools by drawing up drought vulnerability maps related to the groundwater resources and their use in the region.

SADC awarded the component to a consortium consisting of GEUS, the Geological Survey of Denmark and Greenland (Denmark); GRAS (Denmark); DMI, Danish Meteorological Institute (Denmark); and CSIR, Council for Scientific and Industrial Research (South Africa). GEUS is the lead consultant.

The SADC Project Steering Committee members are thanked for the active participation in the project. The SADC Water Division, Infrastructure and Services Directorate representative, Mr. Phera Ramoeli, and the Project Manager, Mr. Philip Beetlestone, are acknowledged for their input to the consultancy. Finally, we are grateful to the World Bank and GEF for their financial support to the project.

Dr. Karen G. Villholth, GEUS

Mr. Christian Tøttrup, GRAS

Martin Stendel, DMI

Ashton Maherry, CSIR

Marius Claassen, CSIR

Claudious Chikozho, CSIR

Christine Colvin, CSIR

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Acronyms

BGS	-	British Geological Survey
CGIAR-CSI	-	Consultative Group for International Agriculture Research Consortium for Spatial Information
CIESIN	-	Center for International Earth Science Information Network
CSIR	-	Council for Scientific and Industrial Research
DMC	-	Drought Monitoring Centre
DMI	-	Danish Meteorological Institute
DRC	-	Democratic Republic of Congo
DRR	-	Disaster Risk Reduction
ECMWF	-	European Centre for Medium-Range Weather Forecasts
ESA	-	European Space Agency
FAO	-	Food and Agricultural Organization (of the United Nations)
GCM	-	Global Circulation Model
GDP	-	Gross Domestic Product
GEUS	-	Geological Survey of Denmark and Greenland
GMISA	-	Groundwater Management Institute of Southern Africa
GRAS	-	Geographic Resource Analysis & Science
HGMA	-	Hydrogeology map and atlas
ICPAC	-	IGAD Climate Prediction and Applications Centre
IGRAC	-	International Groundwater Resources Assessment Centre
INGO	-	International non-governmental organization
ISDR	-	International Strategy for Disaster Reduction
MEI	-	Multivariate ENSO index
MPI	-	Multi-dimensional Poverty Index
NGO	-	Non-governmental organization

NMHS - National Monitoring and Hydrological Services

PSC - Project Steering Committee

RCM - Regional Circulation Model

RFE - Rainfall estimate

RSAP-IWRM - Regional Strategic Action Plan on Integrated Water Resources Development and Management

SADC - Southern African Development Community

SSA - Sub-Saharan Africa

TBA - Transboundary aquifer

USGS - United States Geological Survey

UNEP - United Nations Environment Programme

UNDP - United Nations Development Programme

WS - Water supply

Terminology/Abbreviations for GIMMS

CMA	-	Composite Mapping Analysis
CS	-	Climate sensitivity
GDE	-	Groundwater dependent ecosystem
GIMMS	-	Groundwater Insecurity Mapping and Management System
GW	-	Groundwater
GWD	-	Groundwater drought
GWDV	-	Groundwater drought vulnerability
GWDVM	-	Groundwater drought vulnerability mapping
GWI	-	Groundwater insecurity
GWL	-	Groundwater level
GWT	-	Groundwater threat
HGDP	-	Hydrogeological drought proneness
HuGWDV	-	Human groundwater drought vulnerability
PhGWDV	-	Physical groundwater drought vulnerability

1. Introduction

Drought is the principal type of natural hazard in Africa and the most common trigger for human insecurity, especially in the poorest segments of society. In addition, poverty is prevalent in Africa. Sub-Saharan Africa (SSA) is expected to account for roughly 50 % of the world's poor by 2015, compared with 19 % in 1990 (Devereux and Maxwell, 2001).

Groundwater is increasingly depended on for human development in the SADC region, both for the supply of domestic and drinking water as well as for productive uses, like irrigation, mining, and industry. About one third of the people in SADC live in drought prone areas where groundwater is the primary source of water for human population and livestock and most other activities (World Bank, 2005a).

However, the knowledge of technical, economic and environmental best and most sustainable options for groundwater development and management is limited and residing with few specialists. There is a huge need for capacity building at the individual as well as institutional level to make the degree of attention and governance of this resource commensurate with the level of use and importance that it has for water security and in general for socio-economic development in the region. Water security here is defined as 'availability of, and access to, water sufficient in quantity and quality to meet the livelihood needs of all households throughout the year, without prejudicing the needs of other users' (Calow et al., 2009).

Groundwater is most often considered an infinite and separate resource. This entails that the use is not measured in qualitative and quantitative terms, its use is not associated with granting of user permits, and consequences of its use is not considered in a broader water resources management framework. It is not mainstreamed into the wider IWMR (Integrated Water Resources Management) approach that has been incrementally acknowledged and applied in the region at various geographical scales, most often the catchment or river basin scale, which entails local, national and international level collaboration on water issues. Groundwater simply is underestimated, under-valued, and underrepresented in water management in SADC.

However, with the SADC Groundwater Management Programme and its many activities, significant steps are taken to highlight the important role of groundwater in the region, to build necessary capacity and to enhance regional collaboration on groundwater issues. Collaborating on a larger regional scale has several important advantages:

- Groundwater is often transboundary in character, and hence sharing knowledge and approaches between neighbouring countries enhance the options for sustainable approaches
- Groundwater management enters strategically into already existing mandates of international river basin organisations
- Coordinated approaches to monitoring the resource for early detection of problems and longer-term evaluation of its potential and limitations can be developed

- The regional water framework provides an option for optimizing the use of limited management capacity
- Further enhancement of groundwater management capacity may be facilitated through the regional approach

1.1. Objectives

The objective of the SADC Groundwater Drought Vulnerability Mapping Component is to develop a tool for the mapping and management of groundwater drought vulnerability (GWDV) and groundwater insecurity (GWI) in SADC. The tool is hereafter named the Groundwater Insecurity Mapping and Management System (GIMSS).

Such tool is intended to directly support:

- Groundwater and drought management in the region through the use of maps and integrated tools
- Highlighting , visualizing and linking the physical/drought and socio-economic risk factors that promote groundwater drought vulnerability and the focus areas for prevention and preparedness of groundwater drought and groundwater insecurity
- Coherent data collection and storage for data related to groundwater and drought management
- Highlighting the importance of groundwater in general, and in disaster risk reduction and drought management in particular
- Capacity building and the creation of an enabling environment around inter-disciplinary groundwater and drought management
- Coordination, collaboration, and dialogue in the region and across borders on transboundary aquifers[1] (TBA) and drought management, e.g. on cross-boundary migration as a result of drought

In addition, such tool is intended to indirectly support:

- Highlighting the important and strategic role groundwater plays in water security and socio-economic development in SADC
- Integration of groundwater into the broader framework for water management in SADC (IWRM), at the regional as well as national and more local levels
- Integration of groundwater into climate change adaptation and disaster (in particular drought) risk reduction strategies, policies and practices

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[1] An aquifer is the groundwater system that is accessible and productive for human use

1.2. Outputs

The outputs from the component comprise:

- Final report describing background, objectives, theory, review of historic drought conditions, mapping approach, data material used, map examples, outcomes, recommendations, and lessons learned
- GIMMS, a GIS-based inter-active and dynamic decision support tool for mapping and managing groundwater drought vulnerability and groundwater insecurity
- Hard copy versions of regional groundwater drought and insecurity maps
- A database of data used to generate the GWDV maps
- Training manual and training material for the theory of groundwater drought, groundwater drought management, and the application of GIMMS

1.3. Stakeholders, beneficiaries and uptake organizations

The stakeholders, beneficiaries and uptake organizations of GIMMS and other project outputs are listed in Table 1-1 .

Table 1-1 Stakeholders, uptake organizations and beneficiaries of outputs of the GWDVM Project

	Local	**National**	**Regional/International**
Stakeholders	NGOs	Ministries involved in water, DRR and development	ISDR[a] IAH[b]
Uptake organizations	Water users associations	SADC Member States National river basin organizations NMHS[c]	SADC Water Division GMISA Transboundary river and lake basin organizations SADC DMC[d] ICPAC[e]
Beneficiaries	Local households, farmers	Water authorities Water suppliers	INGOs Donors

[a] International Strategy for Disaster Reduction, http://www.unisdr.org/

[b] International Association of Hydrogeologists

[c] National Monitoring and Hydrological Services

[d] Drought Monitoring Centre, http://www.sadc.int/dmc/

[e] IGAD Climate Prediction and Applications Centre, http://www.icpac.net/

1.4. Potential uses of GIMMS

GIMMS can be applied to:

- Pinpoint critical areas where meteorological drought may quickly turn into groundwater drought with major human consequences in terms of basic water insecurity
- Target wider water supply development and rehabilitation programs and drought proofing initiatives to areas, which are particularly dependent on groundwater and vulnerable to groundwater drought (e.g. through well repair, well deepening, spring protection, groundwater recharge enhancement, rainwater harvesting, options for water trucking and storage)
- Highlight areas where the monitoring of water availability and access is important, e.g. through widening the scope of existing food security assessments and set up integrated indicators for real-time GWD monitoring
- Establish and implement efficient disaster/drought management plans and structures at appropriate levels within the region
- Develop further refined national/local maps to identify local water-insecure areas
- Highlight which factors (climate, physical, socio-economic) factors are overriding in groundwater drought vulnerability in particular areas
- Collate data for and visualize, through mapping, various conditions and aspects of groundwater drought vulnerability as part of water management interventions
- Test the influence of future scenarios related to climate change and other demographic or water infrastructure conditions on groundwater drought vulnerability
- Determine areas that are less vulnerable to GWD in a search for potentially new settlement areas, e.g. for displaced people

1.5. Overview of document

Chapter 2 gives the theory and background behind groundwater drought and groundwater drought vulnerability, which forms the basis for the development of the mapping tool for groundwater drought vulnerability (GIMMS). It is argued why groundwater drought vulnerability is a combined function of the climate and hydrogeological conditions as well as the socio-economic factors and human capacity to encounter droughts. Further, it is stressed that groundwater drought vulnerability is not an inherent and stationary property of a certain geographic area or countries to be mapped, but needs to incorporate dynamics and changes of climate on a longer time scale, possibly shorter temporal variations in climate, as well as human development and interaction with the water resources. Chapter 3 is the core of the report, outlining the GIMMS methodology for mapping groundwater drought vulnerability, the data used, and examples of maps generated. Chapter 4 illustrates the uses of GIMMS in a management context, and validation procedures for the tool. Chapter 5 gives considerations to the perspectives and recommendation for using GIMMS in SADC, including a proposal for an initial training component associated with GIMMS.

2. Groundwater drought and groundwater drought vulnerability

Groundwater traditionally supplies drinking water to 50-75 % of the African population, principally in rural areas (Taylor et al., 2009). Especially in arid areas, groundwater is often the only available and most affordable source of supply. In addition, it provides a relatively reliable perennial source that withstands droughts better than other surface-water based sources (McCartney and Smakhtin, 2010; Taylor, 2009; Steenbergen and Tuinhof, 2009). Hence, the concurrence of relative drought resistance and high dependence of human populations on the groundwater resource entails a relatively high degree of human vulnerability, should the resource fail to support water supply during extreme droughts.

2.1. *Concept of groundwater drought*

In this context, groundwater drought is defined as: **A situation in which groundwater resources decline below long-term average conditions due to meteorological drought, causing failure in availability and access for human use**.

Groundwater is affected in various ways by a drought. The components and characteristics of groundwater and groundwater flow that are affected are (see Figure 2.1):

- Groundwater recharge (the amount of water that infiltrates and replenishes the aquifers)
- Groundwater discharge (the amount of water that discharges from the aquifers into surface water bodies, springs or the sea)
- Groundwater storage (the total volume of water withheld within the aquifer)
- Groundwater levels (the level of the water table in a well drilled down to the aquifer)

It is clear that with a drought, all of these flows and storages decrease with time. However, these effects are not linear and rates not easily predictive. Furthermore, to mark the termination of a groundwater drought, recharge in significant enough amounts need to replenish the aquifers. However, this process can take highly variable time, depending on the depth of the groundwater table and the geological formations that the water need to percolate through. Generally, the longer the groundwater drought, the longer it will take to recover to pre-drought conditions. Hence, it is not a simple task to predict, in strict terms, which areas are more prone to groundwater drought.

Similarly, groundwater storage may seem the most critical parameter in a drought, signifying the volume of water available. However, what is most critical in practical circumstances are often the depth to the water table, as water access points, like wells and boreholes, always have a finite depth, and hence this depth becomes a threshold under which groundwater is not accessible, irrespective of how much water in total is available at that particular time. Drought proofing often means drilling deeper wells to ensure prolonged access to groundwater into a drought. However, this also hinges on other characteristics, as groundwater quality may vary with depth.

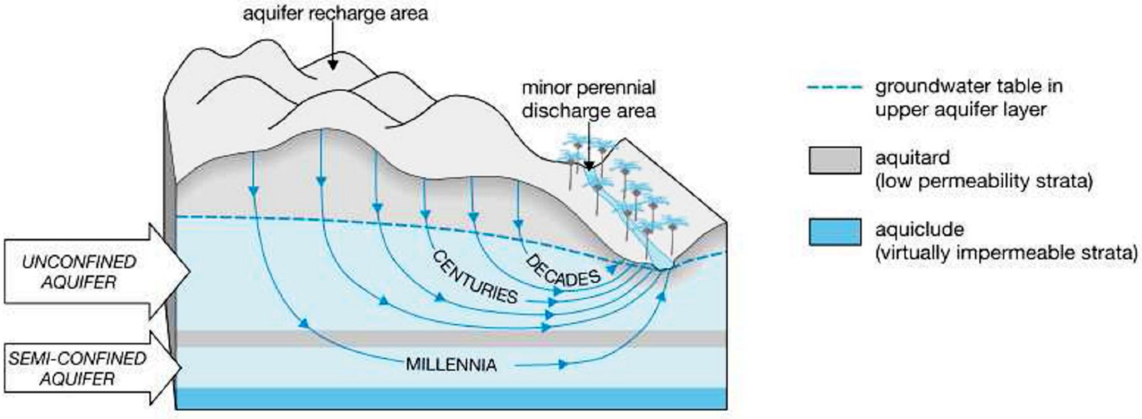


Figure 2.1 Typical groundwater flow regime and residence times of major aquifers under semi-arid climatic conditions (from Foster et al, 2006)

Groundwater is generally relied on in the SADC region for basic water supply and small scale productive livelihoods due to the following factors:

- Groundwater is almost ubiquitously available in the terrain
- Groundwater can be accessed with relatively simple means that individual households or small communities can implement
- Groundwater infrastructures, like wells and boreholes, are relatively cheap to install
- Groundwater, most often, provides a year-round reliable resource
- Groundwater, most often, provides water of adequate quality for drinking without any treatment

The availability of groundwater fluctuates less seasonally than surface water, generally making groundwater a good ‘buffer’ against drought. Another critically important fact is that fluctuations in groundwater availability are attenuated and delayed relative to surface water. This means that groundwater often is available during earlier parts of a drought when surface water has run out or for other reasons has become unpalatable due to drought-inflicted contamination (as a result of e.g. evaporation and salinisation, mixing with waste water, and competition for animal use). Only in later stages of a drought will groundwater storage and hence availability diminish as a result of a continued drought. Groundwater can hence be used as a drought prevention strategy, but only to a certain point. However, and reversely, after a drought event, groundwater may be short in supply even after rainfalls start and surface water bodies start to fill up. Hence, groundwater tends to react with a time lag relative to rainfall and surface waters, both at the unset of a drought and in the end of a drought.

These principles are illustrated in Figure 2.2. Groundwater drought is the phase of an overall drought where groundwater is in short demand.

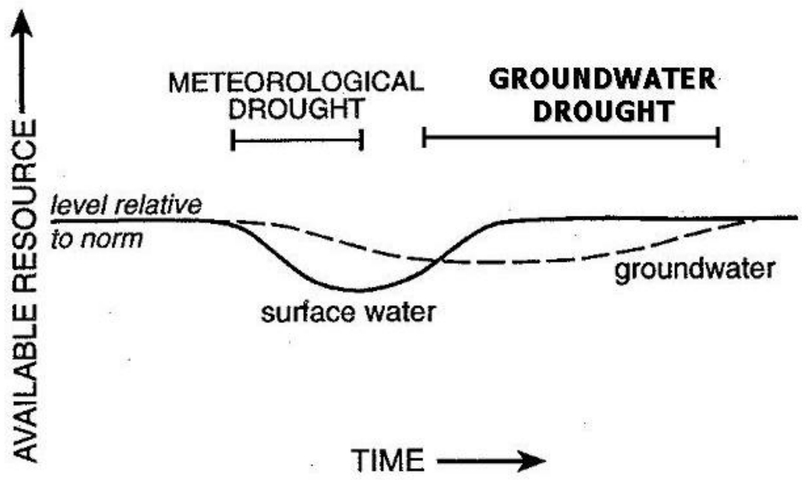


Figure 2.2 Sequential response and recovery functions of groundwater and surface water to drought. (From: Calow et al., 1997)

To further describe the phasing of a drought and the various terms associated with it, reference is given to Figure 2.3.

Phase:	Before the drought	Onset of the drought	During the drought		End of the drought	After the drought
Drought type:		Meteorological drought	Hydrological drought	Groundwater drought		
Availability of:						
Precipitation	+	-	-	±	+	+
Surface water	+	+	-	-	+	+
Groundwater	+	+	+	-	-	+

Figure 2.3 Phases of a drought, indicating various types of drought, including groundwater drought

Various types or phases of a drought are described as follows (Mishra and Singh, 2010):

- **Meteorological drought,** characterized by below average precipitation over a region for a prolonged period of time
- **Hydrological drought,** characterized by inadequate surface and subsurface water resources for established water uses of a given water resources management system
- **Agricultural drought,** characterized by declining soil moisture and consequent crop failure without any reference to surface water resources

- **Socio-economic drought,** characterized by failure of water resources systems to meet water demands and thus associating droughts with supply of and demand for water
- **Surface water drought,** characterized by decline in surface water storage and flows
- **Groundwater drought,** characterized by decline in groundwater recharge, levels, storage and discharge

Finally, groundwater may be present in aquifers that do not receive present day recharge. These aquifers are termed fossil or non-renewable. These may serve as very important water resources in arid and semi-arid areas and often water reserves accumulated in these aquifers are very large. In areas where such aquifers are present, drought vulnerability is usually less, as these resources serve as perennial sources. However, as these sources are not replenished in present times, they also present a risk of over-exploitation in a longer perspective, and the issue of drought management has a special character related to the judicious and planned exhaustion of these recourses (Polak et al., 2007; Foster and Loucks, 2006).

A groundwater drought may be perceived due to (Calow et al., 2009):

- Depletion of an aquifer/general groundwater level (GWL) decline
- Local GWL decline around wells due to excessive abstraction, linked to more intensive pumping during dry/drought periods
- Mechanical failure of wells and pumps

Hence, groundwater drought is not solely governed by the failure of the resource, but also the mechanical (or other) failure of the access structures to the resource. This links groundwater drought to the term groundwater drought vulnerability, described in the following section.

2.2. Vulnerability to groundwater drought

The increasing human dependence on groundwater signifies that the resource and its aquifer systems cannot be analysed in isolation and without reference to the human system that depends on it (Figure 2.4). This entails that groundwater drought vulnerability has a physical as well as a human dimension to it. In order to assess and map groundwater drought vulnerability and the risk of encountering a severe groundwater drought, these two dimensions need to be considered in conjunction.

In disaster risk management terminology, risk is the interaction between hazard and vulnerability (ISDR, 2004; Garatwa and Bollin, 2002):

Disaster Risk = Hazard x Vulnerability [1]

Hazard is the probability of a potentially damaging natural event, while vulnerability is the susceptibility and exposure of the affected system to the impacts of the hazard.

In our context, the hazard is characterized by the probability of meteorological drought resulting in the physical loss of groundwater availability. The vulnerability relates to the human vulnerability and coping capacity to encounter such groundwater drought. In general, groundwater drought vulnerability will be higher in areas that:

- Are arid and prone to meteorological drought
- Are underlain by poor aquifers (poor yield, little storage)
- Are highly dependent on groundwater for human use
- Have poor groundwater infrastructure, insecure water sources and little maintenance/management of same
- Are dominated by general poverty and lack socio-economic development

Poor aquifers could in an African context be hard rock (also called weathered crystalline basement rock) aquifers. These contribute a large fraction of the land surface (40 % of SSA) and is home to about 235 million people (MacDonald et al, 2008).

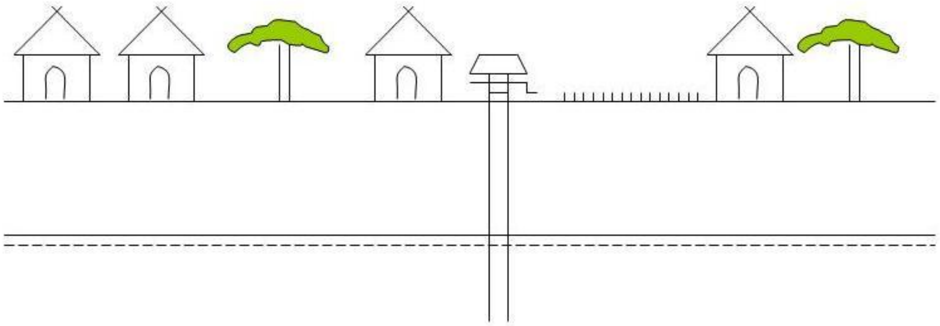


Figure 2.4 The interface and inter-relationship between groundwater and the human system, here in a rural setting

Groundwater drought vulnerability should not be confused with the widely used term 'groundwater vulnerability', which most frequently refers to the susceptibility of groundwater to become polluted, typically by human activities (e.g. Jayasekera et al., 2010; Alemayehu et al., 2008; Schwartz 2006; Al-Adamat et al., 2003, Lowry et al., 1995). Certain aspects of groundwater contamination may also have a bearing on the vulnerability of societies towards drought, hence the two types of vulnerability may be somewhat linked.

2.2.1. Socio-economic factors affecting groundwater drought vulnerability

In the following, factors of importance for the human vulnerability to groundwater drought are discussed.

2.2.2. Dependence on groundwater (domestic and agricultural)

Focus in this assessment is on basic water supply for human drinking and domestic water use. The reason for this is that this is the principal water need that has to be satisfied at all times to secure basic survival. Secondly, groundwater for agriculture, food production, livestock rearing and other productive uses can be analysed. However, there is a dual linkage between satisfying those needs:

- Groundwater infrastructure for irrigation and livestock may increase general access to water (also for drinking and domestic uses) (van Koppen et al., 2006)
- Groundwater for irrigation may limit the use for domestic purposes if not controlled properly (Foster and Garduño, 2004)

Hence, basic groundwater security may be either promoted or hampered by groundwater use for other purposes and these interrelationships need to be analysed in specific circumstances.

Livestock keeping is critical for many of people in the SADC region, often contributing to multiple livelihood objectives: diversification of income sources, insurance against crop failures, as e.g. during droughts. Livestock keeping is also an indispensable asset through its impact on human nutrition and health. Livestock will, as humans, be affected by drought and is therefore an important contributor to human groundwater drought vulnerability. Regions dominated by groundwater-supplied irrigation will in a similar fashion be vulnerable to groundwater drought though as specified above, irrigation water may in certain circumstances shield against drought conditions.

2.2.3. Value of groundwater

Groundwater is generally under-valued though it plays an essential role in providing fundamental drinking water. The fraction of people in SADC dependent on groundwater for their drinking water is higher than that of people using surface water. In addition, groundwater plays a very important role in maintaining ecosystems and other natural landscapes (see also Section 2.2.5). Still, groundwater tends to be valued only when used for productive uses, e.g. in crop production and in mining. It is an important consideration in making a groundwater drought vulnerability assessment and mapping to weigh and distinguish between various uses and values of groundwater. This can be done through the scenarios proposed in Section 4.1. Groundwater vulnerability increases with lack of alternative water resources. Hence access to surface water diminished vulnerability to groundwater.

2.2.4. Capacity to develop and manage groundwater sustainably

Groundwater needs proper development, use, protection and management to ensure sustainable access and long-term groundwater security. Important parameters to look at in this respect include number of groundwater professionals, number of academic institutions devoted to groundwater, level of investments in groundwater development and management, which are normally numbers difficult to get by in SADC. In view of these shortfalls, indirect measures of the technical and management capacity of the region can be estimated from various other 'surrogate' parameters, mostly related to general human and socio-economic development. An important, but overseen, factor in groundwater security is not only the investments and infrastructure for groundwater access available in the region (like number of wells), but also the functioning of such infrastructure. It is estimated that on average, 30 % of installed wells in rural parts of the SADC region do not function (Appendix 1). Unfortunately, these data do not exist for all SADC member states, and certainly not consistently at sub-national levels. However, this is a critical factor to take into account in local and operational management of groundwater drought vulnerability. Often, it is the wells that fail during drought, not the aquifers (Calow et al., 2009).

2.2.5. Groundwater-dependent ecosystems

The indirect impacts on people of groundwater drought may also be felt via the impact on groundwater dependent ecosystems (GDEs). GDEs are ecosystems which include key species that rely on groundwater for all or part of their life cycle (Murray et al., 2003). They may be aquatic - such as groundwater fed wetlands, springs and rivers receiving groundwater baseflow during the dry season; and they may be 'dry land' or terrestrial ecosystems, such as the deeply rooted *Acacia* trees of the Kalahari (Colvin et al., 2007). An ecosystem is obviously linked to groundwater when a spring or an oasis is evident in an otherwise dry landscape. However, most GDEs are not obvious and quite difficult to differentiate from rain-fed systems, or soil moisture dependent systems. A parallel project component to this one is using a combination of spatial techniques from river baseflow concentration to remote sensing vegetation indices, to identify and map the different types of GDEs in different environments in the SADC region. Once GDEs are identified, their vulnerability to groundwater drought based on the availability of alternate water sources can be assessed (Figure 2.5). We cannot directly quantify the relative availability of soil moisture or surface water compared to groundwater, but we can use rainfall amounts and distribution within the year as an indicator of total water availability.

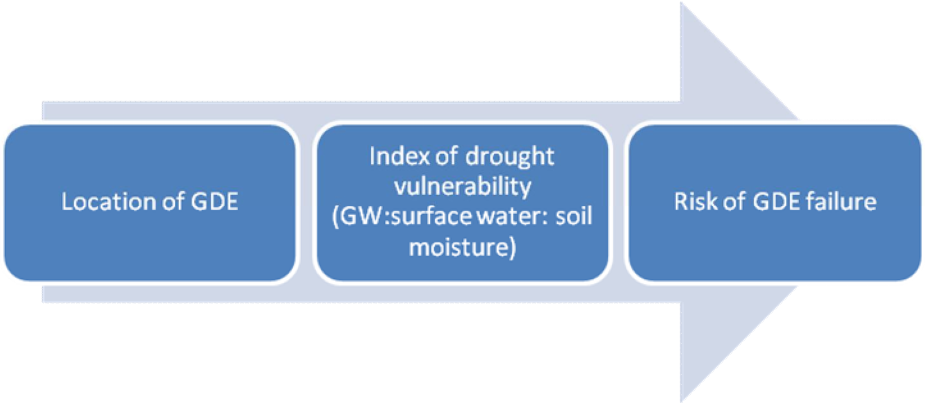


Figure 2.5 Conceptual process of incorporating GDEs into GIMMS

Many rural communities in SADC are closely linked to natural landscapes and biodiversity associated with GDEs, and still use indigenous plants for food, fodder and medicine. GDEs also form an important part of conservation areas and have economic value for ecotourism. Groundwater drought may place these GDE-linked resources in danger. It is important to identify GDEs within the GIMMS tool, so that groundwater managers can be aware that over-pumping groundwater resources during a drought period, or the recovery period, could cause irreversible damage to the ecosystem on which local people depend. In these cases, the decline in the water table should be minimised to maintain its connection to plant roots, wetlands and permanent pools in rivers, which provide critical habitats, especially during drought.

2.3. Dynamics of groundwater drought vulnerability

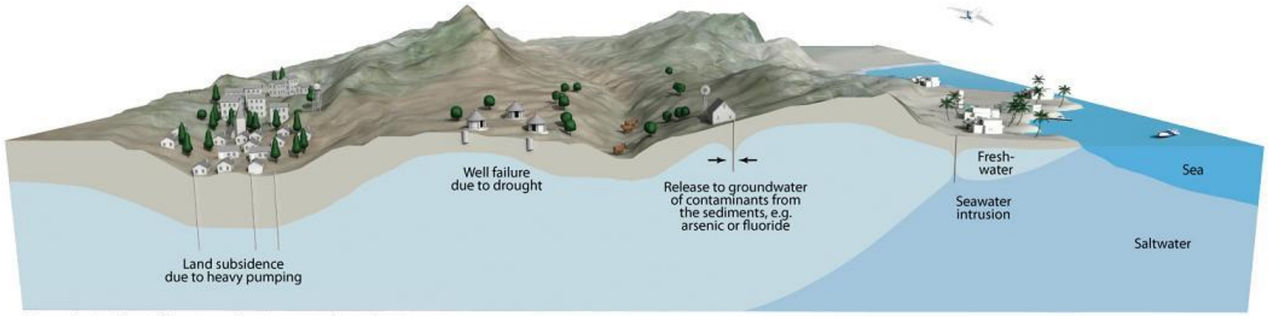
Groundwater drought vulnerability is not a static measure. It has to be seen, as done in the subsequent sections, in the context of time and local and global changes.

2.3.1. Climate change and increased climate variability

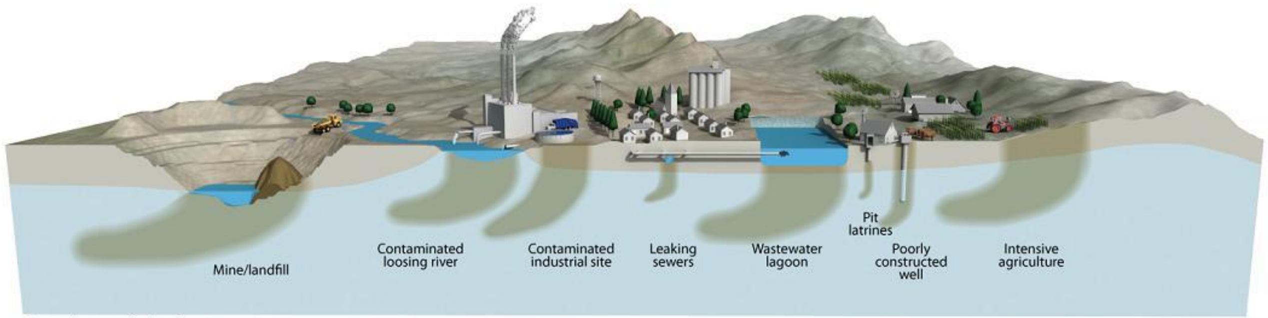
Water availability in Africa is among the most variable in the world (Taylor et al., 2009). This means that water insecurity and recurrent droughts and floods are prevalent in the SADC region. This characteristic will increase with projected climate changes and these impacts need to be incorporated into groundwater insecurity assessments in the future.

2.3.2. Human development and groundwater threats

Potentially overriding climate change, at least in the near future, are the effects of human development, urbanization and increased economic activities, like enhanced agricultural production with irrigation. These factors are expected to significantly influence groundwater drought vulnerability in the region. Human development will increase human capacity to encounter water scarcity problems, but on the other token will also exacerbate already emerging groundwater threats, like water quality degradation and groundwater over-abstraction (Figure 2.6).



Groundwater threats from groundwater use or decreasing storage



Groundwater pollution threats

Figure 2.6 Various anthropogenic and non-anthropogenic threats towards sustainable groundwater use

2.4. *Historic meteorological drought in the SADC region*

Drought is characterized as a hydro-meteorological hazard (ISDR, 2004). Its creeping characteristics and various impacts make the adoption of a precise and universally accepted definition of drought difficult. It is, however, broadly described by its spatial extension, intensity and duration. A recent review paper by Mishra and Singh (2010) discusses the different definitions of meteorological droughts, many of them based on precipitation and a lack thereof with respect to 'normal' values (e.g., Eltahir, 1992 and many subsequent analyses) and/or measurements of duration and intensity (e.g., Chang and Kleopa, 1991 and many subsequent analyses). Based on these considerations, a number of drought indices have been defined.

Following Mishra and Singh (2010), a drought index should, in a single variable, assess the effect of a drought by defining parameters that include intensity, duration, severity and spatial extent. The drought index developed particularly in this project addresses these parameters and, different from many studies based on observational data, also takes into account time scales that exceed one year.

While the proposed drought indices differ in details resulting in different relative ranking of droughts based on the four characteristics mentioned above, they all succeed in describing the more severe droughts that have occurred in the SADC region. For southern and eastern Africa, it is well known that El Niño events normally go along with droughts (Dilley, 2000), in particular during the December to March rainy season following the onset of such an event (Ropelewski and Halpert, 1987; Mason and Goddard, 2001). There are, however, exceptions to the rule, in particular during the El Niño event of 1997/1998, which was the largest of the 20th century. It was predicted with a high degree of certainty so that decision-makers could take actions. A drought was indeed observed in East Africa, but the feared devastating drought in southern Africa did not occur.

Droughts rank among the natural disasters that have the highest death tolls associated with them and particularly Southern Africa, the Greater Horn of Africa and the Sahelian zone are prone and vulnerable to droughts (World Bank, 2005b). Droughts have occurred recurrently in these regions, with five recent major periods of drought during the last three decades, in 1980-1983, 1987-1988, 1991-1992, 1994-1995 and 1997-1998 (World Bank, 2005b), all of these related to or following strong El Niño events (see Figure 2.7). Three of these events were regional in scale, with the 1991-1992 drought considered the worst in living memory, placing more than 20 million people at risk (ISDR, 2004). We note that large and severe droughts are generally related to El Niño conditions; however, droughts can also occur without such conditions. Below, a table is given, with the most significant droughts in Africa in recent decades (Table 2-1). In Figure 2.8, these events are shown on a map. It is clearly visible that some regions, in particular the Greater Horn of Africa, are more prone to drought conditions than others.

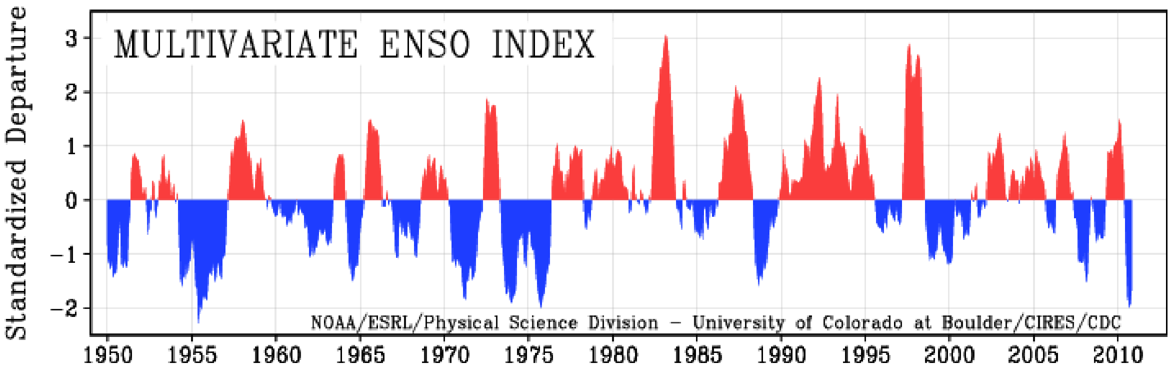


Figure 2.7 Multivariate ENSO index (MEI) in the so-called Niño 3.4 region (170°W-120°W, 5°S- 5°N) in the tropical East Pacific for the period 1950 to present (updated from Wolter and Timlin, 1998)[2]

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[2] The MEI is based on normalized values of the six main observed variables over the tropical Pacific: sea-level pressure, zonal and meridional components of the surface wind, sea surface temperature, surface

Table 2-1 Most significant droughts in Africa in recent history (EMDAT, 2010)

Year	Area	Country/countries
2008-2009	Horn of Africa, Eastern Africa	Ethiopia, Eritrea, Djibouti, Somalia, Kenya, Zimbabwe
2005-2006	Eastern Africa	Burundi, Djibouti, Ethiopia, Kenya, Malawi, Ruanda, Uganda, Mozambique, Zambia
2004	Southern Africa	KwaZulu-Natal, Eastern Cape, Swaziland
2002-2003	Horn of Africa, Southern and Eastern Africa	Ethiopia, Eritrea, Kenya, Malawi, Rwanda, Tanzania, Zimbabwe, Lesotho, Namibia
1997-2000	Eastern Africa	Tanzania, Kenya, Ethiopia, Rwanda
1995-1997	Horn of Africa	Ethiopia, Somalia, Eritrea
1991-1993	Southern and Eastern Africa	Ethiopia, Kenya, Malawi, Zimbabwe, Zambia, Botswana, South Africa, Lesotho, Namibia
1987-1988	Eastern Africa	Ethiopia, Malawi, Botswana
1984-1985	Eastern Africa	Ethiopia, Tanzania, Mozambique, Botswana, Zimbabwe
1983-1984	Horn of Africa	Ethiopia
1981-1984	Southern Africa	Botswana
1973	Horn of Africa	Ethiopia

air temperature and total cloudiness. Red bars in Figure 2.7 Multivariate ENSO index (MEI) in the so-called Niño 3.4 region (170°W-120°W, 5°S- 5°N) in the tropical East Pacific for the period 1950 to present (updated from Wolter and Timlin, 1998)

indicate warm conditions in the equatorial Pacific, and blue bars stand for cool conditions in equatorial waters. Large and prolonged El Niño events are indicated by large values of the MEI (for example 1983 and 1998).

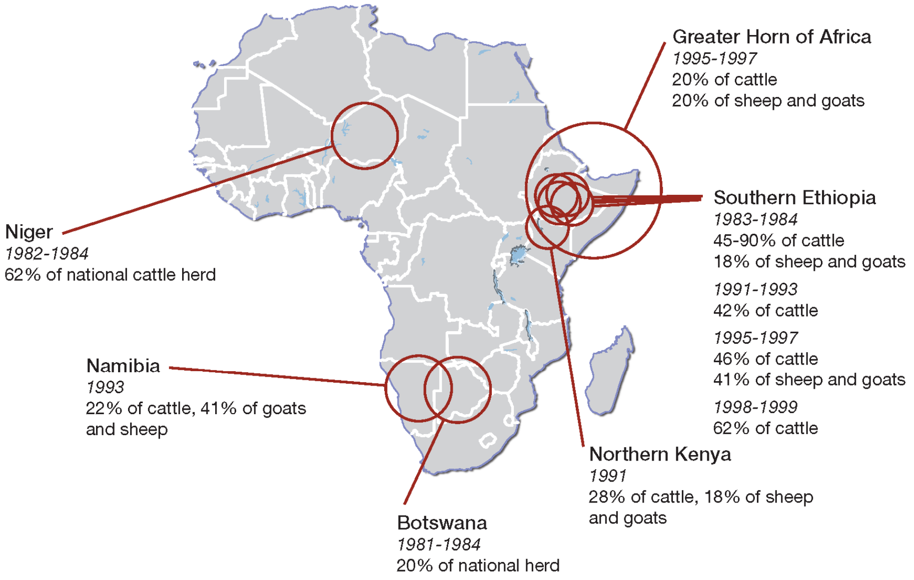

Figure 2.8 Location of the most significant droughts in Africa in recent history and reported loss of livestock, 1981-1999 (data from IPCC, 2007)

Several drought indices have been developed, as outlined above. Each of them has their own strengths and weaknesses, and we shortly discuss the two most common indices that are directly related to precipitation.

The standardized precipitation index fits a long-term precipitation record to a probability distribution and then applies normalization (Mc Kee et al., 1993; Edwards and McKee, 1997). Such an index can be calculated for several time scales; however, the index values depend on the length of the record (Wu et al., 2005), in particular in rainfall regimes with extended dry periods, which severely limits the applications of this index for Africa.

The other index is the Palmer drought severity index (Palmer, 1965). Its advantage is its sensitivity to temperature and precipitation; however, several assumptions are made that do not fit particularly well African conditions (e.g., Alley, 1984; Hayes et al, 1999). The values quantifying drought intensity and signaling the onset or decay of a drought were derived for the U.S. Great Plains and the soil types found there. Smith et al. (1993) demonstrate that in regions with extremes in the variability of rainfall, such as southern Africa and Australia, the Palmer index is of little use.

There are several other indices, but these rely on data that normally are not readily available for large regions of Africa, for example the crop moisture index (Palmer, 1968), the surface water supply index (Shafer and Dezman, 1982) and, more recently, the soil moisture deficit index (Narasimhan and Srinivasan, 2005) and the standardized runoff index (Shukla and Wood, 2008).

For these reasons, we have developed an index, which is based on “processed” rather than direct observations. “Processed” means that the observations are weighted (and observational errors are assigned) based on a priori knowledge obtained through a short-term model forecast. Such an approach, termed a reanalysis, offers five distinctive advantages with respect to the indices discussed in this section:

- The data used here provides full coverage at high resolution in time and space for the whole SADC region.
- The data used here provides consistency as far as possible. The short-range model forecast step ensures that there is physically consistent data even in the complete absence of conventional observations.
- The index used here does not require assumptions that do not apply to the region of interest (such as for the Palmer index), nor does it depend on the length of the time series or the length of the dry periods considered (such as for the standardized precipitation index).
- The data is available for a period of more than 20 years. With the development of improved reanalysis schemes in the future, it can easily be replaced by new fields, and the time period covered can be extended into the past. Taking all available surface and upper-air observations of the past into account, a future reanalysis beginning in the 1930s is envisaged.
- Since the index uses model-generated data, it is not a priori limited to past or present events, but using climate model scenario data, an assessment of future changes can be made. We will illustrate this capability below (Section 4.2).

The details of the set-up of the index used here are further discussed in Section 3.4.1.

2.4.1. Historic meteorological data in relation to groundwater drought

Climate data are important in GWDV mapping. Drought is provoked by lack of precipitation and excess evapotranspiration. Hence, in this mapping exercise, important meteorological parameters relate to rainfall and its distribution over time and space in the SADC region. To include the influence of climate sensitivity in the mapping, a meteorological drought risk index is developed (Section 3.4.1), which describes and encompasses an aggregate susceptibility of a unit area within SADC to drought. The susceptibility is a function of rainfall totals, say over a year, as drought intuitively relates to accumulated lack of rainfall. However, not only totals are important, as the duration over which rainfall is failing is critical, and finally also the deviation from ‘normal’ conditions is important. What make a drought severe is not only lower rainfall amounts, but also how long this failure persists and how uncommon the event is in a given area.

Compared to other regions of the world, there are few direct climate observations available in Africa. This is even true for the most basic variables, temperature and precipitation, and in several countries, such as Angola or the DRC, virtually no observed data is available at all. In addition, where data exist, they are often of doubtful quality, and many gaps exist. Furthermore, it is very difficult to identify such gaps, because often, as an example, precipitation is summed up for several days without a clear indication in the records. However, in regions with erratic and predominantly convective precipitation like most of Africa, it is entirely possible that precipitation summed up over a number of days may have fallen in an individual event. In particular for larger precipitation sums, this makes a big difference due to the totally different behaviour of runoff, and in a drought context, different water availability.

We have therefore decided not to use directly observed data, but instead to draw on reanalysis data. In a nutshell, a reanalysis is a combination of a model (“background”) forecast and observations. The idea is that if we assume we know the three-dimensional properties of the atmosphere at a given point in time, we can conduct a short forecast, e.g. for a six hour period, of the weather conditions using a global circulation model. The advantage of such an approach is that we obtain a three-dimensionally consistent state of the atmosphere at the time for which the forecast is valid. With a perfect model to run this forecast, we would not need any direct observations. The model, however, is not perfect, and therefore we slightly correct the model forecast (which can be considered as a “first guess”) with observed data that we trust as reliable. Once this is done, we can start the next forecast step, correct with observations and so on. The resulting product, called reanalysis, is therefore a mixture of model and observed data in regions where we have enough observations, but it will entirely be a model product in regions without observations. It is therefore essential that the underlying model delivers the “first guess” as realistic as possible. We add that normally, the errors of the observations (for example, misreading of thermometers and rain gauges) are considerably larger than the model errors. The different types of error are one of the reasons why only reliable observations are used to correct the model forecast. In particular, no precipitation measurements are used at all, due to their doubtful quality and representativeness. Due to their point observation nature, they are hardly representative for the typical grid mesh width of a reanalysis, which is on the order of 1 by 1 degree (i.e., roughly 100 km) and hence they can introduce a lot of noise into the analysis.

Several reanalysis products exist. Here, we have chosen the reanalysis from the European Centre for Medium Range Weather Forecasts (ECMWF) in Reading, UK. The underlying global model is generally considered the best for this kind of data. It has proven superior to other reanalyses, both for polar regions and the tropics (Trenberth et al., 2010; Uppala et al., 2008, Bengtsson et al., 2007, 2004; Dee, 2005). At the ECMWF, there are two reanalyses covering the period of interest, namely ERA40 and ERA-Interim. ERA40 was intended to be updated on a regular basis, but it turned out there were problems with the moisture and water budget over the tropical oceans and, in relation to that, the position of the innertropical convergence zone (ITCZ) over Eastern Africa. For these (and a few other) reasons, it was decided to re-run the reanalysis with a better analysis and a considerably improved data assimilation scheme (i.e., how observations are incorporated into the forecast-correction cycle). The resulting dataset is ERA-Interim (dubbed “interim” because it will eventually be replaced by a full reanalysis of the complete period). As of now, ERA40 covers the period 1958-2002, whereas ERA-Interim covers 1989 to present, usually with a delay of two or three months.

In regions with ample and good observations, ERA40 and ERA-Interim deliver almost identical results, even for entirely model-derived quantities like precipitation. In data-sparse regions, however, the differences between the two reanalyses can be substantial, mirroring the differences between the analysis and data assimilation schemes. In particular the latter is much more elaborate in ERA-Interim.

It becomes clear from these considerations that inhomogeneities in reanalysis results data will arise if there are temporal changes in the data coverage over a larger region and/or if the type of observations that enter the analysis changes. Both changes pose substantial difficulties in data-sparse regions like most of Africa. In particular, political conflicts often have had the consequence that there is virtually no data available from a large region (such as the DRC). Furthermore, the observational database has undergone substantial changes over time, in particular related to the availability of satellite observations from November 1978. Satellite data are essential to derive information about upper tropospheric winds in the tropics. As a result, reanalyses from the pre-satellite era are clearly inferior to analyses from more recent periods, and this can be clearly identified in time series of reanalyzed precipitation. Since the reanalysis takes as much useful information as possible from an incomplete, possible error-prone observational database, there is little we can do about this problem.

For the reasons outlined above, we have decided to restrict ourselves to the ERA-Interim period, i.e. from 1989 on. Especially, the requirement for regional and consistent coverage with good resolution justifies the use of reanalysis data, rather than a dataset derived solely from simple interpolated and extrapolated point observations. The underlying ERA-Interim data consists of gridded values on a daily basis. Each grid point is centered in a grid cell with a mesh width of 0.78 degrees, i.e. roughly 80 km. We note, however, that considerable efforts are ongoing to extend these reanalyses as far back in time as possible in an as homogeneous as possible way.

3. Mapping tool, GIMMS

3.1. Composite mapping analysis, CMA

The approach to mapping groundwater insecurity during drought within the SADC region is built on a composite analysis of the factors affecting the risk of groundwater non-availability. This is technically done via a geographical information system (GIS) or platform that can put together and analyse several sources of spatial (mapped) information at once, a so-called composite mapping analysis (CMA) (Lowry et al., 1995; Hassan et al., 2003). The various factors, like for instance rainfall or the major aquifer types, are compiled and portrayed on individual maps and then overlaid and combined via simple mathematical expressions to show, in the final output maps, which areas are both rich in rainfall and have good aquifers, essentially producing areas of high groundwater security during drought. On top of these maps could be superimposed maps that indicate where groundwater is polluted or where the population is concentrated, which would then indicate areas of lower groundwater security. The overall exercise then is to combine all relevant maps, or layers, and assigning ranks or relative numbers to the factors and combining them smartly and simply to come up with a composite or aggregated measure of relative groundwater security, using a number scheme or a relative indicator like small, medium and high security, to the individual areas within the SADC region.

3.2. Modules of factors influencing groundwater insecurity

The database for our GIS-based groundwater insecurity assessment consists of several different data layers that can be meaningfully partitioned into four modules that all affects groundwater insecurity in the SADC region. These four modules are 1] climate sensitivity; 2] hydrogeological drought proneness; 3] Human vulnerability and 4] Groundwater threats. The former three combine to define the regions vulnerability to groundwater drought while the threats (e.g. over-abstraction and human or natural degradation of groundwater quality) add further pressure on groundwater availability and thus have to be included in an assessment of overall groundwater insecurity (cf. Figure 3.1).

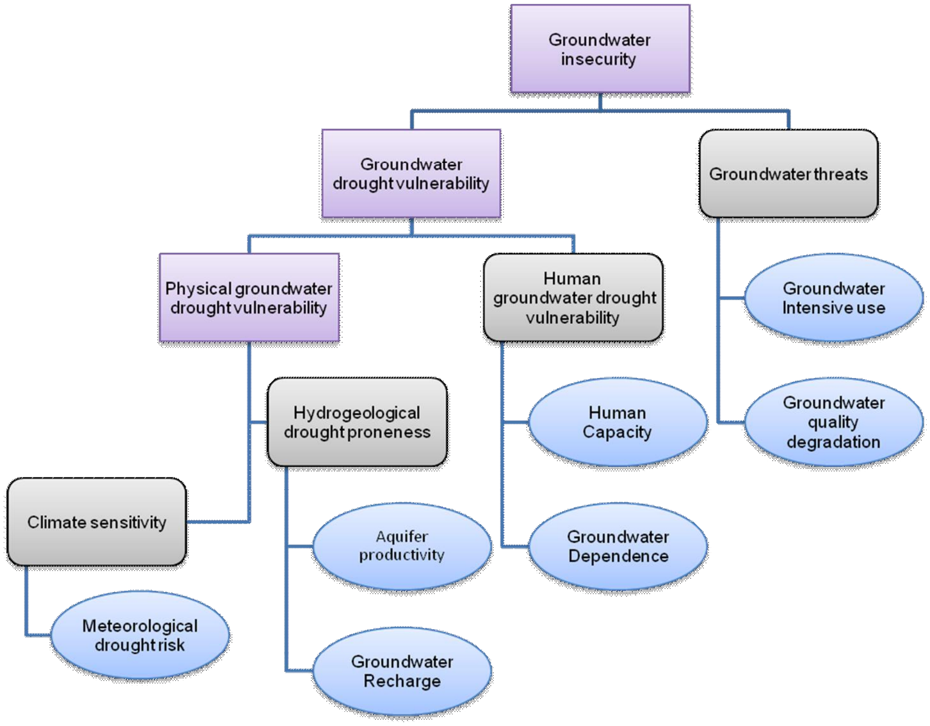

Figure 3.1 Illustration of the modular approach for mapping groundwater drought (GWD) vulnerability and groundwater insecurity (GWI). In the figure, the rounded rectangles represent the analytical modules; oval shapes associated sub-modules, while the rectangles represent the resulting management maps, i.e. the main spatially aggregated layers

The GIS mapping work process will follow this modular division. To distinguish between different contributing factors to groundwater security, single maps aggregating various aspects will be generated. One will be a map showing inherent physical groundwater drought vulnerability, which combines conditions of meteorological drought risk, aquifer productivity, and groundwater recharge potential. Another map will be produced that illustrate the human vulnerability influencing groundwater security, which includes conditions of e.g. population density, socio-economic development, and management and governance capacity. Finally, a map will seek to illustrate groundwater threats from poor groundwater quality and over-extraction of groundwater. These maps may in turn be overlaid for composite views and visualization of the various dimensions of groundwater drought vulnerability and insecurity (Figure 3.1).

The factors considered in the various sub-modules and how they combine to generate maps are listed in Table 3-1, while Box 1 illustrates the factors and how they influence GWDV. A table with data sources and meta data are given in Appendix 2. The majority of data used in the present version of GIMMS are based on existing, readily available (mostly from internet sources) data. An expansion of Figure 3.1, which includes all the factors considered in the sub-modules, is given in Appendix 4. The groundwater drought vulnerability algorithm is discussed in more detail in the following section.

Table 3-1 Modules for the map production (colors correspond to diagram in Figure 3.1)

Modules	Sub-modules	Factors considered	Aggregate spatial layers generated		
1. Climate Sensitivity	Meteorological drought risk	*Rainfall amount* *Rainfall variability* *Length of dry periods*	**Physical groundwater drought vulnerability (PhGWDV)**	**Groundwater drought vulnerability (GWDV)**	**Groundwater insecurity (GWI)**
2. Hydrogeological drought proneness	Aquifer productivity	*Aquifer storage capacity* *Aquifer permeability*			
	Groundwater recharge potential	*Rainfall* *Vegetation cover* *Terrain slope*			
3. Human groundwater drought vulnerability	Groundwater dependence	*Population density* *Livestock density* *Irrigation intensity* *Distance to surface water bodies*			
	Human capacity	*Poverty* *Health* *Science and technical capacity* *Governance and service delivery*			
4. Groundwater threats	Groundwater quality degradation	*Salinity* *Fluoride* *Arsenic*			
	Groundwater intensive use	*Cities dependent on groundwater* *'Overexploitation' areas*			

Box 1. The main factors and how they influence groundwater drought vulnerability

How much groundwater is there? (storage capacity and GWL)

How replenishable is it? (recharge potential)

How good quality is it? (salinity, fluoride, nitrate, etc.)

How accessible is it? (well yields, GWL)

How drought prone is the area? (meteorological drought index)

How many people are there to share it? (population density)

How much alternative water sources are there? (surface water storage capacity, distance to surface water bodies)

How well-functioning are the groundwater access structures? (functionality of wells and springs)

How high is the capacity for managing GW (education, poverty, accountability)

3.3. Groundwater drought vulnerability/groundwater insecurity algorithm

A geographic information system (GIS) is an effective tool for vulnerability mapping as it provides the ability to represent information on the landscape into distinct layers as well as analyzing the spatial overlap and relationship between these layers. The analysis and calculation of groundwater drought vulnerability and groundwater insecurity will be based on a GIS spatial analysis tool, known as composite mapping analysis (CMA), which in mathematical terms can be written as follows:

$$C = \sum_{i=1}^{n} w_i x_i \qquad [2]$$

$$\sum_{i=1}^{n} w_i = 1.0 \qquad [3]$$

where *C* is the composite score for a given spatial unit (in this case an index for GWDV and GWI); x_i is an individual scaled parameter that influences this unit; w_i is the weight assigned to that variable; and *n* is the total number of variables considered important to include in the aggregate analysis. In this work, more than twenty data layers have been acquired and processed in order to supply the different modules and sub-modules. While the data in each module differ, the general composite mapping routine remains similar to Equation 2. The exception in our case is the groundwater threats, which due to data constraints are merely incorporated as separate qualitative layers for overlay visualization, rather than being directly implemented quantitatively in the composite score algorithm. It follows that the final groundwater insecurity map will be the groundwater drought vulnerability map visualized together with an overlay map of various groundwater threats. However, with more and better quantitative data on e.g. groundwater quality, such data could easily be incorporated into the algorithm.

Each parameter, which is numerically represented on individual maps, is scaled to an ordinal, unit-less axis within certain minimum and maximum bounds (e.g. 1 to 5), expressing the relative influence of each factor on the groundwater drought vulnerability. The composite vulnerability score is a relative measure, which again is scaled to give an indicator of relative vulnerability. This is because the factors considered have different dimensions or units (e.g. mm/year for rainfall, people/km^2 for population density) and to be able to rank their importance and influence, they have to be transformed into unit-less and relative scales. As long as the algorithm is applicable to all possible ranges of the variables within the area in question, the vulnerability score becomes a generic yard stick for vulnerability within the area or realm to which it has been developed.

The implementation of the spatial composite model makes use of a grid-based system at 10 km resolution for the analysis and mapping of aggregated maps (except for climate sensitivity, which has a resolution of 0.5 degree (~50 km)). This resolution is considered as being a reasonable compromise between the finer and coarser dataset resolutions of the input data used (cf. Appendix 2). When projected onto a mapping grid, the combination of the various modules will produce an output map, which identifies groundwater drought vulnerability within each 10x10 km grid cell.

The algorithm used to calculate the composite score that reflects overall groundwater drought vulnerability (GWDV) is:

$$GWDV = V_{GWRe}\left(v_{CS}\sum_{i=1}^{n} w_i CS_n + v_{HGDV}\sum_{i=1}^{n} w_i HGDP_n \right) + V_{HV}\sum_{i=1}^{n} w_i HuGWDV_n \qquad [4]$$

where *CS*, *HGDP* and *HuGWDV* represent the modules for Climate Sensitivity, Hydrogeological Drought Proneness and Human Groundwater Drought Vulnerability, respectively; *n* is the number of parameters (or layers) (*i*) in each module, each given by scaled and normalized figures (from 1 to 5); w_i is the micro-level weight ($\Sigma w_i = 1.0$) given to each parameter in each module; v_{CS} and v_{HGDV} are intermediate weights between the climate sensitivity and hydrogeological proneness ($v_{CS} + v_{HGDV} = 1.0$); finally V_{PhV} and V_{HV} are the macro-level weights for the physical and human modules ($V_{PhV} + V_{HV} = 1.0$). Note, if the human module is omitted the calculation will return a score that reflects inherent physical groundwater drought vulnerability. The resultant GWDV for each spatial unit is given on an ordinal scale from 1 to 5, representing 'very low', 'low', 'moderate', high' and 'very high' vulnerability, respectively.

This 3-tier approach to the algorithm has several advantages, in terms of visualization and flexibility. The tier structure allows the model to focus on and separately illustrate various dimensions of the groundwater vulnerability or security as explained earlier. It also allows the model to work, even if some parameters are missing for one of the three modules and without compromising the validity of the other modules. In a similar way, it is easier to integrate and evaluate the effect of new data layers even if they do not provide complete coverage of the SADC region.

3.4. Individual layers in GIMMS

The Groundwater Insecurity Monitoring and Management System (GIMMS) proposed here is based on the analysis of several parameters combined together to provide a comprehensive assessment of the phenomenon. Suitable parameters must be able to capture the main feature that affects groundwater insecurity in the region, and in the following sections, the theoretical principles and rationale for the individual layers are discussed.

3.4.1. Climate sensitivity

The climate sensitivity is incorporated into the groundwater drought vulnerability algorithm via a meteorological drought risk index. Meteorological drought, as a prerequisite for groundwater drought, occurs when and where the daily amount of precipitation over a longer period is small enough (this and all following definitions are discussed in detail below), when there is a sufficiently long dry period in the course of the year, when the variability of precipitation is large enough that dry events can occur even though there is enough precipitation on average, and when there are extended dry periods much longer than the average seasonal drought that is observed in many parts of Africa. These four factors are described and expressed individually in simple mathematical terms in the following and aggregated into a single overall meteorological drought risk index for the SADC region.

Rainfall amount, P_{ANN}

The main factor for drought is, of course, a general lack of precipitation. As the first step in the derivation of a meteorological drought index, we consider grid points as “dry” when they receive less precipitation than a particular threshold, averaged over the 20 year period 1989 to 2008. For drought vulnerability based on ERA-Interim data, we use a threshold (P_T) of 1 mm/day. This amount (equivalent to 365 mm/yr on average) may seem much, as compared to drought definitions derived from point measurements, but gives realistic results when considered for a grid representative of an area of roughly 600 km^2[3]. The less precipitation, on average over the total period in question, the more severe the resulting drought sensitivity is. We calculate the term, P_{ANN}:

$$P_{ANN} = P_T - P_{ave} for P_{ave} < P_T \text{ , } otherwise P_{ANN} = 0 \qquad [5]$$

where P_{ave} is the average daily precipitation over the 20 year reanalysis data period. The resulting term, P_{ANN}, therefore obtains values between zero (enough precipitation) and 1 (no precipitation at all). Note that this term as well as the following ones is weighted in the final calculation of the index, see below.

Length of dry periods, P_{DRS} and P_{EXT}

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[3] Scenario data for future projected climate conditions are generally available on grids different from that for the reanalysis. These grids may be coarser (when Global Circulation Models (GCM) data are used) or finer (when Regional Circulation Model (RCM) data are available, although in this latter case the results of the RCM will also depend on properties of the “driving” GCM). This means that drought conditions based on climate model data have to be calibrated. This is done by adjusting the threshold, but leaving all other contributors (see below) unchanged

The second term takes into account that the same amount of annual precipitation may be distributed temporally quite differently within the year. The main quasi-periodicity of precipitation follows the position of the sun and is therefore annual. In this step, we consider the average length of a potential dry period within a calendar year. Extended dry periods, potentially covering two or more consecutive years, are dealt with below. In the course of one calendar year, a dry period of at least two months is defined to be necessary to have the potential consequence of a drought, or, in other words, if the dry period is shorter, drought conditions will not develop. The second term, P_{DRS}, therefore obtains a value of 1 if there is, on average over the whole period, a dry period of four months or longer within any calendar year and a value of 0 if there is no dry period longer than two months. A dry period of three months gets a value of 0.5. As above, a "dry" day is defined as having a precipitation amount of the threshold value or less.

There is also the possibility of extended drought periods covering more than one calendar year. These extended periods can be considered as significant when the number of consecutive dry days (again defined as having less precipitation than the threshold) exceeds nine months for any sequence of dry days, i.e. not necessarily within one calendar year. If that is the case, the third term, P_{EXT}, is assigned a value of 1. Periods with dry periods less than five months are assigned the value of 0. Consequently, a dry period of, e.g., 7 months will get a value of 0.5, while numbers in between are continuous.

Rainfall variability, P_{STD}

Even though there may be sufficient precipitation on average, the variability of precipitation may be so large that occasionally drought events occur, but one prerequisite is that it is "dry enough" that a drought condition results, i.e. that the number of dry days in the event differs significantly from average dry periods. We meet the requirement for the fourth term by calculating the coefficient of variability (CoV) of the annual precipitation. A CoV of 100 % will result in a value of 1 for the final term, P_{STD}, a CoV of 50 % gives a value of 0.5 and so on. Such a definition gives realistic results for Africa with its large periodicity of rains, but it may be necessary to adjust for other climates/regions.

Estimating meteorological drought risk index

The final step is to weigh these four factors. By taking into account that P_{DRS} and P_{EXT} describe the same feature on different time scales, and further taking into account that the main factor for drought is the general lack of precipitation, so that this factor needs to be weighted heavier and by comparison of results with a priori knowledge of African precipitation distribution and the geographical distribution of historic droughts, e.g. at the Horn of Africa, the optimum weighting is proposed as follows:

$$P_{MET} = 4\ P_{ANN} + 1.5\ P_{DRS} + 1.5\ P_{EXT} + 3\ P_{STD} \qquad [5]$$

where P_{MET} is the meteorological drought risk index. By this approach, the lack of precipitation, irrespective of the temporal distribution, is weighted with 40 %, the variability is weighted by 30 % and the temporal extent of dry periods, divided into the two subgroups of shorter and longer drought periods, is weighted by 30 % as well. The maximum possible value of P_{MET} , if all requirements are fulfilled, thus is 10, and the minimum possible value is 0 if none of the conditions are fulfilled. Investigating the possible combinations of these factors, we can conclude that values of P_{MET} between 0 and 2 mean low risk for meteorological drought, values of 3 to 5 mean a moderate risk, values of 6 to 8 mean a large risk, while values of 9 or 10 result in an extreme risk for meteorological drought.

Figure 3.2 shows the resulting meteorological drought risk index, calculated and distributed over the African region, based on ERA-Interim data for the period 1989 to 2008.

From this assessment for the whole of Africa, it can be seen that, in good agreement with other references (for example Brooks and Adger, 2003; UNECS, 2007), there is moderate risk for meteorological drought for most of Angola, the north-western half of Zambia, the Katanga province of the DRC, most of southern South Africa and Mozambique as well as the coastal and mountainous regions of Tanzania. A large risk for drought is found in Botswana, most of Zimbabwe, the north-western region of South Africa and most of the regions away from the coast in both Tanzania and Kenya. According to this assessment, the largest risk for meteorological drought prevails in most of Namibia as well as the south-western tip of Angola, northern Kenya and Somalia and along the southern edge of the Sahel zone. The remaining regions (most of the Congo basin, south-eastern South Africa, the eastern part of Madagascar and the countries adjacent to the Gulf of Guinea), but also Lesotho and Swaziland, do not have meteorological drought conditions, in good agreement with observations. The composite map of meteorological drought risk for the SADC region is given in Appendix 5, Map1.

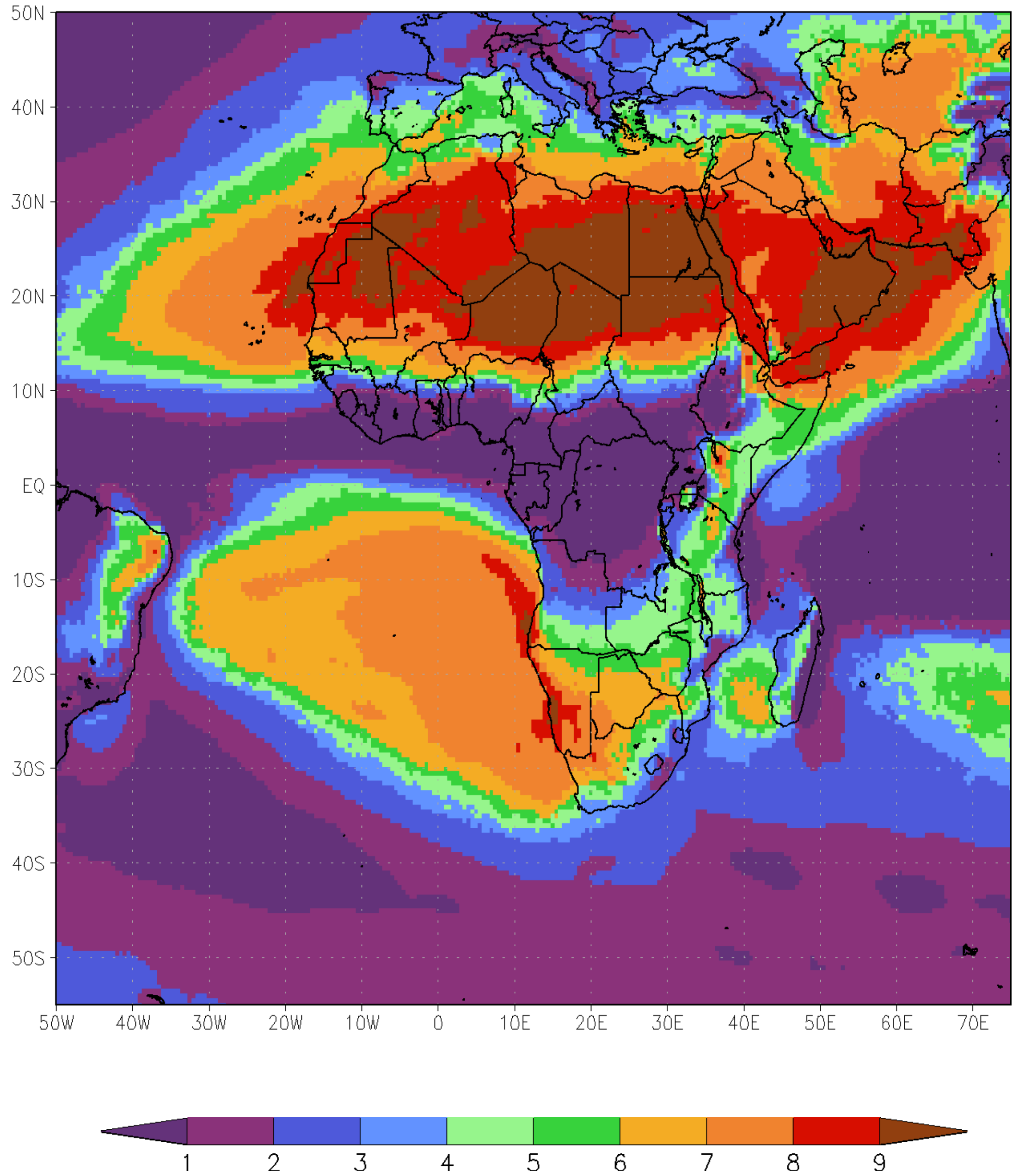


Figure 3.2 Meteorological drought risk index, based on ERA-Interim data for the period 1989 to 2008, as defined in the text. Values below 2 mean low risk for meteorological drought, values of 3, 4 or 5 mean a moderate risk, values of 6, 7 or 8 mean a large risk, while values of 9 or above mean an extreme risk for meteorological drought

Figure 3.3 shows the individual components of the meteorological drought risk index. In good agreements with observations, a dry season is prevailing almost everywhere south of the Congo basin, whereas we find extended dry periods in a region extending from the Namib and Karoo in the southwest to the Horn of Africa (excluding Ethiopia) in the northeast. For these regions, drought situations are mainly caused by more (P_{DRS}) of less (P_{EXT}) regular dry periods, whereas drought in Ethiopia and the Sahel is due to the extreme variability of rainfall (P_{STD}).

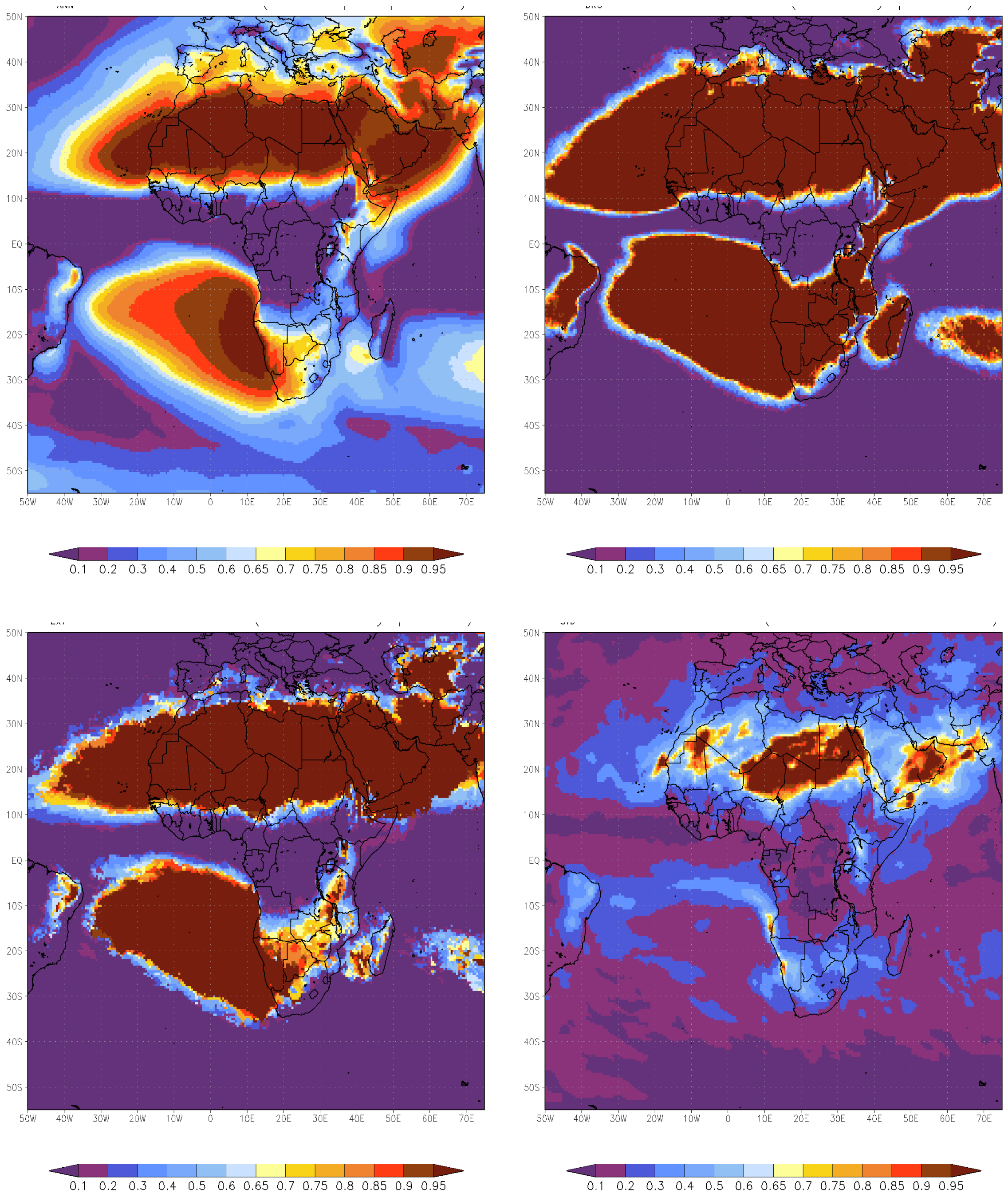


Figure 3.3 Components of the meteorological drought risk index, based on ERA-Interim data for the period 1989 to 2008, as defined in the text. Values are normalized to the range 0….1. Top left: P_{ANN}, average daily precipitation above the threshold of 1 mm/day, top right: P_{DRS}, duration of short dry periods, lower left: P_{EXT}, duration of extended dry periods, and lower right: P_{STD}, coefficient of variability

3.4.2. Hydrogeological drought proneness

The hydrogeological drought proneness relates to the physical factors influencing drought conditions in groundwater systems. Two main aspects are important here: the aquifer productivity and the groundwater recharge potential.

3.4.2.1. Aquifer productivity

A very important determining factor in groundwater drought vulnerability is the capacity of the groundwater systems exploited by humans, the so-called aquifers, to produce water. This aquifer productivity is linked to various inherent properties of the subsurface. They are mostly constant properties, and depend primarily on the geological conditions and how well water is stored and transported within the geological formations. Hence, in our terminology, the aquifer productivity does not include a measure of the actual availability of water in the aquifers (related to the recharge conditions) or the quality of that water.

Aquifer storage capacity

Aquifer storage covers two aspects of groundwater stored within the sub-surface. Firstly, the volume of water withheld in the porous system per volume of aquifer. The more porous the system and the easier the water comes out, the larger the useable storage volume. However, these properties do not always go together. A system with high clay content can have a high porosity, very many fine pores, but the water cannot easily be extracted, due to capillary and tension forces. Sands have somewhat lower overall porosity but are better aquifers because they transmit the water much better. In between are consolidated formations, like hard rock, which may have only porosity in the form of cracks or fissures. They may be easily extracted, if pores are numerous and interconnected, but the overall volume is small. A parameter, which captures this dual property, is the so-called storativity, which expresses how much water is released from an aquifer (in m) as a response to 1 m drawdown in pressure. In practise, this can be estimated from en experiment where a well is pumped until a certain drop in the groundwater level is observed, and the amount of water gained is measured.

Secondly, the storage capacity of an aquifer depends on the physical extent of the aquifer, i.e. how deep is it and over what area it covers. However, this volume is not to be considered as the upper bound of an exploitable amount, as an aquifer cannot be dewatered completely, primarily for environmental sustainability reasons. Much before an aquifer is exhausted, significant impacts will almost always be evident on connecting surface water bodies, which will run dry, or the aquifer itself will become unusable because of water quality degradation (e.g. from salt water intrusion). Never-the-less, a deeper and extensive aquifer will (everything else being equal) almost always be more productive, and by extension, less drought vulnerable, than a shallow and local aquifer.

Aquifer permeability

The other factor that is critical in aquifer productivity is the permeability, which expresses the ease with which water flows in the porous system, and by inference, how much water can be extracted, for a certain power, within a certain time. A practical proxy for this is the well yield, which is expressed in L/s. Other parameters that characterize groundwater permeability are the specific capacity (L/s/m), the permeability (m/d), and the transmissivity (m^2/d). The flow regime (whether fracture/fissure or granular/porous flow) is also important in this aspect.

Estimating aquifer productivity

The overall relative aquifer productivity used for the GIMMS mapping is based on the **SADC lithology map** and the associated **SADC hydrogeology map** from HGMA (Figure 3.4 and Figure 3.5). The lithology map (Figure 3.4) gives the various principal geological formations in the region, classified into 11 different types (sandstone; granite, syenite, gabbro, gneiss and migmatites; shale, mudstone and siltstone; interlayered shales and sandstone; tillite and diamictite; volcanic rocks, extrusive; unconsolidated to consolidated sand, gravel, arenites, locally calcrete, bioclastics; paragneiss, quartzite, schiste, phyllite, amphibolite; dolomite and limestone; unconsolidated sands and gravel; clay, clayey loam, mud, silt, marl). These have been re-classified according to the flow regime and permeability of the formations based on evaluation of borehole data and using expert judgement (European Union and GTZ, 2009a). The following four aquifer types have been defined based on flow regime:

- Unconsolidated intergranular aquifers
- Fissured aquifers
- Karst aquifers
- Low permeability formations

In addition, areas with significant regional multilayered aquifers (confined aquifers below unconfined), as is the case in the Kalahari/Karoo aquifer system shared between Botswana, Namibia and South Africa, are depicted by hatching in the hydrogeology map (Figure 3.5). In the classification, these four groups have each been further divided into two subclasses denoting 'potential', based on recharge (rainfall) (Döll and Fiedler, 2008) conditions and transmissivity properties, to give classes of high and low potential (Figure 3.6). The meta-data related to the details of the classification schemes are not given in European Union and GTZ (2009a). Furthermore, as noted in European Union and GTZ (2009a): 'The productivity map should only be seen as a starting point from which countries should be able to update the information whenever new field data becomes available'.

For the purpose of mapping aquifer productivity in the present mapping exercise, five classes based on the HGMA classification scheme have been defined. Firstly, since recharge is accounted for outside the aquifer productivity definition (i.e. in the recharge potential, see Section 3.4.2.2), the sub-classes for potential have been lumped. Hence, the aquifer productivity mapping, in our case, remains purely a measure of aquifer inherent properties. Secondly, the ranking has been done from 1 to 5, with 1 as the low productivity aquifers and 5 as the highest. 1 is given to aquifers denoted 'Low permeability' in the HGMA classification, 2 is given to aquifers denoted 'Karst', 3 to 'Fissured', and 4 to ' Unconsolidated intergranular' aquifers. To account for aquifers with additional storage from multilayered aquifers, a value of 1 is added to the class of these aquifers. This entails that the total scale goes from 1 to 5, with 5 being possible for mulitilayered 'unconsolidated intergranular' aquifers.

The resultant regional aquifer productivity map is shown in Figure 3.7.

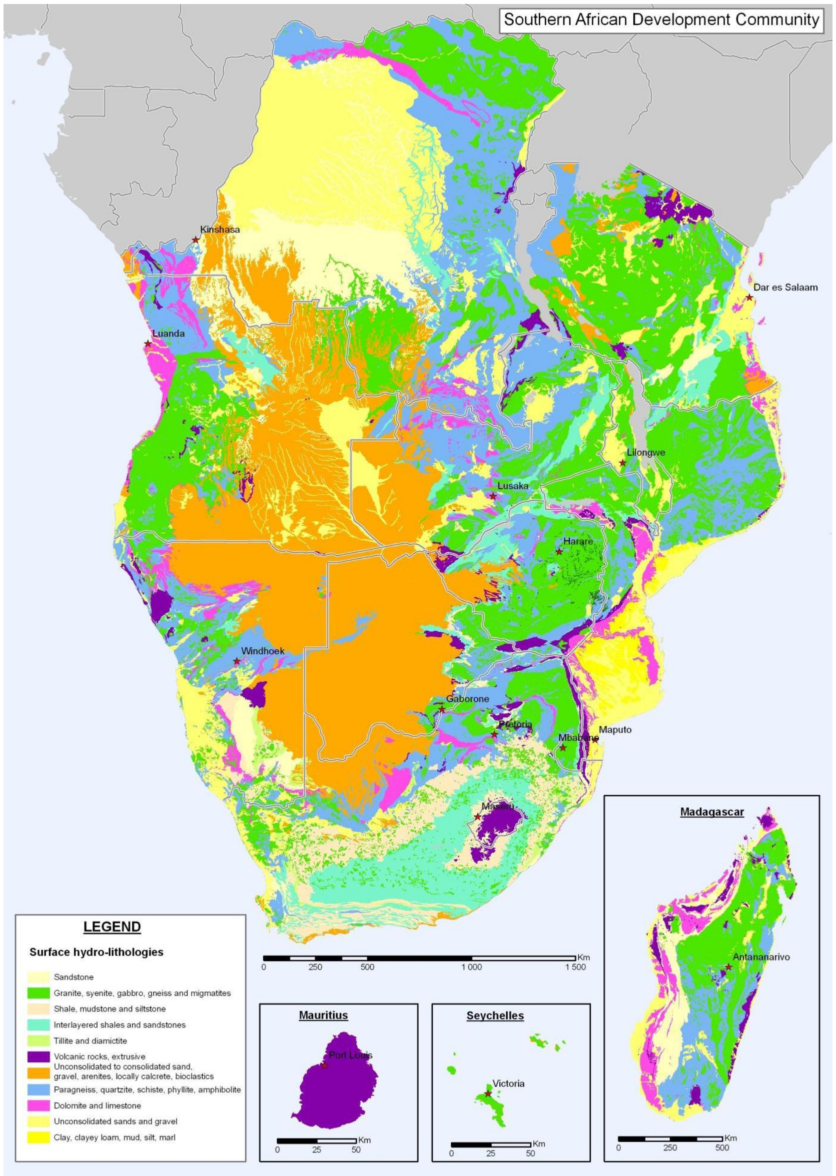


Figure 3.4 Hydro-lithology map of SADC (From European Union and GTZ, 2009a)

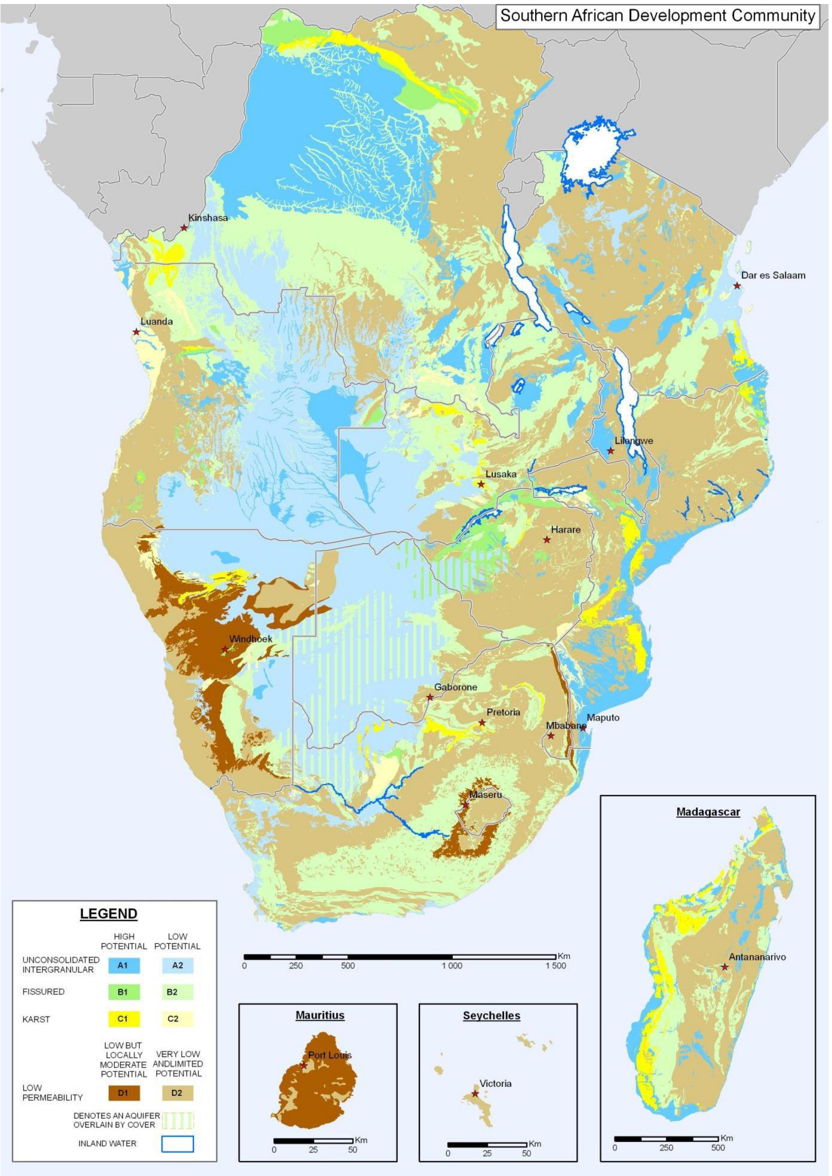


Figure 3.5 Hydrogeology map of SADC (From European Union and GTZ, 2009a)

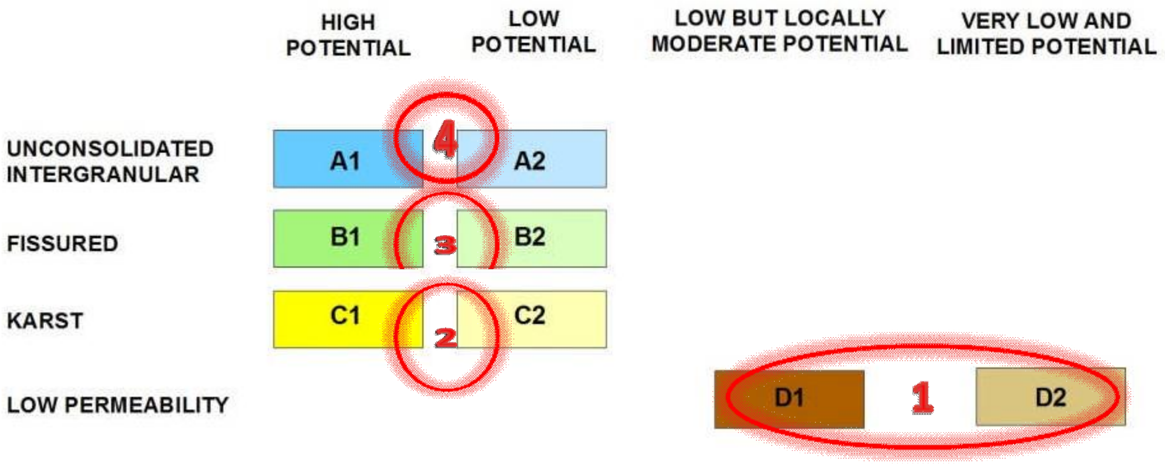


Figure 3.6 Ranking flow regime (on the vertical axis) to derive at a 1-to-4 scale for aquifer productivity (classes for storage capacity and flow regime are from HGMA)

3.4.2.2. Groundwater recharge potential

In the SADC region, precipitation is the most important factor for determining groundwater recharge, yet a recharge potential map based solely on an isohyetal approach would be too simplistic as many other factors also influence the recharge potential, including vegetation/land use, topography and soil properties. Recharge occurs in a distributed sense due to direct infiltration from rainfall. In addition, it occurs in a preferential manner, from water volumes accumulated on the land surface, like streams, lakes and ephemeral water bodies. This latter mechanism, which is particularly important in arid areas with annual precipitation less than 200 mm/year and characterized by erratic low-frequency, high-intensity rain events, is not included in the estimation of relative groundwater recharge potential. However, it is indirectly included in the human groundwater dependence as GWDV determined by this component increases with the distance from surface water bodies (see Section 3.4.4.1).

Rainfall amount and recharge

The long-term average annual precipitation in SADC ranges from less than 100 mm in the southwest to more than 3000 mm in the northwest. To represent this variability in rainfall, we used the long-term mean annual rainfall as calculated on the basis of the RFE (rainfall estimate) blended gauge-satellite rainfall data produced by NOAA's Climate Prediction Center (Xie and Arkin, 1997). The RFE data have been found to be the most appropriate for providing spatially disaggregated estimates (8 km resolution) of long-term annual rainfall in Africa (Fensholt and Rasmussen, 2011), yet it only covers the period 1996 to present, restricting the temporal extent of the analysis. The rainfall map is given in Appendix 5, Map2.

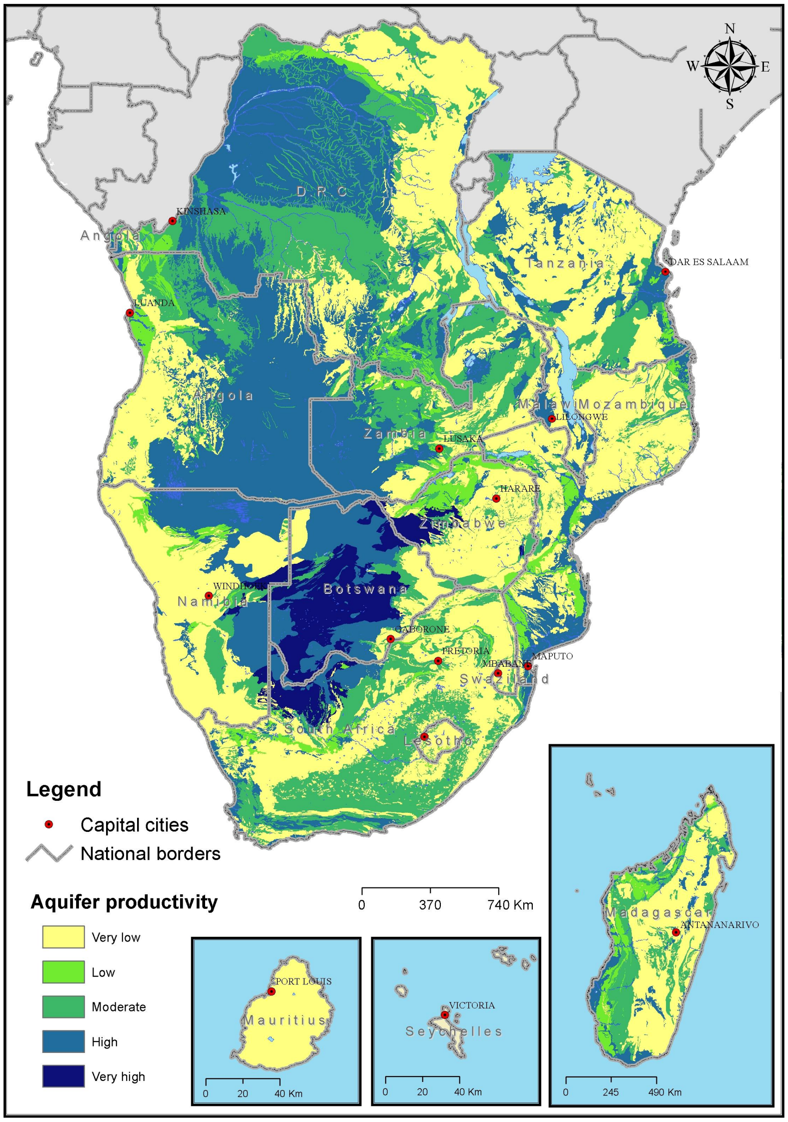


Figure 3.7 Map of regional aquifer productivity

Vegetation and recharge

Vegetation such as forests not only provide shade to the ground that prevent soil water from evaporating, it provides organic matter to the soil which results in an organic-rich top layer called humus, which enhances infiltration rates. It follows that the recharge potential is positively correlated with the vegetation vigor and density. Vegetation may also reduce groundwater recharge through the effect of evapotranspiration, but this effect is assumed smaller than the enhancement of infiltration capacity (D'agnese et al., 1996). In the mapping of recharge potential, the vegetation was represented as the long-term mean Normalized Difference Vegetation Index (NDVI) as derived from the NOAA Global Inventory Modeling and Mapping Studies (GIMMS) NDVI data from July 1981 to December 2003 (8 km resolution). The NDVI is a complex ratio of surface reflectance in the red and near-infrared portions of the electromagnetic spectrum that quantifies the "greenness" of vegetated areas (Tucker, 1979). By design, the NDVI varies between -1.0 and +1.0. Areas containing a dense vegetation canopy will have positive values (say 0.3 to 0.8), while bare soils, which generally exhibit a near-infrared spectral reflectance somewhat larger than the red, tend to generate rather small positive NDVI values (say 0.1 to 0.2). Free standing water (e.g., oceans, seas, lakes and rivers) which have a rather low reflectance in both spectral bands will tend to have slightly negative NDVI values. The vegetation map is given in Appendix 5, Map3.

Terrain slope and recharge

The slope gradient of the land surface directly influences the infiltration of rainfall. Larger slopes produce a smaller recharge because water rapidly runs off the surface of a steep slope during rainfall, not having sufficient time to infiltrate the surface and recharge the saturated zone. In order to include this parameter, a slope map was derived from the Shuttle Radar Topography Mission (SRTM). SRTM is an international research effort that obtained digital elevation models on a near-global scale from 56 °S to 60 °N, to generate the most complete high-resolution digital topographic database of Earth to date (Rabus et al., 2003). Based on 1-km re-sampled SRTM data we derived a slope map for the SADC region and used it to represent the influence of relief on groundwater recharge. The terrain slope map is given in Appendix 5, Map4.

Estimating groundwater recharge potential

The above discussed recharge parameters were combined to derive a region-wide map of relative recharge potential (cf. Figure 3.8).

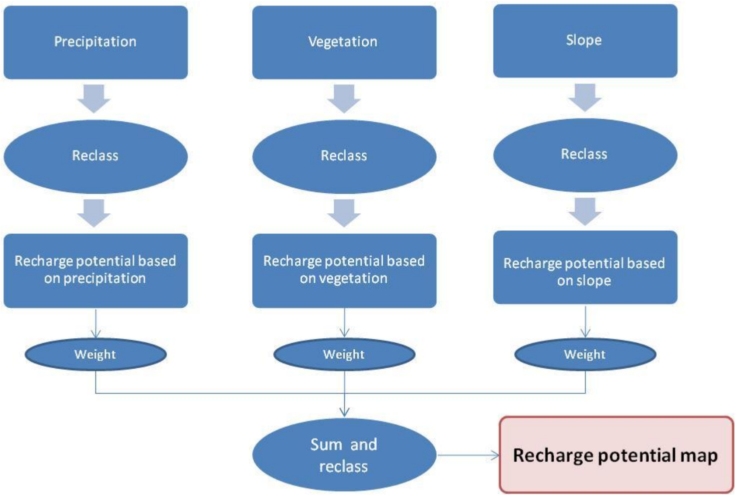


Figure 3.8 Workflow for mapping of regional recharge potential

The map values of these three indicators were each reclassified to represent recharge potential on a zero-to-5 point scale. In each case, a value of 1 indicated low recharge potential and a value of 5 indicated high recharge potential, while a zero indicated no recharge potential. Hereafter, each indicator was assigned a weight according to its perceived relative impact on groundwater recharge (Table 3-2). Finally, the weighted maps were summarized to produce an aggregate map that incorporates the ratings from each map (Figure 3.9).

Table 3-2 Reclassification scheme and weights for recharge indicators

Recharge indicator	Reclassification		Weight
Precipitation (mm/y)	0 - 100	0	0.5
	100 - 250	1	
	250 - 500	2	
	500 - 1000	3	
	1000 - 1500	4	
	More than 1500	5	
NDVI	Less than 0	0	0.35
	0 - 0.2	1	
	0.2-0.4	2	
	0.4-0.5	3	
	0.5-0.6	4	
	More than 0.6	5	
Slope (degrees)	0 – 2.5	5	0.15
	2.5 - 5	4	
	5 – 7.5	3	
	7.5 - 10	2	
	More than 10	1	

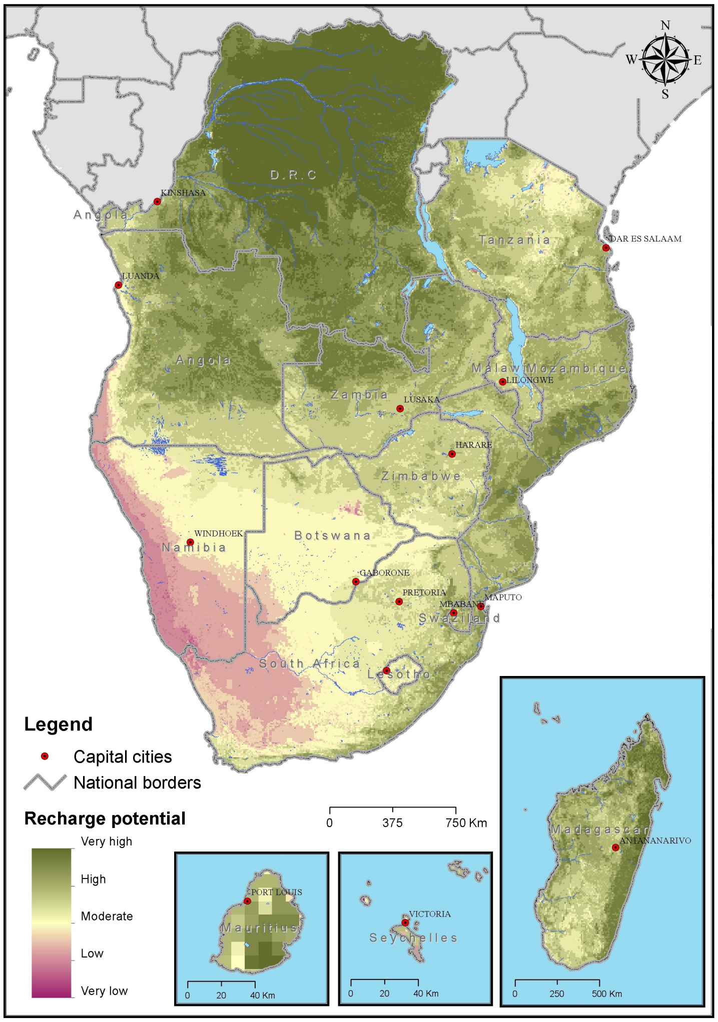


Figure 3.9 Composite map of regional groundwater recharge potential

This map is quite similar to the recharge map by Döll and Flörke (2005). Though our map is not on an absolute scale, there is a good agreement in the spatial variations and trends, which in both cases are dominated by the overall rainfall pattern.

The composite map for the hydrogeological drought proneness, combining the aquifer productivity and the groundwater recharge potential, is shown in Figure 3.10.

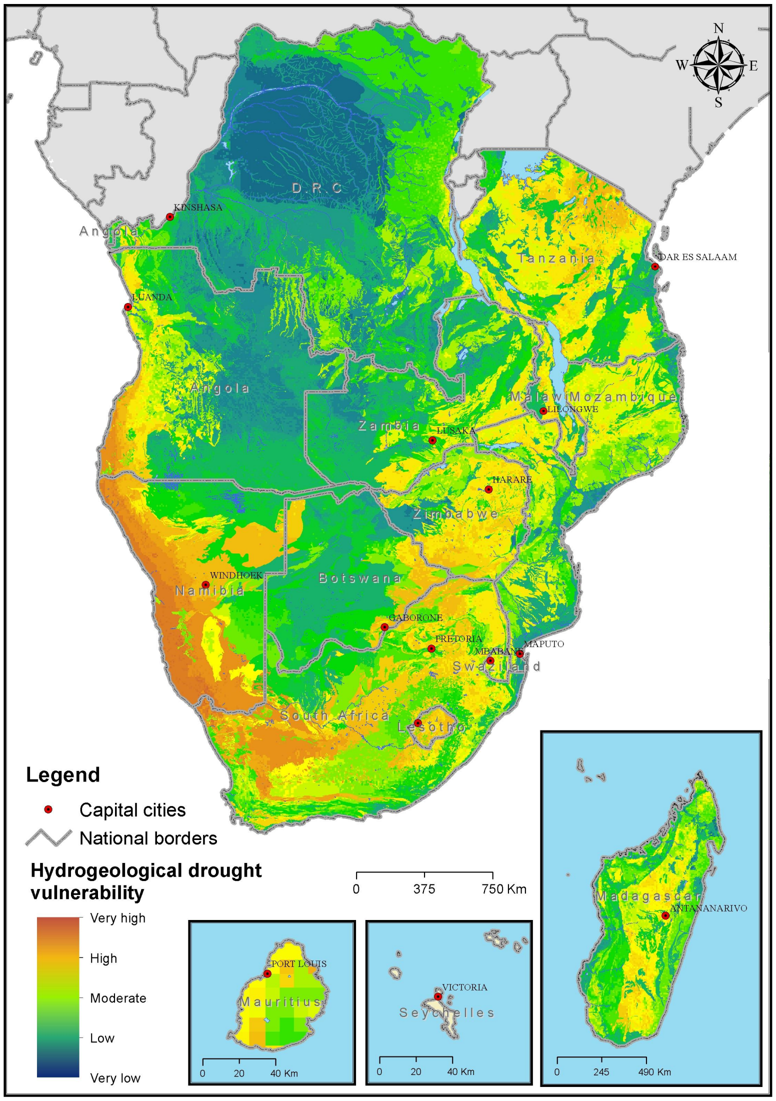


Figure 3.10 Composite map of regional hydrogeological drought proneness

3.4.3. Physical groundwater drought vulnerability

Physical groundwater drought vulnerability is determined from the composite maps of climate sensitivity and hydrogeological drought proneness. Using equal weights to the two, the resulting map in Figure 3.11 is produced.

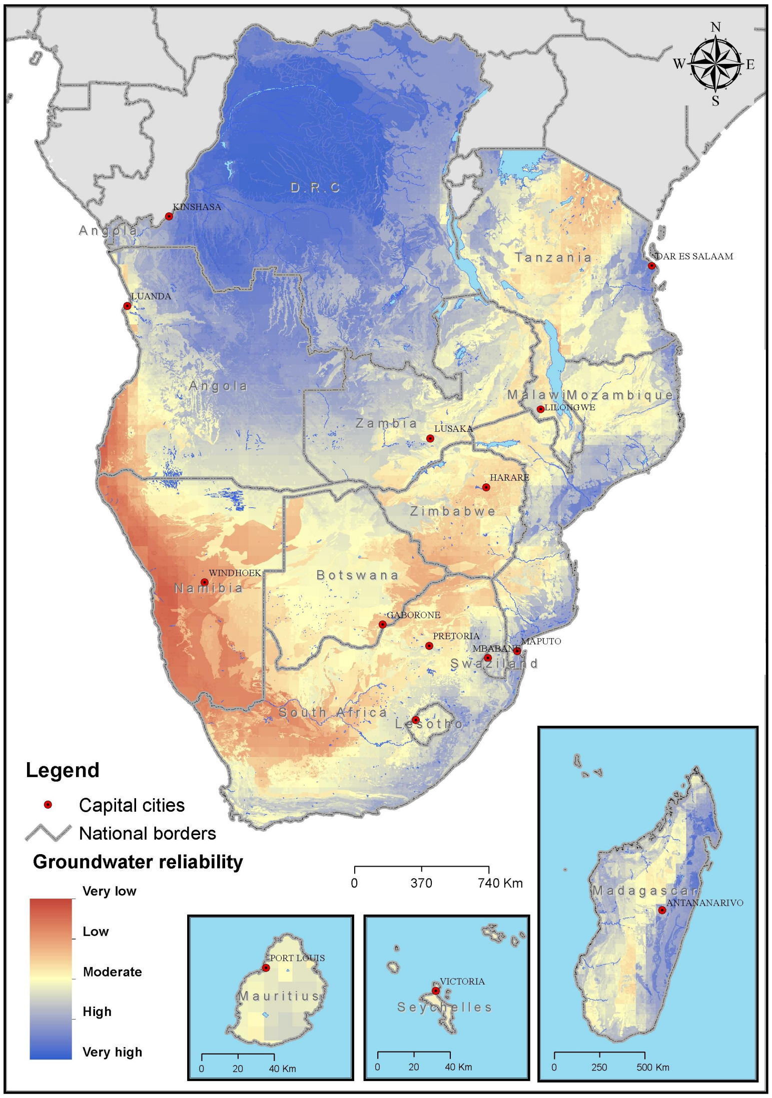


Figure 3.11 Physical groundwater drought vulnerability as a combination of climate sensitivity and hydrogeological drought proneness

3.4.4. Human groundwater drought vulnerability

3.4.4.1. Groundwater dependence

In GIMMS, groundwater dependence is represented by thematic layers that depict population and livestock distribution and fractions of irrigated land. Moreover, lack of alternatives, here seen as the distance to a surface water source, was used as an indirect measure of groundwater dependence.

Population density

The map of population density comes from the African Population Database of UNEP/CIESIN, which is a population map generated from sub-national population statistics (e.g. districts, counties, provinces) and subsequently distributed geographically using population potential estimate as calculated on the basis of the location of urban centres and the main transportation network, i.e. roads, railroads and rivers (Balk et al., 2006). This population map was reclassified to represent vulnerability using an exponential type of function (cf. Table 3-3). The population density map is given in Appendix 5, Map5.

Table 3-3 Reclassification scheme and weights for groundwater dependence

Groundwater dependence indicator	Reclassification	
Population density (people pr km^2)	0	0
	Less than 10	1
	10 – 50	2
	50 – 100	3
	100 – 250	4
	More than 250	5
Livestock density (livestock pr km^2 weighted according to water demands)	0	0
	1 - 5	1
	5 - 25	2
	25 - 50	3
	50 - 100	4
	More than 100	5
Irrigation intensity (percentage of total area equipped for irrigation with groundwater)	0	0
	Less than 0.1	1
	0.1 – 1	2
	1 – 2.5	3
	2.5 – 5	4
	More than 5	5
Distance to surface water (km)	0	0
	Less than 1	1
	1 – 2.5	2
	2.5 – 5	3
	5 – 10	4
	More than 10	5

Livestock density

We obtained a subset of the gridded livestock maps of the world to represent livestock groundwater dependence (FAO, 2007). These maps, which depict the density of cattle, buffalo, sheep, goats, pigs and poultry/chicken, respectively, are created through the spatial disaggregation of sub-national statistical data based on empirical relationships with environmental variables in similar agro-ecological zones. As the water usage of various livestock differs markedly, we created a composite livestock water requirements (LWR) map, where the different livestock densities are weighted in accordance with their relative water demands:

$$LWR = [Cattle*0.5]+[Pigs*0.2]+[Sheep*0.1]+[Goat*0.1]+[Poultry*0.01] \qquad [5]$$

Hereafter, the LWR score were reclassified into vulnerability scores using an exponential relationship between livestock water requirements and vulnerability (cf. **Table** 3-3). The livestock density map is given in Appendix 5, Map6.

Irrigation intensity

In parts of SADC, irrigation depends on groundwater and in order to represent this dependence we included a spatial subset of the Global Map of Irrigation Areas in GIMMS. This map shows the amount of area equipped for irrigation around the turn of the 20th century in percentage of the total area. The Global Map of Irrigation Areas was developed by combining sub-national irrigation statistics (e.g.

districts, counties, provinces, governorates, river basins), with geospatial information (irrigation maps and remote sensing) on the position and extent of irrigation schemes to compute the fraction of 5 arc minute cells (i.e. 8x8 km) that was equipped for irrigation with groundwater and surface water, respectively (Siebert et al., 2010). Only the groundwater component has been included in GIMMS under the term irrigation intensity. The data from Siebert et al. (2010) suggest that the total area equipped for groundwater irrigation in Sub-Saharan Africa is 413,758 ha, which is 5.7 % of the total area equipped for irrigation, 0.19 % of total cultivated area and 0.02 % of total land area, i.e. not a dominating area overall, but important in parts of some SADC countries, like South Africa, Zimbabwe, Zambia, and Tanzania where the percentage of groundwater irrigated area (to cultivated land) is 0.88, 0.38, 0.28, and 0.18, respectively (Pavelic et al., 2011).

It is important to note that data availability with regards to data on water sources for irrigation (surface water vs. groundwater) has been very poor for parts of the SADC region, i.e. for many countries, sub-national data were not available. As a consequence, the estimated fraction of total area equipped for irrigation with groundwater at the national level is applied to all irrigated grid cells for certain countries.

The reclassification of percentage irrigated land into vulnerability scores was performed using a power function (cf. Table 3-3). The irrigation intensity map is given in Appendix 5, Map7.

Distance to surface water bodies

Finally, we calculated the distance to surface water sources (perennial and non-perennial) to be used as surrogate for alternatives to groundwater, i.e. closeness to a surface water body lessen the vulnerability to groundwater drought. The distance calculation was performed as a simple Euclidean distance function and using the hydrological themes from the SADC HGMA as source layer. The relationship between vulnerability and distance and surface water was considered linear (cf. Table 3-3). The distance to surface water bodies map is given in Appendix 5, Map8.

Estimating groundwater dependence

The composite estimate of groundwater dependence is calculated as the equally weighted sum of all five indicators for groundwater dependence (cf. Table 3-3). The final map of groundwater dependence is given in Figure 3.12.

3.4.4.2. Human capacity

Human capacity here relates to the capacity to manage groundwater and drought. It is a function of socio-economic factors though climatic, physiographic and environmental conditions also play a role. For the purpose of this analysis, the human capacity is considered represented by three overall actors: society, government, and science, using the terminology of Turton et al. (2006) (Figure 3.13). In mapping human capacity spatially, quantitative data on these three actors in a distributed geographic sense are required.

Society represents factors such as poverty and equality, while science is given by data on development level and general and high level education. Government can be quantified by data on government effectiveness, transparency and fairness.

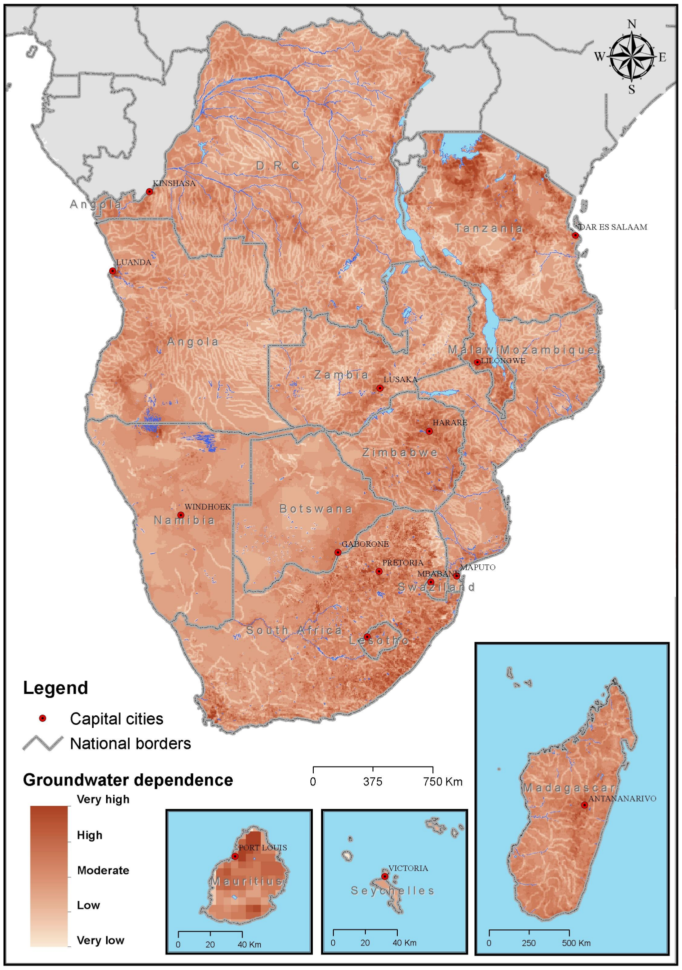


Figure 3.12 Composite map of regional groundwater dependence

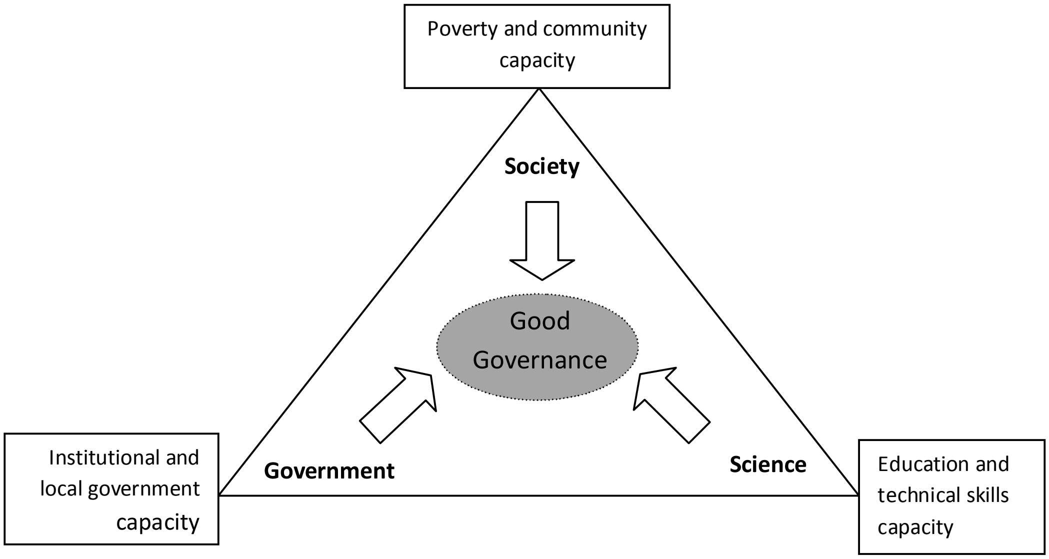


Figure 3.13 Trialogue model of groundwater governance (modified from Turton et al., 2006)

In the following, a two-step approach has been followed. Firstly, data for GIMMS have been developed on a country-by-country basis for the SADC region, acknowledging the data scarcity at sub-national level for these parameters for most SADC countries. Secondly, a more detailed example is presented for South Africa, where sub-national datasets do exist. In the latter case, the human capacity thematic layer has been incorporated into the GIMMS algorithm.

Country-by-country human capacity in SADC

Human capacity at country level for SADC is determined from easily available global datasets (Appendix 2). The society's capacity is represented by the Multidimensional Poverty Index by UNDP. Science capacity is given by UNDP compilation of education indicators as part of the Human Development index. Finally, the government capacity is given by the World Bank Governance Index. The composite score for human capacity for the various countries is given in Table 3-4.

Table 3-4 Human capacity for groundwater and drought management in SADC member states

		Society			**Science**			Governance			Composite
ID	Country	Multidimensional Poverty Index (% of people who are poor)*	Rank	Index	Human Development Index, Education**	Rank	Index	Worldwide Governance Indicators, Government Effectiveness (Percentile Ranking, 2009)***	Rank	Index	Index
1	Angola	77,4	2	4	0,23	13	4	20,0	12	4	4
2	Botswana	31,2	11	2	0,43	4	2	70,0	2	1	2
3	DRC	73,2	3	4	0,26	10	4	1,9	14	5	4
4	Lesotho	48,1	7	2	0,38	8	3	45,7	6	3	3
5	Malawi	72,3	4	3	0,26	11	4	36,7	9	3	3
6	Mauritius	8,0	12	1	0,46	1	1	72,9	1	1	1
7	Mozambique	79,8	1	5	0,19	14	5	43,8	7	3	4
8	Namibia	39,6	9	2	0,39	6	3	61,0	4	2	2
9	Seychelles	2,0	14	1	0,44	2	2	60,0	5	2	2
10	South Africa	3,1	13	1	0,43	3	2	67,6	3	2	2
11	Swaziland	41,1	8	2	0,40	5	3	28,6	11	3	3
12	Tanzania	65,3	5	3	0,24	12	4	39,0	8	3	3
13	Zambia	63,7	6	3	0,26	9	4	30,0	10	3	3
14	Zimbabwe	38,5	10	2	0,39	7	3	2,4	13	5	3

* Multidimensional Poverty Index (MPI): The lives of people living in poverty are affected by more than just their income. The Multidimensional Poverty Index (MPI) complements income poverty measures by reflecting the deprivations that a poor person faces all at once with respect to education, health and living standard. It assesses poverty at the individual level, with poor persons being those who are multiply deprived, and the extent of their poverty being measured by the range of their deprivations.

** The education part of the Worldwide Human Development Index (WDI) for a country measures the following variables: 1) Mean years of schooling (of adults); 2) Expected years of schooling (of children); 3) Adult literacy rate (both sexes); 4) Expenditure on education (%of GDP); 5) Combined cross enrolment in education (both sexes); and 6) Internet users. The index gives an equal weight of 17 % to the six variables.

*** The Worldwide Governance Indicators (WGI) project reports aggregate and individual governance indicators for 213 economies over the period 1996–2009, for six dimensions of governance: 1) Voice and accountability; 2) Political stability and absence of violence; 3) Government effectiveness; 4) Regulatory quality; 5) Rule of law; and 6) Control of corruption. The aggregate indicator combines the views of a large number of enterprise, citizen and expert survey respondents in industrial and developing countries. The individual data sources underlying the aggregate indicator are drawn from a diverse variety of survey institutes, think tanks, non-governmental organizations, and international organizations.

Red figures in Table 3-4 represent missing, but filled values. For the MPI, Botswana, Seychelles and Mauritius do not have an index, why data for the former two come from unstats millennium indicators (http://unstats.un.org/unsd/mdg/Data.aspx) and the Mauritius data from http://www.indexmundi.com/. For the WDI, no figures exist for DRC and Seychelles, why it has been calculated by interpolation, using the correlation between WDI and UNESCOs institute for statistics data on education (http://stats.uis.unesco.org/unesco/).

Incorporating human capacity into GIMMS for South Africa

In order to spatially map human capacity for South Africa, indicators had to be available on a local municipality, district municipality or provincial level.

Society

For the society's capacity, an indicator was chosen which represents poverty. The Deprivation Index from the Health System Trust's District Health Barometer (DHB) was used. The deprivation index is a measure of the relative deprivation across districts in South Africa and is a composite index derived from a set of variables explained fully in the DHB. The data is readily available for all districts in South Africa and published in the DHB along with yearly health statistics for South Africa. Districts with a high deprivation index have a lower capacity than districts with a low deprivation index. The deprivation index was rescaled from 1 to 5 using the quintile classification so that each class from 1 to 5 had the same amount of municipalities within it.

Science

Science was represented by education levels and the technical skills and capacity required to cope with a groundwater drought. Statistics South Africa has education data available on a local municipal level based on the 2007 community survey census data. The higher education category was chosen to represent "science" as the assumption was made that the percentage of higher education graduates within a municipality would be representative of the amount of scientists, engineers or skilled workers within the municipality with the capacity to mitigate the effects of a groundwater drought. The quintile method was used to rank the local municipalities from 1 to 5 so that each class had the same amount of local municipalities in it.

Government

Government capacity can be seen as the municipalities' efficiency and effectiveness in terms of operating on a day to day basis. A well operating local government would have the capacity to manage groundwater resources, especially during a drought. An indicator for government efficiency proved problematic as any indicator for corruption would have political implications. It was eventually decided to use the Auditor General's audit reports for local municipalities. The Auditor General was established through Chapter 9 of the Constitution of the Republic of South Africa in 1996 as a state institution supporting democracy. The Auditor General produces audit reports for all government departments, public entities, municipalities and public institutions. The following Auditor General results were used as an indicator of local government efficiency (Table 3-5).

Table 3-5 Criteria used in Auditor General's evaluations and associated GIMMS score

Auditor General results	Human capacity score on government
Unqualified audit report (with no matters)	1
Financially unqualified (with other matters)	2
Qualified	3
Adverse	4
Disclaimer or not submitted	5
No data available	3

For some local municipalities, no data were available in the Auditor General report. The reason for this was specifically mentioned in the report and as a result, these municipalities were given an index of 3 so that they were not biased in the composite analysis.

Human capacity for South Africa

Human capacity was calculated using equal weights for society, science and government. Areas with a low human capacity were mapped as areas with high human vulnerability (Figure 3.14). Areas with high human vulnerability are seen to be areas within South Africa with poorly functioning local government, low education levels and high poverty demographics. The results show the provinces, which historically have a higher vulnerability as a result of slow transformation and development since the end of Apartheid, name the Eastern Cape, Kwa-Zulu Natal, Limpopo, and the North West province. The map shows that the major metropolitan areas around Cape Town, Durban, Port Elizabeth, Johannesburg and Pretoria have a lower human vulnerability as a result of the high amount of technically skilled professionals as well as the functioning local governments centred in the metropolitan areas.

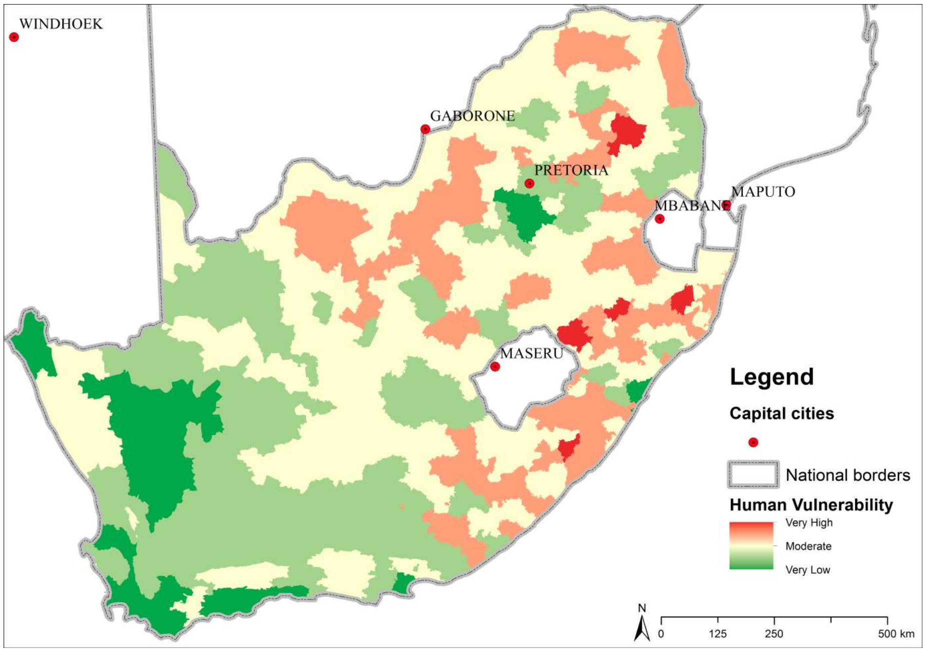


Figure 3.14 Human vulnerability calculated for South Africa, using deprivation index, higher education statistics and the results of the Auditor General report for municipalities

Human groundwater drought vulnerability for South Africa

Human vulnerability and groundwater dependence were combined using equal weights in order to to derive an aggregate layer for human groundwater drought vulnerability (Figure 3.15).

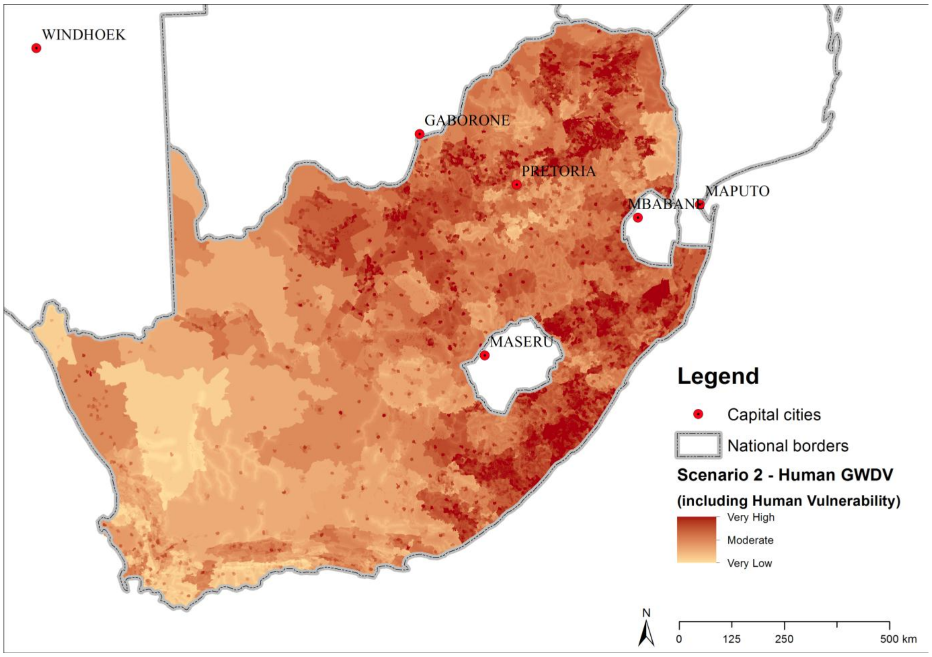


Figure 3.15 Human groundwater drought vulnerability for South Africa

Groundwater drought vulnerability for South Africa, including human capacity

The final groundwater drought vulnerability map for South Africa is produced by combing groundwater reliability and human groundwater drought vulnerability, using equal weights (Figure 3.16).

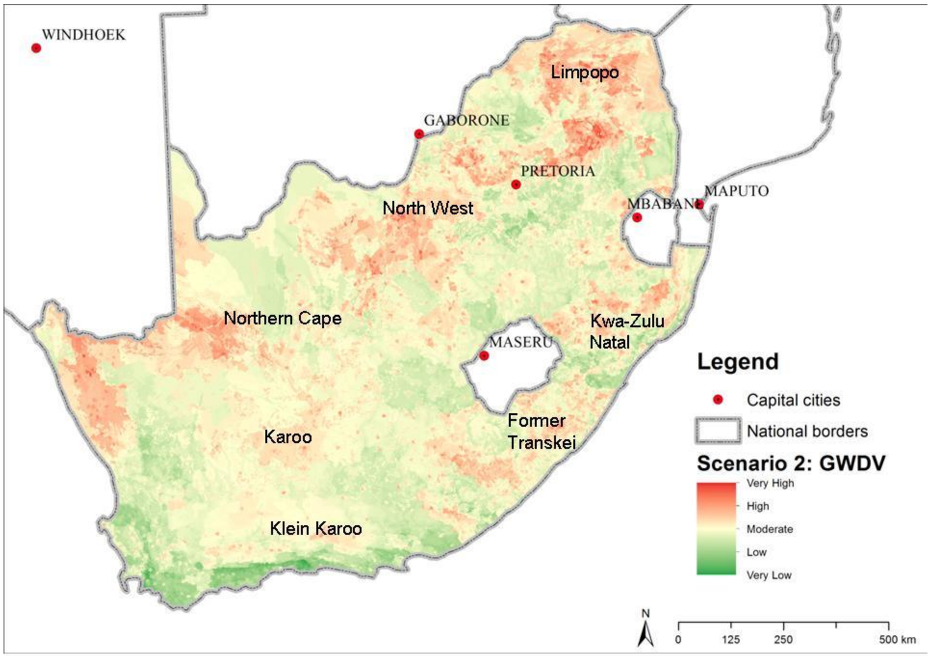


Figure 3.16 Groundwater drought vulnerability map for South Africa, including human vulnerability

The final groundwater drought vulnerability map is more informative if the human vulnerability thematic layer is included. Although this is not possible on a SADC scale due to lack of sub-national datasets, this layer is crucial on the national scale in delineating areas, which are highly vulnerable to groundwater drought because of the human capacity factor. The areas, which are now highlighted for South Africa (compare with Figure 4.6 top on groundwater drought vulnerability for South Africa, which does not include the human capacity) are the areas, which historically have been underdeveloped with little transformation having taken place since the end of apartheid. In South Africa, these areas are Kwa-Zulu Natal, Limpopo, North West Province and the former Transkei. The Northern Cape features in this map because of the high vulnerability to meteorological drought. The semi-arid areas, with a high groundwater dependency, like the Karoo and the Klein Karoo are also highlighted as being moderate to high groundwater drought vulnerability.

3.4.5. Groundwater threats

The aggregate groundwater drought vulnerability index estimated in GIMMS does not take into account the water quality or the possible negative exacerbating impacts of groundwater overexploitation in certain areas. However, such factors influence the overall groundwater insecurity. As an example, areas with low GWDV and hence presumably high groundwater security may be overridden by poor groundwater quality (like in northern Namibia where salinity levels are prohibitively high for drinking water use in otherwise productive and well-replenished aquifers). In the GIMMS, these factors are shown by overlay maps to the GWDV map. The reason for not including them in the algorithm was two-fold. Firstly, some of the water quality and groundwater exploitation data are associated with relatively large uncertainty. Secondly, the factors may influence differently on overall groundwater insecurity and possibly implications for management, and hence separate knowledge on these factors need to be added on top of general knowledge of the inherent groundwater quantity reliability and the human vulnerability.

3.4.5.1. Groundwater quality degradation

Inferior groundwater quality will in certain areas be as critical as drought with respect to overall groundwater usability and water security. Feedback from the various member states via the Project Steering Committee (PSC) on problem areas of excessive occurrence of nitrate, fluoride and salinity was used to develop overlay maps in a GIMMS context (Figure 3.17, Figure 3.18, Figure 3.19). Areas marked with groundwater quality degradation in the maps are not based on strict water quality criteria (i.e. a concentration threshold for max. permissible concentration). Instead, most areas have been loosely defined as 'problem areas' by the PSC. These maps need to be further qualified in subsequent work.

Other chemical parameters may contribute to objectionable groundwater quality, e.g. bacterial and other microbiological contaminants and organic micro-pollutants. However, these tend to be either of a pervasive nature in populated areas and around groundwater and other water supply structures (microbiological contaminants), or of a more local character (organic micro-pollutants), and hence these have not been mapped in this exercise.

Mining and oil extraction activities, which are prevalent in many SADC countries, tend also to threaten groundwater resources (with heavy metals, acidic waters, and organic hydrocarbons). Mining activities have been mapped under groundwater intensive use below (Figure 3.20).

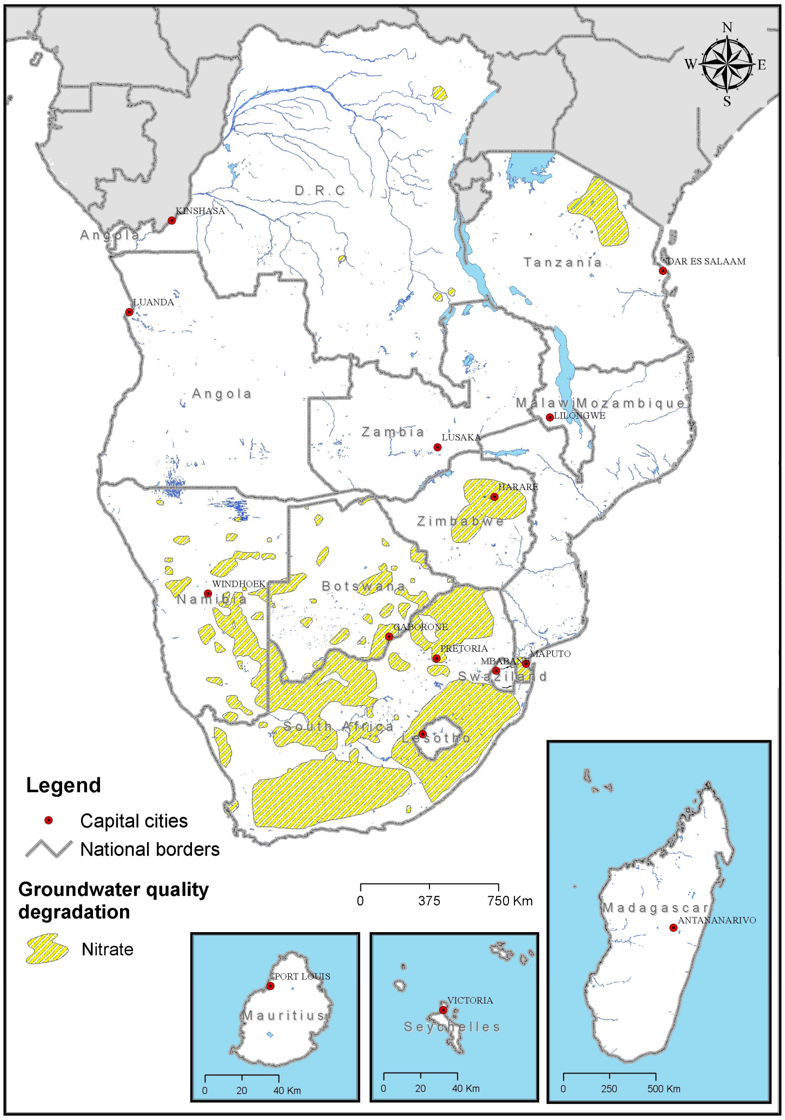


Figure 3.17 Areas with excessive content of nitrate in groundwater in SADC (Data from PSC and Tredoux et al. (2001))

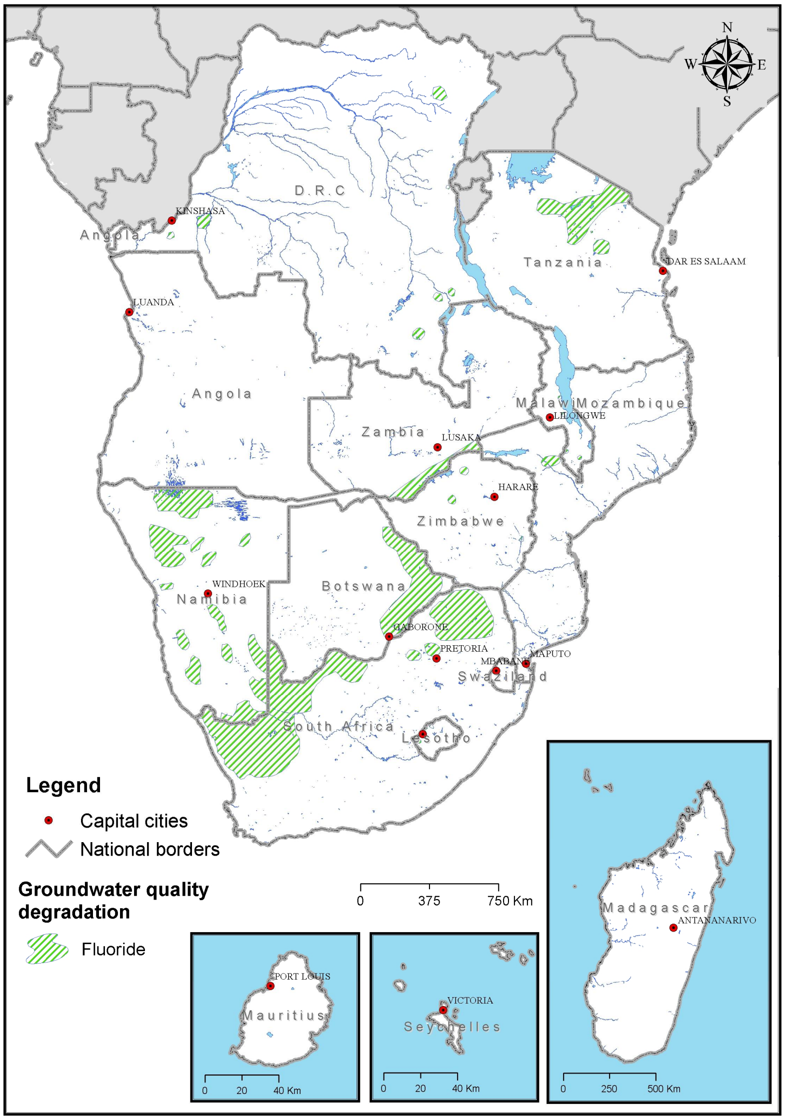


Figure 3.18 Areas with excessive content of fluoride in groundwater in SADC (Data from PSC and Christelis and Struckmeier (2001))

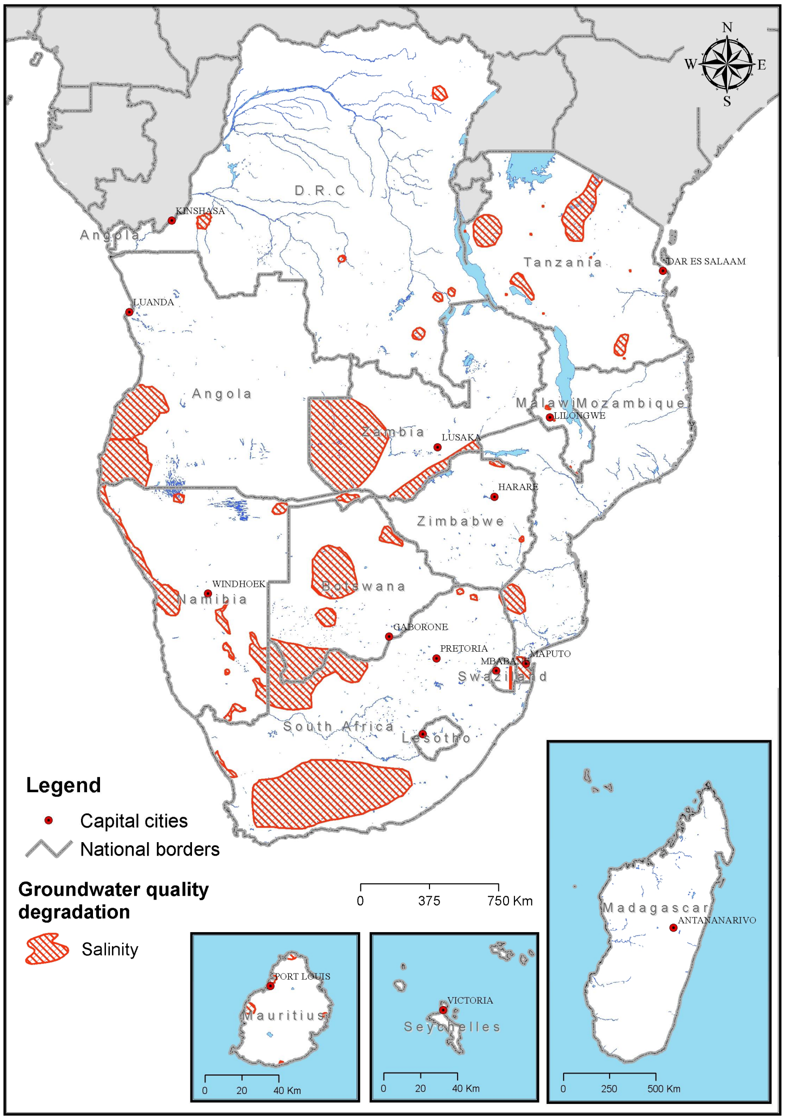


Figure 3.19 Areas with excessive content of salinity in groundwater in SADC (Data from PSC and Christelis and Struckmeier (2001))

3.4.5.2. Groundwater intensive use

Another threat to groundwater resources in SADC is that of over-abstraction of the resource leading to a lowering of the groundwater table and various associated environmental and socio-economic, most often negative, impacts. This is another factor, which is difficult to put on a map, and no systematic estimates of the extent of over-abstraction exist from the SADC region. However, at the Project Steering Committee (PSC) meeting in November 2010, sketch maps were created by the various member states, which highlight regions where over-abstraction occurs. These over-abstraction sites or areas have been entered into a GIS layer to be used as a separate overlay to the resulting maps of groundwater reliability, and drought vulnerability. In addition to areas of general over-abstraction, areas with mining activities (often associated with groundwater pumping for purposely lowering the groundwater table) have been mapped (using SADC HGMA data). Finally, the major cities in the various SADC countries have been mapped according to their overall groundwater dependence for water supply (based on PSC feedback). The three components of groundwater intensive use are shown in a single map in Figure 3.20.

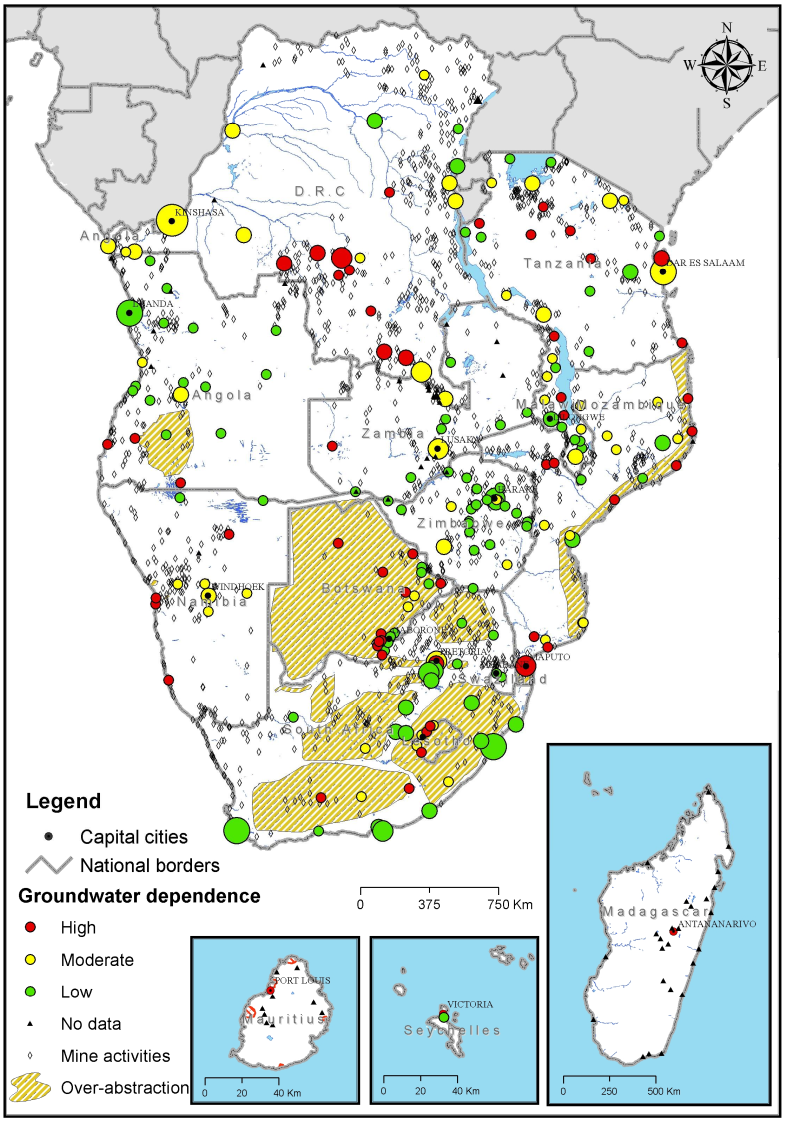


Figure 3.20 Areas of intensive groundwater use in SADC. For groundwater dependence: High: More than 50% of city population, Moderate: 25-50 %, Low: 0-25 %. Size of dots reflects population of cities. Cities with populations larger than 18.000 or the largest 22-25 cities of each country have been included (Data from PCS (urban groundwater dependence and over-abstraction) and HGMA (mine activities))

In Table 3-6, estimates of the proportion of urban population in SADC member states dependent on groundwater are given. It appears that in total, more than one third of the urban population of SADC is dependent on groundwater.

Table 3-6 Estimates of proportion of urban population dependent on groundwater in SADC

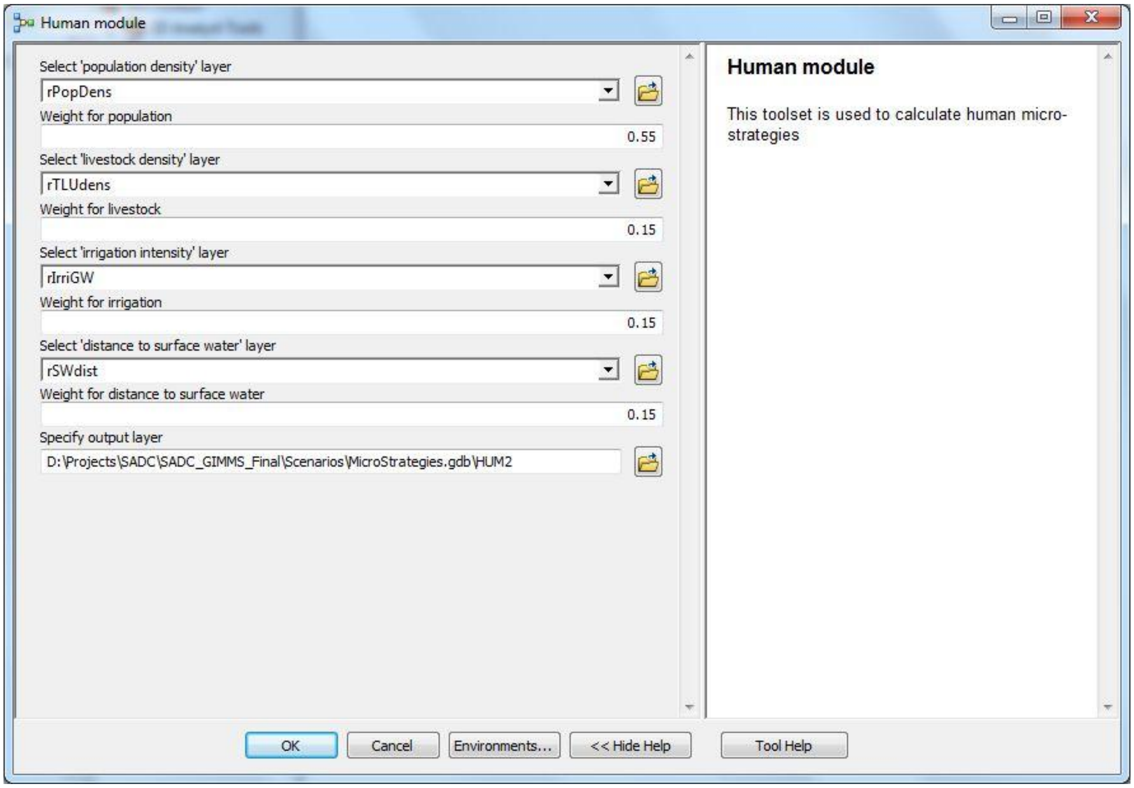
Country	Population of largest cities[a, b]	Population dependent on groundwater	Percentage of urban population dependent on groundwater
Angola	4.985.248	1.051.952	21.1
Botswana	1.058.385	382.194	36.1
DRC	19.108.517	8.514.144	44.6
Lesotho	412.523	181.871	44.1
Malawi	1.966.877	513.511	26.1
Mauritius	-	-	-
Mozambique	5.142.448	2.468.395	48.0
Namibia	77.864	36.076	46.3
Seychelles	21.680	2710	12.5
South Africa	20.145.132	3.307.255	16.4
Swaziland	156.668	19.584	12.5
Tanzania	7.434.075	2.897.957	39.0
Zambia	2.558.998	847.976	33.1
Zimbabwe	4.162.160	755.395	18.1
SADC, in total	67.230.575	20.979.016	31.2

[a] Largest approx. 25 cities of member state, or cities with pop. above 18.000 inhabitants

[b] Data from http://world-gazetteer.com

3.5. Map environment, outputs, format

The GIMMS data layers are stored in ArcGIS file geodatabases and come with customized toolboxes and routines, which allow the user to run the groundwater insecurity model using a given set of input parameters, weights and scenarios (cf. Figure 3.1). All input and output data can be visualized in the form of maps, tables, graphs, and charts, and thus serving a wide range of dissemination objectives and pathways, including the production of hard copy groundwater security planning and guidance maps and the preparation of figures and statistics as inputs to pamphlet, reports, presentations and scientific papers. The platform is built and structured so that it is easy and intuitively straight forward to make any updates and amendments to the maps in accordance with specific management issues and as new data become available.



Select 'population density' layer: rPopDens

Weight for population: 0.55

Select 'livestock density' layer: rTLUdens

Weight for livestock: 0.15

Select 'irrigation intensity' layer: rIrriGW

Weight for irrigation: 0.15

Select 'distance to surface water' layer: rSWdist

Weight for distance to surface water: 0.15

Specify output layer: D:\Projects\SADC\SADC_GIMMS_Final\Scenarios\MicroStrategies.gdb\HUM2

Human module

This toolset is used to calculate human micro-strategies

Figure 3.21 Example of ArcGIS customized toolset for calculating human micro-strategies

3.6. Data maintenance of GIMMS

After building the database, the issue of maintenance becomes an issue to address. A key issue for preserving the consistency of the regional database is the development of procedures and tools for integrating or removing data. Such procedures are vital for maintaining the database and producing reliable results. Most importantly, all input data should pass a quality check before they are entered into the database i.e. they need to pass criteria related to age of data, mapping scale, areal coverage, density of observations and any pre-processing. If possible, the checking procedure should also include checking the maps and positions against sources of higher quality, like aerial imagery and spatially limited, but more accurate national or sub-national databases. Failure to pass these criteria should results in dismissing of the data. Once a decision has been made to include new data (or update existing data) the actual database integration will take place using an integration module designed to detect conflicts, which perturb the consistency of the database during the update step.

A crucial question, which need to be addressed and agreed upon, relate to who will be responsible for maintaining the GIMMS database. It is normal to associate only one department in an organization to handle all data maintenance. But in our case where the database and GIMMS tool are developed to support multiple users within SADC and with different data policies, it is more efficient to decentralize the data maintenance responsibilities to designated departments in the SADC member states while preserving a centralized approval process in the SADC regional Groundwater Management Institute of Southern Africa (GMISA). These ideas are in accordance with suggestions already being proposed during the creation of the SADC HGMA:

"The SADC HGMA will require updating. Key to updating the map is the improvement of groundwater data sets and information systems in the various countries. There needs to be a concerted effort to correct these shortcomings. A future update of the map requires a bottom-up approach to work with countries to ensure representative datasets are obtained from the various geological domains."

The establishment of GMISA is ideal for the future management of GIMMS. A process need to be developed so that member countries can submit their data to the institute, who will then perform the necessary quality check and approval before ingesting the new data into GIMMS.

4. Outputs and dynamic features of GIMMS

The groundwater drought vulnerability and insecurity map outcome of GIMMS is not a single map representing a fixed state, but rather a range of different maps representing a range of actual outcomes that depend on: 1) the raw data used as input, and 2) the aggregation and weighing of these data in the composite maps. In the following two types of dynamics of GIMMS are illustrated:

- Sensitivity to the weights in the CMA
- Impact of climate change

Furthermore, results of the testing and validation of the GIMMS are presented.

4.1. Sensitivity to weights in the CMA

The dynamic feature of the model is ensured through the preparation of different scenarios. The scenarios are developed by changing the weighting scheme of the model's parametric inputs. The ability to tune the weights at both the micro and macro-level makes the algorithm flexible to produce results optimized for localized settings and for different management purposes. Micro-level weights adjust the relative importance of parameters within each module and can be adjusted to optimize the model for specific locations, i.e. individual parameters are likely to differ geographically in terms of their influence on vulnerability. In contrast, the macro level weights are used to adjust the relative importance of the different modules. This distinction is meaningful since it can be used to highlight differences in management objectives. For example, water resource departments may suggest that knowing the location of vulnerable aquifers may be crucial, whereas other departments will suggest human factors, as settlement, are more important. Micro- and macro-level weights may also be used in combination e.g. by downplaying climate sensitivity (macro-level) and emphasize permeability (micro-level) in order to produce maps that reflects groundwater pollution vulnerability rather than drought.

Table 4-1 to Table 4-4 illustrate how various macro- and micro level strategies can be combined to define several different scenarios. A scenario is here represented by the combination of micro and macro-level weights (se Equation 4). Table 4-1 summarizes three suggested macro-level strategies chosen to represent legitimate assumptions regarding groundwater drought vulnerability. Different importance is placed on the physical and the human factors in these scenarios.

Table 4-1 Suggested macro-strategies

Description of strategy	Macro-weighting coefficients
Macro-strategy 1: Human and physical factors weigh equally	HuGWDV = 0.5[a] PhGWDV = 0.5 Total = 1.0
Macro-strategy 2: Human factors favored over physical factors	HuGWDV = 0.75[a] PhGWDV = 0.25 Total = 1.0
Macro-strategy 3: Physical factors favored over human factors	HuGWDV = 0.25[a] PhGWDV = 0.75 Total = 1.0

[a] In these examples, the climate sensitivity and the hydrogeological drought proneness are added equally into the PhGWDV, to represent the physical conditions for groundwater drought

As for the micro-strategies, the objective is to develop weighting coefficients for individual data layers in each module that reflect importance relative to other layers in the module. Table 4-2 and Table 4-3 summarize proposed micro-strategies for the human and physical factors, respectively. In both cases, general vulnerability is represented as a strategy where all factors are weighted equally. In addition, we suggest human micro-strategies that emphasize population over other factors (Hum-2) as well as a case where the distance to water source is favored over other factors (Hum-3). The stronger weight to population in Hum-2 represents a strategy suited for worst-case scenario planning, whereas Hum-3 will help to accentuate areas where alternatives to groundwater are absent or limited and as such be better suited to strategic planning.

Table 4-2 Suggested micro-strategies for the human modules

Description of strategy for human module	ID	Micro-weighting coefficients
Micro-strategy 1: All factors equal - general human vulnerability	Hum-1	Population density = 0.25 Livestock density = 0.25 Irrigation intensity = 0.25 Distance to water source = 0.25 Total = 1.0
Micro-strategy -2: Population density favored over other factors	Hum-2	Population density = 0.55 Livestock density = 0.15 Irrigation intensity = 0.15 Distance to water source = 0.15 Total = 1.0
Micro-strategy 3: Distance to perennial water source favored over other factors	Hum-3	Population density = 0.15 Livestock density = 0.15 Irrigation intensity = 0.15 Distance to water source = 0.55 Total = 1.0

The additional physical micro-strategies are ones where climate sensitivity is favored over the other hydrogeological factors (Phys-2) and one where recharge and aquifer productivity have higher weights that climate (Phys-3). Phys-2 is important in the context of climate change as areas with high climate sensitivity are those that will be affected most by climate change. In contrast Phys-3 will be more relevant in the context of strategic planning as it will highlight the large difference in groundwater potential across the SADC region.

Table 4-3 Suggested micro-strategies for the physical modules (i.e. the combined climatic and hydrogeological factors)

Description of strategy for physical modules	ID	Micro-weighting coefficients
Micro-strategy 1: All factors equal - general physical vulnerability	Phys-1	Climate sensitivity = 0.50 Aquifer productivity + Recharge = 0.50 Total = 1.0
Micro-strategy 2: Climate favored over other factors	Phys-2	Climate sensitivity = 0.75 Aquifer productivity + Recharge = 0.25 Total = 1.0
Micro-strategy 3: Recharge and aquifer productivity favored over climate	Phys-3	Climate sensitivity = 0.25 Aquifer productivity + Recharge = 0 75 Total = 1.0

Macro- and micro-level strategies are then combined into a number of different groundwater drought vulnerability scenarios, as illustrated in Table 4-4. For each scenario one macro-strategy is combined with one human micro-strategy and one physical micro-strategy, and with three macro-strategies and three micro-strategies for both human and physical factors, 27 possible vulnerability scenarios exists (Table 4-4).

Table 4-4 GIMMS scenarios based, on macro- and micro-strategy combinations

Micro-strategy combinations	Macro-strategy 1	Macro-strategy 2	Macro-strategy 3
Hum-1 vs. Phys-1	Scenario 1	Scenario 10	Scenario 19
Hum-2 vs. Phys-1	Scenario 2	Scenario 11	Scenario 20
Hum-3 vs. Phys-1	Scenario 3	Scenario 12	Scenario 21
Hum-1 vs. Phys-2	Scenario 4	Scenario 13	Scenario 22
Hum-2 vs. Phys-2	Scenario 5	Scenario 14	Scenario 23
Hum-3 vs. Phys-2	Scenario 6	Scenario 15	Scenario 24
Hum-1 vs. Phys-3	Scenario 7	Scenario 16	Scenario 25
Hum-2 vs. Phys-3	Scenario 8	Scenario 17	Scenario 26
Hum-3 vs. Phys-3	Scenario 9	Scenario 18	Scenario 27

The implementation of the algorithm with all 27 scenarios is an important feature that adds dynamics to GIMMS as well as it helps to reduce subjectivity which is inevitable part of the weighting assignment. It is also an important part of testing the sensitivity of the outputs i.e. the robustness, variability, and credibility of the results, given changes in data input (cf. Section 4.3.2.4).

4.2. Impact of climate change

A distinct advantage of the approach proposed to determine climate sensitivity is that it can be used with any type of gridded precipitation data. Such data could, for example, stem from a climate change projection using a global or regional climate model. These models will generally not be on the same grid, nor is the underlying physics the same as for reanalysis data. It is therefore necessary to calibrate them against the reanalysis data.

As an example, we consider a simulation with the state-of-the-art regional climate model HIRHAM5 that was developed at the Danish Meteorological Institute (Lucas-Picher et al., 2012; Mottram et al. in prep.). The model is run on the CORDEX domain (Mariotti et al., 2011), which comprises all of Africa with a grid mesh width of 44 km. The period covered is 1950 to 2100. For the first 50 years, observed concentrations of greenhouse gases are used, whereas we follow the IPCC SRES A1B scenario after 2000. This scenario, which, in very broad terms, can be described as "business as usual", is one of the so-called IPCC benchmark scenarios, and hundreds of simulations have been conducted with all kinds of models using this scenario.

The regional model is "driven" by the coupled global atmosphere-ocean model ECHAM5/MPI-OM1, which is as well state-of-the-art. Climate information from the global model is transferred through the lateral boundaries into the domain of the regional model. This implies in particular that no observations whatsoever go into the forecast. The whole scenario is driven only by the forcing of the greenhouse gas concentrations. A "good" model remains close to the observed climate when "driven" with data that are representative for the observed climate. However, this implies that, due to the lack of observational constraints, one cannot compare a particular day in observed (or reanalyzed) climate with the same day in such a climate scenario run. A "good" model, however, has the same statistical properties (such as average value and standard deviation) as observations or reanalyses. For this reason, we have chosen a 20 year period that is representative for the same period (1989-2008) in the scenario run to represent the comparable present day conditions.

Due to the differences in the model setup, grid mesh width etc., the scenario data needs to be calibrated. In order to introduce as few as possible changes, we have only adjusted the threshold below which a day is considered as dry. In this particular setup, the threshold for the scenario run is at 2 mm/day. That may seem much, but, as mentioned above, this is a model value representative for a grid mesh of 44 x 44 km^2, i.e. almost 2000 square kilometres. By this approach we can also account for a wet bias in HIRHAM in some tropical regions (Lucas-Picher et al., 2012).

Figure 4.1 shows, on the left panel, the meteorological drought risk index as derived from the A1B scenario data for present-day (1989-2008) climate. The right panel of Figure 4.1 shows the same index for future climate, namely the 20 year period 2080-2099.

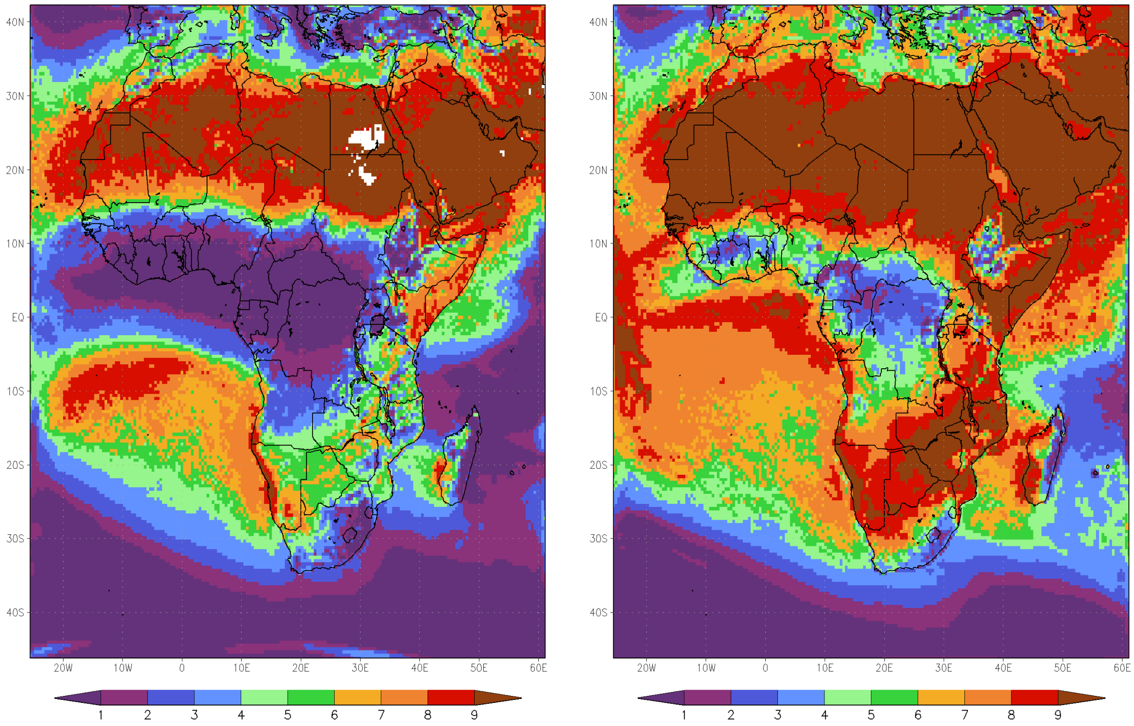


Figure 4.1 Meteorological drought risk index, as defined in the text, for (left panel) the period 1989-2008 and (right panel) the period 2081-2100. Data from a 44 km HIRHAM5 climate change scenario simulation following IPCC scenario A1B. No observations go into the index for present-day climate, so that both panels can be compared directly. Index values and vulnerabilities as in Figure 3.2.

A comparison of Figure 3.2 and the left panel of Figure 4.1 reveals that the climate model for present-day conditions is able to depict most of the properties of the reanalysis-based index. Differences in values of individual grid cells, e.g. in Tanzania and Zambia, are related to the different grid mesh widths. The scenario data indicate higher meteorological drought risk than observed over parts of Kenya and Somalia, whereas a lower vulnerability is simulated over parts of Namibia and Botswana.

For future climate (right panel of Figure 4.1), a general increase in drought vulnerability is apparent. Except for south-eastern South Africa, Lesotho, Swaziland, the east coast of Madagascar, the northern half of Angola and most of the DRC, large or extreme drought vulnerabilities are found. Changes are particularly large for Botswana, northern South Africa, Zimbabwe, most of Mozambique, western Madagascar, Kenya, and Somalia. We note also a much increased drought risk in the Sahel. These changes are partly due to a general decrease of precipitation (mostly over southern Africa, not shown) and partly due to a longer temporal extent of longer dry periods (PEXT, mainly over eastern Africa, not shown). In addition, precipitation is projected to become more variable over Zimbabwe, northern Kenya and most of Somalia.

The implication of this climate scenario on groundwater drought vulnerability is visualized in the maps for present and future climate in Figure 4.2. What these maps suggest is that drought risk and associated groundwater drought vulnerability will increase over most of the SADC region, with already drought-vulnerable areas becoming more vulnerable, and some additional areas becoming vulnerable, like large parts of Zambia, Mozambique and Madagascar. The mapping considers other factors to be equal, i.e. constant population density, which may be rather optimistic. Nevertheless, the map illustrates the flexibility and possible applications of GIMMS.

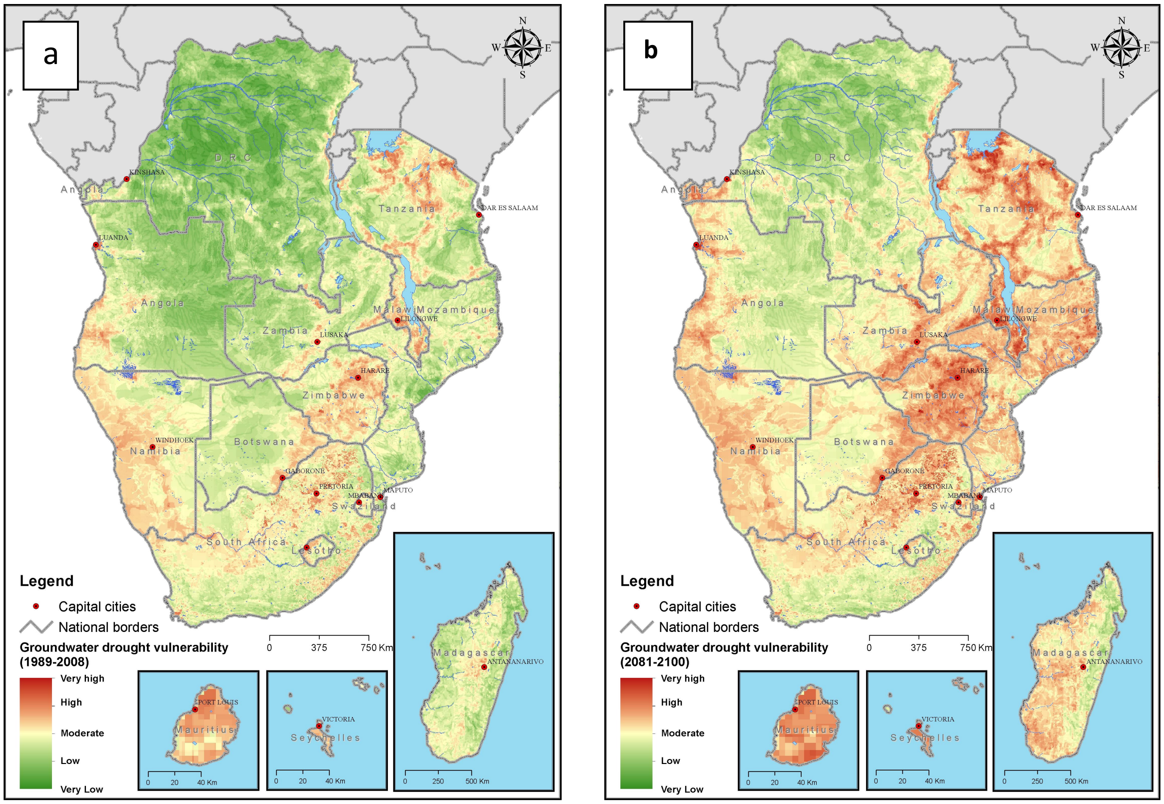


Figure 4.2 SADC map of groundwater drought vulnerability for (a) present climate, and (b) projected future climate (based on IPCC SRES A1B)

4.3. Uncertainty, sensitivity, testing and validation of GIMMS

The utility of GIMMS hinges critically on data quality and availability. Whether helping to map the physical constraint to groundwater reliability or relating groundwater availability to socio-economic variables, as well as predicting the impact of climate change on groundwater resources, the capability and reliability of GIMMS is a function of the availability of accurate data at sufficient fine spatial resolutions.

While every effort has been made to gather and use the best possible data, it is inevitable that the accuracy, adequacy and completeness of data will vary across the SADC region.

4.3.1. Data uncertainty and credibility index of GIMMS

The GIMMS database is composed of many different map layers that depict the spatial distribution of various key factors across the SADC region. These individual map layers are in best case derived from homogenous and objective measurements across the region i.e. they are equally valid for all countries. However, for the most part, the individual map layers have been assembled or calibrated using national databases, which vary in scale, accuracy and frequency of updates. This spatial variation in data quality implies that the reliability and validity of the model outputs will vary across the SADC region, and therefore, a country-by-country credibility index has been constructed and distributed along with the groundwater insecurity maps.

The credibility index shows, on a country-by-country basis, the average data quality score of the individual GIMMS mapping modules, which again reflect the data quality score of individual data layers in each module. The assignment of data quality scores was based on a relative ranking of the individual countries, based on associated meta data, into five classes 1 (very low reliability); 2 (low reliability); 3 (moderate reliability); 4 (high reliability) and 5 (very high reliability). Aggregated credibility scores are then derived as the average data quality score for the individual data layers.

All scores for individual and aggregated map layers are found in Appendix 6, while a map with the final composite credibility score is shown in Figure 4.3.

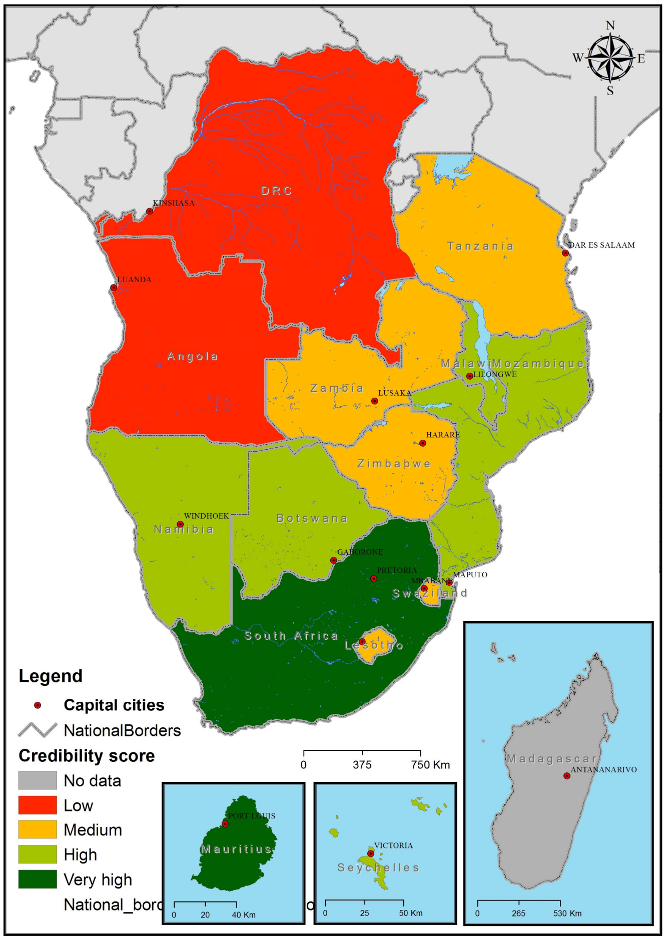


Figure 4.3 Map of data credibility score across SADC

4.3.2. Validation and testing of GIMMS

The uncertainties discussed above relate to the data themselves but the GIS analysis also introduces another type of error, which arises through processing. The solutions reached by the GIS analysis are therefore also validated and calibrated using five complimentary methods:

1. Validation of GIMMS meteorological drought risk index

2. Testing of GIMMS aquifer productivity
3. Independent validation of GIMMS for South Africa
4. Sensitivity of GIMMS
5. PSC review of GIMMS maps

4.3.2.1. Validation of GIMMS meteorological drought risk index

One way to validate GIMMS meteorological drought risk index is by comparing outputs with similar maps generated over the African continent.

Recently, Eriyagama et al. (2009) conducted an exhaustive global assessment of drought vulnerability. Their approach is based on observations, but otherwise goes along the lines of this study. A comparison of Figure 3.2 of this report and their Figure 8 (Figure 4.4 below) reveals many similarities, such as a maximum vulnerability over northern Somalia and secondary maxima over Zimbabwe and Namibia.

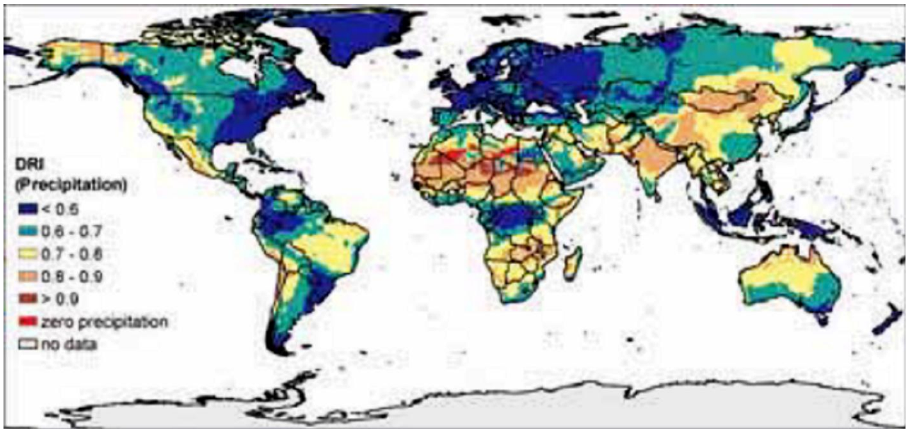


Figure 4.4 Global drought risk index with respect to monthly precipitation (From Eriyagama et al., 2009)

Dai (2011) calculated the Palmer Drought Severity Index on a global scale based on temperature, precipitation, humidity, net radiation and wind speed from 22 IPCC AR4 models on a decadal basis. Despite the deficiencies of the Palmer index in regions like Africa, the general picture is much the same as in this study, with an area of dry conditions from Namibia via Zimbabwe to Kenya and Somalia (Figure 4.5). These studies underpin that a reanalysis-based approach, as used here, is useful.

4.3.2.2. Testing of GIMMS aquifer productivity

The GIMMS layer for aquifer productivity was tested against a similar map developed by BGS (MacDonald et al., 2010). The overall purpose of the BGS effort was to map groundwater resilience to climate change in Africa. A comparison of the GIMMS and the BGS maps of aquifer productivity, which are both depicted on a five-point scale from 'low' to 'very high' aquifer productivity, shows reasonable agreement. For 80 % of the SADC area, there is either no deviation (38 %) or 1 class deviation (42 %) between the two (Appendix 7). The area in the southern part of the Kalahari Basin, which have been mapped by SADC HGMA as having multiple layered aquifers, deviate by 2, presumably because the BGS map does not consider multiple aquifers. If this area (which accounts for 4 % of the SADC area) was reclassified in GIMMS to a class lower (disregarding multiple aquifers), the total correspondence (allowing for +/- 1 class deviation) between the two maps is 84 %. There is no consistent explanation for the 6 % deviation areas (orange/red areas in map, Appendix 7). Hence, more in-depth hydrogeological assessment is needed to address these inconsistencies.

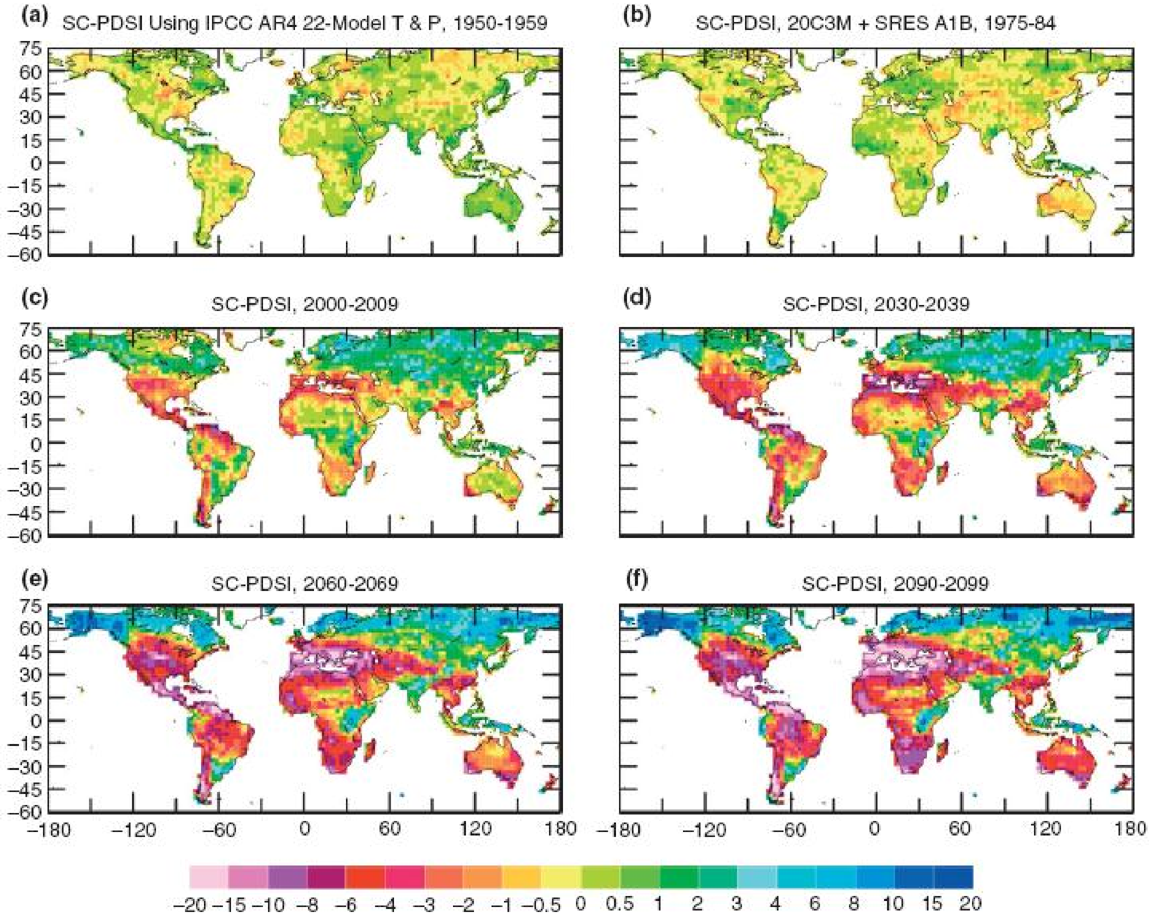
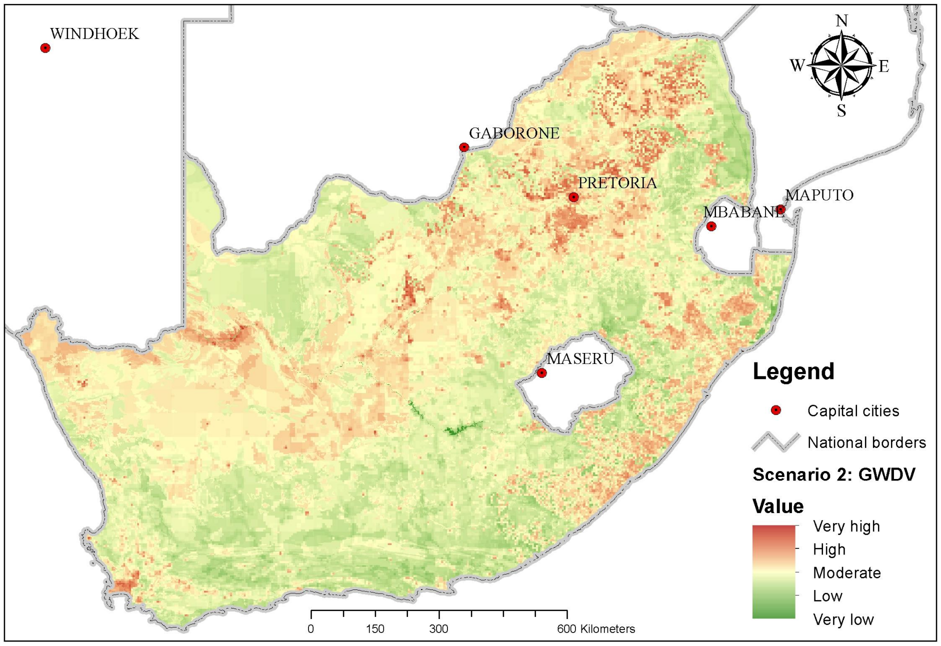


Figure 4.5 Mean annual sc-PDSI pm for years (a) 1950–1959, (b) 1975–1984, (c) 2000–2009, (d) 2030–2039, (e) 2060–2069, and (f) 2090–2099. (From Dai, 2011)

4.3.2.3. Independent validation of GIMMS for South Africa

GIMMS results for groundwater drought vulnerability were tested against the findings produced from completely independent data. For South Africa, national datasets can be acquired, which are presumably as accurate as, or more accurate than the seamless SADC data mostly derived from international sources. Hence, by setting up a similar model for South Africa, using the same algorithm and weights, the degree of matching will produce a measure of the confidence in GIMMS in terms of consistency and in terms of applicability for the rest of the SADC region. If the two maps for South Africa agree, the user has some confidence that the data and modelling procedure are credible.

In Appendix 8, the various layers for South Africa, using independent data (Appendix 3) are shown. Comparing the two maps show a very good agreement (Figure 4.6). This result is very encouraging and supports the applicability of GIMMS for the SADC region, albeit with necessary limitations associated with data availability and reliability.



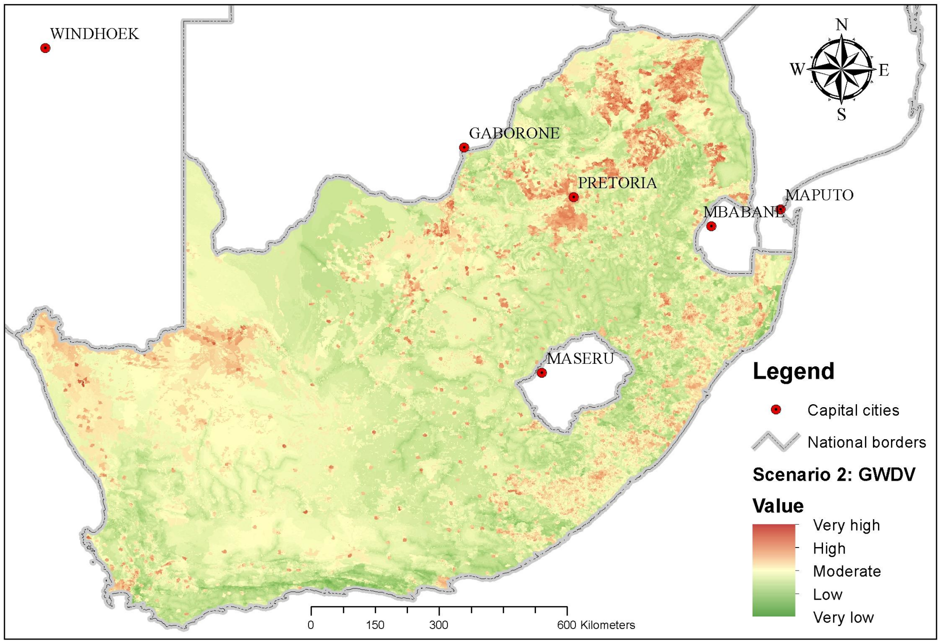


Figure 4.6 Groundwater drought vulnerability map for South Africa. Top: from GIMMS SADC map. Bottom: from independent data, using GIMMS methodology

4.3.2.4. Sensitivity of GIMMS

The third process, by which GIMMS has been checked and calibrated, is referred to as sensitivity analysis. Sensitivity analysis allows the user to test how variations in data and modelling procedure influence a GIS solution. This is done by varying the inputs of the GIS model, or the procedure itself, to see how each change alters the solution. In our case, the sensitivity analysis was based on a range of vulnerability scenarios calculated. All together, 27 different vulnerability scenarios were produced using various combinations of macro- and micro-level weights to change the relative influence of different parameters on groundwater drought vulnerability (cf. Section 4.1). Together, these different scenarios allow us to obtain information, such as minimum, maximum, range, mean and standard deviation based on calculations on each cell and across the whole suite of scenarios.

Visualization of such statistical derivatives provides some interesting information. We can for example look at the mean vulnerability score across all scenarios and thereby get an idea about areas and countries being most vulnerable, not for a specific weighting scheme, but across the range of variability presented by the different scenarios (Figure 4.7). The bars in the map represent, for each member state, the relative distribution of cells (grids of 10*10 km) in the various vulnerability classes. It is seen that the broad groundwater drought vulnerable areas reflect the aridity of the areas and the aquifer productivity (Map 1 in Appendix 5, and Figure 3.7).

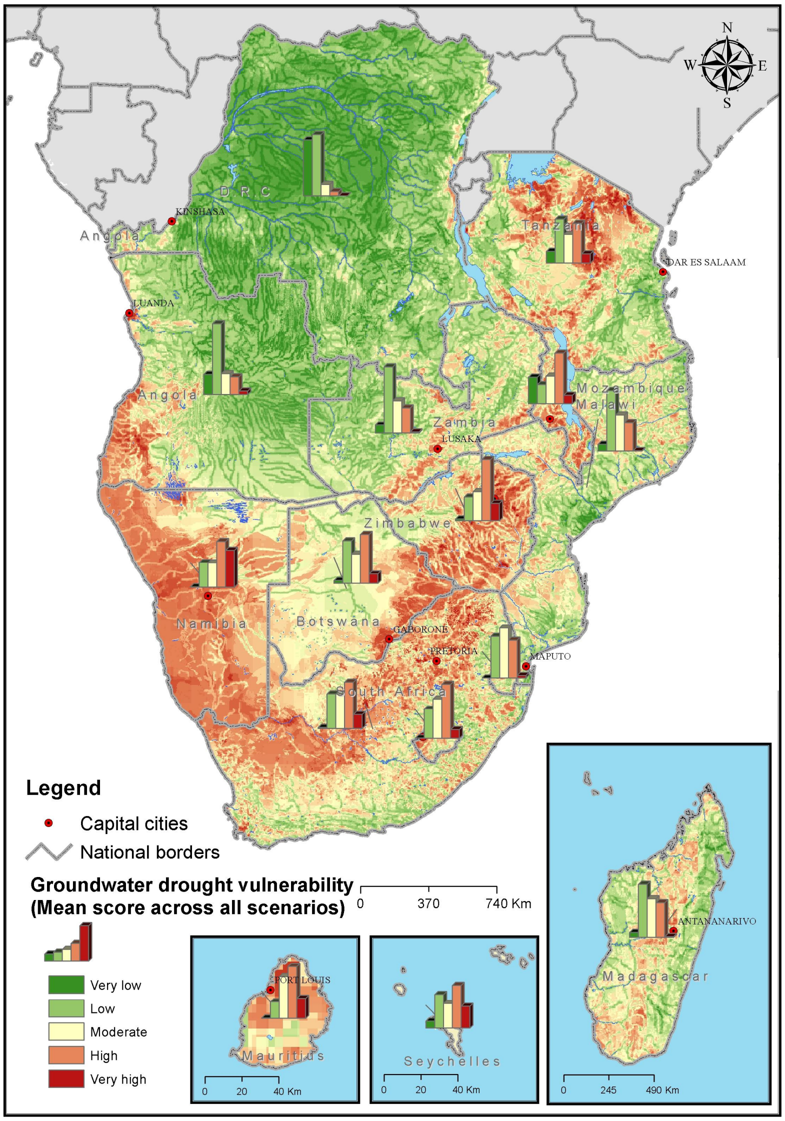


Figure 4.7 Mean groundwater drought vulnerability across all 27 scenarios in Table 4-1 to Table 4-4

Still, it may be more interesting to look at the minimum, rather than the mean, vulnerability score. If we assume that we are testing the model within a valid range of alternatives then the minimum vulnerability score is extremely important since it can be used to identify regions which, irrespective of the model's weighting scheme, are highly vulnerable to groundwater drought. Areas that get consistently high vulnerability scores across all scenarios also has limited variability (i.e. low values for range and standard deviation), which is encouraging since it indicates a robustness of the GIMMS model in identifying areas being intrinsically vulnerable to groundwater drought (Figure 4.8).

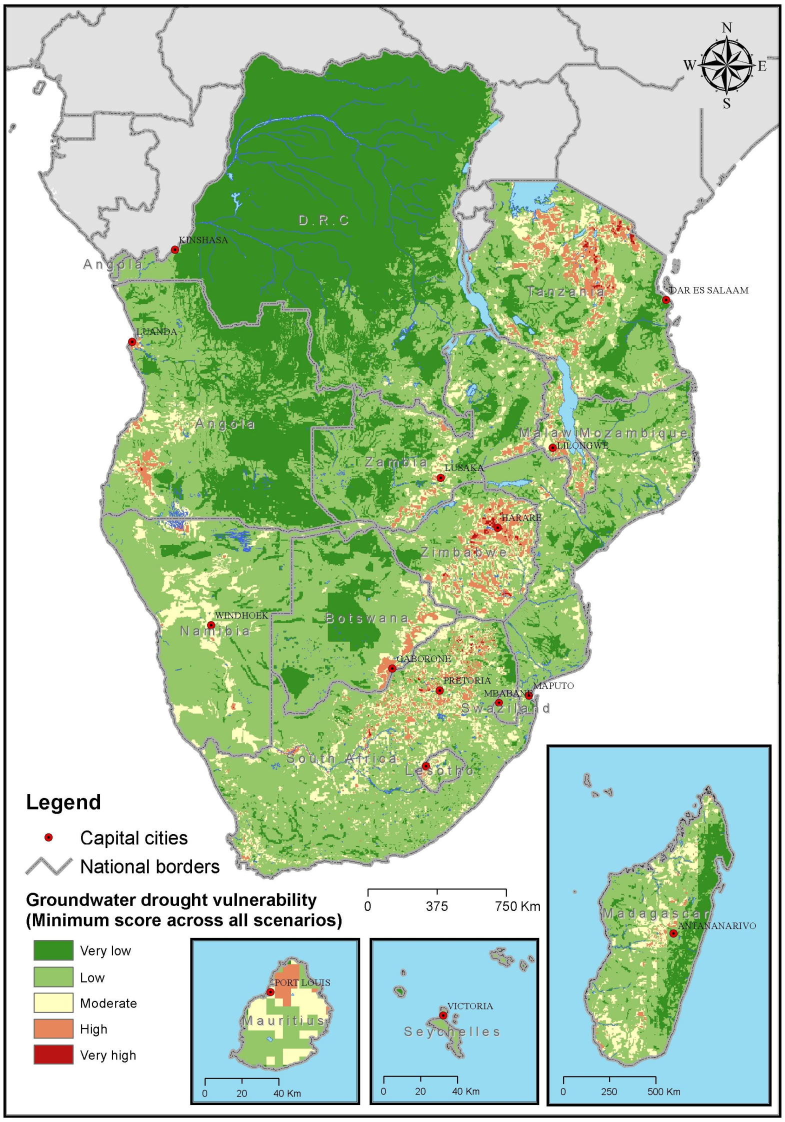


Figure 4.8 Minimum groundwater drought vulnerability across all 27 scenarios

While the multi-scenario statistics provide an important way to understand model behaviour and model variability the individual scenarios has a more practical value in addressing different management issues. By example, we have chosen three different scenarios for illustration.

First, we have Scenario 2 (Figure 4.9), where human and physical factors are considered equal at the macro-level but population density receives a higher weight at the micro-level (cf. Table 4-1 to Table 4-4). The outcome of this scenario is a map where densely populated areas will be emphasised and thus it provides an indication of the areas where most people will be affected by groundwater drought. This may be used to identify areas in risk of human migration due to lack of access to groundwater. In decision making terms, such a map may be seen as an important input to raising awareness about groundwater drought and drought management. In this context, it is seen in Figure 4.9 that areas in North eastern South Africa, Zimbabwe, Malawi and Tanzania are relatively groundwater drought vulnerable. We have chosen Scenario 2 as the 'base case scenario' and hence this weighing scheme is used in the climate change impact assessment (Figure 4.2).

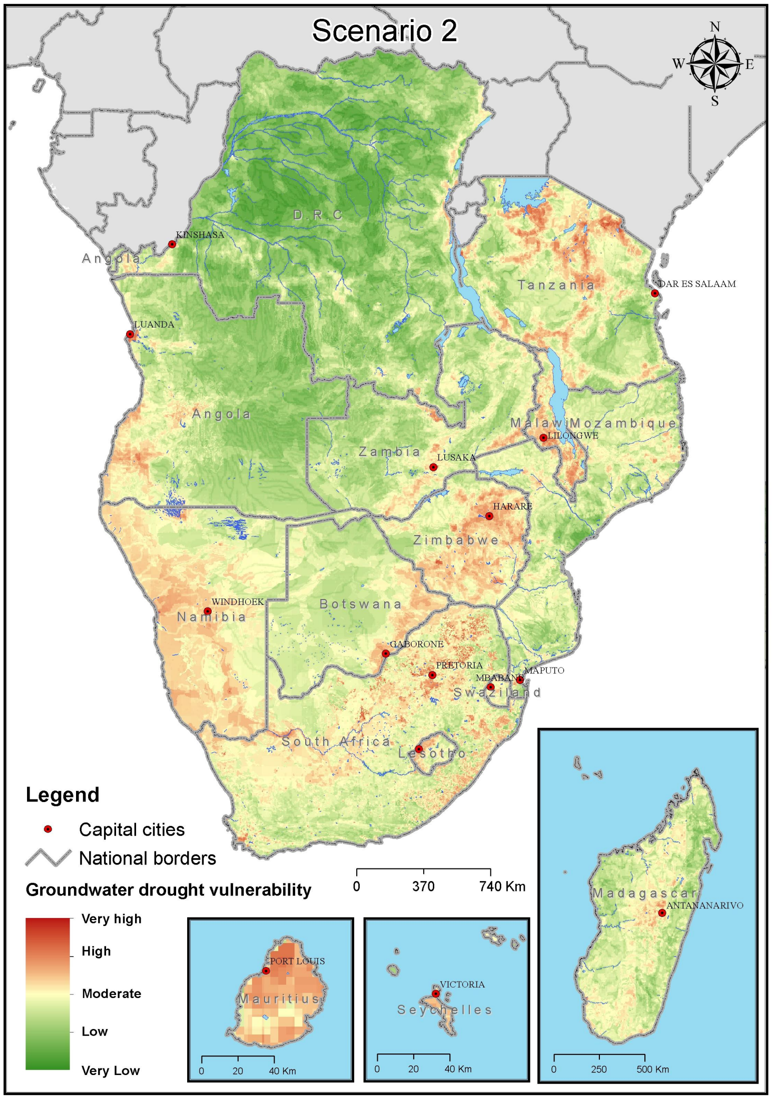


Figure 4.9 Groundwater drought vulnerability for Scenario 2, weighing popualtion density

In contrast, we have also selected Scenario 24, which at the macro-level gives higher weight to climate sensitivity as well as to distance to surface water at the micro level (cf. Table 4-1 to Table 4-4). The vulnerable areas identified by this scenario may not be densely populated, yet people actually living in these areas may depend critically on groundwater since the areas are drought prone and since alternatives to groundwater are limited. For decision makers, this map has a value for strategic physical planning, i.e. how to target government services in certain groundwater drought vulnerable regions and where to potentially develop new land (Figure 4.10). The dessert and arid areas of Southern Africa are clearly dominating the higher GWD vulnerable areas and large tracts of land in between perennial and ephemeral rives become evident.

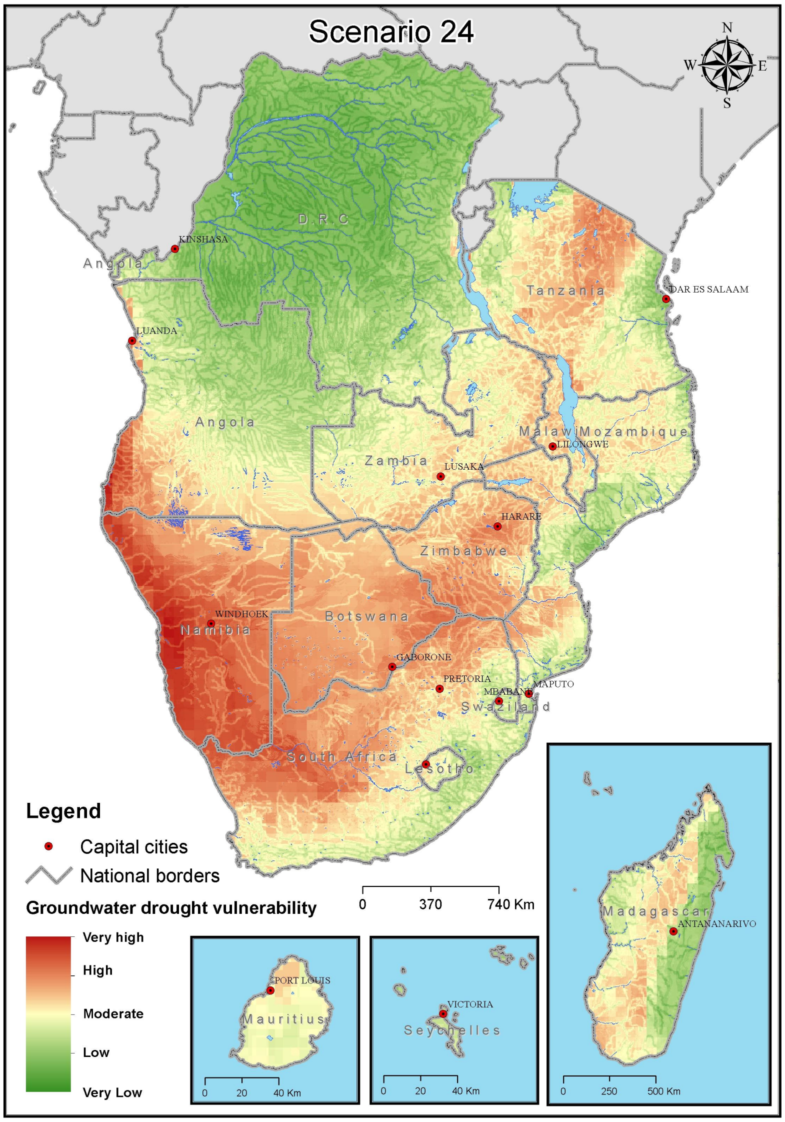


Figure 4.10 Groundwater drought vulnerability, Scenario 24, weighing climate and lack of alternatives to groundwater

The third and final case is Scenario 16, where climate sensitivity has been toned down by putting more weight on human groundwater dependence (macro-level) and on groundwater reliability (micro-level) (cf. Table 4-1 to Table 4-4). The strength of this scenario is the ability to accentuate variation in groundwater reliability (or lack hereof) and human dependence irrespective of the broader meteorological drought risk. The vulnerable areas identified by this scenario are so without being specifically sensitive to meteorological droughts and as such they are not emergency planning zones but rather zones where sound water management and conservation should be promoted in order to ensure sustainability in the long-term (Figure 4.11).

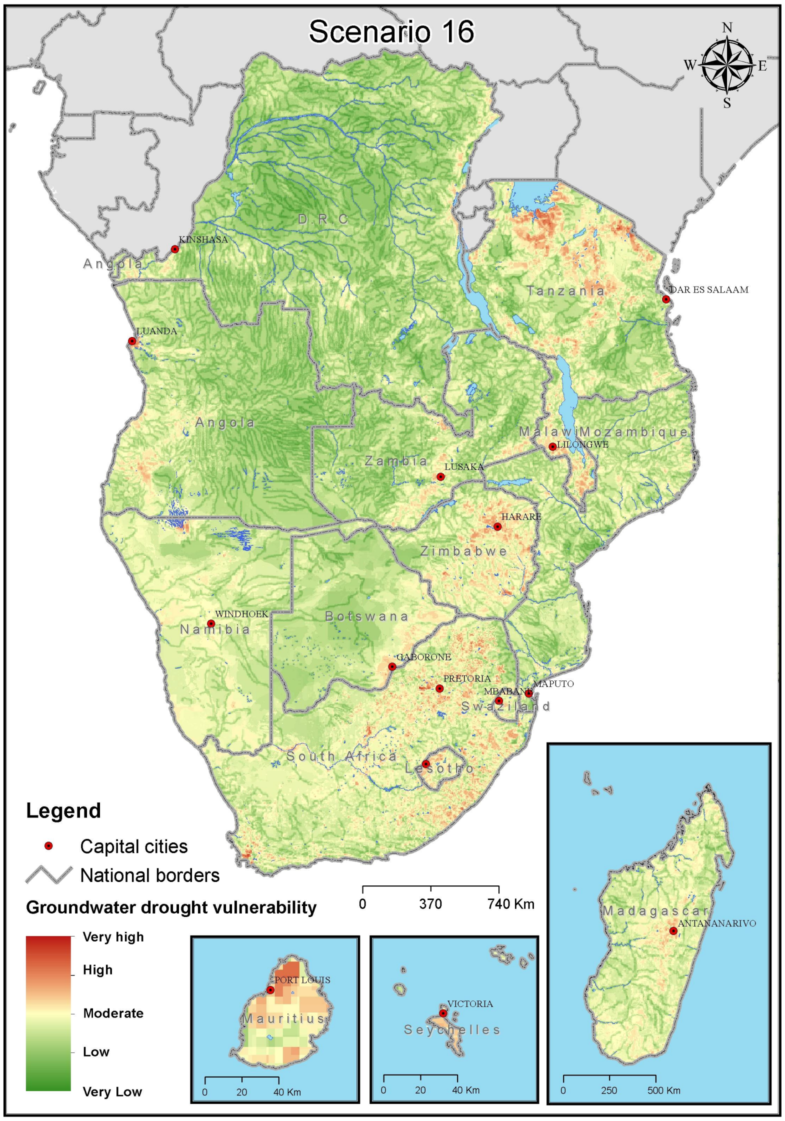


Figure 4.11 Groundwater drought vulnerability, Scenario 16, weighing groundwater reliability and human groundwater dependence

A summary of the outcome of the sensitivity analysis and the potential use of the various scenario map representations are listed ion Table 4-5.

Table 4-5 GIMMS map representations, based on various single scenarios and ensemble scenario statistics and their potential use in groundwater and GWD management

Scenario/ensample statistics	Relative weighing	Potential use of map	Figure
Mean GWDV	None	Map broadly areas potentially vulnerable to GWD	Figure 4.7
Min. GWDV	None	Map areas consistently vulnerable to GWD based on all factors considered	Figure 4.8
Scenario 2	Population density	Map areas with high human vulnerability to GWD ('Base case scenario')	Figure 4.9
Scenario 24	Climate sensitivity and lack of groundwater alternatives	Map drought prone areas where groundwater development needs strategic consideration as only available resource	Figure 4.10
Scenario 16	Human groundwater dependence and groundwater reliability	Map areas with high human dependence on less reliable groundwater resources, irrespective of climate sensitivity	Figure 4.11

4.3.2.5. PSC review of GIMMS maps

An important way to verify the credibility of the GIMMS maps was to subject them to an internal review process within the PSC of the overall SADC Groundwater and Drought Management Project. This was done during June-Aug 2011 by sending hardcopy aggregate maps of aquifer productivity and groundwater drought vulnerability as well as maps of groundwater threats to individual PSC members for their comments, feedback and further inputs. Results of this review process have been used to qualify, modify and update the GIMMS maps in a terminal phase of the project (Appendix 9).

5. Perspectives of using GIMMS in SADC

This report outlines the methodology and development of GIMMS for analysing, visualising and managing groundwater drought in the SADC region. Various maps have been presented, illustrating the capability and flexibility of GIMMS. No single map can be highlighted as the correct or most accurate groundwater drought vulnerability map. Rather, a spectrum of maps, emphasizing various aspects of groundwater drought, can be shown. If a single map is to be selected for broad dissemination, including in hardcopy format, the map of Figure 4.9 (Scenario 2 or the 'base case scenario' in Table 4-4) is recommended, as it gives a balanced weight to the various components.

For further development of GIMMS, certain aspects of groundwater dependent ecosystems may be incorporated. In terms of data availability, more emphasis should be put on consolidating aquifer productivity and groundwater recharge maps, especially at a more local and fine scale as these data are among the more uncertain and yet critical to assess. Data on groundwater levels relative to depths of wells indicating the buffer capacity of groundwater structures are also relevant to put more focus on. In this respect, the HGMA borehole database is a good initial, but rather inconsistent dataset. See also below for recommendations on further data needs for GIMMS.

5.1. Implementation and application of GIMMS

The value of the GIMMS tool will only be tested through its actual implementation and application. In the following, ideas and perspectives for the application of the tool are given.

5.1.1. Scale-dependent management objectives of GIMMS

GIMMS is developed at the regional scale (SADC) and at this level serves the purpose of managing GWD at an overall level. This includes directing and informing general drought management at a supra-national level in the region. At this level and at a multilateral level (between two or more countries), it could also support the management of transboundary aquifers, both for joint cross-boundary drought management but also for more general groundwater management in these shared aquifers between member states. Finally, GIMMS could be functional in the regional and transboundary assessment of climate projections and climate change impacts on groundwater resources and groundwater drought vulnerability (Table 5-1).

Though developed at the regional scale and hence serving supranational and international groundwater management objectives, the GIMMS may further complement and strengthen groundwater and drought management at a lower level. At the national level, GIMMS may contribute to wider national databases of natural resources, like land and water, and in that sense, help qualify decisions on water resources development and allocation as part of IWRM as well as integrated land use planning. Obviously, national drought management strategies could benefit from incorporating groundwater aspects from the GIMMS database. As noted by SADC (2009), groundwater does not at present feature in the drought strategies of many SADC countries. At national level, and particularly at sub-national level, the GIMMS model would benefit from review, revision and amendment of the presently available data, both in terms of refined scale (better spatial resolution) and further data parameters (see also Section 5.4).

The application of GIMMS at the regional scale may be considered more strategic and policy-driven, enhancing the political, SADC-wide focus and collaboration on groundwater and drought management in the region and potentially driving an agenda and more funding for such efforts. At the national and local levels, the use of the GIMMS may find more applied use. Especially at the sub-national level, GIMMS and improved finer-resolution versions of it, may support and direct drought proofing of groundwater-based water supplies, groundwater recharge infrastructure development, local or community-based groundwater management as well as the localisation and development of new human settlements, e.g. as part of relocation of displaced populations due to droughts or other natural, climate-driven or conflict-derived disasters. At all management levels, from regional to local, GIMMS may also serve to inform monitoring activities related to drought and groundwater, albeit with different overall focus. Whereas the monitoring at the regional level would focus on shared groundwater resources (TBAs) and representative contexts of combinations of aquifers, climate and groundwater use, the local monitoring would emphasize the monitoring of actual (real-time) groundwater conditions and water supply and access conditions Table 5-1).

Table 5-1 Potential applications of GIMMS at different management levels

	Management level		
Application type	**Regional/multilateral**	**National**	**Local/sub-national**
Drought management	Strategic drought management	National drought management	Drought proofing of WS
	Climate change projection and drought impact analysis	Real-time drought forecasting	Drought warning
Groundwater	Transboundary aquifer management	Water resources development	Groundwater recharge

management		and allocation	enhancement
	Monitoring of groundwater, with focus on TBAs and regionally rep. groundwater systems	Landuse planning	Development of new human settlements
		Monitoring of groundwater, with focus on nationally rep. groundwater systems	Monitoring of groundwater, with focus on groundwater-dependent areas and local/community-based groundwater management

5.2. Training and guidelines for use of GIMMS

The applicability and success of GIMMS depend on the dissemination and handover/training within SADC of the tool and the perceived usability and usefulness of it.

Geographical information systems (GIS) are a powerful tool, which can be an important support for planning and decision making. However, the wider application of GIS is often hampered by lack of well-trained experts in GIS and by the fact that decision makers and planners are seldom involved in GIS data processing, meaning they hardly understand, trust, or use the results. Therefore GIS training should not only concern GIS functionality but also keep a focus on the decision-making process.

5.2.1. Proposal for training approach in the GWDVM Component

To facilitate GIS training for groundwater insecurity planning, a training package should be developed that includes the compiled GIMMS spatial database, the ArcGIS custom tools, as well as operational guidelines for their usage. The training could be designed as a three-level course:

- The first level is a one-day training course for operational/GIS officers introducing the basic concepts of GIS, which is the core element for GIMMS, used for storing, analyzing and displaying of geographic data with relevance for groundwater insecurity. The course will consist of lectures and exercises. First, the relevant theory for each particular subject will be explained. Next, all participants take part in exercises to get hands-on experience with ArcGIS and aiming at producing various management maps using GIMMS

- The second level is a one-day seminar, involving decision makers and GIS experts where they get a chance to interact and define needs for application and required operational procedures for GIMMS

- The third level is a one-day training course for operational/GIS officers dealing with more advanced GIS topics with relevance for GIMMS. The course will consist of lectures and exercises concerning issues on how to model, manipulate and adjust individual key parameters in order to create flexible outputs as well as dedicated sessions will concern issues on how to maintain and update the system

5.3. Lessons learned

From the development of GIMMS, it is clear that continued collaboration and awareness raising on the important role of groundwater in drought management is required. Involving the member states, through the PSC, but also broader, in future projects, will be critical for the ownership, uptake and successful application of GIMMS.

For GIMMS to be effectively applied, the institutional framework and capacities need to be in place. With the multi-objective and interdisciplinary approach of the SADC Groundwater and Drought Management Project, a good foundation has been laid for the creation of such institutional framework and capacity in SADC.

5.4. Recommendations for GIMMS implementation

To enhance the long-term usability of GIMMS, continued data updating and amendment is required. In Table 5-2, a list of data needs are given, with reference to different relevant scales of application of the tool (refer also to Table 5-1). Though separated for various levels of management, data may be required across the levels, depending on application objectives.

Table 5-2 Additional and refined data to enhance the applicability of GIMMS at different scales

	Management level		
	Regional/multilateral	**National**	**Local/sub-national**
New data	Location/type of GDEs Location of TBAs Location of river basins	Groundwater quality Multiple/overlying aquifers	GWLs vs. well depth Distribution of dry/non-functioning wells Density of wells Water supply coverage
Refined/updated data		Hydrogeological conditions[a] Multifarious groundwater recharge	Population distribution Groundwater irrigation

[a] To further qualify and update the HGMA data base

As part of a roadmap for the assimilation of GIMMS, the following particular recommendations for further development and implementation of GIMMS are given:

Implement pilot projects to map GWDV and groundwater insecurity at national or sub-national level. This should include collaboration with water provision and management organizations, e.g. WaterAid[4]. An example of such an effort exists in Ethiopia (MacDonald et al., 2009a; Calow et al., 2002).

Qualify/update the HGMA database to consolidate the existing regional map but also to improve the hydrogeological mapping at national scales.

Link GIMMS database to other databases, e.g. the Zambezi Water Information System (ZAMWIS) for the Zambezi river basin.

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[4] WaterAid has a local mapping tool called Water Point Mapper, which includes data on operation and maintenance of wells, access distance and coverage, and revenue collection, which in combination with GIMMS could support targeting, efficiency and sustainability of interventions.

Harmonize and augment groundwater quality sampling and data management across SADC. Possibly with initial focus on the most critical transboundary aquifers.

Verify the predictive capacity of GIMMS from future drought events, monitoring key properties and indicators for GWDV commensurate with the factors considered in GIMMS

Set up integrated indicators for real-time GWD monitoring

Link GIMMS with existing drought management systems and real-time earth observation initiatives to map and monitor risks associated with climate, natural resources and food[5] to change from a response and crisis approach to integrated proactive risk reduction. This includes expanding existing systems that account for water balances to include components of groundwater storage.

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[5] E.g. FEWS, Famine Early Warning Systems Netwok (http://www.fews.net/) and the Experimental African Drought Monitor (http://hydrology.princeton.edu/~justin/research/project_global_monitor/).

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Percentage of non-functioning rural water supplies in Africa, by country, source of data, and type of supply (From Kleemeier, 2010)

Source of data[a]	**RWSN**	**PER**	**PER**	**AICD**
Type of Supply	**Handpumps**	**Handpumps**	**Mechanized boreholes & piped schemes**	**Rural water Points**
Country				
Angola	30	-	-	-
Benin	22	15	5	25
Burkina Faso	25	23	33	38
Cameroon	25	35	75	-
Chad	-	-	-	33
DRC	67	-	-	41
Côte d'Ivoire	65	-	-	23
Ethiopia	35	-	-	-
Ghana	-	20-30	20-30	-
Guinea	20	-	-	-
Kenya	30	-	-	-
Lesotho	-	-	-	23
Liberia	31	-	-	-
Madagascar	10	-	-	15
Malawi	40	-	-	36
Mali	34	34	13	-
Mozambique	25	-	-	-
Niger	35	>25	>25	-
Nigeria	65	-		-
Rwanda	-	-		30
Senegal	-	-		5
Sierre Leone	65	-		-
Sudan	-	-		17
Uganda	20	-		21
Zambia	32	-		-
Zimbabwe	30	-		-
Median	30	25	25	24

[a] **RWSN:** Compiled for the Rural Water Supply Network from various sources (Harvey, 2009). **PER:** Data of Benin, Burkina Faso, Ghana, Mali, and Niger (World Bank, 2009a, p. 15). Data on Cameroon (World Bank, 2009b, p. 16-17). **AICD:** (World Bank, 2007a).

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Table of data included in GIMMS

Appendix 2

Data set	Description	Type	Unit of measure	Resolution/scale	Reference period	Source	Link
Administrative							
SADC-countries	National borders	Polygon	-	-	-	SADC-HGMA	Dataset obtained directly from SADC-HGMA
SADC-provinces	Province borders	Polygon	-	-	-	SADC-HGMA	Dataset obtained directly from SADC-HGMA
Climate sensitivity							
Meteorological drought risk index	ERA-Interim 'reanalysis' precipitation	Raster	mm/day	0.78 degree (~ 80 km)	1989-2008	ECMWF	http://www.ecmwf.int/research/era/do/get/era-interim
Hydrogeological drought proneness							
Aquifer type	Aquifer storage properties as indicated by aquifer type	Polygon	Nominal	-	-	SADC-HGMA	Dataset obtained directly from SADC-HGMA
Aquifer yield	Aquifer yield potential	Polygon	Low to high	-	-	SADC-HGMA	Dataset obtained directly from SADC-HGMA
Rainfall	Long-term mean rainfall estimate	Raster	mm/year	8 km	1996-2008	USGS	http://earlywarning.usgs.gov/fews/index.php
NDVI	Long-term mean Normalized Difference Vegetation Index	Raster	-	8 km	1983-2003	USGS	http://earlywarning.usgs.gov/fews/index.php
Terrain slope	SRTM Digital Elevation Model	Raster	m.a.s.l.	1 km	-	CGIAR-CSI	http://srtm.csi.cgiar.org
Groundwater dependence							
Population density	Gridded population data	Raster	Persons per km^2	2.5 arc-minute (~ 4 km)	2000	UNEP/CIESIN	http://na.unep.net/siouxfalls/globalpop/africa/Africa_index.html
Livestock density	Gridded livestock data (weighted according to water demands)	Raster	Number per km^2	3 arc-minute (~ 5 km)	2005	FAO	http://www.fao.org/ag/AGAInfo/resources/en/glw/GLW_dens.html
Irrigation intensity	Intensity of GW irrigated land	Raster	Percentage of total area	5 minutes (~ 8 km)	2000	FAO	http://www.fao.org/nr/water/aquastat/irrigationmap/index10.stm
Access to surface water	Distance to surface water	Raster	km	10 km		SADC-HGMA	Dataset obtained directly from SADC-HGMA

Table of data included in GIMMS

Appendix 2

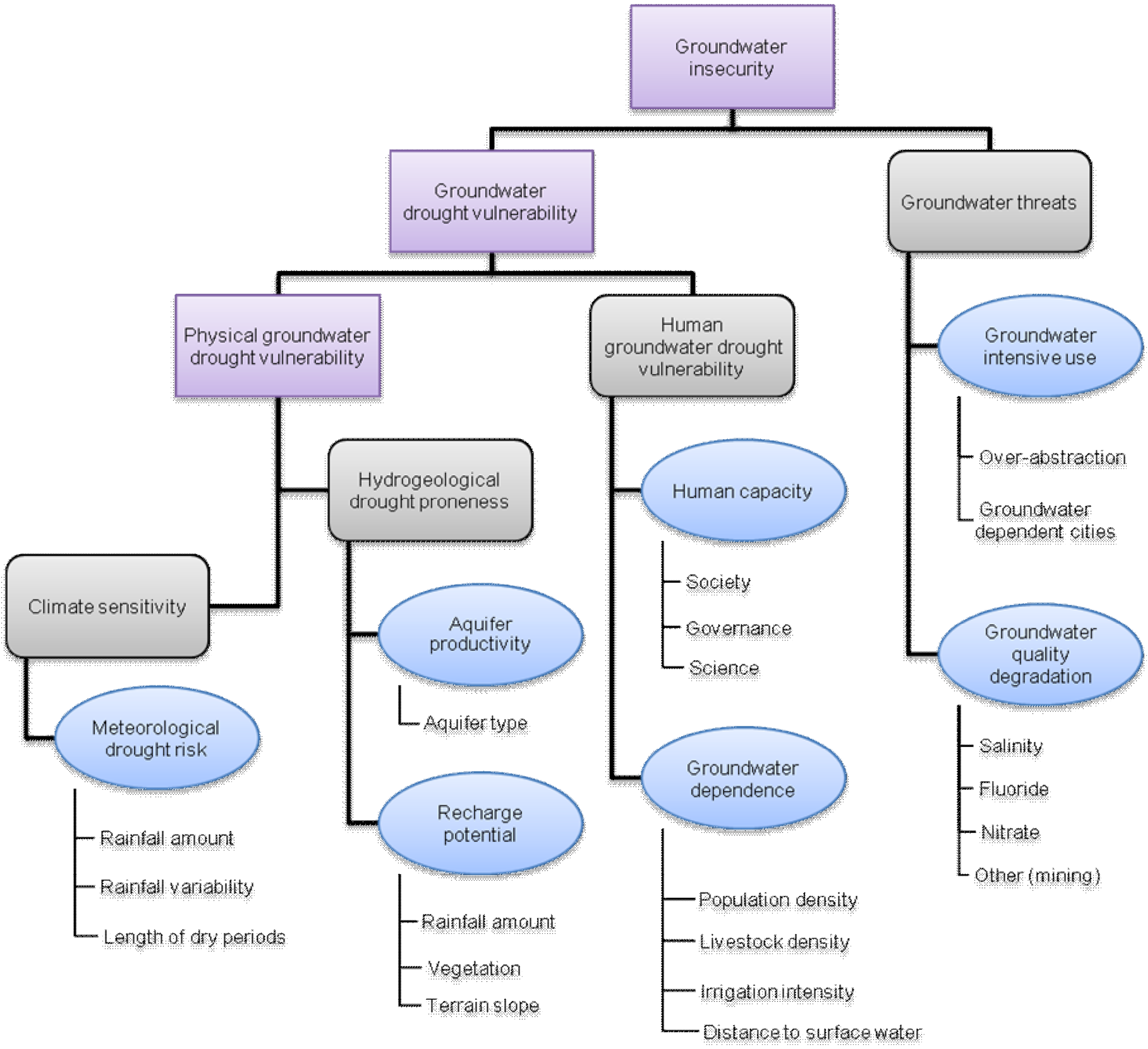
Data set	Description	Type	Unit of measure	Resolution/scale	Reference period	Source	Link
Human Capacity							
Society	Multi-dimensional poverty index	Polygon	-	National	Latest possible	UNDP	http://www.ophi.org.uk/policy/multidimensional-poverty-index
Science	Worldwide Human Development Indicators, education	Polygon	-	National	1960-2009	UNDP	http://hdr.undp.org/en/data/profiles/
Government	Worldwide Governance Indicators	Polygon	-	National	1996-2009	World Bank	http://info.worldbank.org/governance/wgi/index.asp
Groundwater threats							
Salinity	Areas with high salt concentration	Polygon	Nominal	-	2011	PSC and Christelis and Struckmeier (2011)	-
Fluoride	Areas with high fluoride concentration	Polygon	Nominal	-	2011	PSC and Christelis and Struckmeier (2011)	-
Nitrate	Areas with high nitrate concentration	Polygon	Nominal	-	2001 and 2011	PCS and Tredoux et al. (2001)	-
Mine activities	Locations with mine activities	Point	-	-	-	SADC-HGMA	Dataset obtained directly from SADC-HGMA
GW over-abstraction	Areas with GW over-abstraction	Polygon	Nominal	-	-	PCS	-
Urban GW dependence	Degree of dependence on GW in largest cities	Point	Percent	-	-	PCS	-

Table of data used for GIMMS validation for South Africa

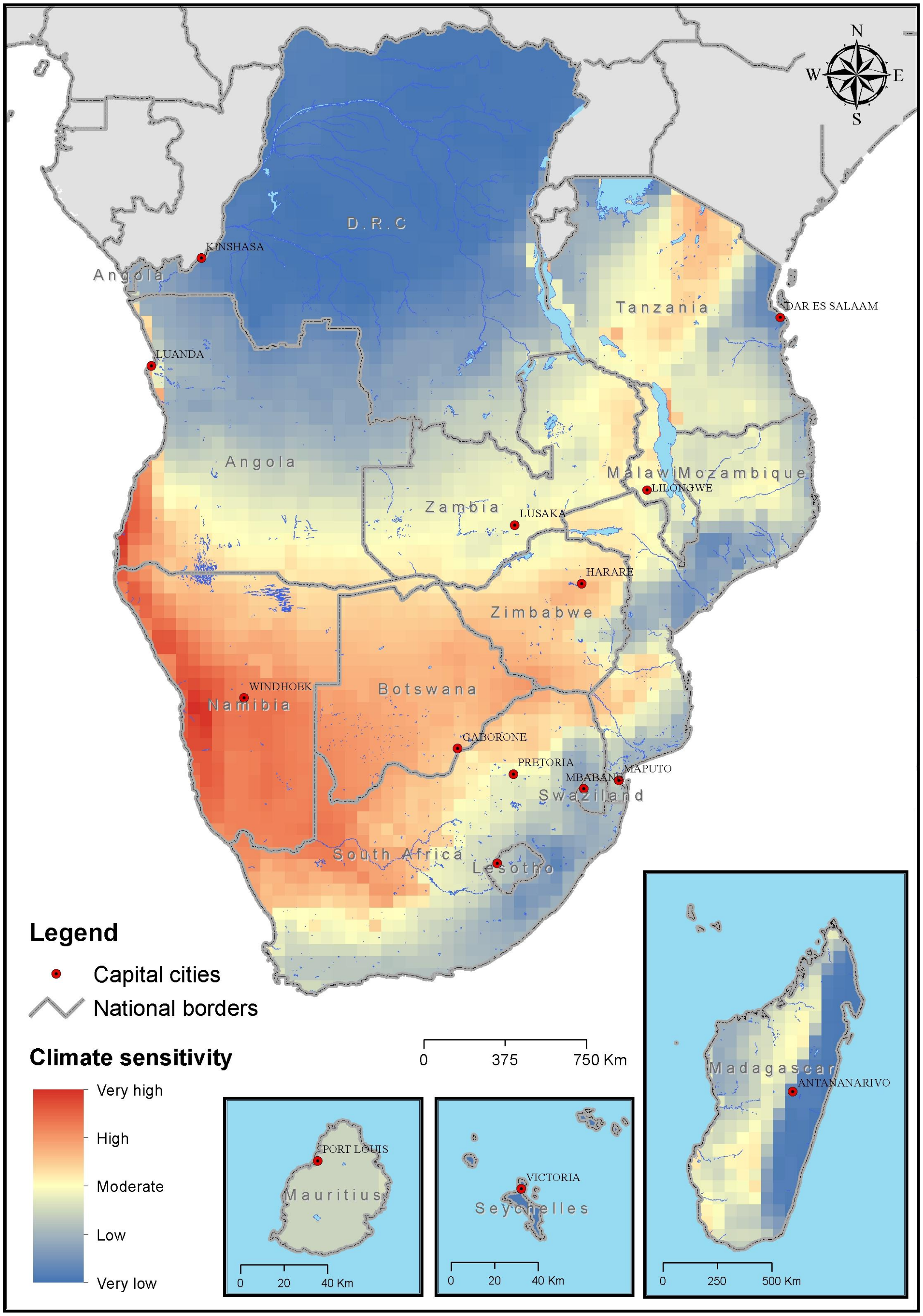
Appendix 3

Data set	Description	Type	Unit of measure	Resolution/scale	Reference period	Source	Link
Climate sensitivity							
Meteorological drought risk index	Mean annual and monthly rainfall	Table	mm/year and mm/month	Quaternary Catchment	+50 years	Water Research Commission	http://www.wrc.org.za/
Hydrogeological drought proneness							
Aquifer productivity	Hydrogeological terrains of South Africa	Polygon	Nominal	1:1 000 000	1997	Water Research Commission	http://www.wrc.org.za/
Rainfall	Long-term mean annual rainfall	Raster	mm/year	1.5 km	+50 years	United States Geological Survey	http://earlywarning.usgs.gov/fews/index.php
NDVI	Annual mean Normalized Difference Vegetation Index	Raster	NDVI	250 m	2000-2010	MODIS	http://glovis.usgs.gov/
Terrain slope	Digital Elevation Model	Raster	m.a.s.l.	1 km	v4.1	CGIAR-CSI	http://srtm.csi.cgiar.org
Groundwater dependence							
Population density	Gridded population data	Table	Persons per km^2	Mesozone (± 50 m^2)	2004	Statistics South Africa	www.gapweb.co.za
Livestock density	Livestock density (weighted according to water demands)	Table	Number per km^2	Provincial	1996	Statistics South Africa	www.StatsSA.org.za
Irrigation intensity	The South African National Land Cover 2000	Raster	Percentage of total area	30 m	2000	Agricultural Research Council	http://www.arc.agric.za/
Distance to surface water	Distance to surface water	Vector	Polyline	1: 500 000	Updated 2010	Department of Water Affairs	http://www.dwa.gov.za/BI/Mapshop/
Human Capacity							
Society	Deprivation Index - District Health Barometer	Table	Nominal	District Municipality	2001	Health Systems Trust	http://www.hst.org.za/district-health-barometer-dhb-2
Science	Higher Education	Table	Nominal	Local Municipality	2001	Statistics South Africa	www.StatsSA.org.za
Governance	Consolidated General Report on the Local Government Audit Outcomes 2008-09	Table	Nominal	Local Municipality	2009	Auditor General	http://www.agsa.co.za

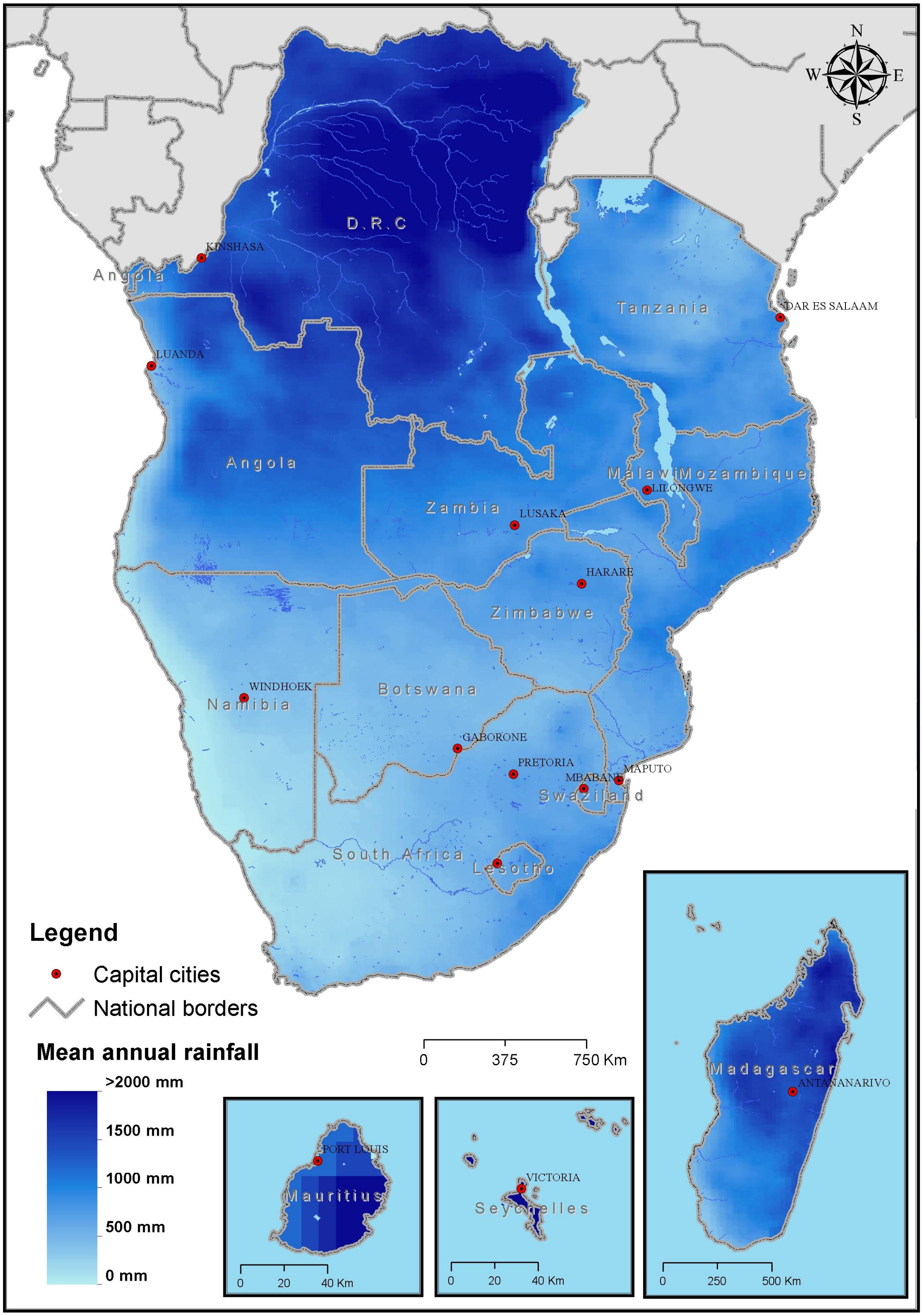
Complete diagram of GIMMS (expansion of Figure 3.1)



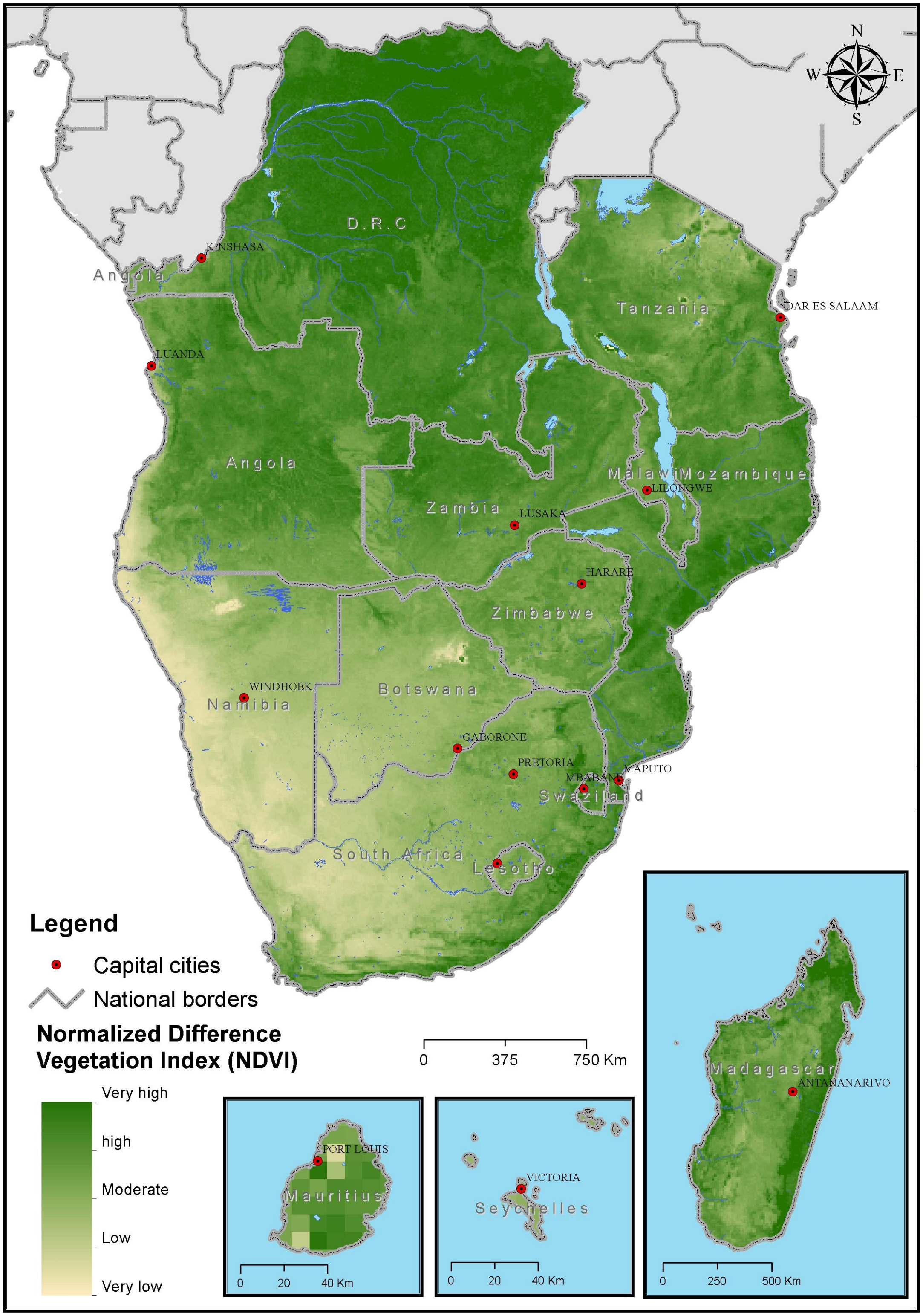
Map 1: Meteorological drought risk



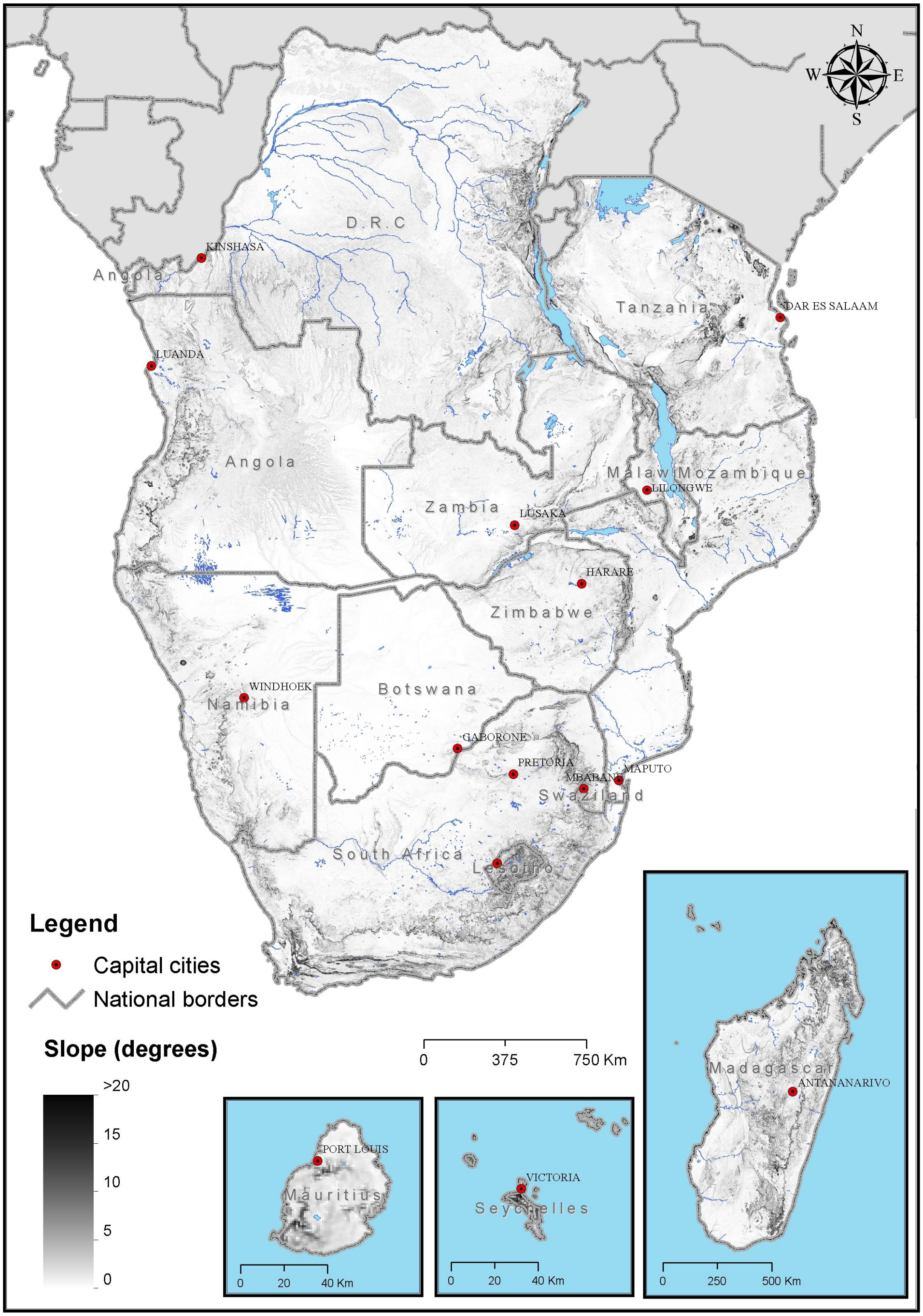
Map2: Rainfall



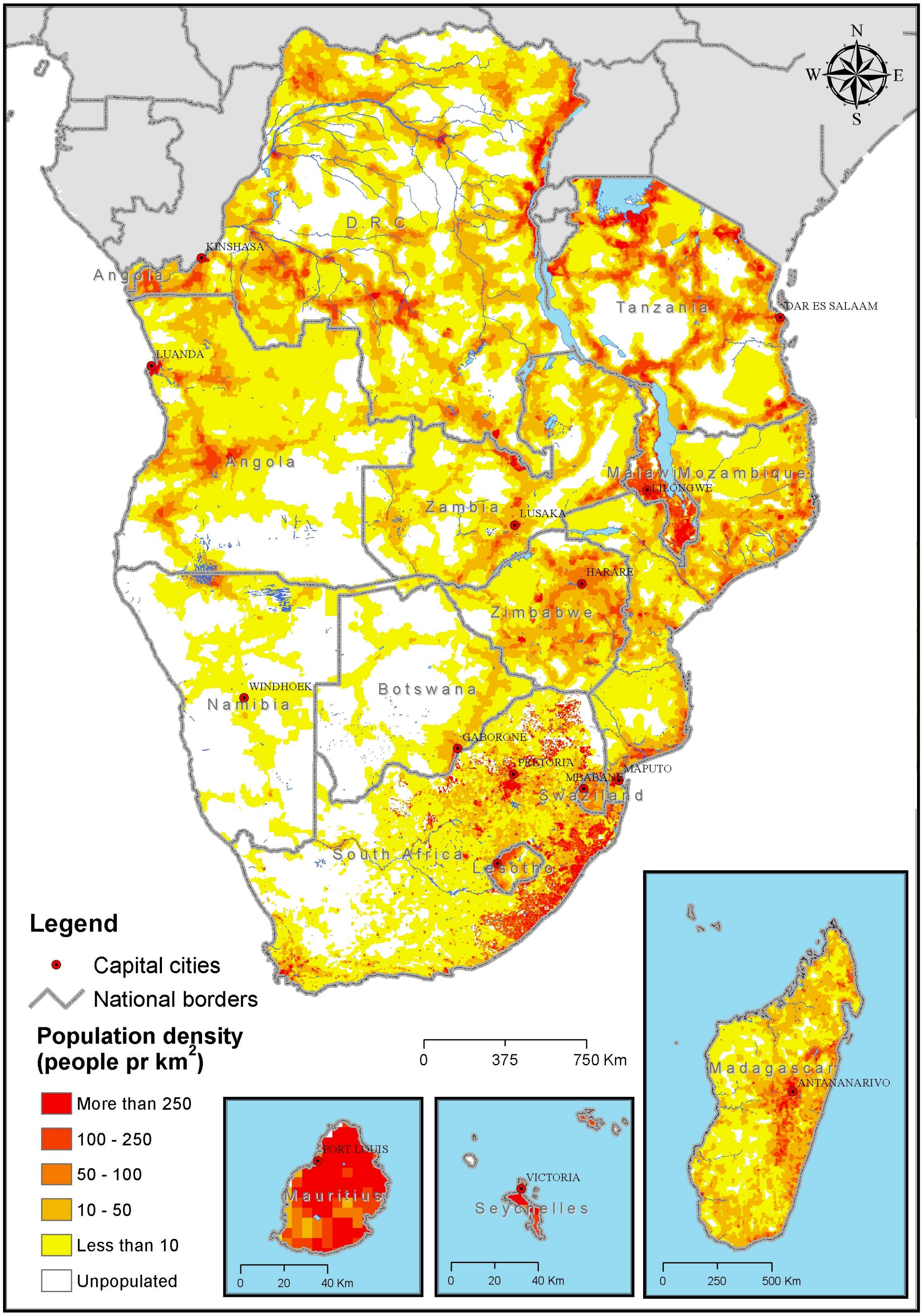
Map 3: Vegetation cover



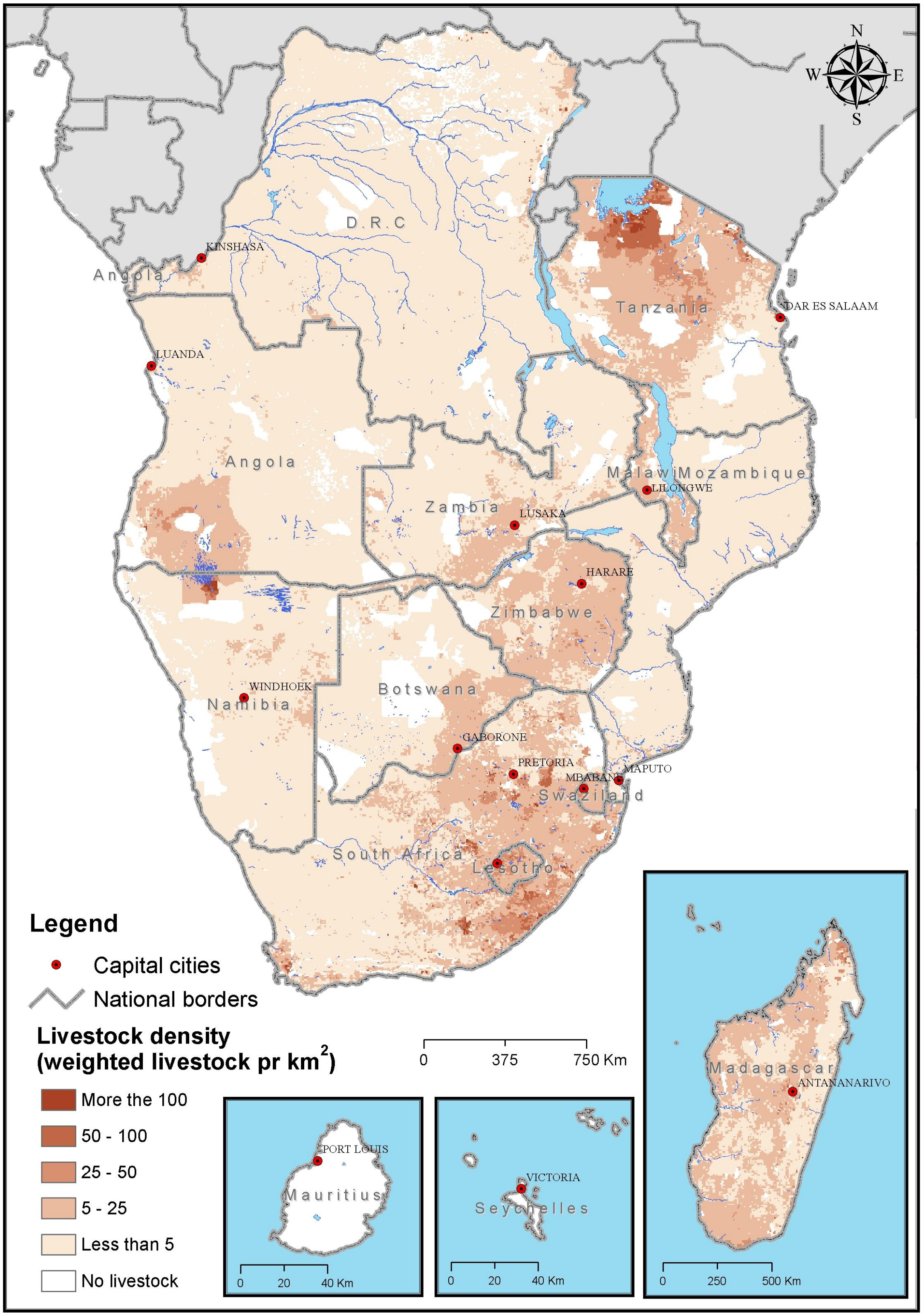
Map 4: Terrain slope



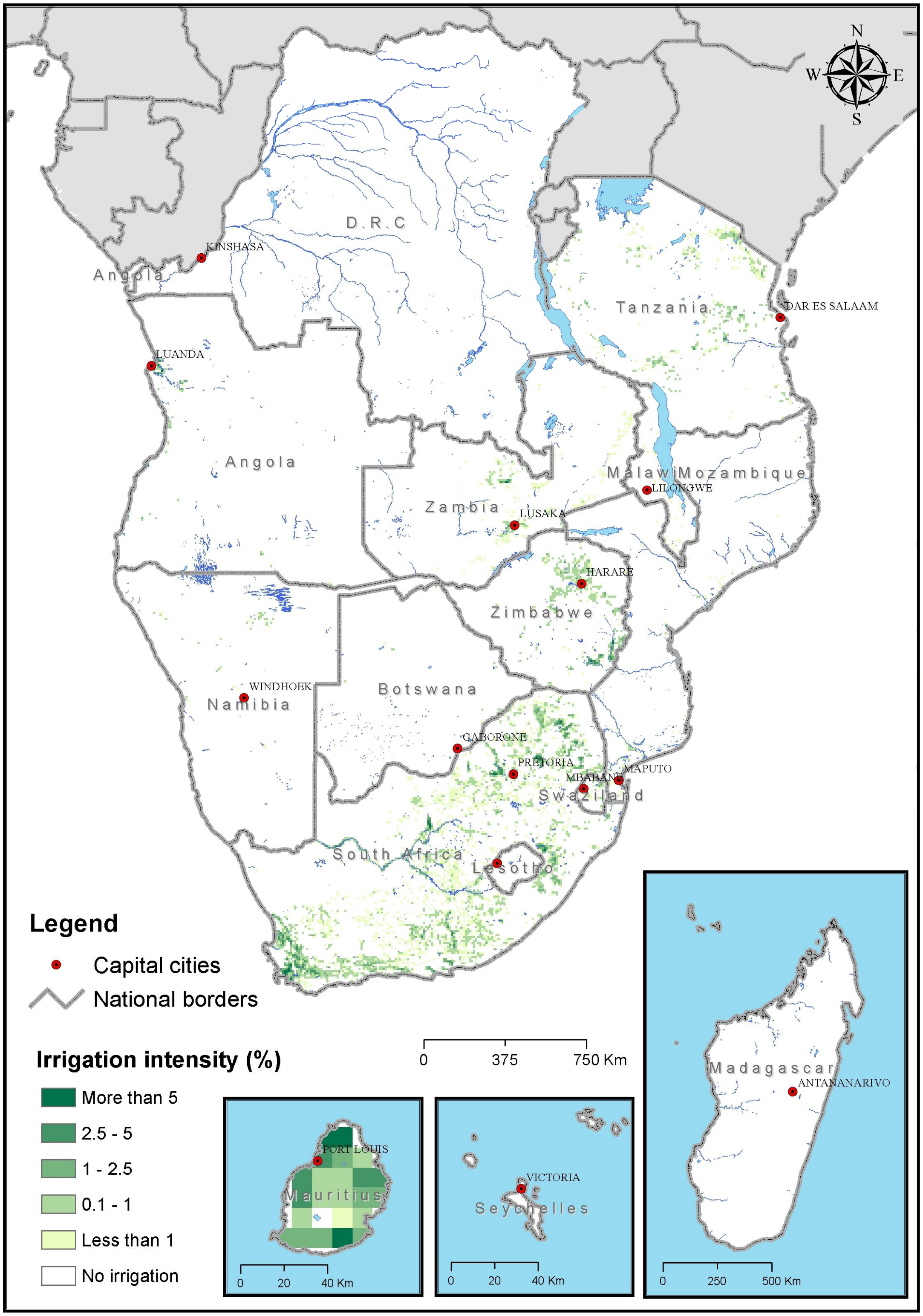
Map 5: Population density



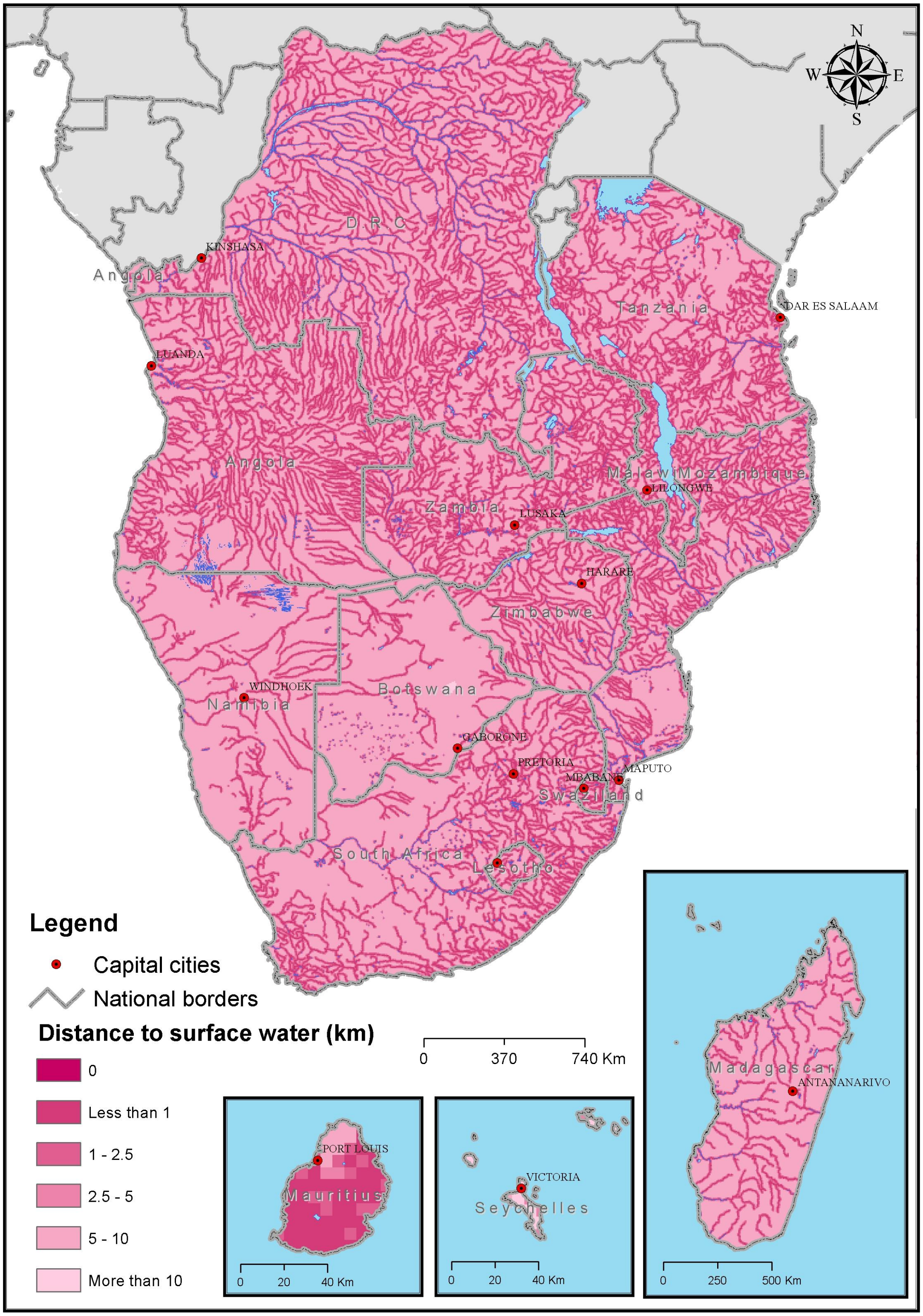
Map 6: Livestock density



Map 7: Irrigation intensity



Map 8: Distance to surface water bodies



The credibility score

The approach for calculating a credibility index is based on a multi-level approach where the credibility of the included data layers is assessed individually on a country-by-country basis (Level 1). The credibility of the individual data layers are then averaged to arrive at an aggregated credibility score for the composite layers of groundwater reliability and human groundwater drought vulnerability (Level 2) and the final ground drought vulnerability map (Level 3) (cf. Figure A1).

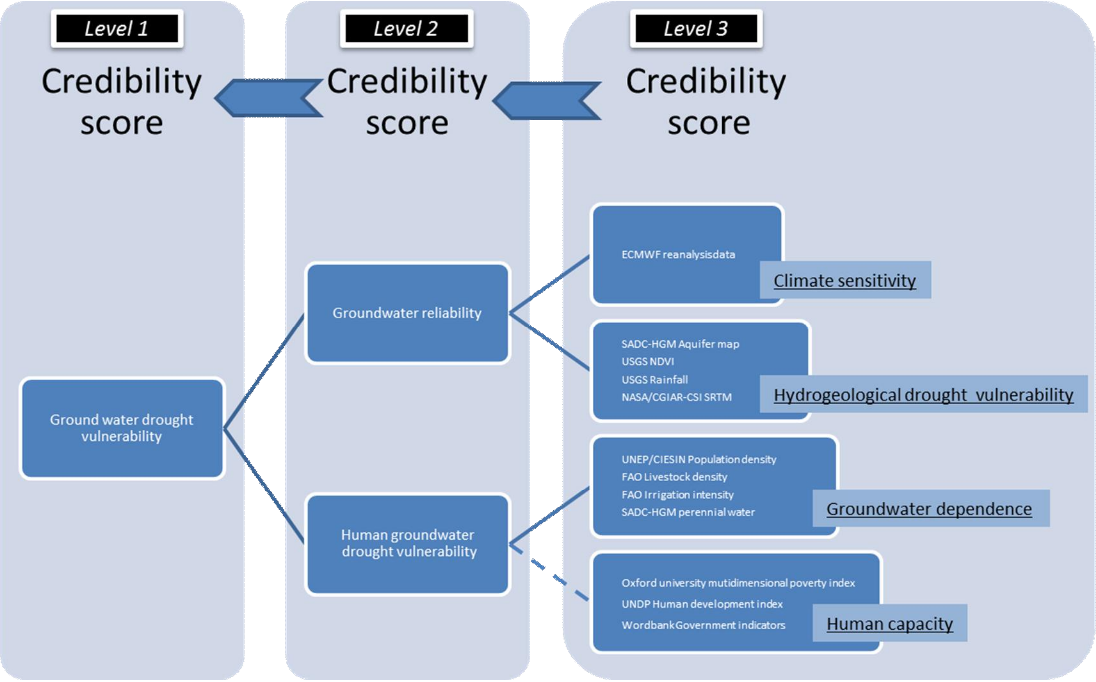


Figure A1. Multi-level approach for calculating the credibility scores for the final groundwater drought vulnerability map.

The credibility of the individual data layers is assessed from associated metadata. In certain cases however, these data have not been at our disposal, why a credibility score has not been calculated. This is for example the case of the SADC HGMA aquifer map and the FAO livestock density layer. In other cases, the data layers are assumed to be equally valid across the SADC region and therefore they are not considered in the calculation of the overall credibility score. Examples of the latter are the satellite derived measures of vegetation density (NDVI), rainfall, and topography used to calculate groundwater recharge. Finally, we do not include the credibility score of human capacity in the Level 2 and 3 calculations, since we do not include human capacity directly in the mapping of groundwater drought vulnerability at the SADC level, but rather we use it as a reference layer for broadly indicating the variation in coping capacities across the SADC member states.

Table A1 shows how the Level 3 scores combine to produce a Level 2 credibility score for the final groundwater drought vulnerability map.

Table A1. Final credibility scores for the calculation of groundwater drought vulnerability*

	LEVEL 2			LEVEL 3	
	GROUNDWATER CREDIBILITY		HUMAN GROUNDWATER DROUGHT VULNERABILITY	CREDIBILITY SCORE	
Country	CLIMATE SENSITIVITY	HYDROGEOLOGICAL DROUGHT VULNERABILITY			
Angola	2	NA/EQ	1	2	Low
Botswana	4	NA/EQ	3	4	High
DRC	1	NA/EQ	3	2	Low
Lesotho	2	NA/EQ	4	3	Medium
Malawi	3	NA/EQ	4	4	High
Mauritius	4	NA/EQ	5	5	Very high
Mozambique	4	NA/EQ	4	4	High
Namibia	4	NA/EQ	4	4	High
Seychelles	3	NA/EQ	5	4	High
South Africa	5	NA/EQ	5	5	Very high
Swaziland	3	NA/EQ	3	3	Medium
Tanzania	3	NA/EQ	2	3	Medium
Zambia	3	NA/EQ	3	3	Medium
Zimbabwe	4	NA/EQ	2	3	Medium

NA/EQ: Means credibility score is not available but Level 3 data layers are assumed to be of equal quality (see text for further information)*

In Table A2 and Table A3 it is shown how the Level 2 scores are calculated on the basis of the Level 3 assessment of individual layers associated with climate sensitivity and groundwater dependence, respectively. In Table A2 it is seen how the credibility score for the estimation of climate sensitivity is based on the amount and credibility of ground weather stations used in the calibration of the ECMWF 'reanalysis' data.

The quality evaluation of the population density map is based on associated metadata (http://na.unep.net/siouxfalls/globalpop/africa/Appendix_2.html). The calculation of the credibility score is based on three indicators i] number of sub-national units, ii] mean size of sub-national units and iii] number of people per sub-national unit. The calculation is constructed so it gives lower credibility when you have large sub-national units covering with a high population count, whereas many or smaller sub-national units with fewer people will result in a higher credibility score.

The credibility score for irrigation intensity is taken directly from the quality assessment of the Global Map of Irrigation Areas. It should be noted, however, that the quality assessment is taken from an earlier version of the Global Map of Irrigation Areas. Still, it is assumed that the previous quality assessment is still representative and in any case no updated quality information were available for the newer version of the Global Map of Irrigation Areas that were used in this project.

Table A2. Assessment of credibility scores for the ECMWF reanalysis data

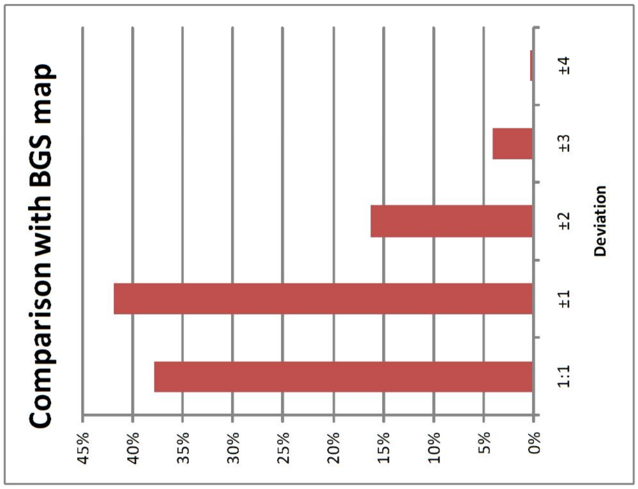
		Credibility score	
Country	**Assessment of ground data availability**	**Value**	**Nominal**
Angola	Observations exist (of "usable" quality), but are not readily	2	Low
Botswana	Adequate	4	High
DRC	Almost no data available	1	Very low
Lesotho	Observations exist (of "usable" quality), but are not readily	2	Low
Malawi	Usable	3	Medium
Mauritius	Adequate	4	High
Mozambique	Adequate	4	High
Namibia	Adequate	4	High
Seychelles	Usable	3	Medium
South Africa	Sufficient	5	Very high
Swaziland	Usable	3	Medium
Tanzania	Usable	3	Medium
Zambia	Usable	3	Medium
Zimbabwe	Adequate	4	High

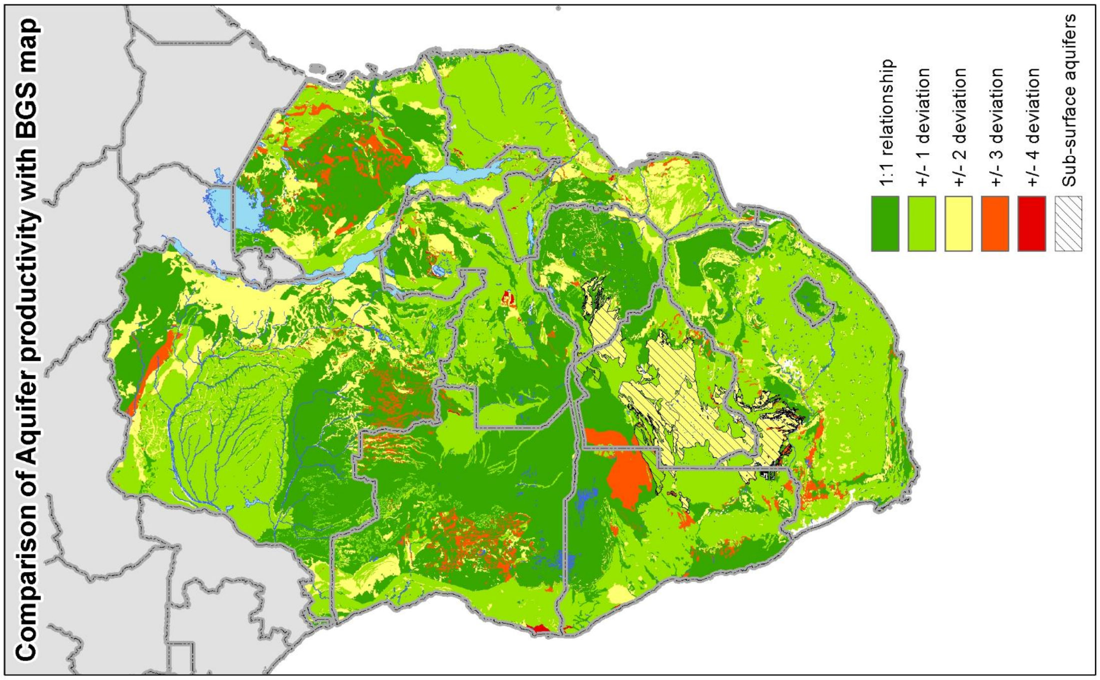
Table A3. Assessment of credibility score for groundwater dependence*

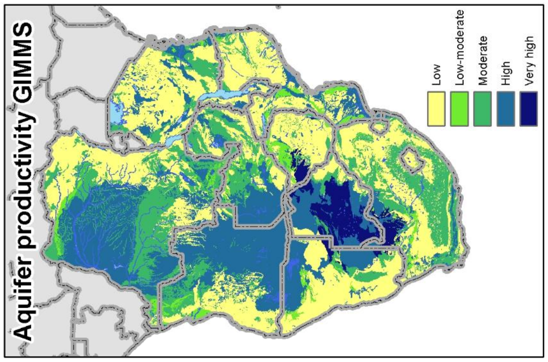
Country	Population density	Livestock density	Irrigation intensity	Distance to surface water	RANK	Credibility score	
						Value	Nominal
Angola	1	NA/EQ	2	1	14	1	Low
Botswana	3	NA/EQ	3	1	9	3	Medium
DRC	2	NA/EQ	4	1	13	3	Medium
Lesotho	4	NA/EQ	4	1	5	4	High
Malawi	5	NA/EQ	3	1	7	4	High
Mauritius	5	NA/EQ	5	1	1	5	Very high
Mozambique	4	NA/EQ	5	1	4	4	High
Namibia	4	NA/EQ	4	1	5	4	High
Seychelles	5	NA/EQ	5	1	1	5	Very high
South Africa	5	NA/EQ	5	1	1	5	Very high
Swaziland	3	NA/EQ	4	1	8	3	Medium
Tanzania	2	NA/EQ	4	1	11	2	Medium
Zambia	3	NA/EQ	3	1	9	3	Medium
Zimbabwe	3	NA/EQ	3	1	12	2	Medium

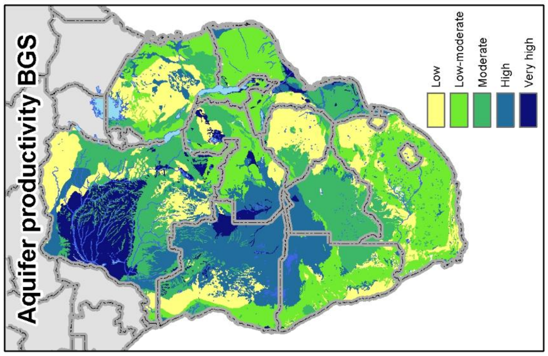
NA/EQ: Means credibility score is not available but Level 3 data layers are assumed to be of equal quality (see text for further information)*

The quality assessment of the irrigation map is based on two indicators i] the availability of sub-national irrigation statistics and ii] the density of geospatial records. The former is used to approximate total irrigated area within sub-national units whereas the latter is used to tie irrigated land to specific locations on the ground (http://www.fao.org/nr/water/aquastat/irrigationmap/index40.stm).


Comparison with BGS map
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
1:1
±1
±2
±3
±4
Deviation


Comparison of Aquifer productivity with BGS map
1:1 relationship
+/- 1 deviation
+/- 2 deviation
+/- 3 deviation
+/- 4 deviation
Sub-surface aquifers


Aquifer productivity GIMMS
Low
Low-moderate
Moderate
High
Very high


Aquifer productivity BGS
Low
Low-moderate
Moderate
High
Very high

Climate sensitivity

The main source of rainfall data was the South African Atlas of Climatology and Agrohydrology (Schulze et al., 2007). The data, in spreadsheet format and in raster grids is supplied on a DVD in the report. The report was compiled by the University of Kwa-Zulu Natal for the Water Research Commission and is readily available from the Water Research Commission. The majority of the rainfall analysis data is available in spreadsheets per quaternary catchment for South Africa. Quaternary catchments are the 4th level hierarchical nested drainage catchments.

Meta data for the GIMMS independent analysis on South Africa are given in Appendix 3.

Rainfall amount

The mean annual rainfall and the monthly rainfall are available per quaternary catchment, based on over 50 years worth of measured station data. The mean daily rainfall was calculated by dividing the mean annual rainfall for the total observation period by the number of days in the year. If the daily average rainfall was greater than 1mm per day, then $P_{ANN} = 0$, else $P_{ANN} = 1$ minus the daily average rainfall.

Length of dry periods

The second term takes into account that the same amount of annual precipitation may be distributed temporally quite differently within the year. In this step, we consider the average length of a potential dry period within a calendar year. The mean monthly precipitation for each quaternary catchment was taken from the South African Atlas of Climatology and Agrohydrology. If the mean monthly rainfall was less than the total days in the month, the month was considered dry. For quaternary catchments, which had 4 or more consecutive dry months (less than 1 mm rain/day) in a calendar year, P_{DRS} was assigned a value of 1. If the quaternary catchment had 3 consecutive dry months, P_{DRS} was assigned a value of 0.5. If there was no dry period longer than 2 months, P_{DRS} was assigned a value of 0.

If the quaternary catchment had a dry period (less than 1 mm/day) for 9 or more consecutive months (within or across calendar years), P_{EXT} was assigned a value of 1. If the mean daily rainfall was less than 1 mm/day for 8 consecutive months, then P_{EXT} was assigned a value of 0.75. P_{EXT} was assigned a value of 0.5 for 7 consecutive dry months and 0.25 for 6 consecutive dry months.

Rainfall variability

The coefficient of variation (CoV) of annual rainfall was used as an indicator for rainfall variability. The CoV can be expressed as:

$$Coefficent\ of\ Variation\ (\%) = 100 \times \frac{Standard\ Deviation}{Abs(mean\ annual\ precipitation)}$$

The CoV as a percentage shows the natural year-to-year variability of rainfall. The higher the CoV is, the more variable the year-to-year (inter-annual) rainfall of a locality is (Schulze et al., 2007). The CoV was calculated using annualised totals of 50 years of daily quality controlled rainfall values (Lynch, 2004 in Schulze et al., 2007). Schulze suggests the rule of thumb proposed by Conrad (1941) from analyses of rainfalls worldwide, that the lower the mean annual precipitation, the higher the inter-annual variability will be. So, areas of low rainfall are doubly worse off because they will additionally suffer from high deviations around their already low average rainfall. The CoV was converted from a percentage to values of P_{STD} between 0 and 1, and used as is, because areas with a higher CoV will be more vulnerable to drought because of the highly inter-annual rainfall.

Estimating meteorological drought risk index

The final step is to weigh these four factors:

$$P_{MET} = 4\ P_{ANN} + 1.5\ P_{DRS} + 1.5\ P_{EXT} + 3\ P_{STD}$$

where P_{MET} is the meteorological drought risk index. P_{MET} was finally divided by 2 in order to give a scale from 0 - 5.

The climate sensitivity for South Africa is shown below.

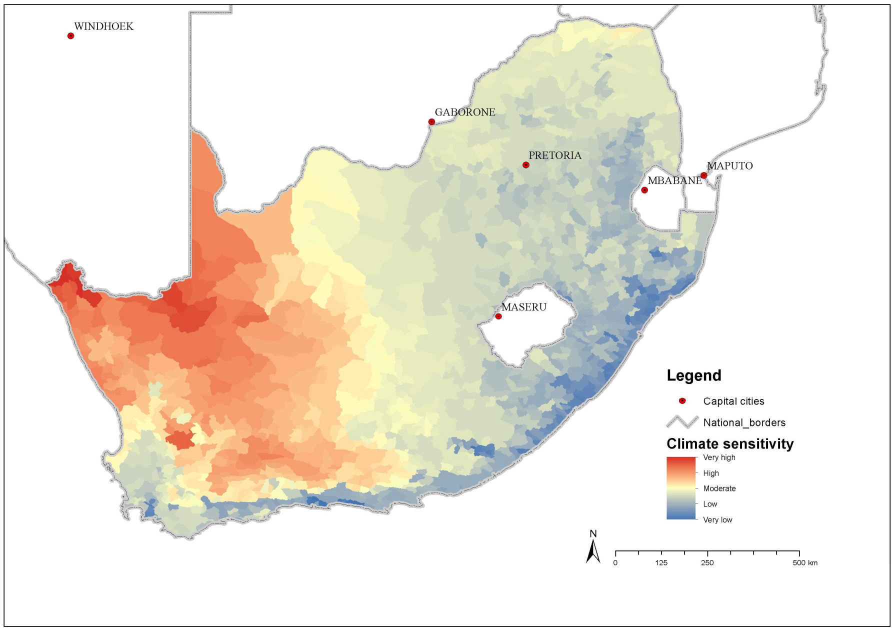


Figure A2. Climate sensitivity for South Africa

Hydrogeological drought proneness

The hydrogeological drought proneness relates to the physical factors influencing drought conditions in groundwater systems. Two main aspects are considered here: aquifer productivity and groundwater recharge potential.

Aquifer productivity

Colvin et al. (2003) developed a hydrogeological terrain classification for South Africa to represent aquifer types important to terrestrial groundwater dependent ecosystems. The hydrogeological terrains were developed by the CSIR from the 1: 1 000 000 Geological Map of South Africa (Council for Geoscience, 1997). Although the classes of the South Africa hydrogeological terrain map are not directly comparable with the SADC HGMA aquifer map, the source data are the same with the hydrogeological terrains being an independent aquifer classification produced by national experts in the groundwater field. The reclassification for the various hydrogeological terrains is shown in the table below.

Hydrogeological terrain	Reclassification[a]
Basement complex and younger granites	1
Extrusives	1
Karoo dykes and sills	1
Carbonate Terrains	2
Fractured metasedimentary	3
Unconsolidated deposits	4

[a] Representing aquifer productivity

The map of aquifer productivity for South Africa is shown below.

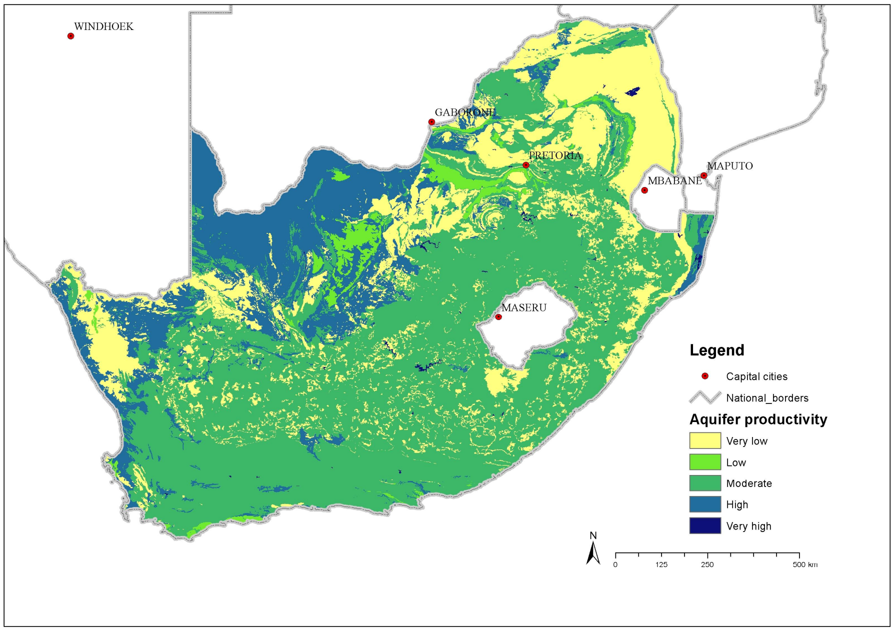


Figure A3. Aquifer productivity for South Africa

Groundwater recharge potential

Groundwater recharge potential was calculated for South Africa using the GIMMS methodology. The Groundwater Resource Assessment Phase II (GRAII) (DWAF, 2005) developed a groundwater recharge map for South Africa, primarily based on the chloride mass balance method. The rasters are available as a 1 minute by 1 minute grid for actual estimated recharge, in mm/y, as well as recharge as a percentage of rainfall. These datasets are the best available data for South Africa and are still used in groundwater reserve determinations across the country. The GRAII data represents an estimate of actual groundwater recharge (Figure A4) compared to the GIMMS calculation of recharge potential (Figure A5).

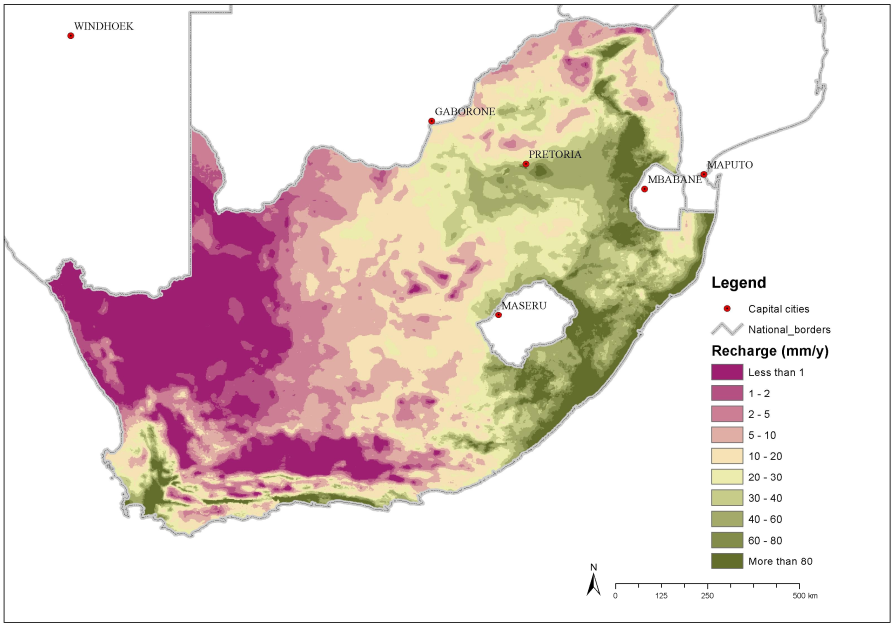


Figure A4. Groundwater recharge map for South Africa, Lesotho and Swaziland. Estimates based on the chloride method (From DWAF, 2005)

Recharge potential for South Africa was calculated using the following recharge indicators, sources, reclassification and weights. The weights used for the South Africa validation exercise are the ones in Scenario 2 (Table 4-1 to Table 4-4).

Recharge indicator	Source	Reclassification		Weight
Precipitation (mm/y)	Mean annual precipitation. South African Atlas of Climatology and Agrohydrology	0 – 100	0	0.5
		100 – 250	1	
		250 – 500	2	
		500 – 1000	3	
		1000 – 1500	4	
		More than 1500	5	
NDVI	MODIS 16 day composite NDVI images from 2000 to 2010	Less than 0	0	0.35
		0 - 0.2	1	
		0.2-0.4	2	
		0.4-0.5	3	
		0.5-0.6	4	
		More than 0.6	5	
Slope (degrees)	SRTM version 4.1 digital elevation model, 1 km by 1 km	0 – 2.5	5	0.15
		2.5 – 5	4	
		5 – 7.5	3	
		7.5 – 10	2	
		More than 10	1	

The map for groundwater recharge potential is shown below.

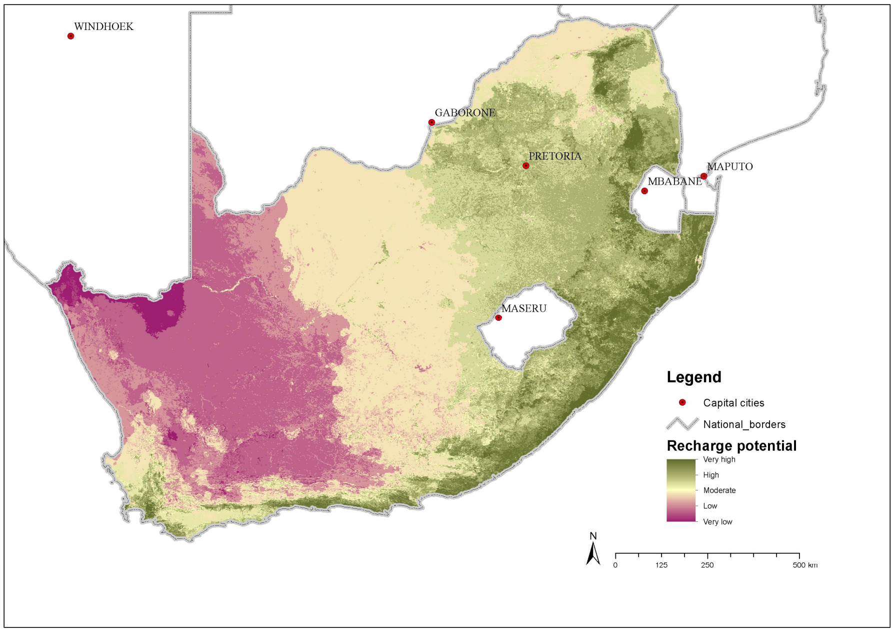


Figure A5. Groundwater recharge potential for South Africa, estimated using the GIMMS methodology

Though the two recharge maps (Figure A4 and Figure A5) have been derived using different methodologies, and one gives absolute values (given in mm per year) whereas the other only a relative potential, the results are quite comparable. This is encouraging for the use of the GIMMS methodology for recharge potential assessment in the rest of the SADC region.

Groundwater reliability

The aggregate map of physical groundwater drought vulnerability, combining hydrogeological drought proneness and climate sensitivity with equal weights, is shown below.

Human groundwater drought vulnerability

Groundwater dependence

In GIMMS, groundwater dependence is represented by thematic layers that depict population density, livestock distribution, and percentage of irrigated land. Furthermore, distance to a perennial surface water source, was used as an indirect measure of groundwater dependence.

Population density

South Africa has reliable population data collected by Statistics South Africa (StatsSA). The population density data come from the Geospatial Analysis Platform (GAP) version 2 (2007) developed by The Presidency, the dti (department of trade and industry) and the CSIR. The source of the population data is Statistics South Africa's Small Areas Layer with the census data being from 2004. The Small Areas Layer is not readily available, but the synthesised GAPII data is readily available. The population density was calculated per mesozone (roughly 50 km^2 or 7 km by 7 km) by dividing the total population of the mesozone by the area of the mesozone. This was converted to a raster of 500 m by 500 m with the pixel value equal to the average population density for that pixel.

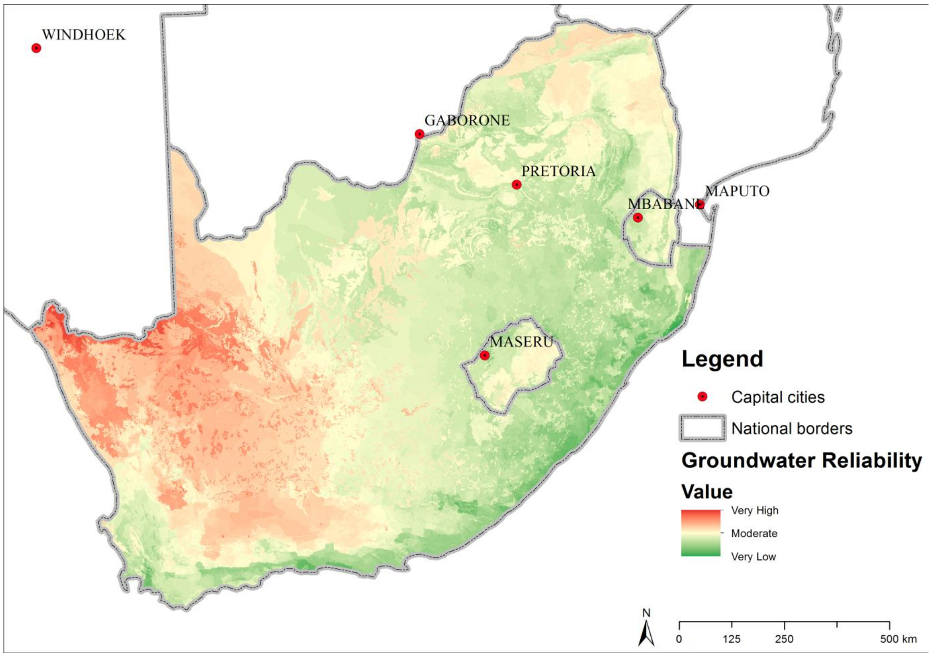


Figure A6. Groundwater reliability for South Africa

Livestock density

Livestock density is currently only available for South Africa on a provincial level. The data was obtained from Statistics South Africa with a date of 1996, although poultry figures could not be readily located for South Africa. The data compared favourably with the gridded livestock from FAO (2007). The livestock density was calculated based on the area of the province. The livestock water requirement was calculated using the following formula:

*LWR = [Cattle*0.5]+[Pigs*0.2]+[Sheep*0.1]+[Goat*0.1]*

Irrigation intensity

In order to calculate irrigation intensity, the South African National Land-Cover 2000 (NLC2000) was used (Van den Berg et al., 2008). The NLC2000 was derived from Landsat imagery from 2000 and is available at a resolution of 30 m by 30 m. There are 49 land cover classes of which 3 were used to calculate irrigation intensity: cultivated, permanent, commercial, irrigated; cultivated, temporary, commercial, irrigated; and cultivated, temporary, subsistence, irrigated. Using focal statistics in ArcGIS, the percentage of irrigated area was calculated for each 500 m by 500 m pixel.

Distance to surface water bodies

The distance to perennial rivers was calculated using the 1: 500 000 Department of Water Affairs river network. Only perennial rivers were used in this calculation as during a drought, non-perennial rivers would not provide a water source. The distance to perennial rivers was calculated for each 500 m by 500 m pixel. A summary of groundwater dependence thematic layers, including data, sources, reclassification and weights are given below.

Groundwater dependence indicator	Source	Reclassification		Weight
Population density (people pr km^2)	GAP2 data taken from Statistics South Africa Small Area Layer for 2004	0	0	0.55
		Less than 10	1	
		10 – 50	2	
		50 – 100	3	
		100 – 250	4	
		More than 250	5	
Livestock density (livestock pr km^2 weighted according to water demands)	Livestock density weighted according to water demands was calculated for each province based on StatsSA from 1996	0	0	0.15
		1 - 5	1	
		5 – 25	2	
		25 – 50	3	
		50 – 100	4	
		More than 100	5	
Irrigation intensity (percentage of total area equipped for irrigation)	Percentage area was calculated from the National Land- cover 2000	0	0	0.15
		Less than 1	1	
		1 – 5	2	
		5 – 10	3	
		10 – 20	4	
		More than 20	5	
Distance to perennial surface water (km)	Perennial rivers from the Department of Water Affairs 1: 500 000 river shapefile	0	0	0.15
		Less than 1	1	
		1 – 2.5	2	
		2.5 – 5	3	
		5 – 10	4	
		More than 10	5	

The groundwater dependence map for South Africa is shown below. Because population density is heavily weighted in this scenario, the highly populated areas stand out in the map. The areas close to perennial water sources are seen to have lower groundwater dependence.

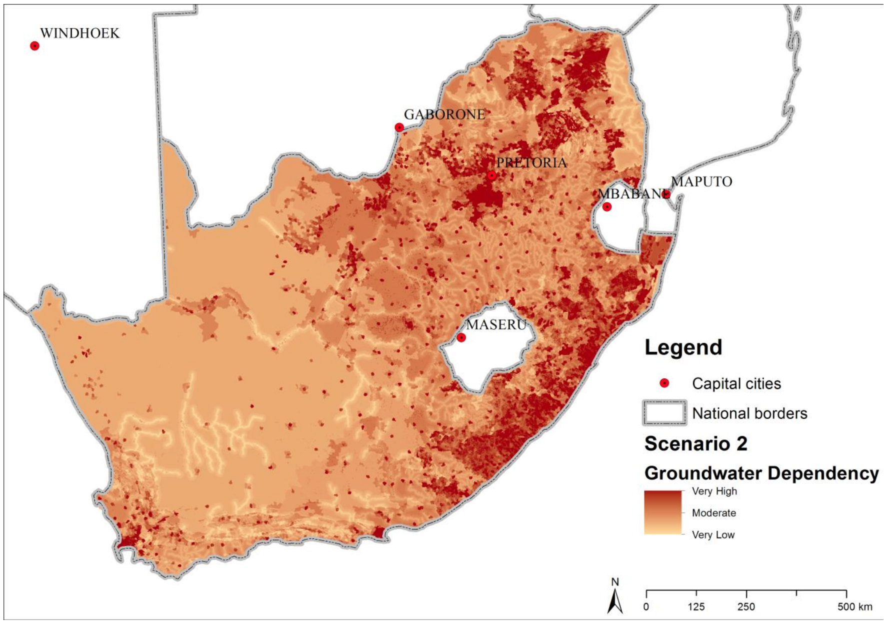


Figure A7. Groundwater dependence for South Africa

References

Colvin C., LE Maitre, D. and Hughes S., 2003. Assessing terrestrial groundwater ecosystems in South Africa, WRC report no. 1090-2/2/0

Conrad, V., 1941. The variability of precipitation. Monthly Weather Review, 69, 5-11. In Schulze, R.E. (Ed). 2007. South African Atlas of Climatology and Agrohydrology. Water Research Commission. Pretoria, RSA, WRC Report 1489/1/06.

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Department of Water Affairs (DWAF), 2005. Groundwater Resource Assessment Phase II. Final Report.

FAO, 2007. Gridded livestock of the world 2007, by G.R.W. Wint and T.P. Robinson. Rome, 131 pp.

Schulze, R.E. (Ed.), 2007. South African Atlas of Climatology and Agrohydrology. Water Research Commission. Pretoria, RSA, WRC Report 1489/1/06.

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SADC Groundwater Drought Vulnerability Map Review

The member states that replied to the review are given in the Table A4 below. In total, 10 out of 14 countries replied.

Table A4. Overview over PSC feedback

Country	Status	Additional material sent
Angola	No feedback	
Botswana	Feedback	
DRC	No feedback	
Lesotho	Feedback	Data and maps of F and NO3
Malawi	Feedback	Areas w. salinity and fluoride
Mauritius	No feedback	
Mozambique	Feedback	
Namibia	Feedback	Report, maps and CDs
Seychelles	Feedback	
Swaziland	No feedback	
South Africa	Feedback	
Tanzania	Feedback	
Zambia	Feedback	
Zimbabwe	Feedback	

The map review has resulted in a few changes to the aquifer productivity map, which again has resulted in a different outcome when compared to the BGS aquifer productivity map. The tables below show summarizes the comparison with BGS before and after map review.

Table A5. Comparison with BGS before map review

Deviation	Count	Percentage
1:1	3080034	37.74%
±1	3417007	41.87%
±2	1322395	16.20%
±3	324770	3.98%
±4	17215	0.21%

Table A6. Comparison with BGS after map review

Deviation	Count	Percentage
1:1	3197824	38.29%
±1	3484551	41.72%
±2	1312557	15.72%
±3	329168	3.94%
±4	28027	0.34%

In the following pages, tables are given country-wise that list the various suggestions for changes (partly based on handwritten corrections on hard-copy maps) and actual changes incorporated in the mops. The overall changes to aquifer productivity are shown in the map on p. 12 of this Appendix.

Botswana

	General comments	Suggestion to change	Final change
1	The city of Jwaneng is wrongly placed	Move city	Jwaneng moved to coordinate **to lat -24.6; lon 24.75**
2		Area	
3			
Specific comments			
	Map 1	***Aquifer Productivity***	***Suggestion to change***
1		Too high AP.	**Remove class 5. Propose to change AP only if comments to GWDV is consistent with comments on AP**
2			
3			
	Map 2	***GW drought vulnerability***	
1		No comments.	
2			
	Map 3a	***Salinity***	
1		Areas too small	Areas expanded
2		Add new area	Area added in the North
3		Area in Kalahari Region in the North should not follow the road	Area increased across border to SA*
	Map 3b	***Nitrate***	
1		Area wrongly placed	Area moved
2			
3			
	Map 3c	***Fluoride***	
1		Area too big	Area decreased
2			
3			

*This should accommodate comments from Eddy as well. In general, check GW areas across border

Lesotho

	General comments	Suggestion to change	Final change
1	Urban GW dep. Too low in three cities	Change from 0-25 to 25-50 %	Completed
2		Change legend names for urban GW dependence to text: low moderate, high	Completed
3			
4			
5			
Specific comments		**Suggestion to change**	**Final change**
	Map 1	***Aquifer Productivity***	
1		Too high AP in southern districts.	Two polygons changed across border to SA from Moderate to low.
2			
3			
	Map 2	***GW drought vulnerability***	
1		No comments	
2			
3			
	Map 3a	***Salinity***	
1		No problems	
2			
3			
	Map 3b	***Nitrate***	
1		Some areas delineated in report provided.	No changes: according to Fig 11 in additional material not really any areas above 20 mg/l
2			
3			
	Map 3c	***Fluoride***	
1		Some areas delineated in report provided.	Areas added according to Fig. 13 in additional material
2			
3			

Malawi

General comments		**Suggestion to change**	**Final change**
1			
2			
3			
4			
5			
Specific comments		**Suggestion to change**	**Final change**
	Map 1	***Aquifer Productivity***	
1		Area in the West too high AP.	No change because there is no comment to GWDV and no polygon to separate out.
2			
3			
	Map 2	***GW drought vulnerability***	
1		No comments	
2			
3			
	Map 3a	***Salinity***	
1		Few areas delineated	New areas added Note: data sheet provided gives coordinates in local system. Data cannot be used.
2			
3			
	Map 3b	***Nitrate***	
1		No problems	
2			
3			
	Map 3c	Fluoride	
1		Few areas delineated	New areas added

Mozambique

	General comments	Suggestion to change	Final change
1	City of mhlume is placed wrongly inside Mozambique.	Check and move or remove.	Mhlume is a town of Swaziland. The map viewing scale makes it looks like being in Mozambique. No change
2	Name of city Garue Garué is wrong (see nitrate map)	Check and correct name	Name corrected to Gurué (wikipedia)
3			
4			
5			
Specific comments			
	Map 1	***Aquifer Productivity***	
1		Areas along border to SA too high AP	AP decreased for some polygons
2			
3			
	Map 2	***GW drought vulnerability***	
1		Area on the border to SA has too low GWDV	Consistent with AP. Means that GWDV should change accordingly
2			
3			
	Map 3a	***Salinity***	
1		Salinity area needed to the West.	New area added
2		Area along coast only susceptible, not affected, by salinity	Area along coast has been removed
3			
	Map 3b	***Nitrate***	
1		Comment on nitrate in sub-urban areas	No change. Comment should be included in report on this issue
2			
3			
	Map 3c	***Fluoride***	
1		Area close to Teté and Moatize missing	New area added

Namibia

General comments		**Suggestion to change**	**Final change**
1		The scale and pixel format of the map doesn't give the right picture	Note it is a regional map so there are limitations regarding the level of detail that can be provided. As for AP the map can be produced on the basis of a vector layer which gives a smoother surface, but as for GWDV the results is based on an aggregation of raster layers some with 50x50 km cells (climate) and some with 1x1 km cells (topography).
2			
Specific comments			
	Map 1	***Aquifer Productivity***	
1		East North East of Gobabis should have low to very low productivity.	Not possible the correct since it will affect a major area i.e a single a major polygon in the SADCHGM aquifer map.
2		Area east of Mariental has artesian aquifers of very high potential	We have to decide whether to account for multiple aquifers. See also comment on Class 5 for AP under Botswana. No change since we use ñVery High Potentialòonly for multiple aquifers then the area east of Mariental will remain as high productivity.
3		Part of area in the North has low potential and GW often brakish to saline	Salinity will appear from the overlay WQ maps. Hence, no change in AP has been made.
4		West flowing ephemeral rivers have alluvial aquifers with good productivity and should be clearly marked as they are very important in an area with general low GW potential	No change in AP in this area. However, non-perennial rivers has been included as part of the distance to surface water algorithm implying that GWDV will be less for these areas.
	Map 2	GW drought vulnerability	
1		All coastal areas with GW-dep. towns should have high GWDV.	GW-dependence due to cities will only be depicted by red dots. Color of areas around dots not influenced by existence of a city. Do not make any changes to GWDV here.
2		Karst aquifers should be low to moderate GWDV	Areas marked as karst in HGMA also come out as either low or moderate GWDV. Do not make changes
3		Area in the North (Oshakati) should have low GWDV because GW is not used due to salinity	Now, GWDV is high due to high population density and hence, high GW dependence. Propose not to change this (cannot be captured in our algorithm) as the salinity overlay will capture poor GWQ in this area and in consequence, high GW insecurity.
4		East of Mariental, unconfined aquifers should have high GWDV while deeper aquifers should be low.	Change depends on decision under comment 2 above.
	Map 3a	Salinity	
1		See HYNAM.	Areas added according to HYNAM
2			
3			
	Map 3b	Nitrate	
1		No comments	Areas added according to Tredoux et al.
2			
	Map 3c	Fluoride	
1		No comments	Areas added according to old map

Seychelles

General comments		**Suggestion to change**	**Final change**
1			
2			
3			
4			
5			
Specific comments			
	Map 1	***Aquifer Productivity***	
1		No comments	
2			
3			
	Map 2	***GW drought vulnerability***	
1		No comments	
2			
3			
	Map 3a	***Salinity***	
1		No comments	
2			
3			
	Map 3b	***Nitrate***	
1		No comments	
2			
3			
	Map 3c	***Fluoride***	
1		No comments	
2			
3			

South Africa

General comments		Suggestion to change	Final change
1		You should consider smoothing of cells.	Note it is a regional map so there are limitations regarding the level of detail that can be provided. As for AP the map can be produced on the basis of a vector layer which gives a smoother surface, but as for GWDV the results is based on an aggregation of raster layers some with 50x50 km cells (climate) and some with 1x1 km cells (topography).
2		Areas across border to Namibia and Botswana should be consistent with respect to GWQ (salinity, nitrate and fluoride)	This has been corrected whenever possible!
Specific comments			
	Map 1	***Aquifer Productivity***	
1		AP in Kalahari (North Western part) is low to very low.	AP changed for three marked polygons
2		Karst/limestone/dolomite aquifers (two pink areas in Map 1B) should be high AP.	AP changed for two areas
3		Table Mountain Aquifers in the South have high AP.	AP changed from low/moderate to high
	Map 2	***GW drought vulnerability***	
1		Remove towns: Tembisa, Benoni, Brakpan, Krugersdorp, Boksburg, Vanderbiilpark, Alberton	Towns have been removed
2	*	Add other towns in rural areas for which data on GW dep. are given (i.e. Upington, Beaufort West, Springbok, Vryburg, Kuruman, Polokwane, Graaf Reinet, Queenstown, Unitata, Mbombela)	New towns have been added
3		GWDV is too low in Botswana (Kalahari Pans). Should be higher due to very infrequent recharge (once every 10 years).	No change. GWDV is low because Groundwater dependence is low and GW reliability is moderate.
	Map 3a	***Salinity***	
1		The coastal aquifer salinity (marked already) is probably POTENTIAL	Polygon along coast has been removed
2		With reference to DWAF GRA2	New areas has been added : 1 along west coast and two in Northeast
	Map 3b	***Nitrate***	
1		Area in the North should stretch into Botswana	Have included Nitrate Map from Tredoux et al. 2001 which add areas in SA, Namibia and Botswana
2			
3			
	Map 3c	***Fluoride***	
1		Small area included west of Pretoria	Area has been added
2		Fluoride also a problem across border into Botswana and Namibia	No information available on this from Botswana. Hence, no change despite the unrealistic/abrupt switch right at the borders. The border to Namibia has been corrected!
3		With reference to DWAF GRA2	Area in northwest has been expanded

Tanzania

General comments		**Suggestion to change**	**Final change**
1		Roads between Tabora, Shinyanga and Mwanza are missing	No change. Roads are taken as base layer from SADCHGM which is not for us to change
2			
Specific comments			
	Map 1	***Aquifer Productivity***	
1		Suggestions to change most of the classification for Tanzania.	Keep as is because comments not consistent with GWDV comments, except for area around Mbeya. Here AP has been changed from low to moderate.
2			
3			
	Map 2	***GW drought vulnerability***	
1		Area around Mbeya should have low GWDV.	Should be (partially) compensated by the change in AP from low to moderate
2		Urban GW dep. for Shinyanga should be changed to red (50-100%).	Has been changed
3		Urban GW dep. for Arusha should be changed to yellow (25-50%).	Has been changed
	Map 3a	***Salinity***	
1		Two areas along Rift valley in the West, two areas in central Tanzania and one along the coast with salinity problems have been added.	Four areas has been be added. The area along the coast should not be added as it more likely indicates risk more than actual measurements
2			
3			
	Map 3b	***Nitrate***	
1		Two areas are mentioned as areas with Nitrate problems: North of Masai Steppe and in the Southern Highlands. Only the former is marked on the map	Area in North has been added. According to Wikipedia The Tanzania Southern Highlands refers to the region encompassing the four provinces of Iringa, Mbeya, Rukwa and Ruvuma - > due to the size of this area no area has been added!
2			
3			
	Map 3c	***Fluoride***	
1		Two areas are marked as having fluoride problems	Areas have been added
2			
3			

Zambia

General comments		Suggestion to change	Final change
1		The town of Kasanshi should read Solwezi	Name has been changed
2			
3			
4			
5			
Specific comments			
	Map 1	***Aquifer Productivity***	
1		Lusaka has high productivity	AP changed from low/moderate to high[a]
2			
3			
	Map 2	***GW drought vulnerability***	
1		No comments	
2			
3			
	Map 3a	***Salinity***	
1		No comments	
2			
3			
	Map 3b	***Nitrate***	
1		No comments	
2			
3			
	Map 3c	***Fluoride***	
1		No comments	
2			
3			

a. Considered only in database map but yet to be incorporated in aquifer productivity map (and rest of GIMMS maps) due to late submission

Zimbabwe

General comments		**Suggestion to change**	**Final change**
1		Cities of Mutare and Ruwa	No problem. Labels are displaced due to viewing scale.
2		Cities of Marondera and Rusape are on top of each other. Should be +/- 100 km apart.	No problem. Labels are displaced due to viewing scale.
3			
Specific comments			
	Map 1	***Aquifer Productivity***	
1		Area Notheast of Chiredzi should have higher AP	AP has been changed
2		Area Close to Chinhoyi should be very high	AP has been changed
3		Northwestern part should be low instead of moderate AP	AP has been changed
	Map 2	***GW drought vulnerability***	
1		Comments on distribution on GWDV	Comments not contradictory to map, except on border to Malawi. Check reason for large gradient in GWDV across border - > More people, more livesotock, less green and higher slopes (i.e. less recharge) on Zimbabwe side!
2			
3			
	Map 3a	***Salinity***	
1		Area around Gokwe has sodium problems, not salinity	Area has been removed
2		Two areas in the North have salinity problems	Areas have been added
3			
	Map 3b	***Nitrate***	
1		No comments	
2			
3			
	Map 3c	***Fluoride***	
1		Two areas, north of Gokwe and Karoi have high fluoride concentration	Areas have been added

PSC review of GIMMS maps

Appendix 9