Southern Cross University
ePublications@SCU

School of Environment, Science and Engineering Papers

School of Environment, Science and Engineering

2011

# Quantifying water vulnerability: a multi-dimensional approach

Caroline A. Sullivan
*Southern Cross University*

## Publication details

Post-print of: Sullivan, CA 2011, 'Quantifying water vulnerability: a multi-dimensional approach', *Stochastic Environmental Research and Risk Assessment,* vol. 25, no. 4, pp. 627-640.
Published version available from:
http://dx.doi.org/10.1007/s00477-010-0426-8

ePublications@SCU is an electronic repository administered by Southern Cross University Library. Its goal is to capture and preserve the intellectual output of Southern Cross University authors and researchers, and to increase visibility and impact through open access to researchers around the world. For further information please contact epubs@scu.edu.au.

# Quantifying Water Vulnerability: a Multidimensional Approach

**Caroline A Sullivan**[1]


## Abstract

In today's uncertain world, vulnerability of water supplies is of increasing concern across the World. A number of factors influence this, ranging from physical conditions, through to human management capacities. If we are to be able to cope with this vulnerability, we must try to understand it better, and this must start by identifying the factors which give rise to it. In this context, vulnerability relates to any exposure to physical or socioeconomic threat which can be mitigated by human capacity for adaptation. Across the Orange basin, these threats arise from overpopulation and farming pressure, with agrochemical and industrial runoff and 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 Resource Management* (IWRM). This means that they have to try to understand all of the complexities of managing water across heterogeneous basins, in order to try to allocate water in an equitable and efficient way.

It is now recognised that effective water management is much more dependent on effective governance than on hydrological regimes (Meybeck, 2003). While access to water resources is clearly a pre-requisite, the ways these can be delivered and used vary considerably both within and between countries. 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 harmonisation 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, we evaluate the *supply driven vulnerability* (from water systems) and the *demand driven vulnerability* (from water users), at the municipal scale. By combining these various dimensions together mathematically, we can generate a *Water Vulnerability Index*. In this paper, this tool has been piloted in Orange basin, in South Africa, and it is hoped that the results illustrated here will provide information of use not only to policy makers across the region, but also to others across the World.


**Keywords:** Water Vulnerability, IWRM, water governance, municipalities, Water Poverty Index, Climate Vulnerability Index


## Acknowledgements

This work has been funded by the European Union NeWater Project '*New Approaches to Adaptive Water Management under Uncertainty*' (contract no. 511179GOCE). The results shown here do not reflect the views of the European Union, and are solely the responsibility of the author. Important contributions to this work have been made by Nicci Diederichs, Myles Mander, Alta Drayer and Chris Dickens. Assistance with the mapping has been provided by Sumith Pathirana.


[1] Southern Cross University, New South Wales, Australia, and Oxford University School of Geography and the Environment Email: caroline.sullivan@scu.edu.au

## 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 summarised in major assessments such as the Millennium Ecosystem Assessment (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 globalisation, 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 industrialisation are exacerbating this situation of water scarcity (WRI, 2000 MEA, 2005).

Management of water resources is fundamental to human development, and has been since the first establishment of human civilisation. 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 the 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 characterised 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 prioritising limited financial resources to support these changes (Sullivan and Meigh,2005). 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 know 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 socioeconomic 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 by situations which may be characterised 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 impacts 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 people by 2015, certainly a not 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 prerequisite 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
- 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 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, (Turner et al., 2003, 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 develop methods and approaches which enable clear understanding and indeed visualisation of relevant conditions. It is with this in mind that an index approach is here proposed, 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.

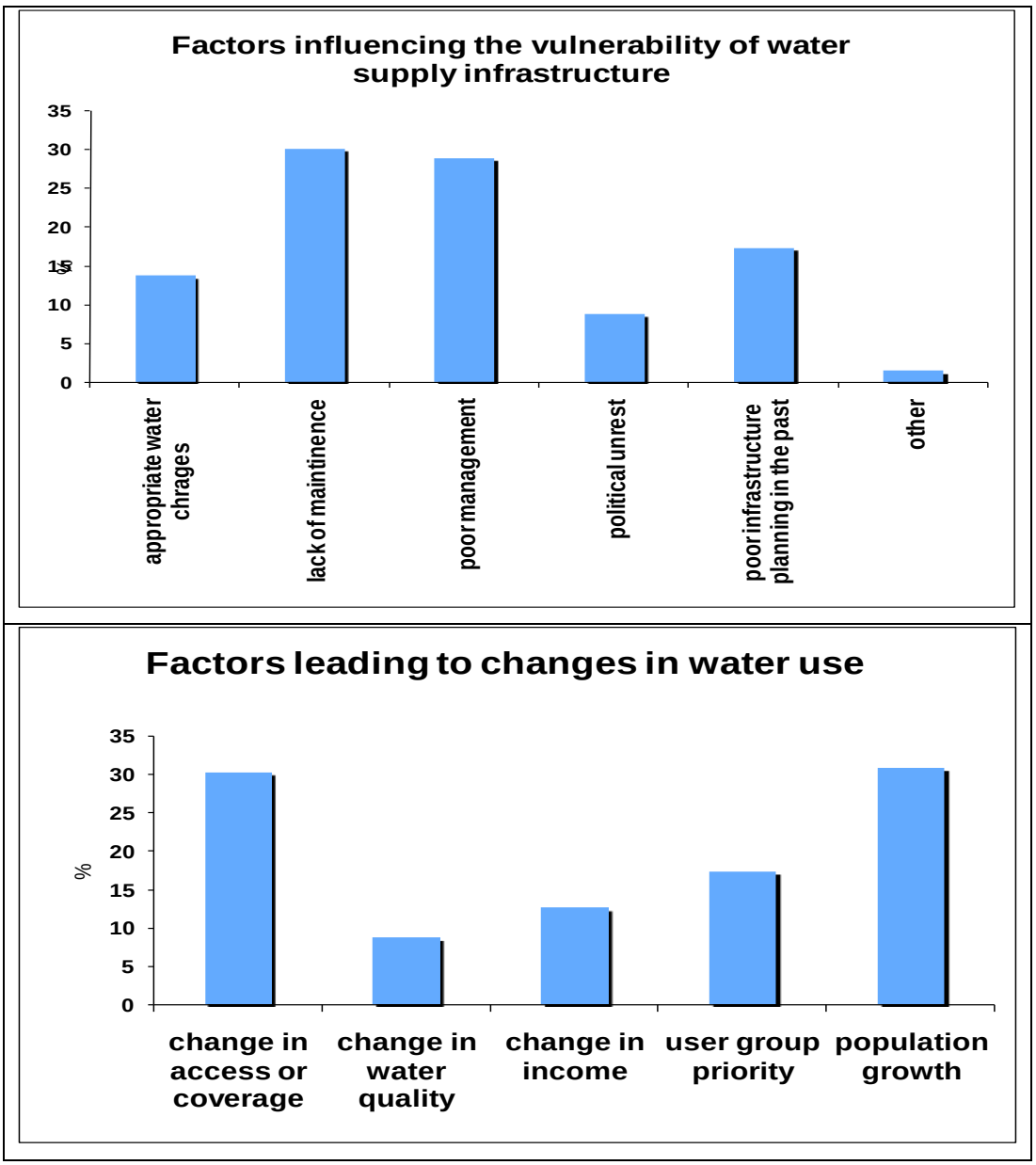
The use of indicators and indices is widespread in both the water sector and in economic policy. Examples of such tools in macroeconomic management include the use of the Retail Price Index (RPI), and in the water sector, there are numerous indicators of water quality and water stress, but mostly these are single indicators, used independently for different purposes. In the context of development, the use of the Human Development Index (HDI) has revolutionised 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 2001-2, and tested in pilot sites in South Africa, Tanzania, and Sri Lanka (Sullivan et al., 2002, Sullivan et al., 2003). Since then it has been used in a number of situations at a variety of scales, and is currently being used as the basis for the 'Canadian Water Sustainability Index' which has been developed by the Privy Council of the Canadian Government (Morin, 2005, PRI Canada, 2007). The Water Poverty Index 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. The approach presented here provides a further development, focussing 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. This work has been recently featured by both UNECE(2009) and The World Bank (2009) as a useful approach to assessing vulnerability.

## 2 The 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 *Water Vulnerability Index* (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, Sullivan et al.,2008) 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 water vulnerability index, some preliminary work was carried 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 Figures 1 and 2, and these findings were incorporated with other qualitative information from interviews and workshops, to determine appropriate variables to be included in the development of the Water Vulnerability Index. 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.

**Figure 1 and 2**




Source: Romero 2007

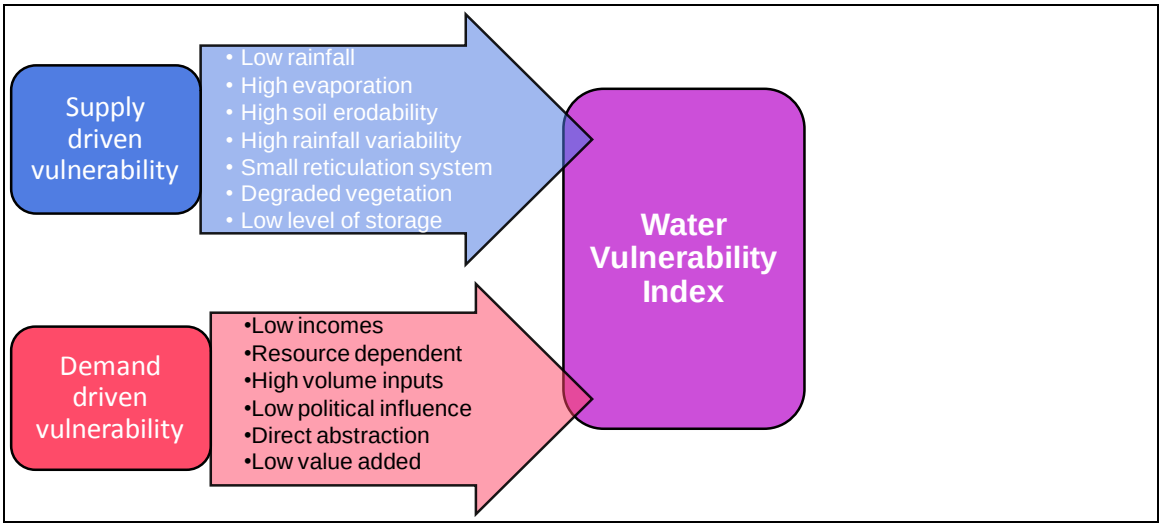
### 3 The Structure of the Water Vulnerability Index (WVI)

Having identified and collated the appropriate, relevant and available data, the *Water Vulnerability Index* (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)

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

**Figure 3 Characteristics of supply driven water vulnerability (water systems) and demand driven water vulnerability (water users)**




The final selection of variables used to capture a measure of water vulnerability which 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.

**Table 1 variables used to calculate Supply Driven Water Vulnerability**

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

Variables used to represent Demand Driven Vulnerability are as provided in Table 2

**Table 2 Variables used to calculate Demand Driven Water Vulnerability**

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

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 for this reason, this has been left out at this time.

## 4 Data requirements

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

**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 (normalised) | Stats SA | | |
| Percentage of economically vulnerable households | Stats SA | | |
| Percentage households using water from direct resource | Stats SA | | |
| Population density (persons / ha) (normalised) | 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 (normalised) | DWAF | 2003 | |
| Evaporative demand (mm/annum) (normalised) | UKZN | 2008 | |
| **Supply driven vulnerability index** | | | |
| **Landcover** | CSIR | 2001 | Satellite |
| Percentage cover of irrigated land | CSIR | | |
| Percentage cover of urbanisation upstream | CSIR | | |
| Dam coverage (Ha per capita) (normalised and inverted) | DWAF | 1995 | 1:50 000 |
| Annual groundwater exploitation potential (normalised and inverted) | DWAF | | |
| Mean annual run-off including upstream contributions (normalised and inverted) | UKZN | 2008 | |
| Coefficient of variation of mean annual precipitaton | UKZN | 2008 | |
| Number of days per annum where rainfall = 0mm (normalised) | UKZN | 2008 | |
| Days per annum with rainfall >25mm (normalised) | UKZN | 2008 | |
| **Other** | | | |
| Catchment Boundaries | DWAF | 1995 | 1:50 000 |
| Water Management Areas | DWAF | 2001 | 1:50 000 |
| Magisterial Districts | Surveyor General | 1995 | 1:50 000 |
| Population Growth Rates | IDP's | Variable | Per Municipality |
| Local Municipality Boundaries | STATSSA | 2001 | 1:50 000 |
| 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 & industry | DWAF | 2003 | |
| Percentage annual water demand for transfers | DWAF | 2003 | |
| Percentage annual water demand for power generation | DWAF | 2003 | |

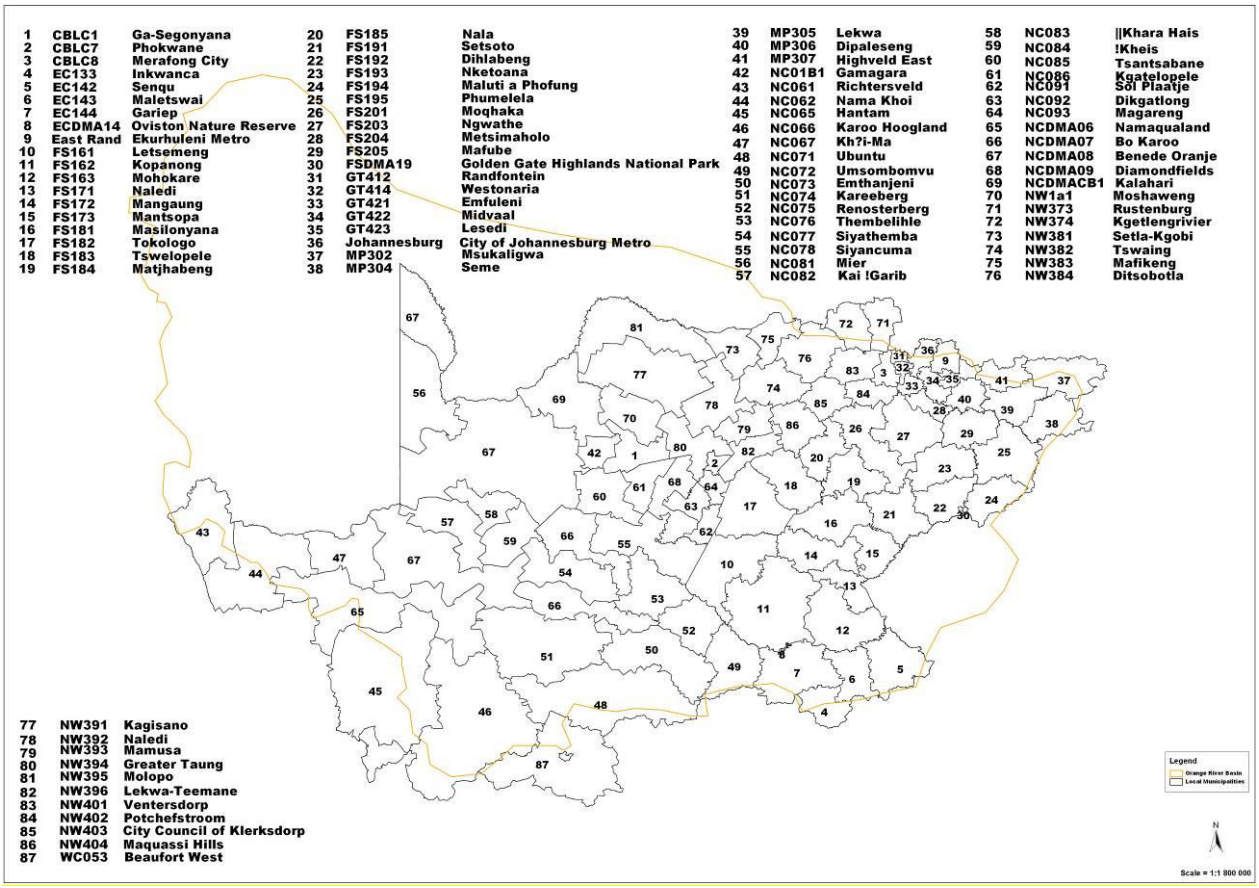
## 5 Location of the pilot study site

For the purpose of this pilot application of the Water Vulnerability Index, a number of municipalities in South Africa have been 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 organised 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 was decided that the whole of the basin could not be considered due to the lack of consistency and availability of data from the other countries in the basin, but it is 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 was decided that the local municipal scale provided the finest resolution possible for the purpose of supporting local efforts towards Integrated Water Resources Management (IWRM). As a result, this approach has been applied to a total of 87 local municipalities which fall within the Orange basin, as illustrated in Figure 4.

**Figure 4 Cases used as pilot tests for the WVI 87 Local Municipalities in the South African portion of the Orange River Basin**




**Source**: Diederichs et al.,2008

## 6 Procedure to calculate the WVI

The commonly used formula for any composite index is a weighted average of all the normalised variable values which are used to compute the final index. The resultant score will range from 0 – 100. In the case of a vulnerability index, a high score will represent 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 will be 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 base line value for each area to be assessed, this risk factor (weight) will be considered as constant for all variables. This will 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, 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 Water vulnerability index

At the most simple level, the Water Vulnerability Index 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:

$$\mathrm{WVI} = \mathrm{SDWV} + \mathrm{DDWV} \qquad [1]$$

where

WVI = Water Vulnerability Index

SDWV = vulnerability of water systems – Supply Driven Water Vulnerability

DDWV = vulnerability of water users - Demand Driven Water Vulnerability

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.

Put more specifically:

$$WVI = \frac{\sum_{i=1}^{N} r_i X_i}{\sum_{i=1}^{N} r_i} \qquad [2]$$

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[2].

The theoretical basis for this approach is one founded on the principles and methods of a MultiCriteria Analysis (MCA) approach, well established as a tool for management in many spheres, ranging from medical applications to natural resource management.

[2] Risk can be defined statistically or based on the subjective view of local experts

**Calculating Supply Driven Water Vulnerability (vulnerability of water systems)**

$$SDWV = \left[ \frac{r_m M + r_{gw} GW + r_z Z + r_{Ex} Ex + r_{uu} UU + r_i I + r_d D + r_{rv} RV}{r_m + r_{gw} + r_z + r_{ex} + r_{er} + r_{uu} + r_i + r_d + r_{rv}} \right] x0.5 \qquad [3]$$

Where:

SDWV = Supply Driven Water Vulnerability (vulnerability of water systems)

M = MAR mean annual rainfall mm/yr

GW = groundwater exploitation potential mm/yr

Z = days per year with zero rainfall

Ex = extreme events – days per year where rainfall >25mm

UU = % of upstream area urbanised

I = % area of irrigated land

D = Dam coverage (Ha/cap)

RV = rainfall variability – coefficient of variation of MAR

$_r$ s = weight for each variable, denoting the risk of each variable giving rise to increased vulnerability

**Calculating Demand Driven Water Vulnerability (vulnerability of water users)**

$$DDWV = \left[ \frac{r_{tp} TP + r_{pd} PD + r_{ec} EC + r_{ds} DS + r_{emp} EMP + r_{gv} GVA + r_{dem} DEM + r_{ed} ED}{r_{tp} + r_{pd} + r_{ec} + r_{ds} + r_{emp} + r_{gva} + r_{dem} + r_{ed}} \right] x0.5 \qquad [4]$$

Where:

*DDWV* = demand driven water vulnerability (vulnerability of water users)

*TP* = total population

*PD* = population density

*EC* = economic vulnerability % of economically vulnerable households

*DS* = % of pop getting water directly from the source

*EMP* = % employment from water dependent sectors

GVA = % Gross Value Added from water dependent sectors

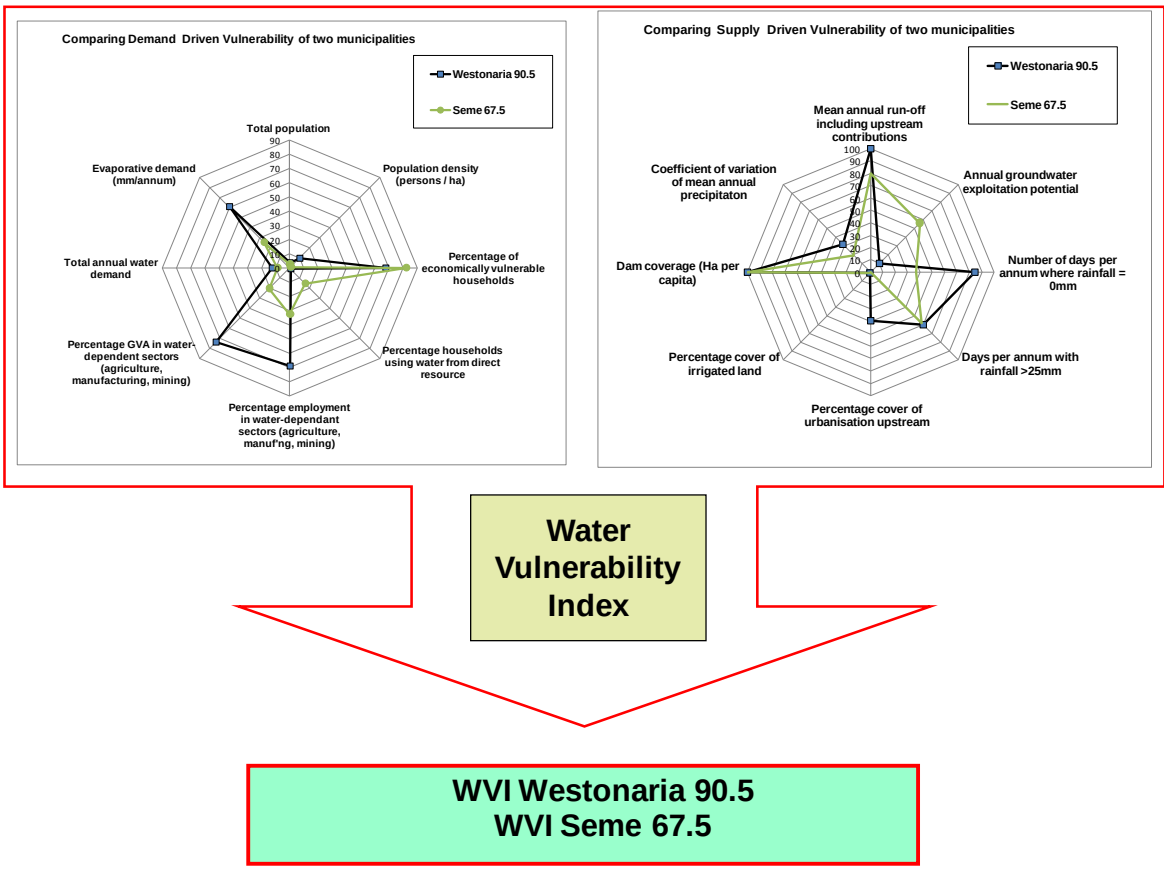
DEM = total annual water demand (mm/yr)

ED = total evaporative demand (mm/yr)

NOTE: In both the user and system components, the inverse of the variable values may have to be used to indicate increased vulnerability (eg. 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.

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 Figure 5,

**Figure 5 Current conditions of water vulnerability in two municipalities in South Africa**




## 6 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 Figure 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 supply driven vulnerability (water system vulnerability). These scores for 87 municipalities is shown in Figure 7.

## 8 How municipalities compare across the basin: Selected examples

When the information from the Water Vulnerability Index is mapped at the municipal scale, the variation in vulnerability can be clearly observed across the basin. This is illustrated in Figure 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 neighbours, 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.

**Figure 6 Water Vulnerability Index scores for South African municipalities in the Orange Basin**

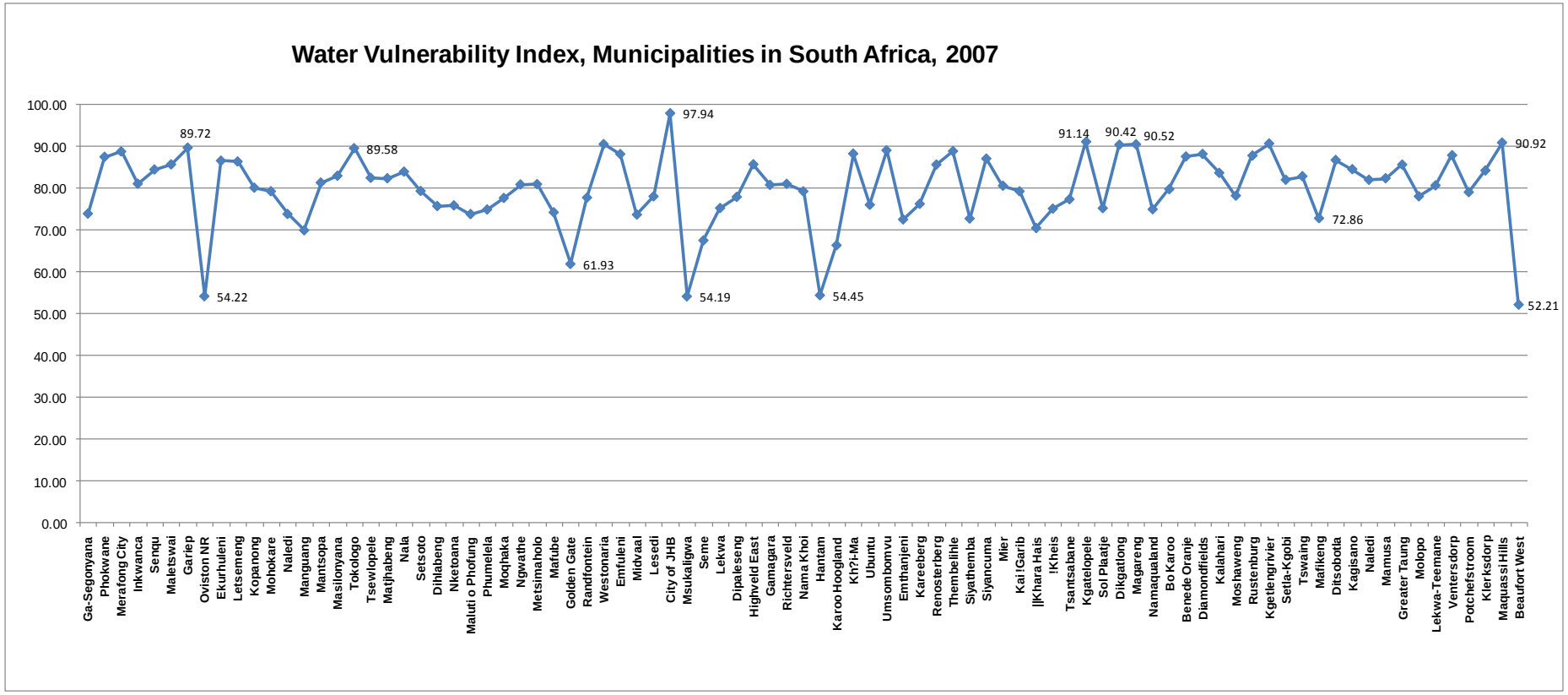


**Figure 7 Water Vulnerability Index value demand and supply drivers**

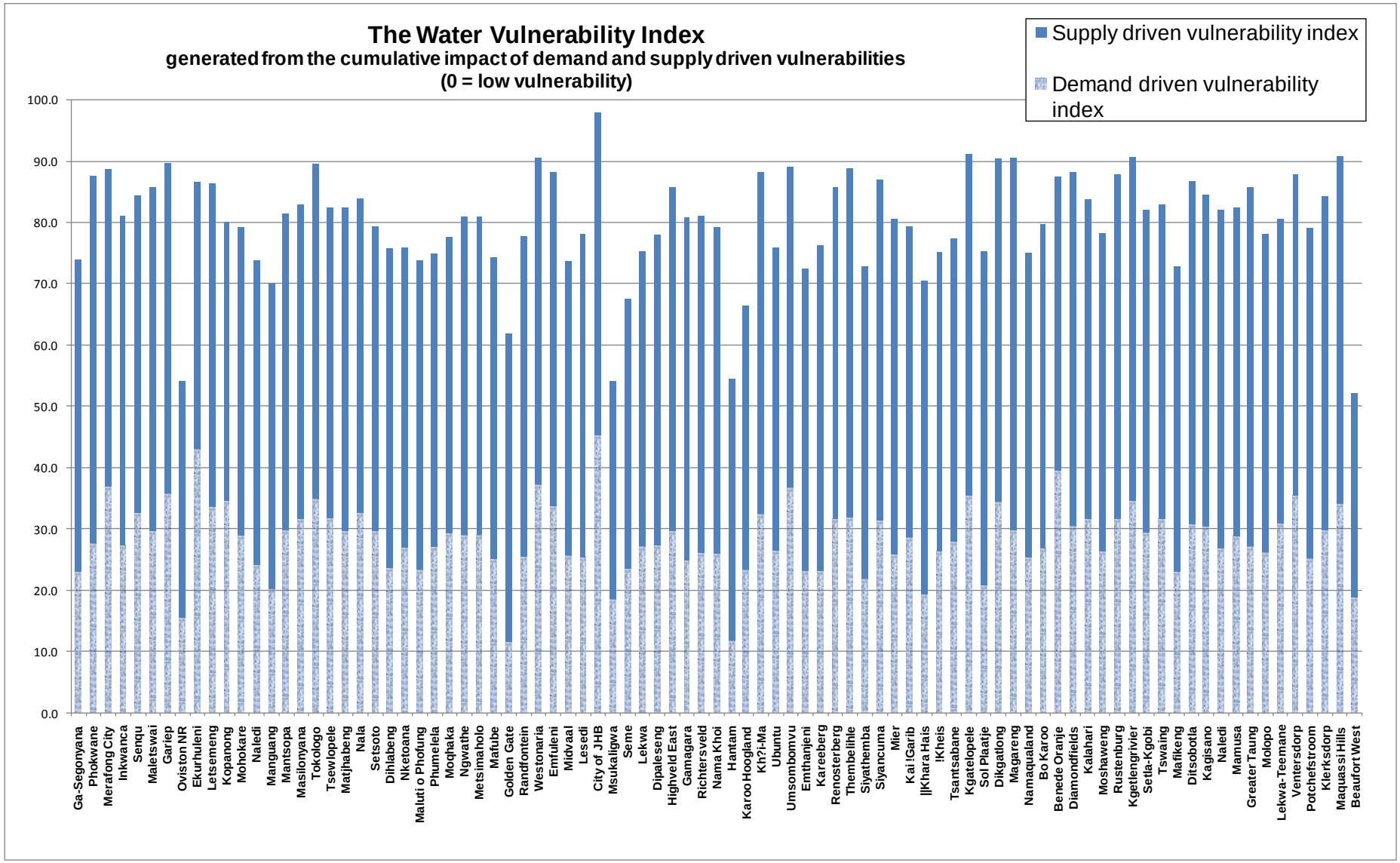
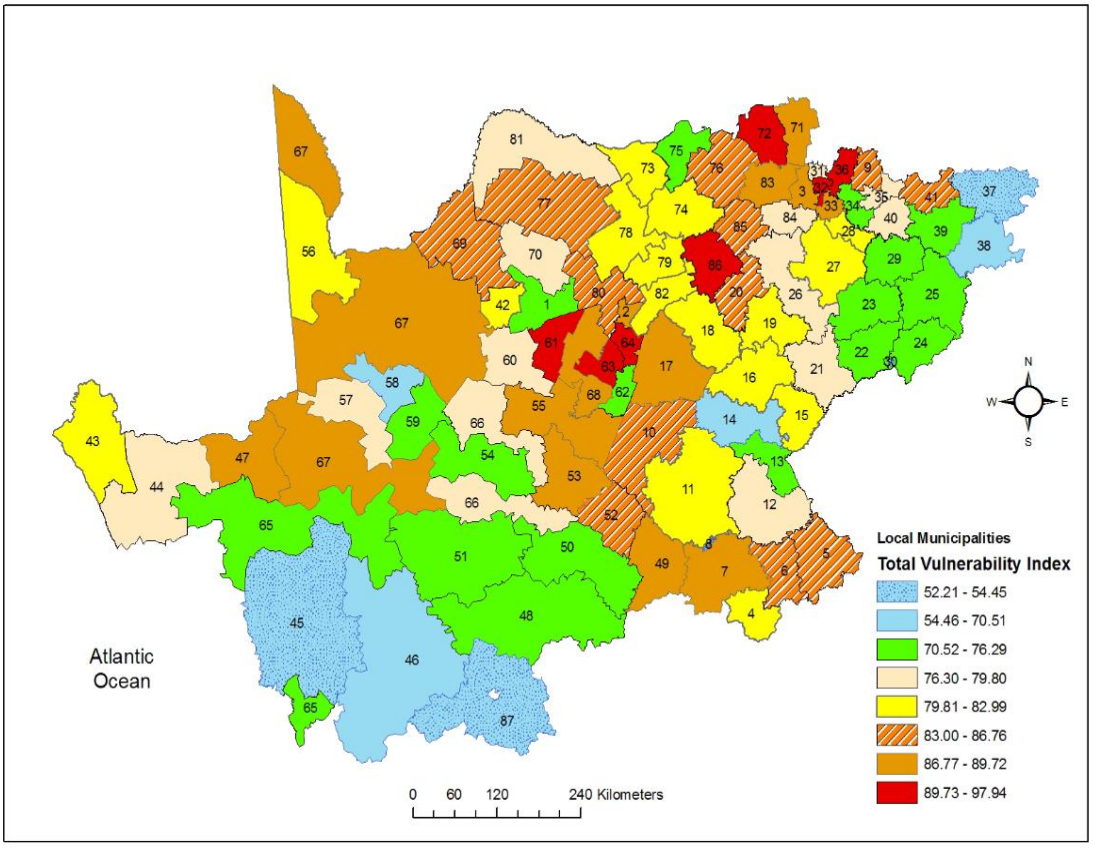


**Figure 8 WVI scores at the municipal scale, mapped across the basin**




| 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 | ||Khara 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 | | |

From Figure 8) it can be seen that certain municipalities across the Orange basin in South Africa are much more vulnerable to future changes than others. This is summarised in Table 4 which shows those municipalities exhibiting higher and lower levels of vulnerability.

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

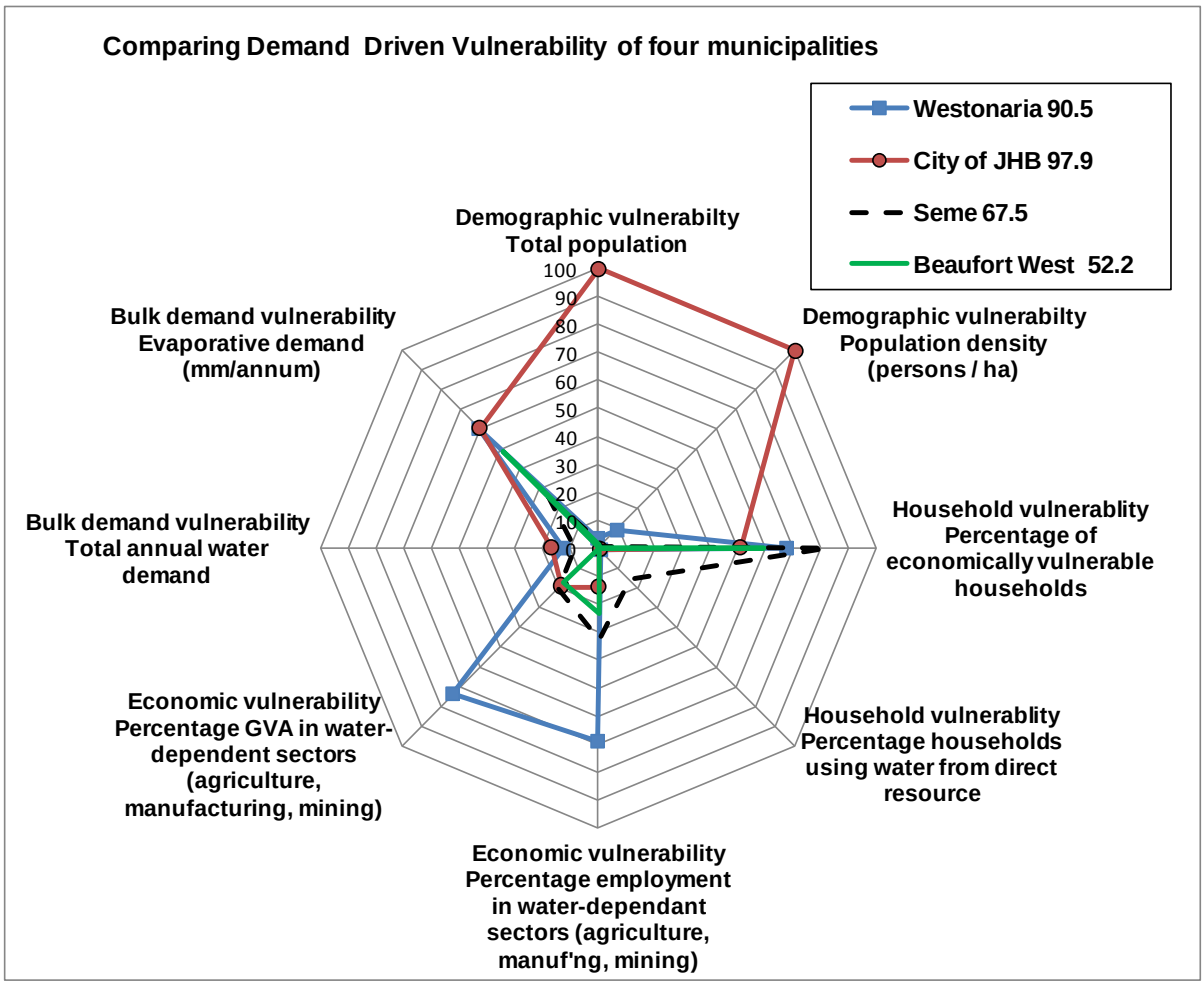
| | | | Westonaria 90.5 | City of JHB 97.9 | Seme 67.5 | Beaufort West 52.2 |
|---|---|---|---|---|---|---|
| Water Resource Users | Demographic vulnerabilty | Total population | 3.5 | 100.0 | 2.6 | 1.2 |
| | | Population density (persons / ha) | 9.5 | 100.0 | 0.8 | 0.1 |
| | Household vulnerablity | Percentage of economically vulnerable households | 67.7 | 51.0 | 82.1 | 59.5 |
| | | Percentage households using water from direct resource | 1.0 | 0.5 | 15.6 | 0.4 |
| | Economic vulnerability | Percentage employment in water-dependant sectors (agriculture, manuf'ng, mining) | 69.2 | 13.9 | 32.6 | 23.6 |
| | | Percentage GVA in water-dependent sectors (agriculture, manufactur | 74.1 | 19.4 | 20.4 | 17.9 |
| | Bulk demand vulnerability | Total annual water demand | 12.6 | 17.2 | 8.6 | 0.0 |
| | | Evaporative demand (mm/annum) | 60.8 | 60.6 | 25.6 | 48.7 |
| | | **Demand driven vulnerability index** | **37.3** | **45.3** | **23.6** | **18.9** |
| | | | **Westonaria 90.5** | **City of JHB 97.9** | **Seme 67.5** | **Beaufort West 52.2** |
| Water Resource Supp | Resource Vulnerability | Mean annual run-off including upstream contributions | 100.0 | 96.0 | 80.4 | 0.0 |
| | | Annual groundwater exploitation potential | 10.0 | 57.9 | 56.4 | 62.1 |
| | Extreme event vulnerability | Number of days per annum where rainfall = 0mm | 84.5 | 72.3 | 36.6 | 75.5 |
| | | Days per annum with rainfall >25mm | 59.8 | 67.8 | 58.0 | 0.0 |
| | Land cover vulnerability | Percentage cover of urbanisation upstream | 39.1 | 0.0 | 0.0 | 0.0 |
| | | Percentage cover of irrigated land | 0.8 | 1.4 | 0.6 | 0.2 |
| | Storage vulnerabilty | Dam coverage (Ha per capita) | 100.0 | 100.0 | 100.0 | 100.0 |
| | | Coefficient of variation of mean annual precipitaton | 31.9 | 25.5 | 20.0 | 28.3 |
| | | **Supply driven vulnerability index** | **53.3** | **52.6** | **44.0** | **33.3** |
| | | **Total Water Vulnerability Index** | **90.6** | **97.9** | **67.6** | **52.2** |

The vulnerability profiles of each municipality from Table 4 is shown in Figures 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 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.

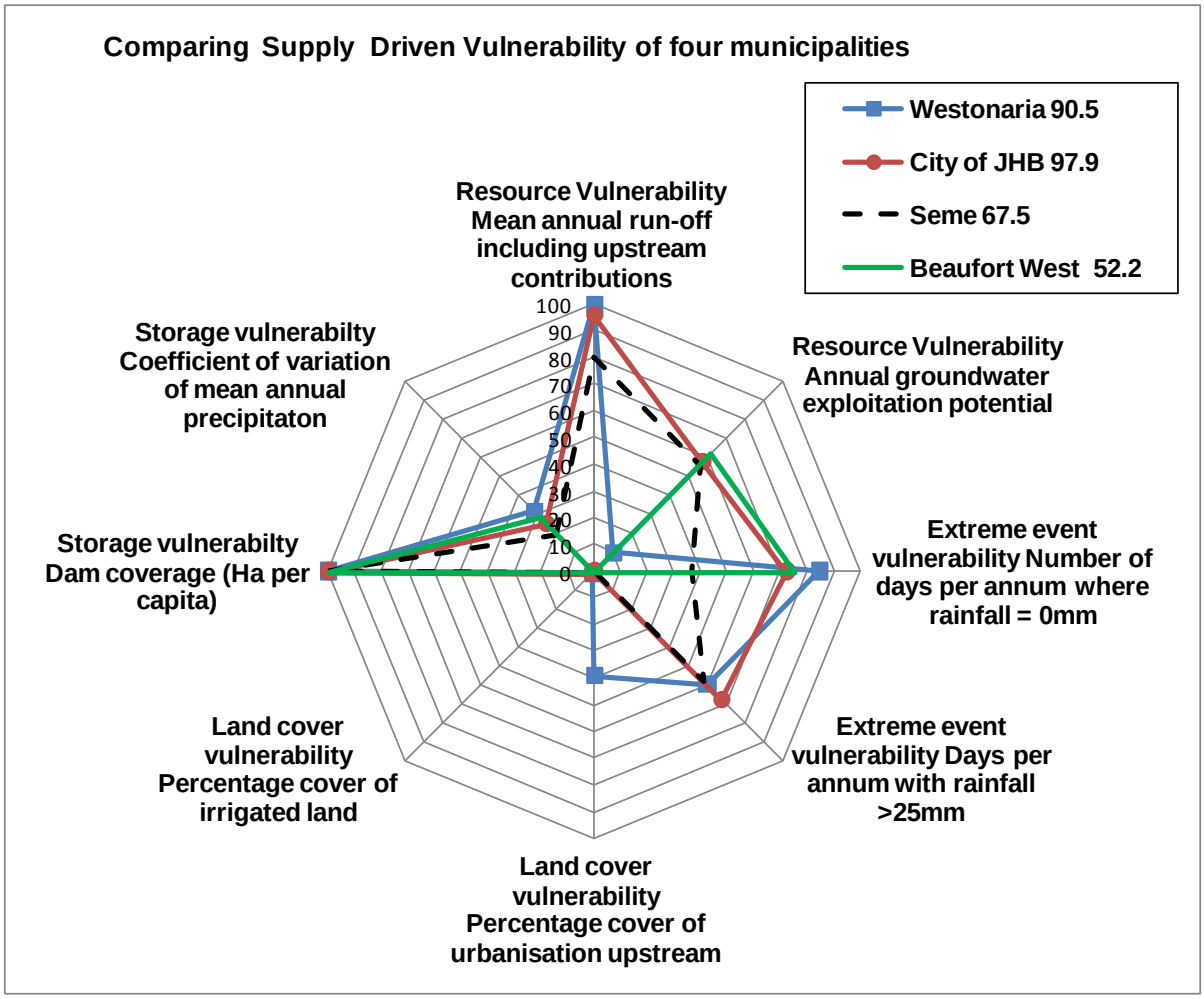
**Figure 9 Illustrating Demand Driven Water Vulnerability**




In the case of supply driven water vulnerability, Figure 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, and from compromised runoff, although Johannesburg appears to have a higher risk from overexploitation of groundwater (or simple 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 hydrological 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.

**Figure 10 Illustrating supply driven water vulnerability**




## 7 Assessing Future Water Vulnerability

To support development planning, it is useful to assess possible future conditions. Such assessment can be made by 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 from this it can be seen that the municipal-specific vulnerability profiles will vary over time.

**Table 5 Comparing vulnerability profiles over time (hypothetical scenario)**

| | Westonaria | City of JHB | Seme | Beaufort West |
|---|---|---|---|---|
| **Original total Water Vulnerability Index** | 90.6 | 97.9 | 67.5 | 52.2 |
| **Demand driven Water Vulnerabilty +20%** | 44.8 | 54.4 | 28.3 | 22.7 |
| **Supply driven Water Vulnerabilty -10%** | 47.9 | 47.3 | 39.6 | 29.9 |
| **Total New Water Vulnerability Index, under climate change** | 92.7 | 101.7 | 67.9 | 52.7 |

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.

## 8 Discussion

The objective of any multidimentional 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[3] 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 Orientated and Bayesian approaches can be applied for greater refinement (Molina et al 2009), but such an approach would be beyond the scope of this paper.

It is certainly 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' i*s used here to mean at 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.

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 is 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.

## 9 Conclusion

The method of calculating the *Water Vulnerability Index* 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, recognising 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 *Climate Vulnerability Index* (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

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

any increase in water security would also increase the level of food security, this would be of crucial importance in the face of the today's global pressures.

There is also much scope to improve the validity of the Water Vulnerability Index by including more information on water quality. To date, this has not been possible due to there 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 *Integrated Water Resources Management* 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 transboundary 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 organisations 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 *Water Vulnerability Index* (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.

## References

Adger WN, et al. (2007) *Climate Change 2007: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, eds Parry ML, Canziani O.F, Palutikof J, van der Linden P, and Hanson C (Cambridge University Press, Cambridge), pp 717–743.

Buma, J., Sullivan, C.A., Neno, K And J Griffioen (2007) Can water stressed regions be characterised when there is sparse data? In Reducing the Vulnerability of Societies to Water Related Risks at the Basin Scale (Proceedings of the third International Symposium on Integrated Water Resources Management, Bochum, Germany, September 2006). IAHS Publ. 317, 2007

Diederichs,N., Van Niekerk,M., Mander, M. and Dreyer, A. (2008) *Study Report: Newater Water Vulnerability Index,* Futureworks! Durban

DWAF (1998), *National Water Act, Act. No. 36 of 1998*. South African Department of Water Affairs and Forestry, Pretoria, South Africa.

GWP (2006) *Setting the stage for Change.* Stockholm.

IPCC, (2007) Summary for Policymakers. In: Climate Change 2007: The Physical Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996pp.

J.L. Molina, J. Bromley, J.L. García-Aróstegui, C. Sullivan and J. Benavente (2009) Integrated water resources management of overexploited hydrogeological systems using Object-Oriented Bayesian Networks. *Environmental Modelling & Software*

Knoesen, D (2009) *Integrating Hydrological Hazards and Climate Change as a Tool for Adaptive Water Resources Management in the Orange River Catchment.* Phd Thesis, University of KwaZulu Natal.

Meadows, M. E. & Hoffman, T. M. (2003) Land Degradation And Climate Change In South Africa. The Geographical Journal, 169.

Meybeck, M. 2003b. Global analysis of river systems : from earth system controls to Anthropocene controls. *Philosophical Transactions of the Royal Academy B*, 358, 1440, 1935-1955.

Milly, P. C. D. Dunne, K. A. & A. V. Vecchia (2005) Global pattern of trends in streamflow and water availability in a changing climate *Nature* 438, 347-350 (17 November 2005)

Molle, F. & Mollinga, P. (2003) Water Poverty Indicators: Conceptual Problems And Policy Issues. Water Policy, 5, 529-544.

Morin, A. (2005) *The Canadian Water Sustainability Index* (CWSI) (PRI Working Paper Series No11). Policy Research Initiative: Ottawa.

O'brien, K. L. & Leichenko, R. M. (2000) Double Exposure: Assessing The Impacts Of Climate Change Within The Context Of Economic Globalization. *Global Environmental Change, 1*0, 221-232.

O'brien, K. L., Leichenko, R. M., Kelkar, U., Venema, H., Aandahl, G., Tompkins, H., Javed, A., Bhadwal, S., Barg, S., Nygaard, L. & West, J. (2004) Mapping Vulnerability To Multiple Stressors: Climate Change And Globalization In India. *Global Environmental Change*, 14, 303-313.

PRI Canada (2007) *The Canadian Water Sustainability Index.* Project Report, Policy Research Initiative, Government of Canada. Ottowa

Ravetz, J. R. (Ed.) (1986) Useable Knowledge, Useable Ignorance: Incomplete Science With Policy Implications, Cambridge, Cambridge University Press.

Romero, A. (2007) *Perceptions of Vulnerability of Water Supplies and Water Users in the Upper Orange Basin, South Africa.* MSc Dissertation, Oxford University Centre for the Environment. Oxford, UK

Satterthwaite D. (2003) The links between poverty and the environment in urban areas of Africa, Asia, and Latin America *Annals Of The American Academy Of Political And Social Science* Vol 590, pp 73-92

Sen, A.K., 1999. *Development as Freedom*. Clarendon Press, Oxford

Sullivan C.A. and Meigh, J.R. (2005) Targeting attention on local vulnerabilities using an integrated indicator approach: the example of the Climate Vulnerability Index. *Water Science and Technology, Special Issue on Climate Change* Vol 51 No 5 pp 69–78

Sullivan C.A. and Meigh, J.R. (2007) Integration of the biophysical and social sciences using an indicator approach: Addressing water problems at different scales *Journal of Water Resources Management* 21:111-128

Sullivan C.A., Meigh J.R., Giacomello A.M., Fediw T., Lawrence P., Samad M., Mlote S., Hutton C., Allan J.A., Schulze R.E., Dlamini, D.J.M., Cosgrove W., Delli Priscoli J., Gleick P., Smout I., CobbingJ., Calow R., Hunt C., Hussain A., Acreman M.C., King J., Malomo S., Tate E.L., O'Regan D., Milner S. and Steyl I. (2003) The Water Poverty Index: Development and application at the community scale. *Natural Resources 27:189-199*

Sullivan, C.A, Deiderichs N. and Mander, M. (2008) *Assessing Water Vulnerability in the Orange River Basin in South Africa* Newater Technical Report, Oxford University UK

Sullivan, C.A., Meigh JR and Fediw T (2002) *Developing and testing the Water Poverty Index: Phase 1 Final Report.* Report to Department for International Development, Centre for Ecology and Hydrology, Wallingford, UK.

Sullivan, C.A., Vörösmarty, C., Bunn, S.,Cline, S., Heidecke, C., Storygard, A.,Proussevitch,A., Douglas, E., Bossio, D., Günther, D., Giacomello, AM.,. O'Regan, D.P. and J.R Meigh (2006) *Mapping the Links between Water, Poverty and Food Security* GWSP Working Paper no 1.Bonn.

Sullivan,C.A., Dickens, C., Mander, M, Bonjean, M, Macfarlane, D. Bharwani, S, Matin, N., van Nieukerk, K,, Diederichs, N., Taylor, A. Shale, M., King-Okumu, C., Kranz, N., Bisaro, S,, Zabala, A., Romero, A, Huntjens, P., and Knoesen, D. (2009) Promoting Adaptive Water Management in The Orange Senqu River Basin: A NeWater case study In: Mysiak, J, Henrikson, H.J., Sullivan, C.A., Bromley, J, and Pahl-Wostl, C. (Eds) (2009) *The Adaptive Water Resource Management Handbook* , (2009) Earthscan, London

Turner Ii, B. L., Kasperson, R. E., Matson, P. A., Mccarthy, J. J., Corell, R. W., Christensen, L., Ecklley, N., Kasperson, J. X., Luers, A., Martello, M. L., Polsky, C., Pulsipher, A. & Schiller, A. (2003) A Framework For Vulnerability Analysis In Sustainability Science. Proceedings Of The National Academy Of Science, 100, 8074-8079.

UNDP (United Nations Development Programme) (2003) *Human Development Report 2003*, Oxford University Press, New York.

UNECE Economic Commission for Europe '*Guidance on Water and Adaptation to Climate Change'* UNECE, Convention on the Protection and Use of Transboundary Watercourses and International Lakes, United Nations Publication Isbn: 978-92-1-117010-8

Vorosmarty, C. J., Green, P. A., Salisbury, J. & Lammers, R. B. (2000) Global Water Resources: Vulnerability From Climate Change And Population Growth. *Science,* 289, 284-289.

World Bank (2009) (2009) *Water and Climate Change: Understanding the Risks and Making Climate-Smart Investment Decisions* World Bank, 52911, Authors: Alavian V.,Qaddumi, H.M. Dickson, E., Diez, S.M., Danilenko, A.V. Hirji, R.F., Puz, G., Pizarro, C., Jacobsen M and Blankespoor, B. Sept 2009

World Resources Institute, (2000) - World Resources Institute: 2000, *World Resources 2000-2001 – People and Ecosystems: The Fraying Web of Life*, World Resources Institute, Washington.

WSSD (2002) *World Summit on Sustainable Development, Plan of Implementation*. Johannesburg, Sept. 2002.