A Novel Modelling Approach to Assess Groundwater Vulnerability to a Depletion in Quantity and a Deterioration in Quality

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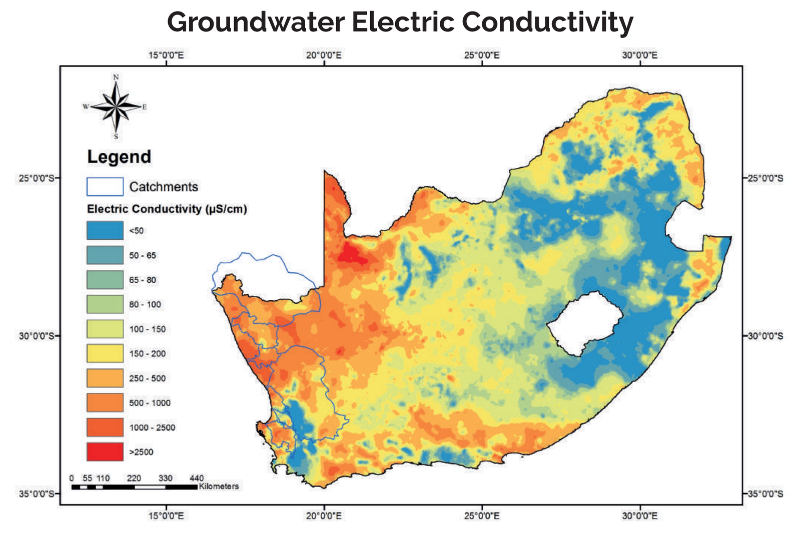
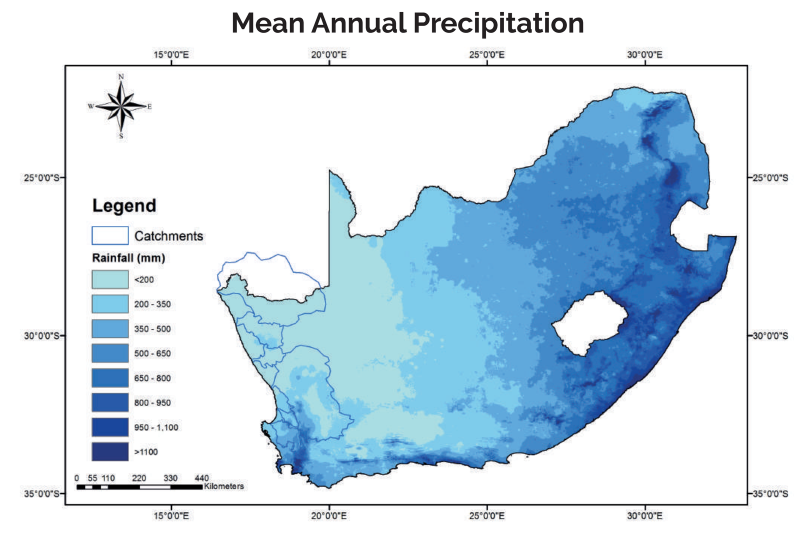
Introduction

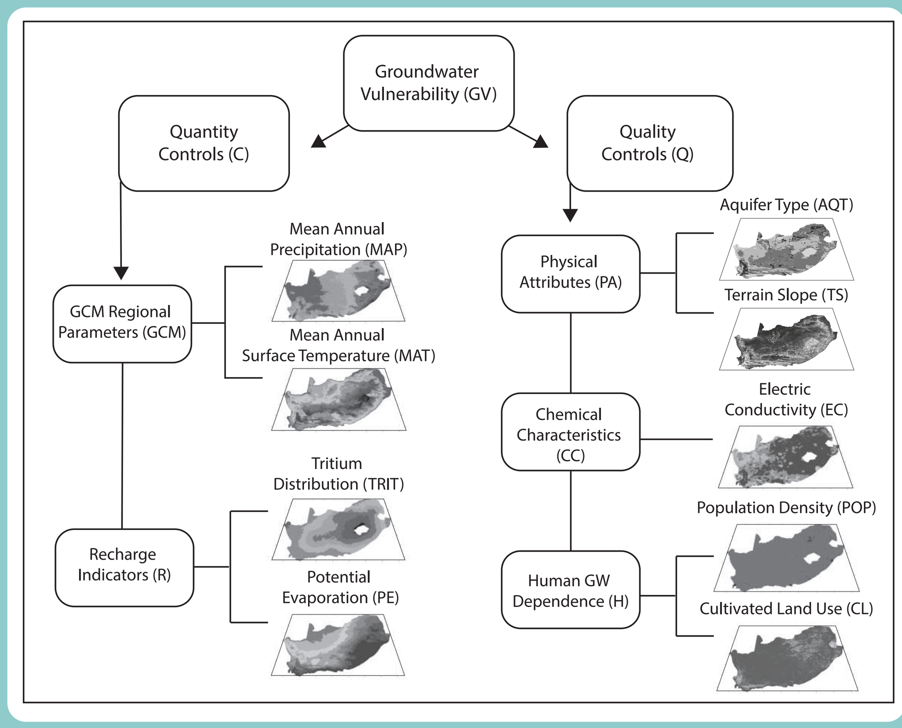
In recent decades, changing climate patterns and increasing rainfall variability have seen groundwater abstraction on a global scale increase significantly (Green et al., 2011; Holman, 2006; Richey et al., 2015; Smerdon, 2017). Much of this increase in abstraction has occurred in highly concentrated areas to support both urbanization of the world's population as well as the agricultural activities that provide food security to them (Famiglietti, 2014)). As a result, groundwater depletion, the permanent lowering of the water table, is occurring across the globe (Treidel et al., 2011; Wada et al., 2010). This process is occurring at a range of scales from individual catchments (Tallaksen et al., 2009); (Woldeamlak et al., 2007);, to regional aquifer systems including transboundary aquifers (Hamed et al., 2014); (Scanlon et al., 2012); (Rodell et al., 2015); (Changming et al., 2001). The consequences of over-abstraction of groundwater resources have important lessons for the management of aquifer systems across the globe, and have contributed significantly to how we think about groundwater sustainability (Aeschbach-Hertig and Gleeson, 2012; Gorelick and Zheng, 2015; Konikow and Kendy, 2005).





Concepts & Methods

The model incorporates nine different spatial datasets of groundwater vulnerability controlling parameters, specifically including an isotope tracer (tritium) and uses a weighted index-overlay method to output the spatial distribution of groundwater vulnerability on a scale from 1 to 8. The assessment is structured with multiple scenarios that focus on either climatic indicators or pollution potential or both. Subsequently, parameters that directly relate to climate can be adjusted according to different global circulation models (GCMs) to predict the evolution of groundwater vulnerability with climate change. The results can be directly translated to larger-scale transboundary aquifer systems and provide a framework for future management of groundwater resources across the globe, whilst still being flexible enough to evaluate the groundwater vulnerability of a single watershed or catchment.

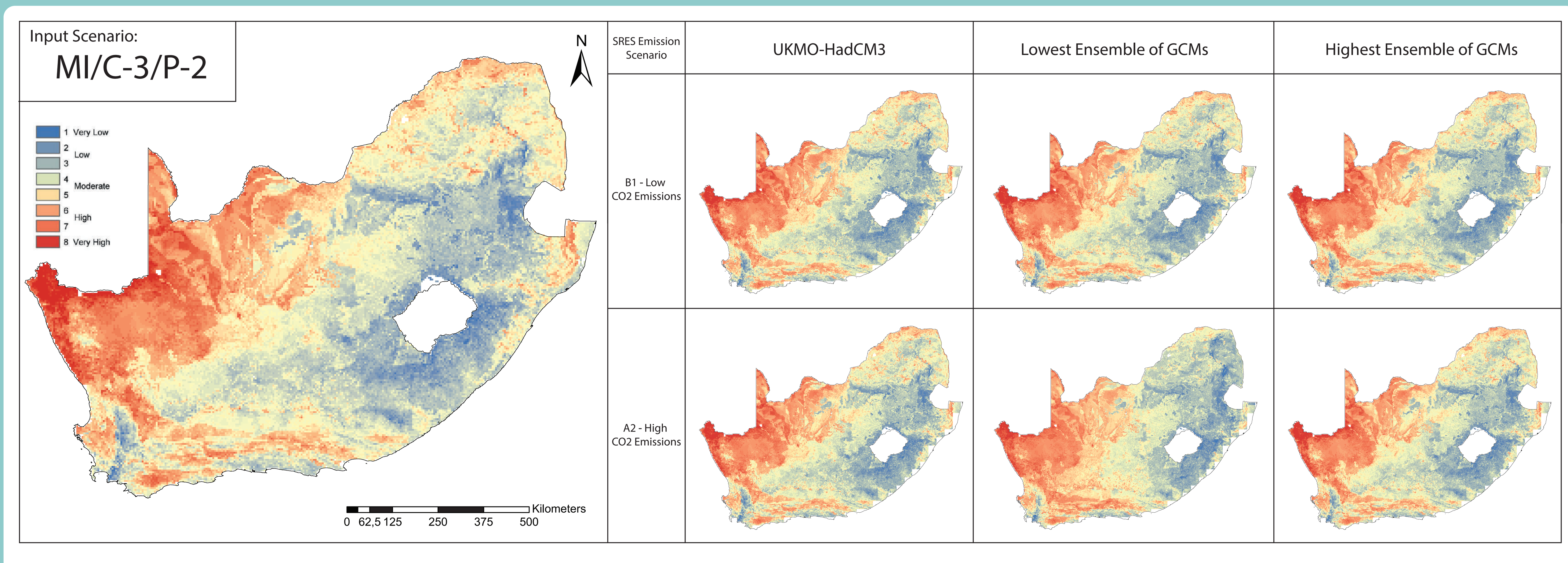


Model framework of the thematic layers, divided into two major subheadings and five minor subheadings, representing major and minor strategies

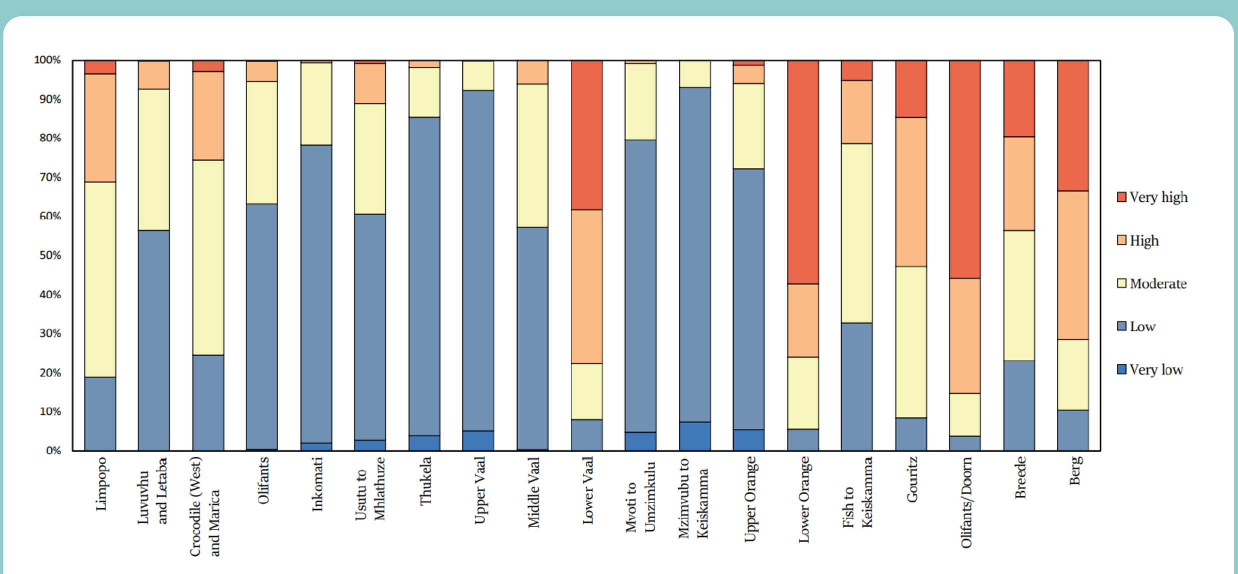
The nine input parameters identified as significant controls on groundwater vulnerability are: (1) mean annual precipitation, (2) mean annual surface temperature, (3) tritium distribution in groundwater, (4) potential evaporation, (5) aquifer type and yield, (6) terrain slope, (7) electrical conductivity, (8) population density and (9) cultivated land use. These nine input parameters are divided across five subheadings according to their collective contributions to the final groundwater vulnerability. The groundwater vulnerability model was constructed using a composite mapping analysis technique that superimposes layers and combines them through a predetermined linear algorithm with an editable weighting scheme. This model can be run iteratively.

Results and Predictions

The final optimized scenario presented, best combines a strong alignment with previous studies and weightings that are not skewed toward particularly sensitive parameter inputs. This ensures that all data incorporated in the analysis is contributing to the output effectively without biasing the model towards any specific input. To illustrate the model, the results are reported in two spatial distributions: (1) South Africa as a whole; and (2) the nineteen individual water management areas (WMA's) within South Africa's boundary as defined by the National Water Resource Strategy one (NWRS-1).). A single weighting scenario (M-I/C-2/P-2) was chosen, that showed good spatial alignment to previous assessments which predicted that 20.9% of the South Africa had very high vulnerability (1.5% very low; 35.7% low; 24.9% moderate and 17.0% high). The model was adjusted to reflect climate conditions 50 years into the future, with an increase in very high vulnerability of 3% and a 6% decrease in low vulnerability. Results suggest that large areas of South Africa have high groundwater vulnerability, especially in areas where groundwater supplements domestic supply and agriculture.



Comparative map showing an example scenario output (left) MI/C-3/P-2 of current groundwater vulnerability with projected maps (50 years): (1) from the UKMO-HanCM3 GCM; (2) the low est ensemble of 16 GCMs and (3) the highest ensemble of 16 GCMs



Groundwater vulnerability per water management area (WMA) produced from scenario MI/C-2/P-2 as a proportion of the total percentage vulnerability per area. WMAs west of 25° E generally have increased vulnerability than those east of 25° E

The model outputs can be forward projected for different time periods using different combinations of GCM scenarios. Figure 11 shows six possible outcomes under one GCM, two GCM ensembles and two emission scenarios projected 50 years into the future. The GCM ensembles and emission scenarios show an average increase in the total area of very high vulnerability from 25.6% to 28.7% and high vulnerability from 24.9% to 25.9. Conversely, there is an average decrease of the total area of low vulnerability from 19.3% to 15.7% and very low vulnerability from 0.9% to 0.5%. It also indicates that low emission scenarios (B1) represent less significant increases in very high vulnerability areas and a more significant increase in moderate zones. All high emission (A2) scenarios result in an increase in the area of very high vulnerability zones. The most radical GCM ensemble (Low ensemble, A2) showed an anomalous increase in very high vulnerability areas from 25.6% to 41.0% (Fig. 12). Future predictions show substantially increased groundwater vulnerability of in the central regions of the country as well moderately increased groundwater vulnerability within the Western Cape and south coastal areas. The northern boundary regions showed lower vulnerabilities in the projected model. The second model for future vulnerability to climate change showed the same regions of change but with increased severity. In this weighting scenario, almost all of the western and central regions have high vulnerabilities and a significantly smaller area of the eastern regions have low vulnerabilities.

Conclusions

Increased groundwater abstraction on a global scale to support population growth and food security requires an effective method to assess groundwater vulnerability to both depletion and deterioration in quality. The approach presented here addresses issues surrounding broader concerns of groundwater vulnerability that more focused methods cannot constrain. Holistic regional groundwater vulnerability assessments that incorporate the differentiation between shallow, actively recharged groundwater and deeper, fossil groundwater represent a step forward in utilizing regional isotopic tracers in groundwater vulnerability assessments. The resultant output of groundwater vulnerability can be investigated across natural and legislative boundaries, providing a mechanism for baseline assessments of groundwater vulnerability in transboundary systems as well as predicting how these vulnerabilities will evolve into the future. By viewing the sustainability of groundwater in a shared light with the vulnerability of groundwater, there is an opportunity to develop adaptive and flexible groundwater management frameworks to prevent conflict over shared resources. In addition, concerns surrounding how susceptible groundwater is to climate change can now be addressed in conjunction with traditional groundwater vulnerability assessments, mitigating the possibility of underestimating the vulnerability of a resource when developing management strategies.

Resources

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