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Quantifying water vulnerability: a multi-dimensional approach

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Abstract In today's uncertain world, vulnerability of water supplies is of increasing concern. A number of factors influence this, ranging from physical conditions through to human management capacities. Across the Orange River Basin in southern Africa, these threats arise from overpopulation and farming pressure, with agrochemical and industrial runoff as well as harsh weather conditions giving rise to severe problems of erosion and land degradation. Under conditions of climate change, these threats are exacerbated, as temperature rises and water resources become more erratic. Since water is both an essential instrument of livelihood support and a crucial factor of production, there is a need to develop more effective mechanisms to identify those areas where its scarcity or poor management can bring about a slowdown in the development process. This urgency is heightened by the international commitment to the Millennium Development Goals (MDGs), supposedly to be reached by 2015. In addition to the MDGs, governments are also committed to the development of basin management plans for *Integrated Water Resources Management* (IWRM). This means that, in order to try to allocate water in an equitable and efficient way, better understanding is needed of all of the complexities of managing water across heterogeneous basins. It is now recognized that effective water management is much more dependent on effective governance than on hydrologic regimes. Ranging from traditional local customary norms and practices dating back through generations to the latest state-of-the-art science-based international agreements, water governance is a key to supporting the lives and livelihoods of local populations. Access to information is an essential feature of any of these approaches, and harmonization of data on water issues is long overdue. This paper provides an outline of an index-based methodology on which an assessment of water vulnerability can be made. In this approach, *supply-driven vulnerability* (from water systems) and the *demand-driven vulnerability* (from water users), are evaluated at the municipal scale. By combining these various dimensions together mathematically, a *Water Vulnerability Index* (WVI) can be generated.

Keywords Water vulnerability · Integrated Water Resources Management · Water governance · Municipalities · Water Poverty Index · Climate Vulnerability Index

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1 Introduction

There have, in recent years, been considerable research efforts related to understanding global environmental change, and the consequences for natural and human systems. A wealth of literature has been produced, much of which has been considered and summarized in major assessments, such as the Millennium Ecosystem Assessment (MEA 2005), the United Nations Environment Programme (UNEP 2002), the World Bank (2002), and the Intergovernmental Panel on Climate Change (IPCC 2007). Significant changes are taking place in space and time in the areas of population, economic development and globalization, environmental institutions, and climate change.

Key areas of concern are the perceived negative impacts on natural and human systems of the effects of climate change. While there is a clear need to consider these impacts in the context of developing countries, it is now evident that all parts of the world will feel these impacts, in particular on water resources, food security, biodiversity, and human health and livelihoods. Added to this, and initially more significant, human population pressure and the impact of industrialization are exacerbating this situation of water scarcity (World Resources Institute 2000; MEA 2005).

Management of water resources is fundamental to human development, and has been since the first establishment of human civilization. While the vagaries of climate variability have always been a challenge, the process of climate change is inevitably going to make this worse. According to IPCC (2007), and others (Milly et al. 2005), significant changes in water resources will occur in most parts of the world. In some places, rainfall will increase, while in others it will be reduced. Similarly, temperatures over both land and sea will change and, as a result, water availability will be characterized by greater variability, with floods and droughts becoming more widespread. What is of particular concern today is the fact that much of this variation in precipitation and temperature will impact on areas which are currently important large-scale food producing regions of the world.

In the light of the more reliable knowledge we have about the likelihood of impending changes in water resources availability, there is a need to develop coping mechanisms and strategies for adaptation (UNECE 2009). While it will be worthwhile for all parts of an economy and society to consider this, the issue is more pressing in some places than others. For effective management of districts or nations, it will be worthwhile to identify where such adaptation is most needed, as a way of prioritizing limited financial resources to support these changes (Sullivan and Meigh 2005, 2007). In the case of the water sector, such changes need to be considered well in advance, as many of the adaptation strategies available may have long lead times before their effects may fully be felt. For example, if it is decided that more water storage will be needed in the future, decisions will have to be made on what forms this may take (more dams, river diversion, aquifer recharge, etc.), along with when these strategies should be implemented. If it is decided today that dams must be constructed, it may take in excess of 20 years to bring these on line. Similarly, if the adaptation strategies are to involve education and capacity building, these may take many years to take effect. While it has to be noted that there is much uncertainty in our knowledge about earth system science, we do have enough knowledge to realize that the future is unlikely to be the same as the past. As a result, we need to take action to build preparedness for the future conditions with which we will have to cope.

In almost every country, these combined impacts of physical and socio-economic conditions are giving rise to a variety of pressures, expressed differently according to their geographies, with some countries being more affected than others. Similarly, some sectors within economies will be more affected than others, as will be some communities (Satterthwaite 2003). At the same time, in many parts of the world, local water managers are faced with situations that may be characterized by low levels of financial viability, little political power, and inadequate human capacity. As a result, they need management tools designed to be usable without a high degree of either human or financial capital inputs, which also contribute to the tasks which are currently within their mandates and areas of responsibility.

For developing countries today, a major policy driver is the achievement of the Millennium Development Goals (MDGs). These serve to focus attention on a number of issues which are currently holding back the development process in many countries, and, through the achievement of these goals (even if only partially), greater capacity will result and the lives of millions of people throughout the world will be improved. While water and access to it impact on all aspects of human existence (Sen 1999), the specific MDGs which are relevant to water management are Goal number 1 (to eradicate extreme poverty and hunger) and Goal number 7 (to ensure environmental sustainability). Within Goal number 7, Target 10 is of particular relevance to water management: to halve by 2015 the proportion of people without sustainable access to safe drinking water (WSSD 2002). To achieve this, there is a need to provide safe water to some 500 million additional people by 2015, certainly not an insignificant task. In terms of Goal number 1, the eradication of extreme poverty and hunger is highly relevant to the water sector, given that, globally, over 70% of all water abstracted from the natural system is used in agriculture.

A pre-requisite to successful water resources planning and policy is better understanding of the drivers of any likely changes, the states that they will bring about, and the potential responses we may make to them. One way to achieve this is to assess the current situation (or state) and then consider how these will change under future conditions. This in itself requires three stages:

- Assessment of current conditions and factors affecting them;
- Identification of likely scenarios of future conditions; and
- Application of these scenarios to the current conditions, to assess what the future may hold in store.

In order for such a process to be useful and practical, it is important to try to use current knowledge wisely to provide insights into the vulnerability we may face. Furthermore, this must be considered at a scale appropriate to the potential actions which may be determined by the findings of the assessment process. Since water is usually managed, to some degree, at a local level, a case can be made to provide a tool which can be used by local municipal water managers to achieve this goal. An important characteristic of this is that such a tool should be based, as far as possible, on existing data, and it should be simple to explain to decision makers and politicians. This paper attempts to address the first phase of this process: the identification of the current state of water vulnerability at a municipal scale, illustrated through a selection of municipalities in South Africa. For the purpose of illustration, an example is also provided of water resource impacts under future conditions.

The ease with which scientific information can be presented to policy makers and practitioners is crucial to its usefulness. The diverse scientific information required in understanding vulnerability is detailed and complex, and will vary with geographic location and social, economic, and environmental conditions. According to UNEP (2002), vulnerability in this context can be defined as:

> *'the interface between exposure to the physical threats to human well-being and the capacity of people and communities to cope with those threats. Threats may arise from a combination of social and physical processes. Human vulnerability thus integrates many environmental concerns'.*

There is an extensive literature on vulnerability relating to environmental systems and human reliance upon them (Vorosmarty et al. 2000; Turner et al. 2003; O'Brien et al. 2004; Adger et al. 2007), and while these all provide useful insights, few actually provide a means for practitioners to explicitly address it. Not only does science need to provide information and evidence, but it must also develop methods and approaches which enable clear understanding, and indeed visualization, of relevant conditions. It is with this in mind that an index approach is proposed here, on the basis that such a tool will capture *the essence* of the complexity of water management challenges, yet will be relatively easy to implement. Such an approach can provide a rapid appraisal methodology which will be of use to support a number of different tasks for which both local and national authorities already have a mandate, but unfortunately often lack the means or capacity to address.

The use of indicators and indices is widespread in both the water sector and in economic policy. Examples of such tools in macro-economic management include the use of the Retail Price Index (RPI), and, in the water sector, there are numerous indicators of water quality and water stress, but mostly these are single indicators, used independently for different purposes. In the context of development, the use of the Human Development Index (HDI) has revolutionized the way the development process is assessed, and has brought about a recognition of the importance of the non-financial aspects of development, such as health and education (UNDP 2003), and the importance of integration of information. The HDI is a composite index, and this structure has been used to develop an integrated index for water management, referred to as the Water Poverty Index (WPI) (Sullivan 2001). The WPI has been developed in an international research project funded by the UK's Department for International Development (DFID) in 2001–2002, and tested in pilot sites in South Africa, Tanzania, and Sri Lanka (Sullivan et al. 2002, 2003). Since then, it has been used in a number of situations at a variety of scales, and is currently being used as the foundation for the 'Canadian Water Sustainability Index' which has been developed by the Privy Council of the Canadian Government (Morin 2005; PRI Canada 2007). The WPI work has also been used as a basis for the evolution of a Climate Vulnerability Index (CVI) (Sullivan and Meigh 2005). This CVI incorporates an extra dimension to capture the geographical aspects of vulnerability, and uses scenarios of global change to examine possible futures. This work has been recently featured by both UNECE (2009) and the World Bank (2009) as a useful approach to assessing vulnerability. The approach presented here provides a further development, focusing on water vulnerability per se, as it impacts on a range of aspects of the economy and society, regardless of social conditions or the level of economic development.

2 Need for a Water Vulnerability Index (WVI)

The purpose of this paper is to describe an approach for capturing a representation of 'water vulnerability' using a combination of information from different sources. The *WVI* described here is composed of a measure of *Water system vulnerability* and *Water user vulnerability*. This work has evolved from earlier work on water vulnerability (Sullivan et al. 2006, 2008, 2010; Knoesen 2009) and attempts to develop an index application, so that it can incorporate information relevant to local municipalities and the enterprises and households that they represent. Local municipalities usually have the mandate to ensure adequate water of suitable quality is supplied for domestic and commercial needs, and this is just one of the responsibilities where local governments have an impact on the water sector.

In an attempt to identify appropriate variables to be included in the WVI, some preliminary work was carried

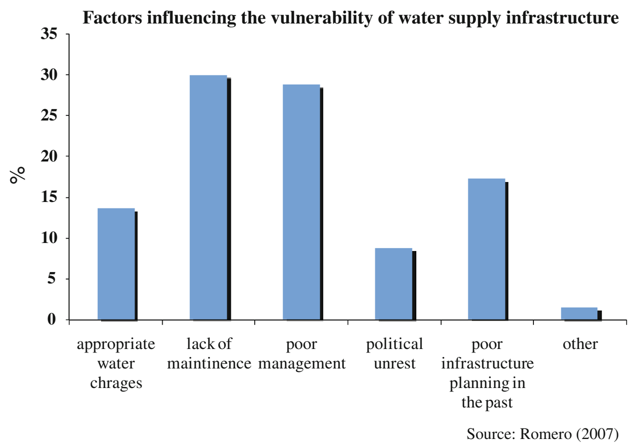


Fig. 1 Vulnerabilities of infrastructure

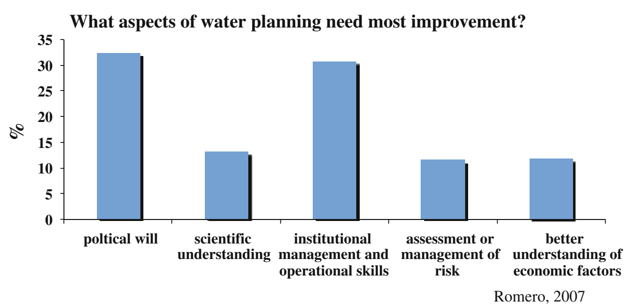


Fig. 2 Perceived weaknesses in water management

out to investigate local perceptions of water vulnerability in the Orange River Basin in South Africa (Romero 2007). Some of the results of this work are shown in Figs. 1 and 2, and these findings are incorporated with other qualitative information from interviews and workshops, to determine appropriate variables to be included in the development of the WVI. This information also provides insights into the relative importance of different aspects of vulnerability from the perspective of local people, and the possible weightings that could be used to represent these more accurately in the assessment process.

3 Structure of the WVI

Having identified and collated the appropriate, relevant, and available data, the *WVI* is then calculated on the basis of two major dimensions:

- supply-driven vulnerability (vulnerability of water systems);
- demand-driven vulnerability (vulnerability of water users).

These dimensions are made up of a selection of components, each of which is calculated from this collated data of sub-indicator (variable) values. Figure 3 shows the

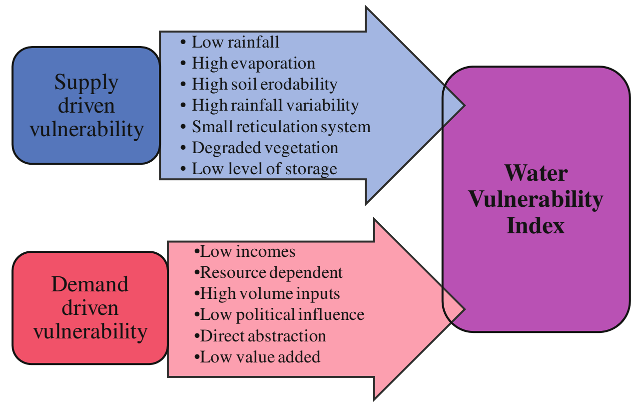


Fig. 3 Characteristics of supply-driven water vulnerability (water systems) and DDWV (water users)

conceptual structure which provides the basis for the selection of the indicators to be used for the *supply-driven vulnerability of water systems* and dimensions of the *demand-driven vulnerability of water users.*

The final selection of variables used to capture a measure of water vulnerability that represents those dimensions of water management, which are relevant at the municipal scale, has been identified on the basis of data availability and expert opinion. The variables used here to represent supply-driven vulnerability are shown in Table 1.

The variables used to represent demand-driven vulnerability are as provided in Table 2.

4 Data requirements

For the purpose of this demonstration of the WVI methodology, the South African part of the Orange River Basin is used, with data sourced from the Statistics South Africa databases, along with national hydrologic and meteorologic data from other relevant sources, as shown in Table 3.

5 Location of the pilot study site

For the purpose of this pilot application of the WVI, a number of municipalities in South Africa are selected. As a contribution to the knowledge available to the authorities responsible for managing water at the basin scale, these municipalities are all located within the Orange River Basin, as it flows through South Africa. Data in South Africa is well organized and available from a variety of sources, including from the national statistical agency, Statistics South Africa. From these national sources, the required data for these municipalities is relatively uniform in quality and meaning. At this stage, it is decided that the whole of the basin could not be considered due to the lack

Table 1 Variables used to calculate supply-driven water vulnerability

Water resource supply	
Resource vulnerability	Mean annual run-off including upstream contributions (normalized and inverted)
	Annual groundwater exploitation potential (normalized and inverted)
Extreme event vulnerability	Number of days per annum where rainfall = 0 mm (normalized)
	Days per annum with rainfall >25 mm (normalized)
Land cover vulnerability	Percentage cover of urbanisation upstream
	Percentage cover of irrigated land
Storage vulnerability	Dam coverage (Ha per capita) (normalized and inverted)
	Coefficient of variation of mean annual precipitation

Table 2 Variables used to calculate DDWV

Note: The variables (sub-indicators) used in this prototype version of this work will be modified in future iterations to include more water quality measures. Such data was not available consistently for all municipalities in this sample, and so this has been left out at this time

Water resource users	
Demographic vulnerability	Total population (normalized)
	Population density (persons/ha) (normalized)
Household vulnerability	Percentage of economically vulnerable households
	Percentage households using water from direct resource
Economic vulnerability	Percentage employment in water-dependant sectors (agric, manufacturing, mining)
	Percentage GVA in water-dependent sectors (agriculture, manufacturing, mining)
Bulk demand vulnerability	Total annual water demand (normalized)
	Evaporative demand (mm/annum) (normalized)

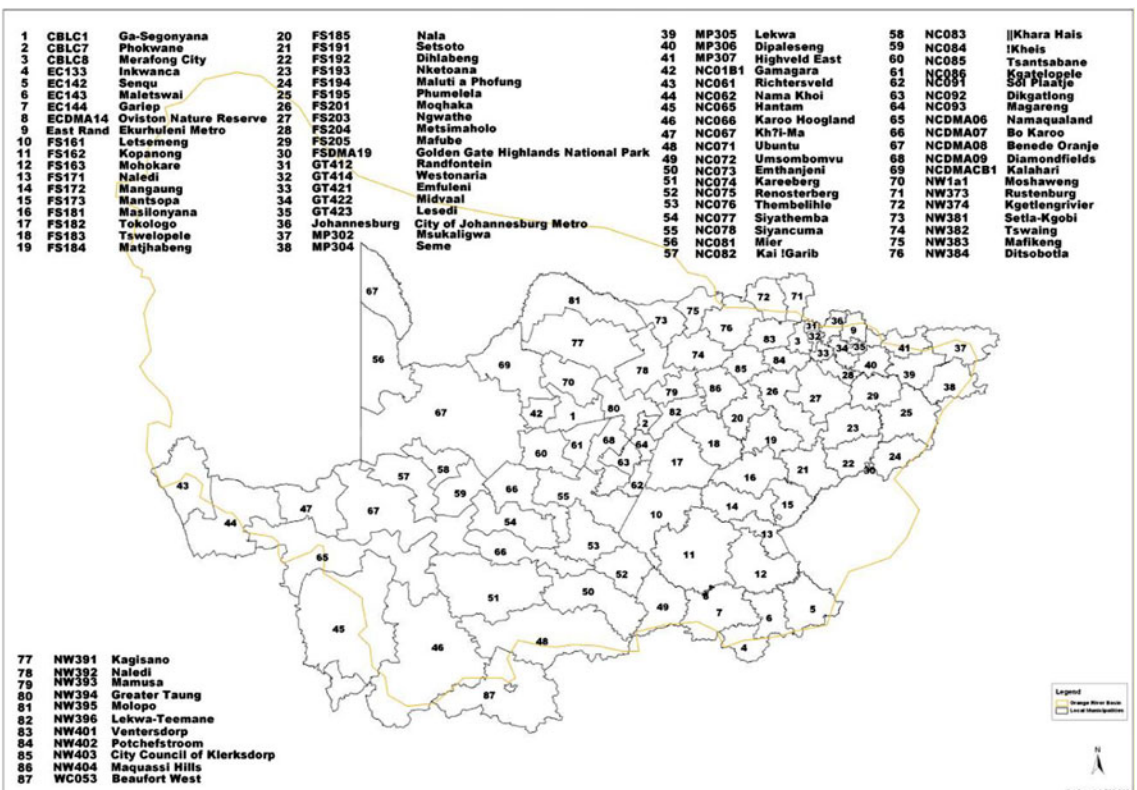


Fig. 4 Cases used as pilot tests for the WVI. Eighty seven local municipalities in the South African portion of the Orange River Basin. *Source*: Diederichs et al. (2008)

Table 3 Data sources used to develop the WVI

Data set	Source	Date	Scale
Demand driven vulnerability index			
Census data	Stats SA	2001	Per municipality
Total population (normalized)	Stats SA		
Percentage of economically vulnerable households	Stats SA		
Percentage households using water from direct resource	Stats SA		
Population density (persons/ha) (normalized)	Stats SA		
Percentage employment in water-dependant sectors (agriculture, manufacturing, mining)	Stats SA		
GVA-R % GVA in water-dependent sectors (agriculture, manufacturing, mining)	Global insight	2007	Per municipality
Total annual water demand (normalized)	DWAF	2003	
Evaporative demand (mm/annum) (normalized)	UKZN	2008	
Supply driven vulnerability index			
Land cover	CSIR	2001	Satellite
Percentage cover of irrigated land	CSIR		
Percentage cover of urbanisation upstream	CSIR		
Dam coverage (Ha per capita) (normalized and inverted)	DWAF	1995	1:50000
Annual groundwater exploitation potential (normalized and inverted)	DWAF		
Mean annual run-off including upstream contributions (normalized and inverted)	UKZN	2008	
Coefficient of variation of mean annual precipitation	UKZN	2008	
Number of days per annum where rainfall = 0 mm (normalized)	UKZN	2008	
Days per annum with rainfall >25 mm (normalized)	UKZN	2008	
Other			
Catchment boundaries	DWAF	1995	1:50000
Water management areas	DWAF	2001	1:50000
Nor	Surveyor general	1995	1:50000
Population growth rates	IDP's	Variable	Per municipality
Local municipality boundaries	STATSSA	2001	1:50000
Soil erodibility index (sediment yield)	UKZN	2008	
Percentage annual water demand for agriculture	DWAF	2003	
Percentage annual water demand for domestic use	DWAF	2003	
Percentage annual water demand for mining and industry	DWAF	2003	
Percentage annual water demand for transfers	DWAF	2003	
Percentage annual water demand for power generation	DWAF	2003	

of consistency and availability of data from the other countries in the basin, but it is also hoped that in the future this approach can be applied to those portions of Lesotho, Botswana, and Namibia that fall within the Orange Basin.

While these local municipalities all fall within 27 distinct District municipal areas, and form part of a small number of larger Water Management Areas, as defined by the Department of Water and Forestry, South Africa, it is decided that the local municipal scale provides the finest resolution possible for the purpose of supporting local efforts towards Integrated Water Resources Management (IWRM). As a result, this approach is applied to a total of 87 local municipalities which fall within the Orange Basin, as illustrated in Fig. 4.

6 Procedure to calculate the WVI

The commonly used formula for any composite index is a weighted average of all the normalized variable values which are used to compute the final index. The resultant score usually ranges from 0 to 100. In the case of a vulnerability index, a high score represents a higher level of vulnerability. Due to the objective of this work being to *provide a representation of vulnerability to changes in conditions in the water sector*, the weights used in the formula are taken to represent the risk (r) associated with a specific variable becoming more likely to lead to a vulnerable condition. In the first instance, this may be based on expert opinion, expressed as high, medium, or low (3, 2, or 1). In order to create a baseline value for each area to be assessed, this risk factor (weight) is considered as constant for all variables. This would ensure that different areas can be compared on the basis of the variable scores, rather than on the basis of subjective risk values. A second iteration of the index calculation can be made with the risk factors applied according to the expressed risk values. This would be useful for specific local evaluation, and would enable local stakeholders to be engaged with the process, empowering them and building acceptance of the tool. At this stage, this paper presents the baseline approach where weightings of components are kept neutral. Much has been written on the subject of the use of weightings in index formulation (Connolly and Chisholm 1999; Senior 2002), and interested readers are advised to examine this if they wish to know more on the subject of weightings.

7 Formulae used to calculate the WVI

At the most simple level, the WVI is made up of a combination of measures of *User* and *System* vulnerabilities. These two sources of vulnerability are combined to generate an overall assessment of *water vulnerability* for a specific place:

$$\mathrm{WVI} = \mathrm{SDWV} + \mathrm{DDWV} \tag{1}$$

where WVI is the Water Vulnerability Index; SDWV (*supply-driven water vulnerability*) is the vulnerability of water systems; and DDWV (*demand-driven water vulnerability*) is the vulnerability of water users.

$$\mathrm{DDWV} = \left[\frac{r_{tp}TP + r_{pd}PD + r_{ec}EC + r_{ds}DS + r_{emp}EMP + r_{gv}GVA + r_{dem}DEM + r_{ed}ED}{r_{tp} + r_{pd} + r_{ec} + r_{ds} + r_{emp} + r_{gva} + r_{dem} + r_{ed}}\right] \times 0.5 \tag{4}$$

Depending on the purpose and location of the application of this tool, varying degrees of sophistication of calculation can be used. Ideally, not only should the magnitude of any attribute or criteria be measured, but also the importance of it to the final outcome, as expressed here by the term *r*, representing the risk of any component giving rise to increased vulnerability. More specifically:

$$\mathrm{WVI} = \frac{\sum_{i=1}^{N} r_i X_i}{\sum_{i=1}^{N} r_i} \tag{2}$$

where WVI is the Water Vulnerability Index value for a particular location; X_i refers to component i of the WVI structure for that location; and r_i is the risk of that component increasing the degree of vulnerability (risk can be defined statistically or based on the subjective view of local experts). The theoretical basis for this approach is one founded on the principles and methods of a Multi-Criteria Analysis (MCA) approach, well established as a tool for management in many spheres, ranging from medical applications to natural resource management.

7.1 Calculating supply-driven water vulnerability (vulnerability of water systems)

The supply-driven water vulnerability (SDWV) is given as:

$$\mathrm{SDWV} = \left[\frac{r_m M + r_{gw} GW + r_z Z + r_{Ex} Ex + r_{uu} UU + r_i I + r_d D + r_{rv} RV}{r_m + r_{gw} + r_z + r_{ex} + r_{er} + r_{uu} + r_i + r_d + r_{rv}}\right] \times 0.5 \tag{3}$$

where M is the mean annual rainfall (MAR) (mm/year); GW is groundwater exploitation potential (mm/year); Z is days per year when rainfall = 0; Ex is extreme events (days per year where rainfall >25 mm); UU is % upstream area urbanized; I is % area of irrigated land; D is dam coverage (Ha/cap); RV is rainfall variability − coefficient of variation of MAR; and r is weight for each variable, denoting the risk of each variable giving rise to increased vulnerability.

7.2 Calculating DDWV (vulnerability of water users)

The DDWV is given as:

where TP is the total population; PD is population density; EC is economic vulnerability (% of economically vulnerable households); DS is % of population getting water directly from the source; EMP is % of employment from water-dependent sectors; GVA is % gross value added from water-dependent sectors; DEM is total annual water demand (mm/year); ED is total evaporative demand (mm/year), and r is the weight for each variable, denoting the risk of each variable giving rise to increased vulnerability.

Note that in both the user and the system components, the inverse of the variable values may have to be used to indicate increased vulnerability (e.g. high storage = low vulnerability, low income = high vulnerability). To enable the use of a scale of 0–100, the supply- and demand-driven vulnerability values are each multiplied by 0.5.

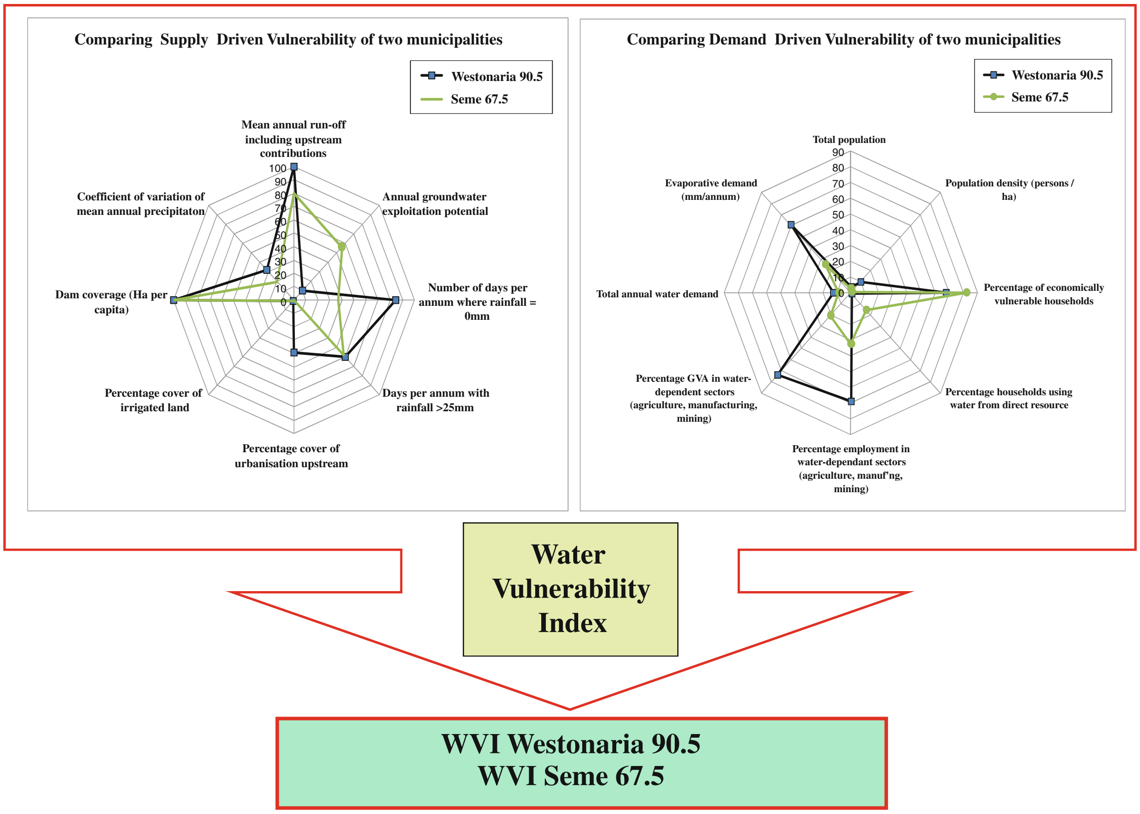


Fig. 5 Current conditions of water vulnerability in two municipalities in South Africa

Through the application of these formulae to the data collated for the purpose of this calculation, a value can be derived to measure water vulnerability. While this information can be combined and expressed in terms of a single index value, it is much more useful if displayed graphically, using a multi-axis graph which can show component values together. An example of how this can be done is shown in Fig. 5.

8 Results

When this approach is applied to municipal scale data, the results show how water vulnerability varies between different municipalities, within the same river basin, as shown in Fig. 6. From this, a significant degree of variability (SD = 8.69) can be observed between municipalities, in terms of water vulnerability as measured in this way. It is also interesting to examine how the level of demand-driven vulnerability (water user vulnerability) compares to that of supply-driven vulnerability (water system vulnerability). These scores for 87 municipalities are shown in Fig. 7.

9 How municipalities compare across the basin: selected examples

When the information from the WVI is mapped at the municipal scale, the variation in vulnerability can be clearly observed across the basin. This is illustrated in Fig. 8, which indicates the pressure points in terms of which municipalities are more vulnerable than others. Through the use of this map, municipal managers can compare their situations to that of their neighbors, and lobby for more attention if needed. At the basin scale, basin managers can identify water-stressed locations which can then be dealt with appropriately, to reduce future vulnerability risk. This methodology also serves to reveal the likely source of such stress, thus indicating the possible direction of future remedial action.

From Fig. 8, it can be seen that certain municipalities across the Orange Basin in South Africa are likely to be much more vulnerable to possible future changes than others. Table 4 presents a selection of municipalities exhibiting higher and lower levels of vulnerability.

The vulnerability profiles of four municipalities from Table 4 are shown in Figs. 9 and 10, and from this it can be seen that there is a lot of variability in the reason why places are vulnerable, and a tool like the WVI serves to

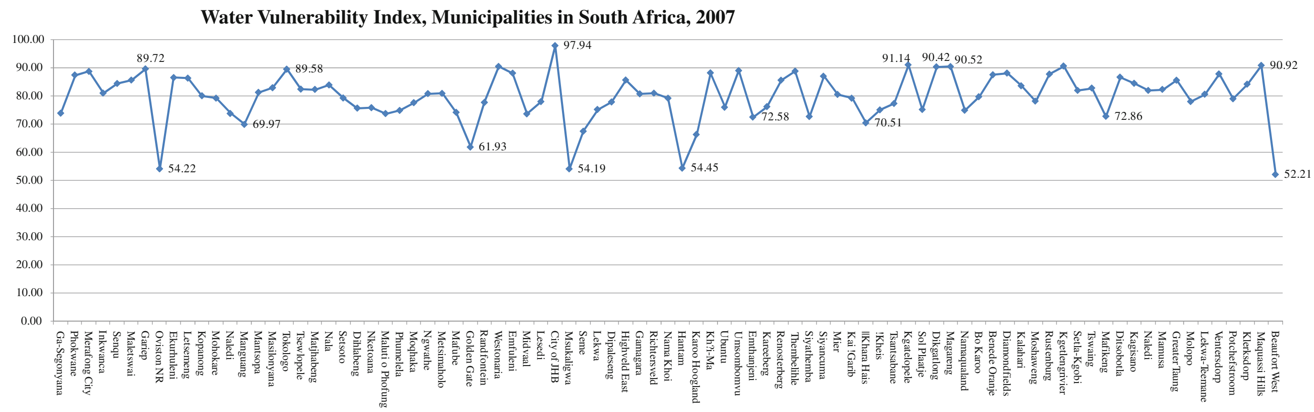


Fig. 6 WVI scores for South African municipalities in the Orange Basin

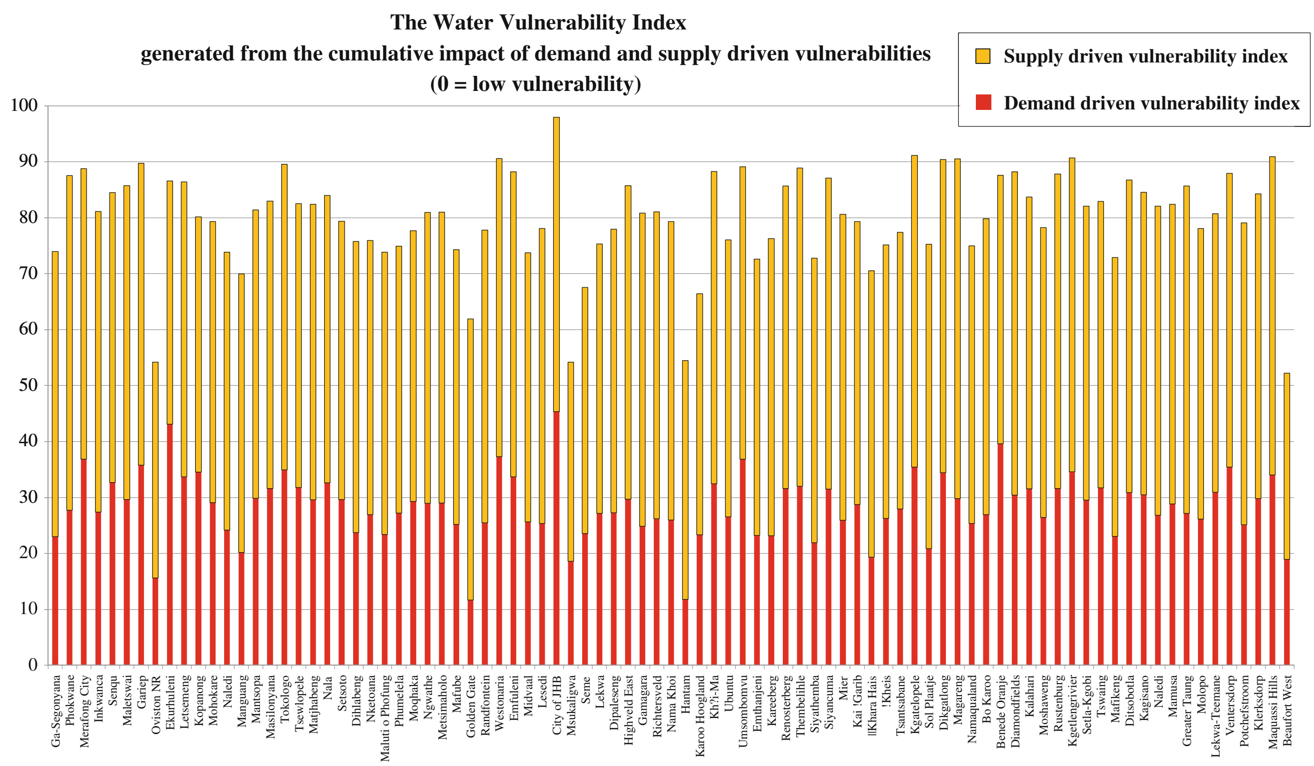
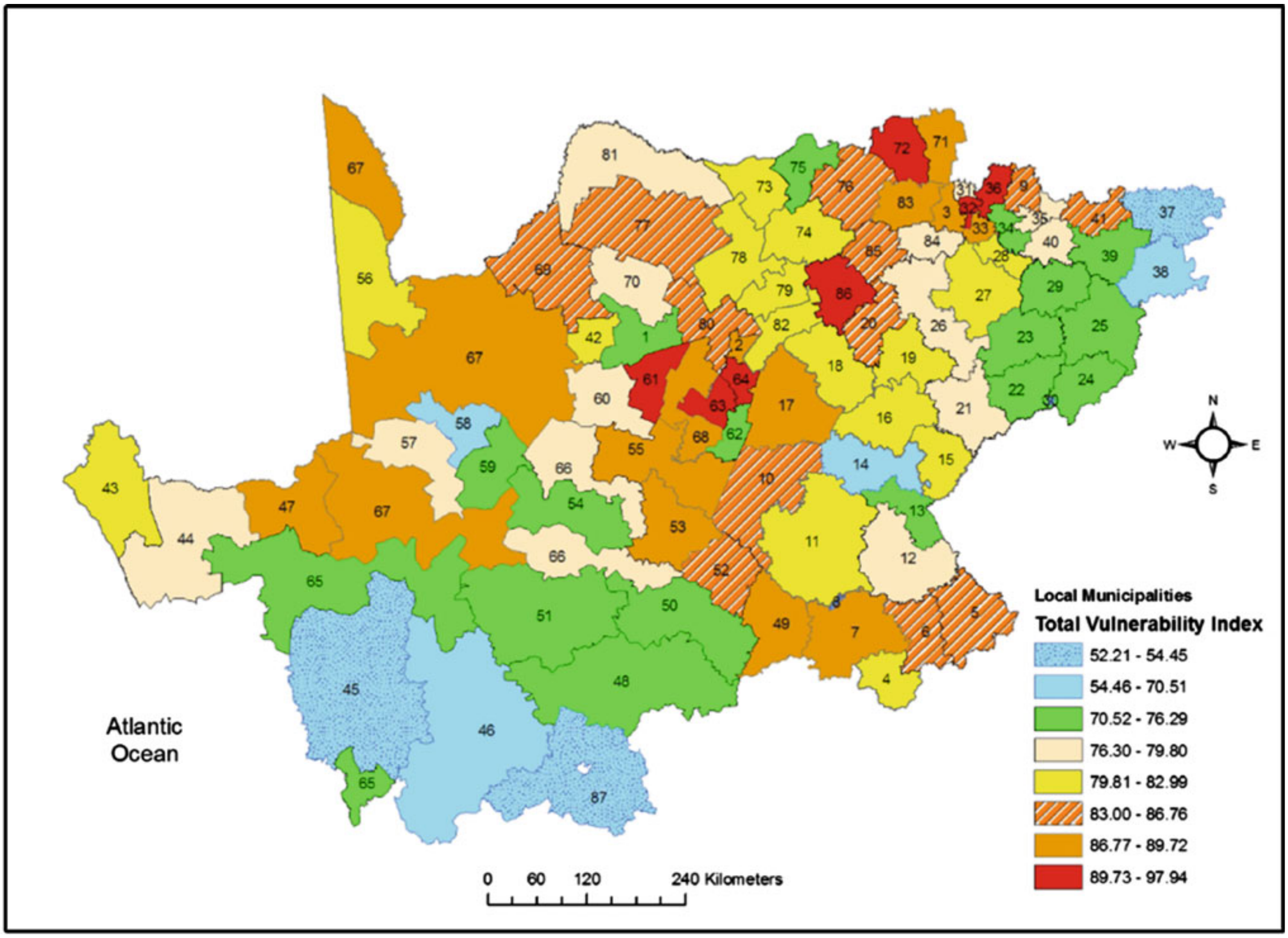


Fig. 7 WVI: combined demand and supply driver values

reveal that variation. This means that site-specific responses are possible. For example, although Westonaria and Johannesburg are both highly vulnerable, they are so for different reasons, from the point of view of both demand- and supply-driven vulnerability. From the perspective of policy makers, this means that more tailored responses can be generated, and action can be taken that is more likely to deliver appropriate adaptive strategies.

From the point of view of the demand drivers, this analysis reveals that the level of water vulnerability in Johannesburg is most heavily influenced by demographic factors, although other sources of vulnerability are more meaningful. For Westonaria, which has just a slightly lower overall vulnerability, the main drivers are economic dependence on water resources for employment, and the generation of value added, rather than population, which has a low driver value.

In the case of the less vulnerable places shown here, Seme and Beaufort West, while their overall vulnerability is lower than the other cases, the reasons for this are quite different. For Seme, the main vulnerability driver is clearly poverty, while for Beaufort West it is more an issue of high levels of evaporative demand, coupled with poverty-driven vulnerability.



Municipality ID	Name	Municipality ID	Name	Municipality ID	Name	Municipality ID	Name	Municipality ID	Name
M 1	Ga-Segonyana	M 21	Setsoto	M 41	Highveld East	M 61	Kgatelopele	M 81	Molopo
M 2	Phokwane	M 22	Dihlabeng	M 42	Gamagara	M 62	Sol Plaatje	M 82	Lekwa-Teemane
M 3	Merafong City	M 23	Nketoana	M 43	Richtersveld	M 63	Dikgatlong	M 83	Ventersdorp
M 4	Inkwanca	M 24	Maluti o Phofung	M 44	Nama Khoi	M 64	Magareng	M 84	Potchefstroom
M 5	Senqu	M 25	Phumelela	M 45	Hantam	M 65	Namaqualand	M 85	Klerksdorp
M 6	Maletswai	M 26	Moqhaka	M 46	Karoo Hoogland	M 66	Bo Karoo	M 86	Maquassi Hills
M 7	Gariep	M 27	Ngwathe	M 47	Kh?i-Ma	M 67	Benede Oranje	M 87	Beaufort West
M 8	Oviston NR	M 28	Metsimaholo	M 48	Ubuntu	M 68	Diamondfields	The municipalities across the portion of Orange Basin that falliing within South Africa are very variable, and include desely populated areas, such as the City of Johannesburg, as well as remote mountain and desert areas.	
M 9	Ekurhuleni	M 29	Mafube	M 49	Umsombomvu	M 69	Kalahari		
M 10	Letsemeng	M 30	Golden Gate	M 50	Emthanjeni	M 70	Moshaweng		
M 11	Kopanong	M 31	Randfontein	M 51	Kareeberg	M 71	Rustenburg		
M 12	Mohokare	M 32	Westonaria	M 52	Renosterberg	M 72	Kgetlengrivier		
M 13	Naledi	M 33	Emfuleni	M 53	Thembelihle	M 73	Setla-Kgobi		
M 14	Manguang	M 34	Midvaal	M 54	Siyathemba	M 74	Tswaing		
M 15	Mantsopa	M 35	Lesedi	M 55	Siyancuma	M 75	Mafikeng		
M 16	Masilonyana	M 36	City of JHB	M 56	Mier	M 76	Ditsobotla		
M 17	Tokologo	M 37	Msukaligwa	M 57	Kai !Garib	M 77	Kagisano		
M 18	Tsewlopele	M 38	Seme	M 58	ǁKhara Hais	M 78	Naledi		
M 19	Matjhabeng	M 39	Lekwa	M 59	!Kheis	M 79	Mamusa		
M 20	Nala	M 40	Dipaleseng	M 60	Tsantsabane	M 80	Greater Taung		

Fig. 8 WVI scores at the municipal scale, mapped across the basin (*darker colors* indicate higher vulnerability)

Table 4 Higher and lower than average WVI values in selected municipalities

	Westonaria 37.3	City of JHB 45.3	Seme 23.6	Karoo Hoogland 23.3
Water resource users				
Demographic vulnerability				
Total population	3.5	100.0	2.6	0.3
Population density (persons/ha)	9.5	100.0	0.8	0.0
Household vulnerability				
Percentage of economically vulnerable households	67.7	51.0	82.1	68.5
Percentage households using water from direct resource	1.0	0.5	15.6	1.0
Economic vulnerability				
Percentage employment in water-dependant sectors (agriculture, manufacturing, mining)	69.2	13.9	32.6	46.8
Percentage GVA in water-dependent sectors (agriculture, manufacturing, mining)	74.1	19.4	20.4	45.9
Bulk demand vulnerability				
Total annual water demand	12.6	17.2	8.6	0.9
Evaporative demand (mm/annum)	60.8	60.6	25.6	23.0
Demand driven vulnerability index	37.3	45.3	23.6	23.3
	Westonaria 53.3	**City of JHB 52.6**	**Seme 44.0**	**Karoo Hoogland 43.1**
Water resource supply				
Resource vulnerability				
Mean annual run-off including upstream contributions	100.0	96.0	80.4	24.9
Annual groundwater exploitation potential	10.0	57.9	56.4	98.8
Extreme event vulnerability				
Number of days per annum where rainfall = 0 mm	84.5	72.3	36.6	57.7
Days per annum with rainfall >25 mm	59.8	67.8	58.0	38.2
Land cover vulnerability				
Percentage cover of urbanisation upstream	39.1	0.0	0.0	0.1
Percentage cover of irrigated land	0.8	1.4	0.6	0.2
Storage vulnerability				
Dam coverage (Ha per capita)	100.0	100.0	100.0	100.0
Coefficient of variation of mean annual precipitation	31.9	25.5	20.0	24.8
Supply driven vulnerability index	53.3	52.6	44.0	43.1
Total WVI	90.6	97.9	67.6	66.4

In the case of supply-driven water vulnerability, Fig. 10 illustrates again how site-specific the drivers of vulnerability can be.

In the case of the two more-vulnerable examples, Johannesburg and Westonaria are both vulnerable from lack of storage (illustrated by a high vulnerability score on that axis), and from compromised runoff, although Johannesburg appears to have a higher risk from overexploitation of groundwater (or simply lack of it), and more extreme events. In the case of the less-vulnerable examples presented here, there is still a threat from lack of storage, but Seme has more risks associated with hydrologic variability, while groundwater appears to be a more likely source of vulnerability in Beaufort West, although surface water is more secure, and other factors have low levels of vulnerability associated with them.

This simple and relatively superficial examination of these examples illustrates the usefulness of this approach. This provides an overview comparative score, which can be used for heuristic and lobbying purposes, while the detailed cross-section values provide insight into the causes of that vulnerability in more detail. This can then be used to guide the development of appropriate adaptation strategies.

10 Assessing future water vulnerability

To support development planning, it is useful to assess possible future conditions. Such assessment can be made by

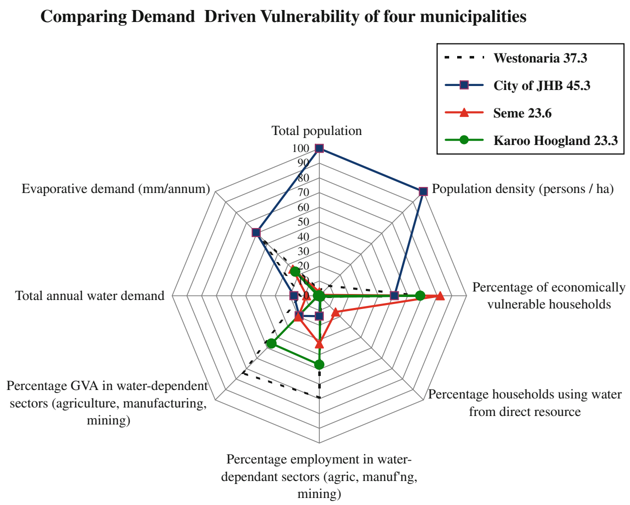


Fig. 9 Illustrating DDWV

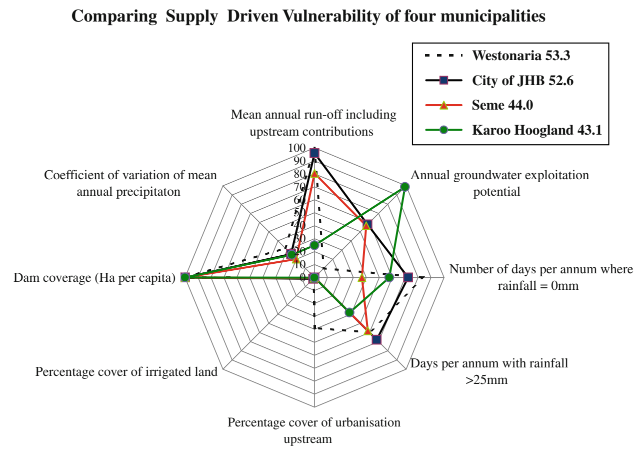


Fig. 10 Illustrating supply-driven water vulnerability

Table 5 Comparing vulnerability profiles over time (hypothetical scenario)

	Westonaria	City of JHB	Seme	Karoo Hoogland
Original total WVI	90.6	97.9	67.6	66.4
Demand driven water vulnerability +20%	44.8	54.4	28.3	28.0
Supply driven water vulnerability −10%	47.9	47.3	39.6	38.8
Total new WVI, under climate change	92.7	101.7	67.9	66.8

adjusting the values of the WVI scores on the basis of expected future conditions. To provide a hypothetical illustration of this, the current values of the demand drivers are increased by 20% (by 2030), while the supply drivers are reduced by 10% (by 2030). The results of this projection for 2030 are shown in Table 5, and it can be seen that the municipal-specific vulnerability profiles will vary over time.

From Table 5, it is interesting to observe that it appears that, without adaptive strategies, the most vulnerable places become even more vulnerable, while there is little change in the less vulnerable locations. This highlights the point that, from an equity perspective, there is urgent need to address the development of more effective, targeted, and adaptive strategies of water management. It is important to note, however, at this point that to apply this process in reality, the future scenarios must be determined, so that real assessments can be made, of how each of these drivers will change over time. At this stage, this work is incomplete, and will be presented in a follow-up paper.

11 Discussion

The objective of any multi-dimensional tool is to provide a cross-section of information, so that the user can consider the options available. This inevitably means that there is uncertainty associated with the values generated by this approach. Such imprecision is simply the nature of the reality of Earth System Science[1] as we know it in 2010, coupled with the qualitative attributes of the social sciences. No doubt, as our techniques of monitoring and database management and design improve, it will be possible to reduce uncertainty in the generated values, increasing their robustness and reliability. Object-oriented and Bayesian approaches can be applied for greater refinement (Molina et al. 2010), but such an approach is beyond the scope of this paper.

It is clear that the approach outlined here does provide a tool which can differentiate between municipalities in a way that enables policy makers to evaluate progress over time, at a manageable scale. The term '*manageable*' is used here to mean that scale *where actions can be directly implemented*, through the existing local governance framework. The presence of this site-specific institutional framework means that locally-generated decisions can be implemented, with benefits delivered more quickly. In the context of the severity of water problems in many areas, speeding up service delivery would be a significant advantage.

[1] See Earth System Science Partnership (ESSP) http://www.essp.org.

There are clearly many shortcomings with this approach as it stands at present. There is much further work to be done to refine the method to improve its validity. In terms of its reliability, “ground truthing” is needed to make a fair evaluation of the generated WVI values, but this work has yet to be done. The work presented here, therefore, is to provide the baseline framework, upon which scenarios can be applied, to generate a multivariate assessment of future conditions relating to water vulnerability.

12 Conclusion

The method of calculating the *WVI* presented here inevitably means that there is uncertainty associated with the values generated by the approach. This, however, should not be seen as a disadvantage of the process, but rather one which provides a more honest picture of the situation, recognizing explicitly that our understanding is not perfect, and that we need to develop policies that are adaptive and flexible in the face of such uncertainty. Recognition of the value of this kind of more fuzzy approach has been demonstrated recently in publications of the UNECE (2009) and the World Bank (2009), which have both identified the *CVI* (Sullivan and Meigh 2005) as a useful tool for vulnerability assessment.

The development of an easy-to-use tool, which can empower water managers and economic planners to assess their water vulnerability, is urgently needed. This will enable them to understand more, both about current conditions and future potential changes in the water sector. As a result, societies will be better able to take action to prepare themselves for future conditions, reducing their water vulnerability and increasing their water security. Since any increase in water security would also increase the level of food security, this would be of crucial importance in the face of today’s global pressures.

There is also much scope to improve the validity of the WVI by including more information on water quality. To date, this has not been possible due to extreme variability in the availability of robust and comparable water quality data. Water quality data is expensive to generate and impractical to collect over wide areas. There is certainly a need for the development of an alternative approach to address this information gap, and some argue that this can be addressed using statistical and qualitative approaches (Buma et al. 2007). In some areas, progress is being made to bring together all available water quality information, as is intended in the formation of the GEMS database. Such information would be of use in the analytical framework described here.

The concept of *IWRM* has become key to water management today, with many nations having signed up to the principle (GWP 2006). Any tool which can help in this process, through systematic geospatial integration of information, will make a positive contribution to the implementation of IWRM.

To make full use of this approach in addressing trans-boundary water management, it would be worthwhile to apply the WVI approach at the same scale, in those parts of the basin which lie in other countries. The reason why this has not been done here is due to the variability in the nature of data availability and lack of resources to cover other parts of the basin. This is planned in future work, and there is little doubt that basin management organizations, such as the Orange Basin Commission (ORASECOM), would have interest in such work.

As human pressure continues to rise on our available water resources, there is a clear need for more effective, integrative tools for water management. The work presented here represents such a tool, by providing a simple, yet comprehensive, analytical framework, which can be applied at a variety of scales. In the examples presented here, the municipal scale is illustrated, as it is felt that this scale is the one most appropriate to address domestic water provision. This example also serves to illustrate the importance of scale in the use of any natural resource management tool.

In the context of climate and other forms of global change, it will be important to ensure that we maintain the maximum degree of flexibility in operational water management. It will be essential that communities maintain diversity of sources and flexibility of allocations, so that responses to changing conditions can be made speedily and effectively. With this objective in mind, the *WVI* provides a cross section of information, so that users can consider site-specific options available to them, in the context of their actual realities.

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