Integrated mapping of groundwater drought risk in the Southern African Development Community (SADC) region

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Abstract Groundwater drought denotes the condition and hazard during a prolonged meteorological drought when groundwater resources decline and become unavailable or inaccessible for human use. Groundwater drought risk refers to the combined physical risk and human vulnerability associated with diminished groundwater availability and access during drought. An integrated management support tool, GRiMMS, is presented, for the mapping and assessment of relative groundwater drought risk in the Southern African Development Community (SADC) region. Based on composite mapping analysis of region-wide gridded relative indices of meteorological drought risk, hydrogeological drought proneness and human groundwater drought vulnerability, the mapping results highlight consistent areas across the region with highest groundwater drought risk and populations in the order of 39 million at risk of groundwater drought at present. Projective climate-model results suggest a potentially significant negative impact of climate change on groundwater drought risk. The tool provides a means for further attention to the key, but neglected, role of groundwater in drought management in Africa.

Keywords Groundwater drought · Risk mapping · Africa · Geographic information systems · Climate change

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Introduction

Groundwater plays a critical role in the Southern African Development Community (SADC) region (Angola, Botswana, Democratic Republic of the Congo (DRC), Lesotho, Malawi, Mauritius, Mozambique, Namibia, Seychelles, South Africa, Swaziland, Tanzania, Zambia, and Zimbabwe), especially in arid and semi-arid areas, where it provides relatively drought-proof water supply for domestic as well as productive uses (livestock, agriculture, mining, tourism, etc.). It is estimated that 70 % of SADC population depends on groundwater (SADC 2012). However, groundwater systems and the sources of supply and populations dependent on them may be susceptible to harm during and as a result of prolonged drought. Most vulnerable to such harm are the rural dispersed communities in these regions because of their often unilateral and life-depending reliance on groundwater and groundwater-fed systems for all uses. Drought resilience in SADC, hence, is strongly linked to secure groundwater access and a proper development and management of this resource.

However, and not commensurate with these facts, little attention is paid to proper groundwater management in this region, and, in this context, particularly sound integration of groundwater into drought management. Groundwater development takes place with insufficient attention to drought resistance (of access structures and aquifers), and drought management is governed by ad-hoc responsive emergency measures, like well deepening and new development (Calow et al. 1997, 2009). This should be seen against a backdrop of already poor basic water-supply coverage and a high degree of malfunctioning of existing groundwater access structures. It is officially estimated that still 40 % of SADC population does not have proper access to drinking water and relies on insecure sources, like poor-quality surface water or

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unprotected wells and dug-outs (SADC 2012). Furey and Danert (2012) show that more than 30 % of rural domestic wells in Africa do not function at any given time. At the same time, standard drought risk monitoring and warning systems do not account for the drought mitigating potential of groundwater (Mendecino et al. 2008).

The term groundwater drought (GWD) was first coined by Rutulis (1987) and later elaborated by Calow et al. (1997) with particular reference to the African context. They suggested the need for a conceptual framework for integrated (human and physical) GWD vulnerability mapping and, subsequently, such maps have been developed for Ethiopia (MacDonald et al. 2009a; Calow et al. 2002). The physical interpretation of GWD relates to the impacts of a meteorological drought on groundwater systems. Absence of rain firstly affects groundwater recharge, and subsequently groundwater storage and discharge. Depending on size and characteristics of these systems, impacts may lag significantly after the meteorological drought (Calow et al. 1997; Rutulis 1987). This propagation of impacts through the hydrological system (Peters et al. 2003), which progressively affects deeper and larger aquifer systems, implies that groundwater may be used as a drought mitigation measure during early stages of a drought. However, it also implies that GWD may occur during later stages of a prolonged drought (months to years) and that impacts may be felt even after the meteorological drought has passed and normal drought mitigation measures have ceased (Calow et al. 1997). The most critical manifestation of a GWD is often the decline in phreatic groundwater levels (Mishra and Singh 2010), which typically hampers access via shallow wells and springs even before significant storage depletion occurs. The implication of propagation of drought through the groundwater system further entails that long-term trends in climate change and variability, as manifested through, e.g., decreases in net precipitation, will accumulate and imprint on groundwater resources over long time scales, an aspect which needs further research to understand the phenomenon of GWD and links between climate change and groundwater resources. MacDonald et al. (2009a) estimate that 90 million people in rural Africa are at risk of losing access to their groundwater-based water supplies, if climate change implies decreases in recharge in low rainfall areas, where groundwater is most heavily depended on. Hence, there is a need for increased efforts and capacity for integrated groundwater and drought management, which includes better knowledge of the physical functionality and susceptibility of aquifer systems to drought and climate change, better planning and targeting of groundwater development, and maintenance and rehabilitation of access points for drought-resistant water supply. It also entails assessment of human vulnerability to drought, with specific reference to groundwater reliance, and incorporation of groundwater in monitoring and drought warning systems.

Partially addressing these needs, a spatial analysis tool, GRiMMS (Groundwater Drought Risk Mapping and Management System) has been developed for the mapping and integrated management of groundwater and drought in the SADC region. A relative measure, or indicator, of overall groundwater drought risk (GWDR), including the physical risk as well as the human vulnerability, is mapped. Reflecting this holistic view, GWD is here defined as: a situation when groundwater resources decline below long-term average conditions due to meteorological drought causing failure in availability and access for human use.

The SADC GRiMMS tool extends the approach of MacDonald et al. (2009a) and Calow et al. (2002) by incorporating meteorological drought risk as an external component of the physical GWD risk thereby obtaining an integral measure of the risk of a hazard related to GWD of the integrated human-physical system (Lavell et al. 2012; Füssel 2005). Vulnerability is here considered independent of the physical event (Lavell et al. 2012). Furthermore, GRiMMS targets a regional scale in order to promote and facilitate regional and transboundary decision-making and collaboration on groundwater and drought management. Finally, a preliminary assessment of the effects of climate change on GWDR is made.

Methodology

GRiMMS derives and depicts GWDR on the basis of relative indicators, using a composite mapping analysis technique (Hassan et al. 2003; Lowry et al. 1995) in a traditional geographic information system (GIS) environment (ArcGIS). Separate thematic layers showing different factors influencing GWDR (through indicators given for the entire SADC region at a certain resolution) are superimposed and mathematically combined through a simple linear algorithm and an associated weighting scheme for the relative importance of the various factors to derive a spatially distributed measure of GWDR across the SADC region. A schematic diagram showing the components and thematic layers included in the model is shown in Fig. 1.

The scheme consists of two modules of which the first (to the left in Fig. 1) represents the physical aspects of GWDR, through the meteorological drought risk and the hydrogeological drought proneness. The second pillar represents the human GWD vulnerability and is a function of the human dependence on groundwater and the human capacity to manage groundwater. Combining the physical risk and the human vulnerability produces the required composite GWDR.

The combined algorithm for calculating GWDR (G) is (see Fig. 1 for notation):

$$G = w_\mathrm{p} P + w_\mathrm{v} V \tag{1}$$

$$P = w_\mathrm{M} M + w_\mathrm{H} H \tag{2}$$

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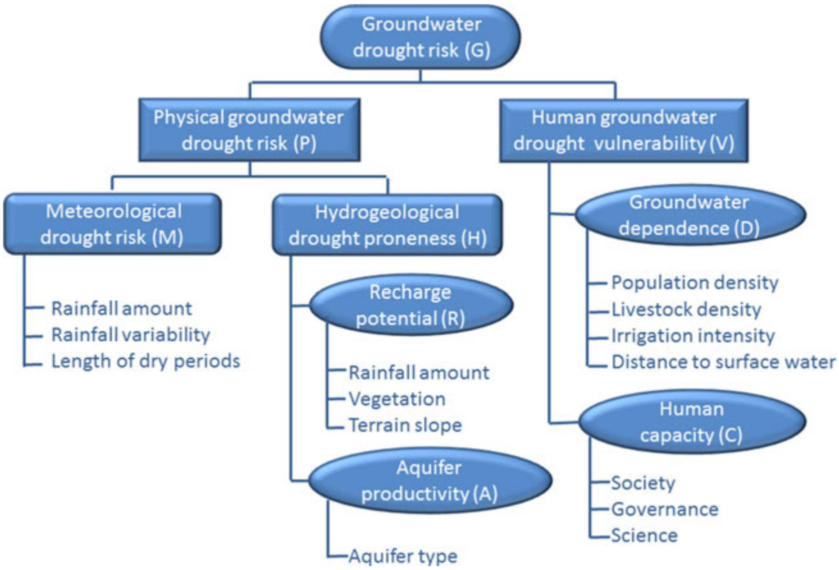

Fig. 1 Schematic diagram of the governing thematic layers entering the composite mapping analysis and resulting aggregated layers in GRiMMS

$$M = 5(0.4f_{\mathrm{ANN}} + 0.15f_{\mathrm{DRS}} + 0.15f_{\mathrm{EXT}} + 0.3f_{\mathrm{CoV}}) \tag{3}$$

$$H = v_{\mathrm{R}}(5 - R) + v_{\mathrm{A}}(5 - A) = v_{\mathrm{R}}\left(5 - \sum_{i=1}^{n} w_{\mathrm{i}} r_{\mathrm{i}}\right) + v_{\mathrm{a}}(5 - A) \tag{4}$$

$$V = v_{\mathrm{D}} D + v_{\mathrm{C}}(5 - C) = v_{\mathrm{D}} \sum_{j=1}^{m} w_{\mathrm{j}} d_{\mathrm{j}} + v_{\mathrm{c}}\left(5 - \sum_{k=1}^{l} w_{\mathrm{k}} c_{\mathrm{k}}\right) \tag{5}$$

subject to the following:

$$w_{\mathrm{P}} + w_{\mathrm{V}} = 1.0 \tag{6}$$

$$w_{\mathrm{M}} + w_{\mathrm{H}} = 1.0 \tag{7}$$

$$v_{\mathrm{R}} + v_{\mathrm{A}} = 1.0 \tag{8}$$

$$v_{\mathrm{D}} + v_{\mathrm{C}} = 1.0 \tag{9}$$

$$\sum_{i=1}^{n} w_{\mathrm{i}} = 1.0 \tag{10}$$

$$\sum_{j=1}^{m} w_{\mathrm{j}} = 1.0 \tag{11}$$

$$\sum_{k=1}^{l} w_{\mathrm{k}} = 1.0 \tag{12}$$

where M, H and V represent the modules for‘ meteorological drought risk’, ‘hydrogeological drought proneness’ and ‘human groundwater drought vulnerability’, respectively; P and G integrates these modules into ‘physical groundwater drought risk’ and the final ‘groundwater drought risk’, respectively; R, A, D, C are the sub-modules for ‘recharge potential’, ‘aquifer productivity’, ‘groundwater dependence’, and ‘human capacity’, respectively; n, m, and l are the numbers of variables (or layers) (i, j, k) in each sub-module of R, D, and C; w_{i}, w_{j}, and w_{k} are the micro-level weights given to each parameter in each sub-module; v_{R}, v_{A}, and v_{D}, v_{C} are intermediate weights between R and A, and D and C, respectively; and finally w_{M} and w_{H} share the macro-level weights between M and H, and w_{P} and w_{V} between P and V. The calculation and parameters of M will be discussed separately (see section “Meteorological drought risk”). Before entering the algorithm, each variable, within the maximum span of values, was reclassified to interval-scaled figures and projected onto a numeric continuous scale of 1–5, reflecting the relationship between the variable and the impact on GWDR. The resultant GWDR, the weighted mean of the variables, was reclassified to a numerical scale from 1 to 5 for mapping on a gradual scale, while each spatial unit was classified on an ordinal scale (by rounding values to integers) from 1 to 5, representing ‘very low’, ‘low’, ‘moderate’, ‘high’ and ‘very high’ risk, respectively to produce statistics on distribution of classes.

Data sources for the mapping exercise consisted of readily available extracts of global datasets, SADC-level mapping of hydrogeological conditions (SADC 2009a), and model climatic data used to derive meteorological drought risk. Meta-data are given in Table 1. Though national datasets also exist, the global datasets were considered adequate, given the large scale of analysis, while also representing the best available consistent datasets for the region. The data came in various spatial resolutions but were all transposed onto a common grid with a 10-km resolution. This resolution is considered as being a reasonable compromise between the finer and coarser input dataset resolutions (cf. Table 1). For testing of GRiMMS, independent data from South Africa were used (see section "Testing of GRiMMS with independent data"). The mapping covers the 14 present SADC countries, as well as Madagascar, which was suspended from the community due to political instability in 2009 (Ploch 2011). In the following, a short description is given of the various components of GRiMMS, the data entry and analysis carried out.

Physical groundwater drought risk

The physical GWD risk combines the risk of meteorological drought and the inherent hydrogeological proneness to drought. The hydrogeological drought proneness is associated with the potential for groundwater recharge and the intrinsic aquifer productivity.

Meteorological drought risk

A relative meteorological drought risk index (M), as an indicator of the frequency and intensity of drought, was calculated for the SADC region, using the global ERA-Interim reanalysis precipitation data from the European Centre for Medium Range Weather Forecast (ECMWF) in Reading, UK. In order to allow for a comparison with more traditional observation-based analyses, the study was restricted to precipitation as the most significant parameter for drought. It was noted that factors such as temperature and evapotranspiration are also important (Seneviratne et al. 2012) though less spatially variable over the SADC region. ERA-Interim is produced with the ECMWF Integrated Forecast System (IFS) release Cy31r2, which incorporates fully coupled components for atmosphere, land surface, and oceans. The reanalysis is produced by conducting sequential forecast steps where a model-based "first guess" in each step is (slightly) modified with observed data by means of a four-dimensional (spatio-temporal) data assimilation procedure (Dee et al. 2011). In the context of this paper, this implies that the resulting analysis is entirely model-based if no observations are available, as is the case for large parts of sub-Saharan Africa. It is therefore crucial that the forecast model has a realistic climatology, which has been demonstrated for several regions of the earth, including the tropics and Africa (Sylla et al. 2010; Trenberth et al. 2010; Uppala et al. 2008; Bengtsson et al. 2007; Dee 2005). The aggregated ERA-Interim dataset consists of gridded precipitation values on a daily basis, covering the 20-year period 1989 to 2008.

An aggregate meteorological drought risk index, M, is calculated (Eq. 3), which takes into account the long-term average rainfall (f_{ANN}), the length of dry periods within (f_{DRS}) and between calendar years (f_{EXT}), and the variability of rainfall (f_{CoV}). f_{ANN} is a measure of average

Table 1 Meta-data for data used in GRiMMS

Data set	Description	Spatial/temporal resolution	Reference period	Source
Meteorological drought risk				
Meteorological drought risk index	ERA[a]-interim reanalysis precipitation	0.78° (~80 km)/6-hourly	1989–2008	ECMWF[b]
Hydrogeological drought proneness				
Aquifer productivity	Based on maps of lithology and aquifer type	–	2009	SADC-HGMA[c]
Rainfall	Mean annual rainfall	8 km	1996–2008	USGS[d]
Vegetation	The long-term mean annual NDVI[e]	8 km	1983–2003	USGS[d]
Terrain slope	SRTM[f] digital elevation model	1 km	v4.1	CGIAR-CSI[g]
Human groundwater drought vulnerability				
Population density	Gridded population data	2.5 arc-minute (~4 km)	2000	UNEP/CIESIN[h]
Livestock density	Gridded livestock data	3 arc-minute (~5 km)	2005	FAO[i]
Irrigation intensity	Intensity of groundwater irrigated land	5 arc-minute (~8 km)	2000	FAO[j]
Access to surface water	Distance to surface water	10 km	2009	SADC-HGMA[c]

[a] *ERA* European Centre for Medium-Range Weather Forecasts (ECMWF) re-analysis

[b] ECMWF (2008)

[c] SADC-HGMA (2010)

[d] *USGS* US Geological Survey (2012). Tucker et al. (2005) (NDVI), Xie and Arkin (1997) (Rainfall)

[e] *NDVI* Normalised Difference Vegetation Index

[f] *SRTM* Shuttle Radar Topography Mission

[g] *CGIAR-CSI* Consultative Group on International Agricultural Research-Consortium for Spatial Information. Jarvis et al. (2008)

[h] UNEP/CIESIN (2005)

[i] *FAO* Food and Agriculture Organization of the United Nations. Wint and Robinson (2007)

[j] FAO. Siebert et al. (2010)

annual precipitation, and attains a value of 0 if the mean daily precipitation over the 20-year period ($Precip_{\mathrm{mean}}$) is larger than 1 mm (no drought) and a value of $1- Precip_{\mathrm{mean}}$, if the mean is less than 1 mm. Since the most prominent quasi-periodicity in precipitation is annual, f_{DRS} is a measure of dry periods within calendar years; it is 1 if the longest consecutive dry period within any calendar year within the observation period is larger than or equal to 4 months, 0 if it is smaller than or equal to 2 months and linear in between. f_{EXT}, as a measure of longer inter-annual dry spells, is 1 if the longest consecutive dry period within the observation period is larger than or equal to 9 months, 0 if it smaller than or equal to 5 months and linear in between. Finally, f_{CoV}, as a measure of rainfall variability, is the coefficient of variation of the annual rainfall. A dry day in this context is defined as a day with precipitation less than 1 mm (Seneviratne et al. 2012). This may seem a large threshold, but results in good agreement with observations, since a grid cell is representative of a large area, roughly 6,000 km^2.

By this approach, the lack of precipitation, irrespective of the temporal distribution, is weighted by 40 %, the variability is weighted by 30 %, and the temporal extent of dry periods, divided into the two equally important subgroups of shorter and longer dry periods, is weighted by 30 % as well. The maximum possible value of M is 5, and the minimum is 0. A major difference between conventional drought analyses based on point observations and reanalyses, respectively, is the different spatial scales. Since the focus here is on long-term precipitation anomalies, measures and weights of drought were chosen that are meaningful for the regional climatology and in the 'model world' of a spatial scale of a few thousand square kilometres.

Hydrogeological drought proneness

A very important determining factor in GWDR is the capacity of the subsurface, or the aquifers, to produce water. Here, this is determined from a combination of recharge potential (R) and the inherent aquifer productivity (A). All areas are assumed to be underlain by 'aquifers', though this may be stretching the traditional view or definition, which considers only fairly voluminous and transmissive subsurface water-holding geological units as aquifers.

Recharge occurs in a distributed sense due to direct infiltration from net rainfall. In semi-arid and arid areas, recharge may also be governed by focused water entry, from ephemeral water bodies (Favreau et al. 2009; Scanlon et al. 2006), partially as a result of low-frequency, high-intensity rain events characteristic of these regions, implying that recharge is not a simple function of long-term rainfall amounts (van Wyk et al. 2011; Owor et al. 2009). These mechanisms are not included in the estimation of relative groundwater recharge potential due to lack of rainfall data with high spatial and temporal resolution. However, recharge from ephemeral water bodies is partially and indirectly included in the human groundwater dependence, as the component of GWDR determined by this module increases with the distance from surface-water bodies (permanent and ephemeral) reflecting less recharge with distance from water bodies (see section "Human groundwater dependence"). Episodic recharge is partly compensated for by using a relatively lower threshold for the annual rainfall below which recharge is assumed to be negligible (Table 2). This value is typically assumed to be 200–400 mm/year (Xu and Beekman 2003), while here it is 100 mm/year. Estimating recharge potential solely on the basis of an isohyetal approach, however, would be too simplistic as other factors influence the recharge potential, including vegetation/land use/land cover, topography, and soil properties. In the present approach, vegetation (and through that indirectly soil properties) and topography are considered, in addition to the long-term average annual rainfall. It is assumed that good vegetation cover—as given by a high long-term average Normalized Difference Vegetation Index (NDVI; Pettorelli et al. 2005)—enhances infiltration (Yeh et al. 2009) and hence recharge, while poor vegetation cover impedes recharge and enhances surface runoff. Topography, or rather terrain slope, influences recharge through the differentiated distribution of net rainfall between overland flow and soil infiltration. A high slope implies less recharge (Yeh et al. 2009; Döll and Fiedler 2008). Table 2 gives the reclassification and weighting scheme used for determining the relative influence of the factors considered in the recharge potential estimation.

The relative aquifer productivity is based on the SADC lithology map and the associated SADC hydrogeology map (SADC 2009a). The lithology map depicts the

Table 2 Reclassification scheme and weights in the base scenario for recharge factors

Recharge factor, r_i	Reclassification [a]		Weight
Precipitation (mm/year)	<100	0[b]	0.5
	100–249	1	
	250–499	2	
	500–999	3	
	1,000–1,499	4	
	≥1,500	5	
NDVI[c]	<0.1.99	1	0.35
	0. 2–0.39	2	
	0.4–0.49	3	
	0.5–0.59	4	
	≥0.6	5	
Slope (degrees)	<2.49	5	0.15
	2.5–4.99	4	
	5–7.49	3	
	7.5–9.99	2	
	≥10	1	

[a] Reclassification relates to recharge potential, which is inverted in Eq. (4) to obtain factor of drought risk

[b] A threshold for recharge occurrence at rainfall above 100 mm/year is assumed (Cavé et al., 2003)

[c] The NDVI has a value over land between 0 and 1. The index is close to zero over non-vegetated areas while it approaches 1 over densely vegetated areas

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, schist, phyllite, amphibolite; dolomite and limestone; unconsolidated sands and gravel; clay, clayey loam, mud, silt, marl). These have been re-classified into aquifer types, according to flow regime and permeability of the formations based on evaluation of borehole data and expert judgement (SADC 2009a). The following four aquifer types have been defined based on flow regime: unconsolidated intergranular aquifers, fissured aquifers, karst aquifers, and low permeability formations (SADC 2009a).

For the purpose of mapping aquifer productivity in the present mapping exercise, and obtaining an interval-scaled variable, five classes and a ranking based on the SADC (2009a) classification scheme have been defined. In addition, areas with significant regional multi-layered aquifers (unconfined aquifers overlying confined aquifers), as is the case in the Kalahari/Karoo aquifer system shared between Botswana, Namibia and South Africa, have been considered. The ranking has been done from 1 to 5 (low to high productivity): 1 is given to aquifers denoted 'low permeability', 2 to aquifers denoted 'karst', 3 to 'fissured', and 4 to 'unconsolidated intergranular' aquifers. To account for aquifers with additional storage from multi-layered 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 multi-layered 'unconsolidated intergranular' aquifers.

Human vulnerability

The human part of GWDR is conceived as a combination of groundwater dependence and capacity for groundwater and drought management among the populations living in SADC.

Human groundwater dependence

Groundwater demand in SADC is primarily governed by dispersed use for domestic purposes, livestock, and irrigation. Consequently, the human groundwater dependence in the algorithm is reflected by simple indices for population and livestock density and irrigation intensity (Table 3). Higher population and livestock densities imply higher GWDR as more individuals essentially have to share the same resource. Population density also reflects human exposure, an essential component of human vulnerability (Dilley et al. 2005). Likewise, greater reliance on groundwater irrigation also signifies higher GWDR. It can be argued that availability of groundwater irrigation infrastructure may increase drought resilience (O'Brien et al. 2004); however, under prolonged GWD, such areas may be considered particularly vulnerable. The latest available gridded data for the three factors were applied. Firstly, for the population density, the data take into account assumptions on population distribution along traffic corridors and urban centers when transforming data from irregularly shaped census or administrative units into a regular shaped raster grid (Balk et al. 2006). Secondly, for the livestock density, water demand by animal count was estimated using spatially disaggregated sub–national statistical data (Wint and Robinson 2007) and a weighting scheme reflecting the relative water demands of different livestock (cattle, buffalo, sheep, goats, pigs and poultry/chicken; Pallas 1986). Thirdly, for the irrigation intensity, the part of the disaggregated data pertaining to groundwater irrigation, as opposed to surface water, were applied (Siebert et al. 2010). Lastly, human groundwater dependence was considered higher in areas with lack of alternative freshwater sources, expressed as correlated positively with the distance to surface water (perennial and non-perennial).

Human capacity for groundwater and drought management

Human capacity for drought preparedness associated with groundwater reliance depends on individual as well as societal knowledge and ability to survey hydrogeological conditions as well as to mitigate hazards of GWD. In general, in rural parts of sub-Saharan Africa, there is a disconnect between deep-rooted indigenous knowledge at the local level for coping with drought and top-down formalized national-level management systems for drought, water resources and water supply (van Koppen et al. 2007; Nyong et al. 2007), though little particular focus has been devoted to the groundwater aspects of this (Calow et al. 2009). For the purpose of mapping human capacity for groundwater and drought management in GRiMMS, emphasis is on the formal capacity for which more information is available, while acknowledging that integration and strengthening of technological, administrative, and informal knowledge are needed to address present and future GWDR.

Applying the generalized paradigm of a trialogue for groundwater governance by Turton et al. (2006), this study distinguishes between three parts of human capacity for groundwater and drought management: society, science, and government, representing general societal development, technological competence, and formal governance capacity, respectively. Individual indices for these are defined, determined, weighted and aggregated into a joint index. A measure of poverty is chosen to represent 'society', a measure of education level to represent 'science', and finally a measure of accountability for 'governance'. However, since distributed data at subnational level on such parameters are unavailable for most SADC nations, this part of the human vulnerability was left out in the SADC level mapping.

To illustrate the distributed applicability of this approach, however, and because of better data coverage, a national GWDR map for South Africa, including human capacity, was developed. The deprivation index from the

Table 3 Reclassification scheme and weights in base scenario for groundwater dependence factors

Groundwater dependence factor, d_j	Reclassification[a]		Weight
Population density (people per km^2)	0	0	0.55
	1–9	1	
	10–49	2	
	50–99	3	
	100–249	4	
	≥250	5	
Livestock density (weighted according to water use of different livestock) (animals per km^2)	0	0	0.15
	1–4	1	
	5–24	2	
	25–49	3	
	50–99	4	
	≥100	5	
Irrigation intensity (percentage of total area equipped for groundwater irrigation)	0	0	0.15
	0.01–0.099	1	
	0.1–0.99	2	
	1.0–2.49	3	
	2.5–4.99	4	
	≥5.0	5	
Distance to surface water (km)	0	0	0.15
	0.01–0.99	1	
	1.0–2.49	2	
	2.5–4.99	3	
	5.0–9.99	4	
	≥10.0	5	

[a] Zero indicate areas where there is no dependence on groundwater

Health Systems Trust's District Health Barometer (DHB) was used as an indicator of poverty and a surrogate for the societal capacity component of human capacity (Table 4). 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 socio-economic and health variables. The deprivation index, given as a decimal number on a scale from 1 to 5, reflecting low to high deprivation, was simply reversed to obtain a measure of capacity, i.e. districts with a high deprivation index have a lower capacity than districts with a low deprivation index. Scientific capacity was represented by, and positively correlated with, the parameter for number of graduates of higher level education as a percentage of the total population from Statistics South Africa data on local municipal level, based on the 2007 community census data, where higher level education is defined as any tertiary education (university degree or Technikon diploma). The "number of graduates of higher level education" was reclassified to capacity, using determined thresholds: 0–1.99 %=1, 2–3.99 %=2, 4–5.99 %=3, 6–7.99 %=4, and ≥8 %=5. Finally, government capacity was represented by outcomes of 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 through monitoring and auditing government or semi-government institutions entrusted with public money (Auditor-General South Africa 2009). The Auditor-General produces annual audit reports for all government departments, public entities, municipalities and public institutions. An index based on the Auditor-General results from the fiscal year 2008–2009 (Auditor-General South Africa 2009) was developed and used as an indicator of local government efficiency (Table 5). Unqualified audit reports (with no matters arising), also known as a "clean audit", were given to municipalities that are administratively and financially well governed, with no irregular expenditure, thus scoring a value of 5, which makes them less vulnerable as a result of higher governance capacity. Local governments, which receive a disclaimer on the audit or fail to submit adequate documentation for an audit are seen as being the most vulnerable as a result of corruption, mismanagement, or poor governance, thus scoring a value of 1 in terms of capacity.

Impact of climate change

Future climate change, as a potential aggravating factor to GWDR, was accounted for in GRiMMS through the impact on meteorological drought risk, adopting changes in precipitation as projected by the regional climate model HIRHAM5 developed at the Danish Meteorological Institute (Lucas-Picher et al. 2012; Christensen et al. 2007). The model is run on the CORDEX domain, which comprises all of Africa, with a horizontal grid mesh width of 0.44° (~50 km) (Mariotti et al. 2011). HIRHAM5 is driven by the coupled global climate model ECHAM5/MPI-OM1 (Roeckner et al. 2006), which was run for the period 1950–2100. For the first 50 years, observed concentrations of greenhouse gases were used, whereas the IPCC SRES A1B scenario (Nakicenovic and Swart 2000) was applied from 2000 onward. This scenario is described by rapid economic growth, a global population of 9 billion by 2050 and a balanced emphasis on fossil and non-fossil energy sources. Initially, model outputs of precipitation time series for the period 1989–2008 were

Table 4 Meta-data for data used in testing and verifying GRiMMS for South Africa

Data set	Description	Resolution	Reference period	Source
Meteorological drought risk				
Meteorological drought risk index	Monthly observed precipitation	Quaternary catchment[a]	+50 years	WRC[b]
Hydrogeological drought proneness				
Aquifer productivity	Based on hydrogeological terrains of South Africa	1:1,000,000	1997	WRC[c]
Rainfall	Long-term mean annual rainfall	1.5 km	+50 years	WRC[a]
Vegetation	The long-term mean NDVI	250 m	2000–2010	USGS[d]
Terrain slope	SRTM Digital Elevation Model, v4.1	1 km		CGIAR-CSI[e]
Human groundwater drought vulnerability				
Population density	Gridded population data	Mesozone[f] (~50 km^2)	2004	CSIR[g]
Livestock density	Gridded livestock data	Provincial	1996	Statistics South Africa[h]
Irrigation intensity	Intensity of groundwater irrigated land	30 m	2000	ARC[i]
Access to surface water	Distance to surface water	1: 500,000	2010	DWAF[j]
Human capacity				
Society	Deprivation Index - District Health Barometer	District municipality[k]	2001	Health Systems Trust[l]
Science	Higher education level	Local municipality	2007	Statistics South Africa[m]
Government	Consolidated general report on the local government audit outcomes 2008–2009	Local municipality	2009	AuditorGeneral[n]

[a] Quaternary catchments are the 4th level nested drainage catchments for South Africa as defined by the Department of Water Affairs. South Africa has 22 primary catchments, 148 secondary catchments, 278 tertiary catchments and 1947 quaternary catchments, which have an average size of 650 km^2

[b] *WRC* Water Research Commission. Schulze (2007)

[c] WRC. Colvin et al. (2003)

[d] USGS (2011)

[e] *CGIAR-CSI* Consultative Group on International Agricultural Research-Consortium for Spatial Information. Jarvis et al. (2008)

[f] Mesozones are a set of irregular geoframes, which are nested within important administrative boundaries (local municipalities). They are roughly 7 km × 7 km or 50 km^2 in area and irregular in shape. This is the finest level at which population data are available for South Africa

[g] *CSIR* Council for Scientific and Industrial Research (2013). Naudé et al. (2007)

[h] Statistics South Africa Agricultural Survey (2012)

[i] *ARC* Agricultural Research Council. Van den Berg et al. (2008)

[j] *DWAF* Department of Water Affairs and Forestry (2006)

[k] South Africa has 9 provinces, 52 district municipalities and 257 local municipalities

[l] Day et al. (2010)

[m] Statistics South Africa (2007)

[n] Auditor-General South Africa (2009)

converted to meteorological drought risk (estimated as described previously). A comparison with drought risk, based on reanalysis-based precipitation fields (Fig. 2), showed good results (data not shown). Subsequently, future meteorological drought risk was calculated for the 20-year period 2080–2099.

Table 5 Auditor-General results applied and translated into a GRiMMS score for the governance component of human capacity at municipal level for South Africa

Auditor-General results	Human capacity score on governance
Unqualified audit report (with no matters: clean audit	5
Financially unqualified (with other matters): financially clean	4
Qualified	3
Adverse	2
Disclaimer or not submitted	1
No data available	3[a]

[a] For some local municipalities, no data were available in the Auditor-General report. These are municipalities where the result of the audit was not completed at the time that the report was published. As a result, these municipalities were given an index of 3 (centre value) to avoid bias in the composite analysis

Results

Figure 2 shows the resulting distribution of meteorological drought risk for the SADC region. The result is comparable to previous drought risk mapping for Africa (Dai 2011; Sylla et al. 2010; Eriyagama et al. 2009). However, as opposed to others that apply only observational data to calculate drought indices (Dai 2011; Eriyagama et al. 2009), the current approach has the advantage of applying a regional climate model incorporating observed climate data, to ensure consistency, physical soundness, and full coverage of the region. Figures 3 and 4 show the regional aquifer-productivity map and the composite recharge-potential map, respectively. Finally, Fig. 5 illustrates the aggregate map for human groundwater dependence. It is

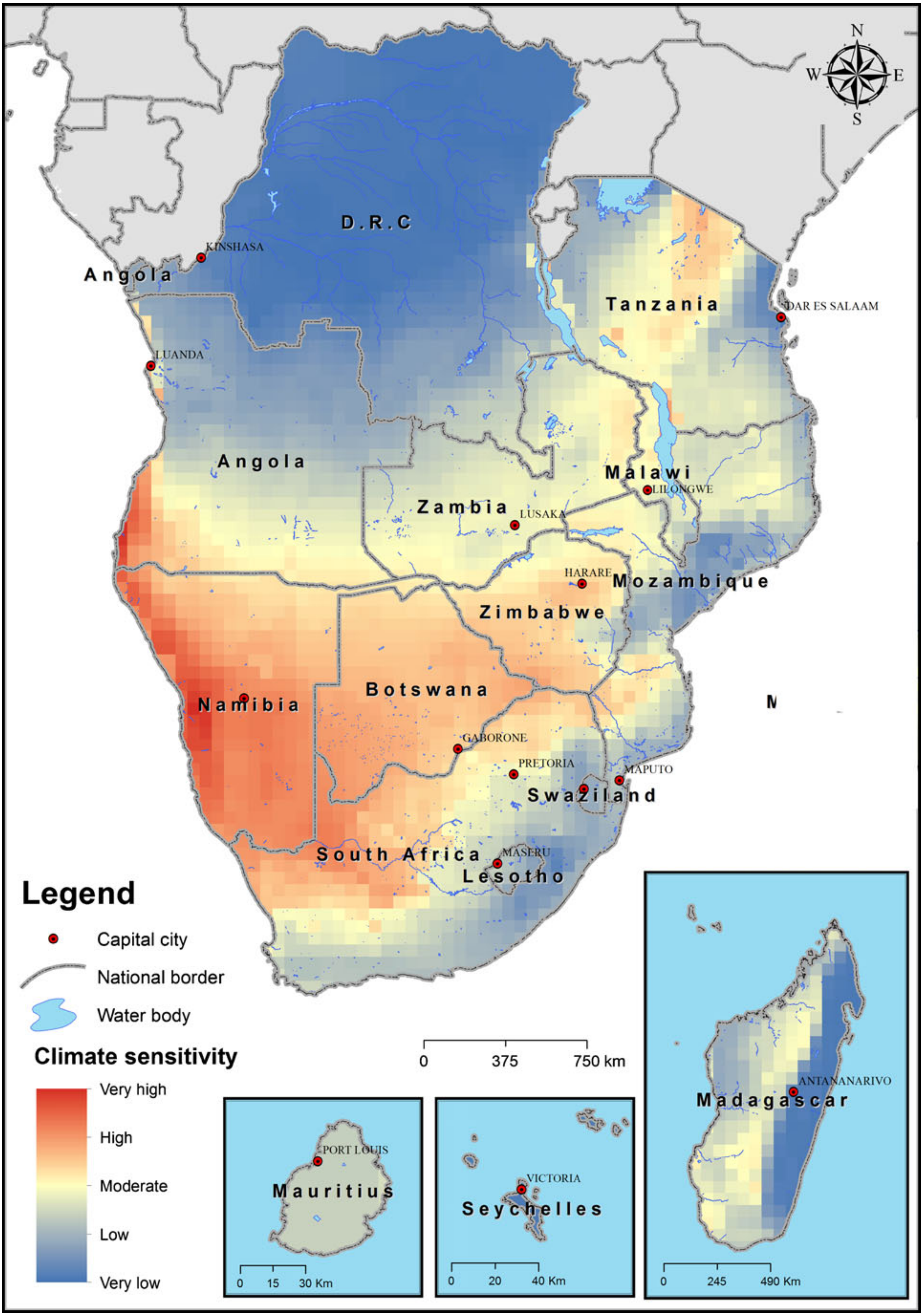

Fig. 2 Meteorological drought risk

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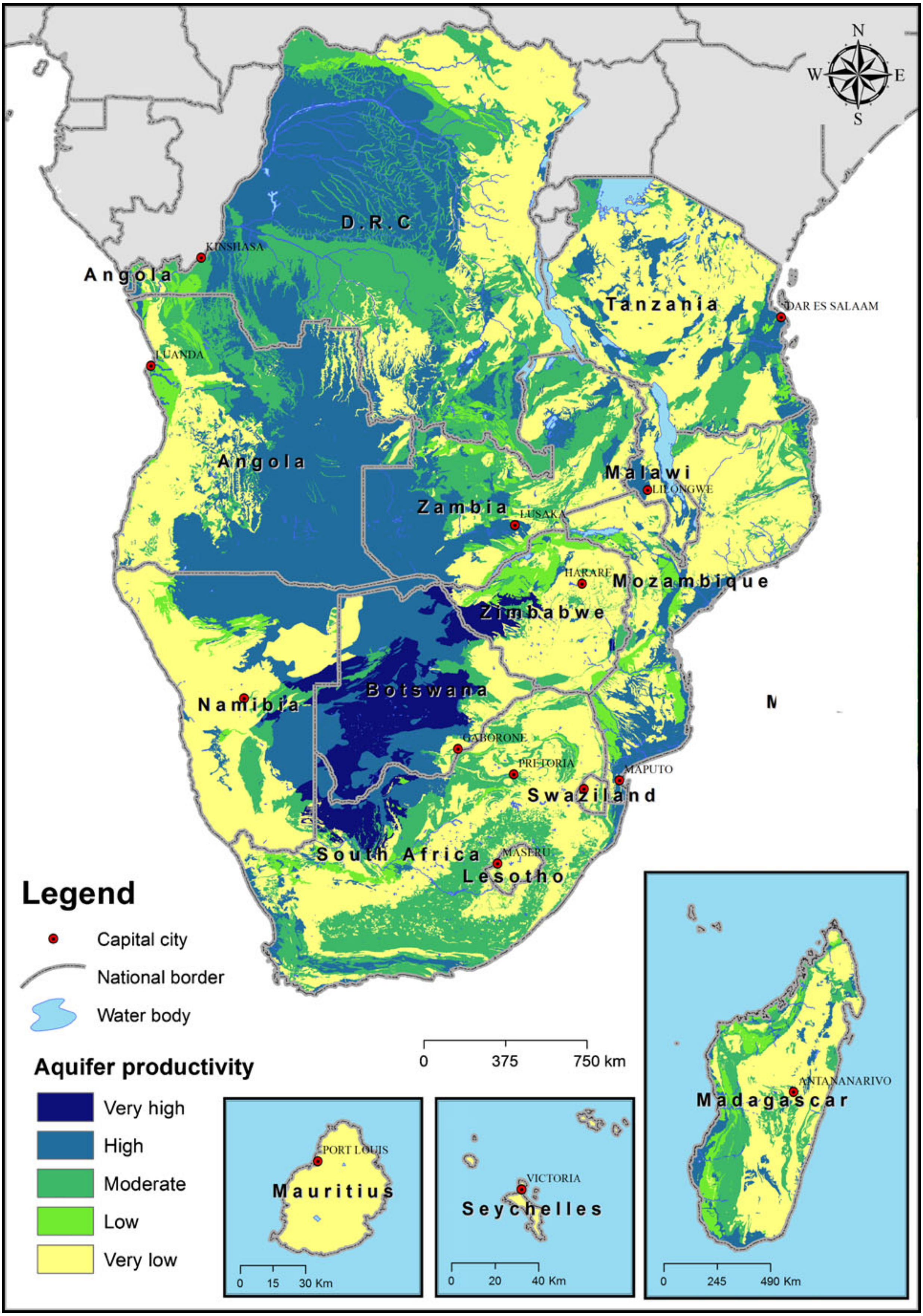

Fig. 3 Aquifer productivity

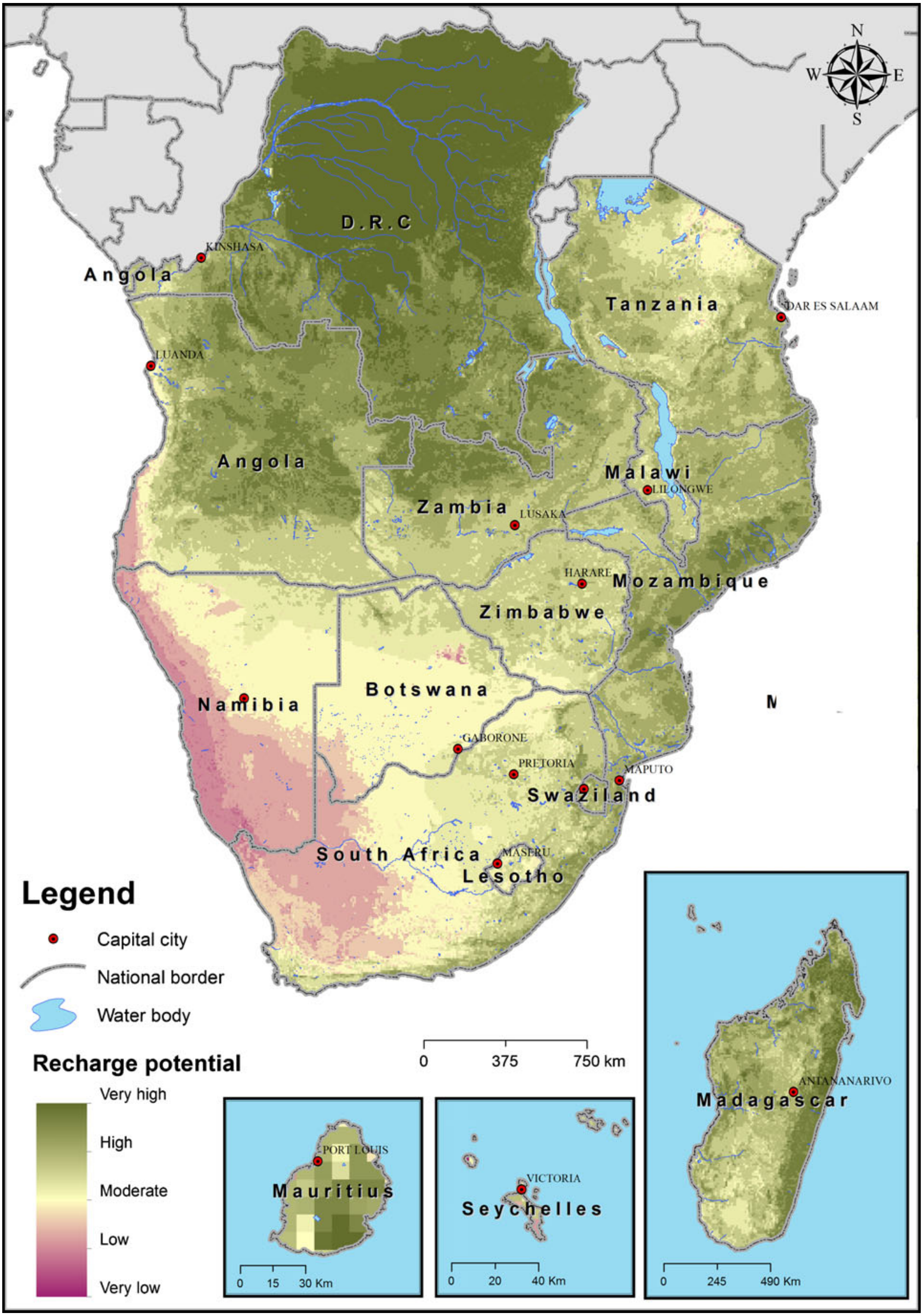

Fig. 4 Composite map of regional groundwater recharge potential

Fig. 5 Aggregate map of regional human groundwater dependence

seen that dependence is dominated by spatial population and livestock rearing patterns along a north–south oriented, central-to-eastern lying stretch through the subcontinent and in areas away from rivers and lakes.

Overall groundwater drought risk

The areas inherently most susceptible to physical GWD (map of physical GWD risk not shown) are located in a broad band across the southern part of Africa, encompassing the south-western part of Angola, most parts of Namibia, Botswana, and Zimbabwe, northern and western parts of South Africa, continuing north through western parts of Mozambique, most of Malawi, eastern parts of Zambia, and central and northern parts of Tanzania. Clear imprints are discernible from the arid zones (see Fig. 2) and poorest aquifers (Fig. 3). The latter includes, to a large extent, the shallow weathered Precambrian basement igneous and metamorphic crystalline rock, also called regolith, aquifers prevalent in sub-Saharan Africa (Foster 2012; Titus et al. 2009).

Using a weighing scheme of equal importance to physical GWD risk and human vulnerability at the macro-level, and a somewhat higher weight to population density at the micro-level (cf. Table 3 and base scenario in Table 6), the outcome of the composite mapping of GWDR is shown in Fig. 6. It is seen that a tract of GWDR is still dominant across southern Africa and continuing north into the central-to-eastern part of the continent, from northern South Africa through to northern Tanzania, except for quite large areas in the south-central part of the sub-continent (Namibia mostly), where aridity is pronounced but population density is low. These results indicate that there is a certain overlap and congruence between areas of inherent GWDR (primarily due to relative aridity and poor, shallow aquifers) and areas of high human groundwater dependence (Fig. 5). In other words, disproportionately many people in SADC live in high-risk areas for GWD and such areas are to be addressed and further prioritized in drought management. High groundwater dependence is a result of high population density, groundwater being the predominant source of water supply in rural areas, as well as high degree of pastoralism, partially dependent on groundwater and other groundwater-dependent ecosystems (Giordano 2006). That drought proneness and livestock density is related is not surprising as pastoralism is a traditional drought response mechanism in these regions (Blench 2001). The population in the consistently very high GWDR zones was estimated to be 39+/−19 million (14 % of the SADC population, excluding Madagascar).

Testing and validation of GRiMMS

GRiMMS underwent several testing and validation procedures as part of its development. A genuine validation is inhibited by lack of data on occurrence and extent of historic GWD incidences in SADC. Only sporadic empirical documented evidence of GWD exists. However, the identified most risk-prone areas coincide with SADC countries severely affected by drought and lack of groundwater availability and access in previous decades—Malawi, Zimbabwe, Limpopo Province of South Africa (Calow et al. 1997, 2009)—which gives overall credibility to the results. Tentatively, GRiMMS underwent a sensitivity analysis to probe its robustness. Furthermore, partial testing included comparison of submodular maps with previously published maps of meteorological drought risk (Dai 2011; Eriyagama et al. 2009), aquifer productivity (MacDonald et al. 2012), and recharge potential of South Africa (DWAF 2006), all with satisfactory results.

Table 6 Weighting coefficients used for scenario development

Micro-strategy	Data layer	Macro-strategy		
		I Physical GW drought risk=0.5 Human vulnerability=0.5	II Physical GW risk=0.25 Human vulnerability=0.75	III Physical GW risk=0.75 Human vulnerability=0.25
Hum-1	Population density	0.25	0.25	0.25
	Livestock density	0.25	0.25	0.25
	Irrigation intensity	0.25	0.25	0.25
	Distance to surface water	0.25	0.25	0.25
Hum-2	Population density	0.55[a]	0.55	0.55
	Livestock density	0.15[a]	0.15	0.15
	Irrigation intensity	0.15[a]	0.15	0.15
	Distance to surface water	0.15[a]	0.15	0.15
Hum-3	Population density	0.15	0.15	0.15
	Livestock density	0.15	0.15	0.15
	Irrigation intensity	0.15	0.15	0.15
	Distance to surface water	0.55	0.55	0.55
Phys-1	Meteorological drought risk	0.5[a]	0.5	0.5
	Hydrogeological drought proneness	0.5[a]	0.5	0.5
Phys-2	Meteorological drought risk	0.75	0.75	0.75
	Hydrogeological drought proneness	0.25	0.25	0.25
Phys-3	Meteorological drought risk	0.25	0.25	0.25
	Hydrogeological drought proneness	0.75	0.75	0.75

[a] Represents base scenario shown in Fig. 6

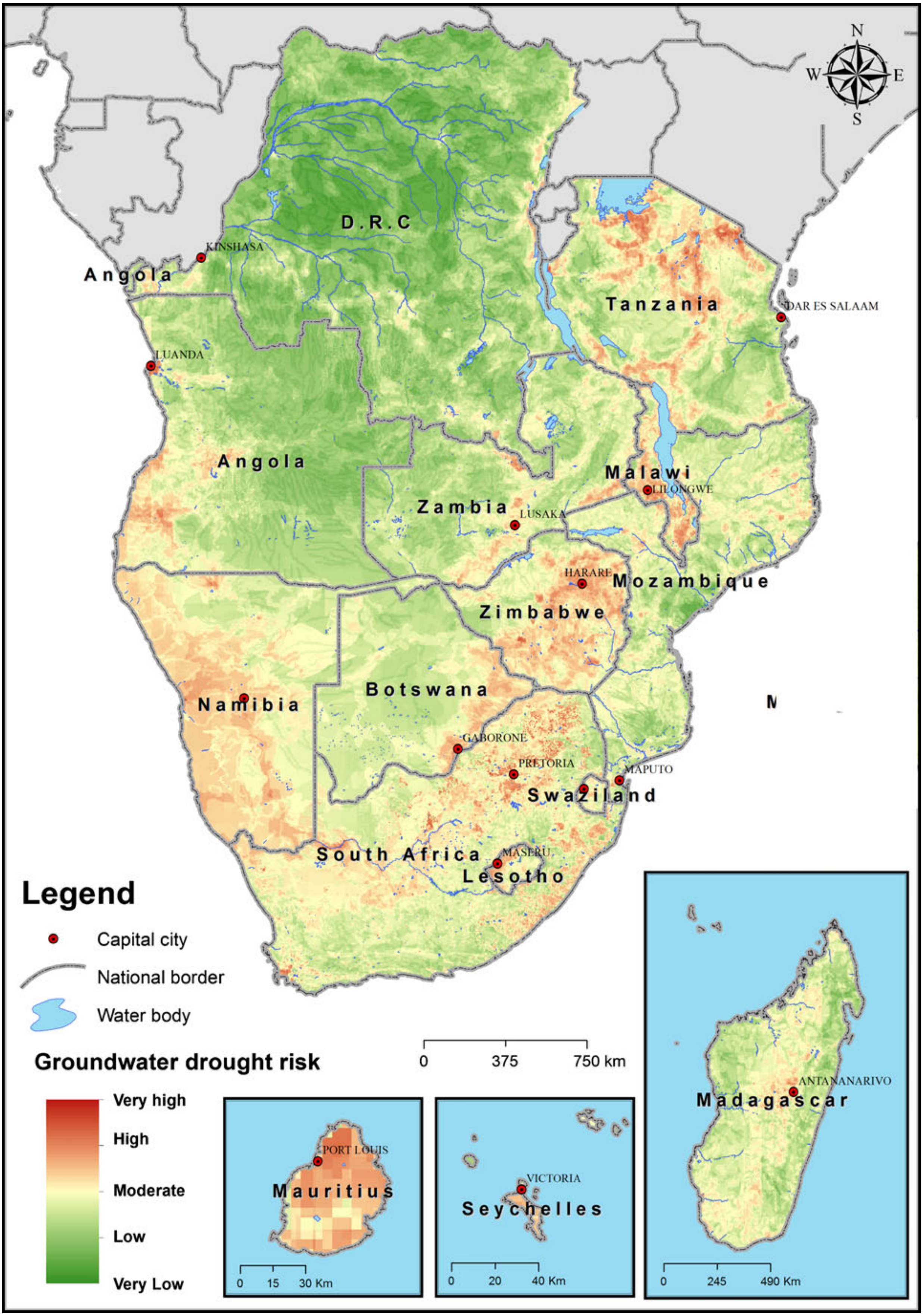

Fig. 6 Final map of regional groundwater drought risk

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Testing of GRiMMS with independent data

A separate exercise consisted of comparing GRiMMS output for South Africa with a map generated with the exact same procedure, but using independent, national data sets (Table 4). In Fig. 7, showing the map for South Africa, using GRiMMS dataset (Fig. 7a) and using independent South Africa data (Fig. 7b), it is seen that the correspondence is very good. This is encouraging and demonstrates that the global/regional datasets used in GRiMMS are credible and most likely among the best available at the SADC regional level, hence also giving confidence in the overall composite GRiMMS maps.

Sensitivity analysis

Due to subjectivity in assigning the micro and macro–level weights in the model, these parameters were varied, within realistic ranges (Table 6), in a set of scenarios to test the variability of the results. At the macro-level, the weighting regards the broad assumption regarding the overall importance of physical and human factors, whereas the micro-level weights vary the importance of human-related factors relative to other human-related factors, and meteorological drought risk relative to hydrogeological drought proneness. Three macro-level combinations together with three micro-level combinations related to each of the human factors and the two physical modules combine to produce a total of 27 scenarios.

A summary plot of all scenarios is shown in Fig. 8, visualizing the distribution of the area among the five risk classes, as a mean and variability across the 27 scenarios. The relatively small variability for the ‘very high’ category indicates that the model is robust and consistent in identifying areas of very high GWDR. This is encouraging since estimation of the highest risk zones is critical for drought management.

Climate change impact

The implication of the future climate scenario is a generally increased meteorological drought risk in SADC, partly due to a general decrease of precipitation (mostly over southern Africa) and partly due to an increased temporal extent of longer dry periods (mainly over eastern Africa) and more variable precipitation projected over Zimbabwe, northern Kenya and most of Somalia (not shown). This increased drought risk is also reflected in enhanced GWDR over most of the SADC region, as visualized in Fig. 9. Comparing with Fig. 6, it appears that already drought-prone areas become more at risk, and some additional countries are projected to become highly susceptible to GWD, like large parts of Zambia, Mozambique, and Madagascar (Table 7). The projection considers other factors to be constant, i.e. constant population density and no adaptation capacity, which is unrealistic. Furthermore, only one greenhouse gas emission scenario and one set of nested climate models are considered, hence not representing the full range of uncertainty of climate impacts. Nevertheless, the map illustrates the applicability of GRiMMS. It shows that the climatic effect, everything else being equal, may quadruple the population exposed to GWDR and the area by a factor of 14 for the end of the present century (Table 7).

Including human capacity in risk assessment

The composite map for South Africa, taking into account human capacity (with equal weights for each of the three parts and equal weight between human dependence and capacity) are shown in Fig. 10. Apparent is the increase in GWDR in the interior northern, central, and eastern Cape areas, the North West and the Limpopo area (compare with Fig. 7a). These locations are principally those that historically have been underdeveloped since the end of apartheid in 1994. Furthermore, the map shows that major metropolitan areas, like around Johannesburg, Pretoria, Cape Town and Port Elisabeth, attain a lower GWDR as a result of lower human vulnerability, reflecting the high number of technically skilled professionals and well-functioning local governments centred in these areas. Although including human capacity was not possible on a SADC-wide scale due to lack of sub-national datasets, this layer is critical at the national scale in delineating areas that are vulnerable to GWD because of the human capacity factor.

Discussion and perspectives

The paper outlines methodology and development of the mapping and decision support tool GRiMMS for analysing, visualising and managing GWDR in the SADC region. Composite mapping analysis demonstrated that certain areas of SADC are relatively vulnerable to GWD due primarily to a combination and intersection of high meteorological drought risk, poor aquifers, and high human dependence on groundwater. These high-risk areas, covering significant groundwater-dependent populations (approximately 40 million) require special attention in drought management and water-security interventions, especially for basic rural water supply.

Preliminary climate-change-impact assessment demonstrated the analytical capacity of GRiMMS. A single precipitation projection, using the IPCC SRES A1B scenario, suggests a significant increase in GWDR in new as well as already vulnerable areas in the region up to 2100. Simple testing of GRiMMS for South Africa, which is relatively data intense, indicates good reliability of the database compiled for GRiMMS. A sensitivity analysis of the GRiMMS results, accounting for variability and subjectivity of the weights, indicated good consistency in the identification of very highly GWDR prone areas. Including human capacity for groundwater and drought management by surrogate indicators was demonstrated, through the example from South Africa, to enhance the differentiation between physical susceptibility and human

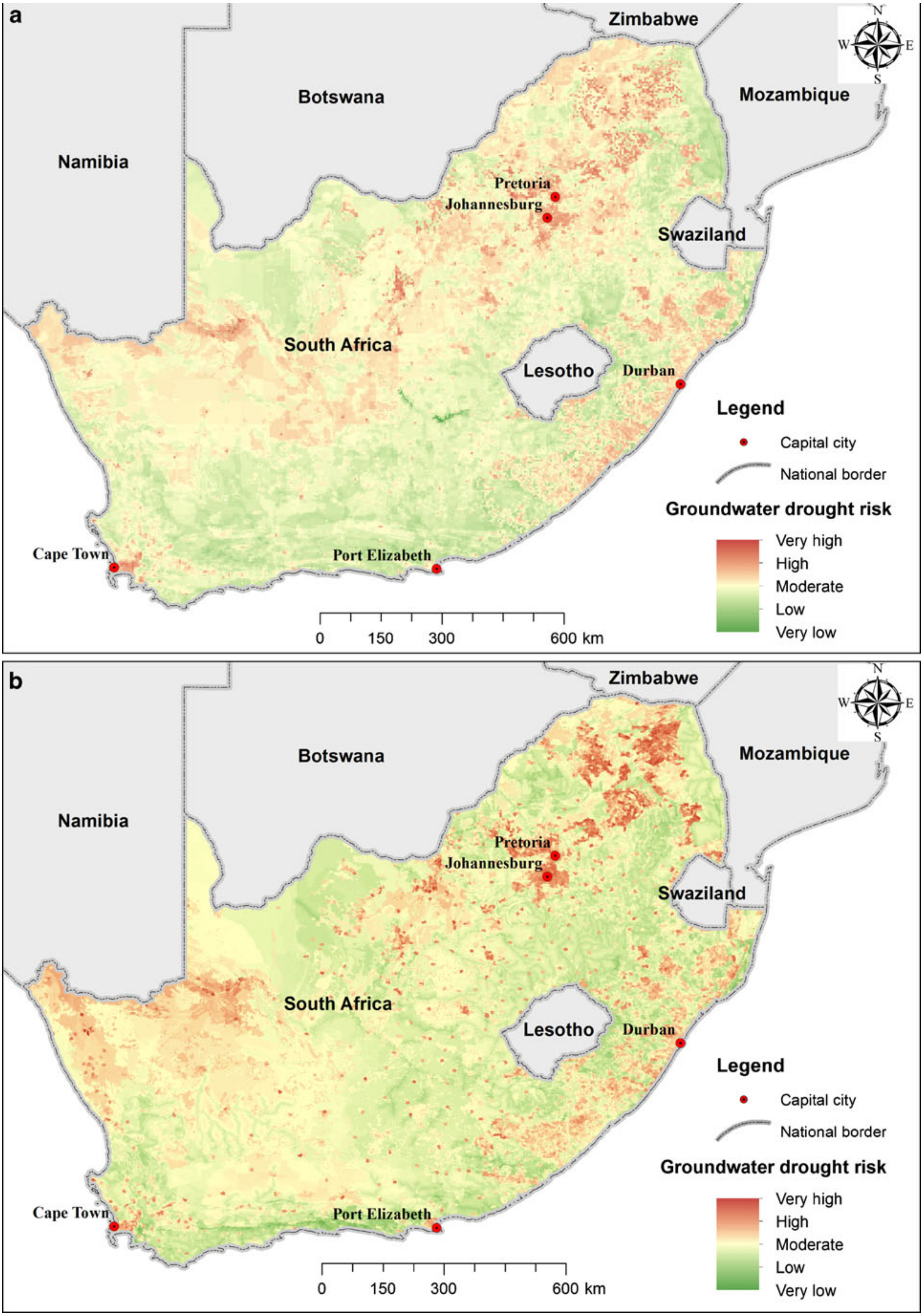

Fig. 7 Groundwater drought risk map for South Africa. **a** from GRiMMS SADC map, **b** from independent data, using GRiMMS methodology

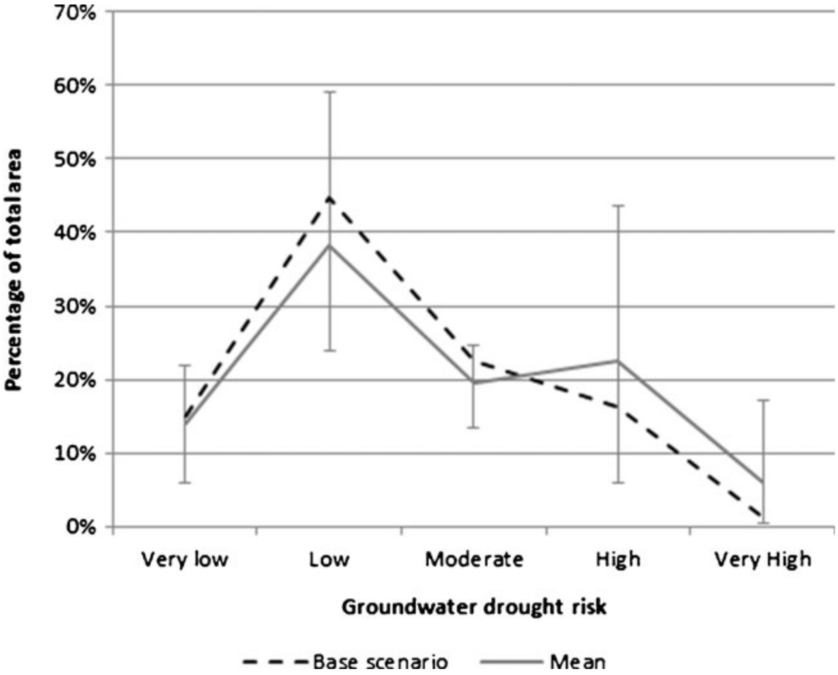

Fig. 8 The mean area as per groundwater drought risk class across all scenarios and with indication of variability (i.e. min/max error bars). Base scenario is plotted for reference

vulnerability. This is critical when targeting management and drought interventions to marginalized areas.

GRiMMS provides a first-line assessment tool for integrated SADC-wide mapping and analysis of GWDR. It serves an important purpose of highlighting and enhancing the nexus between drought and groundwater, previously neglected in national drought strategies (SADC 2009b). At the same time, the results point to the important role of areas underlain by poor aquifers, predominantly the crystalline basement aquifers (sometimes not even considered aquifers) that are relied on to a large extent throughout most parts of arid and semi-arid SADC (MacDonald et al. 2008). More research and understanding of the linkage between drought, groundwater impacts and human groundwater access options are required for these areas. The tool also emphasizes the significance of an inter-disciplinary approach in highlighting most vulnerable areas, not solely focusing on the productivity and drought resilience of the aquifers but also including socio-economic parameters.

Though simple testing and validation of the GRiMMS dataset and methodology has been performed, data uncertainty is still an issue. Data on aquifer productivity, based on knowledge and maps of hydrogeological conditions, and recharge potential need improvement, especially for possible downscaling applications. To partly address this, a consultation with member states' responsible units for hydrogeology was carried out to get comments and suggestions to corrections of the aquifer productivity map, which were subsequently incorporated. Assumptions applied regarding the relationship between recharge potential and vegetation may not hold for the vast region under consideration, covering several climatic zones, large spatial variability in rainfall (from less than 50 to more than 3,400 mm long-term average annual rainfall), soils, and land cover. More detailed studies, testing, and validation at smaller scale are needed. Important data not widely available at disaggregate level, like well density, well functionality and susceptibility for breakdown during drought (mechanically, or as a function of declining groundwater levels, related to well depth and dynamic groundwater levels) could further enhance the applicability of GRiIMMS, potentially supporting real-time monitoring and early warning assessment of GWD (Taylor and Alley 2001; Calow et al. 1997). A SADC borehole database exists (SADC 2009a); however, it has inconsistent coverage and content across the region and lacks time series of dynamic parameters, requiring further updating and consolidation. GRiMMS could, with implementation of long-term monitoring of dynamics of groundwater levels in critical and representative locations, be linked with existing drought management systems and real-time earth observation initiatives. These traditionally focus on precipitation, soil moisture and surface water when monitoring and mapping risk associated with climate, natural resources and food production. While a groundwater recharge, storage and discharge component is incorporated in the more advanced systems that look at distributed water balances (Mendicino et al. 2008; Nijssen et al. 2001), there is no estimation of groundwater levels, often the most critical parameter in GWD (Mishra and Singh 2010). This is particularly important, either from direct monitoring or from extended modelling or a combination, due to the different phasing of GWD relative to meteorological drought. GRiMMS should provide the basis for further national or sub-national level analysis on the association between groundwater, drought and water

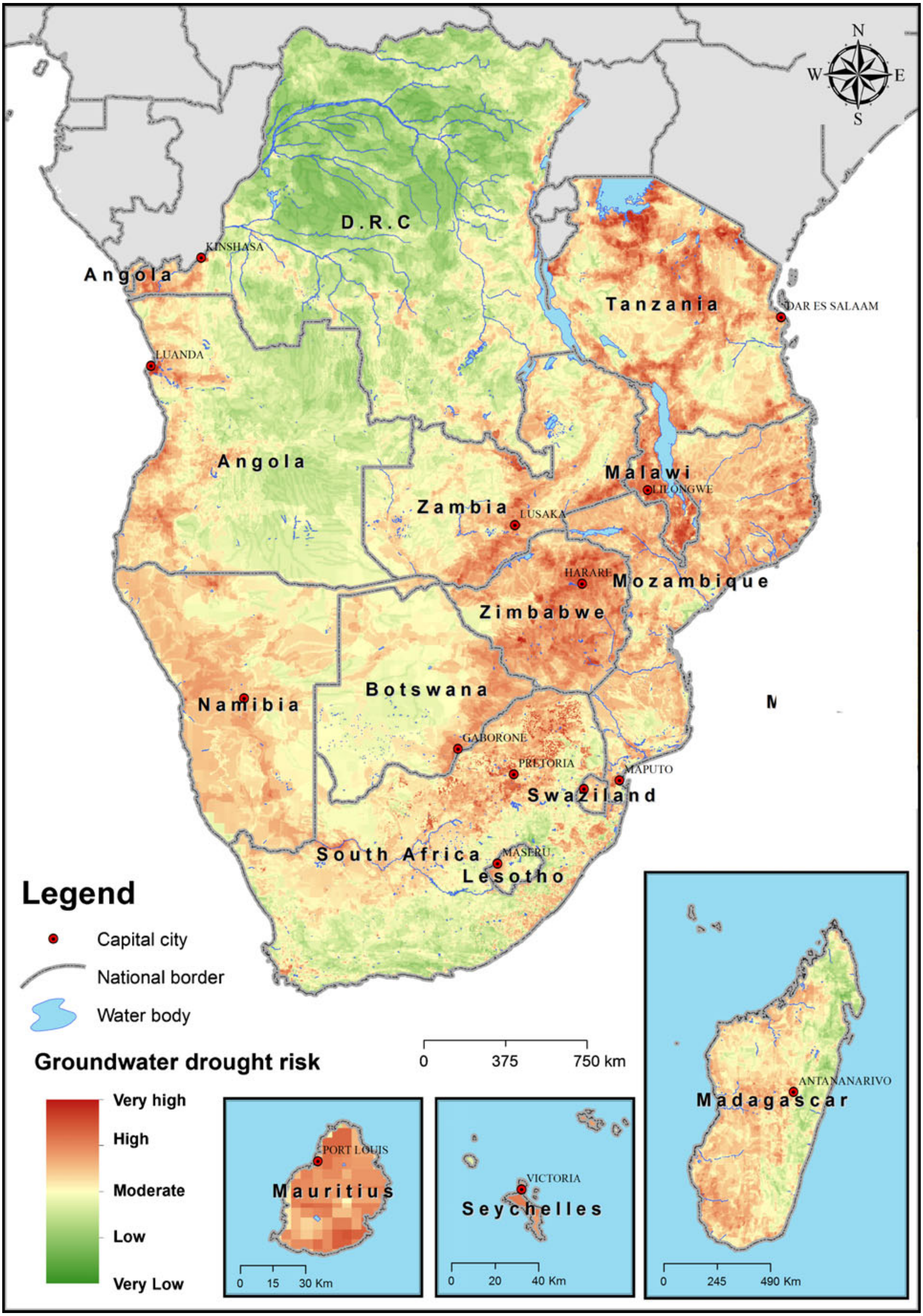

Fig. 9 Groundwater drought risk for projected future climate (based on IPCC SRES A1B)

Table 7 Area and population subject to very high groundwater drought risk in SADC countries (from the base scenario and future climate scenario)

Country	Present climate (1989-2008)				Future climate (2080-2099)			
	Area		Population		Area		Population	
	km^2	%	Million	%	km^2	%	Million	%
Angola	6,908	0.6	2.6	14.9	95,405	7.7	4.6	26.2
Botswana	2,378	0.4	0.2	13.7	74,569	12.9	0.8	53.2
DRC	624	0.0	0.2	0.3	60,107	2.6	16.7	23.6
Lesotho	2,008	6.6	0.3	12.4	5,416	17.8	0.6	28.5
Madagascar	1,198	0.2	0.6	3.0	109,141	18.5	6.3	30.3
Malawi	11,549	9.8	4.4	31.9	77,663	65.8	13.4	96.4
Mauritius	649	32.7	0.7	56.5	1,650	83.3	1.1	98.9
Mozambique	1,250	0.2	0.5	2.5	325,466	41.4	14.1	66.0
Namibia	4,502	0.5	0.5	26.0	188,095	22.8	1.2	56.7
Seychelles	0	0.0	0.0	0.0	162	77.5	0.1	93.2
South Africa	36,893	3.0	16.8	37.5	197,378	16.2	31.5	70.4
Swaziland	49	0.3	0.0	0.7	3,872	22.4	0.3	26.5
Tanzania	44,506	4.7	5.2	11.9	361,416	38.4	26.4	60.7
Zambia	4,157	0.6	2.1	16.2	176,409	23.5	6.7	52.0
Zimbabwe	20,595	5.3	4.8	31.8	278,802	71.4	12.8	85.7
Total	137,266	1.4	38.9	14.5	1,955,551	19.9	136.7	50.9

security. Similar objectives are pursued through mapping exercises as part of water-supply planning and surveillance (Jiménez and Pérez-Foguet 2011). There is a need to merge the two approaches, which focus on the local water point/water access conditions and the larger-scale resource conditions, respectively. Such tools could significantly enhance assessment of actual GWDR and support the development of groundwater for the common good of the

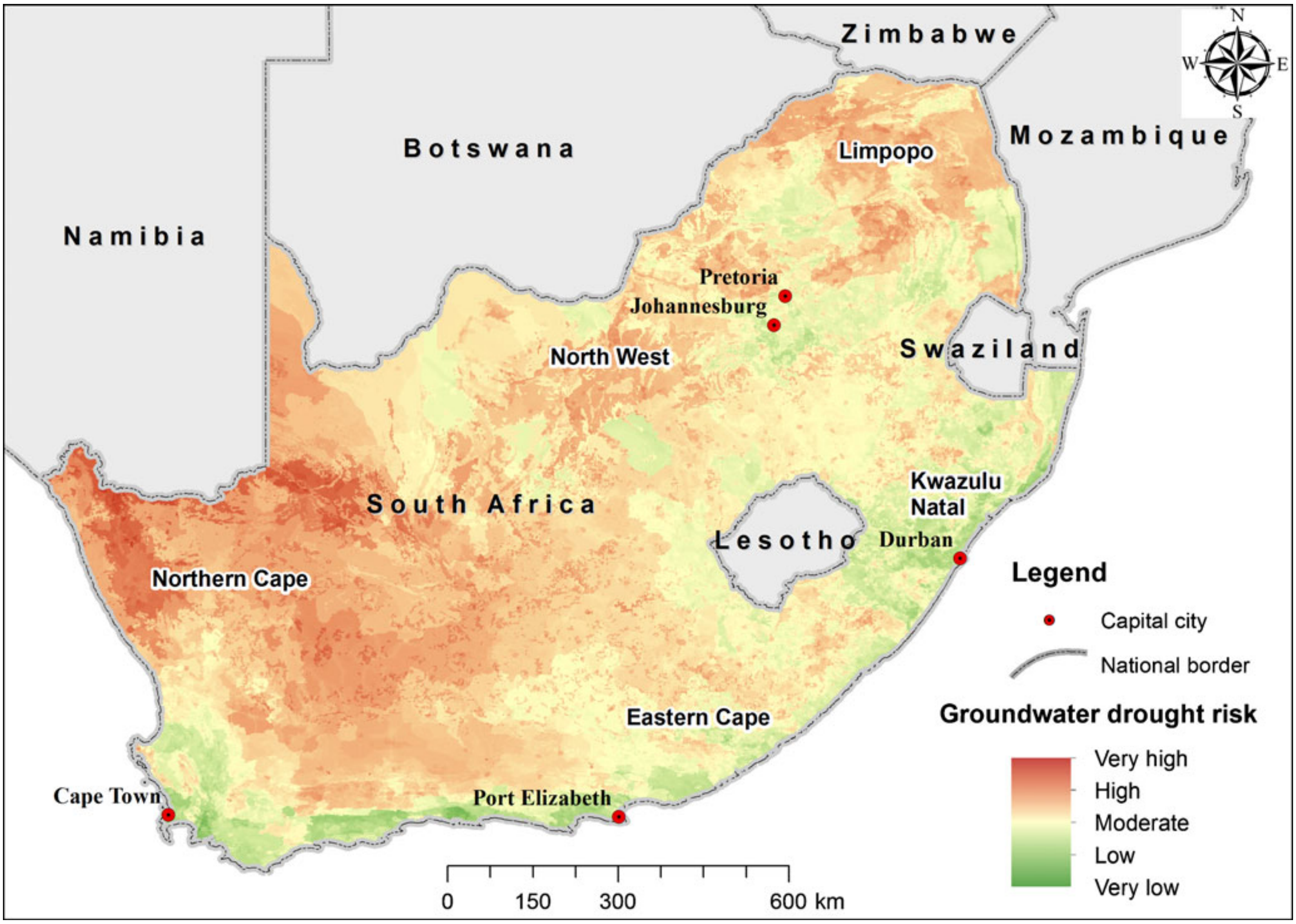

Fig. 10 Groundwater drought risk map for South Africa, including human capacity

Table 8 Potential applications of GRiMMS at different management levels

	Management level		
Application type	Regional/multilateral	National	Local/sub-national
Drought management	Strategic drought management Climate change projection and groundwater drought impact analysis	National drought management Real-time groundwater drought forecasting	Drought proofing of water supply Groundwater drought warning
Groundwater management	Transboundary aquifer (TBA) management	Groundwater resources development and allocation	Groundwater recharge enhancement
	Monitoring of groundwater, with focus on TBAs and regionally representative groundwater systems	Land-use and development planning Monitoring of groundwater, with focus on nationally representative groundwater systems	Development of new human settlements Monitoring of groundwater, with focus on groundwater-dependent areas and local/community-based groundwater management

most vulnerable populations, increasing their water security and drought resilience.

Incorporating data and maps on groundwater-dependent ecosystems (Colvin et al. 2007; MacKay 2005) would enhance the identification of ecosystems linked to, or fed by, groundwater and, hence, vulnerable to GWD. Because such systems are often significantly relied on for human settlements, ecosystem services, and livelihoods in the African context (Giordano 2006), they may both provide early protection against drought but also later risk of severe ecological and human impacts during and after long-term droughts. Finally, data on groundwater quality are essential for future assessment of integrated risk of water insecurity in the region—for example, the central Kalahari region (south western Botswana, eastern Namibia, and northern-central South Africa) and northern Namibia are shown to be relatively drought proof in this analysis (Fig. 6), while there are significant problems of salinity in parts of these aquifers (Christelis and Struckmeier 2011; van Weert et al. 2009).

Potential uses of GRiMMS, in present or further developed form, at various levels for long-range as well as emergency planning, are given in Table 8. As GRiMMS may support the identification of GWD prone areas in need of priority actions for improved water supply and groundwater management, it may also be used to pinpoint areas that are less susceptible to GWD and may hence inform future human settlements or habitation, e.g., of people displaced as a consequence of drought or other natural hazards or human conflicts. Often, such exercises are carried out with limited attention to water resources and their potential for meeting human demands (Carter 2007).

Furthermore, GRiMMS may function as a regional joint and general repository and access platform for groundwater data and facilitate the use of maps in groundwater and drought management (MacDonald et al. 2009b). The ability to interactively illustrate groundwater-related characteristics linked to socio-economic factors may enhance the attention to groundwater and help emphasize the critical importance of proper and systematic monitoring of groundwater and supply conditions, something that is generally under-prioritized in SADC (SADC 2009b). Finally, it may support focus and international collaboration on transboundary groundwater and cross-boundary drought management, which is recognized as a significant future challenge (Cobbing et al. 2008), as both demographics and climate change. In such an effort, the GRiMMS database should be linked to existing transboundary databases, typically focused on surface water, e.g., the Zambezi Water Resources Information System (ZAMWIS) for the Zambezi River basin (SADC 2007).

Conclusions

From the development of GRiMMS, it is clear that continued collaboration and awareness raising on the important role of groundwater in drought management in SADC is required. Groundwater may provide a critical buffer in the early phases of a drought while certain vulnerable groundwater systems themselves becoming subject to desiccation and failing access during, and after, prolonged drought. In such a scenario, the best strategy is to understand the hydrogeological processes involved and likely impacts, identify the vulnerable areas and populations, and ensure sustained utilization of the resource through proper and pro-active management at appropriate scales. The GRiMMS tool is meant to support such a process. Temporal groundwater storage changes generally reflect long-term climatic change and variability through accumulation of deviations from historic means of, e.g., net precipitation. Hence, understanding and reacting properly to such impacts become crucial in drought management and climate-change adaptation. Involving member states through the SADC Water Division and other organisations and further enhancing the institutional framework will be critical for the ownership, uptake and successful application of GRiMMS.

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Action Plan (RSAP) for Integrated Water Resources Management and Development in SADC. The valuable inputs of SADC national representatives from central water resources management units are acknowledged.

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