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2011-05-05
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DECISION SUPPORT SYSTEM FOR SUSTAINABLE RAINWATER HARVESTING IN SOUTH AFRICA

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A Thesis submitted to the Faculty of Engineering and the Built Environment,
University of the Witwatersrand, Johannesburg, in fulfilment
of the requirements for the degree of Doctor of Philosophy

JOHANNESBURG, 2010

DECLARATION

I declare that this Thesis is my own unaided work. It is being submitted for the Degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University

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ABSTRACT

To reconcile its scarce water resources with the ever increasing demand for fresh water, the South African government continues to explore and investigate various demand management and water supply options such as: effluent reuse, interbasin water transfers, rainwater harvesting (RWH), water conservation as well as sea water desalinisation. RWH is an old but underutilised technology that can play a key role in the improvement of rural livelihoods, thus the need to investigate the potential it holds for South Africa.

This thesis presents the Rainwater HArvesting Decision Support System (RHADESS) that was developed to facilitate the integration of three streamlined categories of RWH in the management and development of the country's water resources at the quaternary catchment scale ($\pm$ 500 km^2).

Using biophysical and socioeconomic datasets, RHADESS assesses the RWH footprint of any given area of South Africa. Although physical factors are important parameters in the assessment of the RWH suitability of a given area the non-consideration of ecological and socioeconomic parameters lead to inappropriate targeting of RWH. Once the footprint is determined, the ecohydrological impact of RWH as reduction in river flow can be established. Despite the increasing adoption of RWH, very little is known about its potential ecohydrological impact. This thesis contributes to understanding these impacts for different levels of adoption of RWH at the quaternary catchment scale. Finally, RHADESS sizes the RWH tank per quaternary catchment, assesses its water security and calculates the area of land needed for a household to achieve food security when RWH is implemented. The decision support system was tested in two quaternary catchments which have contrasting rainfall regimes, the semi-arid C52A and the humid V13D.

To my wife and the jewel of my life

Christine TSHITENGE-MWENGE

ACKNOWLEDGMENTS

Praise be to Jesus, the God almighty who is my rock.

A PhD study is a path of roses and thorns. I am delighted to have the opportunity to acknowledge the contribution of those who threw some rose petals on my path and spared me the sting of few thorns.

I acknowledge the contribution of organisations and institutions during the course of this study:

- The Water research commission for funding the three-year project K5/1563 under which this work was carried out, and;
- The Department of Water Affairs and Forestry, Statistics South Africa, the Agricultural Research Council, the Council for Scientific and Industrial Research, the Smallholder system innovations in integrated watershed management, the School of Bioresources Engineering & Environmental Hydrology of the University of KwaZulu-Natal as well as the South African Weather Service for providing data used in this study.

I express my sincere gratitude to the following people:

- Prof. A. E. Taigbenu for the constructive discussions and useful advice. If he was not my supervisor, I would have left Wits for another university few months after registering;
- Jean Boroto, for his constant moral and financial support. There are still some genuinely good people out there;
- All the team members of the WRC project K5/1563 for their outstanding contributions;
- Prof. P van der Zaag and Prof. G. Kundhlande for respectively making available the roof model and the IRWH Economic Simulation model;
- Prof. J. Rockström for his contribution at the early stage of this study;
- My brother Jean-marie Kileshye Onema as well as my colleagues postgraduate students M. Magombeyi, P. Kagoda, Z. Katambara, J. Adewumi, M. Ncube for their advice, assistance and interest;
- My parents and my brothers for standing by me no matter what;
- My beloved wife, for her love and support. You rock my world.

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ABBREVIATIONS AND ACRONYMS

AGIS	Agricultural Geo-referenced Information System
Agt	Aboveground tank
ARC	Agricultural Research Council
CSIR	Council for Scientific and Industrial Research
CV	Coefficient of Variation
DAFF	Department of Agriculture, Forestry and Fishery (Former DOA)
DEM	Digital Elevation Model
DoA	Department of Agriculture (Now named DAFF)
DRWH	Domestic rainwater harvesting
DSS	Decision Support System
DWAF	Department of Water Affairs and Forestry (now renamed DWA)
DWA	Department of Water Affairs (Former DWAF)
EISC	Ecological Importance and Sensitivity Category
ER	Environmental requirement
FAO	Food and Agriculture Organisation
FRWH	Field rainwater harvesting (IRWH & XRWH)
GWP	Global Water Partnership
HRU	Hydrological Response Unit
ICID	International Commission on Irrigation and Drainage
IESM	Infield rainwater harvesting Economic Simulation Model
IPTRID	International Programme for Technology and Research in Irrigation and Drainage
IRWH	Infield rainwater harvesting
ISRDP	Integrated Sustainable Rural Development Programme
MAP	Mean Annual Precipitation
MCE	Multi-criteria Evaluation
MDGs	Millennium Development Goals
MMP	Mean Monthly Precipitation
NEMA	National Environmental Management Act

NLC	National Land Cover
NWA	National water Act
NWRS	National water Resources Strategy
PET	Potential Evapotranspiration
QC	Quaternary catchment
RHADESS	Rainwater harvesting Decision support system
RM	Roof model
RSM	Rainwater harvesting suitability model
RWH	Rainwater harvesting
SIWI	Stockholm International Water Institute
SSA	Statistics South Africa
Std Dev	Standard Deviation
SWAT	Soil Water Assessment Tool 2005
Ugt	Underground tank
UMMRB	Upper Middle Modder River Basin
UNEP	United Nations Environment Programme
WH	Water harvesting
WMA	Water management are
WOP	Weighted Overlay process
WRSM	Water Resources Simulation Model 2000
WSA	Water Services Act
XRWH	Exfield rainwater harvesting
ZAR	Rand

NOMENCLATURE

Symbol	Parameter Description	Dimension	Unit
a	Regression constant	0.24	
A_j	final suitability score in each pixel		
A_R	total area of the catchment or river basin		m^2
A_S	area under a RWH system		m^2
b	Regression constant	0.53	
ΔA_S	increase in area under RWH		
ΔQ_r	total catchment/river basin runoff reduction by RWH systems	L^3	
$\Delta Q_{r(S)}$	runoff reduction caused by a RWH system		%
$\Delta Q_{r(S)}$	runoff reduction by a RWH system		%
D	deep percolation	LT^{-1}	
E	soil evaporation and interception	LT^{-1}	
e	efficiency coefficient	0.8	
f	interception coefficient	LT^{-1}	
j_{th}	layer		
N	maximum possible sunshine duration	T	
n	actual sunshine duration	T	
P_{harv}	harvestable rainfall	LT^{-1}	
R	Rainfall	LT^{-1}	
R_a	extra-terrestrial solar radiation	$M\ T^{-3}$	
R_{off}	surface runoff	L^3/T^{-1}	
R_s	short wave radiation	$M\ T^{-3}$	
S	soil moisture	L^3	
T	plant transpiration	LT^{-1}	
w_i	normalised weight		
x_{ij}	suitability of the $i_{th\ layer}$		

Chapter 1 INTRODUCTION

1.1 Background

South Africa is a water scarce country. Its average rainfall of 465 mm is slightly above half of the world's average of 857mm. Low and unevenly distributed rainfall coupled with high evaporation rates and uneven topography generate low runoff; approximately 9% of precipitation drains into rivers (Mukheibir, 2008; ICID, 2004). The country's water resources comprise three sources: surface water (77%), return flows (14%) and groundwater (9%). Over the past decades, some 320 major dams with full supply capacity exceeding 1 million cubic metres have been built (DWAF, 2004), leaving only few remaining options for building new dams. Thus walls of existing dams are being raised and inter-basin transfers occur within the country in 18 of the 19 Water Management Areas (WMA) and outside the country. While most of the available water has already been captured, stored and allocated to users, population growth and economic development increase water demand and pollution of available resources. There is a continuous assessment of the ability of available water infrastructure to meet present and future water needs. The planning section of the then Department of Water Affairs and Forestry (DWAF) now Department of Water Affairs (DWA) has a lead team in planning for new infrastructure to meet projected demand which is driven by the growing economy. It is expected that the demand for scarce water resources will increase as the government addresses the deep inequalities existing in the distribution of water. The current water situation is further convoluted by climate change which is a supplementary

hazard that has the potential to impact very significantly on both the availability of and requirements for water in South Africa.

One of the country's water challenge is to supply enough water of good quality to meet the basic need of the rural population and enable them to embark on small scale productive activities as some 40 percent of the total population live in rural areas of which about 70 percent of rural households earn less than ZAR 9,600 per annum and are below the poverty line (SSA, 2006).

There are eleven different types of water sources for households (Table 1.1) that are grouped in two main categories: piped and non-piped.

Table 1.1 Existing type of water sources in South Africa (SSA, 2006).

No.	Category	Type of water source
1	Piped	Piped water (tap) inside dwelling
2		Piped water (tap) inside yard
3		Piped water on community stand: distance ≤ 200m from dwelling
4		Piped water on community stand: distance > 200m from dwelling
5	Non-piped	Borehole
6		Spring
7		Rainwater tank
8		Dam/pool/stagnant water
9		River/stream
10		Water vendor
11		Other

Although the official database (Figure 1.1) indicates that about 68 percent of the population has piped water either inside their dwelling or in their yard, it must be stressed that this does not guarantee water availability since water taps can be dry for days or even weeks (Figure 1.2).

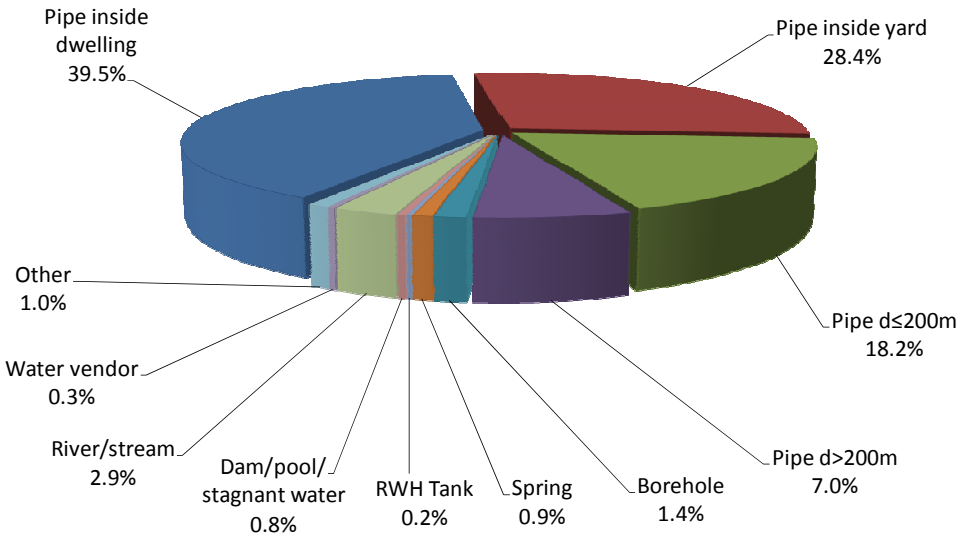


Figure 1.1. Percentages of rural household use of existing water sources (DWAF, 2007a).



Figure 1.2. Line of water vessels at a community tap in the Olifants basin (Photo, Magombeyi).

Smallholder farmers only use 15 to 30 percent of the rains (Figure 1.3). Low crop yield of about 1 ton ha^{-1} (Whitbread et al., 2010; Barron, 2004; Jones and

Thornton, 2003; Rockström and Falkenmark, 2000) often experienced by smallholder farmers is caused by unreliable rains. 91% of the country is semi arid and both off season and inter seasonal dry spells greatly reduce the yield of rainfed agriculture, making it a risky enterprise for smallholder farmers. The rainfall variability makes supplementary or full irrigation indispensable.

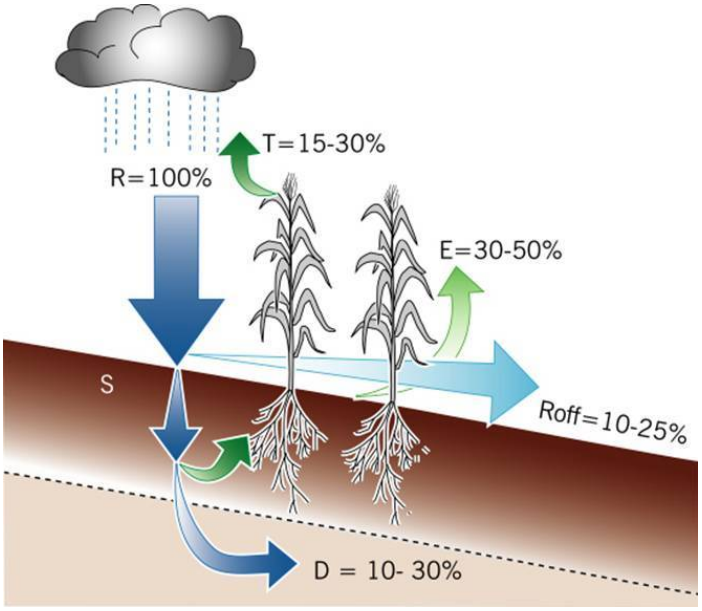


Figure 1.3. Partitioning of rainwater at smallholder farm scale in semi-arid area. R = seasonal rainfall, E = soil evaporation and interception, S = soil moisture, T = plant transpiration, Roff = surface runoff and D = deep percolation (Rockström, 2001).

Practiced on 10 percent of the arable land (IPTRID, 2000), irrigation accounts for 62 % of the country's total water requirement (Figure 1.4). Considering the above mentioned rising demand for water, there is no more water to allocate to agriculture. Furthermore, the current energy crisis experienced in South Africa prevents the implementation of agriculture and water projects requiring high input of fossil energy and electricity.

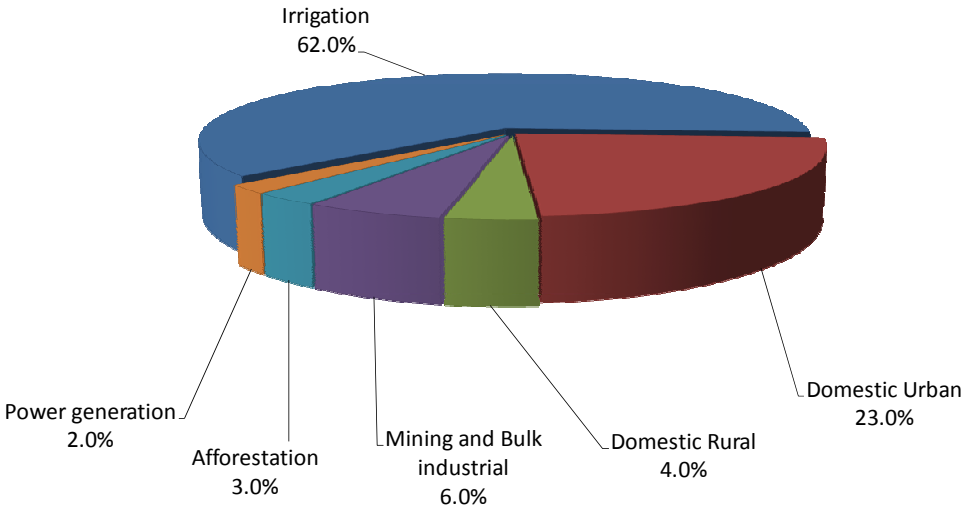


Figure 1.4. South African water requirements by sector (DWAF, 2004).

A sustainable small scale farming system should attempt to attain food security and enable income generation, reduce soil erosion while improving infiltration and require a low capital investment (Rijkenber, 2002).

To meet the ever growing water demand and achieve the Millennium Development Goals (MDGs), the country needs managerial and technological innovations that maximise and augment the use of existing and unexploited sources of freshwater. Rainwater harvesting (RWH) is a revived technological innovation worth investigating as it holds the potential to augment plant water availability, thus improving water productivity of smallholder farmers (Makurira et al., 2009; Mwenge Kahinda et al., 2007a; Rockström and Barron, 2007; Ngigi, 2006; Oweis and Hachum, 2006; Rosegrant et al., 2002) and supply water beyond the basic human needs (Mwenge Kahinda et al., 2007 b). RWH also presents itself as an adaptation strategy that the water sector need to undertake to cope with future climate change (Rutashobya, 2008; Pandey et al., 2003; Salas et al., 2009; Mukheibir, 2008) as it has the potential to enhance ecosystem and livelihood resilience (Muller, 2007). Until recently the importance of RWH as a buffer against climate-linked extreme weather events has been almost invisible

in water planning since countries rely almost exclusively on rivers and underground supplies (Mati et al., 2006).

The RWH potential of South Africa is still untapped and with the support received from Non-governmental organisations (NGOs) and the recent support of the government, it is spreading all over the country. As the current use of RWH is well below its potential, the technique is likely to spread in the coming decades. At present RWH is implemented and practiced without appropriate integration into the country's water resources and lacks proper guidelines and regulations.

Whereas the benefits of RWH are explored, its potential adverse effects tend to be overlooked. A river basin is a complex system further convoluted by all the anthropogenic activities it encompasses. Human interventions (dams, diversions, abstractions, agriculture, etc) alter (lengthen or shorten) the water cycle and RWH is no exception. Tillage practices increase the soil surface roughness, which enhances the water infiltration and reduces the runoff. Construction of ridges and bunds retards overland flows and causes them to re-infiltrate, while practices such as mulching enhance infiltrability and reduce evaporative losses from the soil surface. RWH tanks capture runoff generated from rooftop and ground surfaces and thus may likely result in the attenuation of runoff peak flows. Studies of the ecohydrological impacts of RWH focused on plot and plant scales, leaving a knowledge gap on its impacts at catchment scale.

Before embarking on a nationwide implementation of RWH, the opportunity that it offers to redress past racial and gender discrimination has to be investigated and balanced against possible adverse ecohydrological and socioeconomic impacts. A system approach is needed to integrate RWH in the development and management of the water resources in South Africa. This integration requires the development of tools and methodologies that enable the assessment of RWH footprint and quantify its associated ecohydrological and socioeconomic impacts.

1.2 Study aim and objectives

1.2.1 Study aim

The aim of the study is to build a decision support system (DSS) that will enable the sustainable use and implementation of rainwater harvesting within an Integrated Water Resources Management (IWRM) framework. The DSS should therefore assist water practitioners integrate RWH in the development and management of water resources in South Africa.

1.2.2 Study objectives

To address the above aim, the following objectives have been identified:

1. To analyse the current state of RWH in South Africa;
2. To assess the potential footprints of RWH, and;
3. To establish the ecohydrological impacts of different levels of adoption of RWH at quaternary catchment (QC) scale.

1.3 Layout of the thesis

The preceding sections of this chapter explain the aim and objectives of this study, namely to build a Decision Support System for RWH in South Africa.

In chapter 2 a general introduction is given to RWH. Its origin, definition and classification are discussed and further categorisation used in the remaining chapters of the thesis is presented. An overview of RWH techniques and its uses in both developing and developed country are presented. Finally, the current

extent of implementation of RWH in South Africa and its legislative support are analysed.

In Chapter 3, the spatial resolution of the study is discussed and the semi-arid C52A and humid V13D, two quaternary catchments in which the study is conducted, are presented.

In Chapter 4, the potential of RWH in South Africa is assessed using biophysical and socioeconomic datasets. Model Builder, a geographic information system extension, that enables a weighted overlay of the factors, is used to create a suitability model, which comprise physical, ecological and vulnerability (socioeconomic) and constraint sub-models. These sub-models provide the physical, ecological vulnerability and constraint maps. The maps are then weighted and combined to produce suitability maps.

The first innovation in this thesis is the incorporation of socioeconomic and ecological dataset in the assessment of the potential of RWH and a weighted overlay that translates into the suitability map, representing the best compromise among competing interests. Earlier scholars (Hensley et al., 2007; Mbilinyi et al., 2006; Mati et al., 2006; Senay and Verdin, 2004; Mou et al., 1999; Prinz et al., 1998 and Patrick 1997) who developed methodologies to assess the RWH potential of an area only used physical factors (rainfall, soil, topography) and only incorporated socioeconomic factors after the mapping. The post inclusion of socioeconomic factors often leads to inappropriate targeting of RWH.

In Chapter 5, a methodology to assess the ecohydrological impact of RWH at QC level is presented. The ecohydrological impact of RWH is quantified as monthly reduction in runoff using the Soil Water Assessment Tools 2005 (SWAT) which is a process based model. The impact of the up scaling of IRWH in C52A is assessed for different levels of adoption at different spatial locations within the QC.

Results obtained with SWAT are then compared to those obtained using the Water Resources Simulation Model 2000 (WRSM) which is a calibration model. Unlike the WRSM, SWAT models the ecohydrological impact of the same level of adoption of IRWH with different spatial distributions within the same QC. However, the WRSM is not as data intensive as SWAT and its input parameters have been prescribed for all quaternary catchments in South Africa.

Thus, the second innovation of this thesis is the assessment of the ecohydrological impact of RWH at QC scale using a process based model and comparing the results with a calibration model. Earlier Researchers (Mwenge Kahinda et al., 2007a; Botha et al., 2003; Hensley, 2000) have focused on the hydrological impact of RWH at plant and plot level and overlooked the impact at QC level.

In Chapter 6, the Rainwater HArvesting DEcision Support System (RHADESS) is presented. RHADESS is a combination of 5 models:

- the RWH suitability model (RSM) which assesses the footprint of RWH in any given area;
- the Soil Water Assessment Tool (SWAT) and the Water Resources Simulation Model (WRSM) which assesses the ecohydrological impact of RWH at QC level. Either model can be used to assess the ecohydrological impact of RWH at QC level;
- the Roof Model (RM) which optimises RWH tank size of a selected area and provides its water security level, and;
- the IRWH Economic Simulation Model (IESM), which calculates the area of land (ha) needed to meet the caloric requirement of a household

The application of RHADESS in two above mentioned QCs is also presented.

In Chapter 7 the major findings of this study are summarised, the contribution to knowledge highlighted and the limitations of the study as well as recommendations for further work formulated.

Chapter 2 RAINWATER HARVESTING

2.1 Definition

RWH is an umbrella term describing a range of techniques of concentrating, collecting, storing, and using rainwater runoff. Besides its application to agriculture, RWH may be used to provide water for both human and animal consumption, as well as for a number of small-scale activities. Hence, in its broadest sense, RWH is the collection of rainwater for productive use (Siegert, 1994) and includes a sample of techniques used to improve the use of rainwater at a specific site before it leaves a geographical region/space (SIWI, 2001). Although there are several definitions of RWH little difference is made about its function and purpose in relation to domestic and agricultural use (Denison and Wotshela, 2009).

2.2 Brief History

It is difficult to trace the origin of RWH and scholars believe that the various techniques were independently invented in different regions of the world:

- About 7,000 BC, in southern Jordan, early structures were constructed (Oweis et al., 2001);
- Around 4,500 BC, in southern Mesopotamia, RWH systems were used (Oweis et al., 2001);

- 5000 years ago, in Iraq in the so-called Fertile Crescent regarded as the cradle of agriculture, RWH techniques were used (SIWI, 2001);
- Evidence of RWH used 4000 years ago or more are present in the Negev desert of Israel (Evenari et al., 1971);
- More than 4000 years ago, in India and China, RWH was in use (SIWI, 2001);
- Some 100 years BC, throughout the Mediterranean and Middle East, RWH was already a common technique (Smet and Moriarty, 2001);
- Two thousand years ago, in the loess plateau of China -Ganzu Province, rainwater was collected in wells and jars (Gnadlinger, 2000).

Hence RWH is one of the oldest means of collecting runoff. In spite of its long story, for many years RWH was forgotten and even disappeared in many regions. Leading causes of the disappearance of RWH are:

- Wars between nations and within nations (Prinz, 1996);
- socioeconomic changes, such as colonialism (Aeurbach, 2003);
- Climatic changes, increasing aridity and change in precipitation regime (Prinz, 1996);
- The development of mass supply systems (Gnadlinger 2000).

In the last decades, there has been a resurgent interest in RWH and use driven by environmental concerns and a renewed interest in small scale distributed and appropriate technologies of all kinds (Smet and Moriarty, 2001) as high-energy input water projects have proven to be unsustainable (Gnadlinger 2000). RHW is rapidly expanding in regions where it was used and implemented in regions where it was unknown.

2.3 Rainwater harvesting categories

2.3.1 Rainwater harvesting Classification

There are different classifications of RWH. Rockström (2000) has the following water harvesting classes (for agriculture): in-situ water conservation, flood irrigation and storage for supplemental irrigation. FAO (2003) use the following RWH classes: rooftop WH, micro catchment, macro catchment and floodwater harvesting. Prinz (2002) gives the following types of water harvesting: fog - dew, rainwater, floodwater and groundwater harvesting.

In this thesis RWH is categorised according to the catchment area, into: domestic RWH (DRWH), infield RWH (IRWH) and, exfield RWH (XRWH). IRWH is also known as in situ, within field and micro catchment RWH while XRWH is also known as external or macro catchment RWH. IRWH and XRWH will be referred to as Field RWH (FRWH). As water harvesting encompasses RWH and floodwater harvesting or flood irrigation, the two terms will not be used interchangeably.

2.3.2 Domestic Rainwater harvesting

Water is collected from rooftops (Figure 2.1), courtyards and similar compacted or treated surfaces (Figure 2.2) and used for domestic purpose or garden crops.



Figure 2.1. DRWH aboveground tank in Glen (Central South Africa).



Figure 2.2. DRWH underground tank (Photo, Dams for Africa).

2.3.3 Infield Rainwater harvesting

The catchment area and the target area are directly adjacent (Figure 2.3). Part of the arable land is used as catchment.



Figure 2.3. Infield Rainwater Harvesting in the Taba N'chu area, Central South Africa.

2.3.4 Exfield Rainwater harvesting

There is a noticeable distance between the catchment area (usually not cultivable) and the target area (Figure 2.4).



Figure 2.4. XRWH with storage system (Photo, The World Agroforestry Centre).

2.3.5 RWH components

A RWH system has three major physical components (Table 2.1):

- a catchment area: where water is harvested;
- a storage facility and/or conveyance system: where water is stored (a reservoir, a cistern, the soil profile, etc), and
- a target area: where water is used (human beings, crops, plants, animals, enterprise, etc).

The management of RWH is a non-physical component and is key to its success.

Table 2.1 Components of the different RWH categories.

RWH category	Catchment area	Storage Facility	Target Area
DRWH	rooftop, a path, a road, a rock, a marginal land	Aboveground tank (Agt), Underground tank (Ugt)	Human beings, Animals, Crop and Small businesses
IRWH	Arable land	Soil surface, mini-pond or basin	Crop
XRWH	Marginal land, arable land,	Dam, reservoir, pond, soil, tanks	Animals, Enterprise, Crop

2.3.6 Rainwater harvesting techniques

There are several RWH techniques. Table 2.2 presents some of these techniques.

Table 2.2 RWH techniques per categories (After Oweis, 2001).

Category	Technique	Use	Storage type
DRWH	Rooftop	Drinking	(sub)surface
		cooking, etc	(sub)surface
		Vegetables	(sub)surface
IRWH	Contour ridges	Field/ crops	soil profile
		Vegetables	soil profile
	Semi-circular and trapezoidal bunds	Field/ crops	soil profile
		Vegetables	soil profile
	Small Pits	Field	soil profile
	Small runoff basin	Trees/ Forestry	soil profile
	Runoff strips	Field…	soil profile
	Inter-row	Vegetables	soil profile
		Field	soil profile
	Meskat	Field	soil profile
	Contour bench terraces	Field	soil profile
XRWH	Small reservoirs	All crops	(sub)surface
	River-bed	Trees/vegetables	surface/soil profile
	Water spreading	Field/trees	soil profile
	Large bunds	Field	soil profile
	Tanks	All crops	(sub)surface
	Cisterns	Drinking/trees/vegetables	subsurface
	Hillside runoff	Field/trees	soil profile

2.4 Rainwater harvesting in the world

RWH is increasingly adopted in various countries around the world. Below are few examples of RWH in different rainfall zones.

Kenya

RWH has a long history in Kenya. Several FRWH have been used for decades by small holder farmers. Mbugua (1999) estimated at 42 Mm^3 per annum the water supply potential to be derived from RWH. RWH is regarded as an alternative technology that supplements existing water supply and recognised as such in the country's water related legislation.

China

The 1-2-1 RWH project which consists of 1 concrete catchment of about 100 m^2, 2 concrete storage tanks and 1 irrigated cropland of 1/15 ha for production of high market value cash crop was implemented in the Gansu province of China. By 2000, 2.18 million storage tanks, supplying drinking water to 1.97 million rural residents and supplemental irrigation to 236,400 ha farmland were constructed (UNEP, 2002). According to Xiaoyan et al. (2002), RWH provides drinking water to about 23.80 million rural residents and 17.30 million livestock.

Germany

Germany encourages the utilisation of RWH for domestic supply (non-potable uses) and other purposes. About 50,000 new RWH systems are installed every year to add to an existing 500,000 systems (Salas, 2008). In several towns and cities, grants and subsidies are available to encourage the construction of rainwater tanks and seepage wells (Sutherland and Fenn, 2000; Gould, 1999).

Australia

RWH is common in both rural and urban Australia. About one tenth of all households use RWH as the main source of drinking water (Diaper, 2004). The country has national guidelines that advise on the best practices regarding the use of RWH tanks.

2.5 Rainwater harvesting in South Africa

2.5.1 History

The origin of RWH is difficult to trace, especially in South Africa where three historical dispensations have disrupted the indigenous agricultural practices (Auerbach, 2003):

- the expansion of the Zulu nation in the time of King Shaka;
- the colonial era which further destroyed what remained of the indigenous farming systems, and;
- the apartheid era during which the indigenous population was moved to designated areas called homelands.

DRWH was used in farms, schools, trading stations and mission hospitals decades before sophisticated centralised water supply systems became available (Dyer, 1999; Houston and Still, 2002). Commercial farms, now mainly supplied by boreholes, also have evidence of old rainwater tanks, which are sometimes still used. The political pressure for reticulated water schemes, the lack of a ceiling on the capital costs of such schemes, the scarcity of RWH design guidelines, as well as insufficient RWH advocacy has resulted in South Africa lagging behind other African countries in the exploitation of this valuable alternative water source (Houston, and Still 2002).

2.5.2 RWH techniques

Rooftop RWH is a major source of drinking water in rural areas (Figure 2.5) especially in the Eastern Cape and KwaZulu-Natal (Mwenge Kahinda et al., 2010; Mwenge Kahinda et al., 2007b).

RWH is used as a substitute source of drinking water where groundwater is inadequate. Houston and Still (2002) documented the synergistic relationship between RWH and groundwater in the following areas:

- Xolo (KwaZulu-Natal) and Garies (Nothern Cape), RWH is used as a substitute to brackish groundwater;
- Karkams (Northern Cape) RWH provides a reliable and cheap alternative water source to households;
- Paulshoek (Northern Cape), RWH is used to recharge the aquifer;
- Lepelfontein (Northern Cape), raw saline groundwater is blended with water harvested on the granite dome rainwater before being treated by reverse osmosis.

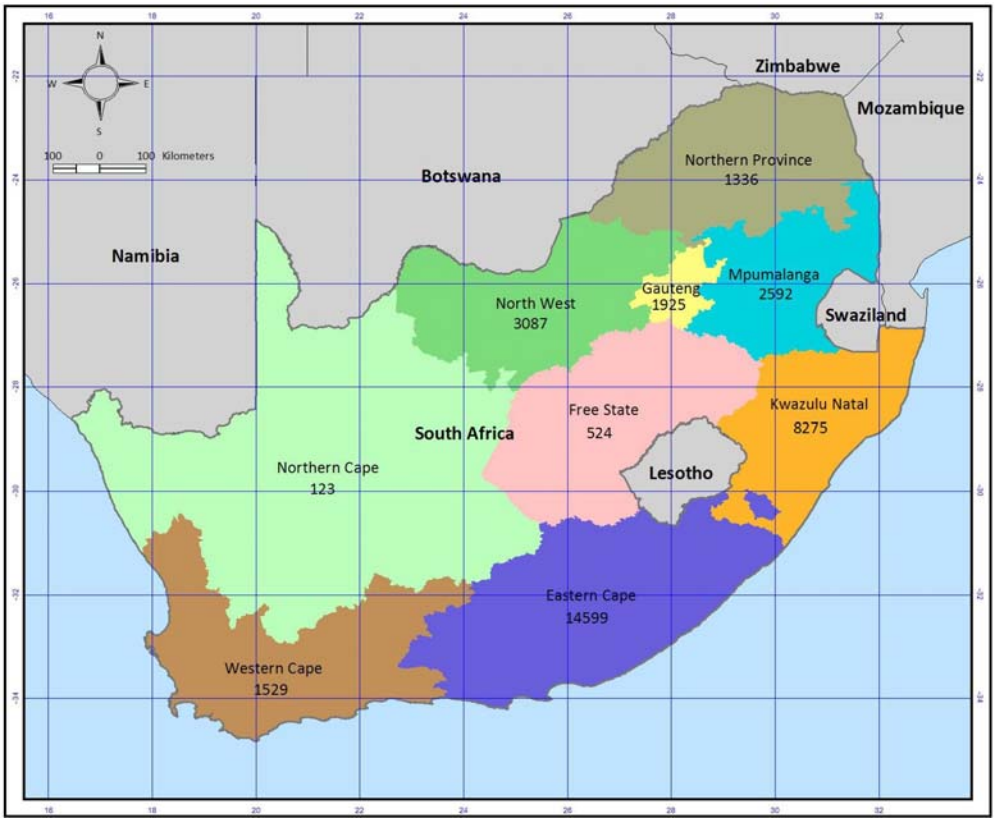


Figure 2.5. Number of households using RWH tanks as main water source in each of the nine provinces of South Africa.

Denison and Wotshela (2009) documented the following FRWH techniques:

- In Guquka (Eastern Cape) and Gogela (KwaZulu-Natal), a technique called gelesha in isiXhosa is used. It is a crop production system that involved mid-winter ripping of the sod of previous crop, followed by seed bed preparation after the first good spring rains have fallen.
- In Gogela (KwaZulu-Natal) they use Stone terracing. Specific portions of lands are enclosed by boulders and stones that prevent runoffs from cascading further down the fields.
- In Thaba N'chu (Free State) and in Tyume Valley (Eastern Cape), hand dug ponds (Matamo in Sotho or Ipitsi in isiXhosa) are used to store rainwater.
- Across South Africa, the trench bed gardening is used. The trench system consists of removing soil from the bed, back filling with organic material at the bottom of the trench and the soil earlier removed to form a terraced bed which serves is to hold water.
- In the Northern Cape areas around Clanwilliam, north-east of the Cedarberg Mountains and north of the Roggeveldberge, planting dams (Saaidamme in Afrikaans) are used. The fertile, silt-laden floodwater from the distant mountains (some 100 to 150 km in this case) is diverted with structures into a series of large, flat basins which extend between 1 ha and 100 ha in size. Each basin is ringed by a low earth wall of height of between 1 and 2 metres. The water is allowed to stand in the basins for between 1 and 3 days to saturate the very deep alluvial soils.
- In Stilbaai (Western Cape), natural hardened and impermeable surface is cleaned and compacted in order harvest rainwater that is channelled to an underground tank.
- In Ploegvore (Northern Cape), planting pits are constructed in a variety of circles and ellipses, to depths of 5 cm to 1 metre and with spacings of 2 to 5 m for tree crops and closer for field crops.

- In the Thaba N'chu area (Free State), Kayalethu and Guquka (Eastern Cape) and KwaMncane and Entembeni (KwaZulu-Natal), the micro-basin tillage technique which consists of 2 m wide sloping runoff strips and 1 m wide basins is used. The main characteristics of the technique include promoting surface runoff on the runoff strips and storing the runoff water in the basins where it infiltrates.

2.5.3 Water related legislation and RWH[1]

Since the advent of democracy in 1994, the South African government has undertaken a comprehensive reform of the water sector during the last decade. The National Water Act (NWA) (Act No. 36 of 1998) is the overarching legal instrument of water resources management in South Africa. It has equity, efficiency, sustainability and representivity as central guiding principles. The Water Services Act (WSA) (Act No. 108 of 1997) provides a regulatory framework for the provision of water supply and sanitation services to which people are entitled. It deals with reticulated water supply and sanitation services. It specifically provides for the rights of access to basic water supply and sanitation and for the manner in which municipalities carry out their duties to provide these services to their communities. The interpretation of the WSA is subject to the NWA. Water resources management is also subject to the specific requirements of other national policies and legislation, such as the National Environmental Management Act (NEMA) (Act No. 107 of 1998) and those parts of the Environment Conservation Act (ECA) (Act No. 73 of 1989) that have not yet been repealed by NEMA, which govern activities that are dependent on water or which affect water resources. These policies and legislation are administered by departments of the three spheres of government. The National Water Resources Strategy (NWRS) sets out how the water resources of South Africa will be

[1] This section is based on: Mwenge Kahinda, J., Boroto, R.J. and Taigbenu, A. E., 2005. Developing an Integrated water resources management and rainwater harvesting systems in South Africa. Paper presented at the 12th SANCIAHS Symposium. September 5-7, 2005, Johannesburg, RSA, (CD format).

protected, used, developed, conserved, managed and controlled in accordance with the requirements of the NWA.

2.5.3.1 The National Water Act

Section 4 of Chapter 1 of the NWA recognises the right to use water for purposes such as reasonable domestic use, domestic gardening, and animal watering. But it excludes any commercial activity. This is further emphasised in Chapter 4, Part 1, section 22 (1) where permissible water uses explicitly exclude small gardening for commercial purposes under schedule 1. Nevertheless, schedule 1 (permissible water uses) allows for the storage and use of runoff water from a roof.

Depending on its scale of adoption, field RWH can be categorised as land-based activities which reduce stream flow, and therefore require regulation by the Minister of Water and Environmental Affairs under Chapter 4, Part 4, Section 36 (2). Some RWH systems require works that bear semblance to water works and their use might be restricted under section 27 (1) (a) to (d) of the NWA. However, it remains unclear what scale of RWH matches water works.

Stream flow reduction activities are defined in Chapter 4, Part 4, section 36 (2) to (3) of the NWA as land-based activities which reduce stream flow. Whether or not an activity is declared to be a stream flow reduction activity depends on various factors, such as the extent of stream flow reduction, its duration, and its impact on any relevant water resource and on other water use. Although further studies are needed to establish that RWH is a stream flow reduction activity, it nonetheless has the potential of diverting considerable amount of surface runoff, depending of the scale, from the water course.

2.5.3.2 The Water Services Act

Although section 3 of chapter 1 of the WSA states that rainwater can be harvested from a dwelling's roof to provide water for basic needs, strict interpretation of section 6 (1) requires users of rooftop RWH systems to get the approval of their water services providers. Hence the act gives to water services providers the power to authorise or prohibit the implementation of a DRWH system in the area where they have jurisdiction.

2.5.3.3 The National Water Resources Strategy

The NWRS serves to give practical expression to the NWA. In Box 3.2.1 of the NWRS the use of RWH is promoted provided it has limited effects on water resources or downstream users and supplements conventional water supply. The NWRS is ambiguous on the scale at which RWH should have limited effect and there is a knowledge gap in quantifying its downstream effects. Thus, the limit to which RWH can be up scaled, without adverse ecohydrological and socioeconomic impact, is yet to be determined.

2.5.3.4 The National Environmental Management Act

Chapter 1, section 2 of the National Environmental Management Act states a number of principles relevant to RWH, stressing the need for an integrated approach to implementing any RWH technique susceptible to have an environmental impact. All interventions to reconcile the requirements for and availability of water are likely to have some impacts, which need to be identified and evaluated together with other relevant factors to enable an informed decision to be reached (DWAF, 2004).

RWH does not fall under the list of activities listed in section 24(5) of the NEMA (published in Government Notice No. R. 385-387 of 2006) that require an Environmental Impact Assessment. Nevertheless, in quaternaries where its widespread is likely to have a significant impact on the low flows, a prior assessment may be required.

2.5.3.5 Other water related legislation

To halve the number of food insecure households, DWAF initiated a RWH programme that provides financial assistance to resource-poor irrigation farmers for the capital cost of storage tanks for rainwater and related RWH works (DWAF, 2005). During the demonstration phase of its pilot programme, DWAF constructed, through implementing agencies, 64 underground tanks (Ugts) in 26 villages distributed in 4 provinces, namely Eastern Cape, Limpopo, KwaZulu-Natal and Free State (de Lange, 2006). The roll out phase which should have seen the construction of about 1000 RWH tanks per annum is still on hold because by strict application of water related legislation RWH can be considered to be a practice not founded on well prescribed legislative structures.

2.5.4 Existing knowledge on RWH in South Africa

Over the past two decades, a number of researches and projects on RWH in South Africa have advanced the frontiers of knowledge of the practice and at the same time highlighted the need for more research.

There has been extensive research conducted by the University of the Free State and the Agricultural Research Council (ARC) in the Thaba N'chu area on the micro-basin tillage technique that provides enough knowledge to guide the implementation of the technique in South Africa. Agrohydrological studies of IRWH in the Thaba N'chu area, central South Africa, suggest that it is an

agronomic sustainable crop production tool that can be used to improve rural livelihood by reducing the level of food insecurity (Botha et al., 2005; Botha et al., 2003).

Woyessa et al. (2006a) and Woyessa et al (2006b) who attempted to assess the impact of upscaling the IRWH technique in four QCs in central South Africa advocated that there is more economic benefit in retaining runoff upstream by implementing IRWH than to let it flow downstream store it and then use it for irrigation.

There have also been a number of socioeconomic studies on the micro-basin tillage technique. Subject to output levels and the profitability of crop production, between a third and half of the portion of land under conventional agriculture practice can be allocated to IRWH in order to meet the food requirement of a rural family (Baiphethi et al., 2006; Kundhlande et al., 2004). However, high poverty levels, limited family labour (Monde et al., 2006), lack of tools and fences were identified as the main demotivators to the expansion of the technique, while increase in crop yield and food availability as well as the current support from NGOs were identified as the main motivators (van Heerden et al., 2005). Therefore, due to socioeconomic constraints and the lack of institutional support, the current expansion of IRWH within homestead gardens is unlikely, in the short term, to spread to crop lands and beyond (van Heerden et al., 2005).

From the RWH pilot programme, de Lange (2006) drafted guidelines for the implementation of DRWH Ugt systems. These guidelines not only assist with the construction of DRWH Ugts (technical aspect) of but also with their use and maintenance (management aspect).

Similarly, from studies in the central Free State, guidelines were developed for the implementation of IRWH (Botha et al., 2007a; Botha et al., 2007b; Hensley, 2007).

Some aspects of RWH that have not been addressed in these previous studies relate to country-wide adoption of the practice, potentially suitable areas for different variants of the practice and its ecohydrological impacts, hence this study.

2.6 RWH and Integrated water resources management (IWRM)[2]

GWP (2000) defines IWRM as: "A process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems".

IWRM is based on the following four principles known as the Rio-Dublin principles.

- "Freshwater is a finite and vulnerable resource essential to sustain life, development and environment".
- "Water development should be based on a participatory approach, involving users, planners and policy makers at all levels".
- "Women play a central part in the provision, management, and safeguarding of water".
- "Water has an economic value in all its competing uses and should be recognised as an economic good".

[2] This section is based on: Mwenge Kahinda, J., Boroto, R.J. and Taigbenu, A. E., 2005. Developing an Integrated water resources management and rainwater harvesting systems in South Africa. Paper presented at the 12th SANCIAHS Symposium. September 5-7, 2005, Johannesburg, RSA, (CD format).

2.6.1 First Principle: Water as a finite and vulnerable resource essential to sustain life, development and the environment

Surface water, ground water, RWH, etc are all part of the same water cycle. While supplying water for basic human needs and increasing water productivity of rainfed agriculture, RWH modifies the water cycle. Any increase in crop yield resulting from higher water intake by the plants modifies the water balance at plant level and, depending on the level of adoption, it has consequences at basin level. Plot level studies of IRWH clearly indicate considerable reduction of runoff (Botha et al., 2003). XRWH systems using small reservoirs to store water increase evaporation and infiltration. Thus, it is worth to investigate if the use of RWH reduces surface flow, while increasing base flow with the overall cumulative increase of the catchment yield.

Since the first principle advocates a holistic approach in the management of water, there is a need to investigate the ecohydrological and socioeconomic impacts of RWH on communities. Although the overall amount of water is not affected, RWH practices are likely to affect its geographical distribution and therefore the vulnerability of its communities.

2.6.2 Second Principle: The need for a participatory approach

RWH projects are mostly promoted by NGOs. At present, although RWH is being promoted as a water supply option, it is not integrated in the planning of the country's water resources. The involvement of the communities from the planning phase to the operation and maintenance often results in successful implementation and use of RWH. However, due to the current bottom up approach RWH projects are scattered, lack coordination and are difficult to replicate. In addition, mechanisms for conflict prevention and resolution can

only be effective when recognised at decision makers' level. A legal basis for the use of RWH will only reinforce its sustainability.

2.6.3 Third Principle: The important role of women

In rural South Africa women and children still have to fetch water (Figure 2.6).



Figure 2.6. Left, children burrowing the river bed in Sekororo (Photo: Magombeyi); Right, woman fetching water from a borehole in Potshini.

Where communal taps are available, long queues of water vessels are common sights (Figure 1.2). Providing water at the dwelling using RWH should alleviate such hardships on women and enable them to embark on other activities. There is therefore the need to have women as an integral part of decisions regarding RWH projects. Likewise, vulnerable groups such as orphans and HIV infected persons should be fully accommodated in RWH projects. In areas with high prevalence of HIV/AIDS, a high percentage of households are headed by orphans who are burdened by associated chores such as fetching water. Beyond its domestic use, RWH will uplift the standard of living of women who are involved in agriculture through increased crop yields and therefore increased household incomes.

2.6.4 Fourth principle: Water as an economic good

The economic value of RWH can be best understood by considering the opportunities lost through lack of RWH in areas where the potential exists. These can be expressed as time wasted in collecting water, lower yields from agriculture and consequently higher food insecurity, *etc*. Economic evaluation is therefore a critical aspect of the implementation of RWH. Current economic evaluation methods of RWH range from yield comparison to risk analysis methods such as stochastic dominance analysis (Senkondo et al., 2004). RWH raises the profile of water as an economic input in a culture where water is often taken as a gift from God or a social commodity which should be obtained for free. Equally important is the social value of water that is evident in upliftment of human dignity through RWH systems. A healthy balance between the social and economic values of RWH systems provides the impetus for a proper appreciation of the value of water as well as pricing strategy for cost and investment recovery.

2.6.5 Integrated RWH management

When considering the driving forces of water management (Figure 2.7) with particular reference to RWH, the environmental impacts are yet to be explored and the management and regulatory institutions are not in place. There is an increasing demand on a limited water resource. If RWH is to be considered as a water supply option, appropriate regulation need to be developed. South African water related legislation should cater comprehensively for RWH. The recent policy on the subsidy of RWH for households is a good step in the right direction; however, its institutional mandate is already questioned because of the existing legislative vacuum.

Beyond the environmental and institutional considerations of RWH there are the social and economical considerations. Many projects are not sustainable

because the social and economic aspects are overlooked. Time allowance should be made for the community to adjust and accept the new technology. Moreover, the material culture adapts at a faster pace than the non-material aspects of a community's culture (Botha et al., 2005).

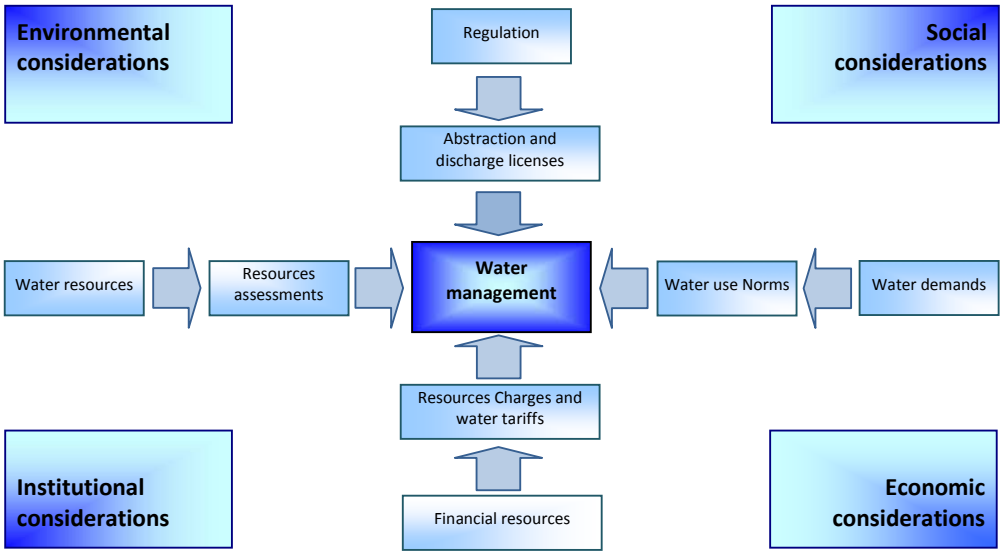


Figure 2.7. Driving forces of water management (Robinson, 2003).

The use of DRWH directly impacts the water supply especially when the excess water is injected into the aquifer. DRWH reduces storm water runoff, delaying the construction of new wastewater treatment plants. Coombes and Kuczera (2003) found that RWH induces a reduction in base demand which acts as a buffer against the effects of droughts and growth in water demand due to population growth. Apart from being a water-saving method, RWH is also an innovative energy-saving approach for hilly and/or dispersed communities (Chiu et al., 2009).

Due to the current contradictions in water related legislation of the country, it will be prudent for DRWH in urban areas to be managed in coordination with the water supply provider. In rural areas, guidelines on the construction, operation

and maintenance developed by DWAF 2007b should be translated in local languages.

Although IRWH increases water availability at the root zone and helps reduce the risk of crop failure, as in traditional rainfed agriculture, it still relies on rainfall. XRWH on the other hand is similar to irrigated agriculture since it enables to bridge dry spells through supplementary irrigation. Hence, RWH holds an intermediate status between rainfed and irrigated agriculture.

An important component of South African agricultural policy is to increase incomes of the poorest groups in society through opportunities for small/medium-scale farmers. Thus, the department of Agriculture Forestry and Fishery (DAFF) has the following three strategic aims (IPTRID, 2000):

- improve the efficiency and competitiveness of the sector;
- support smallholder farmers, and;
- conserve agricultural natural resources.

The conjunctive use of RWH and irrigation can be promoted in irrigation schemes that have to accommodate smallholder farmers. To support smallholder farmers, an interdepartmental committee comprising DWAF, the national and the provincial Department of Agriculture (DoA) was established. RWH should benefit and build on such existing cooperation, with an overriding implication being the integration of rainfed and irrigation agriculture.

Chapter 3 STUDY AREA

3.1 Background

The study is conducted at quaternary catchment (QC) scale, which is the lowest and most detailed level of operational catchment in South Africa for general planning purposes (Midgley et al., 1994). The primary catchments, drainage areas, (Figure 3.1) of South Africa comprise areas of which the topography is such that all water precipitating in the catchments is drained up into the catchment's main river.

South Africa counts 1949 QCs (Figure 3.1) interlinked and hydrologically cascading (Schulze, 2006) that have an average surface area of 650 km^2 (maximum 18146 km^2 and minimum 48 km^2). The QC numbered C52A is interpreted as follows (Midgley et al., 1994):

- The letter 'C' denotes that the QC is in Primary drainage region 'C', which is the Vaal catchment (there are 22 primary drainage regions which cover southern Africa, numbered alphabetically from 'A' to 'X', but excluding the letters 'I' and 'O').
- The number '5' denotes that the QC is in the Secondary drainage region number 5 (maximum of 9 secondaries per primary).
- The number '2' denotes that the QC is located in the tertiary drainage region number 2 (maximum of 9 tertiaries per secondary).
- 'A' denotes the QC per se. There are at most 12 QC per tertiary labelled 'A' to 'M', with 'I' omitted.

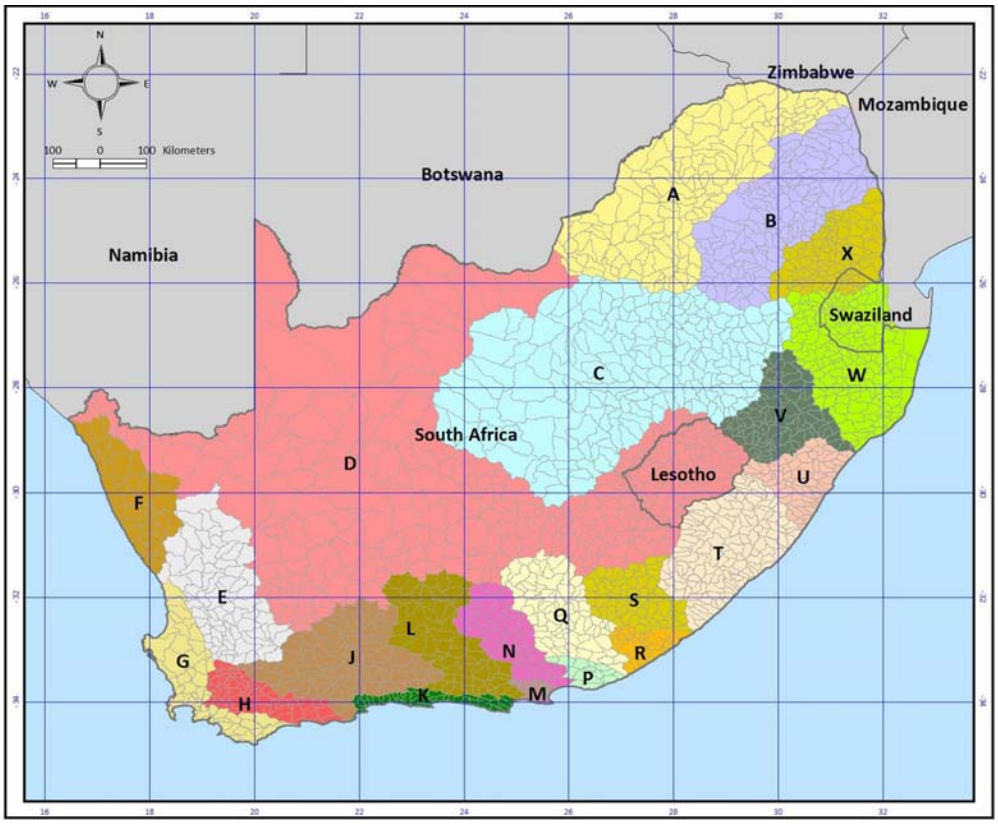


Figure 3.1. Delimitation of quaternary catchments. Primary catchments (drainage areas) are distinguished by different shading.

To fulfil the objective of assessing the footprint of RWH in any given area of South Africa, the water management area (WMA) scale was also considered. The country has 19 water management areas (WMA) (Figure 3.2). The national water resources strategy defines a WMA as a management unit within which a catchment management agency oversees the use, protection, development, conservation, management and control of water resources (DWAF, 2004).



Figure 3.2. Delimitation of the 19 Water Management Areas.

Since QCs fall into different aridity zones, two contrasting ones were considered as study areas, a semi-arid and a humid one. The semi-arid QC is C52A and the humid QC is V13D. In neighbouring catchments to C52A, namely C52B and C52C, IRWH practices have been championed by the ARC for over a decade.

This chapter describes the spatial scale at which the study was conducted and the humid and semi-arid quaternary catchments selected as study areas.

3.2 The semi-arid C52A quaternary catchment

The C52A QC is one of the four QCs that constitute the Upper Middle Modder River Basin (UMMRB) which is part of the Upper Orange WMA (92,269 km^2) located in central South Africa (Figure 3.3). The Upper Orange Water Management Area (WMA) (92,269 km^2), and its main land cover is grassland. Extensive sheep and cattle farming characterise the Upper Orange (DWAF, 2004). C52A covers 938 km^2 in the downstream part of the UMMRB (Figure 3.4).

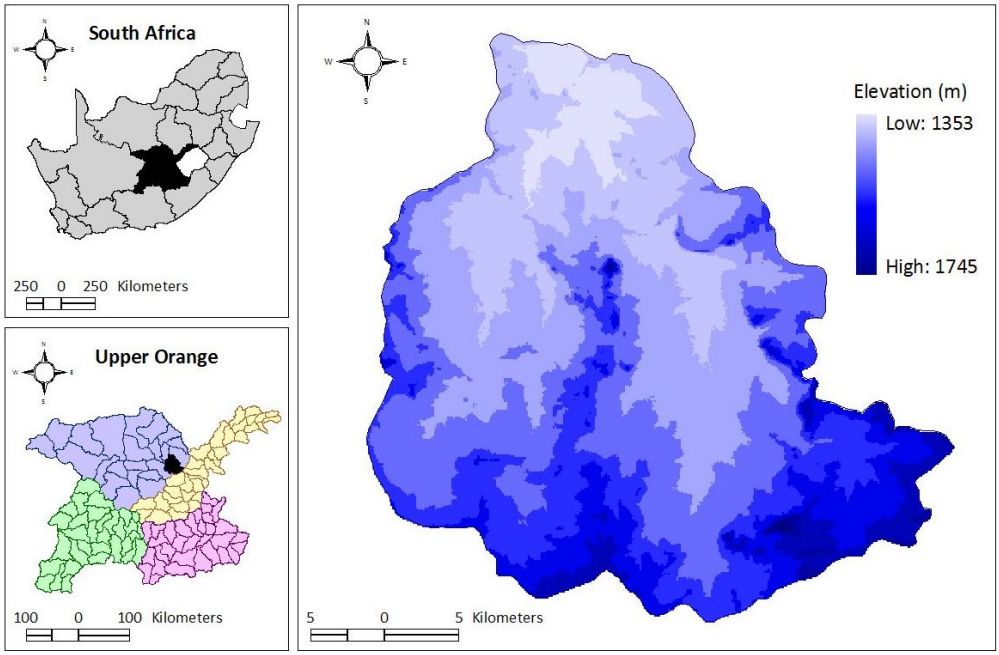


Figure 3.3. Location of the C52A quaternary catchment.

C52A has 16 different land cover (Table 3.1 and Figure 3.4). Grasslands cover about 84 percent of the total area while urban areas only cover about 0.3 percent. Consequently, much of the area is used for cattle and game farming. Cultivated lands cover about 8 % of the total area, of which 6.8 % is under commercial crop production and the remaining 1.2 % under subsistence farming.

Table 3.1 Land cover of the C52A.

Description	km^2	% of the total area
Bare Rock and Soil (erosion : dongas / gullies)	2.84	0.30
Bare Rock and Soil (erosion : sheet)	0.04	0.01
Bare Rock and Soil (natural)	0.04	0.01
Cultivated, temporary, commercial, irrigated	3.76	0.40
Cultivated, temporary, commercial, dryland	59.94	6.39
Cultivated, temporary, subsistence, dryland	9.63	1.03
Cultivated, temporary, subsistence, irrigated	2.01	0.22
Forest Plantations (Eucalyptus spp)	2.11	0.23
Forest Plantations (Pine spp)	0.06	0.01
Improved Grassland	0.38	0.04
Unimproved (natural) Grassland	785.71	83.77
Degraded Unimproved (natural) Grassland	0.58	0.06
Thicket, Bushland, Bush Clumps, High Fynbos	43.13	4.60
Urban / Built-up, (industrial / transport : light)	3.17	0.34
Waterbodies	10.54	1.12
Wetlands	14.02	1.50

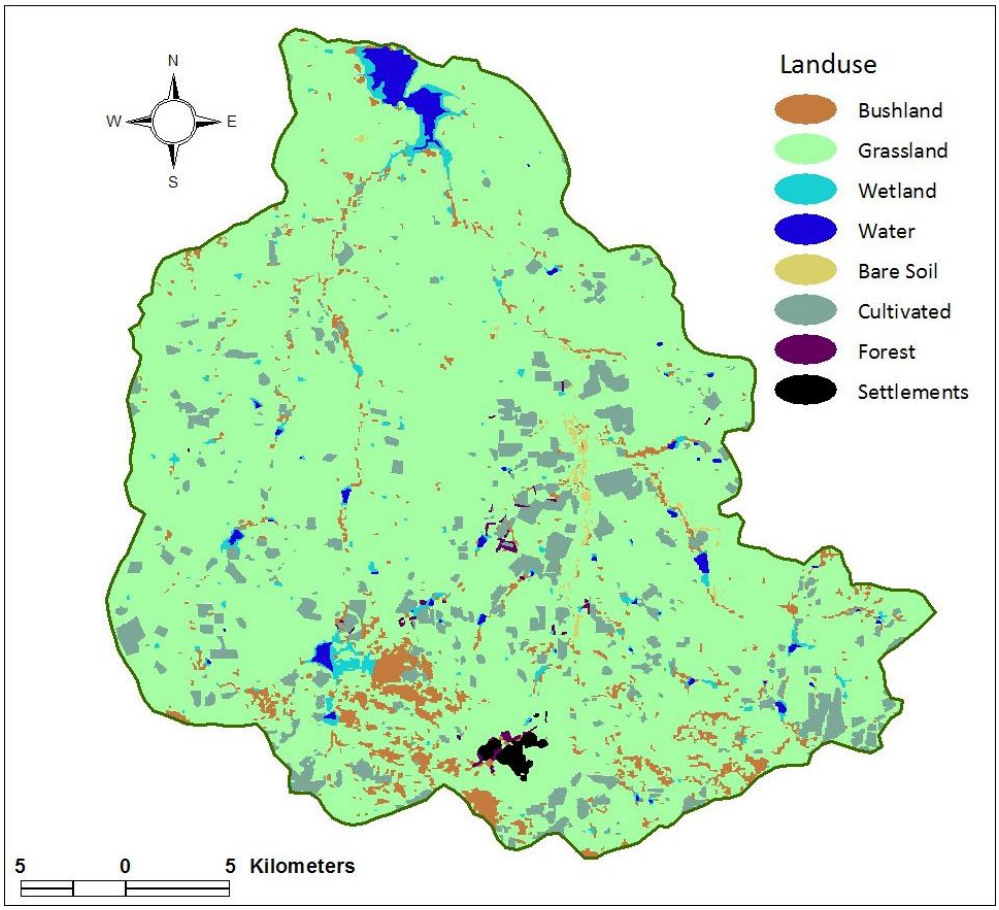


Figure 3.4. C52A land Cover (CSIR and ARC, 2004).

The mean annual precipitation (MAP) of C52A is estimated to be 543 mm and the estimated mean annual potential evaporation 1,600 mm. Values of the mean monthly precipitation of C52A are presented in Table 3.2.

Table 3.2 Mean Monthly precipitation and monthly coefficient of variation for C52A.

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
MMP (mm)	95	93	80	53	21	7	15	13	29	46	59	79
CV (mm)	76	67	57	80	113	130	156	151	150	74	68	65

MMP= Mean Monthly Precipitation, CV = Monthly coefficient of Variation

Dewetsdorp and Morojaneng (Table 3.3) are the only settlements present in the catchment.

Table 3.3 Settlements in C52A (DWAF, 2007a).

Name	Type	Population	Households
Dewetsdorp	Urban - Formal Town	1266	367
Morojaneng	Urban - Former Township	11452	3320
Total		12718	3687

3.3 The humid V13D quaternary catchment

V13D is a quaternary catchment (283 km^2) located in the Thukela WMA (29,036 km^2) in the foothills of the Drakensberg mountains in South Africa (Figure 3.5). The Thukela has several tributaries draining from the Drakensberg escarpment towards the Indian Ocean and is predominantly rural in character with forestry, agriculture and eco-tourism as primary activities (DWAF, 2004).

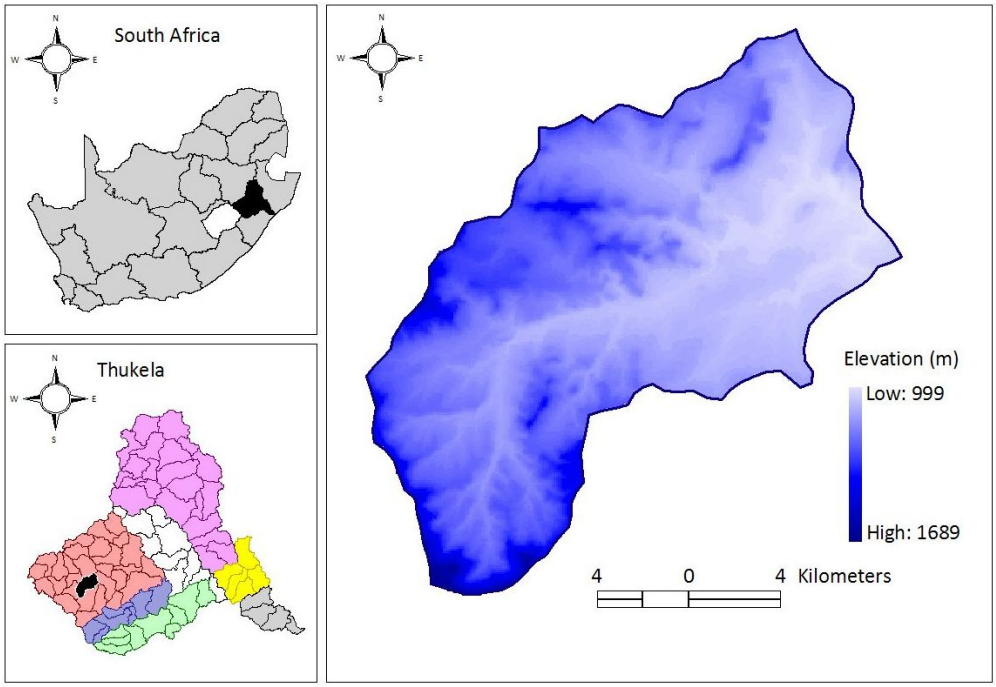


Figure 3.5. Location of the V13D quaternary catchment.

Unlike C52A, V13D has important rural settlements covering 14% of the catchment area (Table 3.4).

Table 3.4 Land cover of the V13D.

Description	km^2	% of the total area	Dominant classes
Bare Rock and Soil	0.80	0.28	Bare Soil
Cultivated, temporary, commercial, dryland	35.03	12.34	Cultivated
Cultivated, temporary, commercial, irrigated	12.07	4.25	
Cultivated, temporary, subsistence, dryland	11.02	3.88	
Degraded Unimproved (natural) Grassland	7.85	2.77	Grassland
Unimproved (natural) Grassland	157.52	55.51	
Forest Plantations (clearfelled)	1.62	0.57	Forest
Forest Plantations (Eucalyptus spp)	10.48	3.69	
Forest Plantations (Other / mixed spp)	2.98	1.05	
Forest Plantations (Pine spp)	0.73	0.26	
Thicket, Bushland, Bush Clumps, High Fynbos	2.32	0.82	Bushland
Urban / Built-up (residential)	38.49	13.56	Urban
Urban / Built-up (residential, formal suburb	0.50	0.17	
Urban / Built-up (residential, formal townsh	0.27	0.10	
Waterbodies	1.07	0.38	Water
Wetlands	0.56	0.20	Wetlands
Woodland	0.46	0.16	Woodland

Agriculture is the primary activity of the QC. Subsistence agriculture, which accounts for 11% of the catchment area (Table 3.4), takes place around the rural settlements while commercial agriculture, which accounts for 16% of the catchment area, takes place in the western part of the catchment (Figure 3.6). Grassland which covers 55% of the catchment is once again the dominant land cover.

The mean annual precipitation of V13D is estimated to be 814 mm/year and the estimated mean annual potential evaporation is 1350 mm/year. Values of the mean monthly precipitation of V13D are presented in Table 3.5.

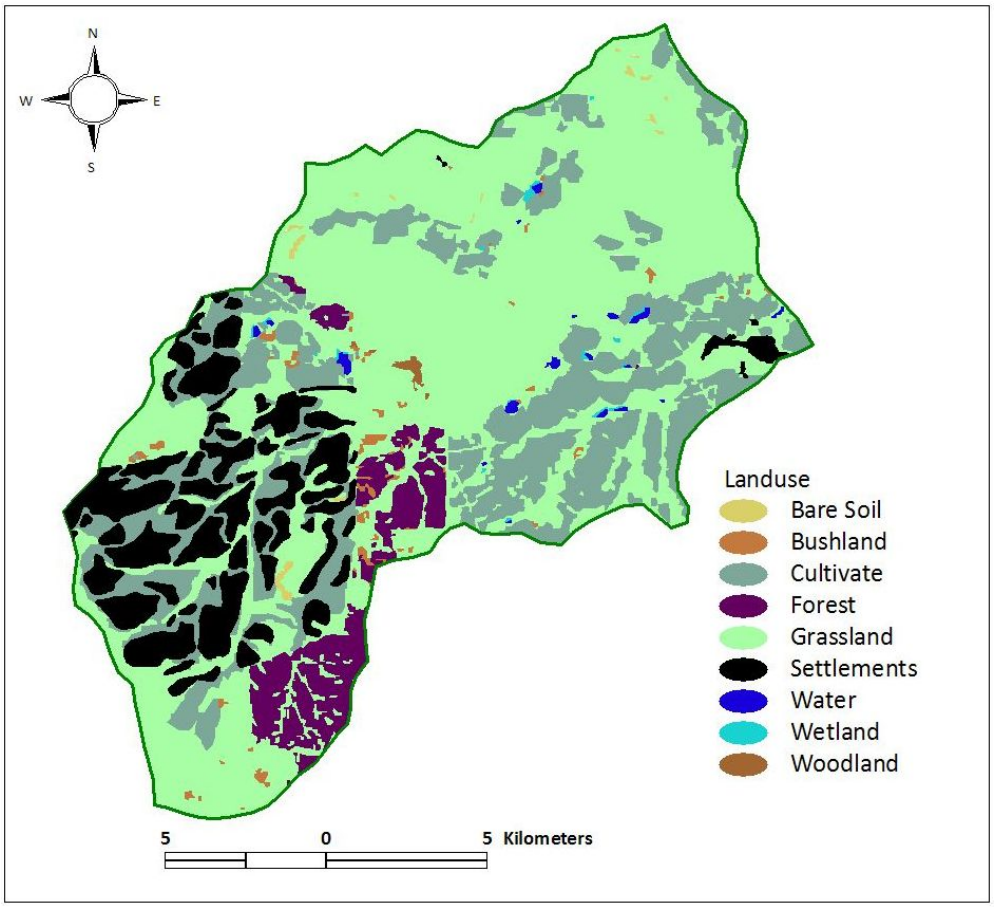


Figure 3.6. V13D land Cover (CSIR and ARC, 2004).

Table 3.5 Mean Monthly precipitation and monthly coefficient of variation for C52A.

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
MMP (mm)	117	109	72	34	15	10	9	14	41	73	92	112
CV (mm)	44	64	55	59	138	205	176	133	154	74	53	50

MMP= Mean Monthly Precipitation, CV = Monthly coefficient of Variation

With 57 rural settlements lumped into 6 groups (Table 3.6) and only 1 urban settlement, the catchment is essentially rural in character.

Table 3.6 List of settlement in V13D (DWAF, 2007a).

Name	Type	Population	Households
Bergville Nu 01	Rural Scattered village	249	51
Estcourt Nu 04	Rural Scattered village	191	39
Khwela 1-29	Rural Scattered village	7760	1573
Kwela Mabhulesini 1-9	Rural Scattered village	2492	506
Mafemfethini 2, 3, 7, 9, 11 and 13	Rural Scattered village	4490	911
Stulwane 1-10	Rural Scattered village	3742	759
Winterton	Urban - Formal Town	1522	309
Total		20446	4148

3.4 Driver rainfall stations

South Africa has over 23,000 rural communities distributed in 1949 QCs. Thus, it is preferable to optimise the RWH tank size at QC level. However, this implies that the daily time series of rainfall selected must be representative of the hydrological response of the QCs. A driver rainfall station is such a representative station that drives the hydrological response of a QC (Schulze, 2006). Although it helps preserve the statistical properties of point rainfall, it oversimplifies daily areal rainfall in large QCs. The driver station is chosen according to the following criteria (Schulze, 2006):

- it is in close proximity to, or within, the quaternary;
- its altitude is representative of the quaternary's mean altitude;

- it has a long continuous record with a minimum of missing or suspect data;
- Where data are missing, the next best driver station (according to the above criteria) is used to estimate the missing rainfall.
- The median monthly precipitation of the driver station is comparable to the median monthly precipitation of the catchment.

The concept of driver rainfall station is used in the ACRU model. The characteristics of the station selected to drive the hydrological response of the quaternary are presented in Table 3.7.

Table 3.7 Location and characteristics of the driver rainfall stations in C52A and V13D.

QC	Station name	Station no.	MAP (mm)	CV (mm)	Longitude	Latitude	Altitude (m)
C52A	Dewetsdorp	0232275 W	595	27	26°40’	-29°35’	1539
V13D	Bergville	0299614 W	714	25	29°21’	-28°44’	1151

CV=Annual Coefficient of variation

The long term daily data from the driver rainfall stations (assumed to be representative of the QC) were used for trend analysis.

The meteorological data (Figure 3.7 and Table 3.8) suggest that rainfall in C52A QC increased between the 1930s and 50s, with highest 10-year averages in the 1900s and 70s, reducing after 1910, with the lowest of 527 mm a^{-1} in the 1960s (Figure 3.7).

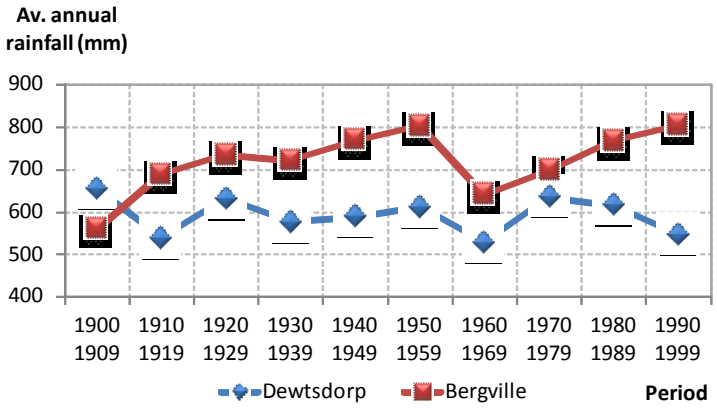


Figure 3.7. 10 years average annual rainfall at Dewetsdorp (C52A) and Bergville (V13D) stations.

While in V13D QC, the meteorological data (Figure 3.7 and Table 3.8) suggest that rainfall increases for three to four decades (1900s to 20s, 1930s to 50s and 1960s to 90s) with a decrease in between (1920s-30s and 1950s -60s). Thus there has been an overall increase in the 10-year averages.

Table 3.8 Average rainfall and standard deviation of the rainfall, at Dewetsdorp (C52A) and Bergville (V13D) stations.

	Dewetsdorp		Bergville	
Period	Annual Average (mm)	Std Dev (mm)	Annual Average (mm)	Std Dev (mm)
1900 - 1909	654	155	558	127
1910 - 1919	538	146	688	123
1920 – 1929	631	193	734	133
1930 – 1939	576	158	720	194
1940 – 1949	589	194	768	208
1950 – 1959	612	91	803	134
1960 – 1969	527	76	641	160
1970 – 1979	634	173	697	126
1980 – 1989	616	198	767	181
1990 - 1999	547	141	804	187

A trend analysis on the number of rainy days shows that the numbers of rainy days are decreasing in both QCs; however, the decrease is more significant in the humid V13D (Figure 3.8 and Figure 3.9).

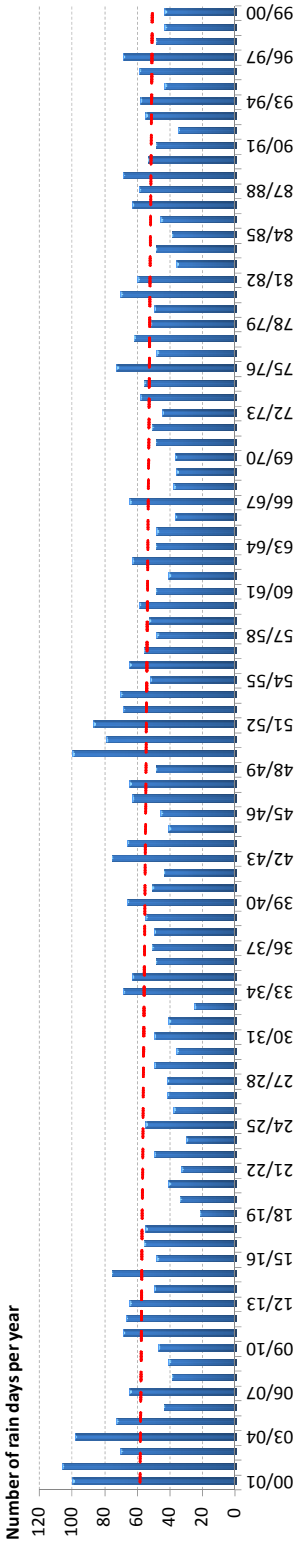


Figure 3.8. Number of rain days per year at Dewetsdorp meteorological station.

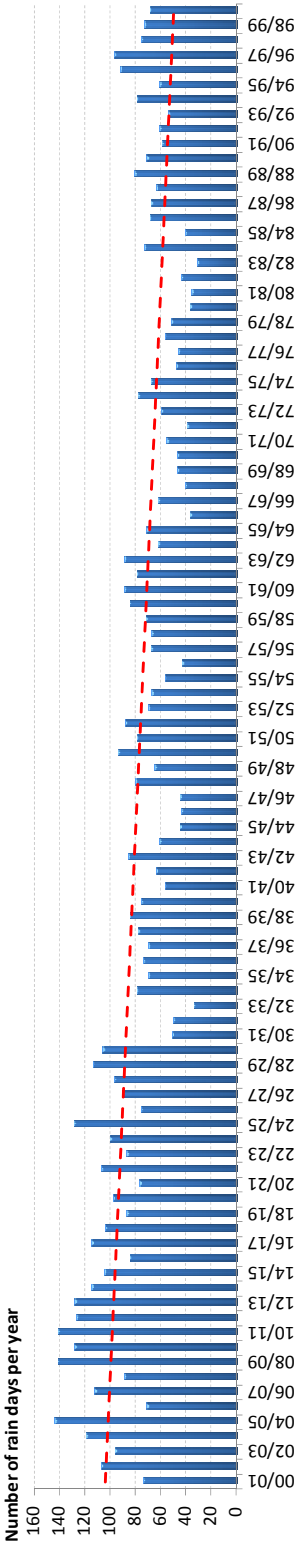


Figure 3.9. Number of rain days per year at Bergville meteorological station.

Chapter 4 ASSESSMENT OF THE RAINWATER HARVESTING FOOTPRINT[3]

4.1 Background

One of the objectives of this study is to assess RWH suitability in South Africa. The purpose of this chapter is, therefore, to present a methodology for assessing the RWH footprint in South Africa using biophysical and socioeconomic datasets.

Climate (rainfall), hydrology (rainfall–runoff relationship and intermittent watercourses), topography (slope), agronomy (crop characteristics), soils (texture, structure and depth) and socioeconomic (population density, work force, people's priorities, experience with RWH, land tenure, water laws, accessibility and related costs) are the six key parameters FAO (2003) considers when identifying suitable RWH sites. A number of studies present methods for assessing RWH suitability of a given area. Those studies use physical factors such as rainfall, land cover/use, soil characteristics and topography for the assessment of suitability. For instance, Hensley et al. (2007) used an improved land survey technique to delineate land suitable for IRWH. Mbilinyi et al. (2006) used rainfall, soil depth, soil texture, differential global positioning system points, aerial photos, ground truthing and topographic maps while Mati et al. (2006) used baseline thematic maps (rainfall, topography, soils, population density and land use) to produce composite maps that show attributes or "development domains" that serve as indicators of suitability for targeted RWH interventions.

[3] This chapter is based on: Mwenge Kahinda, J., Lillie, E.S.B., Taigbenu A. E., Taute, M and Boroto, R.J., 2008. Developing suitability maps for Rainwater harvesting in South Africa. J. Phys. Chem. Earth 33 (8-13), 88–799.

To determine index maps of RWH potential (ponds) in Africa, Senay and Verdin (2004) used runoff data derived from rainfall data using the Soil Conservation Service runoff curve number methods and delineated watersheds from the Africa-wide Hydro-1K digital elevation model. To identify suitable RWH areas, Mou et al. (1999) used rainfall (average rainfall, annual rain days, annual rainfall fluctuation rate) and topography while Prinz et al. (1998) used remote sensed data and thematic maps in conjunction with field investigations. In his iterative decision tree, Patrick (1997) incorporated socioeconomic factors after the mapping of RWH sites. The need to integrate socioeconomic factors into deciding the suitability of an area to RWH largely underscores the failure or success of RWH systems (Oweis et al., 2001; Critchley and Siegert, 1991). The non-consideration of socioeconomic aspects leads to inappropriate targeting of RWH (He et al., 2007).

4.2 Methodology

The RWH suitability models (RSMs) are built in ModelBuilder, an extension of ArcView 3.3, where parameters may be changed easily and the model rerun to explore alternatives. Results of the RSMs are displayed on maps with five suitability levels (very low to very high). Different suitability values were assigned to the physical, ecological and socioeconomic layers based on literature review. Thereafter, pixel values of each physical, ecological and socioeconomic layer were reclassified from 1 to 5. The most suitable parameters were classified as 5, while the least suitable were classified as 1. To customise the RSM and reduce the computational time, the conversion to grid theme and the reclassification was done during the data processing using Spatial Analyst (an extension of ArcView 3.3).

4.2.1 The scale of the RSM

The average size of smallholder farmers' crop field is about 10,000 m^2 (de Winnaar et al., 2007; Botha et al., 2003). Since the size of the pixel should be half of the smallest distance to be represented, a 50mx50m pixel would have represented RWH more appropriately. However, to strike a balance between large data volume resulting from too fine cell size and over generalisation resulting from too coarse cell size and taking into account the resolution of the available dataset, a cell size of 100mx100m was adopted.

The datasets used were collected in different years from different sources and therefore have different resolutions (Table 4.1). The rainfall and the aridity zones datasets that have coarser resolution (2km x 2km) were resampled to produce new datasets with smaller grid size (100m x 100m). The model prediction is generalised because it is based on country scaled data. Figure 4.1 shows how the generalisation reduces both the number of objects, and the amount of detail of the land use dataset.

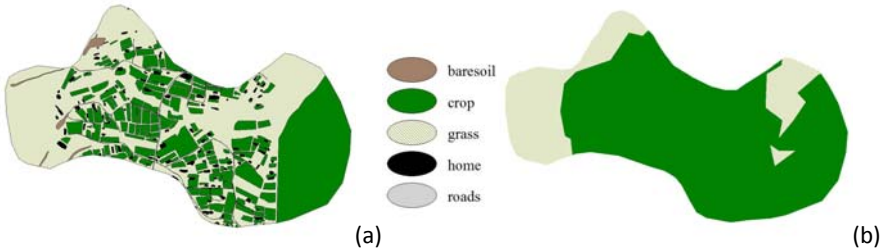


Figure 4.1. Land use for the Potshini catchment: (a) at 1:50,000 resolution (de Winnaar et al., 2007), (b) from the National Land cover 2000 with 1:250,000 resolution.

Geographic data are rarely distinguished by regularly spaced shapes. Hence, variation in any of the layers within the cells is lost and replaced by a single value that serves as representative value. Though the conversion of the data into the raster format was a necessary step of the analysis, it further reduced the quality and accuracy of the results generated by the model.

The RSM allows the user to work at two scales: Country scale and WMA scale.

4.2.2 Thematic maps

Biophysical and socioeconomic datasets (Table 4.1.) compiled by various government departments and institutions were used as input into the RSMs.

Table 4.1 Biophysical and socioeconomic datasets used in the RSMs.

No.	Attributes	Layers	Resolution	Source
1	Physical	Aridity zones	2km x 2km	AGIS
2		Annual Rainfall with 80% Probability of Exceedence	2km x 2km	Schulze et al., 1996
3		National land cover 2000	1/250,000	CSIR & ARC, 2004
4		Soil Texture	1/250,000	Land type of the ARC
5		Soil depth	1/250,000	Schulze, 2006
6		Settlements	1/250,000	DWAF, 2007a
7		Slopes	90m x 90m	
8	Ecological	Ecological Importance and Sensitivity Category	1/250,000	DWAF, 1999
9	Socioeconomic	Percentage households without piped water	1/250,000	SSA, 2005a; SSA, 2005b
10		Percentage households without proper sanitation	1/250,000	
11		Percentage household below poverty datum	1/250,000	
12		Percentage of population not economically active	1/250,000	
13	Constraint	Rivers	1/250,000	DWAF
14		Dams and lakes	1/250,000	
15		Roads	1/250,000	
16		Railways	1/250,000	
17		Conservation Areas	1/250,000	
18		Urban Areas	1/250,000	
19		5km buffer around settlements	1/250,000	

AGIS: Agricultural Geo-referenced Information System

Maps of the above datasets are attached in Appendix A.

4.2.2.1 Physical layers

i. Aridity Zones

Six aridity zones (Table 4.4) are delineated based on the ratio of precipitation to potential evapotranspiration (PET). About 91% of the country has a ratio of rainfall to PET that lies between 0.05 and 0.65. In general, RWH is suitable in arid, semi-arid and dry sub-humid areas (FAO, 2003).

ii. Rainfall

The magnitude of rainfall plays a significant role in assessing the suitability of RWH for a given area. Rainfalls in semi-arid and arid regions of South Africa are of short duration, relatively high intensity, limited spatial extent and large variability. It is therefore inadequate to use the mean annual precipitation to find suitable sites for RWH since it does not account for its variability. To account for this variability, FAO (2003) recommends the use of design rainfall of 67% probability of exceedence which corresponds to a return period of 1.5 years (table 4.2). In this study, the Annual rainfall with 80% probability of exceedence was used.

Table 4.2 Relation percentage rainfall probability of exceedence and return period.

Probability of Exceedence (%)	Return Period (Years)	Rainfall equalled or exceeded
100	1	Every year
80	1.25	4 times in 5 years
75	1.33	3 times in 4 years
67	1.5	Twice in 3 years
1	100	Once in 100 years

Promoting RWH in areas receiving less than 100mm or more than 1000mm of rains is a tall order (Mou et al., 1999; Mati et al., 2006; FAO, 2003). There is hardly any productive water-based activity that is feasible in areas that receive less than 100mm per annum of rain, while there is little incentive to implement RWH infrastructure in areas with annual rains in excess of 1000mm per annum. However, DRWH does take place in high rainfall areas due to socioeconomic conditions of underdevelopment in scattered settlements where centralised piped systems are uneconomically viable. This again brings to light the socioeconomic dimension in RWH.

The model gives the user the option of using either the aridity zones or the rainfall as a physical layer.

iii. National Land Cover 2000

There is a correlation between the land cover and the runoff produced by a given area for a rainfall event. Increase in the vegetation density results in a corresponding increase in interception and infiltration rates thereby reducing runoff (Thompson, 1999).

Table 4.3 Ranking of land cover classes for RSM.

No.	IRWH	XRWH	Land Cover Class
1	1	1	Forest (indigenous)
2	2	2	Woodland (previously termed Forest & Woodland)
3	1	1	Thicket, Bushland, Bush Clumps, High Fynbos
4	1	1	Shrubland and Low Fynbos
5	4	4	Herbland
6	3	3	Natural Grassland (previously termed Unimproved Grassland)
7	3	3	Planted Grassland (previously termed Improved Grassland)
8	2	2	Forest Plantations (Eucalyptus spp)
9	2	2	Forest Plantations (Pine spp)
10	2	2	Forest Plantations (Acacia spp)
11	2	2	Forest Plantations (Other / mixed spp)
12	2	2	Forest Plantations (clearfelled)
13	1	1	Waterbodies
14	1	1	Wetlands
15	1	2	Bare Rock and Soil (natural)
16	1	3	Bare Rock and Soil (erosion : dongas / gullies)
17	2	3	Bare Rock and Soil (erosion: sheet)
18	3	3	Degraded Forest & Woodland
19	3	3	Degraded Thicket, Bushland, etc
20	2	2	Degraded Shrubland and Low Fynbos
21	3	3	Degraded Herbland
22	2	2	Degraded Unimproved (natural) Grassland
23	1	1	Cultivated, permanent, commercial, irrigated
24	3	3	Cultivated, permanent, commercial, dryland
25	1	1	Cultivated, permanent, commercial, sugarcane
26	2	2	Cultivated, temporary, commercial, irrigated
27	4	4	Cultivated, temporary, commercial, dryland
28	5	5	Cultivated, temporary, subsistence, dryland
29	3	5	Cultivated, temporary, subsistence, irrigated
30	1	1	Urban / Built-up
31	3	2	Urban / Built-up (rural cluster)
32	1	1	Urban / Built-up (residential, formal suburbs)
33	1	1	Urban / Built-up (residential, flatland)
34	1	1	Urban / Built-up (residential, mixed)
35	1	1	Urban / Built-up (residential, hostels)
36	1	1	Urban / Built-up (residential, formal township)
37	1	1	Urban / Built-up (residential, informal township
38	1	1	Urban / Built-up (residential, informal squatter camp)
39	3	3	Urban / Built-up (smallholdings, forest & woodland …)
40	3	3	Urban / Built-up (smallholdings, thicket, bushland …)
41	3	3	Urban / Built-up (smallholdings, shrubland …)
42	3	3	Urban / Built-up (smallholdings, grassland …)
43	1	1	Urban / Built-up, (commercial, mercantile)
44	1	1	Urban / Built-up, (commercial, education, health, IT)
45	1	1	Urban / Built-up, (industrial / transport : heavy)
46	1	1	Urban / Built-up, (industrial / transport : light
47	1	1	Mines & Quarries (underground / subsurface mining)
48	1	1	Mines & Quarries (surface-based mining)
49	1	1	Mines & Quarries (mine tailings, waste dumps)

Thus the design of RWH takes cognisance of the runoff component of the hydrological process. The national land cover 2000 (NLC2000), developed by the Council for Scientific and Industrial Research (CSIR) & the ARC, is the latest and most detailed land cover dataset at national level. The land cover classes in the dataset were ranked according to their suitability to RWH (Table 4.3).

iv. Soil texture

The soil texture was derived from the land type dataset of the ARC. The land type dataset has six clay classes to which textural classes are associated. Most South African soils have about 10% of silt content (Schulze, 2006 citing Hutson, 1984). Each textural class was then reclassified (Table 4.4) following the FAO (2003) soil texture triangle (Figure 4.2), which indicates the relative proportion of sand, silt and clay suitable for RWH either as catchment area (Runoff area) or crop basin (Runon area).

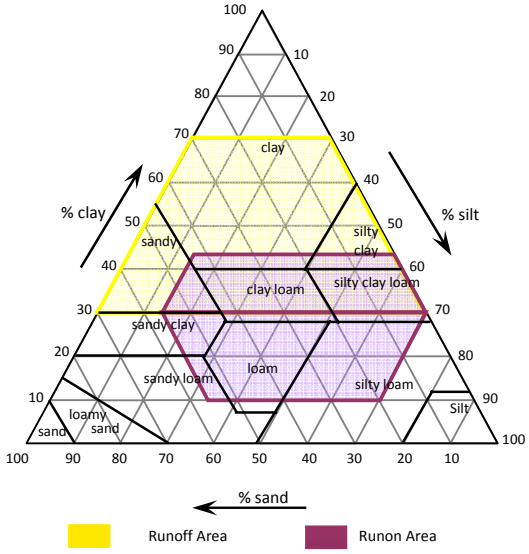


Figure 4.2. Soil texture triangle with RWH Runon and Runoff area (FAO, 2003).

v. Soil depth

The total soil depth was calculated by adding the thicknesses of topsoil and subsoil horizons. Most topsoils in South Africa, especially in the eastern regions, extend to a depth of 0.25 - 0.30m, with slightly thinner topsoils at 0.20 - 0.25m in the semi-arid central-west regions and smaller tracts at < 0.20m (Schulze, 2006). The soil depth dataset was divided into 5 classes, from very shallow to very deep and ranked according to their suitability to IRWH (Table 4.4). The deeper the soil, the more suitable it is for IRWH (FAO, 2003).

Table 4.4 RWH suitability ranking for aridity zones, rainfall, soil texture, soil depth, EISC, settlements and socioeconomic layers.

Layer Class		Suitability ranking				Layer Class		Suitability ranking			
		I*	X*	DRWH				I	X	DRWH	
				Agt	Ugt					Agt	Ugt
Rainfall (mm)	0-100	1	1	1	1	Aridity Zone	Hyper-Arid	1	1	N/A	N/A
	100-200	2	2	2	2		Arid	4	3	N/A	N/A
	200-400	5	3	3	3		Semi-Arid	5	4	N/A	N/A
	400-600	4	4	4	4		Dry sub-humid	3	5	N/A	N/A
	600-800	3	5	5	5		Humid	1	2	N/A	N/A
	800-1000	3	3	4	2	Soil Depth (m)	>0.75	5	N/A	N/A	N/A
	>1000	1	1	3	1		0.4 - 0.75	4	N/A	N/A	N/A
							0.3 - 0.4	3	N/A	N/A	N/A
Soil Texture	clay	1	3	N/A	5		0.2 - 0.3	2	N/A	N/A	N/A
	Loamy sand	2	2	N/A	1		<0.2	1	N/A	N/A	N/A
	sand	1	1	N/A	1	EISC	Very high	1	1	1	1
	Sandy Clay Loam	5	4	N/A	3		High	2	2	2	2
	sandy clay	3	5	N/A	2		No data	3	3	3	3
	sandy loam	4	3	N/A	2		Moderate	4	4	4	4
							Low/ marginal	5	5	5	5
Settlements	Former Township	N/A	N/A	3	2	Slopes (%)	0-2	N/A	N/A	N/A	1
	Informal Settlement	N/A	N/A	3	2		2-8	N/A	N/A	N/A	2
	Metropolitan Area	N/A	N/A	2	2		8-16	N/A	N/A	N/A	3
	Former Town	N/A	N/A	3	3		16-30	N/A	N/A	N/A	4
	Working Towns	N/A	N/A	4	4		>30	N/A	N/A	N/A	5
	Farming	N/A	N/A	5	5	Socioeconomic	0-20	1	1	1	1
	Service Centres	N/A	N/A	5	5		21-40	2	2	2	2
	Ex-homelands	N/A	N/A	4	4		41-60	3	3	3	3
	Dense Villages	N/A	N/A	4	4		61-80	4	4	4	4
	Small and scattered Villages	N/A	N/A	5	5		81-100	5	5	5	5

I* = IRWH, X* = XRWH and N/A = Not Applicable. The most suitable parameters were classified as 5, while the least suitable were classified as 1.

The soil dataset was not used as a physical attribute in the XRWH suitability model since good XRWH catchment areas are those with shallow soils whereas XRWH crop basins are these with deep soils.

vi. Slope

The slope dataset was derived from the country 90M Digital Elevation Model using spatial analyst. The dataset was divided into 5 classes, from Flat to Mountainous following the FAO (1990) classification and ranked according to their suitability to DRWH-Ugt (Table 4.4). The steeper the soil, the more suitable it is for DRWH-Ugt.

vii. Settlements

The DWAF Water Services' community 2007 dataset has 11 settlement classes: metropolitan area, former town, former township, working towns, informal settlement, ex-homeland, dense village (>5000 inhabitants), small village (≤5000 inhabitants), scattered village, farming and service centres. Each class was allocated a suitability rank from 1 to 5 (Table 4.4). Metropolitan areas which receive water service at levels comparable to those of developed countries are not likely, unless a policy is targeted to encourage rainwater use, to embark on DRWH, so were ranked 2. Dense and small/scattered villages where DRWH can increase the water security were ranked 4 and 5 respectively.

4.2.2.2 Ecological layer

i. Ecological Importance and Sensitivity Category

The ecological importance of a river is indicative of its importance to maintain ecological diversity and functioning on local and wider scales (DWAF, 1999).

Ecological sensitivity (or fragility) refers to the system's capacity to resist disturbance and to recover from disturbance once it has occurred (resilience) (DWAF, 1999 citing Milner 1994). The EISC dataset has four classes: very high, high, moderate and low/marginal. A very high EISC indicates that the biodiversity of the river is very sensitive to flow modifications, hence least suited for RWH (Table 4.4).

4.2.2.3 Socioeconomic layers

Four socioeconomic datasets were derived from the 2001 population census which provides data at sub place and small area levels (Table 4.4). A sub place represents a local social boundary equivalent to a split suburb in urban formal areas, a locality in informal settlements and a village in traditional areas (SSA, 2004a), while a small area is a sub-division of a sub place created by combining all areas with a population of less than 500 (SSA, 2004b). The country is divided into 21,243 sub places and 56,255 small areas. The four socioeconomic datasets used to assess the vulnerability level of rural communities are:

i. Households below poverty datum

Any household with an annual income not exceeding ZAR 9,600 is considered below the poverty datum. It is conjectured that financially constrained households will benefit the most from any additional income that RWH might provide.

ii. Population not economically active

A person aged below 15 or over 65 is considered economically inactive and dependant on income generated by others. Thus, community with high number

of economically inactive individual are the most vulnerable to poverty and hence most likely to benefit from RWH interventions.

iii. Percentage of households without piped water

About 47% of rural households have non-piped water (springs, boreholes, dam/pool/stagnant water, water vendors, etc) as their main water source and only 28% of households have piped water either inside their dwelling or in their yard (Mwenge Kahinda et al., 2007c). Household without proper water services can use RWH either as main or supplementary water source.

iv. Households without water borne sanitation

There is a direct link between the provision of clean water, adequate sanitation and improved health (Gleick, 1996). The lower the level of sanitation, the higher the risk of contracting water related diseases. Since RWH improves the reliability of water supply and thus the level of sanitation, it directly contributes to reduce the incidence of waterborne diseases.

The socioeconomic datasets were reclassified from 1 to 5 (Table 4.4). The highly vulnerable sub places or small areas were classified as 5 (80 - 100 % of the population), while the least vulnerable were classified as 1 (0 – 20% of the population).

4.2.2.4 Constraint layers

It is physically not possible to implement RWH in a reservoir or a river. Similarly, roads and railways are also no go areas for RWH. While DRWH is implemented within a settlement, FRWH is only expected to take place in homesteads gardens and in farm plots within a 5km radius around the settlements. Consequently,

seven layers identified as constraints (Table 4.1) were converted into binary maps. A value of 0 was assigned to restricted areas and a value of 1 was assigned to suitable areas (Diamond and Parteno, 2004).

4.3 The Rainwater harvesting suitability model

The Rainwater harvesting Suitability Model (RSM) has a modular structure that enables the user to establish or delete the links between its two sub-models, the potential model and the constraint model as illustrated in Figure 4.3.

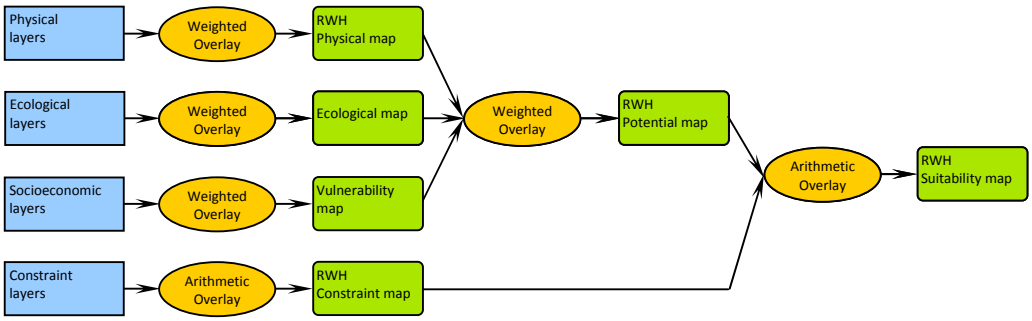


Figure 4.3 Schematic of the RSM showing the Potential model and Constraint sub-models.

4.3.1 The potential Model

The potential model produces the potential map by associating through weighted overlay physical, ecological and vulnerability (socio-economic) maps (Figure 4.3). The weighted overlay process (WOP) allows the combination of data from several input grid themes by converting their cell values to a common scale, assigning a weight (percent influence) to each theme, and then aggregating the weighted cell values together. The WOP, also known as the multi-criteria evaluation (MCE), is a weighted linear method commonly used in GIS-based decision-making (Store and Jokimäki, 2003). Each layer is multiplied

by its weight and the results summed according to equation 4.1 (Malczewski, 1999):

$$A_j = \sum_{i=1}^{m} w_i x_{ij} \qquad 4.1$$

Where A_j = final suitability score in each pixel;

x_{ij} = suitability of the i_{th} cell with respect to the j_{th} layer, and;

w_i = normalised weight so that $\Sigma\, w_i=1$.

The weights enable the solution to reflect the importance (as perceived by the user) of the input layer relative to each other. For all the models using the WOP, since there is no scientific basis for attributing a higher weight to a particular layer, an equal weight was assigned to all the layers.

As alluded to previously, the physical layers that are employed in the physical model are chosen to reflect the peculiar features of the four categories of RWH.

4.3.2 The RWH physical models

The DRWH-Agt physical model (Figure 4.4a) overlays two physical layers (rainfall, and settlements) to produce the DRWH-Agt physical map, while the DRWH-Ugt physical model (Figure 4.4b) overlays four physical layers (rainfall, settlements, soil texture and slope) to produce the DRWH-Ugt physical map.

The IRWH physical model (Figure 4.4c) overlays four physical layers (aridity zones, land cover, soil depth and soil texture, with weights of 0.33, 0.33, 0.17 and 0.17, respectively) to generate the IRWH physical map. The XRWH physical map (Figure 4.4d) is obtained from the XRWH physical model by overlaying three physical layers: aridity zones, land cover and soil texture.

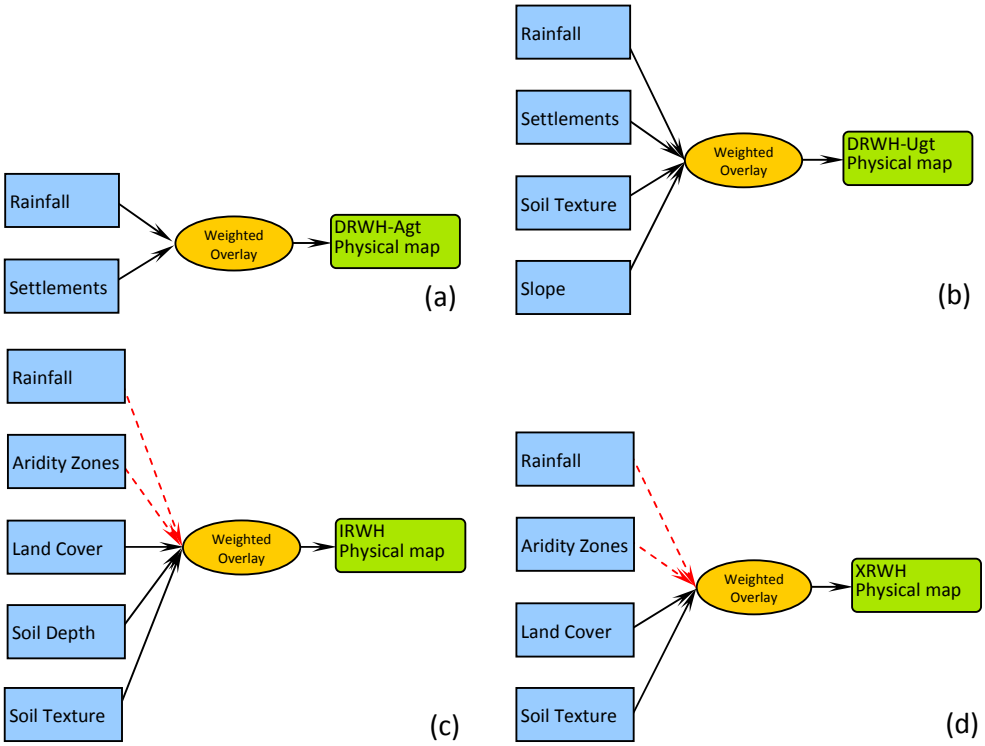


Figure 4.4 IRWH Physical model of (a) DRWH-Agt, (b) DRWH-Ugt, (c) IRWH and (d) XRWH (The user has the option of using either the aridity zones or the rainfall as a physical layer).

Although all physical models perform a weighted overlay with equal weight assigned to each physical dataset, there are instances where the weight has to be split between components of the same dataset. This is the case with the soil dataset where assigned weight is split between soil depth and soil texture (Figure 4.4c).

4.3.3 The vulnerability model

The vulnerability model produces the vulnerability map by overlaying four socioeconomic datasets (the percentage of households without piped water, households without water borne sanitation, households below the poverty

datum and the population not economically active) with equal weights (Figure 4.5).

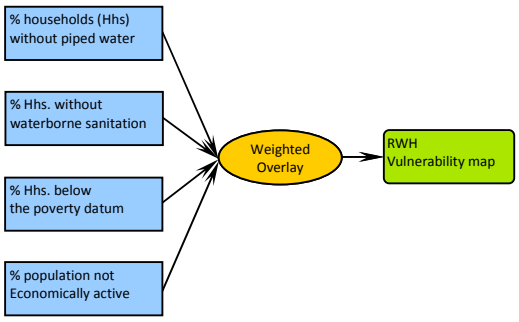


Figure 4.5 RWH vulnerability model.

4.3.4 The ecological model

The ecological model produces the ecological map by overlaying ecological dataset. In this study, the EISC layer was the only ecological layer available at national level.

4.3.5 The constraint model

The constraint model generates the constraint map by combining binary constraint layers using model builder's arithmetic overlay (Figure 4.6). The arithmetic overlay process allows the combination of several input grid themes by assigning an operator and/or multiplier to each theme. The constraint map generated from the overlay assigned 0 to unsuitable areas and 1 to suitable areas.

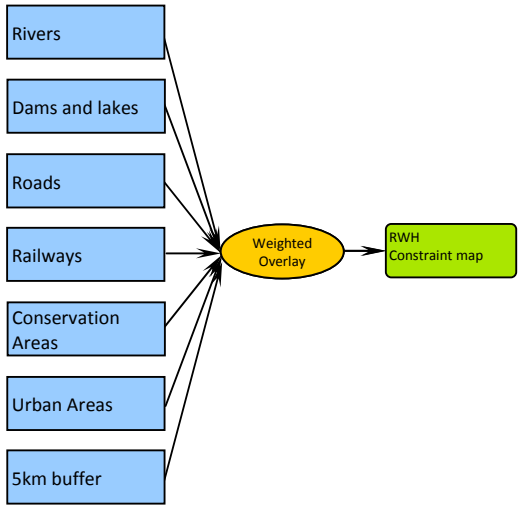


Figure 4.6 RWH constraint model.

4.4 Rainwater harvesting suitability maps

As illustrated in Figure 4.3, the RWH suitability maps are produced from an overlay of the physical, ecological, vulnerability and constraint maps. They provide from a country perspective an indicative likelihood of areas suited for various practices.

4.4.1 The vulnerability map

The vulnerability map (Figure 4.7) was generated by the WOP of the 4 socioeconomic layers. The vulnerability map indicates that the most vulnerable communities are mainly located in the eastern part of the country, in Kwazulu-Natal and the Eastern Cape provinces (Figure 4.7). Some vulnerable communities are also located in the Limpopo and the North West provinces. It is in those communities that interventions such as RWH are most needed. The results are in line with those of Holl et al. (2007) as most of the identified

vulnerable areas correspond to the old Transkei, Bophuthatswana, Venda, and Ciskei states. These areas share high levels of poverty and unemployment, low levels of investment, inadequate infrastructure, and a disproportionately low level of development of human resources (ISRDP, 2006).

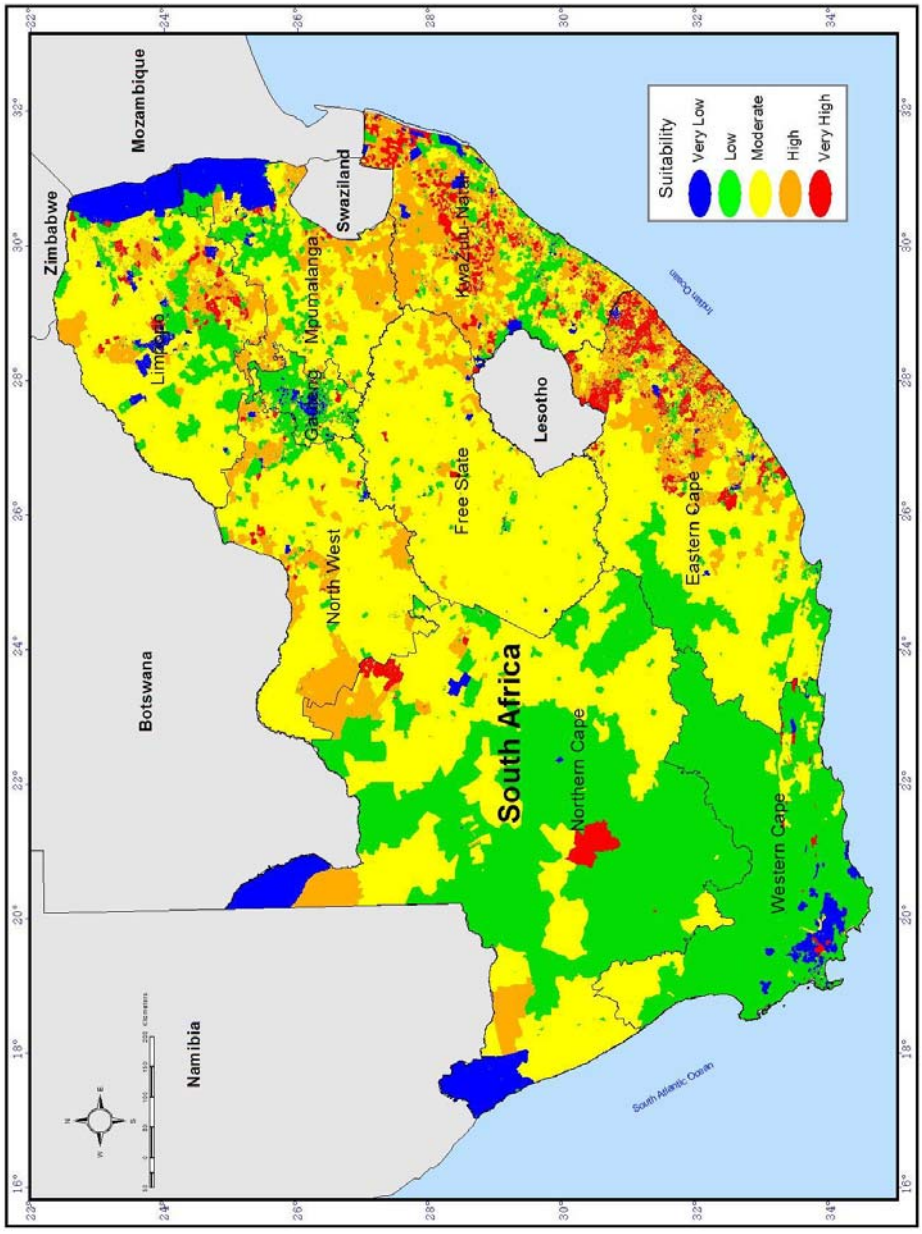


Figure 4.7 RWH vulnerability map.

4.4.2 The ecological map

The ecological model (Figure 4.8) indicates areas to the South-East and North-East as most ecologically sensitive, hence requiring cautious wide scale adoption of RWH.

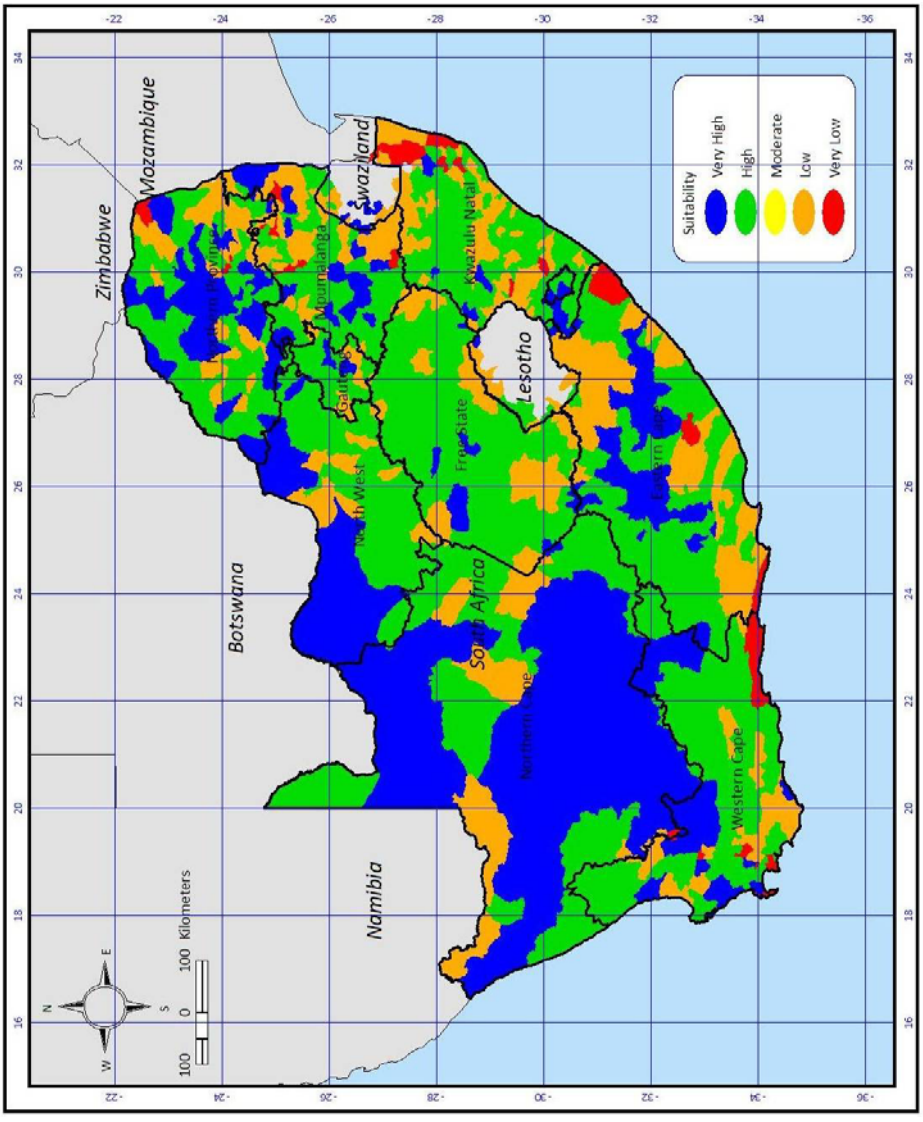


Figure 4.8 Ecological map.

4.4.3 RWH physical maps

About 65% of the total settlements' area (Figure 4.9a) is suitable (high & very high) to DRWH-Agt. Most of the suitable settlements to DRWH-Agt are located in KwaZulu-Natal and the Eastern Cape Province (Figure 4.10a and Figure 4.11).

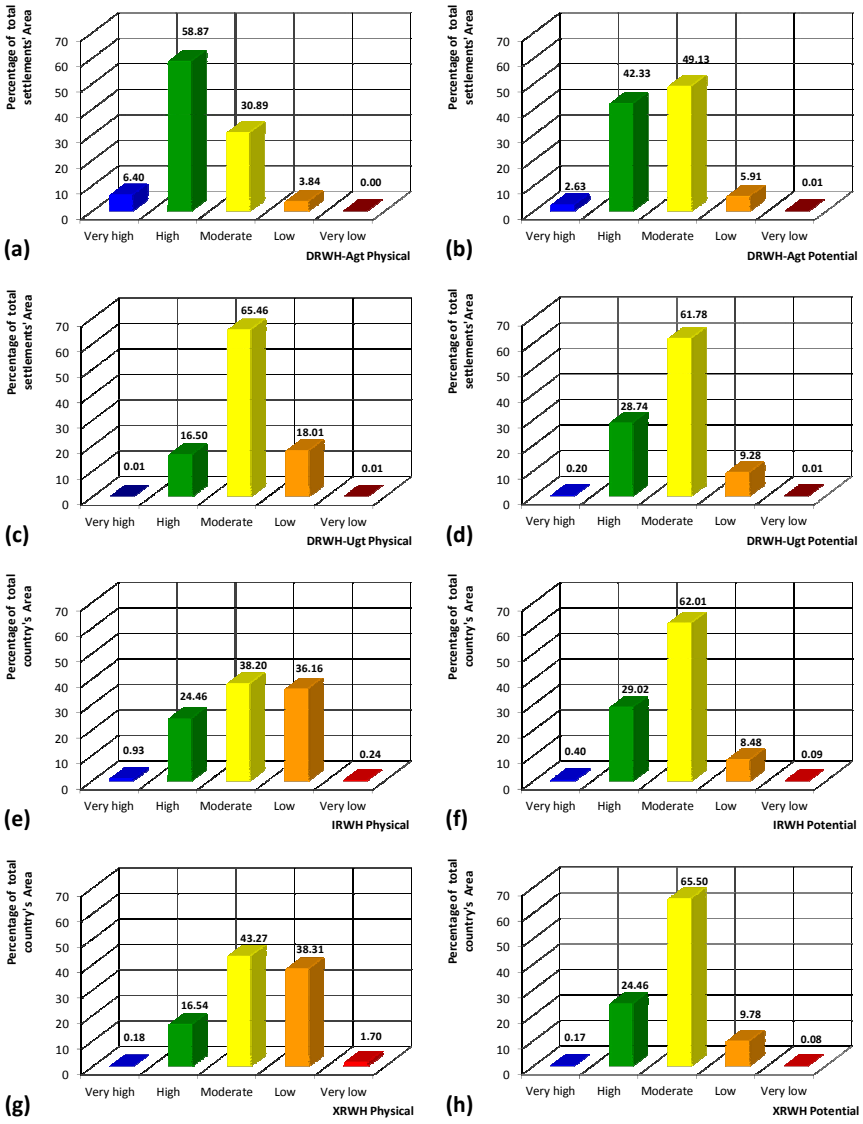
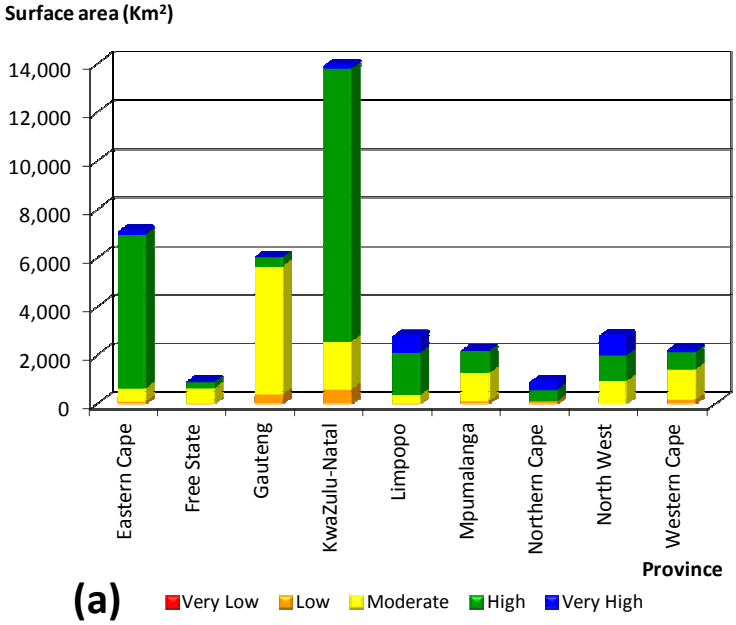
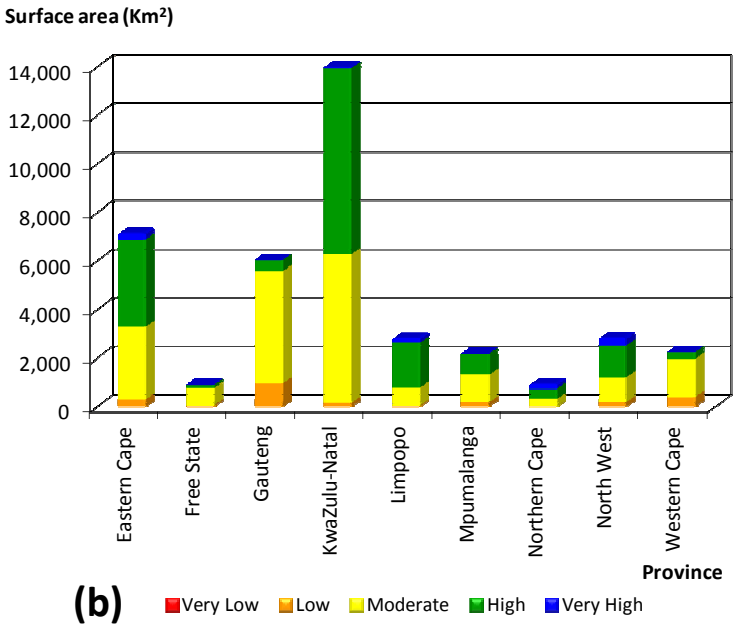


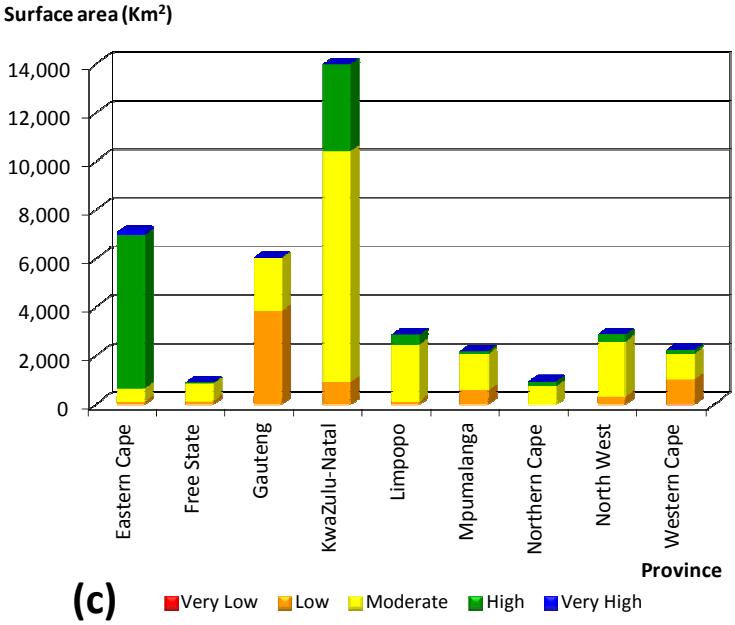
Figure 4.9 Percentage of land area for each suitability class in South Africa: (a) DRWH-Agt physical, (b) DRWH-Agt potential, (c) DRWH-Ugt physical, (d) DRWH-Ugt potential, (e) IRWH physical, (f) IRWH potential, (g) XRWH physical and (h) XRWH potential (RWH potential maps are presented in section 4.4.4).

Around 17% of the total settlements' area is suitable (high & very high) to DRWH-Ugt (Figure 4.9c). The majority of the suitable settlements to DRWH-Ugt are once again located in KwaZulu-Natal and the Eastern Cape Province (Figure 4.10c and Figure 4.12). It should be noted that a more appropriate unit for the adoption of DRWH is household rather than settlement area which does not reflect population density. However, to simplify the modelling process on country-wide scale, the settlement area is used.




Surface area (Km²)
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Eastern Cape
Free State
Gauteng
KwaZulu-Natal
Limpopo
Mpumalanga
Northern Cape
North West
Western Cape
Province
Very Low
Low
Moderate
High
Very High

(b)


Surface area (Km²)
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Eastern Cape
Free State
Gauteng
KwaZulu-Natal
Limpopo
Mpumalanga
Northern Cape
North West
Western Cape
Province
Very Low
Low
Moderate
High
Very High

(c)

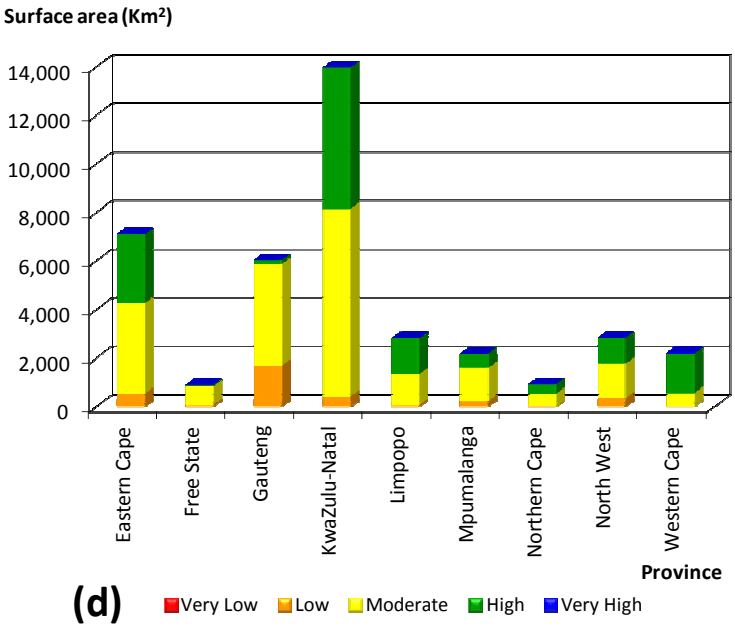


Figure 4.10 Surface area of each suitability class in the 9 provinces of South Africa: (a) DRWH-Agt physical, (b) DRWH-Agt potential, (c) DRWH-Ugt physical and (d) DRWH-Ugt potential.

Based on the physical layers, suitable (high & very high) IRWH areas cover about 25% of South Africa (Figure 4.9e), and are mainly located in the Free State, Mpumalanga, Limpopo, Gauteng, North West and the central part of the Eastern Cape (Figure 4.13). The southern part of the Western Cape and the northern part of Kwazulu-Natal are also suitable while the Northern Cape is the least suitable.

The XRWH physical map indicates that 17% of the country is suitable (high & very high) for XRWH (Figure 4.9g). The most suitable areas are mainly located in the Free State, North West and Limpopo (Figure 4.14). The North Eastern region of the Eastern Cape and the South Eastern part of Kwazulu-Natal were found to be the least suitable.

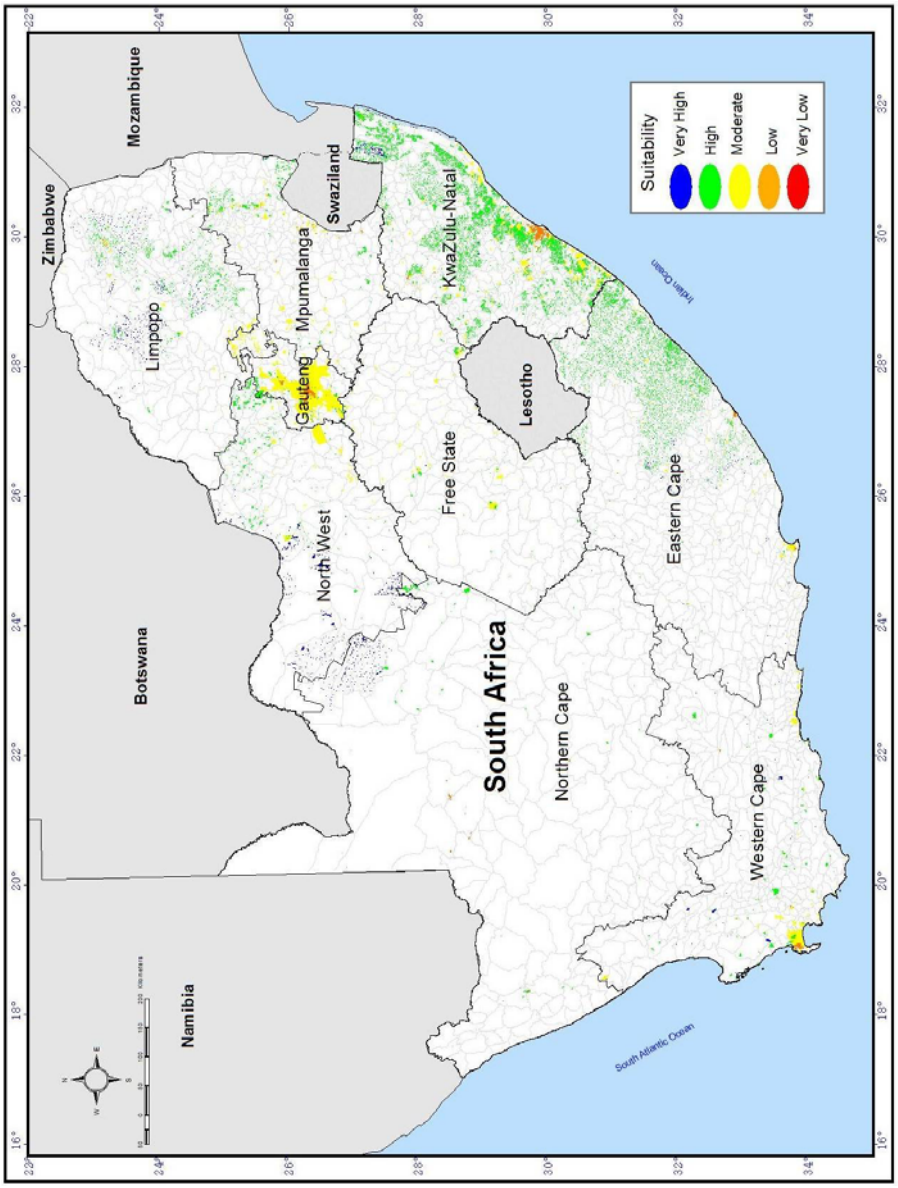


Figure 4.11 DRWH-Agt Physical map partitioning South Africa into five suitability classes; Very low, low, moderate, high and very high that respectively make up 0%, 3.84%, 30.89%, 58.87%, and 6.40% of the settlement's total area.

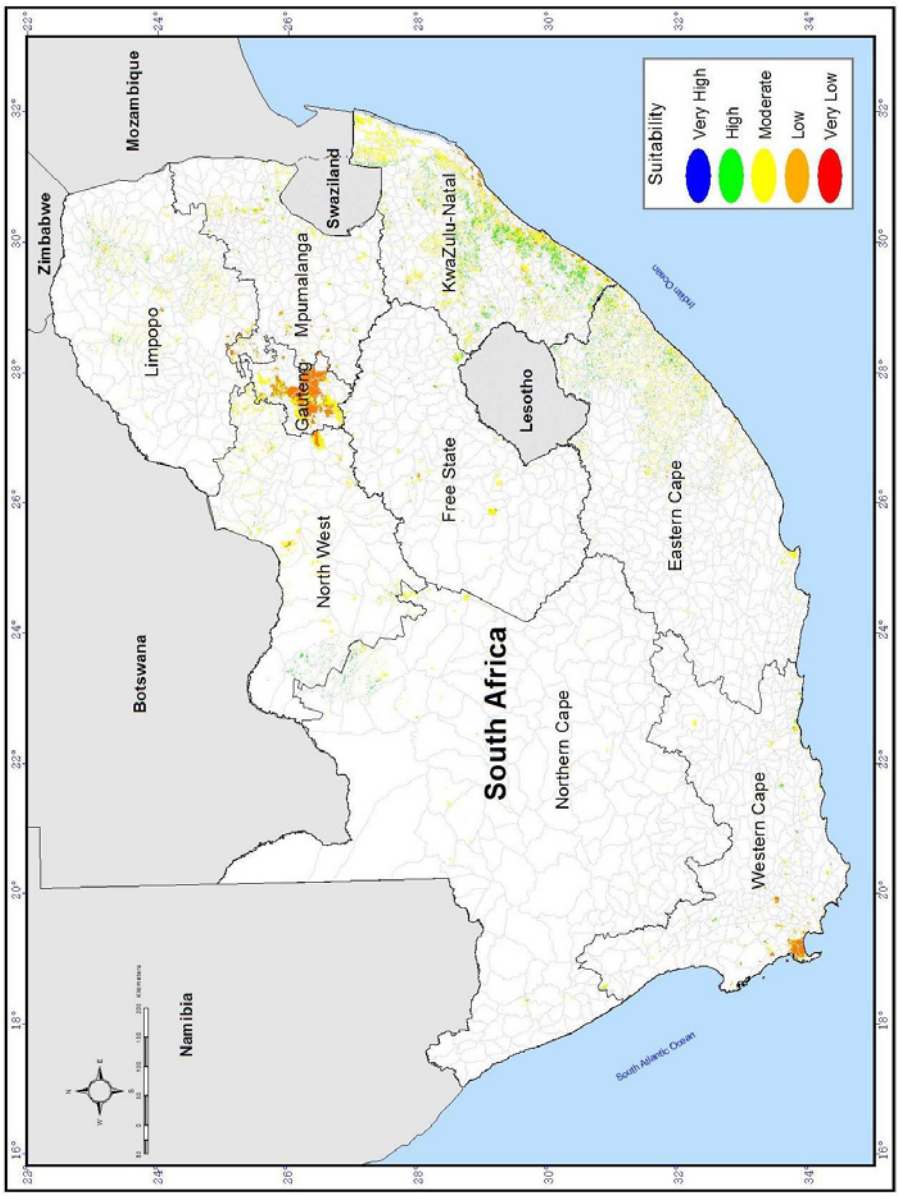


Figure 4.12 DRWH-Ugt Physical map partitioning South Africa into five suitability classes; Very low, low, moderate, high and very high that respectively make up 0.01%, 18.01%, 65.46%, 16.50%, and 0.01% of the settlement's total area.

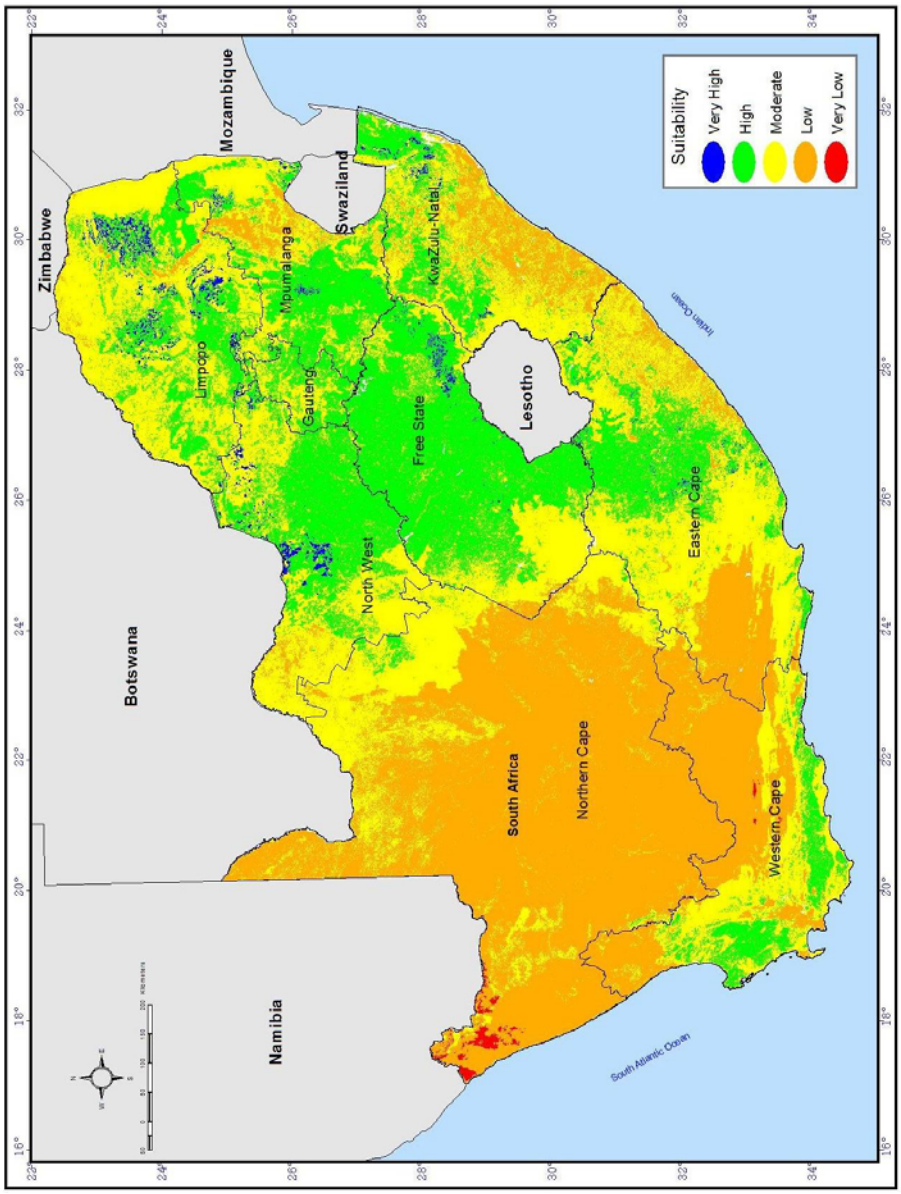


Figure 4.13 IRWH Physical map partitioning South Africa into five suitability classes; Very low, low, moderate, high and very high that respectively make up 0.25%, 36.16%, 38.2%, 24.46%, and 0.93% of the total area.

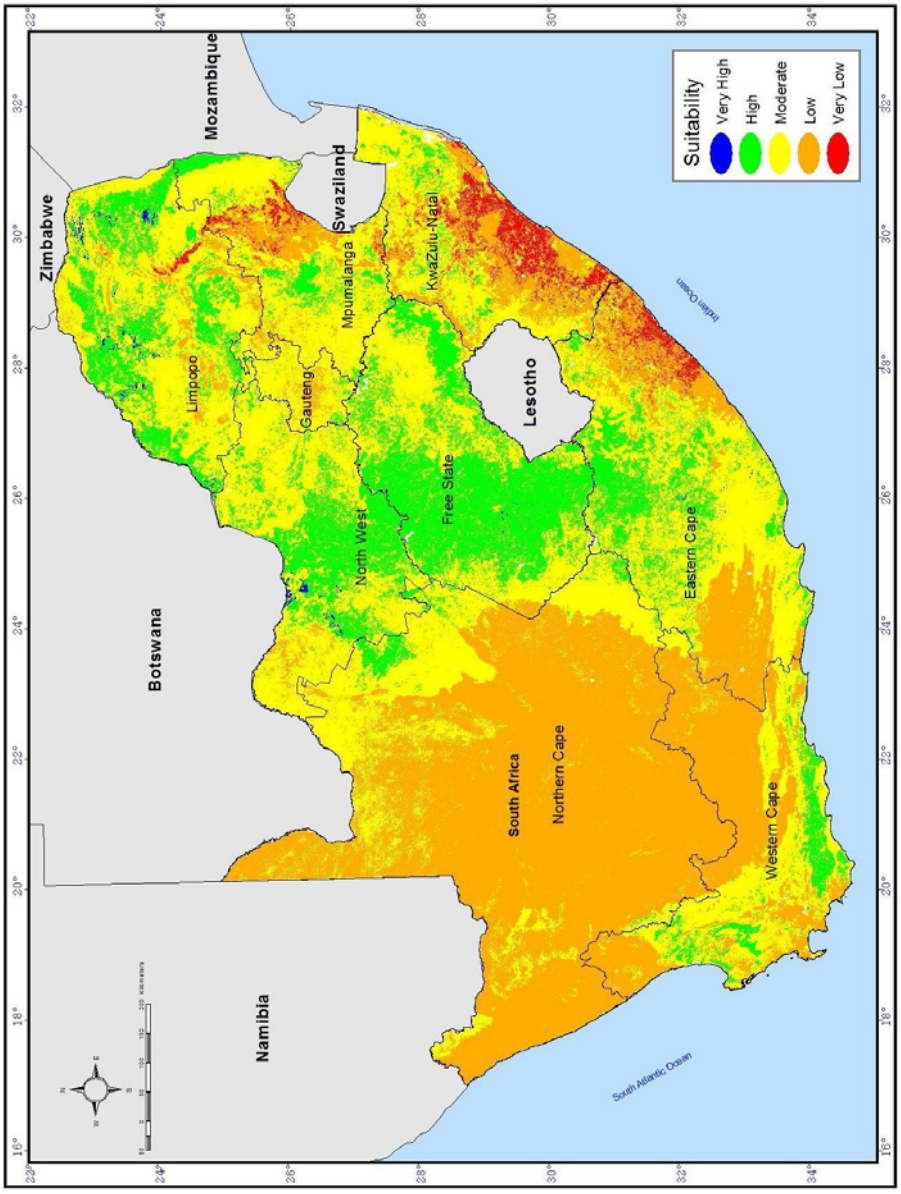


Figure 4.14 XRWH Physical map partitioning South Africa into five suitability classes; Very low, low, moderate, high and very high that respectively make up 1.7%, 38.31%, 43.27%, 16.54%, and 0.18% of the total area.

4.4.4 RWH potential maps

The overlay of physical, ecological and socioeconomic layers produces the potential map which reflects a 20% decrease of area potentially suited for DRWH Agt (Figure 4.9b) and a 12% increase of area potentially suited for DRWH Ugt (Figure 4.9d). The variations in areas potentially suited for DRWH Agt and DRWH Agt can be observed at a provincial level in Figure 4.10b and Figure 4.10d respectively. Since the constraint map does not apply to DRWH, the DRWH-Agt (Figure 4.15) and the DRWH-Ugt (Figure 4.16) potential maps are the final DRWH maps.

There is an overall increase in areas suitable for IRWH when transiting from the IRWH physical map (Figure 4.13) to its potential map (Figure 4.17). The WOP of the physical, vulnerability and ecological maps produces an increase of moderately suitable areas from 38% to 62% (Figure 4.9f) while the least suitable areas decreased from 36% to 9%. Similar results are observed for the XRWH potential map, with an increase of moderately suitable areas from 43% to 66% (Figure 4.9g). There is also an overall increase in areas suitable for XRWH when transiting from the XRWH physical map (Figure 4.14) to the XRWH potential map (Figure 4.18).

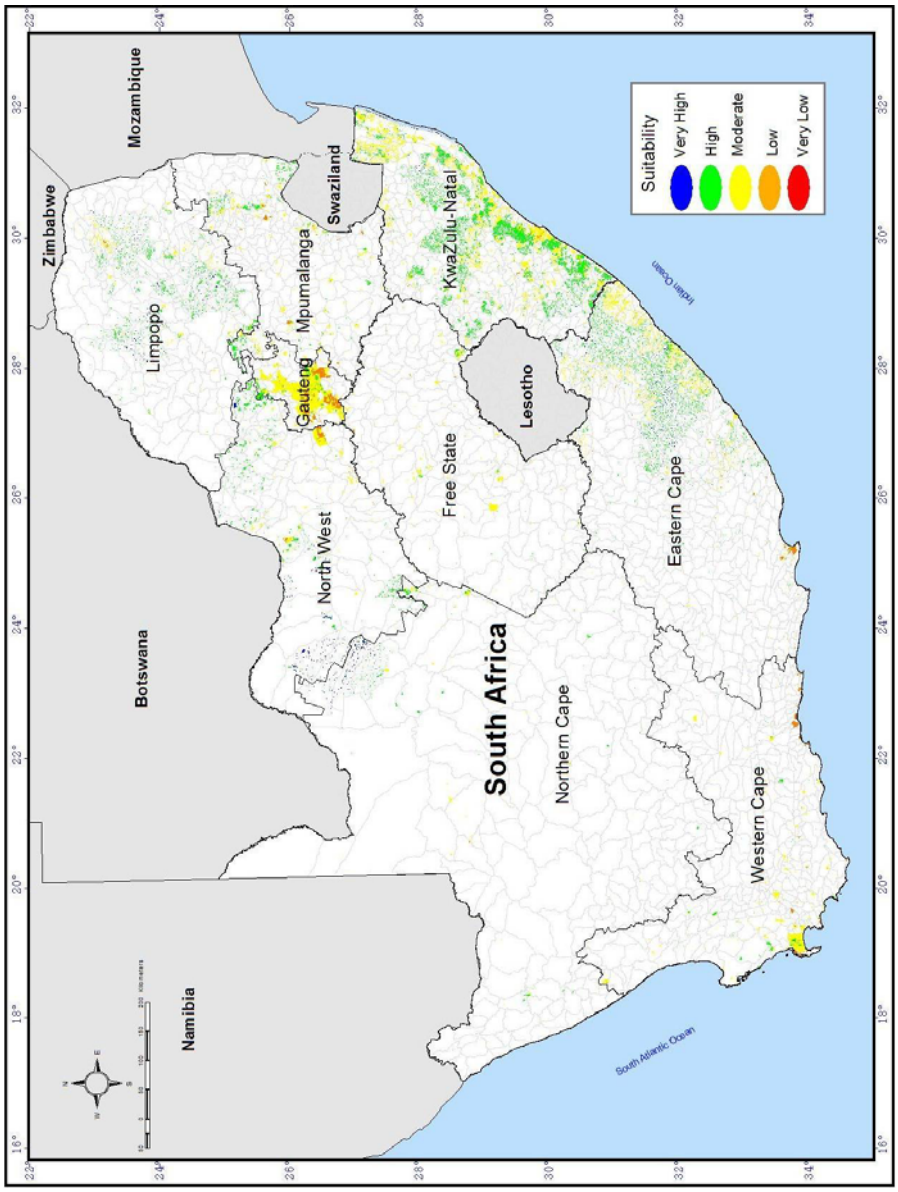


Figure 4.15 DRWH-Agt Potential map partitioning the country into five suitability classes; Very low, low, moderate, high and very high that respectively make up 0.01%, 5.91%, 49.13%, 42.33%, and 2.63% of the settlements' total area.

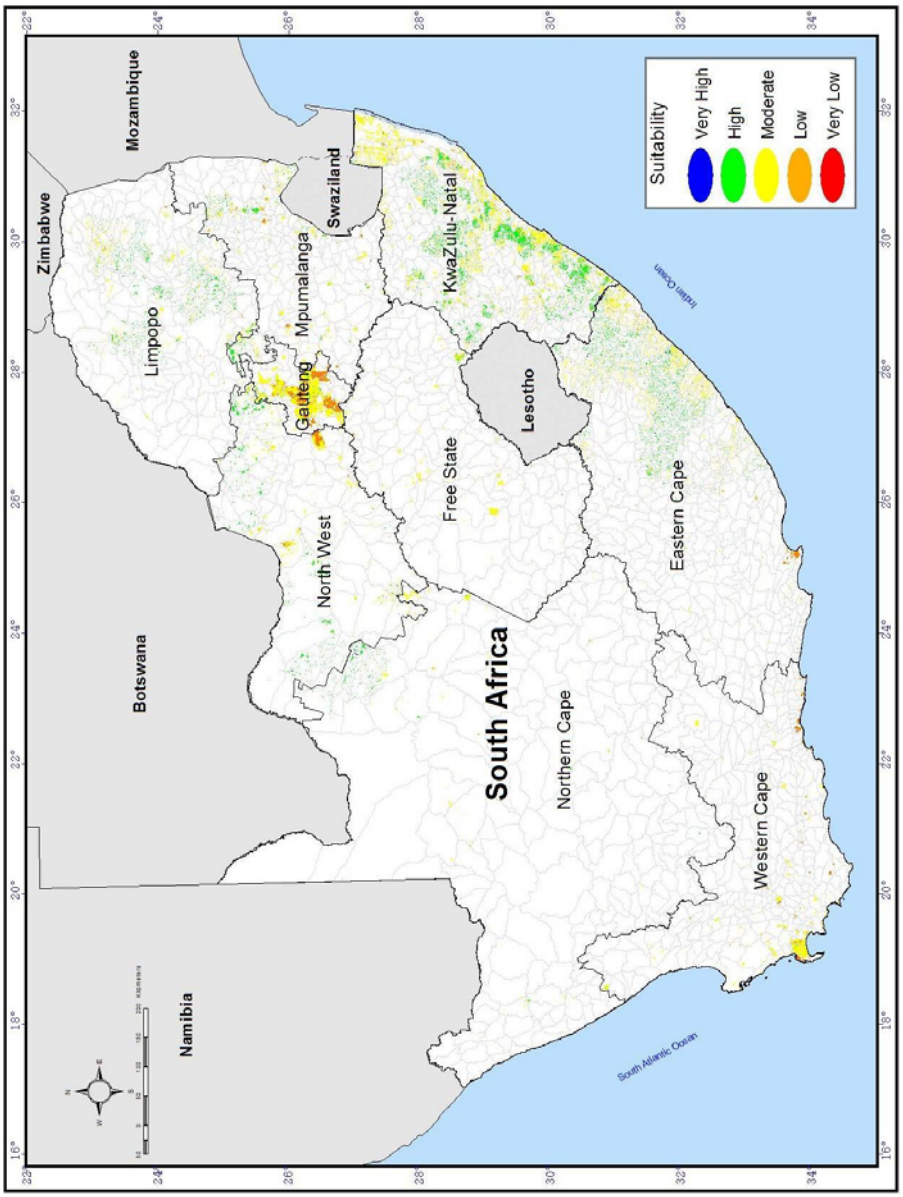


Figure 4.16 DRWH-Ugt Potential map partitioning the country into five suitability classes; Very low, low, moderate, high and very high that respectively make up 0.01%, 9.28%, 61.78%, 28.74%, and 0.20% of the settlements' total area.

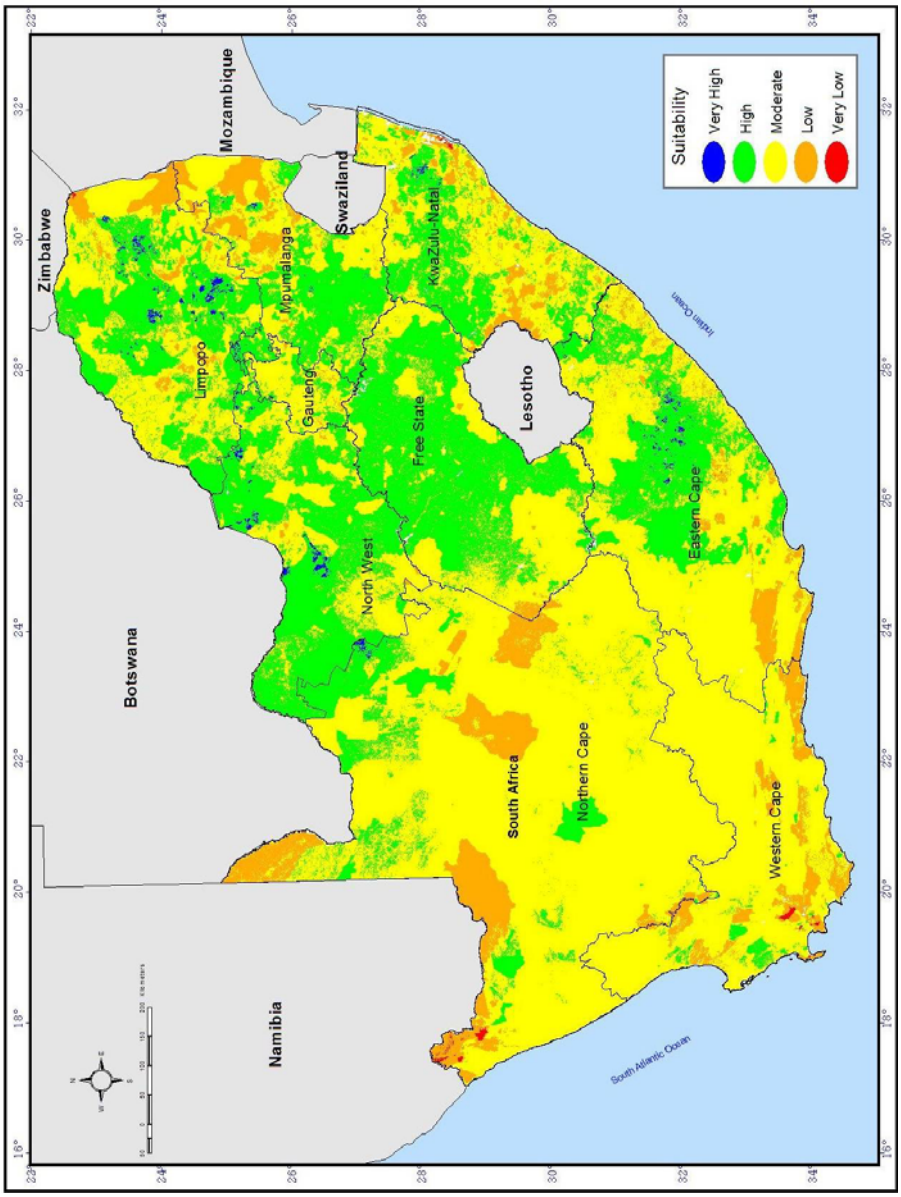


Figure 4.17 IRWH potential map partitioning South Africa into five suitability classes; Very low, low, moderate, high and very high that respectively make up 0.09%, 8.48%, 62.01%, 29.02%, and 0.40% of the total area.

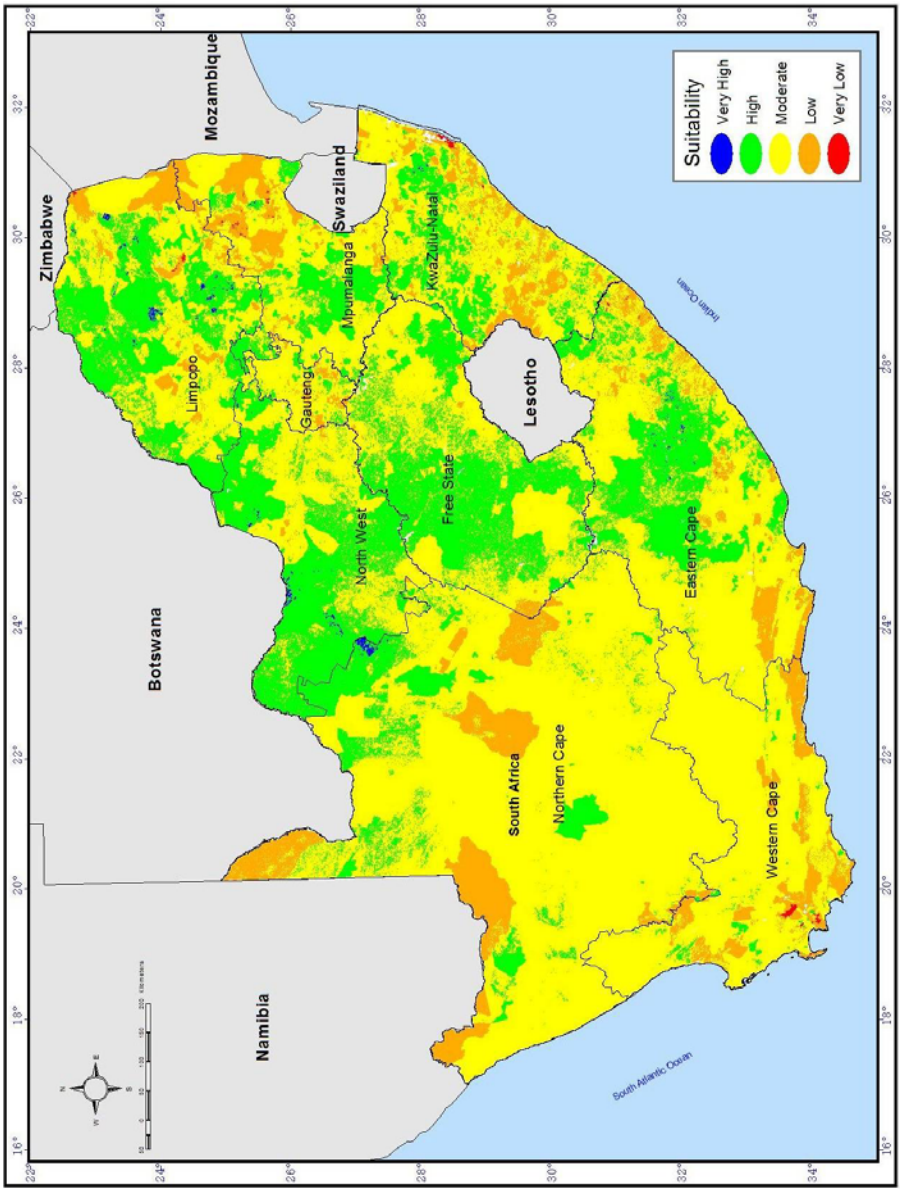


Figure 4.18 XRWH Potential map partitioning the country into five suitability classes; Very low, low, moderate, high and very high that respectively make up 0.08%, 9.78%, 65.5%, 24.46%, and 0.17% of the total area.

4.4.5 The constraint map

The constraint map was found to classify 76% of the country as unsuitable for FRWH. The Kruger National Park at the border with Mozambique and metropolitan areas such as the cities of Johannesburg and Pretoria in Gauteng are part of these unsuitable areas (Figure 4.19).

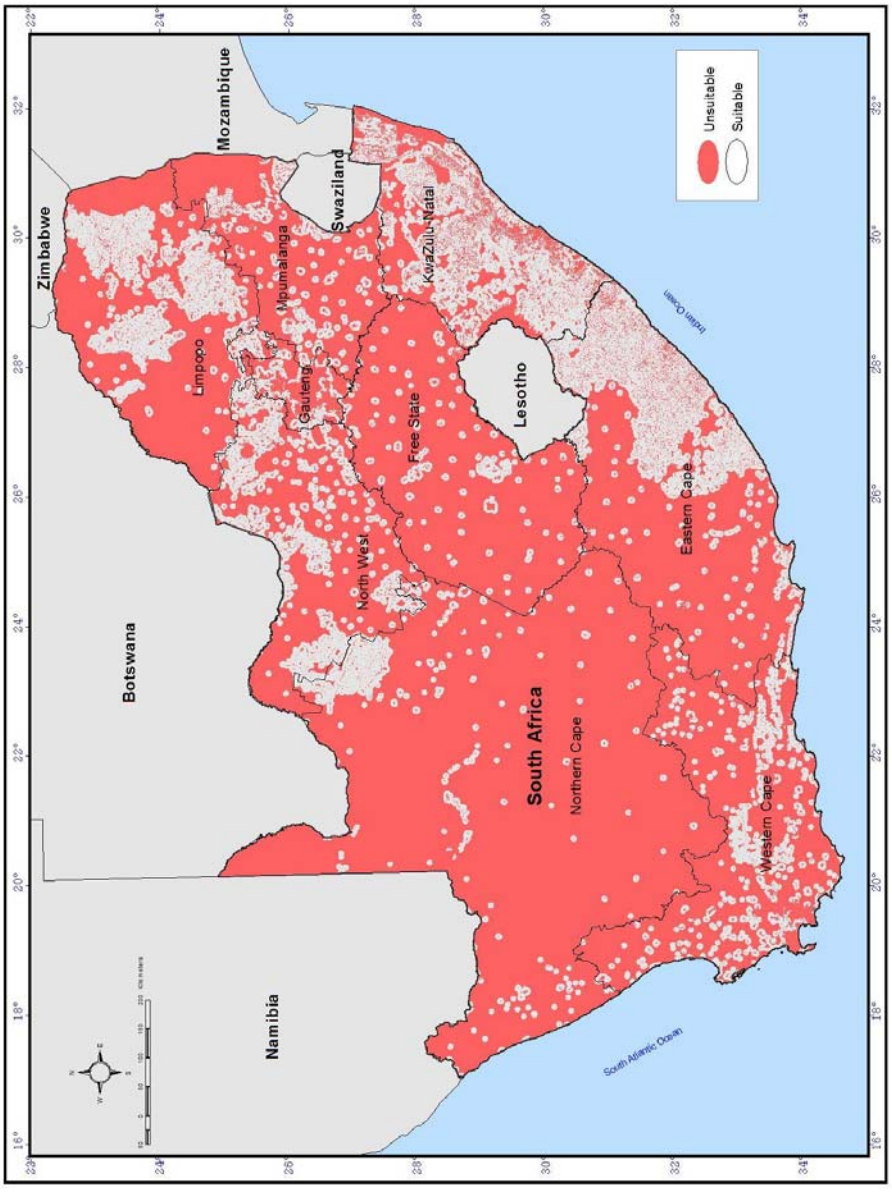


Figure 4.19 RWH constraint map, representing 76% of South Africa as unsuitable for Field RWH when considering the 7 constraint layers listed in Table 4.1.

4.4.6 FRWH suitability maps

The very high IRWH suitable areas are mainly located in Limpopo, the North West and the Eastern Cape (Figure 4.20). The IRWH suitability map classifies most of the coastal areas along the KwaZulu-Natal and Eastern Cape coast, as moderately suitable. This is a result of the fact that although the IRWH physical map (Figure 4.13) assigns low suitability to coastal areas along the KwaZulu-Natal and Eastern Cape coast by virtue of their biophysical conditions, their high vulnerability increases their RWH suitability (Figure 4.7).

With respect to XRWH, these coastal areas along the KwaZulu-Natal and Eastern Cape are even less suitable (Figure 4.21) because the biophysical conditions reflected in the XRWH physical map (Figure 4.14) are not conducive to the practice.

All the white areas of the suitability maps (Figure 4.20 and Figure 4.21) are areas classified as unsuitable in the constraint map. Using, as a constraint layer, the 5km radius buffer around the rural settlement greatly reduces the countries suitability to FRWH.

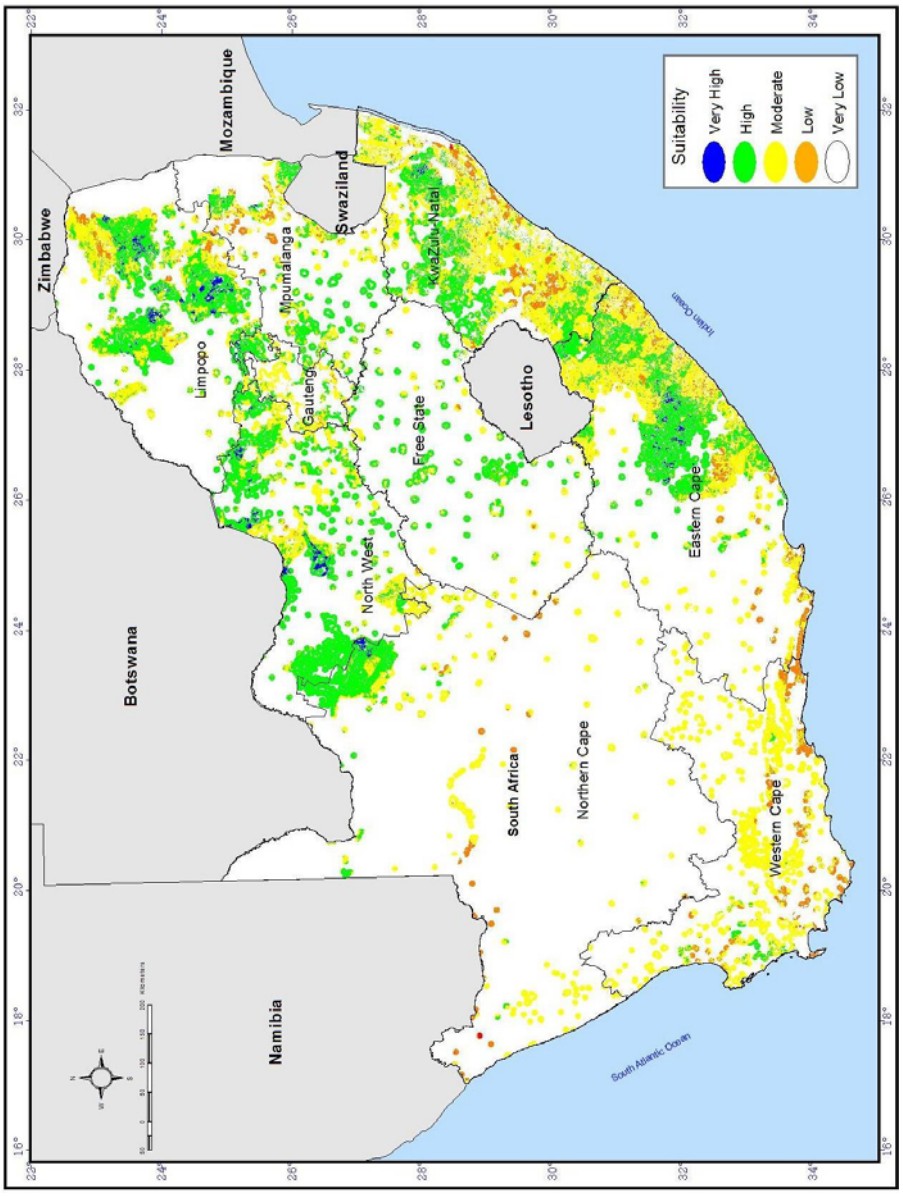


Figure 4.20 IRWH Suitability map partitioning South Africa into five suitability classes from very high to very low.

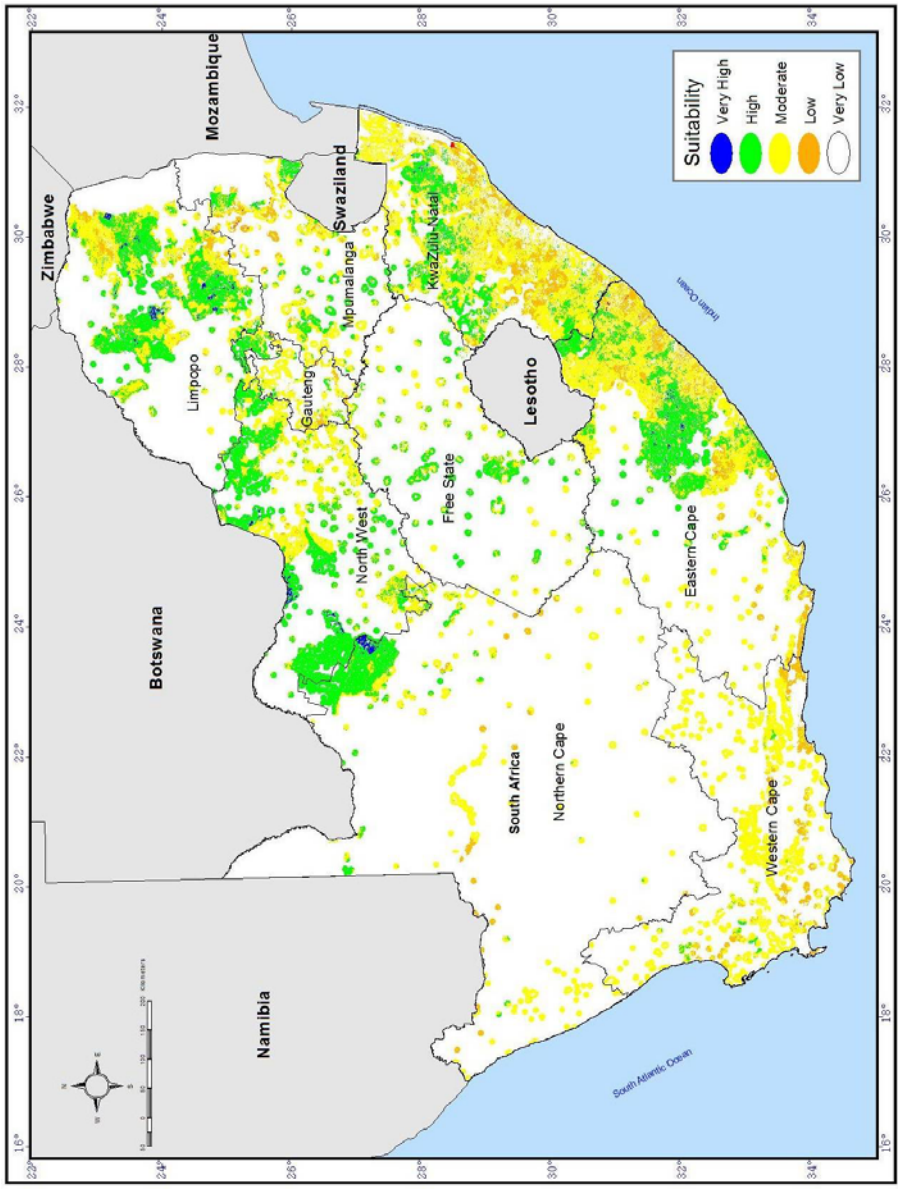


Figure 4.21 XRWH Suitability map partitioning South Africa into five suitability classes from very low to very high.

4.5 Verification

Within the South African context, there was need to receive feedbacks from professionals and water users on their assessment of the RWH suitability maps that had earlier been presented. Hence, these maps were presented to a panel of experts and various stakeholders from NGOs and the government in a workshop organised on January 30th 2008 at St George Hotel in Pretoria, South Africa. The panel was generally satisfied by the process followed by the RSM to assess the RWH potential, with indication that this could serve as a national planning tool for targeted interventions for increased access to water and improved water productivity and food security. However, the soil depth dataset was found to be too shallow compared to deeper soils some participants had encountered in the country.

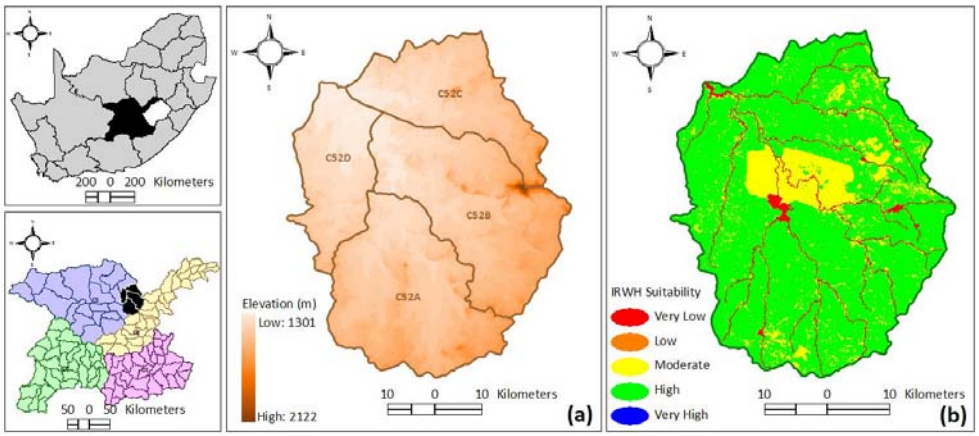


Figure 4.22 (a) Location map of the study site and delineated sub-catchments in the UMMRB. (b) Infield RWH suitability map partitioning the UMMRB into three suitability classes; very low, moderate and high that respectively make up 4%, 17% and 79% of the basin area.

Suitability results of the RSM were also compared to those in the UMMRB and the Potshini catchment where some RWH activities have taken place. The UMMRB (Figure 4.22a) is located North-East of the city of Bloemfontein, and in the central part of South Africa. Based on soil type and topographical features,

Woyessa et al. (2006) estimated the area of land suitable for the IRWH technique to be 806.67 km^2 or 27% of the total area. They investigated the micro-basin tillage technique, presented in section 2.5.2, which is suitable on duplex and clay soils of at least 700 mm depth and slopes of less than 3%. The RSM indicates that 79% (Figure 4.22b) of the catchment is highly suitable to IRWH. This higher value of area suitable for RWH is expected, taking into account the range of IRWH techniques accommodated in the RSM in contrast to the single technique considered by Woyessa et al. (2006).

The model was also tested in the Potshini catchment, a sub-catchment of V13D of the Thukela. According to de Winnaar et al. (2007), 18% of the Potshini catchment is highly suitable for developing rainwater harvesting system innovations (Figure 4.23a) while the result from the RSM indicates that 33% of the catchment is highly suitable to IRWH (Figure 4.23b). Considering the resolution of the RSM, a difference of 15% in the estimation of suitable areas is within acceptable limits.

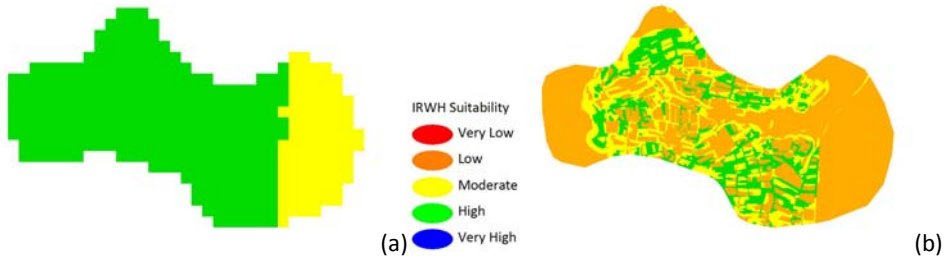


Figure 4.23 IRWH suitability map ranking the Potshini catchment: (a) into two RWH suitability classes, Medium (67%) and high (33%) (resolution 100mx100m); (b) into three RWH suitability classes 60% (low), 22% (medium) and 18% (high) (resolution 20mx20m) (de Winnaar et al., 2007).

4.6 Summary

The chapter presented the GIS-based rainwater harvesting model (RSM) which combines through a multi criteria evaluation process biophysical and socioeconomic datasets to produce two types of DRWH maps (physical and potential maps) and three types of RWH maps for IRWH and XRWH (physical, potential and suitability maps). Consequently, the RWH suitability map gives indicative areas/communities that would most benefit from RWH while at the same time preserve ecological functioning. The RSM has a high degree of customizability in that it enables the user to add, remove layers and change the relative importance weights of the layers.

Having assessed the RWH footprint in this chapter, we are in a position to evaluate its ecohydrological impact, which is the subject of the next chapter.

Chapter 5 ASSESSMENT OF THE ECOHYDROLOGICAL IMPACTS OF RAINWATER HARVESTING

5.1 Background[4]

RWH, like any anthropogenic interaction, has several effects on the hydrological cycle depending on the scale at which it occurs. By retaining more water using RWH, smallholder farmers increase water security while reducing surface runoff reaching streams. Thus, the up scaling of RWH on a river basin is likely to impact on the flow rate or yield of the water system of a catchment. As illustrated in Figure 5.1, stream flows are subject to large fluctuations over a given year. There is abundant water during the raining season while the opposite applies during the dry season.

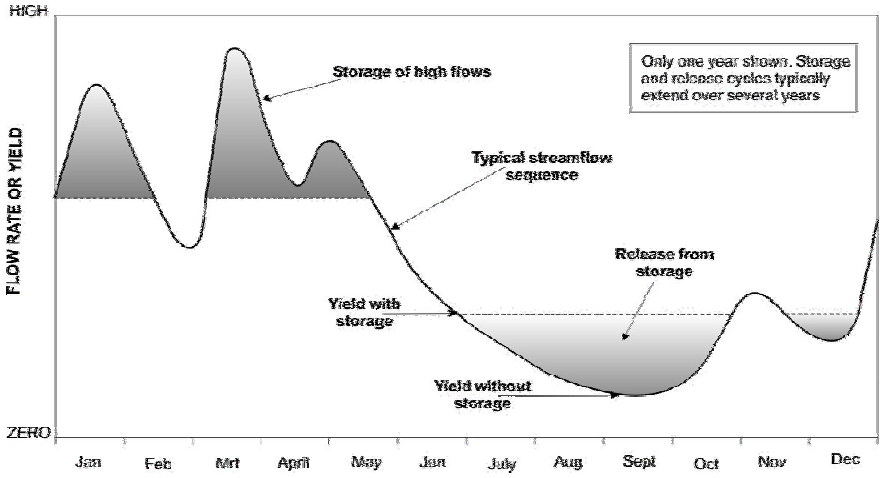


Figure 5.1 Diagrammatic presentation of stream flow and storage (DWAF, 2004).

[4] This section is based on: Mwenge Kahinda, J., Sejamoholo B.B. P., Taigbenu, A. E., Boroto, R.J., Lillie, E.S.B., Taute, M., and Cousins, T., 2009a. Water Resources in Rainwater Harvesting: An Integrated Systems Approach. Report No. KV 1563-1-08, Water Research Commission, Pretoria, South Africa

To assure an acceptable level of supply to different water users, dams are built across streams to store water during periods of high flows and release it during periods of low flows. Because water for basic human needs and for ecological functioning have highest priorities in the National Water Act, a significant reduction of flows in regulated rivers directly affects the yield as a result of reduced storage but not necessarily the environment functioning that can be met by releases for ecological reserve requirements. In contrast, where storage is unavailable and the river is unregulated, significant reduction in flows not only directly affects the yield but also the environment.

The amount of runoff retained by RWH systems and hence the reduction in river flows downstream has to be accounted for, with emphasis given to the surface runoff component that is significantly affected by upscaling of RWH (Ngigi, 2006). A strategic approach to upscaling should ensure that the river flow does not fall below the ecological reserve or flow required to protect the aquatic ecosystems of the water resource (DWAF, 1999).

An increase in area under RWH (ΔA_S) leads to more runoff retention. Thus, the runoff reduction ($\Delta Q_{r(S)}$) caused by a RWH system is proportional to ΔA_S (Equation 5.1).

$$\Delta Q_{r(s)} = f\left(\frac{A_S}{A_R}\right) \quad 5.1$$

Where A_S = area under a RWH system (m^2);

A_R = total area of the catchment or river basin (m^2), and;

$\Delta Q_{r(S)}$ = runoff reduction by a RWH system (%).

The total runoff reduction (ΔQ_r), in a catchment or river basin, caused by RWH is computed from Equation 5.2:

$$\Delta Q_r = \Delta Q_{r(DRWH)} + \Delta Q_{r(IRWH)} + \Delta Q_{r(XRWH)} \quad 5.2$$

Where ΔQ_r = total runoff reduction caused by RWH

$\Delta Q_{r\,(DRWH)}$ = total runoff reduction caused by DRWH

$\Delta Q_{r\,(IRWH)}$ = total runoff reduction caused by IRWH

$\Delta Q_{r\,(XRWH)}$ = total runoff reduction caused by XRWH

The values of ecological reserve of the 19 water management areas are listed in Table 5.1 (1-19) below.

Table 5.1 Natural mean annual runoff (MAR) and ecological Reserve (million m³/a) of the 19 WMA of South Africa and their sub-areas (DWAF, 2004).

(1) Limpopo		
Sub-area	Natural MAR	Ecological Reserve
Matlabas/Mokolo	382	76
Lephalala	150	17
Mogalakwena	269	41
Sand	72	10
Nzhelele/Nwanedzi	113	12
Total for WMA	986	156

(2) Luvuvhu and Letaba		
Sub-area	Natural MAR	Ecological Reserve
Luvuvhu/Mutale	520	105
Shingwedzi	90	14
Groot Letaba	382	72
Klein Letaba	151	20
Lower Letaba	42	13
Total for WMA	1185	224

(3) Crocodile (west) and Marico		
Sub-area	Natural MAR	Ecological Reserve
Apies/Pienaars	142	34
Upper Crocodile	253	57
Elands	113	15
Lower Crocodile	138	25
Marico	172	29
Upper Molopo	37	4
Total for WMA	855	164

(4) Mzimvubu to Keiskamma		
Sub-area	Natural MAR	Ecological Reserve
Mzimvubu	2897	338
Mtata	836	163
Mbashe	1126	203
Kei	1027	154
Amatola	559	116
Wild Coast	796	148
Total for WMA	7241	1122

(5) Olifants		
Sub-area	Natural MAR	Ecological Reserve
Upper Olifants	465	83
Middle Olifants	481	69
Steelpoort	396	94
Lower Olifants	698	214
Total for WMA	2040	460

(6) Thukela		
Sub-area	Natural MAR	Ecological Reserve
Upper Thukela	1502	392
Mooi/Sundays	992	213
Buffalo	941	182
Lower Thukela	364	72
Total for WMA	3799	859

(7) Inkomati		
Sub-area	Natural MAR	Ecological Reserve
Komati (W Swazi)	749	239
Swaziland	517	100
Komati (N Swazi)	130	25
Crocodile	1277	328
Sabie	866	316
Total for WMA	3539	1008

(8) Usutu to Mhlatuze		
Sub-area	Natural MAR	Ecological Reserve
Upper Usutu	901	328
Pongola4	1344	200
Mkuze	635	218
Mfolozi	962	275
Mhlatuze	938	171
Total for WMA	4780	1192

(9) Upper Vaal		
Sub-area	Natural MAR	Ecological Reserve
Wilge	868	116
Vaal Dam - upstream	1109	126
Vaal Dam - downsream	446	57
Total for WMA	2423	299

(10) Middle Vaal		
Sub-area	Natural MAR	Ecological Reserve
Rhenoster-Vals	295	35
Middle Vaal	170	29
Sand-Vet	423	45
Total for WMA	888	109

(11) Lower Vaal		
Sub-area	Natural MAR	Ecological Reserve
Harts	138	15
Vaal d/s Bloemhof	43	5
Molopo	1974	29
Total for WMA	181	49

(12) Lower Orange		
Sub-area	Natural MAR	Ecological Reserve
Orange	198	32
Orange Tributaries	280	35
Orange Coastal	24	2
Total for WMA	502	69

(13) Mvoti to Umzimkulu		
Sub-area	Natural MAR	Ecological Reserve
Mvoti	595	150
Mgeni	992	187
Mkomazi	1080	295
Coastal	758	211
Umzimkulu	1373	317
Total for WMA	4798	1160

(14) Gouritz		
Sub-area	Natural MAR	Ecological Reserve
Gamka	227	19
Groot	105	5
Olifants	229	17
Gouritz	347	56
Coastal	771	228
Total for WMA	1679	325

(15) Upper Orange		
Sub-area	Natural MAR	Ecological Reserve
Senqu Lesotho	4012	933
Caledon Lesotho	753	92
Caledon RSA	650	90
Kraai	956	158
Riet / Modder	407	45
Vanderkloof	203	31
Total for WMA	6981	1349

(16) Fish to Tsitsikamma		
Sub-area	Natural MAR	Ecological Reserve
Fish	518	47
Bushmans	174	15
Sundays	280	20
Gamtoos	491	39
Algoa	147	15
Tsitsikamma	544	107
Total for WMA	2154	243

(17) Olifants/Doorn		
Sub-area	Natural MAR	Ecological Reserve
Koue Bokkeveld	279	29
Sandveld	60	8
Olifants	514	77
Knersvlakte	27	3
Doring	228	39
Total for WMA	1108	156

(18) Breede		
Sub-area	Natural MAR	Ecological Reserve
Upper Breede	1212	178
Riviersonderend	460	65
Lower Breede	210	34
Overberg East	110	13
Overberg West	480	94
Total for WMA	2472	384

(19) Berg		
Sub-area	Natural MAR	Ecological Reserve
Greater Cape Town	373	61
Upper Berg	849	124
Lower Berg	207	32
Total for WMA	1429	217

5.1.1 Scale considerations

A river basin is a complex system further convoluted by the anthropogenic activities that take place in it. Humankind alter (lengthen or shorten) the water cycle with its diverse interventions (dams, diversions, abstractions, agriculture, etc) and RWH is no exception. The hydrological impacts of RWH in a river basin depend on the scale at which it is observed. In addition, hydrological processes are influenced at different spatial scales by the various RWH techniques (Ncube et al., 2009). The different spatial scales for its hydrological impact assessment are field/farm ($0 – 5.10^{-3}$ km^2), medium catchment (1 - 2 km^2), sub-basin (20 - 500 km^2) and basin (> 500 km^2) (Ngigi, 2006). The increased degree of uncertainty and complexity across scales pose a challenge of extrapolating or interpolating results from one scale to another (Ngigi, 2006). Thus, focusing on a single scale might obscure important processes that only become obvious at either finer or broader scales (Lovell et al., 2002). While at field and medium scale, infiltration is a key process that determines the runoff generated, at basin scale, channel flow is only observed at larger scales above a channel initiation area (Blöschl and Sivapalan, 1995). Thus dominant processes change with scale (Schulze, 2000).

Heterogeneities, which increase from field scale where physical components (climate, soil, etc) are considered homogeneous, to river basin scale where physical components are heterogeneous, convolute the transfer of information from field to river basin scale and are often accounted for using hydrological models. Hydrological models are used to understand processes that are difficult to measure because of complexity at temporal and/or spatial scale, and to study the effects of changes in land cover, water management or climate (Kite and Droogers, 2000). At QC scale, the reduction in river flows is considered an important parameter in assessing the impact of RWH. Thus the reduction in naturalised river flow by different levels of adoption of IRWH in the semi arid QC C52A was modelled using the Soil and Water Assessment model (SWAT).

This chapter presents the results of the assessment of the ecohydrological impact of RWH at QC level using SWAT and compares them to a similar assessment done using the Water Resources Simulation Model 2000 (WRSM).

5.2 The Soil and Water Assessment model (SWAT)

The Soil and Water Assessment model (SWAT) is a semi distributed model that operates on a daily time step. The model is a continuation of 30 years of modelling experience of the Agricultural Research Service of the United State Department of Agriculture (Gassman, 2007). SWAT is a physical based model developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions (Neitsch et al., 2002). Major model components relevant to this study include weather, hydrology, soil temperature and properties, plant growth and land management. SWAT partitions the watershed into subbasins which are further divided into hydrologic response units that possess unique landuse, management and soil attributes. The hydrological processes are individually simulated in each hydrological response unit (HRU) and aggregated at the subbasin level. In this study, we use SWAT2005 denoted AVSWAT-X, to model the ecohydrological impact of different levels of adoption of IRWH for the period of 1st August 1988 to 31st July 2000 in the semi arid C52A QCs.

5.3 Methodology

The semi-arid C52A QC was naturalised in order to isolate the impact of IRWH on the river flows. Given that less than 20% of the C52A Qc is currently developed (Figure 5.2a), it was relatively easy to naturalise its land cover (Figure 5.2b).

SWAT uses the Soil Conservation Service curve number procedure to estimate surface runoff. Consequently, the runoff curve numbers of areas where IRWH is implemented were appropriately adjusted. The model was used to model five scenarios):

- Naturalised conditions (virgin);
- IRWH implemented on suitable area assessed by the RSM (Figure 4.20);
- IRWH implemented on 50% of the total area, near upstream (NU) relative to the catchment outlet;
- IRWH implemented on 50% of the total area, further upstream (FU) relative to the catchment outlet, and;
- IRWH upscaled on the entire surface of the QC (100%).

For the 11 years of streamflow records in C52A (1st August 1988 to 31st July 2000), the median rainfall year occurred in 1990. Thus the hydrological year considered is from October 1990 to September 1991.

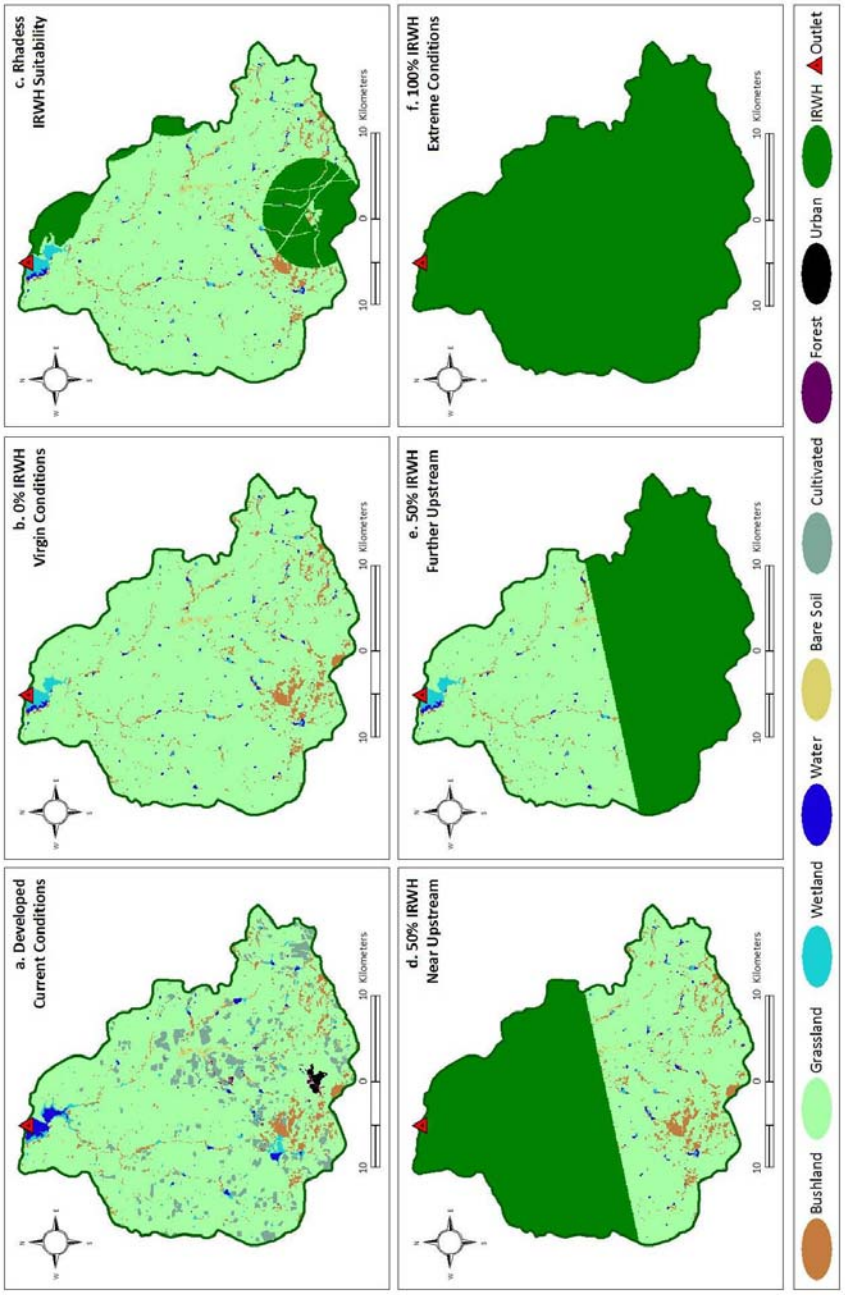


Figure 5.2 Scenarios modelled using SWAT: (a) current development (NLC2000), (b) Naturalised conditions (virgin), (c) IRWH implemented in suitable area (RHADESS), (d) IRWH implemented in 50% of the total area, near upstream, (e) IRWH implemented in 50% of the total area, further upstream and (f) IRWH upscale in all the QC (100%).

5.4 Base Data for the Hydrological Modelling

5.4.1 Thematic maps

The SWAT model requires three thematic maps: a digital elevation model, a land cover map and a soil map.

5.4.1.1 The Digital elevation

The Digital elevation model (DEM) of 100 m x 100 m resolution (Figure 3.3) used to delineate the watershed is derived from the 90 m DEM of the Shuttle Radar Topography Mission (SRTM). The stream network was delineated for a threshold area of 3000 ha. The delineated stream network and the subbasins are shown in Figure 5.3.

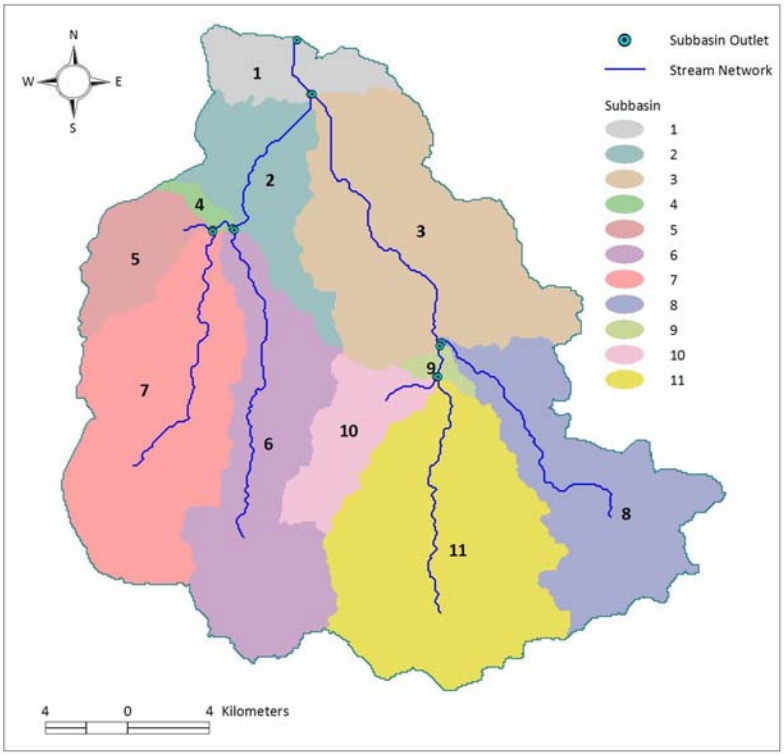


Figure 5.3 Stream network and Subbasins delineated by SWAT.

5.4.1.2 Land cover

The 16 land cover classes of the NLC2000 were lumped into 8 dominant classes, parameterised for SWAT (Table 5.2) and naturalised.

Table 5.2 Land cover of the C52A (National Land Cover, 2000).

Description	Dominant classes	SWAT Land use
Bare Rock and Soil (erosion : dongas / gullies)	Bare Rock and Soil	BASO
Bare Rock and Soil (erosion : sheet)		
Bare Rock and Soil (natural)		
Cultivated, temporary, commercial, irrigated	Agriculture	AGRR
Cultivated, temporary, commercial, dryland	Summer Agriculture	AGRL
Cultivated, temporary, subsistence, dryland		
Cultivated, temporary, subsistence, irrigated		
Forest Plantations (Eucalyptus spp)	Forest	FRST
Forest Plantations (Pine spp)		
Improved Grassland	Grassland	RNGE
Unimproved (natural) Grassland		
Degraded Unimproved (natural) Grassland		
Thicket, Bushland, Bush Clumps, High Fynbos	Bushland	RNGB
Urban / Built-up, (industrial / transport : light)	Settlement	URLD
Waterbodies	Water	WATR
Wetlands	Wetland	WETL

5.4.1.3 Soil

The land type which is, at present, the most comprehensive set of mapped soils information available to hydrologists (Schulze, 1995) provided the main dataset from which some of the soil properties are derived. A land type is an area of land in which the macro-climate, terrain morphology and soil pattern are reasonably homogenous at the 1:250 000 scale (Pretorius et al., 2005). The first two letters “Dc” Dc define the soil pattern while the last numbers “17” differentiate the land unit from all other land units which occur in South Africa.

Thus the dominant soil series of the 4 land types present in C52A QC (Figure 5.4) are extracted from the land type inventory. Other soil properties were derived from the soil cover dataset of the Agrohydrological Atlas of South Africa.

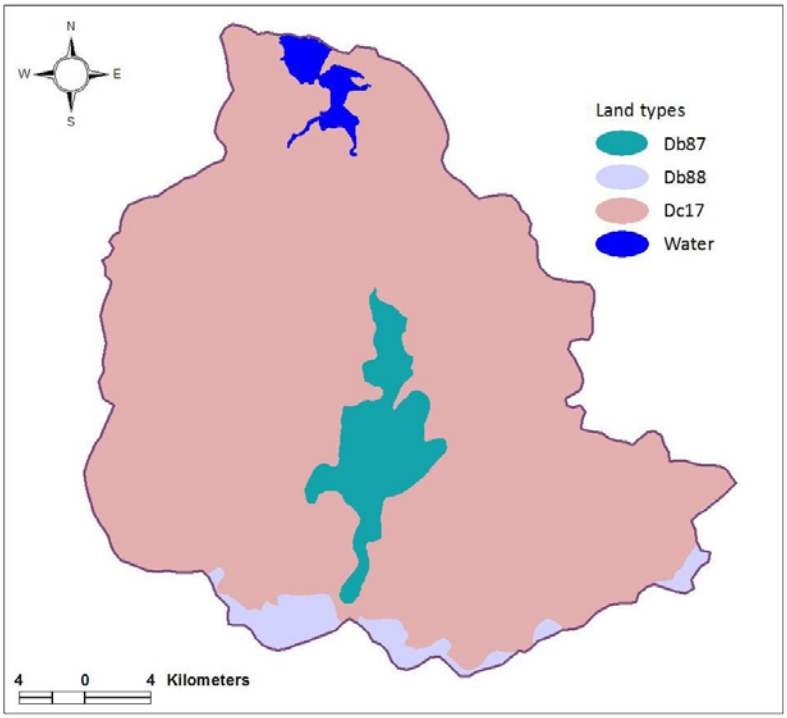


Figure 5.4 C52A land types.

The following were the adopted soil series for the land types;

- Db87: Kanonkop Gs13;
- Db88: Mispah Ms10, and;
- Dc17: Shorrocks Hu36.

The typical textural class given in MacVicar et al. (1977) as well as the corresponding hydrological soil group are individually added. The available water moisture of the 5 land type present in C52A are obtained from the ACRU soils dataset for South Africa, while bulk density, effective porosity, organic carbon and saturated hydraulic conductivity were obtained from Table 5.3. Other soil properties such as erosion hazards and soil albedo values were obtained from the soil cover dataset.

Table 5.3 Typical values of soil hydrological input parameters for different textural classes (Schulze, 1995).

Soil Texture Class	Horizon	Typical percentages				Bulk density*, Mgm^{-3}	Effective porosity, m^3m^{-3}	Saturated Hydraulic conductivity, mmh^{-1}
		Clay	Silt	Sand	OC			
Clay	Topsoil	50	37	13	0.38	1.21	0.536	0.6
	Subsoil					1.37	0.470	
Loam	Topsoil	18	25	57	0.52	1.18	0.512	13
	Subsoil					1.42	0.464	
Sand	Topsoil	3	4	93	0.71	1.25	0.452	210
	Subsoil					1.5	0.430	
Loamy sand	Topsoil	7	7	86	0.61	1.24	0.457	61
	Subsoil					1.51	0.432	
Sandy loam	Topsoil	10	15	75	0.71	1.19	0.505	26
	Subsoil					1.46	0.448	
Silty loam	Topsoil	18	55	27	0.58	1.07	0.527	6.8
	Subsoil					1.34	0.495	
Sandy clay loam	Topsoil	27	8	65	0.19	1.3	0.486	4.3
	Subsoil					1.58	0.393	
Clay loam	Topsoil	32	22	46	0.1	1.17	0.497	2.3
	Subsoil					1.41	0.451	
Silty clay loam	Topsoil	33	46	51	0.13	1.23	0.509	1.5
	Subsoil					1.4	0.469	
Sandy clay	Topsoil	40	5	55	0.38	1.3	0.430	1.2
	Subsoil					1.53	0.423	
Silty clay	Topsoil	50	37	13	0.38	1.22	0.531	0.9
	Subsoil					1.38	0.476	

OC = Organic Carbon

A report generated by SWAT detailing the land use and soil overlay is attached in Appendix B.

5.4.2 Time series

The climatic variables required by SWAT are:

- daily precipitation;
- maximum and minimum air temperature;
- solar radiation;
- wind speed, and;

- relative humidity.

5.4.2.1 Rainfall

Rainfall is the most critical input that drives the water budgeting processes. 22 Daily rainfall data of 22 rainfall stations (Figure 5.5) were sourced from Lynch (2003).

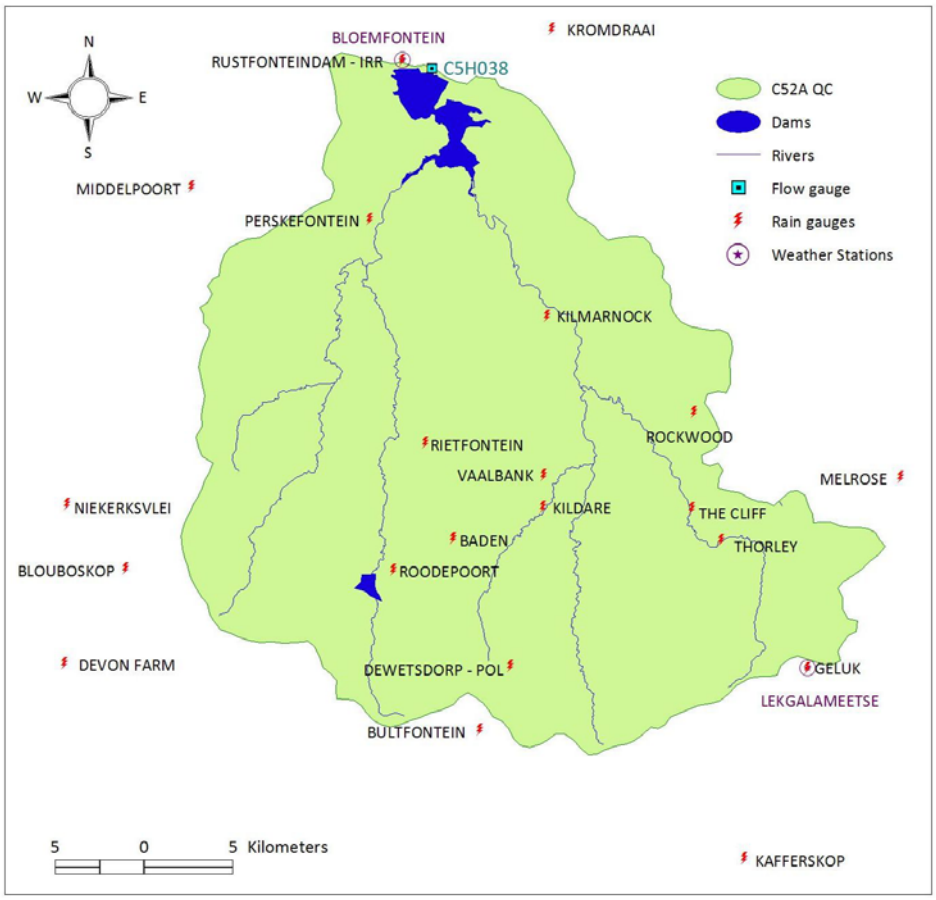


Figure 5.5 Location of rain gauges, flow gauging stations and weather stations used to model IRWH with SWAT in C52A QC.

Table 5.4 rainfall stations used to model C52A with SWAT.

Station No.	Station Name	Code	Altitude (m)	Longitude (degree)	Latitude (degree)
0231725 W	Devon farm	pcp-devo	1524	26.417	-29.583
0231754 W	Blouboskop	pcp-blou	1509	26.450	-29.533
0232123 W	Roodepoort	pcp-rood	1509	26.600	-29.533
0232181 W	Baden	pcp-bade	1524	26.633	-29.517
0232211 W	Nuwejaarsfontein	pcp-nuwe	1524	26.633	-29.517
0232218 W	Bultfontein	pcp-bult	1608	26.650	-29.617
0232275 W	Dewetsdorp	pcp-dewe	1555	26.667	-29.583
0232301 W	Kildare	pcp-kild	1518	26.683	-29.500
0232512 W	Thorley	pcp-thor	1555	26.783	-29.517
0232522 W	Kafferskop	pcp-kaff	1600	26.800	-29.683
0232575 W	Geluk	pcp-gelu	1600	26.833	-29.583
0261750 W	Niekerksvlei	pcp-niek	1491	26.417	-29.500
0261890 W	Middelpoort	pcp-midd	1432	26.483	-29.333
0262141 W	Perskefontein	pcp-pers	1448	26.583	-29.350
0262166 W	Rustfonteindam	pcp-rust	1382	26.600	-29.267
0262207 W	Rietfontein	pcp-riet	1524	26.617	-29.467
0262314 W	Kromdraai	pcp-krom	1402	26.683	-29.250
0262353 W	Kilmarnock	pcp-kilm	1463	26.683	-29.400
0262359 W	Vaalbank	pcp-vaal	1478	26.683	-29.483
0262478 W	Rockwood	pcp-rock	1539	26.767	-29.450
0262479 W	The cliff	pcp-clif	1509	26.767	-29.500
0262690 W	Melrose	pcp-melr	1600	26.883	-29.483

5.4.2.2 Weather stations

Two weather stations (Figure 5.5), which coordinates are presented in Table 5.5, were used to model C52A.

Table 5.5 Weather stations considered for temperature (maximum and minimum), relative humidity, wind speed and solar radiation.

Station name	Latitude (deg)	Longitude (deg)	Altitude (m)	Length of record
Lekgalameetse	-24.14	30.3	800	1993-2006
Bloemfontein	-23.87	29.45	1,230	1960-2008

Daily hours of sunshine values of Lekgalameetse and Bloemfontein were used to calculate short wave radiation using Equation 5.3 (Ångström, 1924).

$$R_s = \left[a + b\frac{n}{D} \right] R_a \qquad (MJm^{-2}day^{-1}) \qquad 5.3$$

Where a, b = Regression constants for estimation of shortwave radiation from sunshine duration estimated to be 0.24 and 0.53 respectively (Schulze, 1995) in southern Africa;

n = actual sunshine duration (hours);

D= maximum possible sunshine duration (hours), and;

R_a = extra-terrestrial solar radiation

5.5 Results and discussion

Since it is embedded in ArcView GIS, SWAT has the capability to model the ecohydrological impacts of the same gross level of adoption of IRWH with different spatial distribution within the same QC. For simplicity, only two spatial distribution were chosen, namely 50% IRWH adoption with area just upstream of the catchment outlet (50% near upstream - NU) and with area farther upstream of the catchment outlet (50% far upstream - FU). Any other spatial distribution of 50% IRWH will most probably produce a hydrograph that lies between the 50% NU and 50% FU. The simulated results are presented in terms of flow duration curves and flow hydrographs during the median year of rainfall, i.e. 1990/1991.

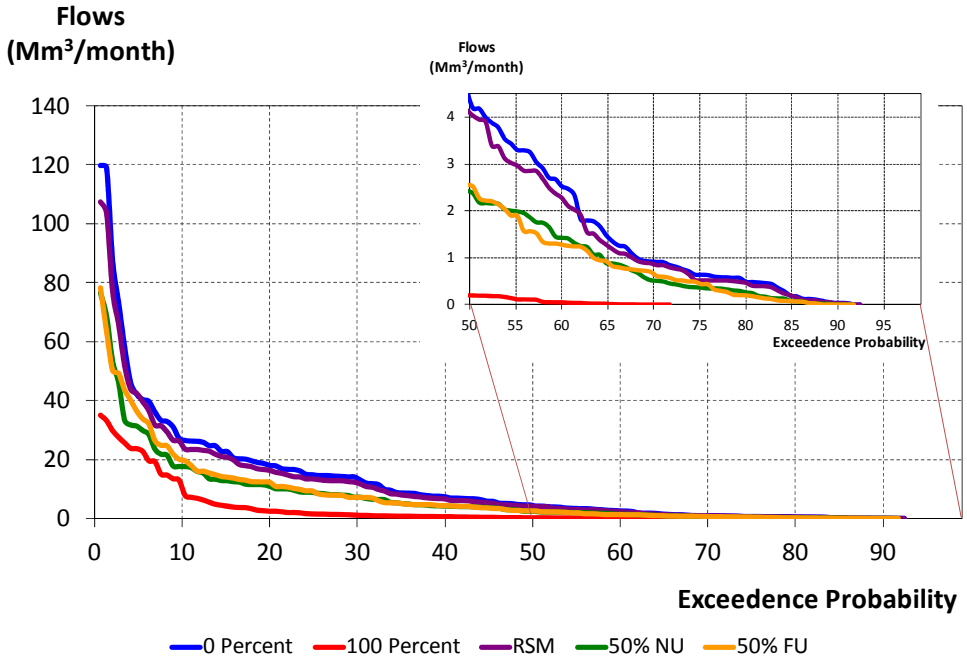


Figure 5.6 Flow Duration Curves for different levels of IRWH adoption C52A (SWAT).

In this Study, following Smakhtin (2001), the section of the curve with flows within the range of 50–99% time exceedence represents low flow conditions.

100% adoption of IRWH in the QC reduces the high flows by about 70% and low flows by about 13% (Figure 5.6). After the 70% probability of exceedence corresponding to the low flows, 100% RWH essentially leaves the river dry. These low flows are crucial for ecological functioning of the river.

It can be observed on the median year hydrograph (1990/1991) that the various levels of adoption of IRWH reduce the monthly flows (Figure 5.7). This can be explained by the increase in runoff interception and soil storage due to IRWH. The water stored in the soil profile is partly utilised by the crops through transpiration. Additionally, a delay in the peak flow (about 30 days) is observed on the hydrograph of the median year (Figure 5.7 and Table 5.6) when the 100 percent adoption of IRWH is compared with the other levels of adoption.

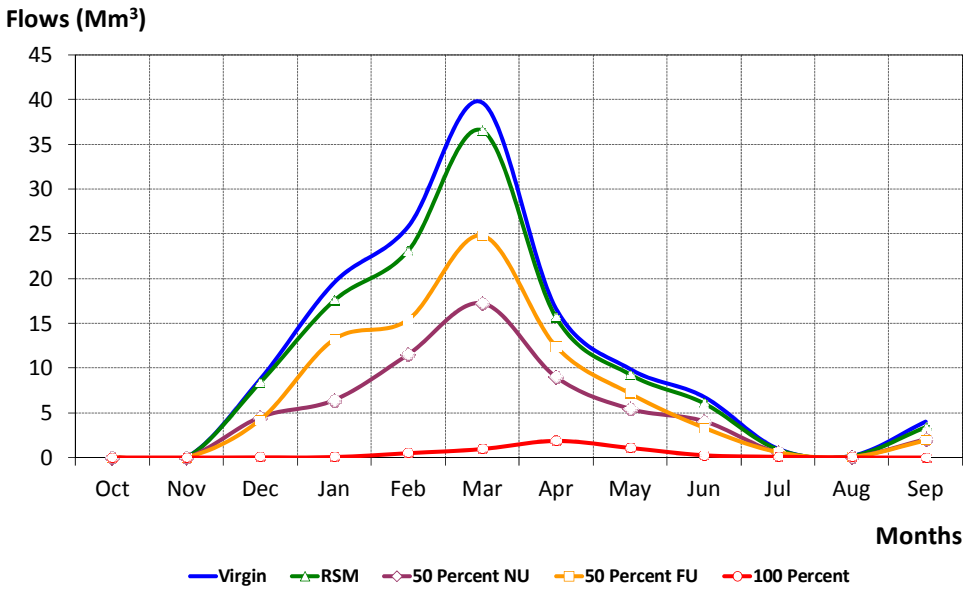


Figure 5.7 Median monthly hydrograph (October 1990 to September 1991) of different levels of IRWH adoption in C52A (SWAT).

Table 5.6 Results of median monthly hydrograph (Mm^3) for different levels of IRWH adoption in C52A (SWAT).

Date	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Virgin	0.00	0.00	8.75	19.54	25.79	39.68	16.64	9.89	6.79	0.98	0.17	3.99
100%	0.00	0.00	0.00	0.04	0.48	0.94	1.85	1.06	0.24	0.08	0.00	0.00
RSM	0.00	0.00	8.38	17.54	23.09	36.55	15.66	9.28	6.06	0.89	0.15	3.38
50%nu	0.00	0.00	4.50	6.41	11.50	17.24	8.99	5.43	4.06	0.58	0.07	2.03
50%fu	0.00	0.00	4.21	13.20	15.39	24.80	12.41	7.16	3.33	0.59	0.07	1.90

Depending on the location of the area where IRWH is adopted, the ecohydrological impact differs. The flow duration curves (Figure 5.6) show, as expected, that the 50% IRWH near upstream of outlet reduces runoff slightly more than 50% FU. IRWH reduces the runoff in a distributed manner in the 50% of the QC located near the catchment's outlet, while it is reduced further upstream mainly by channel transmission losses. Channel transmission losses are important processes of the water balance of a catchment especially in arid and semi-arid regions such as the C52A QC (Hugues, 2006; Görgens and Boroto,

2003; Arnold et al. 1998; Hughes 1995). Transmission losses are more dominant during high flows than during small to medium flows (Lange, 2005) and can be more substantial in the very uppermost parts of a catchment (Hickok, 1968). When IRWH is implemented in the half of the QC total area located further upstream of the catchment's outlet, the runoff is firstly distributed by IRWH and then by transmission losses. It should be noted that the groundwater flow component has not been accounted for in the SWAT model. It is conjectured that the flow reduction by IRWH transmission losses could account for increased low flows due to groundwater contribution, particularly if the right conditions exist for surface – groundwater interaction.

The modelling of RWH at QC scale with the Water Resources Simulation Model 2000 (WRSM) was largely carried out by Sejamoholo et al. (2008) and it is only succintingly presented here. Its simulation results are compared with those of SWAT earlier presented.

5.6 Modelling RWH using the Water resources simulation model

5.6.1 The Water Resources Simulation Model (WRSM)

The Pitman model is a semi-distributed calibration model developed in the 1970s. The model has undergone a number of revisions and exists in several forms that preserve the core concepts of the original model (Hughes, 2006). Figure 5.8 shows the structure of the Pitman model while Table 5.7 presents the 12 parameters of the Pitman model.

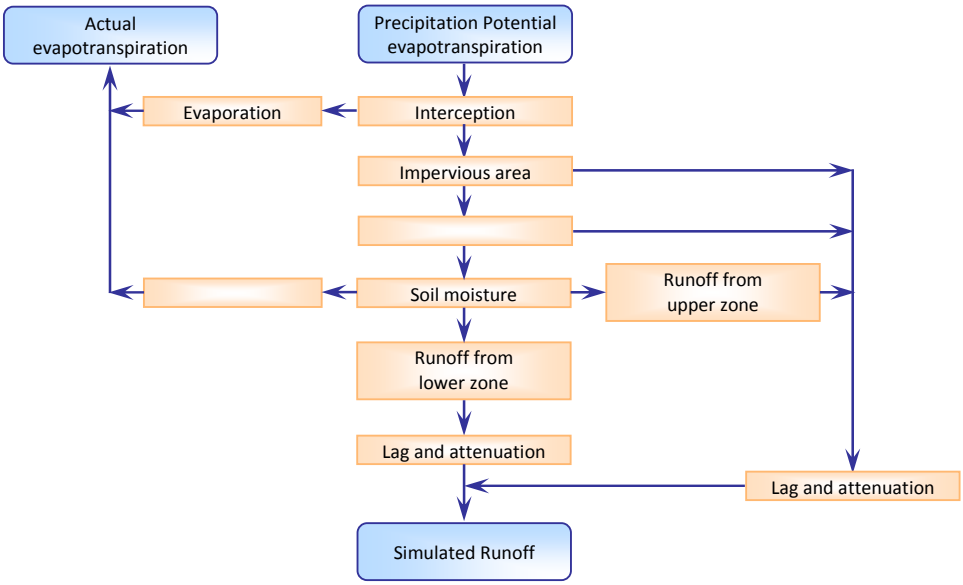


Figure 5.8 Core structure of the Pitman model (Pitman, 1973).

The water resources simulation model 2000 (WRSM), used in this study, is one of its latest update that involves the calibration of the model on naturalised observed flow data, the regionalisation of the model parameters and generation of 85-year time series of natural monthly streamflow (1920 – 2004) for the 1950 QCs of South Africa.

Table 5.7 Parameters of the original Pitman model (Pitman, 1973).

Parameter	Units	Description
PI	mm	Interception storage
AI	none	Ratio of impervious to total area
ZMIN	mm/month	Minimum catchment absorption rate
ZMAX	mm/month	Maximum catchment absorption rate
ST	mm	Maximum moisture storage capacity
SL	mm	Moisture storage capacity below which no runoff occurs
FT	mm/month	Runoff from moisture storage at full capacity
GW	mm/month	Maximum groundwater runoff
R	none	Evaporation-moisture storage relationship parameter
POW	none	Power of the moisture storage-runoff equation
TL	months	Lag for surface and soil moisture
GL	months	Lag for groundwater runoff

5.6.2 Methodology

Sejamoholo et al. (2008) used the model to simulate naturalised time series for 85 years (1920 to 2004) and as well as time series for different levels of adoption of RWH in the semi-arid C52A QC and the humid V13D QC.

IRWH was modelled by appropriately adjusting the interception storage (PI), the Soil moisture holding capacity (ST) and the Minimum absorption rate (Zmin) (Sejamoholo et al., 2008). This adjustment of the Pitman calibration parameters is done at maximum adoption level of IRWH (i.e. 100 percent adoption) where it is assumed that the IRWH practice is applied through the entire catchment area. With the correct combination of these 3 Pitman calibration parameters determined for the 100 % IRWH, other lower levels of adoption were modelled by reducing the actual IRWH areas proportionally. Other Pitman calibration parameters for the catchment under study are kept the same as determined in the Pitman Model calibration process.

Apart from IRWH, DRWH and XRWH were also modelled with WRSM. DRWH was modelled using a dummy dam providing supplementary irrigation to maize crop planted during the raining season in each homestead garden (Sejamoholo et al., 2008). Two different types of rural settlements were modelled:

- Dense Rural Settlements, where the dwellings are spatially grouped, and;
- Scattered Settlements where the dwellings are spatially dispersed.

XRWH was modelled as an irrigation block module supplied from a dummy dam, representing all the XRWH storages, located at the outlet of the catchment (Sejamoholo et al., 2008).

5.7 Comparison between IRWH modelling results obtained with SWAT and WRSM.

In order to compare the results of both hydrological models, only the period of 1st August 1988 to 31st July 2000, was considered. This period has the hydrological year October 1990 to September 1991 as the median rainfall year.

For the period under consideration, results indicate that naturalised flows simulated by SWAT (Figure 5.9) are higher than those simulated by WRSM (Figure 5.10), while the latter model simulates higher values of the low flows (>75% exceedence probability). Thus, while for a 100 % adoption of IRWH SWAT suggests that the river is dry, WRSM indicates that there is flow, albeit very little.

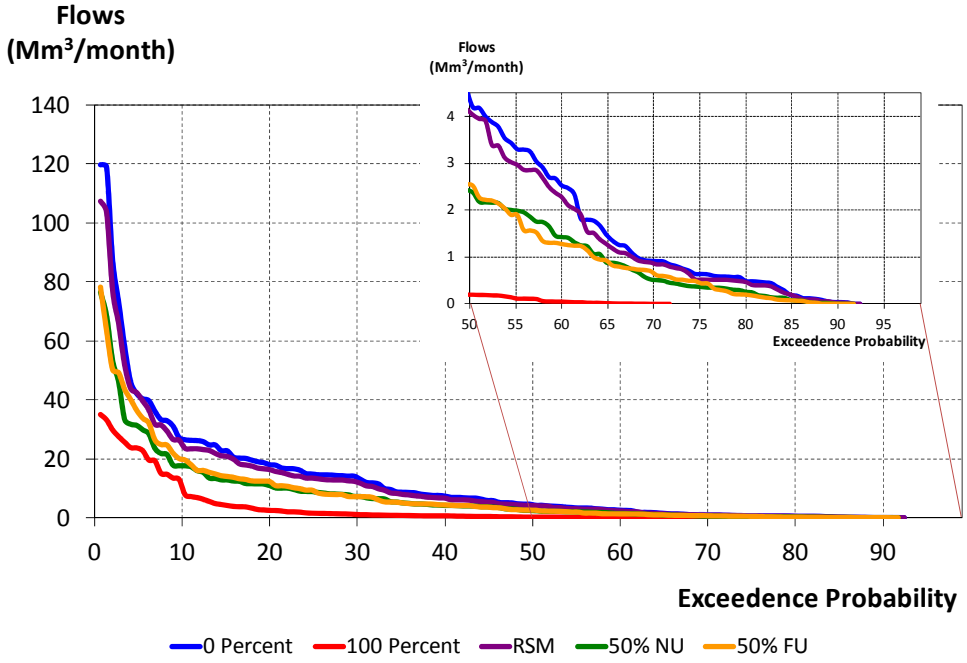


Figure 5.9 Flow Duration Curves for different levels of IRWH adoption in C52A obtained using SWAT.

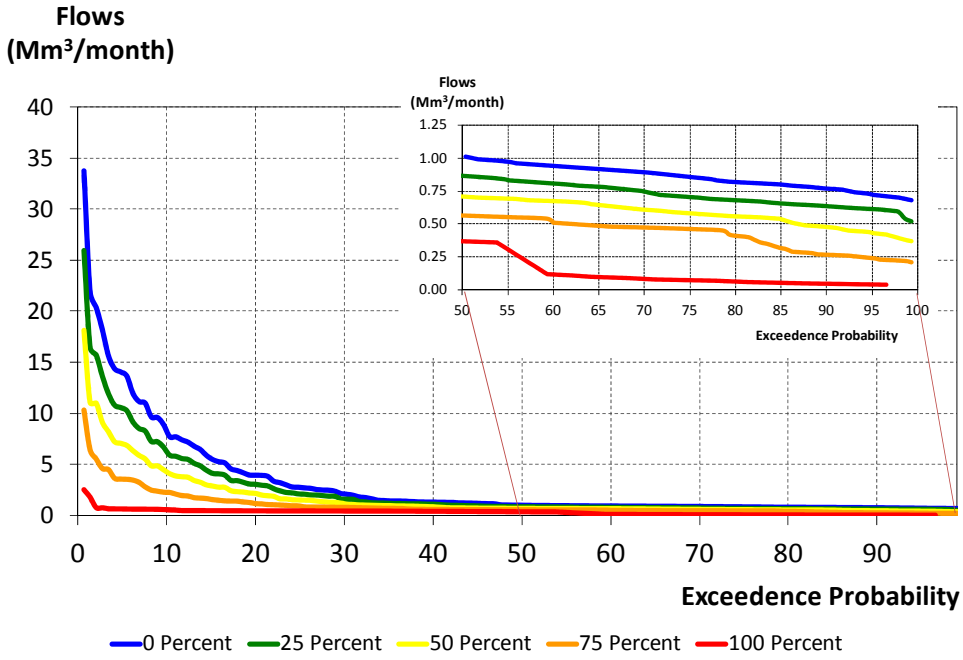


Figure 5.10 Flow Duration Curves for different levels of IRWH adoption in C52A obtained using WRSM (Sejamoholo et al., 2008).

An attempt is made to carry out a comparative analysis of the SWAT and WRSM results for IRWH in C52A QC in order to identify which model elicits higher confidence. It should be noted that there are no observed time series of natural flows with which to make comparison.

- First the rainfalls from 12 gauging stations are plotted with simulated flows from both models in the time period from 1988 to 2000. The runoff from a given rainstorm is a function of the rainfall intensity distribution and sequence, the rainstorm event, the soil infiltration rates and the soil surface storage capacity (FAO, 1993). Thus when the rainfall and the river discharge generated by the models are compared, one expects to observe a correlation between the two curves. While such a correlation is observed between measured rainfall and the naturalised river discharge generated by SWAT (Figure 5.11), that is not the case with WRSM. In many instances, the naturalised river discharge of WRSM

exhibits peaks when the rainfall gauges did not record significant rains and vice-versa (Figure 5.11). While there is consistency in the rainfall hyetographs from all stations, this inconsistency between WRSM simulated hydrograph and rainfall records calls to question the reliability of its simulated results.

- Sejamoholo et al. (2008) used observed streamflow records from October 1955 to September 1975 to calibrate the WRSM. As illustrated in Figure 5.12, the model consistently overestimates the low flows.

- However, the time series of naturalised river discharge (Figure 5.11) simulated by SWAT and WRSM are of the same order of magnitude.

In view of the above, there is greater confidence in the capability of SWAT in predicting the naturalised flow than WRSM. Furthermore, unlike SWAT, the WRSM cannot model the ecohydrological impact of the same level of adoption of IRWH with different spatial distributions within the same QC. Nevertheless, the WRSM has the advantage that its input parameters have been prescribed for all quaternary catchments in South Africa, in contrast to SWAT which is data intensive. Thus findings by Sejamoholo et al. (2008) summarised as flow duration curves (Appendix C) for the period of 1920 to 2004 are still utilised in the decision support system which is developed at country scale in the subsequent chapter.

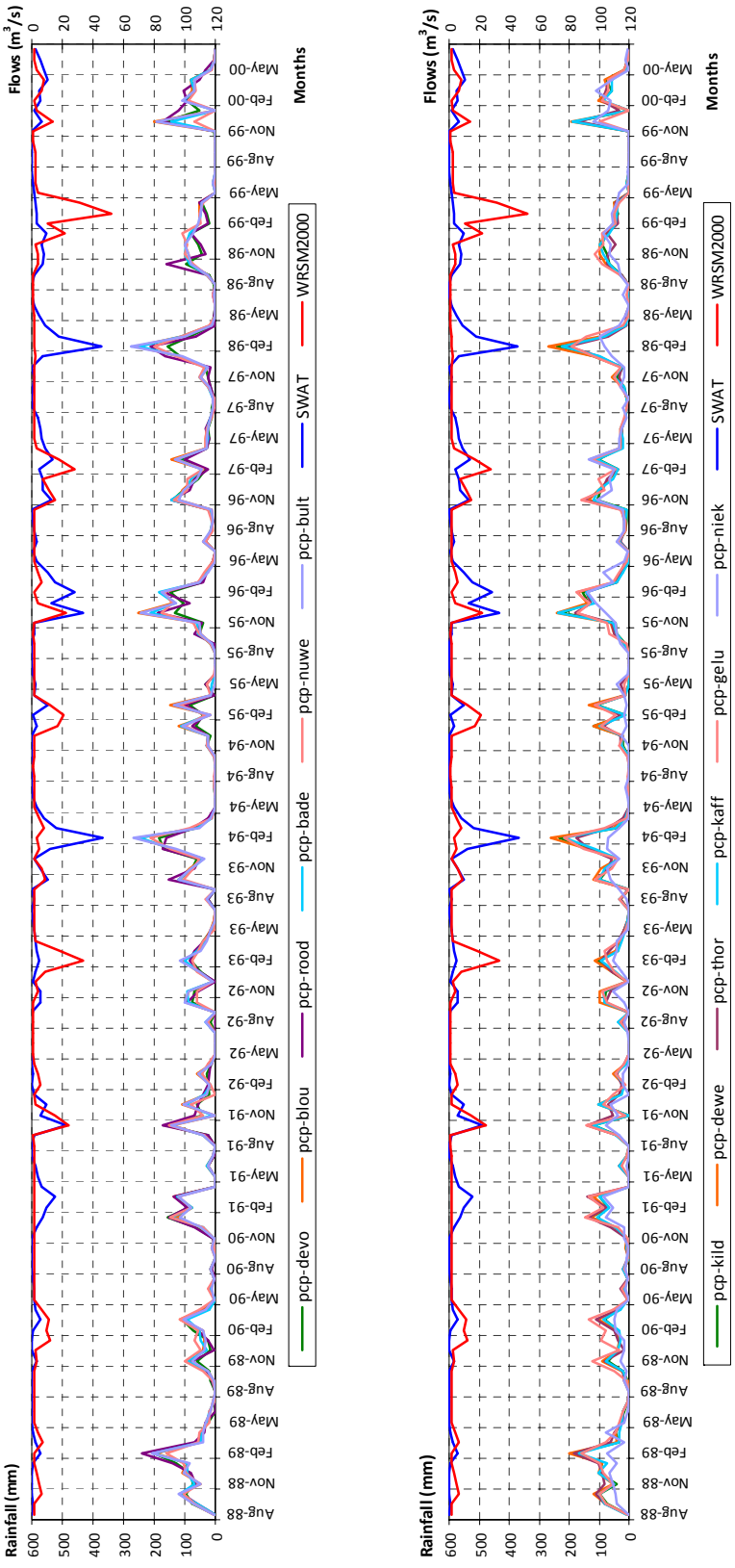


Figure 5.11 Monthly rainfall and monthly naturalised flows generated by SWAT and WRSM.

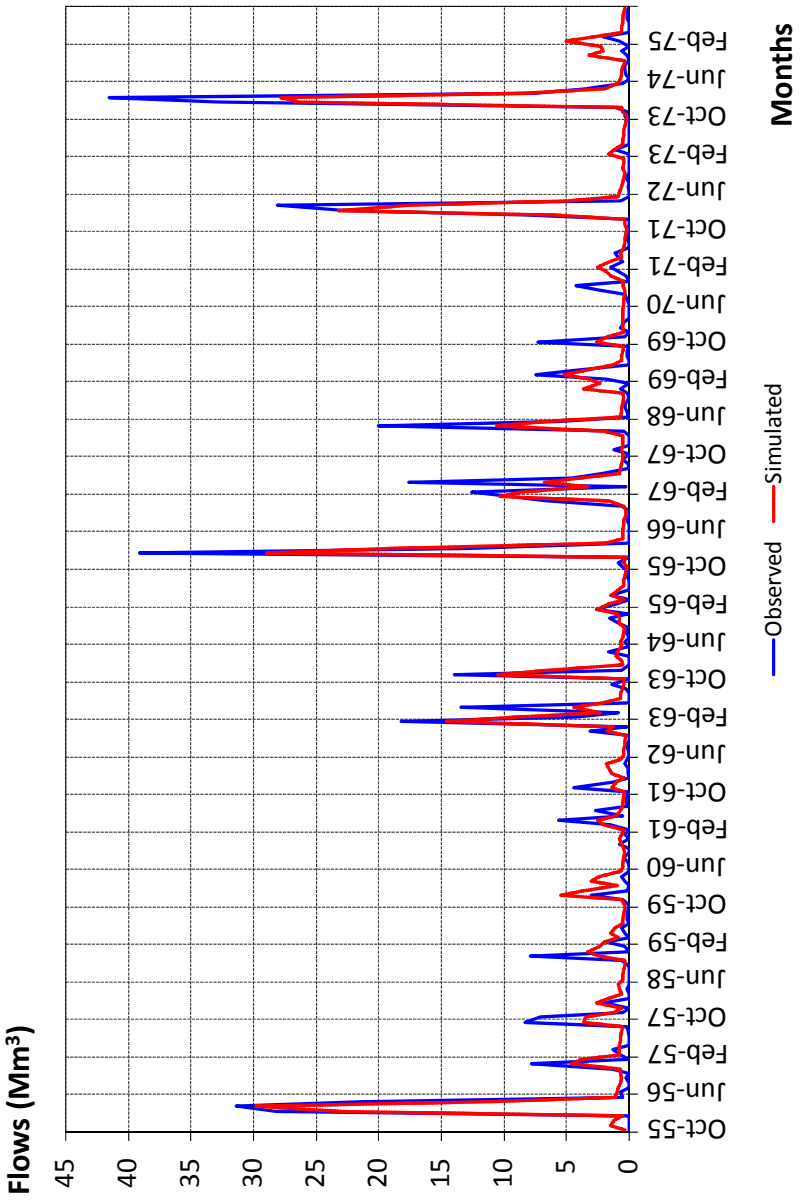


Figure 5.12 Observed and simulated monthly discharge using WRSM for the period of October 1955 to September 1975 in the Semi-Arid C52A QC.

5.8 Summary

The chapter presented a methodology for assessing the ecohydrological impact of different level of adoption of IRWH in the semi-arid C52A QC using the SWAT. The model was first used to generate naturalised time series of river discharge for a period of August 1988 to July 2000 before IRWH was implemented and its impact assessed. For the 11 years of rainfall records in C52A, the median rainfall occurred in 1990, thus the October 1990 to September 1991 hydrograph was used for analysis.

The simulated results of SWAT are compared with those of WRSM and they indicate that the former predicts higher values of the high flows whereas the latter predicts higher values of the low flows.

Results of the WRSM indicate that IRWH reduces high flows more than low flows. For the same level of adoption, IRWH located close to the outlet combined with channel transmission losses farther upstream resulted in higher reduction in high flows than when the reverse is the case. Therefore, both the spatial distribution and the level of adoption are critical in the assessment of the ecohydrological impact of RWH.

Although more confidence was given to the SWAT results, the WRSM results were not completely disregarded considering that the WRSM has the advantage of being set for all quaternary catchments in South Africa unlike SWAT which is data intensive. Subsequently, Table 5.8 and Table 5.9 generated by WRSM will be used as input into the decision support system presented in the next chapter to determine the ecohydrological impact of different levels of adoption of RWH in C52A and V13D. The flow duration curves generated by Sejamoholo et al. (2008) using the WRSM for DRWH and XRWH are presented in Appendix C.

Table 5.8 Semi Arid Region – Estimated impact on flow duration curve for DRWH, IRWH and XRWH in C52A

Category	% Adoption	10 P	20 P	30 P	40 P	50 P	60 P	70 P	80 P	90 P	99 P
DRWH scattered	0	5.3	2.7	1.6	1.2	1.0	0.9	0.8	0.8	0.7	0.5
	25	5.8	3.3	2.4	1.9	1.6	1.3	1.1	1.0	0.8	0.6
	50	6.7	4.2	3.1	2.3	1.9	1.6	1.2	1.0	0.8	0.6
	75	7.8	5.0	3.7	2.7	2.2	1.7	1.3	1.0	0.8	0.6
	100	9.2	6.0	4.2	3.2	2.4	1.8	1.3	1.0	0.8	0.6
IRWH	0	5.3	2.7	1.6	1.2	1.0	0.9	0.8	0.8	0.7	0.5
	25	4.0	2.1	1.3	1.0	0.8	0.8	0.7	0.7	0.6	0.4
	50	2.8	1.5	1.0	0.8	0.7	0.6	0.6	0.5	0.5	0.3
	75	1.5	0.9	0.7	0.6	0.5	0.5	0.5	0.4	0.3	0.2
	100	0.5	0.5	0.4	0.4	0.4	0.1	0.1	0.1	0.1	0.0
XRWH	0	5.3	2.7	1.6	1.2	1.0	0.9	0.8	0.8	0.7	0.5
	25	4.0	2.1	1.3	1.0	0.8	0.8	0.7	0.7	0.6	0.4
	50	2.8	1.5	1.0	0.8	0.7	0.6	0.6	0.5	0.5	0.3
	75	1.5	0.9	0.7	0.6	0.5	0.5	0.5	0.4	0.3	0.2
	100	0.5	0.5	0.4	0.4	0.4	0.1	0.1	0.1	0.1	0.0

With P = percentile; units in Mm^3/month

Table 5.9 Humid Region – Estimated impact on flow duration curve for DRWH, IRWH and XRWH in V13D

Category	% Adoption	10 P	20 P	30 P	40 P	50 P	60 P	70 P	80 P	90 P	99 P
DRWH scattered	0	12.3	6.5	4.0	2.7	1.7	1.0	0.7	0.5	0.4	0.3
	25	12.5	6.9	4.4	2.9	1.9	1.2	0.9	0.6	0.5	0.3
	50	12.8	7.2	4.9	3.4	2.1	1.4	1.0	0.7	0.5	0.3
	75	13.1	7.7	5.3	3.7	2.4	1.7	1.2	0.8	0.5	0.3
	100	13.3	8.1	5.7	4.1	2.7	1.8	1.3	0.8	0.6	0.3
IRWH	0	12.3	6.5	4.0	2.7	1.7	1.0	0.7	0.5	0.4	0.3
	25	10.2	5.3	3.2	2.1	1.4	0.9	0.6	0.4	0.3	0.2
	50	7.9	4.0	2.4	1.6	1.1	0.7	0.5	0.4	0.3	0.2
	75	5.7	2.7	1.5	1.0	0.7	0.5	0.4	0.3	0.2	0.1
	100	3.4	1.6	0.8	0.5	0.3	0.2	0.2	0.1	0.1	0.1
XRWH	0	12.3	6.5	4.0	2.7	1.7	1.0	0.7	0.5	0.4	0.3
	25	10.6	5.4	3.2	2.1	1.3	0.8	0.6	0.4	0.4	0.3
	50	8.9	4.1	2.2	1.5	1.0	0.6	0.5	0.4	0.3	0.2
	75	7.0	2.5	1.3	0.9	0.6	0.4	0.3	0.3	0.3	0.2
	100	5.8	0.4	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2

With P = percentile; units in Mm^3/month

Chapter 6 THE RAINWATER HARVESTING DECISION SUPPORT SYSTEM (RHADESS)[5]

6.1 Background

Decision support systems (DSS) are interactive computer based systems built to help decision makers utilise data and models to solve unstructured problems (Sprague, 1980). Water resources management transcends boundaries between water, land and environment, and interrelates water with broader policy questions associated with social and economic development. Due to the multidimensional nature of water resource decisions, tools enabling the analysis of alternatives are required (Paruccini et al., 1997). DSSs assist by defining the problem, generating alternatives, evaluating alternatives and indicating the best alternative for implementation. GIS technologies significantly ease the decision making process by capturing the spatial variability of water resources and providing a visual representation of the problem thereby increasing the user's comprehension and enhancing his/her analytical capabilities. When combined with GIS, conventional DSS are referred to as Spatial Decision Support Systems (Tkach and Simonovic, 1997). In this thesis, the GIS based DSS is referred simply as the DSS or the system.

[5] This chapter is based on:
Mwenge Kahinda, J., Sejamoholo B.B. P., Taigbenu, A. E., Boroto, R.J., Lillie, E.S.B., Taute, M., and Cousins, T., 2009a. Water Resources in Rainwater Harvesting: An Integrated Systems Approach. Report No. KV 1563-1-08, Water Research Commission, Pretoria, South Africa;
Mwenge Kahinda, J., Sejamoholo, B.P.P., Taigbenu, A. E., Lillie, E.S.B. and Boroto, R.J., 2009b. A GIS-based decision support system for Rainwater harvesting (RHADESS). J. Phys. Chem. Earth 34 (13-16) 767–775, and;
Mwenge Kahinda, J., Lillie, E.S.B., Boroto, R.J., Dube R.; Taigbenu A. E., 2006. Preliminary conceptual model of the GIS Based Rainwater Harvesting Decision Support System. Proc. of the IASTED International Conference on Environmentally Sound Technology in Water Resource Management (ESTW 2006) September 11-13, 2006 Gaborone, Botswana.

Most existing DSSs are either not used at all or not used as intended by their developers (Uran et al., 2003). This is a sobering thought for any team embarking on the development of a DSS, and one that requires identifying and learning from the mistakes of previous efforts. The main pitfalls identified can be summarised as the high levels of complexity of DSSs which make them difficult to understand or use, lack of friendliness of use, lack of training to use the DSS, the poor scoping of the initial requirements from intended uses, and failure to adequately identify the potential users. Thus, the dilemma most DSS developers face is that usually a more complex system better represents reality but is more difficult to understand and use by those who are not the developers. Too complex systems are not widely used as the time needed to learn the model outweighs the benefits. Results of too simplistic system are often ridiculed and easily become discredited although the system can be friendly and amenable to a wide range of users. The balance between developing a highly complex system which provides many options and accurate results and a simpler and more transparent system that can be easily understood and widely used was the single biggest challenge. The complexity of making alternatives (scenarios) depends on, among other things, how many parameters need to be changed, and how easy it is to make changes to the parameters. Thus, RHADESS limits the number of parameters required to generate scenarios in order to ease the navigation through the system.

6.2 RHADESS Overview

6.2.1 RHADESS structure

RHADESS combines the following five models (Figure 6.1):

- the RWH suitability model (RSM);
- SWAT and WRSM;

- the Roof model (RM), and;
- the IRWH Economic Simulation Model (IESM).

When assessing the ecohydrological impact of IRWH, there is an alternative to substitute the WRSM with SWAT. It should be noted that unlike WRSM whose parameters for all catchments in South Africa have been set, SWAT has to be formatted with appropriate thematic datasets.

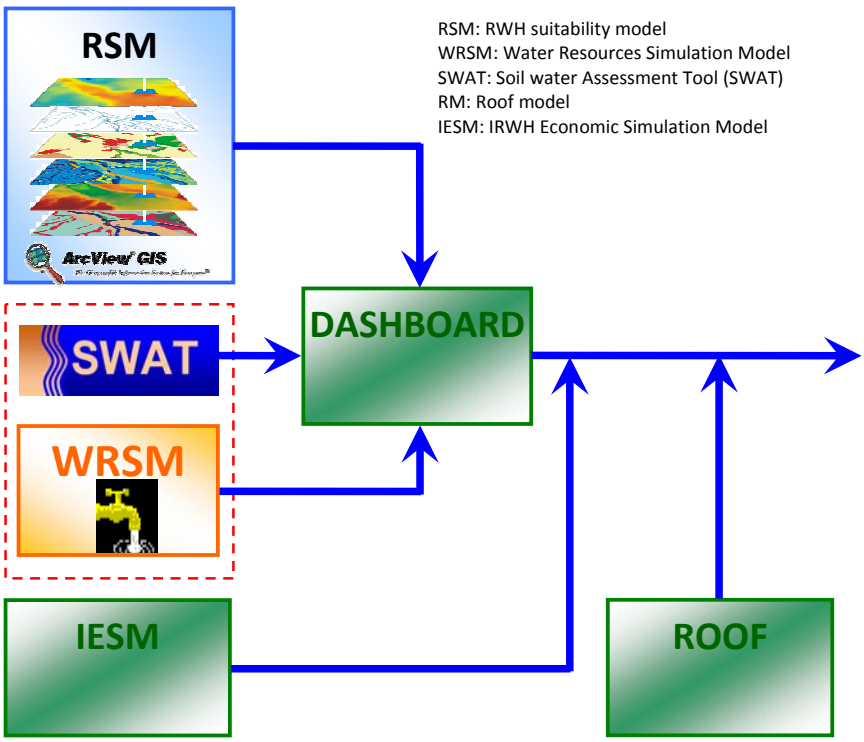


Figure 6.1 RHADESS structure.

Built as an extension of ArcView 3.3, RHADESS uses it as a platform (Figure 6.1) to assess the potential for RWH in South Africa or in one of its 19 WMAs. The RHADESS interface enables the user to load the project file of the RWH category of interest and access its RWH suitability model (RSM).

The RSMs are built in ModelBuilder, an extension of ArcView 3.3, where parameters may be changed easily and the model rerun to explore alternatives. Results of the RSM are displayed on maps with five suitability levels (very low to

very high), and the footprint (surface area of each suitability class) at quaternary catchment level can be estimated and displayed as a map and in an Excel spreadsheet. The hydrological impact of RWH is assessed in the Excel environment as reduction in mean annual runoff depending on the potential level of adoption in a quaternary catchment. The estimated river runoff reduction is obtained by interpolation, in the RWH dashboard, between the results obtained from the Pitman model or the SWAT model at different levels of adoption (0, 25, 50, 75 and 100%) of RWH area. The RSM, the WRSM and SWAT are described in the preceding chapters.

Considering the knowledge generated by previous studies on the socioeconomic impacts of RWH in South Africa, only two socioeconomic factors were incorporated into RHADESS:

- The level of water security attained by DRWH in a rural South Africa setting, which is assessed by the Roof model, and;
- The area of land needed for a household to achieve food security when IRWH is implemented, which is assessed by the IESM.

6.2.1.1 Roof model

The water security (percentage of demand satisfied) by DRWH-Agt was estimated using a modified version of Roof. Roof is a model developed by van der Zaag (2000) which calculates storage capacity when daily water use and roof area are known. Roof is essentially a water balance model that requires a complete series of daily rainfall data for at least three consecutive years. Using monthly rainfall data to calculate the storage requirements results in a severe underestimation of the required storage capacity (van der Zaag, 2000; Roebuck, 2007). The coefficients for the calculation of the harvestable part of total daily precipitation can be input, according to the following formula (Equation 6.1):

$$R_{harv} = e \, MAX \, (R - f \, , 0) \quad 6.1$$

Where R_{harv} = harvestable rainfall (mm d^{-1}),

R = rainfall (mm d^{-1}),

e = efficiency coefficient, and;

f = interception coefficient (mm d^{-1}).

The roof model is available in the DVD accompanying the thesis.

6.2.1.2 The IRWH Economic Simulation Model (IESM)

The model calculates the minimum farm size required to provide a farming household, using the different IRWH techniques, with enough food/income to attain household food security using two approaches of household food security: the household caloric requirement and the income requirement (Kundhlande et al., 2004).

IESM requires the following input data:

- Variable input prices (labour, chemicals, seed)
- Household labour availability;
- Land available, and;
- Output prices.

The model provides the following outputs:

- Total per hectare gross margin;
- Enterprise budget, and;
- Minimum farm size (Caloric and income).

The IESM can be applied to different types IRWH techniques since they have similar enterprise budget. Although the model considers the conventional technique and six variants of IRWH techniques, for the purpose of this study and

to ensure that the DSS is simple for users, only two techniques are considered, that is, Conventional and Bare basin and runoff strip referred to as IRWH.

The IEMS is available in the DVD accompanying the thesis.

6.2.2 Potential users

Considering the planning nature of RHADESS and its spatial scale of application, its potential users include: national government (i.e.: Department of Water Affairs, Department of Agriculture Forestry and Fishery); local government (i.e.: District Councils, Municipalities); catchment management agencies; water users associations; water services authorities; Conservation Authorities; tertiary educational institutions; research organisations; NGOs; consultants; etc. Nevertheless, to accommodate a wide range of users, RHADESS has two levels of customisability, one for more advanced users and another, using default values for less advanced users. The RHADESS user manual is attached in Appendix D.

6.3 Rainwater harvesting suitability

RHADESS was applied to the semi-arid C52A and the humid V13D QCs. The suitability map produced by the RSM indicates that all households located in C52A are classified as moderately suitable for DRWH and cover 2.8 percent of the total area of C52A, while 70 % of the households located in V13D are classified as highly suitable for DRWH and cover about 13 percent of the total area (Figure 6.2 and Figure 6.3).

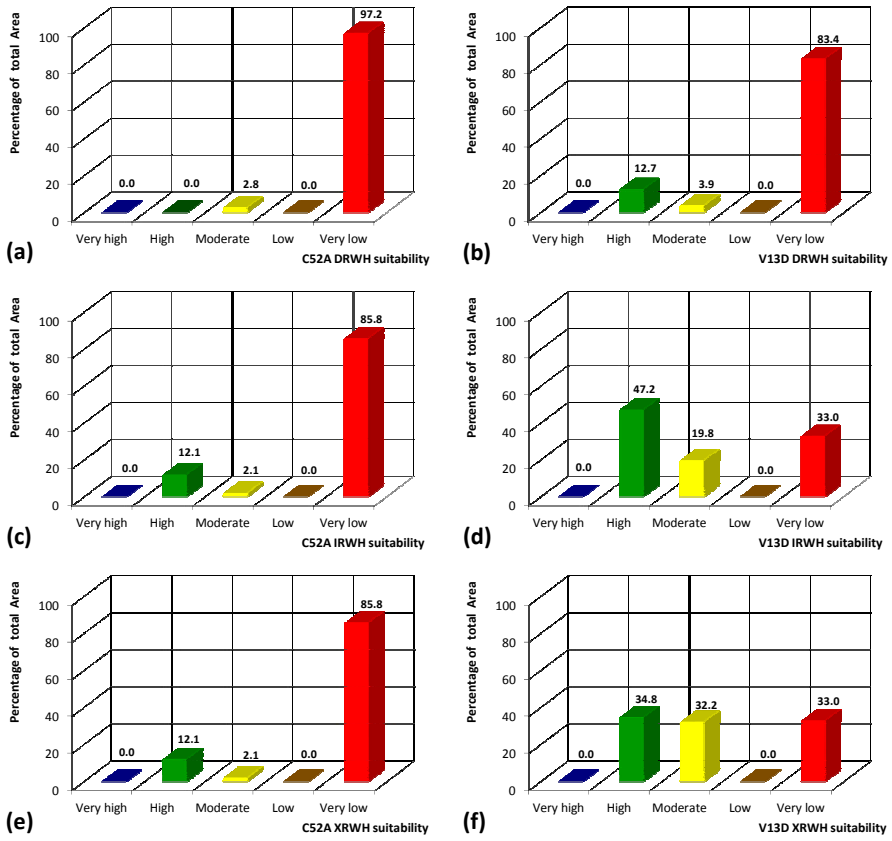


Figure 6.2 Percentage of land area per suitability class in: (a) C52A DRWH, (b) V13D DRWH, (c) C52A IRWH, (d) V13D IRWH, (e) C52A XRWH, and (f) V13D XRWH.

Suitable IRWH areas cover about 14 percent (12 percent high and 2 percent moderate) of C52A and 67 percent (20 percent high and 47 percent moderate) of V13D while suitable XRWH areas cover about 14 percent (12 percent very high and 2 percent moderate) of C52A and 67 percent (35 percent high and 32 percent moderate) of V13D (Figure 6.2 and Figure 6.3).

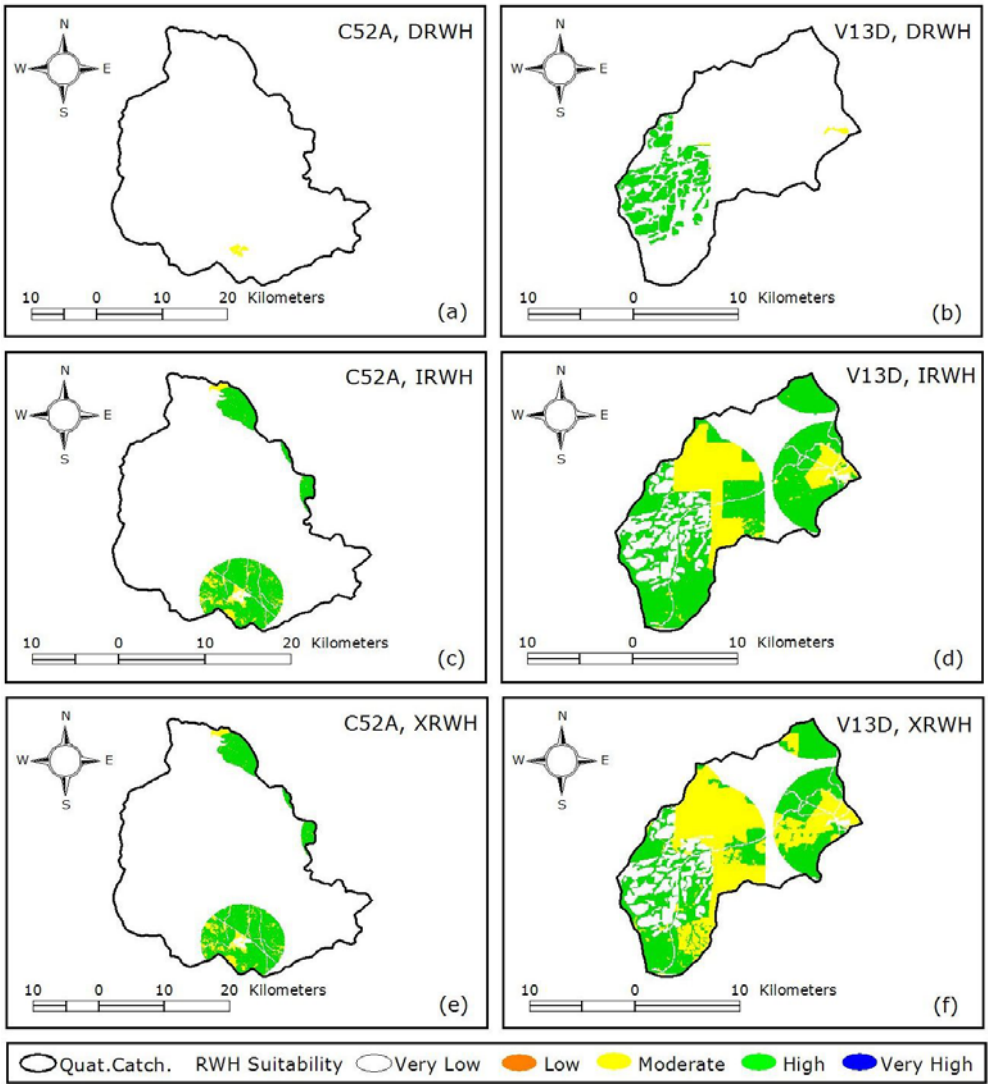


Figure 6.3 Map partitioning, (a) C52A and (b) V13D into five DRWH suitability classes; (c) C52A and (d) V13D into five IRWH suitability classes as well as (e) C52A and (f) V13D into five XRWH suitability classes.

6.4 Rainwater harvesting impacts

6.4.1 Socioeconomic impacts of Rainwater harvesting

The water security (percentage of demand satisfied) of the DRWH-Agt was evaluated based on 10 consecutive years of daily rainfall data from the driver rainfall stations (see section 3.4), using the Roof model in both QCs, for a

household covered by a roof of 20-40 m^2 and assuming a daily demand of 125 litres/day.

Results indicate that in C52A, a 1 m^3 Agt harvesting water from a 20 m^2 roof satisfies 15% of the demand (Figure 6.4) while an Agt of the same capacity harvesting water from a 40m^2 roof satisfies 28% of the demand. The maximum water security of 35% is achieved when a 7 m^3 Agt harvests rainwater from a 40 m^2 roof. A further increase in tank capacity serves no useful purpose (Figure 6.4).

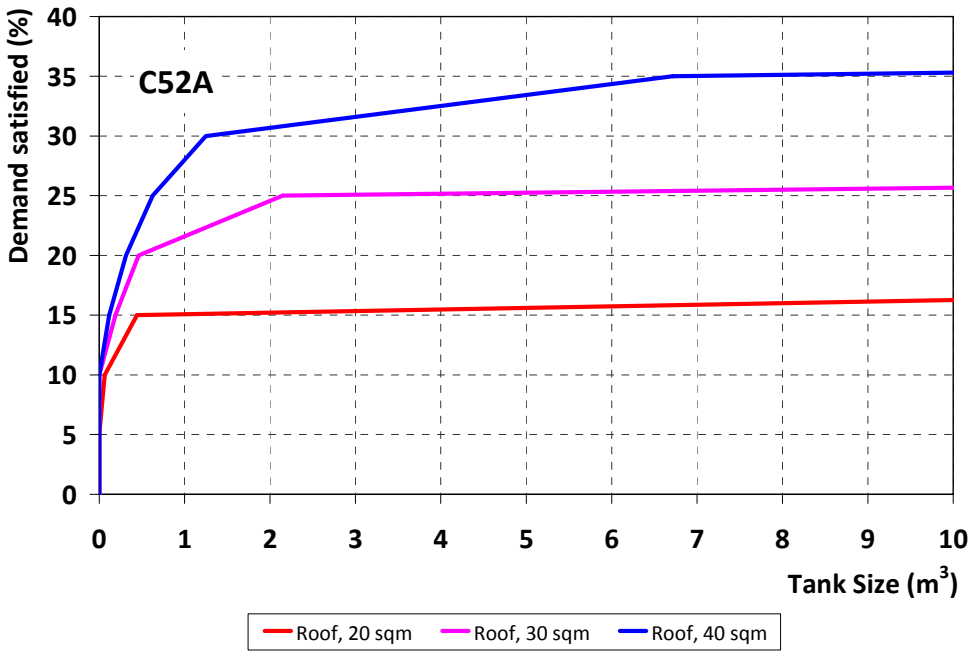


Figure 6.4 Percentage of demand satisfied for varying tank size and different roof areas in C52A.

In V13D, for a roof area of 20 m^2, a 2.5 m^3 Agt satisfies 35.5% of the demand, while a 1 m^3 only satisfies 25% of the demand (Figure 6.5).

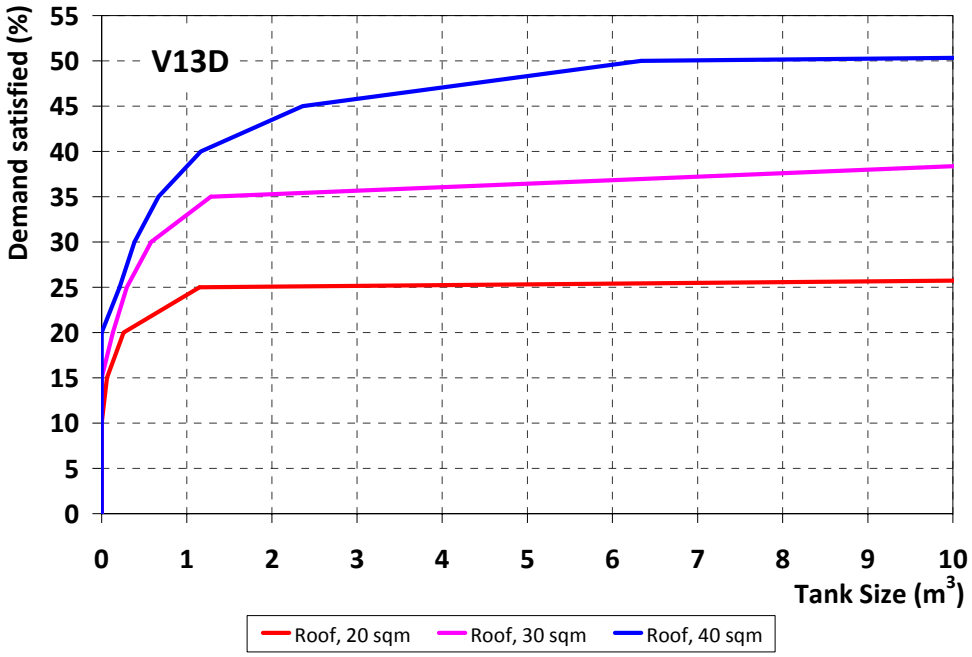


Figure 6.5 Percentage of demand satisfied for varying tank size and different roof areas in C52A.

Water security (0-100%) reached by standard Agts available on the market for different roof areas (20, 30 and 40 m^2) are presented in Table 6.1.

Table 6.1 Demand satisfaction met by a 1, 2.5 and 5 m^3 Agt in C52A and V13D for different roof areas.

Roof Areas m^2	% of demand Satisfied by a 1 m^3 Agt		% of demand Satisfied by a 2.5 m^3 Agt		% of demand Satisfied by a 5 m^3 Agt	
	C52A	V13D	C52A	V13D	C52A	V13D
20	15	24	15.5	25	16	25.5
30	22	33	25	35.5	25	36.5
40	28	38	31.5	45	33	48

An increase in roof area for the same tank size results in an increased satisfaction of the demand. Although the size of the rainwater tank should ideally be taken at the points where the curves begin to flatten, other decisive factors such as the cost, the available space and the tank sizes available on the market must be considered.

Furthermore, V13D catchment provides higher demand satisfaction than the dryer C52A (Table 6.1).

Considering the uni-modal rainfall distribution and the long dry season of semi-arid environments, one can argue that the water security reached by the Agts in such environment is better assessed seasonally rather than annually. However, since these figures are more applicable for planning purposes, the annual assessment of water security should be viewed in the light of multiple sources scenarios.

The IESM was used to calculate the minimum farm size required to provide a farming household, using IRWH, with enough food/income to attain household food security. With either of the two approaches, the implementation of IRWH results in a 70% decrease in the minimum area of land area required to achieve household food/income security (Table 6.2).

Table 6.2 Minimum area of land required to ensure food security for an average household (4 inhabitants) in C52A for the conventional agricultural practice and IRWH.

Method	Minimum area based on income (ha)	Minimum farm size based on caloric requirement (ha)
Conventional	5.77	6.39
IRWH	1.7	1.88

To attain food security, based on the household caloric requirement approach, 6.4 ha of land must be cultivated under the conventional approach compared to 1.9 ha when IRWH is implemented (Table 6.2). This value is slightly higher than that when the household income requirement approach is used (Table 6.2).

6.4.2 Ecohydrological impacts

The impacts of the upscaling of RWH in C52A and V13D were assessed for different levels of adoption (Table 6.3): significant, intermediate, insignificant and the most probable level of adoption.

Table 6.3 RWH levels of adoption.

	Scenarios		
Suitability	Significant	Intermediate	Insignificant
Very High	100	75	50
High	75	50	25
Moderate	50	25	0
Low	25	0	0
Very Low	0	0	0

A significant level of adoption is considered to be one in which RWH is implemented on 100 % of the very high suitable areas, 75 % of the suitable areas, 50 % of the moderate suitable areas, 25 % of the low suitable areas and 0 % of the very low suitable areas (Table 6.3). Similarly, the suitable areas for the intermediate and insignificant levels of adoption are indicated in Table 6.3. The most likely level of adoption of FRWH takes into account the land tenure system. It is assumed that FRWH will receive greater support for implementation in former homelands (homelands were self-governing territories predominantly populated by black South Africans, engaged in the production of crops and livestock mainly for own consumption (Wessels et al., 2004).

Once the percentage adoption of a RWH variant is determined for a selected scenario, it is interpolated from Table 5.8 for C52A and Table 5.9 for V13D to assess the ecohydrological impact of RWH in the RWH impact dashboard spreadsheet.

6.4.2.1 Scenario 1: Insignificant level of adoption

Under the insignificant level of adoption scenario, 12% of V13D is suitable to IRWH while only 3% in C52A (Table 6.4). XRWH is only suitable in 9% of V13D

(Table 6.4). Using Table 5.8 for C52A and Table 5.9 for V13D, the above levels of adoptions are interpolated to estimate the ecohydrological impact of RWH.

Table 6.4 Percentage adoption of RWH in C52A and V13D under the insignificant level of adoption scenario.

Category	QC	Area (Km^2)	RWH suitability km^2					Total RWH Area (Km^2)	RWH Percentage Adoption
			Very High	High	Mod.	Low	Very Low		
			0.5	0.25	0	0	0		
DRWH	C52A	938	0.0	0.0	26.1	0.0	911.9	0.00	0.0
	V13D	283.8	0.0	36.1	11.2	0.0	236.6	9.01	3.2
IRWH	C52A	938	0.0	113.3	19.7	0.0	805.0	28.32	3.0
	V13D	283.8	0.0	134.0	56.3	0.0	93.5	33.50	11.8
XRWH	C52A	938	0.0	113.3	19.7	0.0	805.0	28.32	3.0
	V13D	283.8	0.0	99.0	91.3	0.0	93.5	24.76	8.7

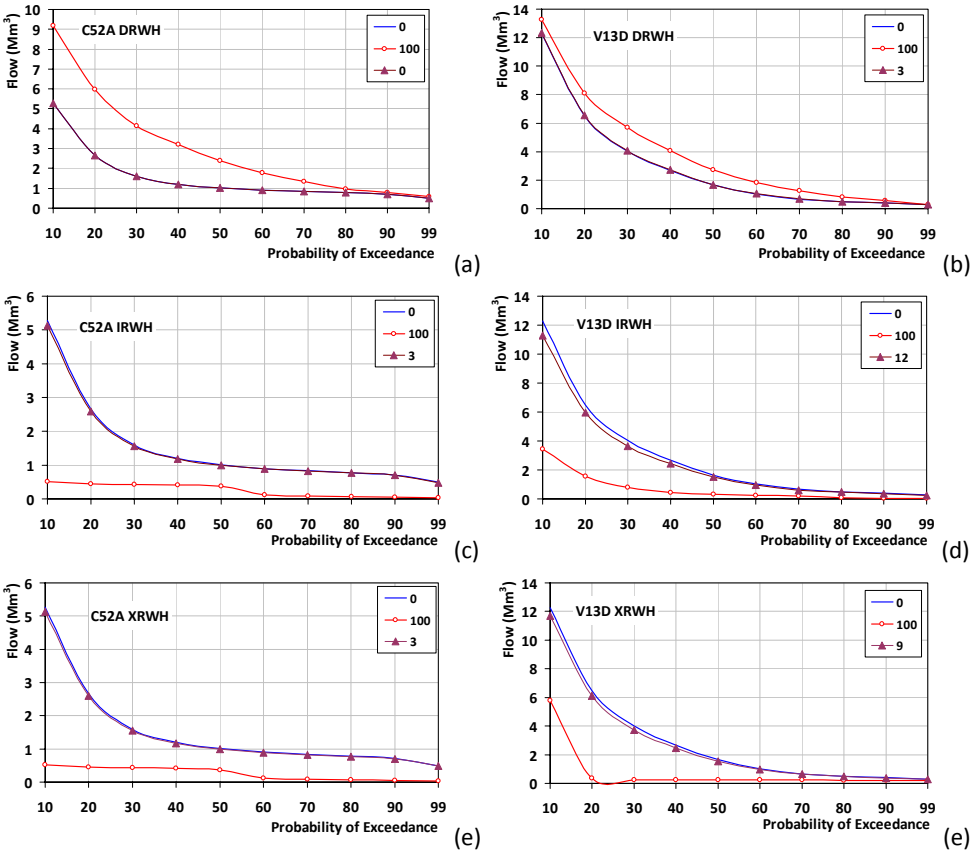


Figure 6.6 Ecohydrological impact for the insignificant level of adoption scenario of: DRWH in (a) C52A and (b) V13D, IRWH in (c) C52A and (d) V13D and XRWH in: (e) C52A and (f) V13D.

The results suggest that if this scenario has to be implemented, the impact of RWH on the river flow will be barely felt in both QCs (Figure 6.6).

The implementation of settlements that precedes the implementation of DRWH in a QC increases surface runoff by increasing impervious areas. As seen in Figure 6.6 (a and b), although the subsequent implementation of DRWH reduces the runoff from the now developed areas, the runoff remains well above the natural runoff (0% DRWH).

6.4.2.2 Scenario 2: Intermediate levels of adoption

Under this scenario, the percentage areas for the three categories of RWH in C52A and V13D QCs are presented in the last column of Table 6.5. The levels of adoption of FRWH in V13D noticeably reduce high flows but barely impacts low flows (Figure 6.7). Such reductions in flows are unlikely to adversely affect the rivers' ecosystem.

Table 6.5 Percentage adoption of RWH in C52A and V13D under Intermediate level of adoption scenario.

Category	QC	Area (Km^2)	RWH suitability km^2					Total RWH Area (Km^2)	RWH Percentage Adoption
			Very High	High	Mod.	Low	Very Low		
			0.75	0.5	0.25	0	0		
DRWH	C52A	938	0.0	0.0	26.1	0.0	911.9	6.53	0.7
	V13D	283.8	0.0	36.1	11.2	0.0	236.6	20.83	7.3
IRWH	C52A	938	0.0	113.3	19.7	0.0	805.0	61.56	6.6
	V13D	283.8	0.0	134.0	56.3	0.0	93.5	81.07	28.6
XRWH	C52A	938	0.0	113.3	19.7	0.0	805.0	61.55	6.6
	V13D	283.8	0.0	99.0	91.3	0.0	93.5	72.33	25.4

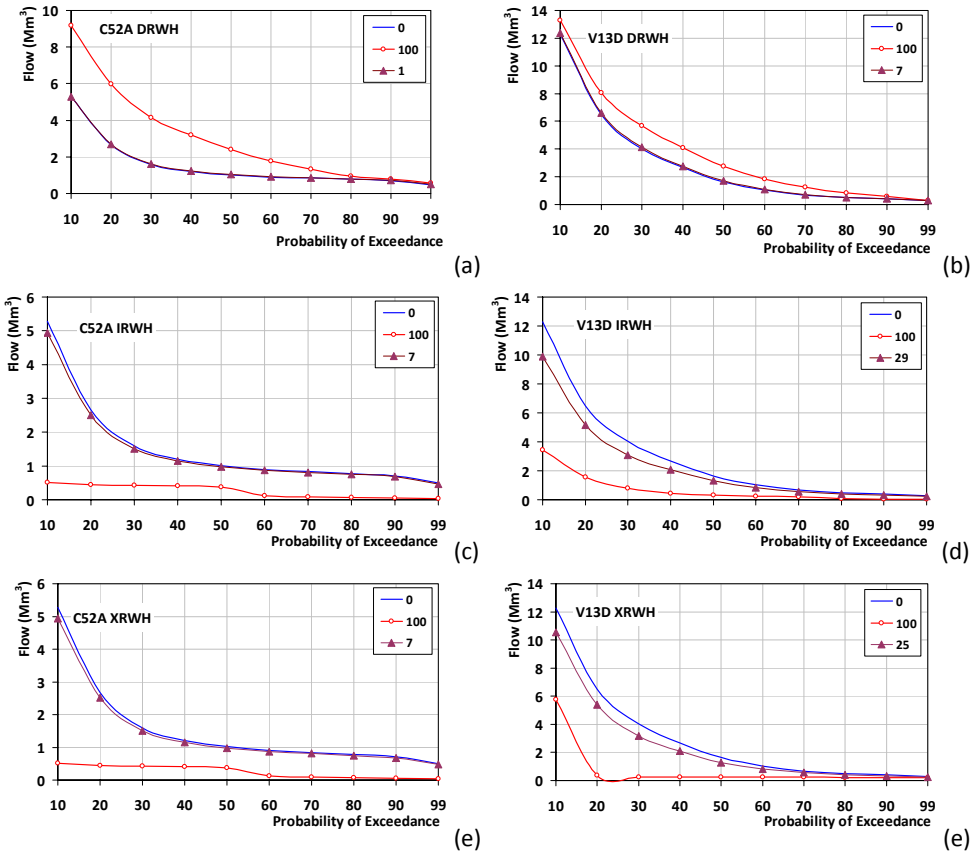


Figure 6.7 Ecohydrological impact for the medium level of adoption scenario of: DRWH in (a) C52A and (b) V13D, IRWH in (c) C52A and (d) V13D and XRWH in: (e) C52A and (f) V13D.

6.4.2.3 Scenario 3: Significant level of adoption

The significant level of adoption scenario puts a large portion of the V13D QC under FRWH (45% for IRWH and 42% for XRWH) while only about 10% of C52A is suitable (Table 6.6). The impact of this scenario on the flow is observed in Figure 6.8 which indicates much more considerable reduction of the high flows by FRWH in V13D than in C52A.

Table 6.6 Percentage adoption of FRWH in C52A and V13D under the significant level of adoption scenario.

Category	QC	Area (Km^2)	RWH suitability km^2					Total RWH Area (Km^2)	RWH Percentage Adoption
			Very High	High	Mod.	Low	Very Low		
			1	0.75	0.5	0.25	0		
DRWH	C52A	938	0.0	0.0	26.1	0.0	911.9	13.05	1.4
	V13D	283.8	0.0	36.1	11.2	0.0	236.6	32.64	11.5
IRWH	C52A	938	0.0	113.3	19.7	0.0	805.0	94.81	10.1
	V13D	283.8	0.0	134.0	56.3	0.0	93.5	128.64	45.3
XRWH	C52A	938	0.0	113.3	19.7	0.0	805.0	94.79	10.1
	V13D	283.8	0.0	99.0	91.3	0.0	93.5	119.90	42.3

Thus if FRWH is implemented to its full potential in V13D, other water users such as commercial farmers will be adversely affected.

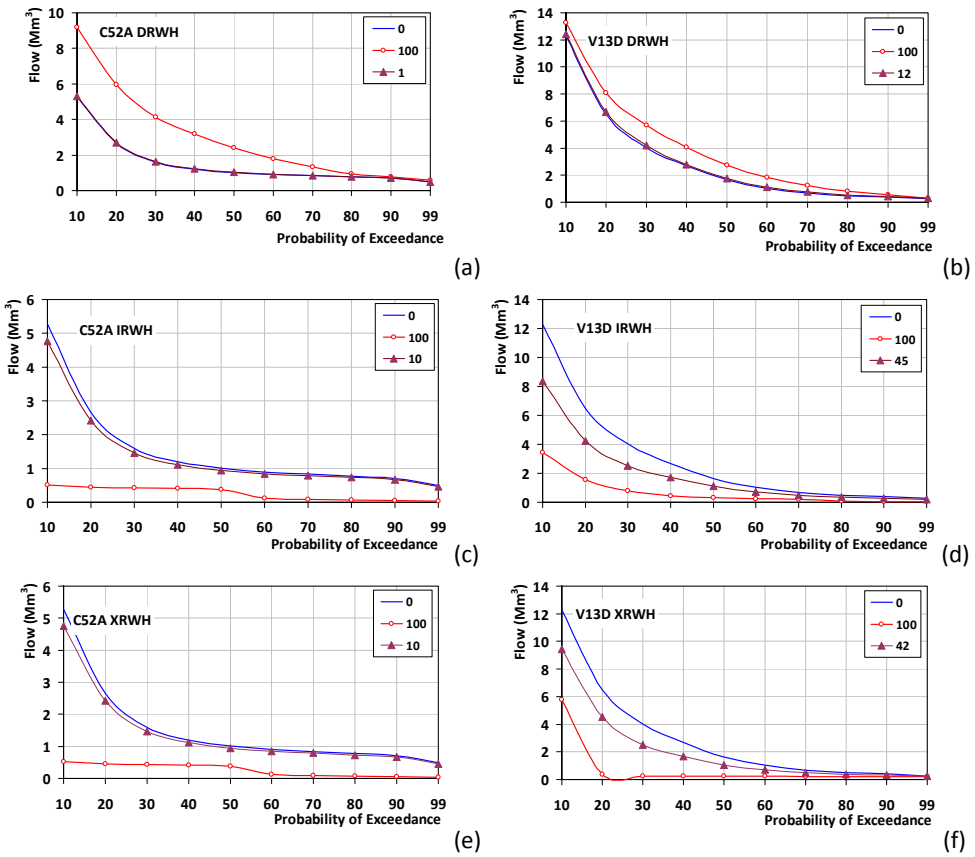


Figure 6.8 Ecohydrological impact for the significant levels of adoption scenario of: DRWH in (a) C52A and (b) V13D, IRWH in (c) C52A and (d) V13D and XRWH in: (e) C52A and (f) V13D.

6.4.2.4 Most probable level adoption

The most probable level of adoption of DRWH was determined by eliminating households which receive water in their dwellings and their yards. It is assumed, based on the current land tenure, that FRWH will receive greater support for implementation in the former homelands (Figure 6.9).

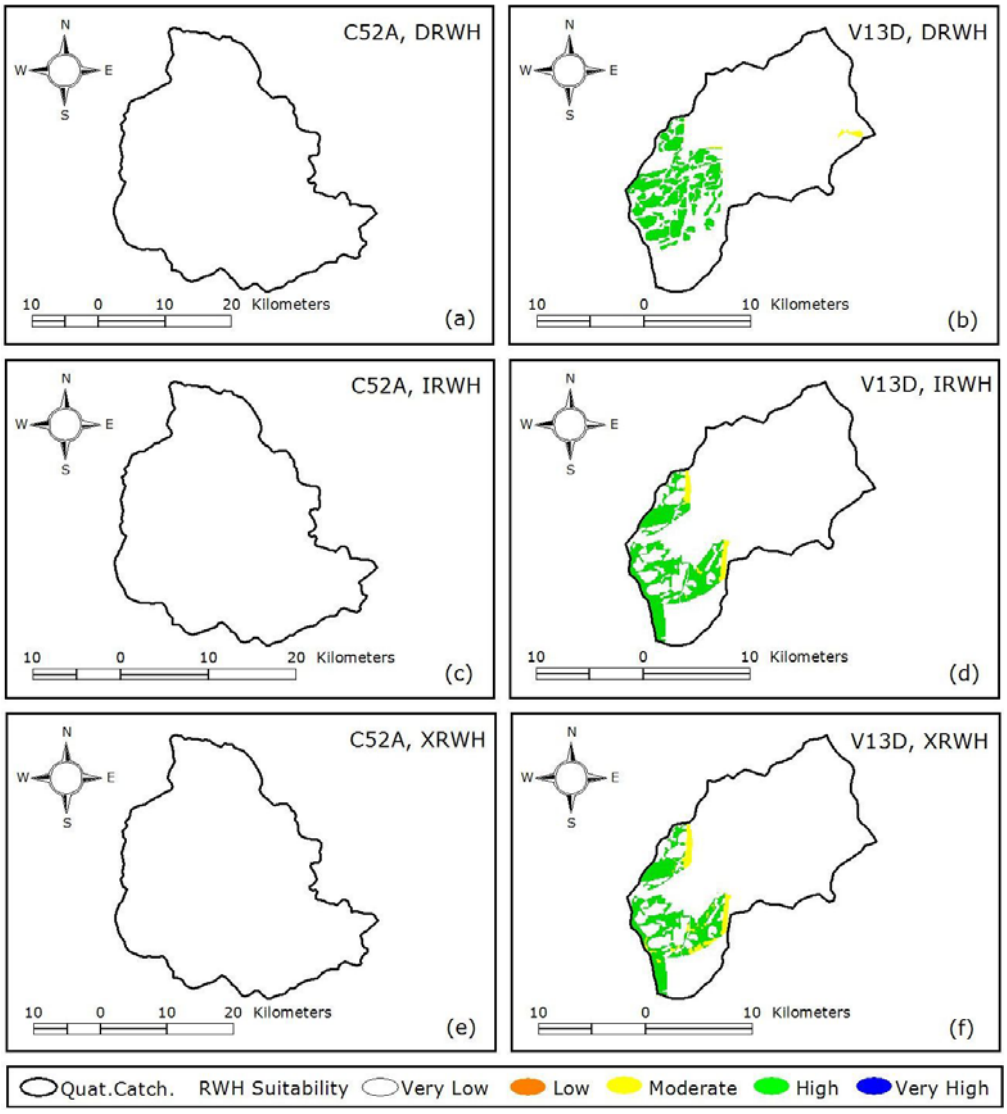


Figure 6.9. Map partitioning, (a) C52A and (b) V13D into five DRWH classes; (c) C52A and (d) V13D into five IRWH suitability classes as well as (e) C52A and (f) V13D into five XRWH suitability classes. The RWH areas are restricted to former homelands.

Table 6.7 Most probable percentage adoption of RWH in C52A and V13D.

Category	QC	Area (Km^2)	RWH suitability km^2					Total RWH Area (Km^2)	RWH Percentage Adoption
			Very High	High	Mod.	Low	Very Low		
			1	1	1	0	0		
DRWH	C52A	938	0.1	0.0	0.0	0.0	937.9	0.12	0.0
	V13D	283.8	12.6	0.0	0.0	0.0	271.2	12.55	4.4
IRWH	C52A	938	0.0	0.0	0.0	0.0	0.0	0.00	0.0
	V13D	283.8	0.0	33.1	3.8	0.0	246.9	34.99	12.3
XRWH	C52A	938	0.0	0.0	0.0	0.0	0.0	0.00	0.0
	V13D	283.8	0.0	30.1	6.8	0.0	246.9	33.47	11.8

FRWH is suitable on about 12 % of V13D (Table 6.7). Since there is no former homeland in C52A, it is assumed that no FRWH will be implemented. The implementation of RWH has no noticeable impact on the river flows of both QCs (Figure 6.10).

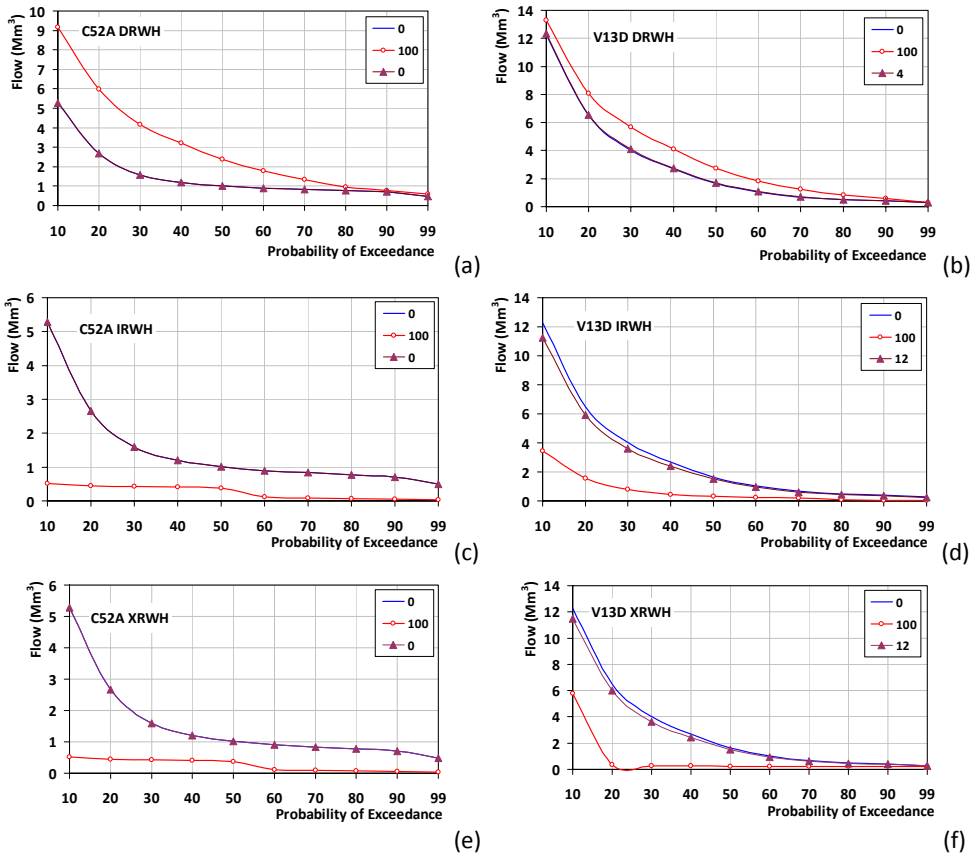


Figure 6.10 Impact on runoff for the most probable levels of adoption scenario of: DRWH in (a) C52A and (b) V13D, IRWH in (c) C52A and (d) V13D and XRWH in: (e) C52A and (f) V13D.

RHADESS is available in the DVD accompanying the thesis.

6.5 Summary

The chapter presented RHADESS, a GIS-based decision support system that:

- calculates the optimum size of an Agt in a QC and the water security it provides. It can also be used to assess the impact of climate change on the water security, thus enabling the incorporation of DRWH as a water source;
- provides the area required for a household to achieve food security, thus enabling national planning toward the alleviation of hunger;
- assesses the RWH footprint of any area in the country, and;
- quantifies the ecohydrological impact, as runoff reduction, of any selected RWH percentage of adoption.

RHADESS clearly indicates that the surface area of V13D on which FRWH has to be implemented needs to be restricted since substantial reductions in river flows were observed for the significant level of adoption scenario. Nevertheless, it is unlikely that FRWH will ever reach such high levels of adoption. In both QCs, the widespread adoption of DRWH has negligible effect on the river flows. Applications of RHADESS in semi-arid C52A and humid V13D indicate its ability to assist in the implementation of RWH in the overall water resources management of the QCs.

Chapter 7 CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

RHADESS is a GIS-based Decision support system which combines, through a MCE process, biophysical and socioeconomic thematic maps to produce suitability maps for all three major categories of RWH (DRWH, IRWH and XRWH). When choosing the weights one is ultimately selecting the best compromise among competing interests. Hence, results should be interpreted in terms of how the MCE process can guide policy formulation. RHADESS is a planning tool whose minimum spatial scale of application is a quaternary catchment. Thus the suitability maps produced do not have the required resolution to query details of known areas but provide at country scale valuable information for implementing a strategy that guides the sustainable wide scale adoption of RWH in South Africa.

Although rooftop rainwater harvesting is the most common RWH system in South Africa, the systems are often overdesigned since three key factors: roof area, daily rainfall as well as daily demand are not considered. Results from the Roof model in C52A and V13D clearly contradict the general belief that a large tank increases water security. To reach the full potential of DRWH it is necessary to combine roof systems with ground systems. DRWH is an alternative water source that has the potential to lessen the burden of the populace if it is considered within the framework of multiple water sources. Hence, to increase the water security of rural households, all potential water sources should be evaluated.

RWH can provide historically disadvantage groups with access to water, thereby ensuring food security at household level but its adoption remain well below the countries potential. While increased and stable crop yield are the main motivator for the adoption of FRWH, widespread poverty in rural areas, lack of financial resources and labour prevent its expansion beyond homestead scale. Thus apart from appropriate legislative framework and institutional mechanisms to support RWH, financial stimuli packages from government and NGOs are needed to assist farmers to implement RWH to about 2 ha of land (as prescribed by the IESM) in order to attain household food security.

The assessment of the ecohydrological impact of RWH practices indicates how the different RWH practices modify the river discharge from a catchment. The results suggest that the impacts differ depending of the type of RWH, the level of adoption and the topographic and the climatic conditions. The hydrological impacts have been quantified using SWAT by using existing model functionalities to reflect the possible alterations of the catchment characteristics that a RWH practice could bring about.

The assessment of the ecohydrological impacts of IRWH in C52A using SWAT also indicates that apart from the level of adoption, the spatial distribution of the practice also plays a crucial role in river flow alterations. Although this point to the fact that spatial process based models, such as SWAT, are more suited for assessing the ecohydrological impacts of RWH it should be borne in mind that the data requirements of these models are too intensive and not readily available. Thus, due to the lack of measured input data, process based models are often used as calibration models.

It is unlikely to find a situation where any particular type of RWH system covers an entire QC. Consequently, the most probable level of adoption of RWH in any given QCs can be obtained from RHADESS and its ecohydrological impact assessed by interpolation between the curves obtained using the hydrological model (SWAT or WRSM).

7.2 Contributions to knowledge

The contributions of this thesis to the existing knowledge base are:

- the incorporation of socioeconomic and ecological thematic maps in the assessment of RWH footprint is the first innovation brought by this study. Furthermore, the weighted overlay process enables the user to find the best compromise among competing interests. Thus it is possible to translate into the assessment of the RWH footprint the government's priorities.

- the assessment of the ecohydrological impact of RWH, as reduction in monthly flows, at QC scale using a process based model and comparing the results with those of a calibration models is the second innovation of this study. Earlier researchers have focused on the socioeconomic impact of RWH at household level or the hydrological impact at plant and plot level and overlooked the impact at QC level.

7.3 Limitations of the study

The study had the following limitations:

- There is no existing QC in South Africa where RWH is widely adopted. In adjoining catchments to C52A, namely C52B and C where the most concerted IRWH practices have been championed by the ARC since 2000, only 0.1 percent of the area of these catchments has come under this practice. It is no surprise that there has not been any noticeable change of flows at gauge stations in those catchments.

- the lack of national dataset of high resolution that will enable RHADESS to query RWH sites at scale lower than QC.

- the lack of good soil datasets that prevented the assessment of the ecohydrological impact of RWH, using SWAT, in other QCs.

7.4 Recommendations for further work

During the course of the study, a number of potential avenues for future research were identified. These include:

- The Roof model should be upgraded to have a daily water demand as input parameter to enable the assessment of the reliability of DRWH as a seasonal water supply system. Furthermore, the model should be upgraded to assess the reliability of DRWH-Ugts which currently receive financial support from government;

- The IEMS should be updated to model DRWH and XRWH, particularly that XRWH and DRWH-Ugt are efficient in bridging intra-seasonal dry spells;

- The assessment of the ecohydrological impact of IRWH using SWAT clearly indicates that both the level of adoption and spatial distribution of RWH are important factors. It is therefore recommended that DRWH and XRWH be also modelled using a process based model such as SWAT;

- The ecohydrological impacts of RWH modelled by SWAT and the WRSM need to be validated by field experiments.

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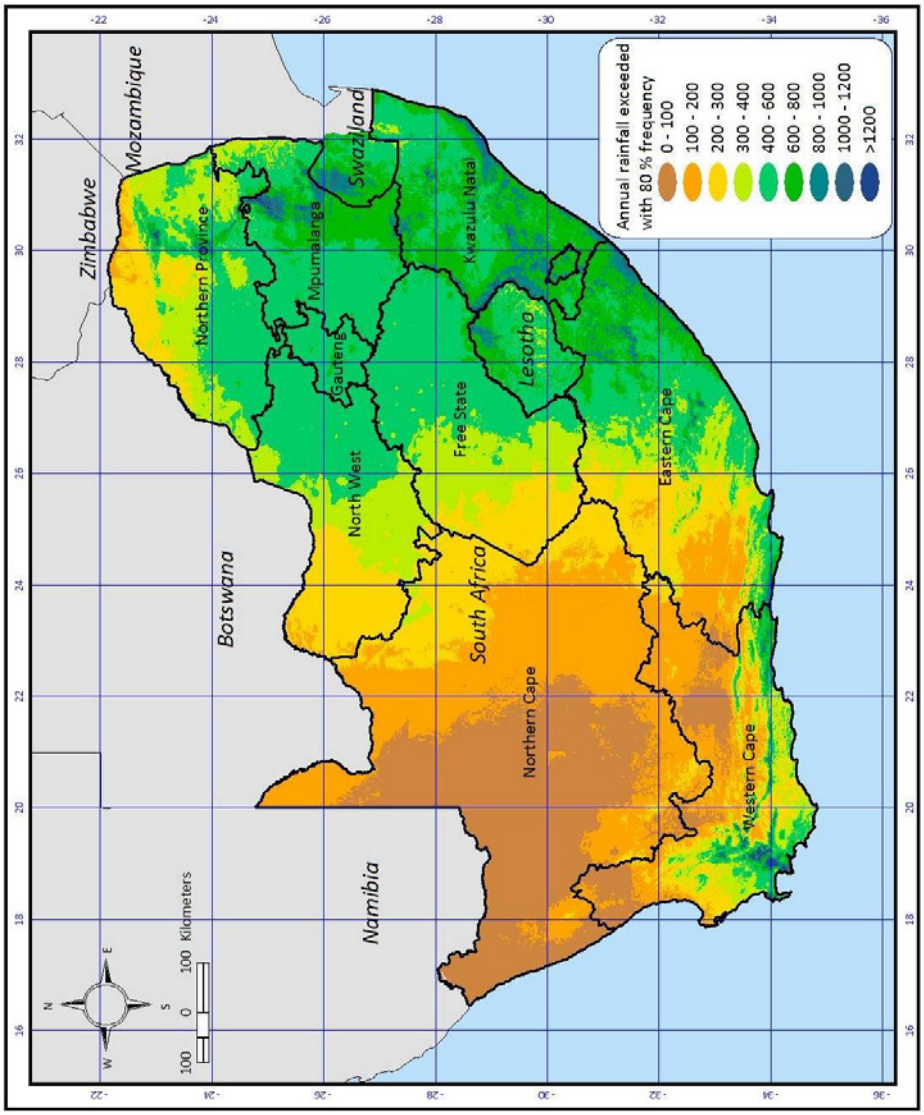
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APPENDICES

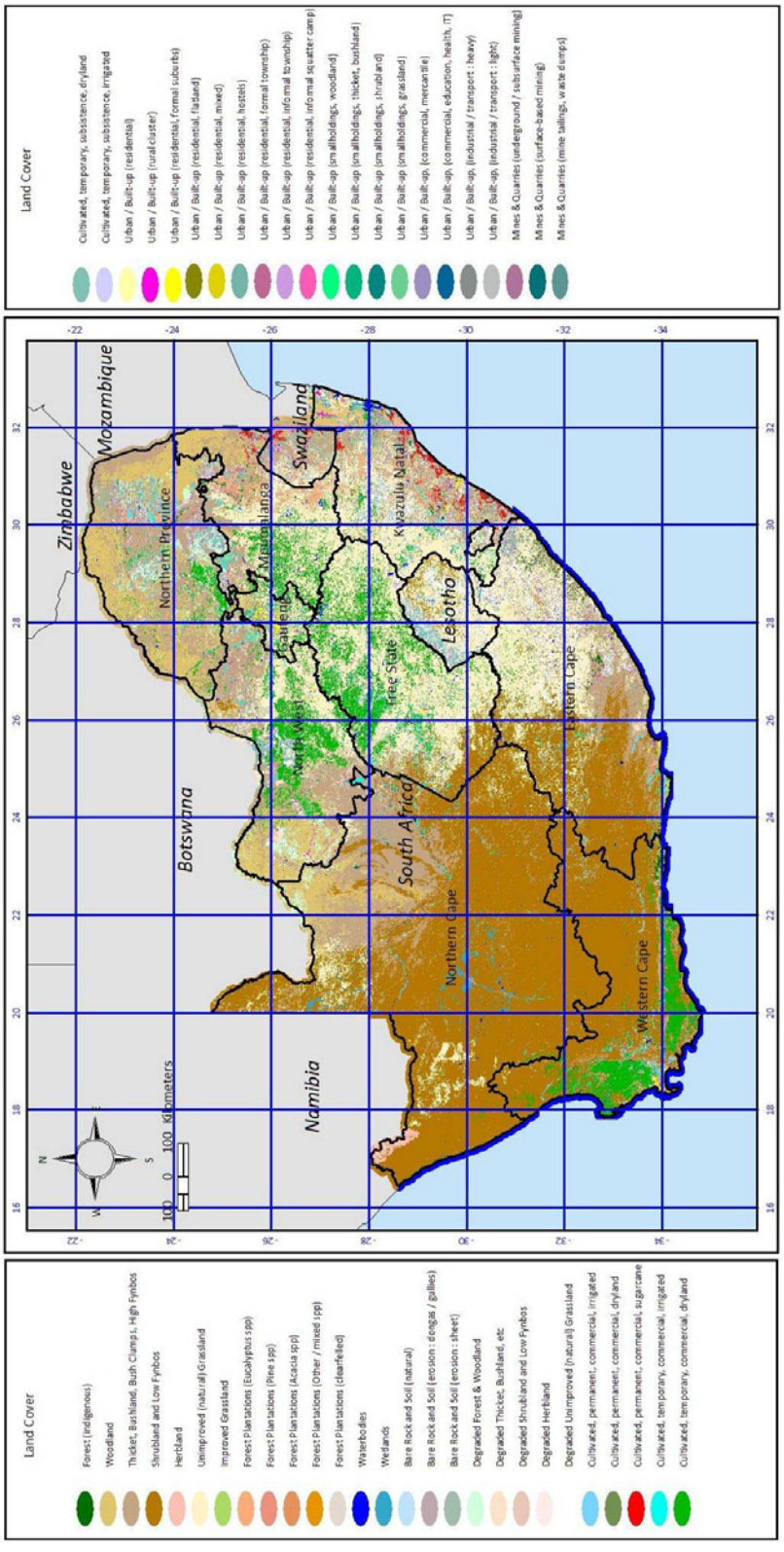
APPENDIX A: DATASETS USED

1. PHYSICAL ATTRIBUTES

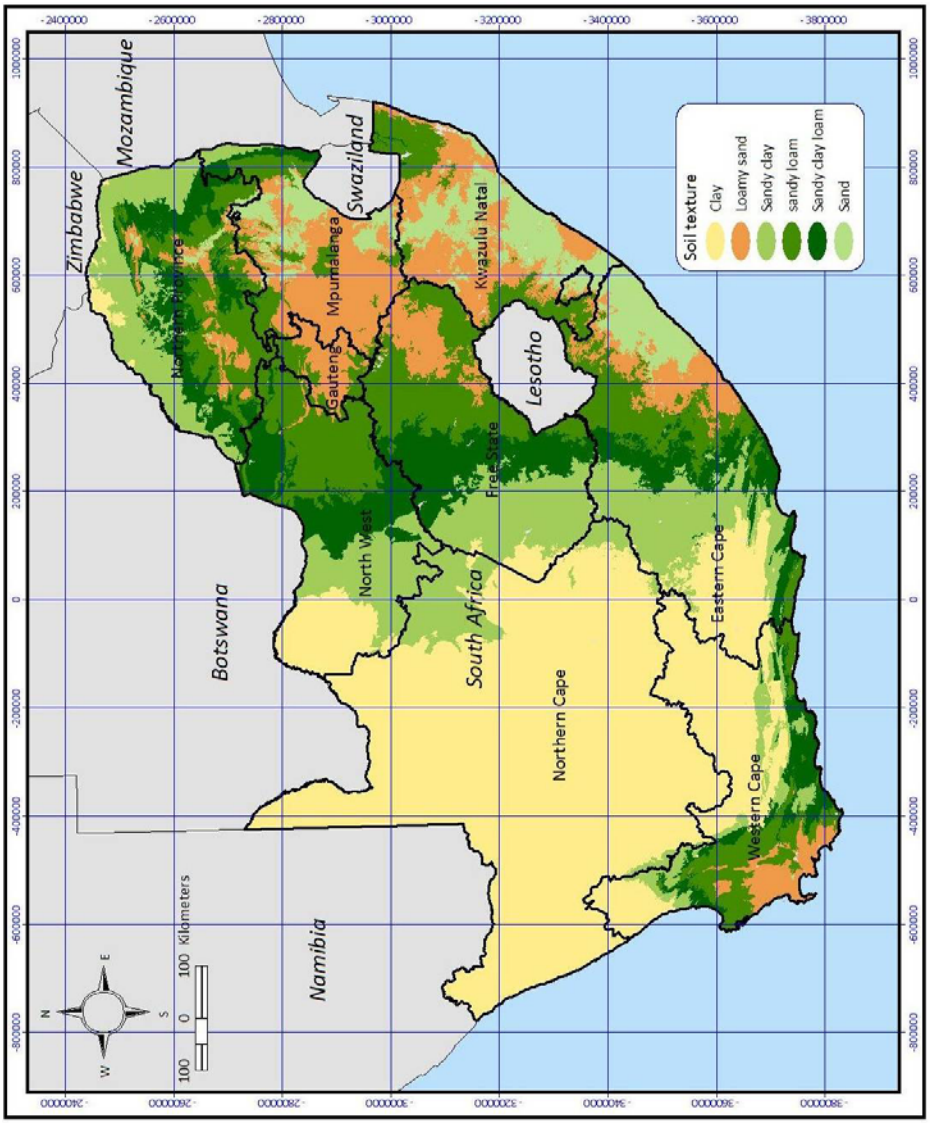
A. Annual rainfall exceeded with 80% frequency



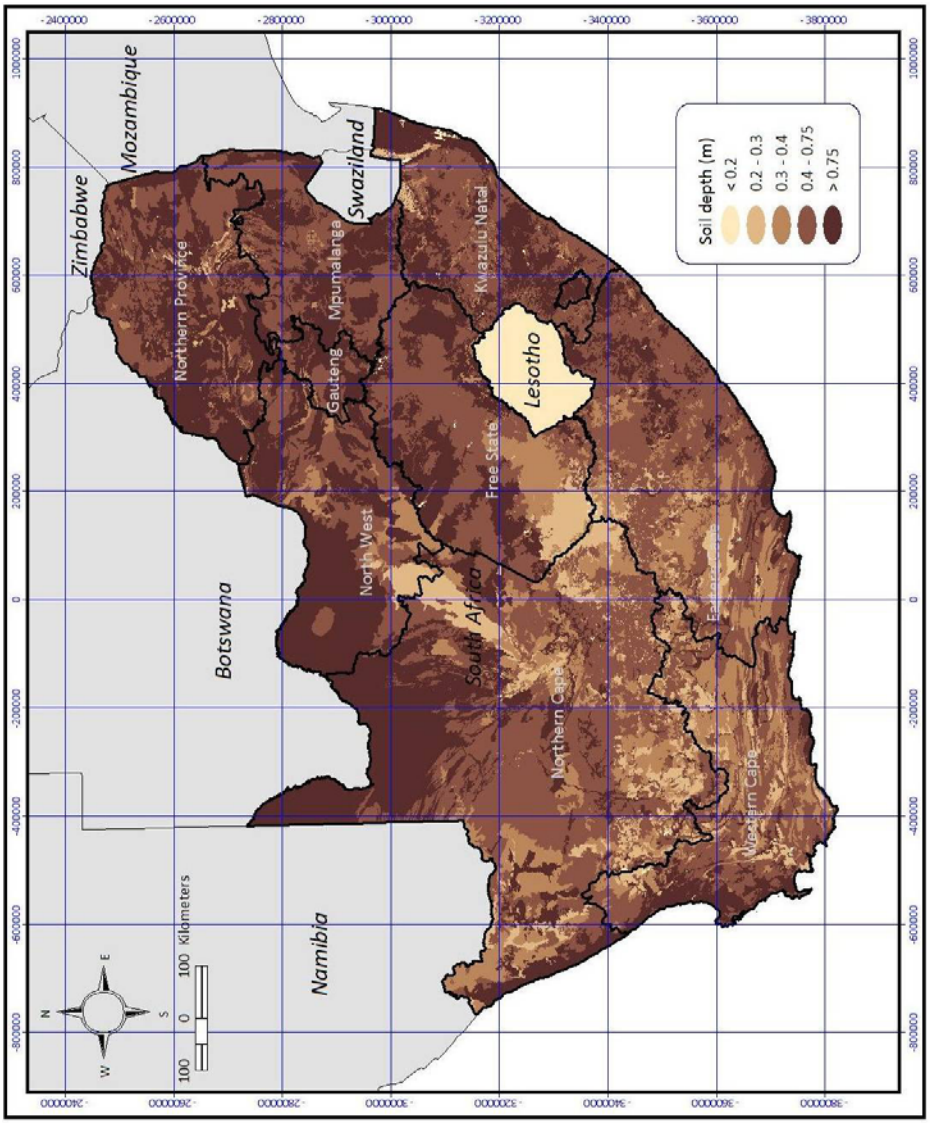
B. National land cover 2000



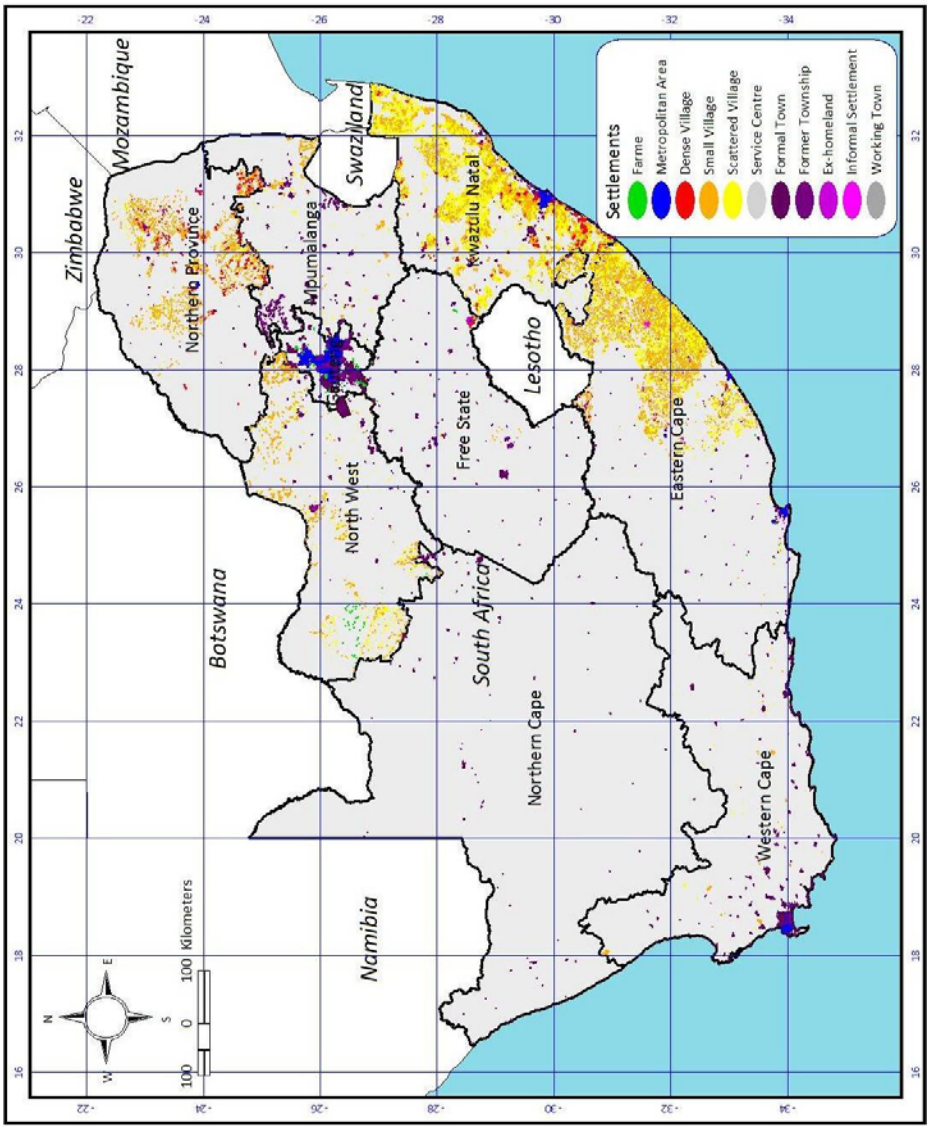
C. Soil texture



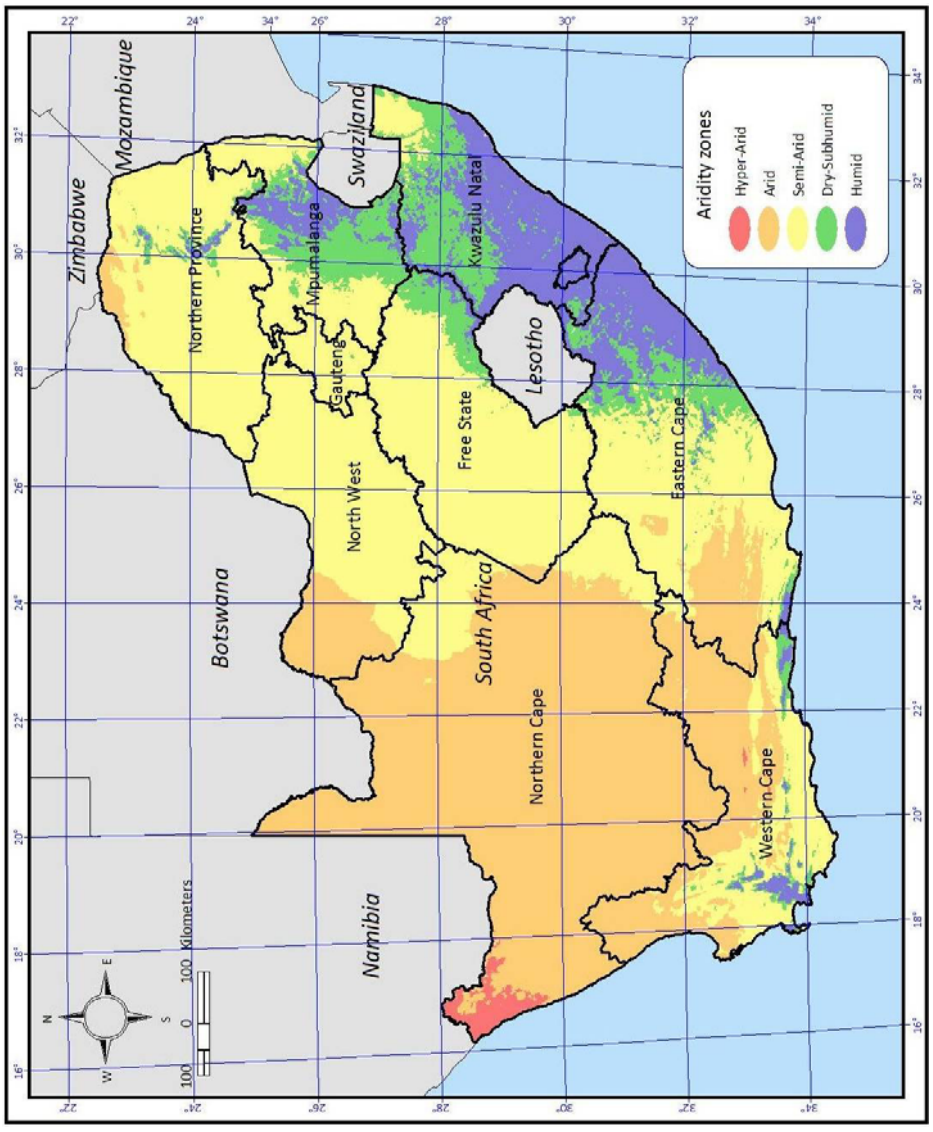
D. Soil depth


Soil depth (m)
< 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.75
> 0.75
Mozambique
Zimbabwe
Swaziland
Lesotho
Botswana
Namibia
South Africa
Northern Province
Mpumalanga
Gauteng
North West
Free State
KwaZulu Natal
Northern Cape
Western Cape
Kilometers
100
0
100

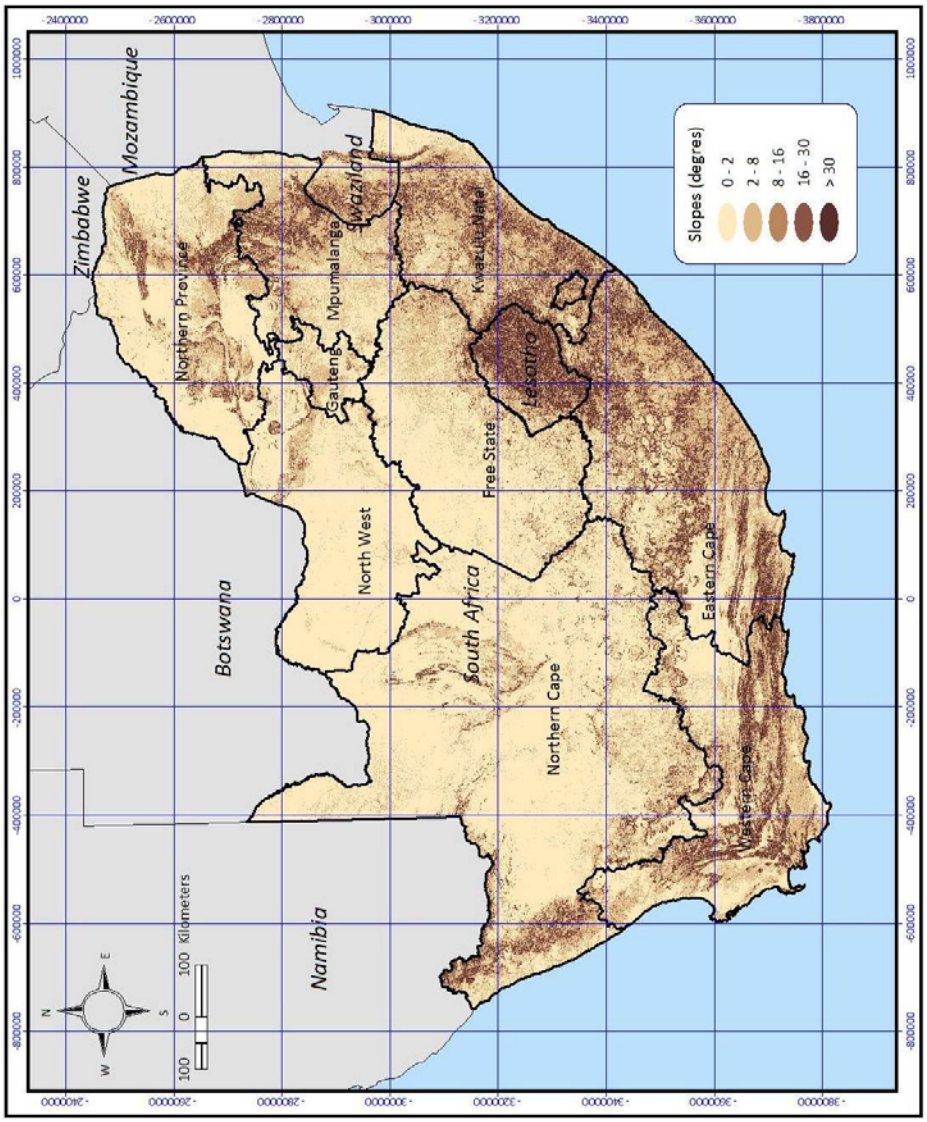
E. Settlements



F. Aridity zones

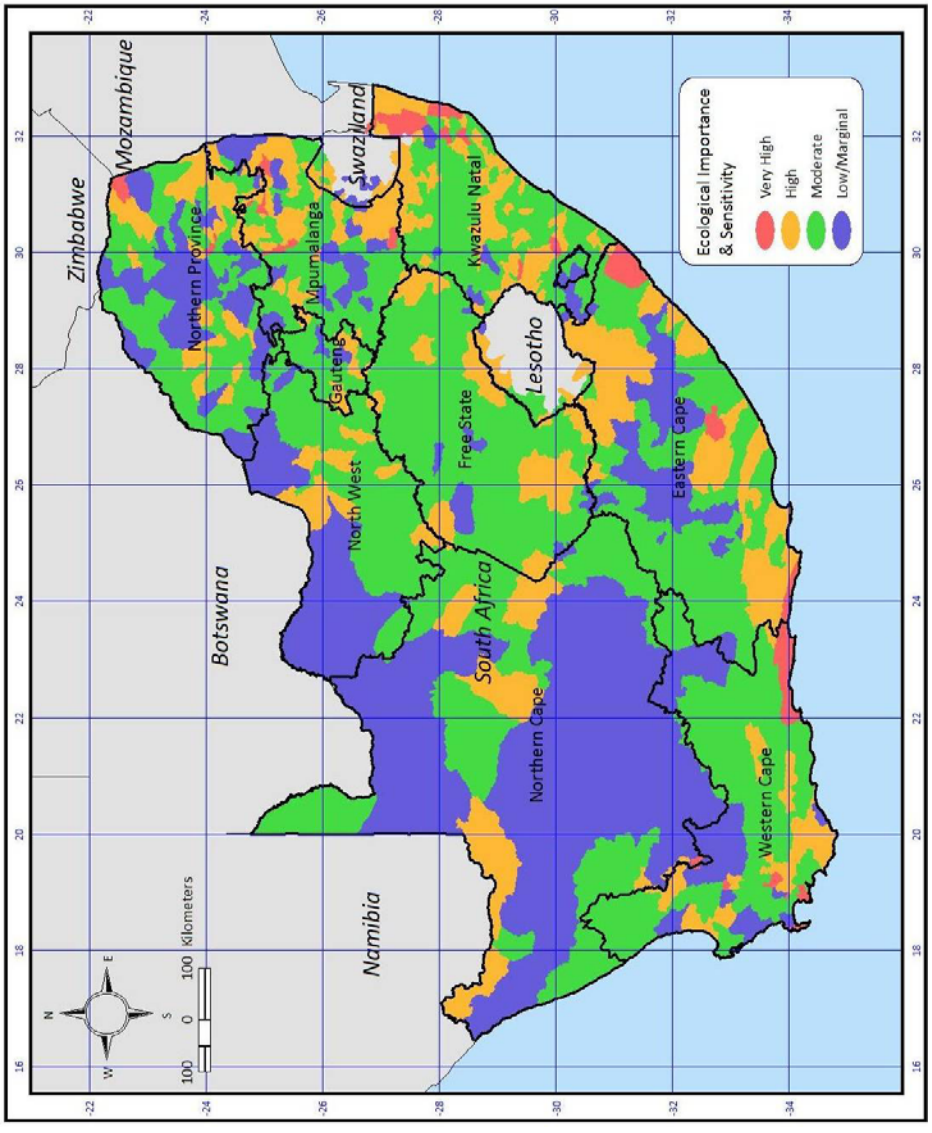


G. Slope


Slopes (degres)
0 - 2
2 - 8
8 - 16
16 - 30
> 30
Zimbabwe
Mozambique
Swaziland
Botswana
Namibia
South Africa
Lesotho
Northern Province
Mpumalanga
Gauteng
North West
Free State
Kwazulu-Natal
Eastern Cape
Northern Cape
Western Cape
100 0 100 Kilometers
N
S
E
W

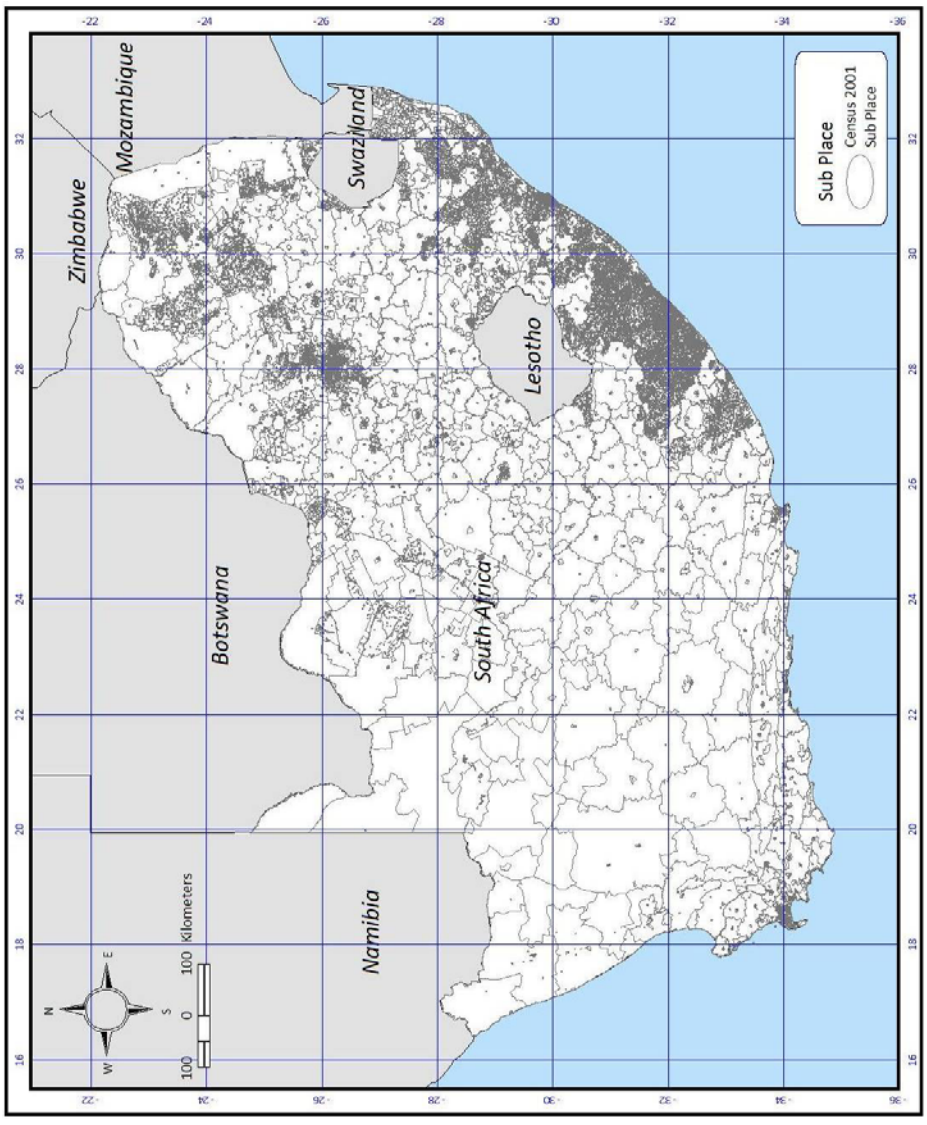
2. ECOLOGICAL ATTRIBUTES

A. Ecological importance and sensitivity category

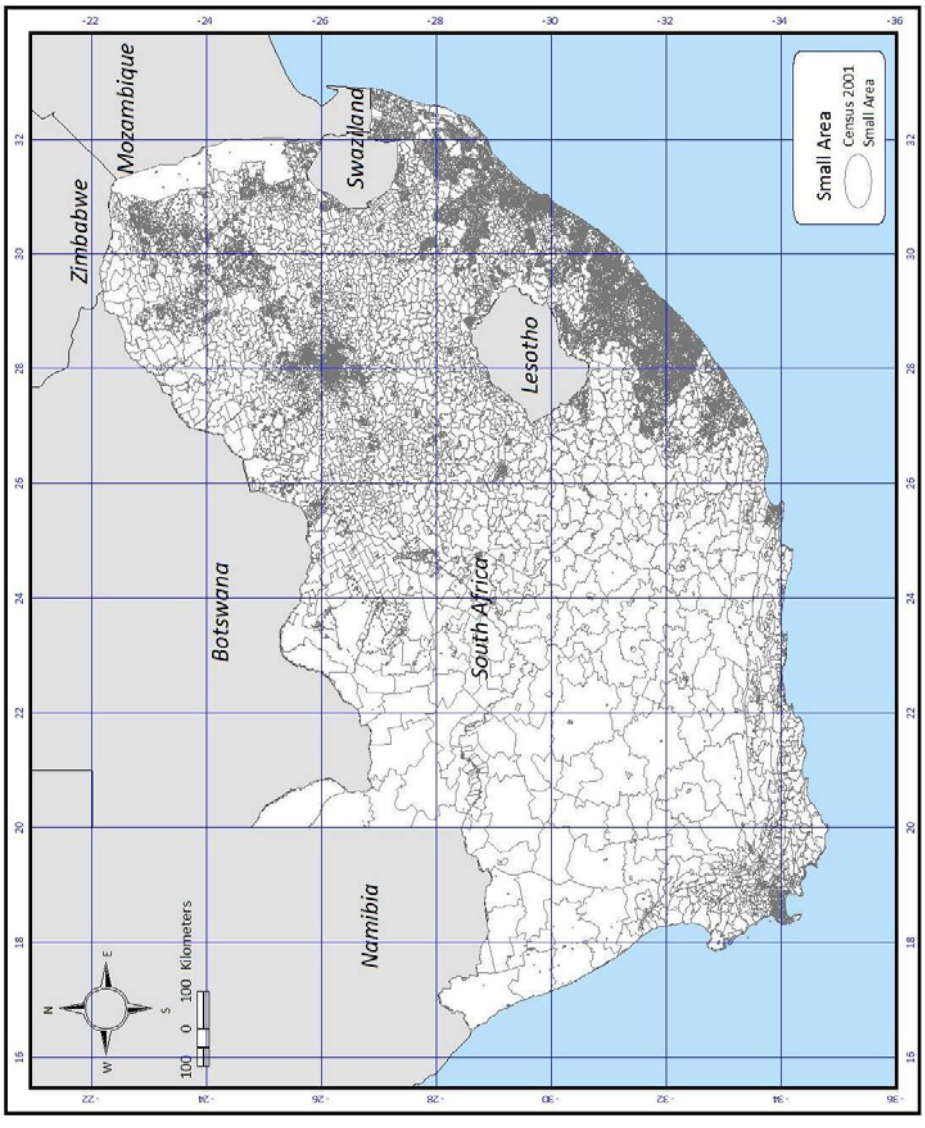


3. SOCIO-ECONOMIC ATTRIBUTES

A. Sub-places



B. Small Areas



APPENDIX B: SWAT REPORTS

1. DETAILED LANDUSE/SOIL DISTRIBUTION

A. C52A Virgin

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-----------------------------------------------------------------

SWAT  model simulation
Wed Sep 16 10:53:16 2009        MDL

MULTIPLE HRUs LandUse/Soil OPTION      THRESHOLDS : 0 / 0 [%]
Number of HRUs: 65
Number of Subbasins: 11

-----------------------------------------------------------------
                     Area [ha]          Area [acres]

Watershed
                   92619.0000         228866.1799

LANDUSE
Range-Brush (RNGB)      4443.7885      10980.8236      4.80
Range-Grasses (RNGE)   86135.8320     212845.9477     93.00
Water (WATR)             820.0065       2026.2771      0.89
Wetlands-Mixed (WETL)    921.4305       2276.9008      0.99
BareSoil (BASO)          297.9424        736.2307      0.32

SOIL
Db87                    5429.7628      13417.2154      5.86
Db88                    2444.0000       6039.2462      2.64
Dc17                   84745.2372     209409.7184     91.50
-----------------------------------------------------------------
-----------------------------------------------------------------


                     Area [ha]  Area [acres]  %Wat.Area  %Sub.Area

SUBBASIN # 1         3474.0000     8584.4277      3.75

LANDUSE:
Range-Brush (RNGB)     84.7317      209.3763       0.09       2.44
Range-Grasses (RNGE) 2647.1002     6541.1170       2.86      76.20
Water (WATR)          139.8584      345.5970       0.15       4.03
Wetlands-Mixed (WETL) 602.3097     1488.3375       0.65      17.34

SOIL:
Dc17                 3474.0000     8584.4277       3.75     100.00

HRUs:
1  RNGB/Dc17          84.7317        209.3763       0.09       2.44
2  RNGE/Dc17        2647.1002        6541.1170       2.86      76.20
3   WATR/Dc17        139.8584        345.5970       0.15       4.03
4  WETL/Dc17         602.3097       1488.3375       0.65      17.34
-----------------------------------------------------------------
-----------------------------------------------------------------
```

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 2	**6247.0000**	**15436.6494**	**6.74**	
LANDUSE:				
Range-Brush (RNGB)	189.3030	467.7773	0.20	3.03
Range-Grasses (RNGE)	6028.6505	14897.0968	6.51	96.50
Water (WATR)	14.0224	34.6502	0.02	0.22
Wetlands-Mixed (WETL)	5.0080	12.3751	0.01	0.08
BareSoil (BASO)	10.0160	24.7501	0.01	0.16
SOIL:				
Dc17	6247.0000	15436.6494	6.74	100.00
HRUs:				
5 RNGB/Dc17	189.3030	467.7773	0.20	3.03
6 RNGE/Dc17	6028.6505	14897.0968	6.51	96.50
7 WATR/Dc17	14.0224	34.6502	0.02	0.22
8 WETL/Dc17	5.0080	12.3751	0.01	0.08
9 BASO/Dc17	10.0160	24.7501	0.01	0.16

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 3	**16533.0000**	**40853.8697**	**17.85**	
LANDUSE:				
Range-Brush (RNGB)	257.2957	635.7905	0.28	1.56
Range-Grasses (RNGE)	16062.4592	39691.1399	17.34	97.15
Water (WATR)	69.0794	170.6986	0.07	0.42
Wetlands-Mixed (WETL)	98.1128	242.4415	0.11	0.59
BareSoil (BASO)	46.0529	113.7991	0.05	0.28
SOIL:				
Db87	663.7628	1640.1911	0.72	4.01
Dc17	15869.2372	39213.6786	17.13	95.99
HRUs:				
10 RNGB/Dc17	254.2922	628.3688	0.27	1.54
11 RNGB/Db87	3.0035	7.4217	0.00	0.02
12 RNGE/Dc17	15402.7010	38060.8444	16.63	93.16
13 RNGE/Db87	659.7582	1630.2955	0.71	3.99
14 WATR/Dc17	68.0782	168.2247	0.07	0.41
15 WATR/Db87	1.0012	2.4739	0.00	0.01
16 WETL/Dc17	98.1128	242.4415	0.11	0.59
17 BASO/Dc17	46.0529	113.7991	0.05	0.28

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 4	**525.0000**	**1297.3013**	**0.57**	
LANDUSE:				
Range-Brush (RNGB)	12.0000	29.6526	0.01	2.29
Range-Grasses (RNGE)	509.0000	1257.7645	0.55	96.95
Water (WATR)	4.0000	9.8842	0.00	0.76
SOIL:				
Dc17	525.0000	1297.3013	0.57	100.00
HRUs:				
18 RNGB/Dc17	12.0000	29.6526	0.01	2.29
19 RNGE/Dc17	509.0000	1257.7644	0.55	96.95
20 WATR/Dc17	4.0000	9.8842	0.00	0.76

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 5	**3638.0000**	**8989.6799**	**3.93**	
LANDUSE:				
Range-Brush (RNGB)	96.3177	238.0059	0.10	2.65
Range-Grasses (RNGE)	3527.6360	8716.9648	3.81	96.97
Water (WATR)	14.0463	34.7092	0.02	0.39
SOIL:				
Dc17	3638.0000	8989.6799	3.93	100.00
HRUs:				
21 RNGB/Dc17	96.3177	238.0059	0.10	2.65
22 RNGE/Dc17	3527.6360	8716.9648	3.81	96.97
23 WATR/Dc17	14.0463	34.7092	0.02	0.39

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 6	**13247.0000**	**32733.9993**	**14.30**	
LANDUSE:				
Range-Brush (RNGB)	1406.0000	3474.2963	1.52	10.61
Range-Grasses (RNGE)	11660.0000	28812.4430	12.59	88.02
Water (WATR)	145.0000	358.3023	0.16	1.09
Wetlands-Mixed (WETL)	36.0000	88.9578	0.04	0.27
SOIL:				
Db87	103.0000	254.5181	0.11	0.78
Db88	1415.0000	3496.5358	1.53	10.68
Dc17	11729.0000	28982.9454	12.66	88.54
HRUs:				
24 RNGB/Dc17	1233.0000	3046.8047	1.33	9.31
25 RNGB/Db87	17.0000	42.0079	0.02	0.13

26	RNGB/Db88	156.0000	385.4838	0.17	1.18
27	RNGE/Dc17	10319.0000	25498.7649	11.14	77.90
28	RNGE/Db87	86.0000	212.5103	0.09	0.65
29	RNGE/Db88	1255.0000	3101.1678	1.36	9.47
30	WATR/Dc17	141.0000	348.4180	0.15	1.06
31	WATR/Db88	4.0000	9.8842	0.00	0.03
32	WETL/Dc17	36.0000	88.9578	0.04	0.27

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 7	**14907.0000**	**36835.9423**	**16.09**	
LANDUSE:				
Range-Brush (RNGB)	306.0000	756.1413	0.33	2.05
Range-Grasses (RNGE)	14484.0000	35790.6882	15.64	97.16
Water (WATR)	96.0000	237.2208	0.10	0.64
Wetlands-Mixed (WETL)	17.0000	42.0078	0.02	0.11
BareSoil (BASO)	4.0000	9.8842	0.00	0.03
SOIL:				
Dc17	14907.0000	36835.9423	16.09	100.00
HRUs:				
33 RNGB/Dc17	306.0000	756.1413	0.33	2.05
34 RNGE/Dc17	14484.0000	35790.6882	15.64	97.16
35 WATR/Dc17	96.0000	237.2208	0.10	0.64
36 WETL/Dc17	17.0000	42.0078	0.02	0.11
37 BASO/Dc17	4.0000	9.8842	0.00	0.03

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 8	**11496.0000**	**28407.1908**	**12.41**	
LANDUSE:				
Range-Brush (RNGB)	640.0000	1581.4720	0.69	5.57
Range-Grasses (RNGE)	10592.0000	26173.3616	11.44	92.14
Water (WATR)	117.0000	289.1128	0.13	1.02
Wetlands-Mixed (WETL)	79.0000	195.2130	0.09	0.69
BareSoil (BASO)	68.0000	168.0314	0.07	0.59
SOIL:				
Db88	144.0000	355.8312	0.16	1.25
Dc17	11352.000	28051.3596	12.26	98.75
HRUs:				
38 RNGB/Dc17	640.0000	1581.4720	0.69	5.57
39 RNGE/Dc17	10448.0000	25817.5304	11.28	90.88
40 RNGE/Db88	144.0000	355.8312	0.16	1.25
41 WATR/Dc17	117.0000	289.1129	0.13	1.02
42 WETL/Dc17	79.0000	195.2130	0.09	0.69
43 BASO/Dc17	68.0000	168.0314	0.07	0.59

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 9	**586.0000**	**1448.0353**	**0.63**	
LANDUSE:				
Range-Brush (RNGB)	9.1404	22.5863	0.01	1.56
Range-Grasses (RNGE)	519.9861	1284.9117	0.56	88.73
BareSoil (BASO)	56.8735	140.5372	0.06	9.71
SOIL:				
Dc17	586.0000	1448.0353	0.63	100.00
HRUs:				
44 RNGB/Dc17	9.1404	22.5863	0.01	1.56
45 RNGE/Dc17	519.9861	1284.9117	0.56	88.73
46 BASO/Dc17	56.8735	140.5372	0.06	9.71

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 10	**4237.0000**	**10469.8389**	**4.57**	
LANDUSE:				
Range-Brush (RNGB)	188.0000	464.5574	0.20	4.44
Range-Grasses (RNGE)	3947.0000	9753.2344	4.26	93.16
Water (WATR)	63.0000	155.6762	0.07	1.49
Wetlands-Mixed (WETL)	32.0000	79.0736	0.03	0.76
BareSoil (BASO)	7.0000	17.2974	0.01	0.17
SOIL:				
Db87	2628.0000	6493.9194	2.84	62.03
Dc17	1609.0000	3975.9195	1.74	37.97
HRUs:				
47 RNGB/Dc17	83.0000	205.0972	0.09	1.96
48 RNGB/Db87	105.0000	259.4602	0.11	2.48
49 RNGE/Dc17	1513.0000	3738.6987	1.63	35.71
50 RNGE/Db87	2434.0000	6014.5357	2.63	57.45
51 WATR/Dc17	6.0000	14.8263	0.01	0.14
52 WATR/Db87	57.0000	140.8499	0.06	1.35
53 WETL/Db87	32.0000	79.0736	0.03	0.76
54 BASO/Dc17	7.0000	17.2974	0.01	0.17

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 11	**17729.0000**	**43809.2455**	**19.14**	
LANDUSE:				
Range-Brush (RNGB)	1255.0000	3101.1678	1.36	7.08
Range-Grasses (RNGE)	16158.0000	39927.2259	17.45	91.14
Water (WATR)	158.0000	390.4259	0.17	0.89

Wetlands-Mixed (WETL)	52.0000	128.4946	0.06	0.29
BareSoil (BASO)	106.0000	261.9313	0.11	0.60
SOIL:				
Db87	2035.0000	5028.5867	2.20	11.48
Db88	885.0000	2186.8793	0.96	4.99
Dc17	14809.0000	36593.7794	15.99	83.53
HRUs:				
55 RNGB/Dc17	889.0000	2196.7635	0.96	5.01
56 RNGB/Db87	111.0000	274.2865	0.12	0.63
57 RNGB/Db88	255.0000	630.1178	0.28	1.44
58 RNGE/Dc17	13638.0000	33700.1799	14.72	76.92
59 RNGE/Db87	1890.0000	4670.2845	2.04	10.66
60 RNGE/Db88	630.0000	1556.7615	0.68	3.55
61 WATR/Dc17	143.0000	353.3602	0.15	0.81
62 WATR/Db87	15.0000	37.0658	0.02	0.08
63 WETL/Dc17	33.0000	81.5447	0.04	0.19
64 WETL/Db87	19.0000	46.9499	0.02	0.11
65 BASO/Dc17	106.0000	261.9313	0.11	0.60

B. C52A Further Upstream

SWAT model simulation
Wed Sep 16 15:28:29 2009 MDL

MULTIPLE HRUs LandUse/Soil OPTION THRESHOLDS : 0 / 0 [%]
Number of HRUs: 61
Number of Subbasins: 11

	Area [ha]	Area [acres]
Watershed	92619.0000	228866.1799

	Area [ha]	Area [acres]	%Wat.Area
LANDUSE			
Range-Brush (RNGB)	1020.7573	2522.3424	1.10
Range-Grasses (RNGE)	44278.3658	109414.0559	47.81
Water (WATR)	381.0065	941.4862	0.41
Wetlands-Mixed (WETL)	744.4305	1839.5250	0.80
BareSoil (BASO)	142.9424	353.2179	0.15
Maize (MAZE)	46051.4974	113795.5527	49.72
SOIL			
DB87	5429.7628	13417.2154	5.86
Db88	2444.0000	6039.2462	2.64
Dc17	84745.2372	209409.7184	91.50

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 1	**3474.0000**	**8584.4277**	**3.75**	
LANDUSE:				
Range-Brush (RNGB)	84.7317	209.3763	0.09	2.44
Range-Grasses (RNGE)	2647.1002	6541.1170	2.86	76.20
Water (WATR)	139.8584	345.5970	0.15	4.03
Wetlands-Mixed (WETL)	602.3097	1488.3375	0.65	17.34
SOIL:				
Dc17	3474.0000	8584.4277	3.75	100.00
HRUs:				
1 RNGB/Dc17	84.7317	209.3763	0.09	2.44
2 RNGE/Dc17	2647.1002	6541.1170	2.86	76.20
3 WATR/Dc17	139.8584	345.5970	0.15	4.03
4 WETL/Dc17	602.3097	1488.3375	0.65	17.34

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 2	**6247.0000**	**15436.6494**	**6.74**	
LANDUSE:				
Range-Brush (RNGB)	189.3030	467.7773	0.20	3.03
Range-Grasses (RNGE)	6028.6505	14897.0968	6.51	96.50
Water (WATR)	14.0224	34.6502	0.02	0.22
Wetlands-Mixed (WETL)	5.0080	12.3751	0.01	0.08
BareSoil (BASO)	10.0160	24.7501	0.01	0.16
SOIL:				
Dc17	6247.0000	15436.6494	6.74	100.00
HRUs:				
5 RNGB/Dc17	189.3030	467.7773	0.20	3.03
6 RNGE/Dc17	6028.6505	14897.0968	6.51	96.50
7 WATR/Dc17	14.0224	34.6502	0.02	0.22
8 WETL/Dc17	5.0080	12.3751	0.01	0.08
9 BASO/Dc17	10.0160	24.7501	0.01	0.16

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 3	**16533.0000**	**40853.8697**	**17.85**	
LANDUSE:				
Range-Brush (RNGB)	257.2957	635.7905	0.28	1.56
Range-Grasses (RNGE)	16062.4592	39691.1399	17.34	97.15
Water (WATR)	69.0794	170.6986	0.07	0.42
Wetlands-Mixed (WETL)	98.1128	242.4415	0.11	0.59

BareSoil (BASO)	46.0529	113.7991	0.05	0.28
SOIL:				
DB87	663.7628	1640.1911	0.72	4.01
Dc17	15869.2372	39213.6786	17.13	95.99
HRUs:				
10 RNGB/Dc17	254.2922	628.3688	0.27	1.54
11 RNGB/Db87	3.0035	7.4217	0.00	0.02
12 RNGE/Dc17	15402.7010	38060.8444	16.63	93.16
13 RNGE/Db87	659.7582	1630.2955	0.71	3.99
14 WATR/Dc17	68.0782	168.2247	0.07	0.41
15 WATR/Db87	1.0012	2.4739	0.00	0.01
16 WETL/Dc17	98.1128	242.4415	0.11	0.59
17 BASO/Dc17	46.0529	113.7991	0.05	0.28

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 4	**525.0000**	**1297.3013**	**0.57**	
LANDUSE:				
Range-Brush (RNGB)	12.0000	29.6526	0.01	2.29
Range-Grasses (RNGE)	509.0000	1257.7645	0.55	96.95
Water (WATR)	4.0000	9.8842	0.00	0.76
SOIL:				
Dc17	525.0000	1297.3013	0.57	100.00
HRUs:				
18 RNGB/Dc17	12.0000	29.6526	0.01	2.29
19 RNGE/Dc17	509.0000	1257.7644	0.55	96.95
20 WATR/Dc17	4.0000	9.8842	0.00	0.76

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 5	**3638.0000**	**8989.6799**	**3.93**	
LANDUSE:				
Range-Brush (RNGB)	96.3177	238.0059	0.10	2.65
Range-Grasses (RNGE)	3527.6360	8716.9648	3.81	96.97
Water (WATR)	14.0463	34.7092	0.02	0.39
SOIL:				
Dc17	3638.0000	8989.6799	3.93	100.00
HRUs:				
21 RNGB/Dc17	96.3177	238.0059	0.10	2.65
22 RNGE/Dc17	3527.6360	8716.9648	3.81	96.97
23 WATR/Dc17	14.0463	34.7092	0.02	0.39

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 6	**13247.0000**	**32733.9993**	14.30	
LANDUSE:				
Range-Brush (RNGB)	145.0000	358.3023	0.16	1.09
Range-Grasses (RNGE)	4435.0000	10959.1067	4.79	33.48
Water (WATR)	56.0000	138.3788	0.06	0.42
Wetlands-Mixed (WETL)	18.0000	44.4789	0.02	0.14
Maize (MAZE)	8593.0000	21233.7326	9.28	64.87
SOIL:				
DB87	103.0000	254.5182	0.11	0.78
Db88	1415.0000	3496.5358	1.53	10.68
Dc17	11729.0000	28982.9455	12.66	88.54
HRUs:				
24 RNGB/Dc17	145.0000	358.3023	0.16	1.09
25 RNGE/Dc17	4435.0000	10959.1067	4.79	33.48
26 WATR/Dc17	56.0000	138.3788	0.06	0.42
27 WETL/Dc17	18.0000	44.4789	0.02	0.14
28 MAZE/Dc17	7075.0000	17482.6787	7.64	53.41
29 MAZE/Db87	103.0000	254.5181	0.11	0.78
30 MAZE/Db88	1415.0000	3496.5358	1.53	10.68

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 7	**14907.0000**	**36835.9423**	16.09	
LANDUSE:				
Range-Brush (RNGB)	125.0000	308.8813	0.13	0.84
Range-Grasses (RNGE)	8710.0000	21522.8455	9.40	58.43
Water (WATR)	54.0000	133.4367	0.06	0.36
Wetlands-Mixed (WETL)	14.0000	34.5947	0.02	0.09
Maize (MAZE)	6004.0000	14836.1842	6.48	40.28
SOIL:				
Dc17	14907.0000	36835.9424	16.09	100.00
HRUs:				
31 RNGB/Dc17	125.0000	308.8813	0.13	0.84
32 RNGE/Dc17	8710.0000	21522.8455	9.40	58.43
33 WATR/Dc17	54.0000	133.4367	0.06	0.36
34 WETL/Dc17	14.0000	34.5947	0.02	0.09
35 MAZE/Dc17	6004.0000	14836.1842	6.48	40.28

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 8	**11496.0000**	**28407.1908**	**12.41**	
LANDUSE:				
Range-Brush (RNGB)	97.0000	239.6919	0.10	0.84

Range-Grasses (RNGE)	881.0000	2176.9951	0.95	7.66
Water (WATR)	20.0000	49.4210	0.02	0.17
Wetlands-Mixed (WETL)	2.0000	4.9421	0.00	0.02
BareSoil (BASO)	12.0000	29.6526	0.01	0.10
Maize (MAZE)	10484.0000	25906.4882	11.32	91.20
SOIL:				
Db88	144.0000	355.8312	0.16	1.25
Dc17	11352.0000	28051.3596	12.26	98.75
HRUs:				
36 RNGB/Dc17	97.0000	239.6918	0.10	0.84
37 RNGE/Dc17	881.0000	2176.9951	0.95	7.66
38 WATR/Dc17	20.0000	49.4210	0.02	0.17
39 WETL/Dc17	2.0000	4.9421	0.00	0.02
40 BASO/Dc17	12.0000	29.6526	0.01	0.10
41 MAZE/Dc17	10340.0000	25550.6570	11.16	89.94
42 MAZE/Db88	144.0000	355.8312	0.16	1.25

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 9	**586.0000**	**1448.0353**	**0.63**	
LANDUSE:				
Range-Brush (RNGB)	7.1092	17.5672	0.01	1.21
Range-Grasses (RNGE)	424.5199	1049.0100	0.46	72.44
BareSoil (BASO)	56.8735	140.5372	0.06	9.71
Maize (MAZE)	97.4974	240.9210	0.11	16.64
SOIL:				
Dc17	586.0000	1448.0353	0.63	100.00
HRUs:				
43 RNGB/Dc17	7.1092	17.5672	0.01	1.21
44 RNGE/Dc17	424.5199	1049.0100	0.46	72.44
45 BASO/Dc17	56.8735	140.5372	0.06	9.71
46 MAZE/Dc17	97.4974	240.9210	0.11	16.64

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 10	**4237.0000**	**10469.8389**	**4.57**	
LANDUSE:				
Range-Brush (RNGB)	7.0000	17.2974	0.01	0.17
Range-Grasses (RNGE)	1038.0000	2564.9499	1.12	24.50
Water (WATR)	10.0000	24.7105	0.01	0.24
Wetlands-Mixed (WETL)	5.0000	12.3553	0.01	0.12
BareSoil (BASO)	6.0000	14.8263	0.01	0.14
Maize (MAZE)	3171.0000	7835.6996	3.42	74.84
SOIL:				
DB87	2628.0000	6493.9194	2.84	62.03
Dc17	1609.0000	3975.9195	1.74	37.97

HRUs:

47	RNGB/Dc17	3.0000	7.4131	0.00	0.07
48	RNGB/Db87	4.0000	9.8842	0.00	0.09
49	RNGE/Dc17	585.0000	1445.5643	0.63	13.81
50	RNGE/Db87	453.0000	1119.3856	0.49	10.69
51	WATR/Dc17	6.0000	14.8263	0.01	0.14
52	WATR/Db87	4.0000	9.8842	0.00	0.09
53	WETL/Db87	5.0000	12.3552	0.01	0.12
54	BASO/Dc17	6.0000	14.8263	0.01	0.14
55	MAZE/Dc17	1009.0000	2493.2895	1.09	23.81
56	MAZE/Db87	2162.0000	5342.4101	2.33	51.03

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 11	**17729.0000**	**43809.2455**	**19.14**	
LANDUSE:				
Range-Grasses (RNGE)	15.0000	37.0658	0.02	0.08
BareSoil (BASO)	12.0000	29.6526	0.01	0.07
Maize (MAZE)	17702.0000	43742.5271	19.11	99.85
SOIL:				
DB87	2035.0000	5028.5868	2.20	11.48
Db88	885.0000	2186.8793	0.96	4.99
Dc17	14809.0000	36593.7795	15.99	83.53
HRUs:				
57 RNGE/Dc17	15.0000	37.0658	0.02	0.08
58 BASO/Dc17	12.0000	29.6526	0.01	0.07
59 MAZE/Dc17	14782.0000	36527.0611	15.96	83.38
60 MAZE/Db87	2035.0000	5028.5868	2.20	11.48
61 MAZE/Db88	885.0000	2186.8793	0.96	4.99

C. C52A near upstream

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SWAT  model simulation
Wed Sep 16 15:15:01 2009        MDL

MULTIPLE HRUs LandUse/Soil OPTION      THRESHOLDS : 0 / 0 [%]
Number of HRUs: 52
Number of Subbasins: 11
```

	Area [ha]	Area [acres]
Watershed	92619.0000	228866.1799

	Area [ha]	Area [acres]	%Wat.Area
LANDUSE			
Range-Brush (RNGB)	3421.0000	8453.4621	3.69
Range-Grasses (RNGE)	41859.4974	103436.9111	45.20
Water (WATR)	439.0000	1084.7910	0.47
Wetlands-Mixed (WETL)	167.0000	412.6653	0.18
BareSoil (BASO)	155.0000	383.0127	0.17
Maize (MAZE)	46577.5026	115095.3378	50.29
SOIL			
DB87	5429.7628	13417.2154	5.86
Db88	2444.0000	6039.2462	2.64
Dc17	84745.2372	209409.7184	91.50

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 1	**3474.0000**	**8584.4277**	**3.75**	
LANDUSE:				
Maize (MAZE)	3474.0000	8584.4277	3.75	100.00
SOIL:				
Dc17	3474.0000	8584.4277	3.75	100.00
HRUs:				
1 MAZE/Dc17	3474.0000	8584.4277	3.75	100.00

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 2	**6247.0000**	**15436.6494**	**6.74**	
LANDUSE:				
Maize (MAZE)	6247.0000	15436.6494	6.74	100.00
SOIL:				
Dc17	6247.0000	15436.6494	6.74	100.00
HRUs:				
2 MAZE/Dc17	6247.0000	15436.6494	6.74	100.00

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 3	**16533.0000**	**40853.8697**	**17.85**	
LANDUSE:				

Maize (MAZE)	16533.0000	40853.8697	17.85	100.00
SOIL:				
DB87	663.7628	1640.1911	0.72	4.01
Dc17	15869.2372	39213.6786	17.13	95.99
HRUs:				
3 MAZE/Dc17	15869.2372	39213.6786	17.13	95.99
4 MAZE/Db87	663.7628	1640.1911	0.72	4.01

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 4	**525.0000**	**1297.3013**	**0.57**	
LANDUSE:				
Maize (MAZE)	525.0000	1297.3013	0.57	100.00
SOIL:				
Dc17	525.0000	1297.3013	0.57	100.00
HRUs:				
5 MAZE/Dc17	525.0000	1297.3013	0.57	100.00

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 5	**3638.0000**	**8989.6799**	**3.93**	
LANDUSE:				
Maize (MAZE)	3638.0000	8989.6799	3.93	100.00
SOIL:				
Dc17	3638.0000	8989.6799	3.93	100.00
HRUs:				
6 MAZE/Dc17	3638.0000	8989.6799	3.93	100.00

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 6	**13247.0000**	**32733.9993**	**14.30**	
LANDUSE:				
Range-Brush (RNGB)	1261.0000	3115.9940	1.36	9.52
Range-Grasses (RNGE)	7225.0000	17853.3363	7.80	54.54
Water (WATR)	89.0000	219.9235	0.10	0.67
Wetlands-Mixed (WETL)	18.0000	44.4789	0.02	0.14
Maize (MAZE)	4654.0000	11500.2667	5.02	35.13
SOIL:				

DB87	103.0000	254.5181	0.11	0.78
Db88	1415.0000	3496.5358	1.53	10.68
Dc17	11729.0000	28982.9454	12.66	88.54
HRUs:				
7 RNGB/Dc17	1088.0000	2688.5024	1.17	8.21
8 RNGB/Db87	17.0000	42.0078	0.02	0.13
9 RNGB/Db88	156.0000	385.4838	0.17	1.18
10 RNGE/Dc17	5884.0000	14539.6582	6.35	44.42
11 RNGE/Db87	86.0000	212.5103	0.09	0.65
12 RNGE/Db88	1255.0000	3101.1678	1.36	9.47
13 WATR/Dc17	85.0000	210.0393	0.09	0.64
14 WATR/Db88	4.0000	9.8842	0.00	0.03
15 WETL/Dc17	18.0000	44.4789	0.02	0.14
16 MAZE/Dc17	4654.0000	11500.2667	5.02	35.13

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 7	**14907.0000**	**36835.9423**	**16.09**	
LANDUSE:				
Range-Brush (RNGB)	181.0000	447.2600	0.20	1.21
Range-Grasses (RNGE)	5774.0000	14267.8427	6.23	38.73
Water (WATR)	42.0000	103.7841	0.05	0.28
Wetlands-Mixed (WETL)	3.0000	7.4131	0.00	0.02
BareSoil (BASO)	4.0000	9.8842	0.00	0.03
Maize (MAZE)	8903.0000	21999.7582	9.61	59.72
SOIL:				
Dc17	14907.0000	36835.9423	16.09	100.00
HRUs:				
17 RNGB/Dc17	181.0000	447.2600	0.20	1.21
18 RNGE/Dc17	5774.0000	14267.8427	6.23	38.73
19 WATR/Dc17	42.0000	103.7841	0.05	0.28
20 WETL/Dc17	3.0000	7.4131	0.00	0.02
21 BASO/Dc17	4.0000	9.8842	0.00	0.03
22 MAZE/Dc17	8903.0000	21999.7582	9.61	59.72

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 8	**11496.0000**	**28407.1908**	**12.41**	
LANDUSE:				
Range-Brush (RNGB)	543.0000	1341.7802	0.59	4.72
Range-Grasses (RNGE)	9711.0000	23996.3665	10.48	84.47
Water (WATR)	97.0000	239.6919	0.10	0.84
Wetlands-Mixed (WETL)	67.0000	165.5604	0.07	0.58
BareSoil (BASO)	56.0000	138.3788	0.06	0.49
Maize (MAZE)	1022.0000	2525.4131	1.10	8.89
SOIL:				
Db88	144.0000	355.8312	0.16	1.25

Dc17	11352.0000	28051.3596	12.26	98.75
HRUs:				
23 RNGB/Dc17	543.0000	1341.7802	0.59	4.72
24 RNGE/Dc17	9567.0000	23640.5354	10.33	83.22
25 RNGE/Db88	144.0000	355.8312	0.16	1.25
26 WATR/Dc17	97.0000	239.6918	0.10	0.84
27 WETL/Dc17	67.0000	165.5604	0.07	0.58
28 BASO/Dc17	56.0000	138.3788	0.06	0.49
29 MAZE/Dc17	1022.0000	2525.4131	1.10	8.89

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 9	**586.0000**	**1448.0353**	**0.63**	
LANDUSE:				
Range-Grasses (RNGE)	97.4974	240.9210	0.11	16.64
Maize (MAZE)	488.5026	1207.1143	0.53	83.36
SOIL				
Dc17	586.0000	1448.0353	0.63	100.00
HRUs:				
30 RNGE/Dc17	97.4974	240.9210	0.11	16.64
31 MAZE/Dc17	488.5026	1207.1143	0.53	83.36

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 10	**4237.0000**	**10469.8389**	**4.57**	
LANDUSE:				
Range-Brush (RNGB)	181.0000	447.2600	0.20	4.27
Range-Grasses (RNGE)	2909.0000	7188.2845	3.14	68.66
Water (WATR)	53.0000	130.9657	0.06	1.25
Wetlands-Mixed (WETL)	27.0000	66.7184	0.03	0.64
BareSoil (BASO)	1.0000	2.4710	0.00	0.02
Maize (MAZE)	1066.0000	2634.1393	1.15	25.16
SOIL:				
DB87	2628.0000	6493.9194	2.84	62.03
Dc17	1609.0000	3975.9195	1.74	37.97
HRUs:				
32 RNGB/Dc17	80.0000	197.6840	0.09	1.89
33 RNGB/Db87	101.0000	249.5761	0.11	2.38
34 RNGE/Dc17	928.0000	2293.1344	1.00	21.90
35 RNGE/Db87	1981.0000	4895.1501	2.14	46.75
36 WATR/Db87	53.0000	130.9656	0.06	1.25
37 WETL/Db87	27.0000	66.7184	0.03	0.64
38 BASO/Dc17	1.0000	2.4710	0.00	0.02
39 MAZE/Dc17	600.0000	1482.6300	0.65	14.16
40 MAZE/Db87	466.0000	1151.5093	0.50	11.00

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 11	**17729.0000**	**43809.2455**	**19.14**	
LANDUSE:				
Range-Brush (RNGB)	1255.0000	3101.1678	1.36	7.08
Range-Grasses (RNGE)	16143.0000	39890.1601	17.43	91.05
Water (WATR)	158.0000	390.4259	0.17	0.89
Wetlands-Mixed (WETL)	52.0000	128.4946	0.06	0.29
BareSoil (BASO)	94.0000	232.2787	0.10	0.53
Maize (MAZE)	27.0000	66.7184	0.03	0.15
SOIL:				
DB87	2035.0000	5028.5867	2.20	11.48
Db88	885.0000	2186.8793	0.96	4.99
Dc17	14809.0000	36593.7794	15.99	83.53
HRUs:				
41 RNGB/Dc17	889.0000	2196.7635	0.96	5.01
42 RNGB/Db87	111.0000	274.2865	0.12	0.63
43 RNGB/Db88	255.0000	630.1178	0.28	1.44
44 RNGE/Dc17	13623.0000	33663.1142	14.71	76.84
45 RNGE/Db87	1890.0000	4670.2845	2.04	10.66
46 RNGE/Db88	630.0000	1556.7615	0.68	3.55
47 WATR/Dc17	143.0000	353.3602	0.15	0.81
48 WATR/Db87	15.0000	37.0658	0.02	0.08
49 WETL/Dc17	33.0000	81.5447	0.04	0.19
50 WETL/Db87	19.0000	46.9499	0.02	0.11
51 BASO/Dc17	94.0000	232.2787	0.10	0.53
52 MAZE/Dc17	27.0000	66.7184	0.03	0.15

D. C52A RHADESS

SWAT model simulation
Wed Sep 16 13:26:54 2009 MDL

MULTIPLE HRUs LandUse/Soil OPTION THRESHOLDS : 0 / 0 [%]
Number of HRUs: 74
Number of Subbasins: 11

	Area [ha]	Area [acres]
Watershed	92619.0000	228866.1799

	Area [ha]	Area [acres]	%Wat.Area
LANDUSE			
Range-Brush (RNGB)	3309.7728	8178.6141	3.57
Range-Grasses (RNGE)	74508.5122	184114.2592	80.45
Water (WATR)	752.0099	1858.2540	0.81
Wetlands-Mixed (WETL)	907.4275	2242.2988	0.98
BareSoil (BASO)	294.9541	728.8462	0.32
Maize (MAZE)	12846.3235	31743.9077	13.87
SOIL			
Db87	5427.9922	13412.8401	5.86
Db88	2444.0998	6039.4929	2.64
Dc17	84746.9080	209413.8470	91.50

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 1	**3474.0000**	**8584.4277**	**3.75**	
LANDUSE:				
Range-Brush (RNGB)	81.6691	201.8085	0.09	2.35
Range-Grasses (RNGE)	1899.8278	4694.5695	2.05	54.69
Water (WATR)	139.8584	345.5970	0.15	4.03
Wetlands-Mixed (WETL)	602.3097	1488.3375	0.65	17.34
Maize (MAZE)	750.3350	1854.1153	0.81	21.60
SOIL:				
Dc17	3474.0000	8584.4277	3.75	100.00
HRUs:				
1 RNGB/Dc17	81.6691	201.8085	0.09	2.35
2 RNGE/Dc17	1899.8278	4694.5695	2.05	54.69
3 WATR/Dc17	139.8584	345.5970	0.15	4.03
4 WETL/Dc17	602.3097	1488.3375	0.65	17.34
5 MAZE/Dc17	750.3350	1854.1153	0.81	21.60

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 2	**6247.0000**	**15436.6494**	**6.74**	
LANDUSE:				
Range-Brush (RNGB)	189.3030	467.7773	0.20	3.03
Range-Grasses (RNGE)	6028.6505	14897.0968	6.51	96.50
Water (WATR)	14.0224	34.6502	0.02	0.22
Wetlands-Mixed (WETL)	5.0080	12.3751	0.01	0.08
BareSoil (BASO)	10.0160	24.7501	0.01	0.16
SOIL:				
Dc17	6247.0000	15436.6494	6.74	100.00
HRUs:				
6 RNGB/Dc17	189.3030	467.7773	0.20	3.03

7 RNGE/Dc17	6028.6505	14897.0968	6.51	96.50
8 WATR/Dc17	14.0224	34.6502	0.02	0.22
9 WETL/Dc17	5.0080	12.3751	0.01	0.08
10 BASO/Dc17	10.0160	24.7501	0.01	0.16

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 3	**16533.0000**	**40853.8697**	**17.85**	
LANDUSE:				
Range-Brush (RNGB)	240.2761	593.7343	0.26	1.45
Range-Grasses (RNGE)	13400.4000	33113.0583	14.47	81.05
Water (WATR)	62.0713	153.3814	0.07	0.38
Wetlands-Mixed (WETL)	91.1047	225.1243	0.10	0.55
BareSoil (BASO)	46.0529	113.7991	0.05	0.28
Maize (MAZE)	2693.0949	6654.7723	2.91	16.29
SOIL:				
Db87	663.7628	1640.1911	0.72	4.01
Dc17	15869.2372	39213.6786	17.13	95.99
HRUs:				
11 RNGB/Dc17	237.2727	586.3127	0.26	1.44
12 RNGB/Db87	3.0035	7.4217	0.00	0.02
13 RNGE/Dc17	12740.6418	31482.7628	13.76	77.06
14 RNGE/Db87	659.7582	1630.2955	0.71	3.99
15 WATR/Dc17	61.0702	150.9075	0.07	0.37
16 WATR/Db87	1.0012	2.4739	0.00	0.01
17 WETL/Dc17	91.1047	225.1243	0.10	0.55
18 BASO/Dc17	46.0529	113.7991	0.05	0.28
19 MAZE/Dc17	2693.0949	6654.7723	2.91	16.29

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 4	**525.0000**	**1297.3013**	**0.57**	
LANDUSE:				
Range-Brush (RNGB)	12.0000	29.6526	0.01	2.29
Range-Grasses (RNGE)	509.0000	1257.7645	0.55	96.95
Water (WATR)	4.0000	9.8842	0.00	0.76
SOIL:				
Dc17	525.0000	1297.3013	0.57	100.00
HRUs:				
20 RNGB/Dc17	12.0000	29.6526	0.01	2.29
21 RNGE/Dc17	509.0000	1257.7644	0.55	96.95
22 WATR/Dc17	4.0000	9.8842	0.00	0.76

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 5	**3638.0000**	**8989.6799**	**3.93**	
LANDUSE:				
Range-Brush (RNGB)	96.3177	238.0059	0.10	2.65
Range-Grasses (RNGE)	3527.6360	8716.9648	3.81	96.97
Water (WATR)	14.0463	34.7092	0.02	0.39
SOIL:				
Dc17	3638.0000	8989.6799	3.93	100.00
HRUs:				
23 RNGB/Dc17	96.3177	238.0059	0.10	2.65
24 RNGE/Dc17	3527.6360	8716.9648	3.81	96.97
25 WATR/Dc17	14.0463	34.7092	0.02	0.39

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 6	**13247.0000**	**32733.9993**	**14.30**	
LANDUSE:				
Range-Brush (RNGB)	962.0000	2377.1501	1.04	7.26
Range-Grasses (RNGE)	10786.0000	26652.7453	11.65	81.42
Water (WATR)	141.0000	348.4180	0.15	1.06
Wetlands-Mixed (WETL)	36.0000	88.9578	0.04	0.27
Maize (MAZE)	1322.0000	3266.7281	1.43	9.98
SOIL:				
Db87	103.0000	254.5181	0.11	0.78
Db88	1415.0000	3496.5358	1.53	10.68
Dc17	11729.0000	28982.9454	12.66	88.54
HRUs:				
26 RNGB/Dc17	892.0000	2204.1766	0.96	6.73
27 RNGB/Db88	70.0000	172.9735	0.08	0.53
28 RNGE/Dc17	9693.0000	23951.8876	10.47	73.17
29 RNGE/Db87	8.0000	19.7684	0.01	0.06
30 RNGE/Db88	1085.0000	2681.0892	1.17	8.19
31 WATR/Dc17	137.0000	338.5338	0.15	1.03
32 WATR/Db88	4.0000	9.8842	0.00	0.03
33 WETL/Dc17	36.0000	88.9578	0.04	0.27
34 MAZE/Dc17	971.0000	2399.3895	1.05	7.33
35 MAZE/Db87	95.0000	234.7497	0.10	0.72
36 MAZE/Db88	256.0000	632.5888	0.28	1.93

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 7	**14907.0000**	**36835.9423**	**16.09**	
LANDUSE:				
Range-Brush (RNGB)	306.0000	756.1413	0.33	2.05

Range-Grasses (RNGE)	14484.0000	35790.6882	15.64	97.16
Water (WATR)	96.0000	237.2208	0.10	0.64
Wetlands-Mixed (WETL)	17.0000	42.0078	0.02	0.11
BareSoil (BASO)	4.0000	9.8842	0.00	0.03
SOIL:				
Dc17	14907.0000	36835.9423	16.09	100.00
HRUs:				
37 RNGB/Dc17	306.0000	756.1413	0.33	2.05
38 RNGE/Dc17	14484.0000	35790.6882	15.64	97.16
39 WATR/Dc17	96.0000	237.2208	0.10	0.64
40 WETL/Dc17	17.0000	42.0078	0.02	0.11
41 BASO/Dc17	4.0000	9.8842	0.00	0.03

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 8	**11496.0000**	**28407.1908**	**12.41**	
LANDUSE:				
Range-Brush (RNGB)	637.0000	1574.0588	0.69	5.54
Range-Grasses (RNGE)	10475.0000	25884.2487	11.31	91.12
Water (WATR)	117.0000	289.1128	0.13	1.02
Wetlands-Mixed (WETL)	79.0000	195.2130	0.09	0.69
BareSoil (BASO)	68.0000	168.0314	0.07	0.59
Maize (MAZE)	120.0000	296.5260	0.13	1.04
SOIL:				
Db88	144.0000	355.8312	0.16	1.25
Dc17	11352.0000	28051.3596	12.26	98.75
HRUs:				
42 RNGB/Dc17	637.0000	1574.0588	0.69	5.54
43 RNGE/Dc17	10331.0000	25528.4176	11.15	89.87
44 RNGE/Db88	144.0000	355.8312	0.16	1.25
45 WATR/Dc17	117.0000	289.1129	0.13	1.02
46 WETL/Dc17	79.0000	195.2130	0.09	0.69
47 BASO/Dc17	68.0000	168.0314	0.07	0.59
48 MAZE/Dc17	120.0000	296.5260	0.13	1.04

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 9	**586.0000**	**1448.0353**	**0.63**	
LANDUSE:				
Range-Brush (RNGB)	9.1404	22.5863	0.01	1.56
Range-Grasses (RNGE)	519.9861	1284.9117	0.56	88.73
BareSoil (BASO)	56.8735	40.5372	0.06	9.71
SOIL:				
Dc17	586.0000	1448.0353	0.63	100.00
HRUs:				

49	RNGB/Dc17	9.1404	22.5863	0.01	1.56
50	RNGE/Dc17	519.9861	1284.9117	0.56	88.73
51	BASO/Dc17	56.8735	140.5372	0.06	9.71

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 10	**4237.0000**	**10469.8389**	**4.57**	
LANDUSE:				
Range-Brush (RNGB)	187.0000	462.0864	0.20	4.41
Range-Grasses (RNGE)	3908.0000	9656.8634	4.22	92.24
Water (WATR)	63.0000	155.6762	0.07	1.49
Wetlands-Mixed (WETL)	32.0000	79.0736	0.03	0.76
BareSoil (BASO)	7.0000	17.2974	0.01	0.17
Maize (MAZE)	40.0000	98.8420	0.04	0.94
SOIL:				
Db87	2628.0000	6493.9194	2.84	62.03
Dc17	1609.0000	3975.9194	1.74	37.97
HRUs:				
52 RNGB/Dc17	82.0000	202.6261	0.09	1.94
53 RNGB/Db87	105.0000	259.4603	0.11	2.48
54 RNGE/Dc17	1474.0000	3642.3277	1.59	34.79
55 RNGE/Db87	2434.0000	6014.5357	2.63	57.45
56 WATR/Dc17	6.0000	14.8263	0.01	0.14
57 WATR/Db87	57.0000	140.8499	0.06	1.35
58 WETL/Db87	32.0000	79.0736	0.03	0.76
59 BASO/Dc17	7.0000	17.2974	0.01	0.17
60 MAZE/Dc17	40.0000	98.8420	0.04	0.94

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 11	**17729.0000**	**43809.2455**	**19.14**	
LANDUSE:				
Range-Brush (RNGB)	589.0665	1455.6127	0.64	3.32
Range-Grasses (RNGE)	8970.0119	22165.3479	9.68	50.60
Water (WATR)	101.0114	249.6042	0.11	0.57
Wetlands-Mixed (WETL)	45.0051	111.2098	0.05	0.25
BareSoil (BASO)	103.0116	254.5469	0.11	0.58
Maize (MAZE)	7920.8936	19572.9240	8.55	44.68
SOIL:				
DB87	2033.2294	5024.2114	2.20	11.47
Db88	885.0998	2187.1260	0.96	4.99
Dc17	14810.6708	36597.9080	15.99	83.54
HRUs:				
61 RNGB/Dc17	493.0556	1218.3651	0.53	2.78
62 RNGB/Db87	69.0078	170.5217	0.07	0.39
63 RNGB/Db88	27.0030	66.7259	0.03	0.15
64 RNGE/Dc17	7488.8448	18505.3100	8.09	42.24

65	RNGE/Db87	1348.1521	3331.3512	1.46	7.60
66	RNGE/Db88	133.0150	328.6867	0.14	0.75
67	WATR/Dc17	90.0102	222.4196	0.10	0.51
68	WATR/Db87	11.0012	27.1846	0.01	0.06
69	WETL/Dc17	26.0029	64.2545	0.03	0.15
70	WETL/Db87	19.0021	46.9552	0.02	0.11
71	BASO/Dc17	103.0116	254.5469	0.11	0.58
72	MAZE/Dc17	6609.7456	16333.0120	7.14	37.28
73	MAZE/Db87	586.0661	1448.1987	0.63	3.31
74	MAZE/Db88	725.0818	1791.7134	0.78	4.09

E. C52A 100% adoption

SWAT model simulation
Thu Sep 17 08:43:18 2009 MDL

MULTIPLE HRUs LandUse/Soil OPTION THRESHOLDS : 0 / 0 [%]
Number of HRUs: 18
Number of Subbasins: 11

	Area [ha]	Area [acres]
Watershed		
	92619.0000	228866.1799

	Area [ha]	Area [acres]	%Wat.Area
LANDUSE			
Maize (MAZE)	92619.0000	228866.1799	100.00
SOIL			
Db87	5429.7628	13417.2154	5.86
Db88	2444.0000	6039.2462	2.64
Dc17	84745.2372	209409.7184	91.50

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 1	**3474.0000**	**8584.4277**	**3.75**	
LANDUSE:				
Maize (MAZE)	3474.0000	8584.4277	3.75	100.00
SOIL:				
Dc17	3474.0000	8584.4277	3.75	100.00
HRUs:				
1 MAZE/Dc17	3474.0000	8584.4277	3.75	100.00

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 2	**6247.0000**	**15436.6494**	**6.74**	
LANDUSE:				
Maize (MAZE)	6247.0000	15436.6494	6.74	100.00
SOIL:				
Dc17	6247.0000	15436.6494	6.74	100.00
HRUs:				
2 MAZE/Dc17	6247.0000	15436.6494	6.74	100.00

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 3	**16533.0000**	**40853.8697**	**17.85**	
LANDUSE:				
Maize (MAZE)	16533.0000	40853.8697	17.85	100.00
SOIL:				
Db87	663.7628	1640.1911	0.72	4.01
Dc17	15869.2372	39213.6786	17.13	95.99
HRUs:				
3 MAZE/Dc17	15869.2372	39213.6786	17.13	95.99
4 MAZE/Db87	663.7628	1640.1911	0.72	4.01

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 4	**525.0000**	**1297.3013**	**0.57**	
LANDUSE:				
Maize (MAZE)	525.0000	1297.3013	0.57	100.00
SOIL:				
Dc17	525.0000	1297.3013	0.57	100.00
HRUs:				
5 MAZE/Dc17	525.0000	1297.3013	0.57	100.00

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 5	**3638.0000**	**8989.6799**	**3.93**	
LANDUSE:				
Maize (MAZE)	3638.0000	8989.6799	3.93	100.00

SOIL:				
Dc17	3638.0000	8989.6799	3.93	100.00
HRUs:				
6 MAZE/Dc17	3638.0000	8989.6799	3.93	100.00

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 6	**13247.0000**	**32733.9993**	**14.30**	
LANDUSE:				
Maize (MAZE)	13247.0000	32733.9993	14.30	100.00
SOIL:				
Db87	103.0000	254.5181	0.11	0.78
Db88	1415.0000	3496.5358	1.53	10.68
Dc17	11729.0000	28982.9454	12.66	88.54
HRUs:				
7 MAZE/Dc17	11729.0000	28982.9454	12.66	88.54
8 MAZE/Db87	103.0000	254.5181	0.11	0.78
9 MAZE/Db88	1415.0000	3496.5358	1.53	10.68

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 7	**14907.0000**	**36835.9423**	**16.09**	
LANDUSE:				
Maize (MAZE)	14907.0000	36835.9423	16.09	100.00
SOIL:				
Dc17	14907.0000	36835.9423	16.09	100.00
HRUs:				
10 MAZE/Dc17	14907.0000	36835.9423	16.09	100.00

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 8	**11496.0000**	**28407.1908**	**12.41**	
LANDUSE:				
Maize (MAZE)	11496.0000	28407.1908	12.41	100.00
SOIL:				
Db88	144.0000	355.8312	0.16	1.25
Dc17	11352.0000	28051.3596	12.26	98.75
HRUs:				
11 MAZE/Dc17	11352.0000	28051.3596	12.26	98.75
12 MAZE/Db88	144.0000	355.8312	0.16	1.25

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 9	**586.0000**	**1448.0353**	**0.63**	
LANDUSE:				
Maize (MAZE)	586.0000	1448.0353	0.63	100.00
SOIL:				
Dc17	586.0000	1448.0353	0.63	100.00
HRUs:				
13 MAZE/Dc17	586.0000	1448.0353	0.63	100.00

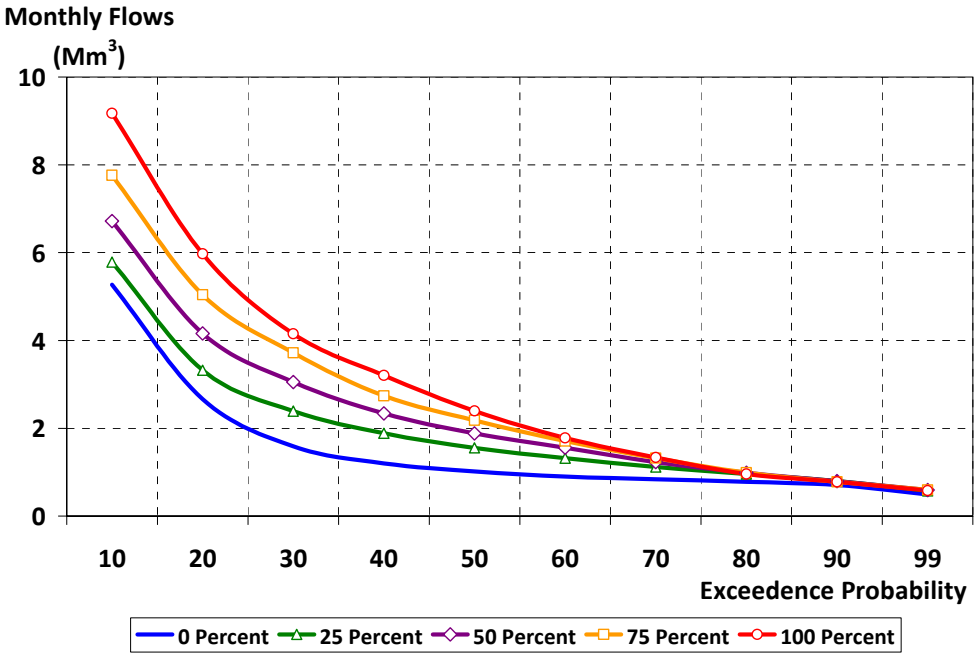
	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 10	**4237.0000**	**10469.8389**	**4.57**	
LANDUSE:				
Maize (MAZE)	4237.0000	10469.8389	4.57	100.00
SOIL:				
Db87	2628.0000	6493.9194	2.84	62.03
Dc17	1609.0000	3975.9195	1.74	37.97
HRUs:				
14 MAZE/Dc17	1609.0000	3975.9194	1.74	37.97
15 MAZE/Db87	2628.0000	6493.9194	2.84	62.03

	Area [ha]	Area [acres]	%Wat.Area	%Sub.Area
SUBBASIN # 11	**17729.0000**	**43809.2455**	**19.14**	
LANDUSE:				
Maize (MAZE)	17729.0000	43809.2455	19.14	100.00
SOIL:				
Db87	2035.0000	5028.5867	2.20	11.48
Db88	885.0000	2186.8793	0.96	4.99
Dc17	14809.0000	36593.7794	15.99	83.53
HRUs:				
16 MAZE/Dc17	14809.0000	36593.7795	15.99	83.53
17 MAZE/Db87	2035.0000	5028.5868	2.20	11.48
18 MAZE/Db88	885.0000	2186.8793	0.96	4.99

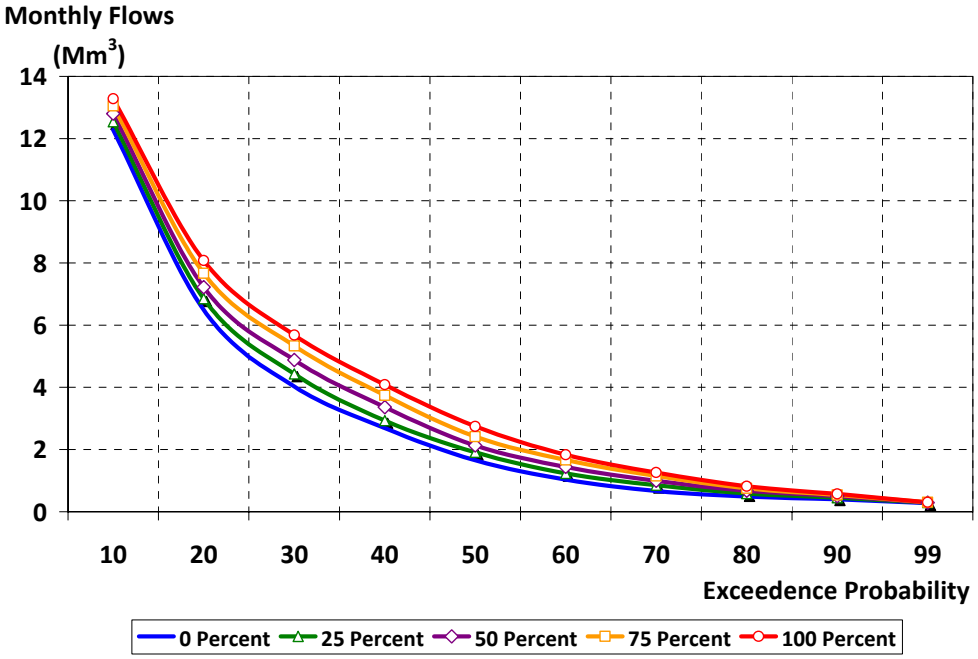
APPENDIX C: MONTHLY HYDROGRAPH AND FLOW DURATION CURVE

1. FLOW DURATION CURVES FOR DIFFERENT LEVELS OF ADOPTION OF RWH IN C52A AND V13D, SIMULATED BY WRSM (SEJAMOHOLO ET AL., 2008)

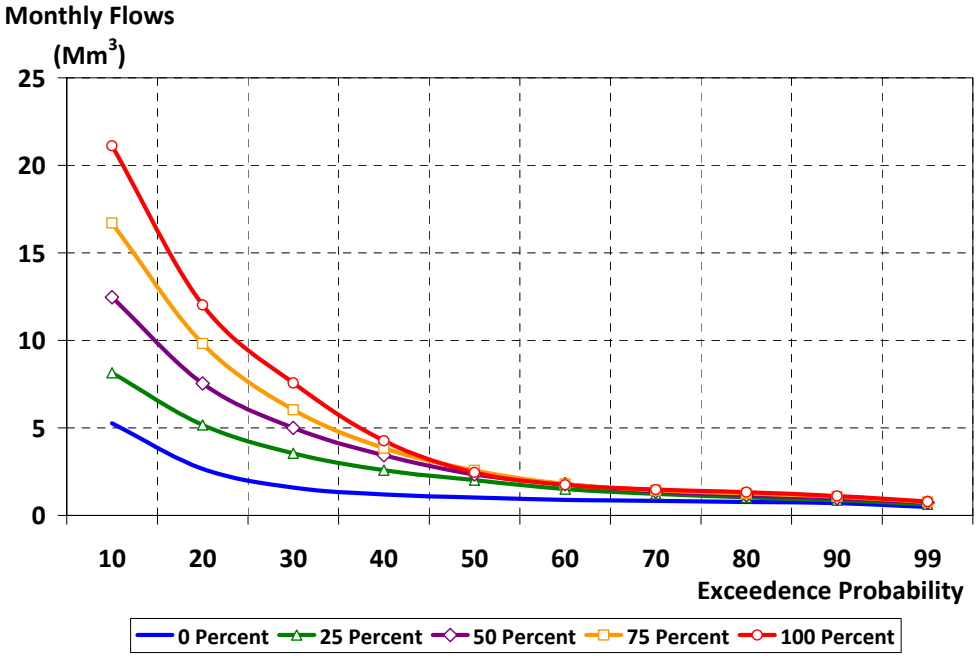
A. Flow Duration Curves for different levels of DRWH adoption in C52A for scattered settlements.



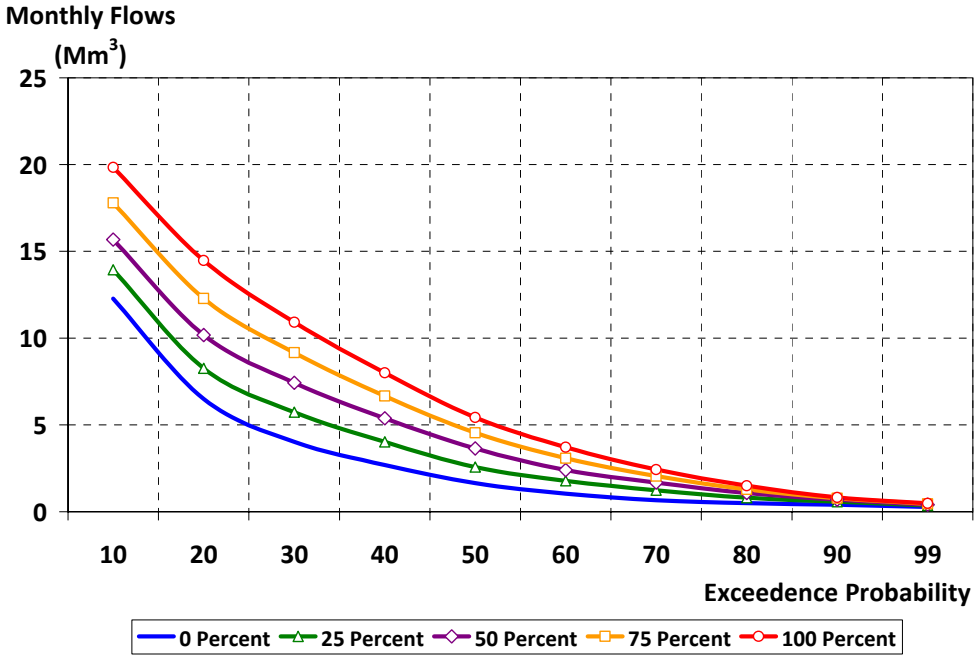
B. Flow Duration Curves for different levels of DRWH adoption in V13D for scattered settlements.



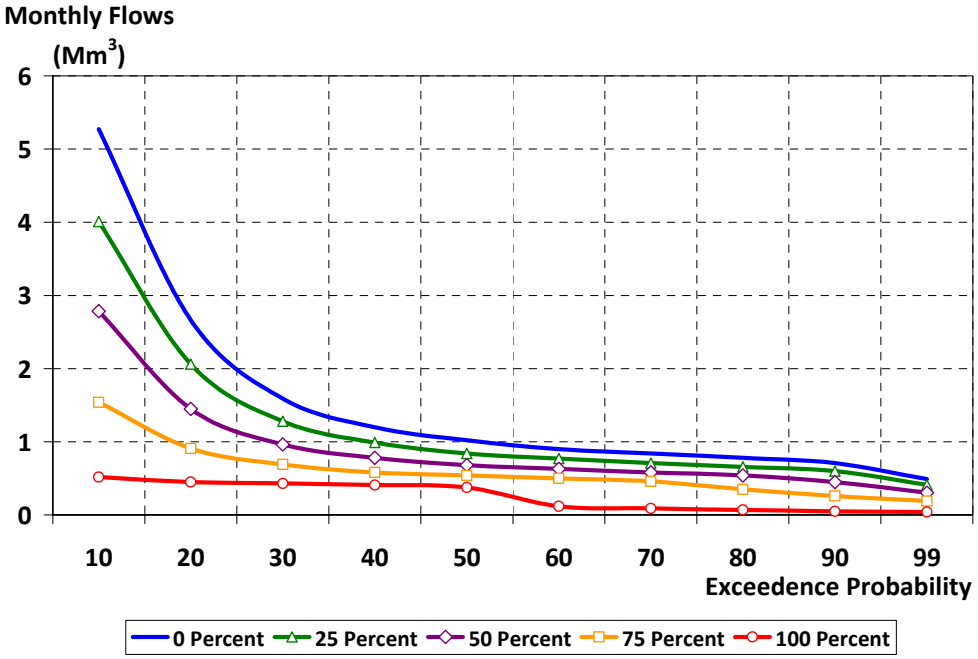
C. Flow Duration Curves for different levels of DRWH adoption in C52A for dense settlements.



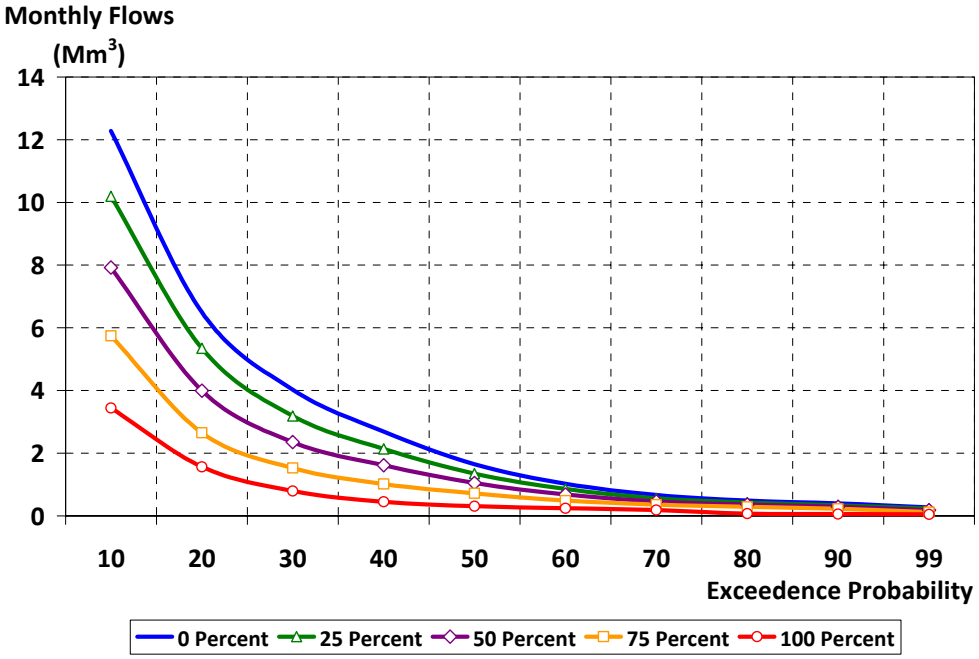
D. Flow Duration Curves for different levels of DRWH adoption in V13D for dense settlements.



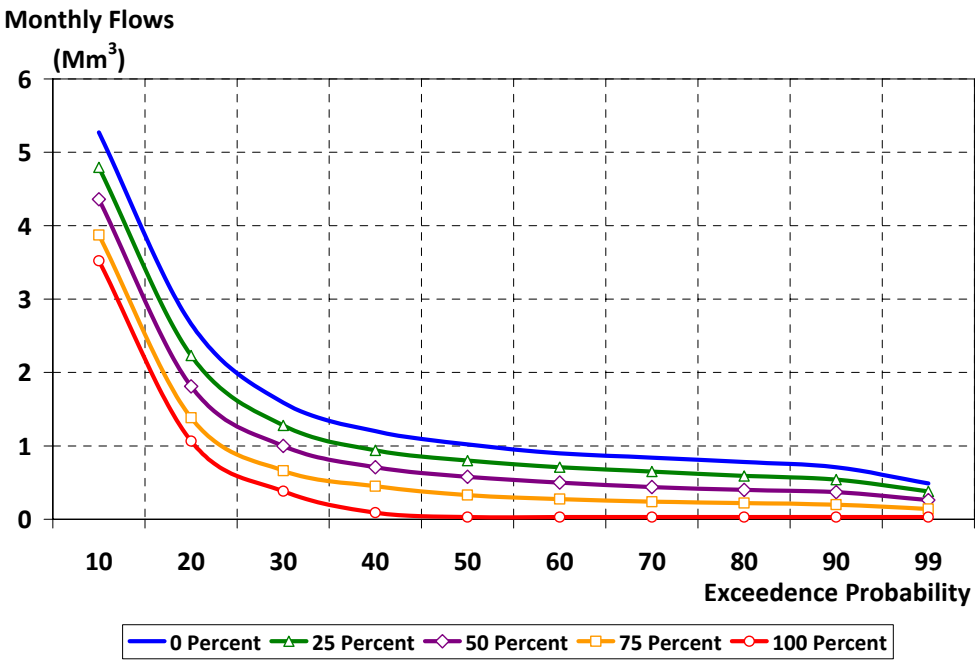
E. Flow Duration Curves for different levels of IRWH adoption in C52A.



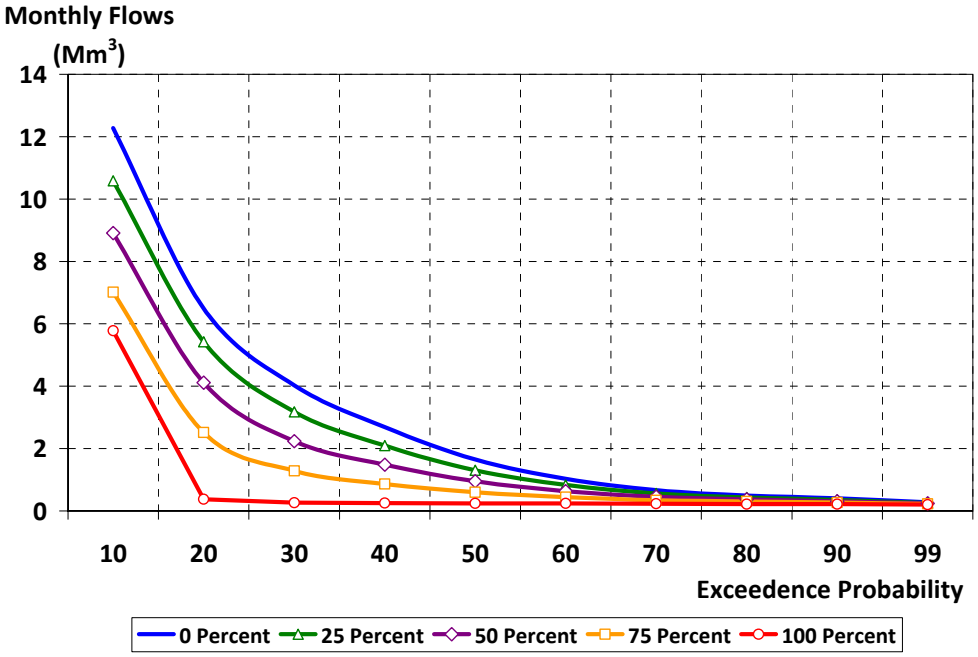
F. Flow Duration Curves for different levels of IRWH adoption V13D.



G. Flow Duration Curves for different levels of XRWH adoption in C52A.

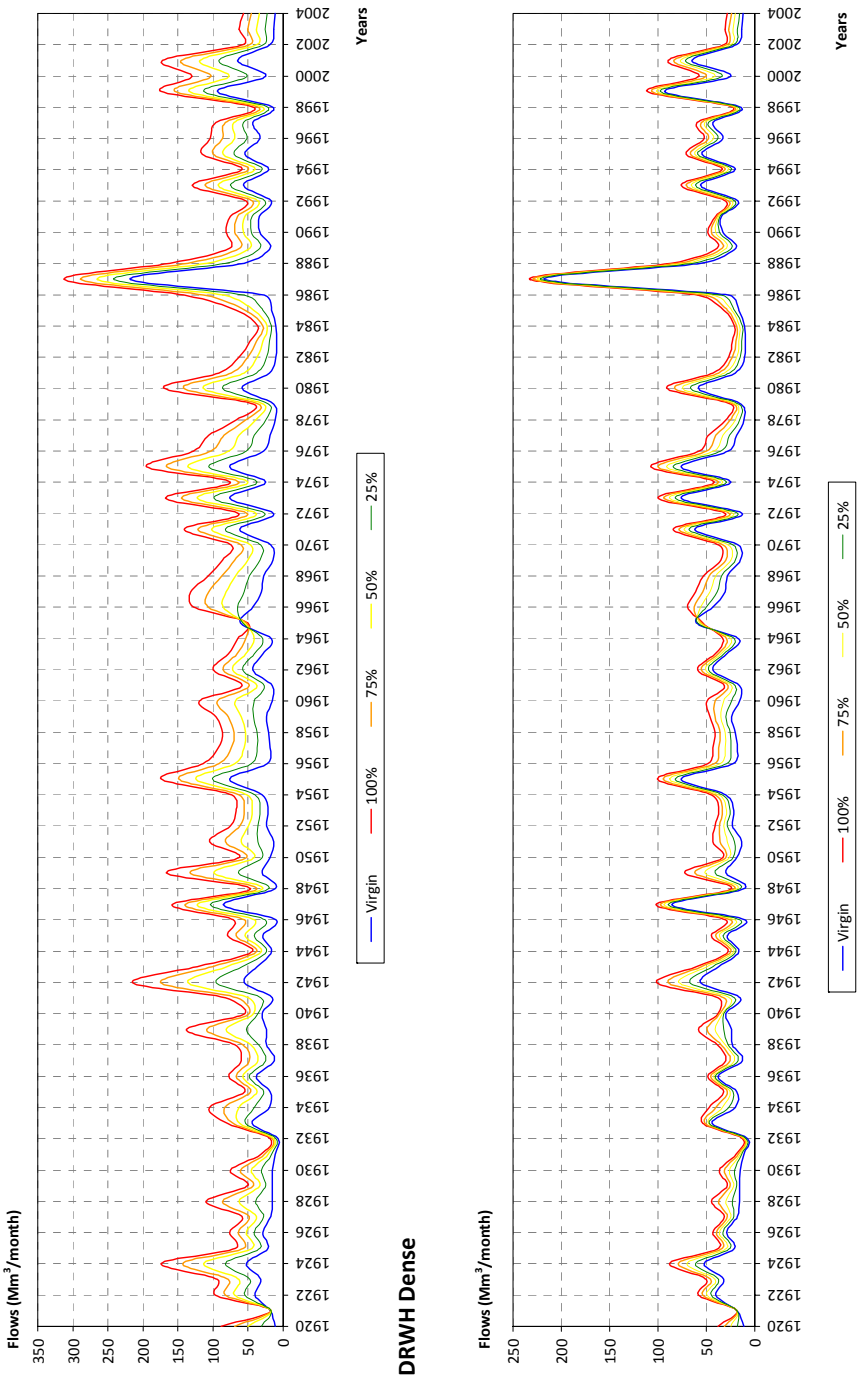


H. Flow Duration Curves for different levels of XRWH adoption V13D.

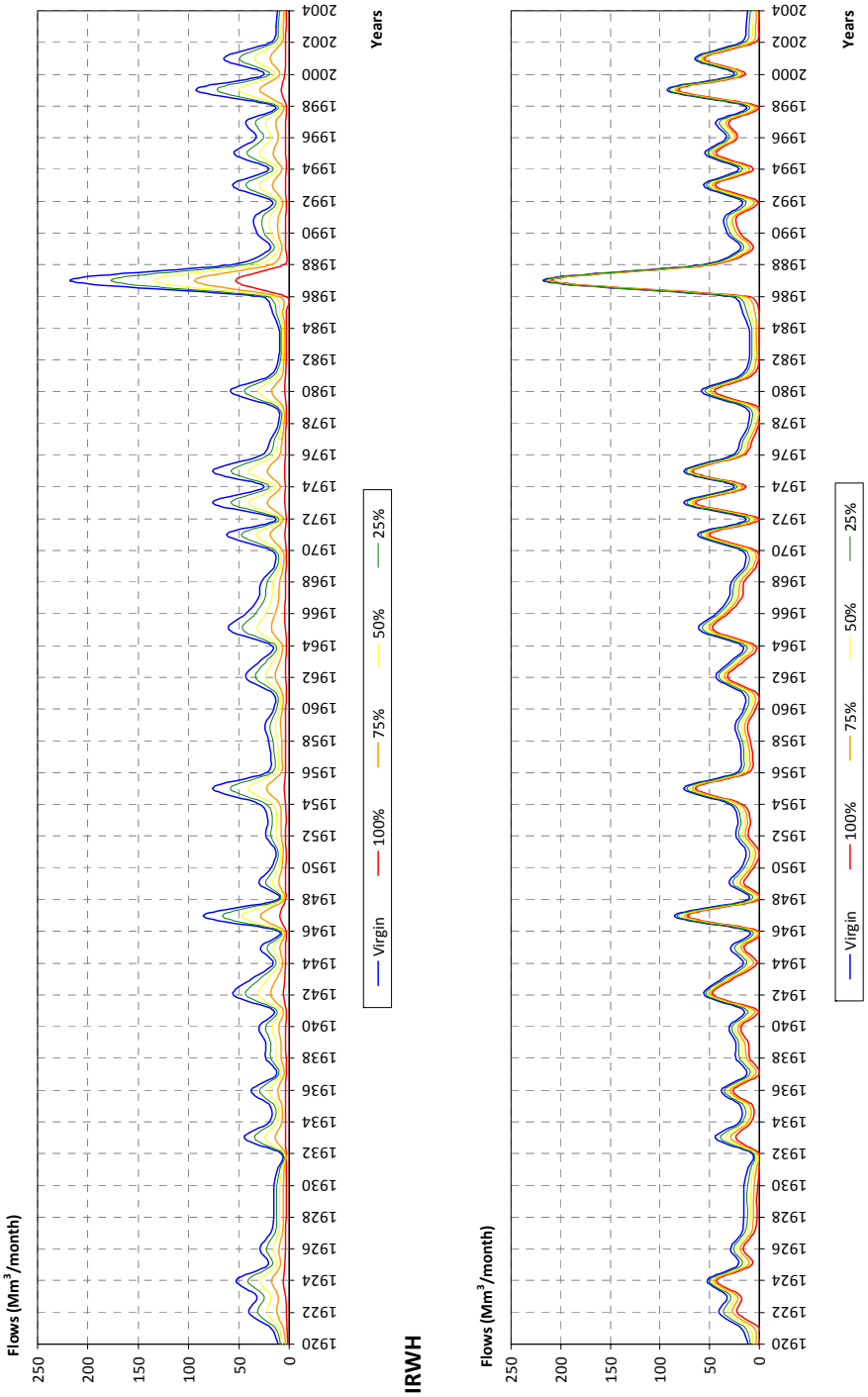


2. MONTHLY HYDROGRAPHS FOR DIFFERENT LEVELS OF RWH ADOPTION IN C52A AND V13D FROM 1920 TO 2004.

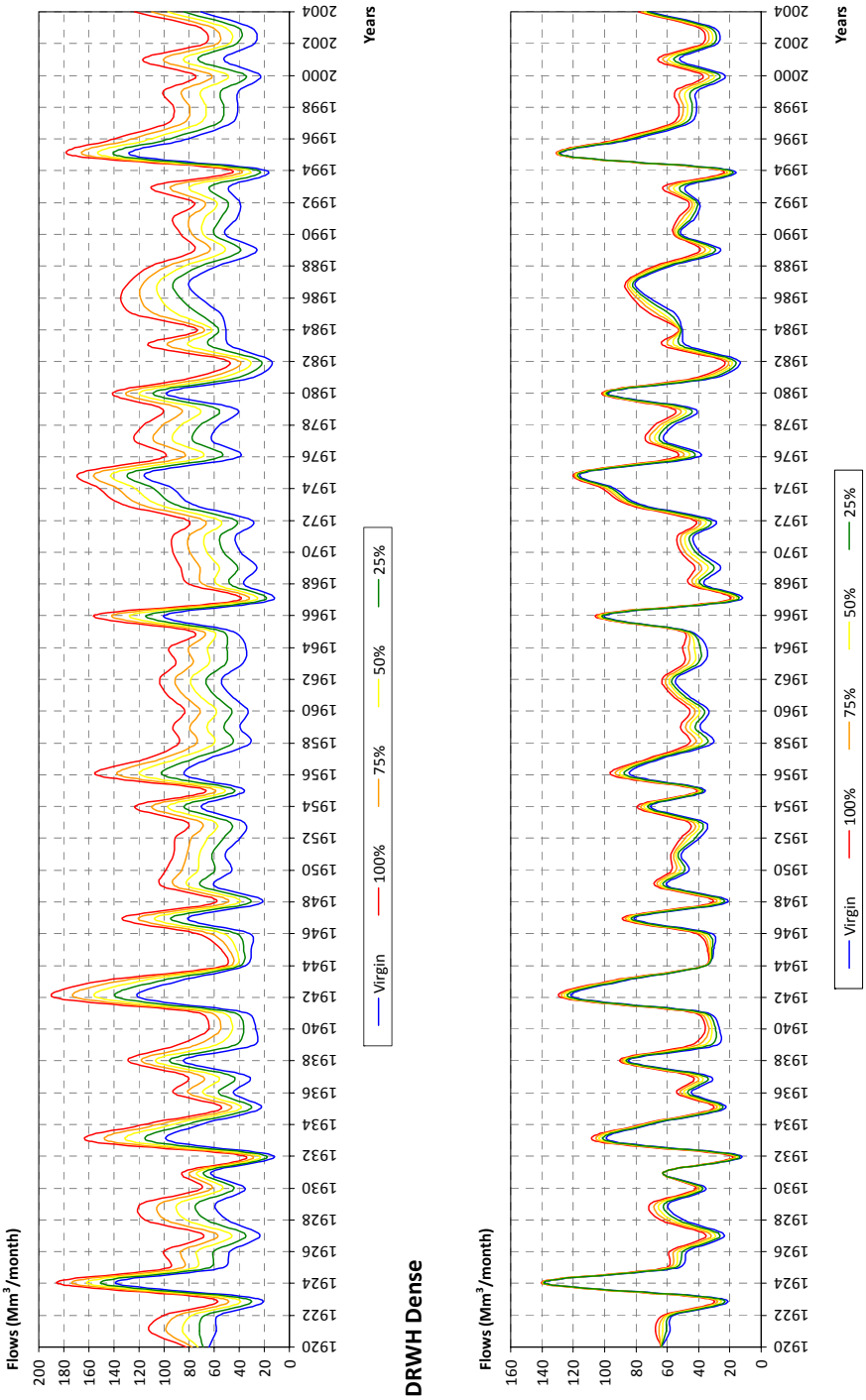
Monthly hydrographs for different levels of RWH adoption in C52A (Period: 1920 to 2004).



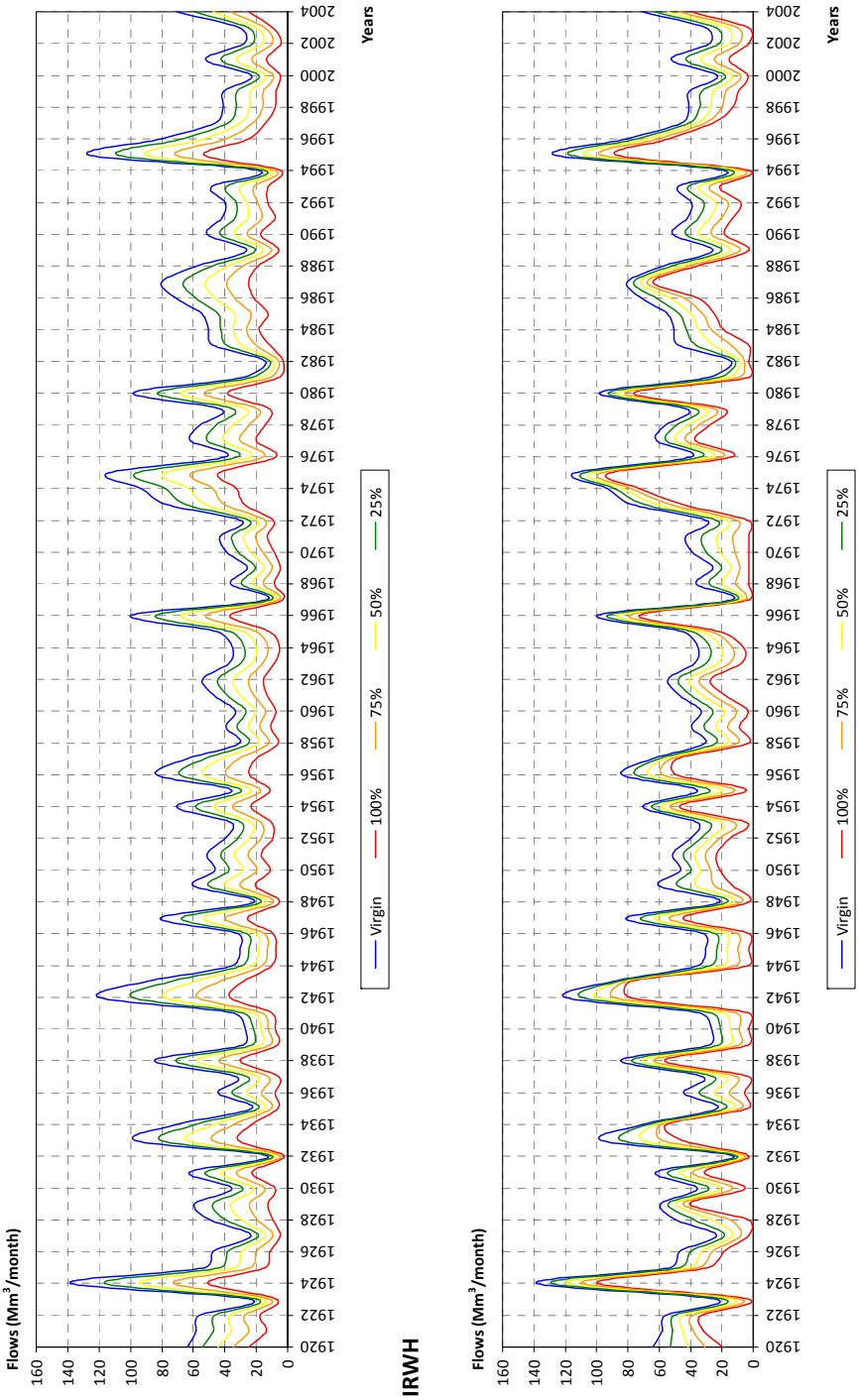
Monthly hydrographs for different levels of RWH adoption in C52A (Period: 1920 to 2004).



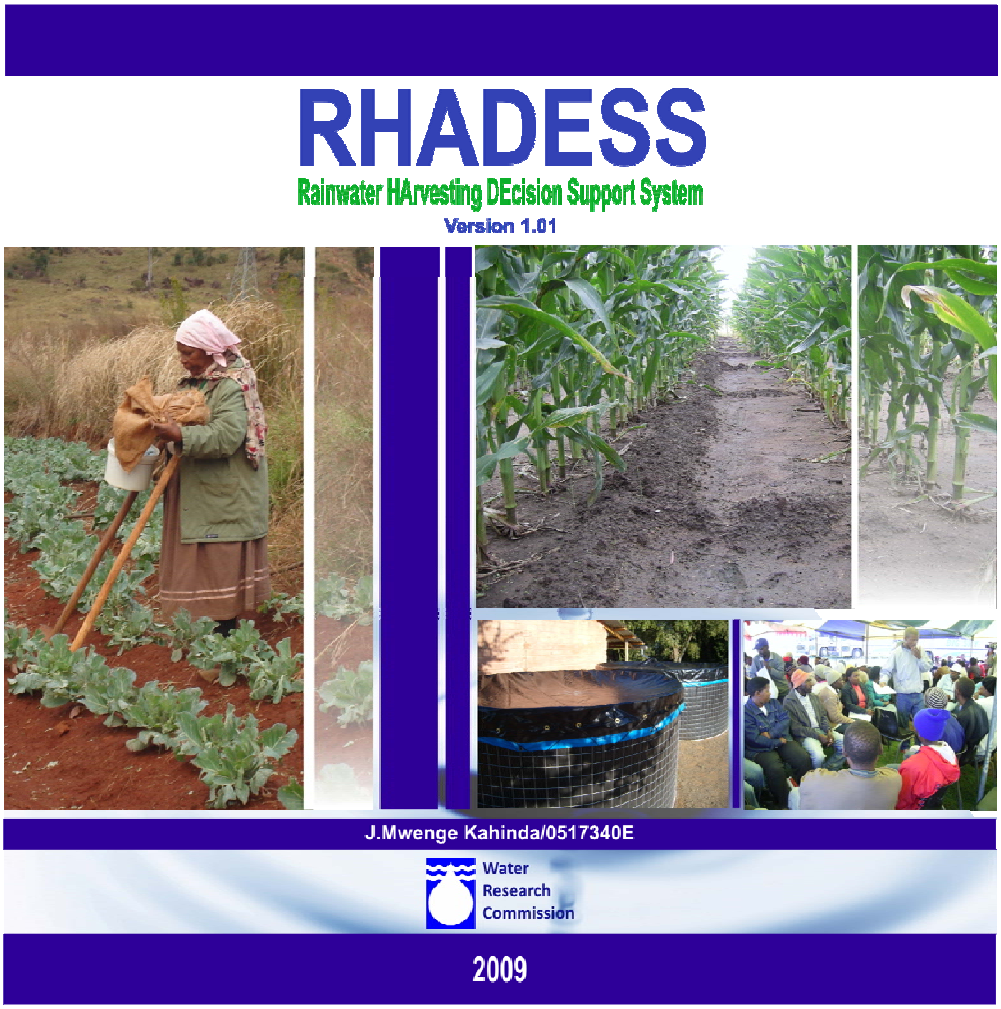
Monthly hydrographs for different levels of RWH adoption in V13D (Period: 1920 to 2004).



Monthly hydrographs for different levels of RWH adoption in V13D (Period: 1920 to 2004).



APPENDIX D: RHADESS USER MANUAL



1. INTRODUCTION

The Rainwater Harvesting Decision Support System (RHADESS) aims to indicate the RWH suitability for any given area and to provide the means for quantifying and qualifying potential impacts associated with its wide scale adoption in South Africa.

RHADESS is an extension of ESRI ArcView 3.3 that enables users to efficiently and effectively run the required processes to produce suitability maps for the identification of areas suitable for rainwater harvesting.

These processes use grid format data sets, called **Input Grids** that are pre-classified according to predetermined evaluations. ModelBuilder uses these input grids in predetermined Models and produces the suitability maps as **Output Grids**. Output grids can be altered by changing the weight of the different layers using ModelBuilder.

The RHADESS extension has two selection options. This is due to the large data sets used to do the analysis, and the run time of only one RWH category can take up to 15min (using Pentium 4, 2.4 Ghz with 2Gb RAM).

RHADESS allows running multiple scenarios. Recognising that user will mostly use much smaller areas than the whole RSA, the data sets were split into Water Management Areas (WMA). The option to select a WMA is to speed up the process. Time required to run a WMA area is approximately 1 minute.

2. SYSTEM REQUIREMENTS

2.1. SOFTWARE REQUIREMENTS

- Microsoft Windows XP operating system;
- ArcView 3.3;
- ArcView Spatial Analyst 3.3 extension;
- Microsoft Excel;
- Adobe Acrobat Reader version 7 or higher, and;
- Win-Zip.

2.2. HARDWARE REQUIREMENTS

- Pentium IV, 2.0 Ghz or higher;
- Personal computer using a Pentium IV processor or higher, which runs at 2 gigahertz or faster.
- 1 GB RAM minimum;
- About 10 Giga byte free memory on the hard drive for full installation (including models at Water management level), and;
- DVD Rom.

3. INSTALLATION

RHADESS is supplied with the following compressed files on a DVD:

- Rhadessavx.exe;
- Rhadessini.exe;
- Rhadess.exe.

To install RHADESS simply double click on these WinZip Self-Extracting files. After installing, first reboot the computer before beginning to use the model.

4. USING RHADESS

This user manual could be used as a step-by-step guide for training, provided the RHADESS software and hardware requirements are met.

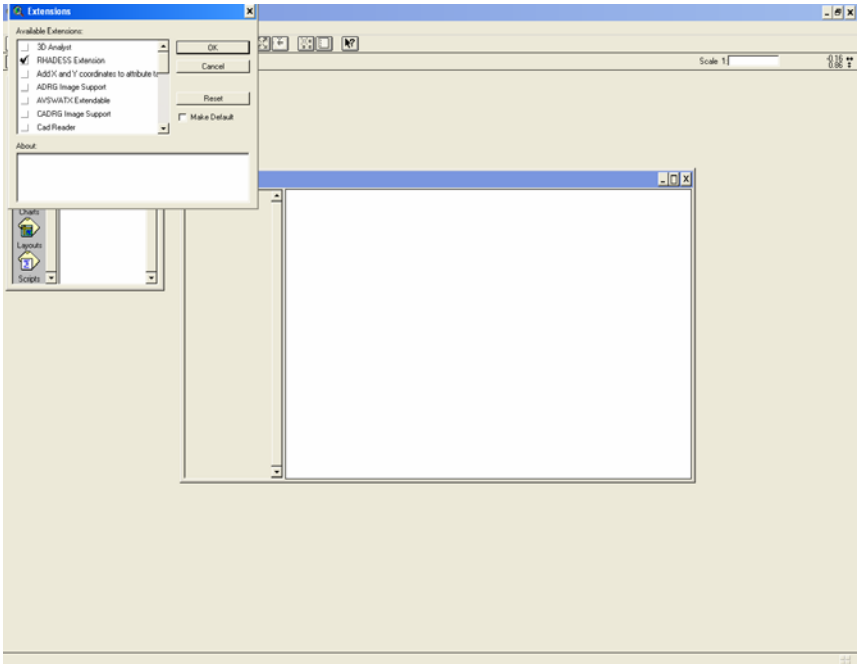
The key Procedures are:

- Select scale (Whole RSA or WMA)
- Select RWH category
- Load model
- Change weight
- Run model
- Assess footprint at quaternary catchment level
- Quantify impact

4.1. STARTING RHADESS

1. Open an ArcView 3.3 session.

2. Open a new View, go to File and click on Extensions, Tick the RHADESS extension and click Ok.



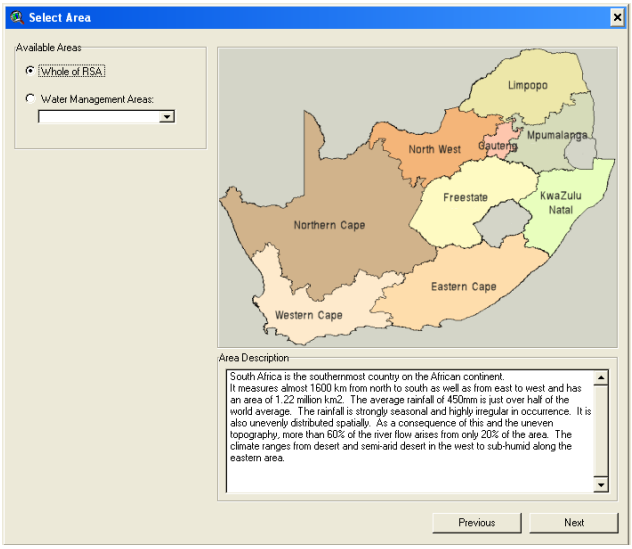
3. Click the RHADESS button  to load RHADESS.



4. Click the Next button .

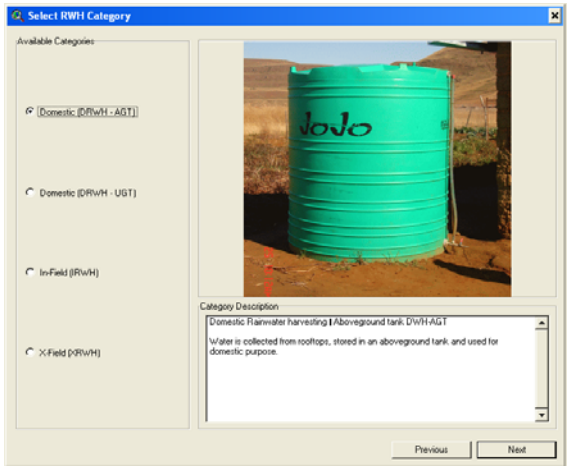
4.2. WORKING AT COUNTRY LEVEL (RSA LEVEL)

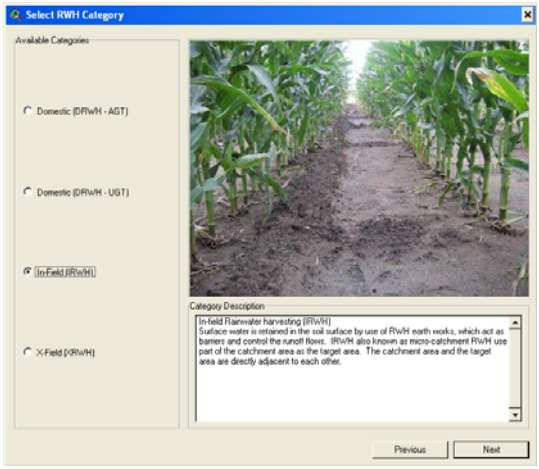
1. After the welcome screen, the interface brings up the Area selection screen. The user has a choice between whole RSA and Water management Areas. Leave on Whole of RSA and Click the Next button. 



2. Pressing the previous button Previous allows going back to the previous screen, while pressing the next button Next enables the user to see the next screen. Press next to open the select RWH category screen.

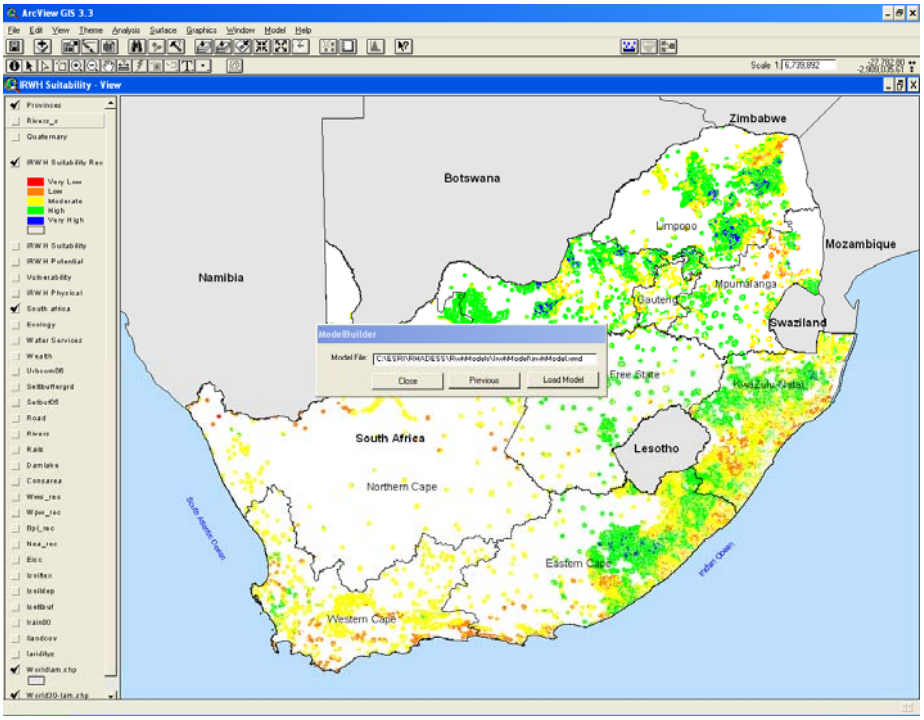
3. You can choose one of the four RWH categories by ticking a radio button. Tick the radio button of In-field RWH and Click the Next button. Each time you select a category, the description as well as the picture are updated.



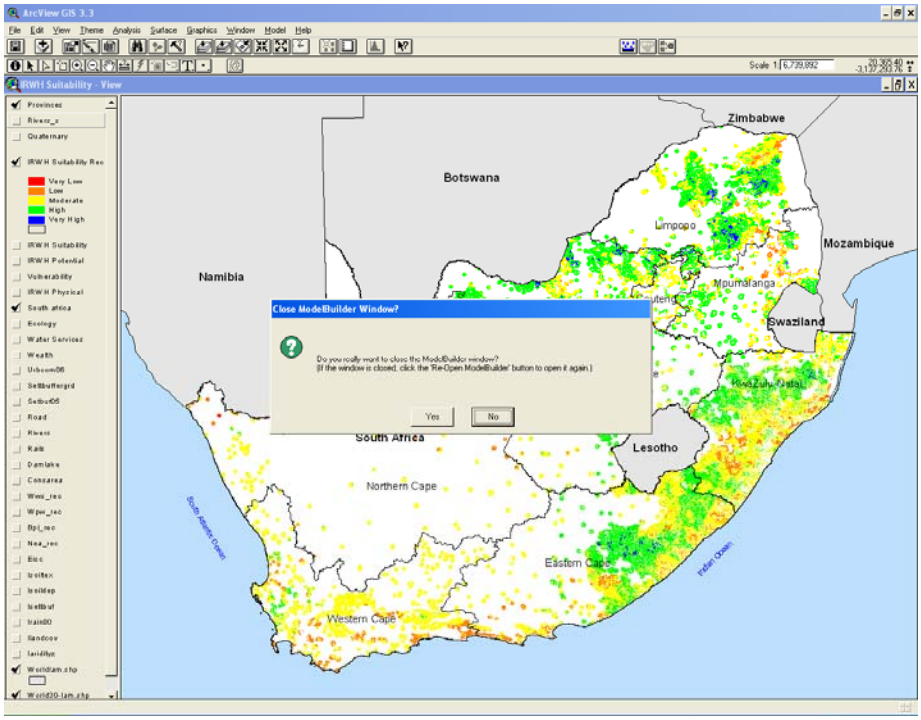


4. The IRWH Suitability - View is opened with all the required extensions loaded. The ModelBuilder Interface that allows loading the IRWH model is also open. Note the three buttons on the Model Builder interface. The close button Close closes the ModelBuilder interface, while the

ModelBuilder button  enables the user to reopen it. Close ModelBuilder's Interface by clicking the close button.

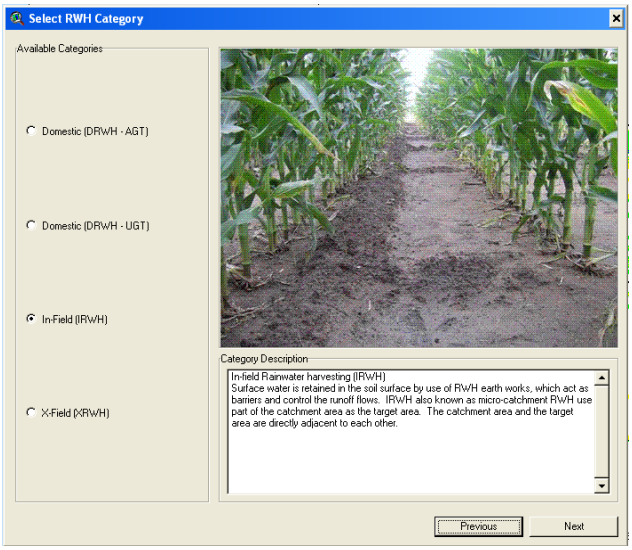


5. Press the Yes button to Close ModelBuilder pop-up window.



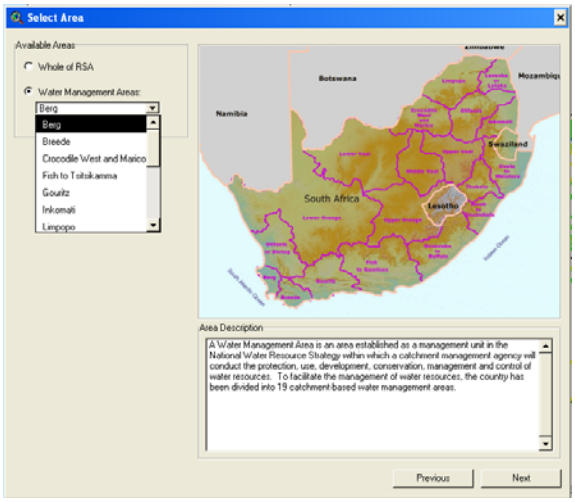
6. Press the ModelBuilder button  to reopen ModelBuilder's Interface.

7. Press the previous button of the ModelBuilder Interface to go back to the RWH category window. This takes you back here. Press the previous button of the RWH category interface.

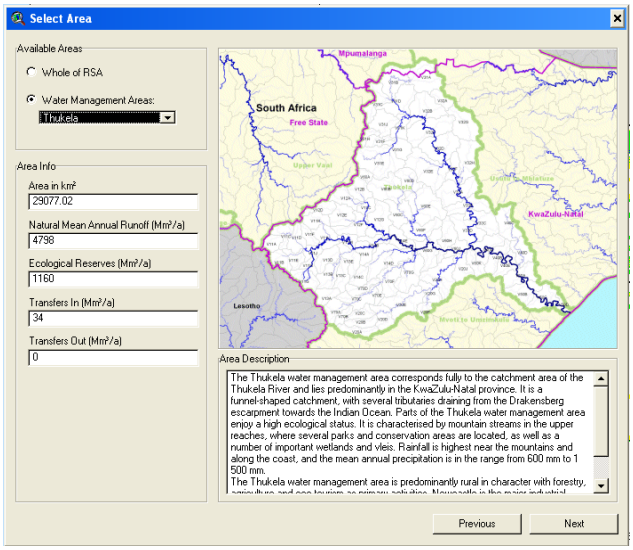


4.3. WORKING AT WATER MANAGEMENT AREA LEVEL

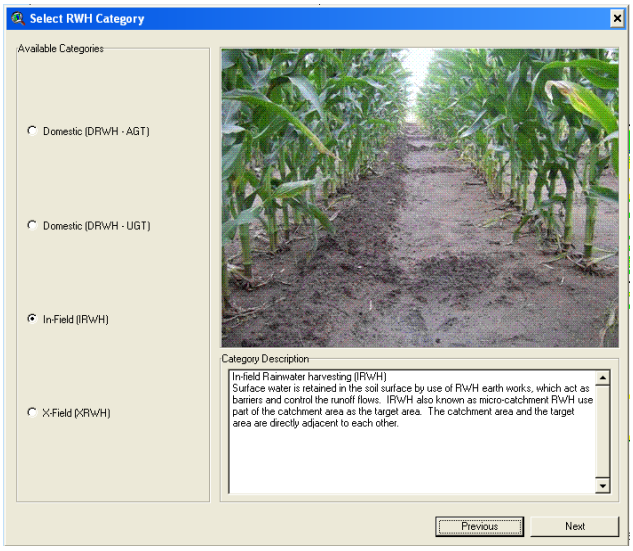
1. Select Water Management Areas by clicking the radio button. And next press the dropdown menu arrow.



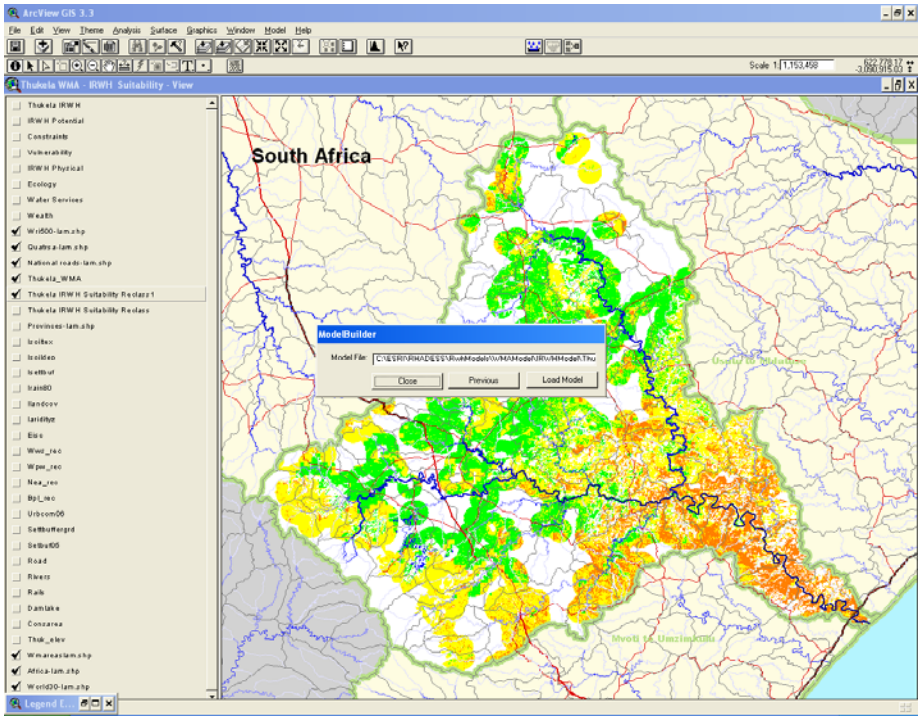
2. Select the Tukhela WMA. Note how the map, Area description and area info change. The Area info and the area description are specific to Tukhela WMA. Press Next.



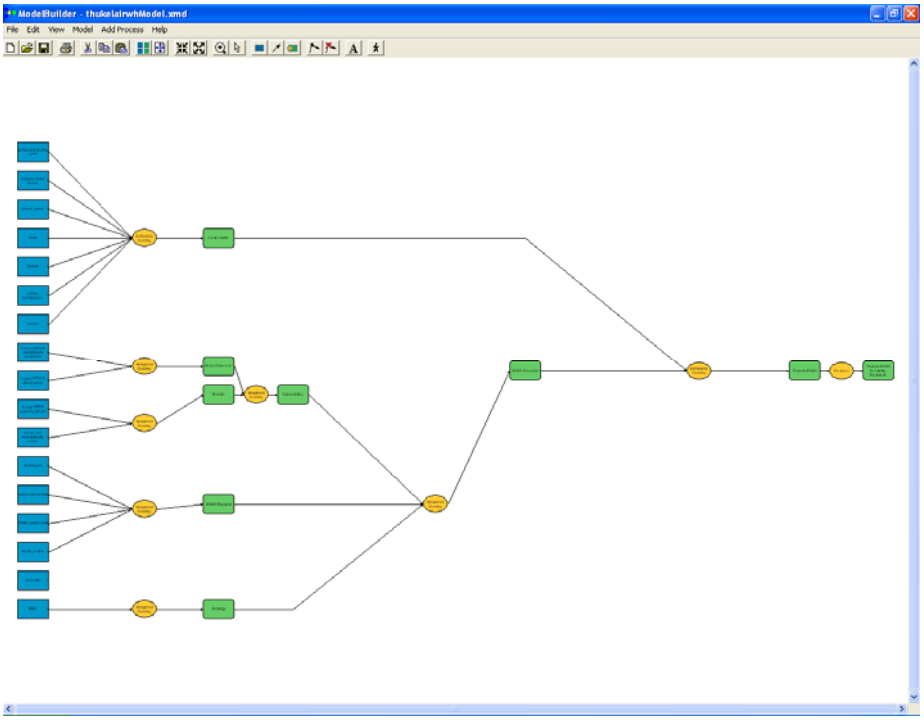
3. The Area info and the area description are specific to Tukhela WMA. Select In-field RWH and press Next.



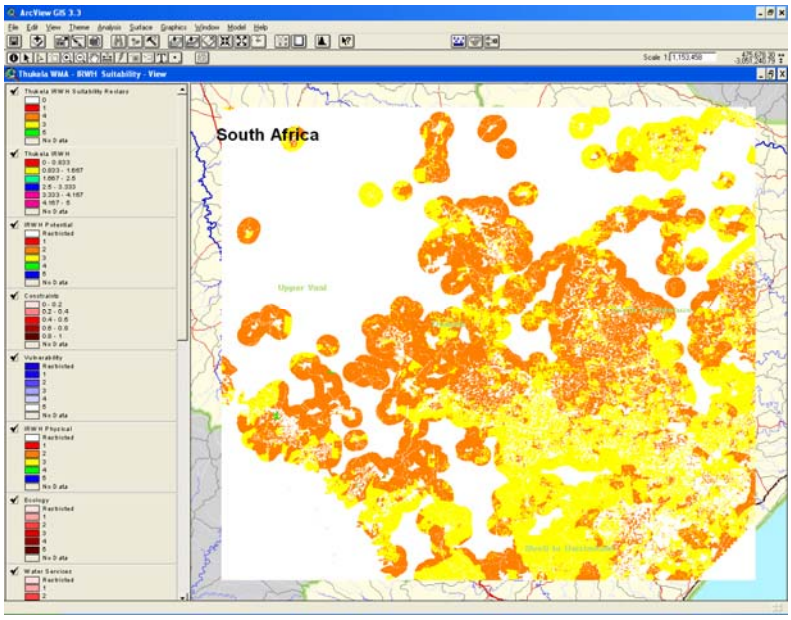
4. Press the Load Model button to open the ModelBuilder Interface.



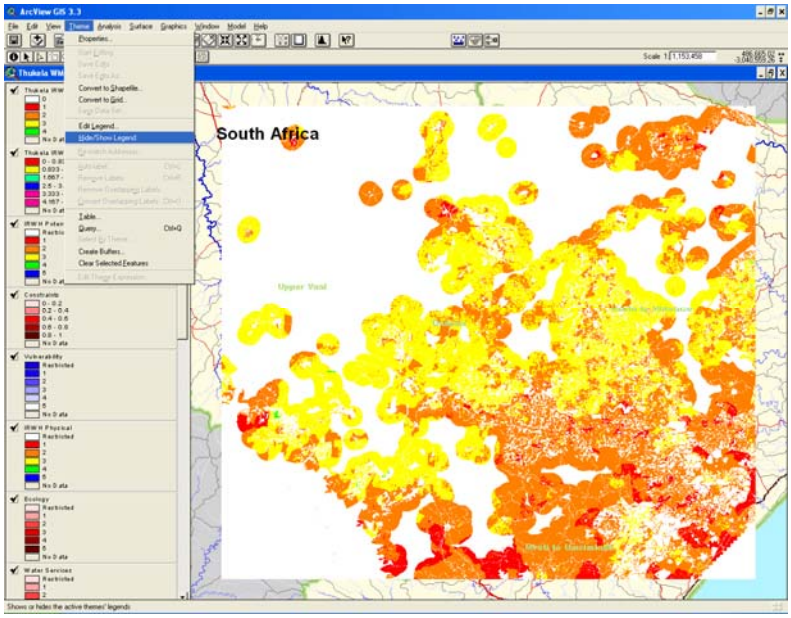
5. Click Run button to run the model.



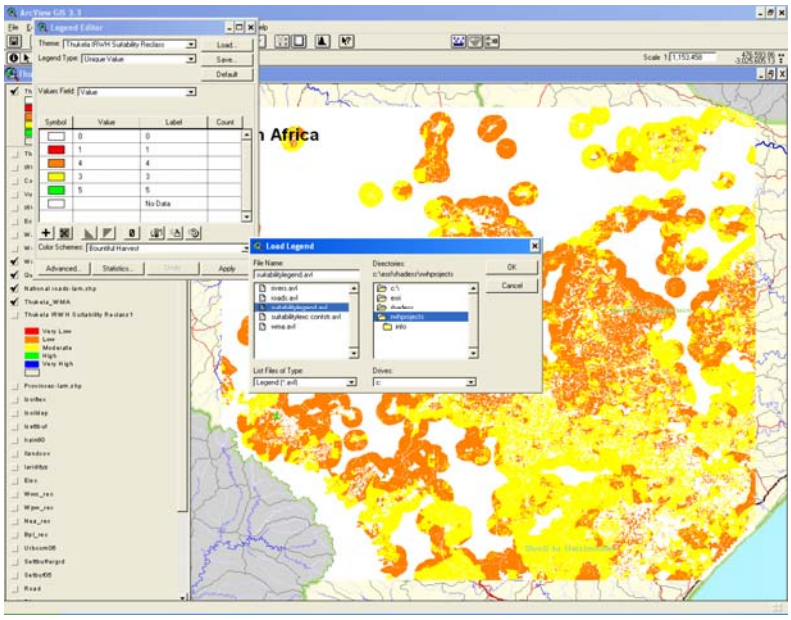
6. The Water Services Grid, Wealth Grid, Ecology Grid, IRWH physical Grid, Vulnerability Grid, Constraint Grid, IRWH potential Grid, IRWH suitability Grid and IRWH suitability reclassified Grid are created in the Tukhela WMA – IRWH Suitability view.



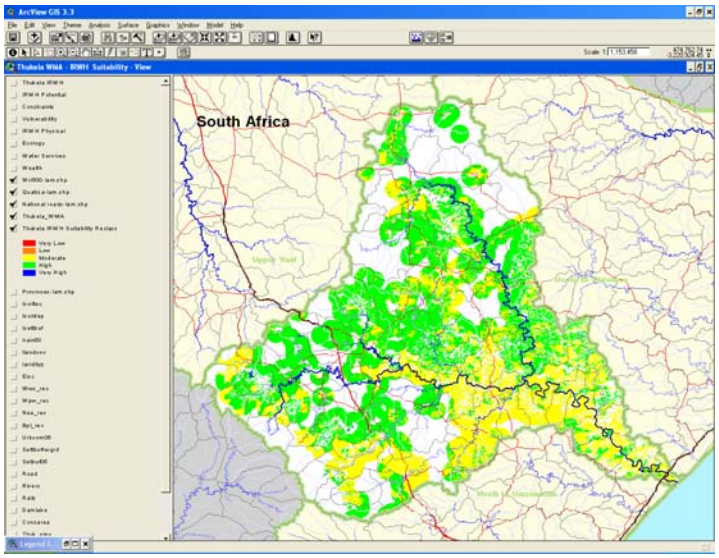
7. Cleanup the view, by hiding the legends of the grids generated and only leaving the IRWH suitability reclass Grid on.



8. To remove the white area generated for the restricted area of the IRWH suitability reclassified Grid, is to load the legend. Open the Legend editor window by double clicking. Double click the Load button, go to the directory C:\ESRI\RHADESS\RwhProjects and select suitabilitylegend. Click ok on the load legend window and click apply in the Legend editor window.

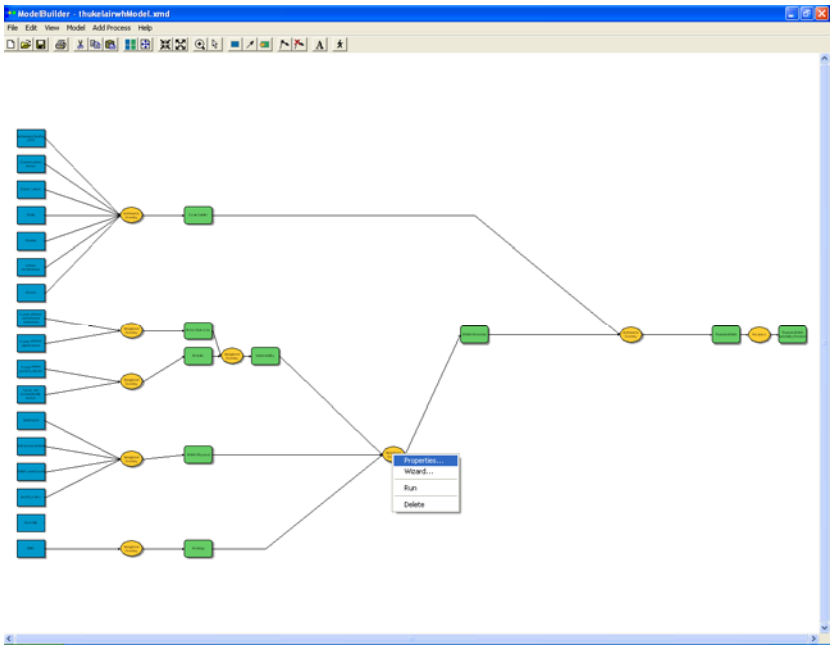


9. Click the Thukela_WMA theme, provinces theme, the roads theme, the river theme and the quaternary catchment theme and drag it to the top of the Table of Contents. The potential map could be printed using the layouts provided, or the model could be adjusted for a different result.

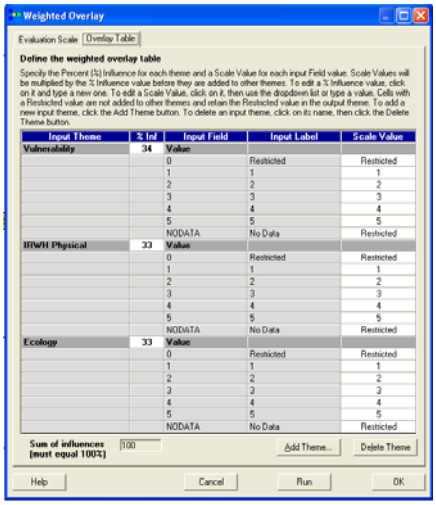


4.4. SCENARIOS

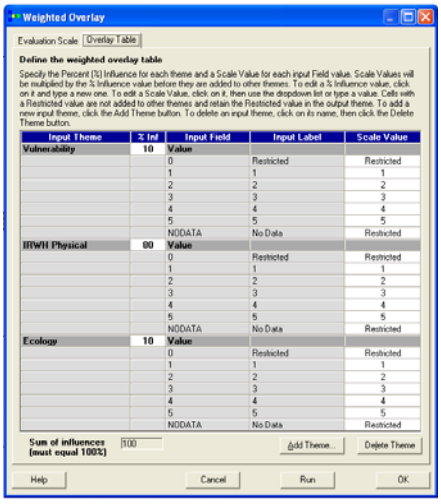
1. Scenarios are created by changing the weighting of the layers. Press the Open ModelBuilder Button. Load the model. Right-click the Weighted Overlay function node just before the IRWH potential theme and click Properties to open the Weighted Overlay property sheet.



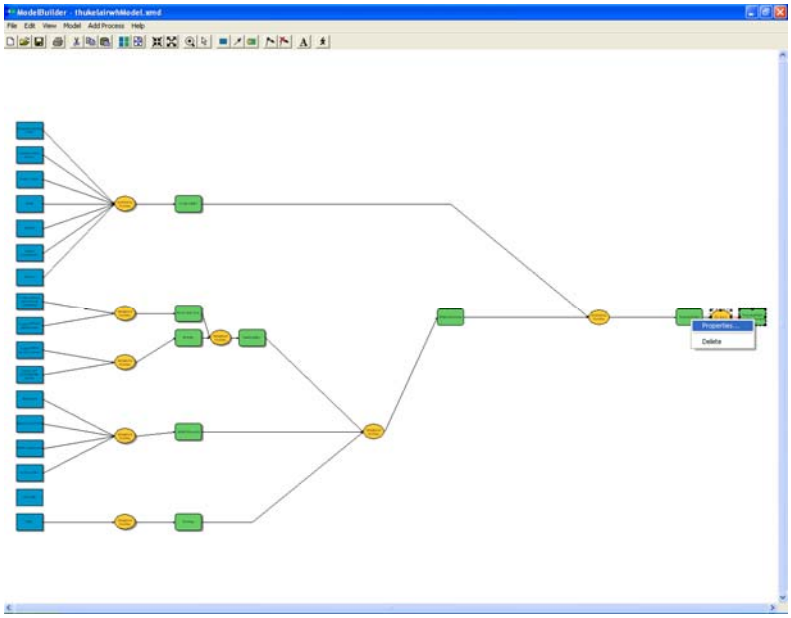
2. The Overlay Table tab is selected. The weighted overlay table is where the input themes, their weights, and the scale values of each input in each theme can be defined.



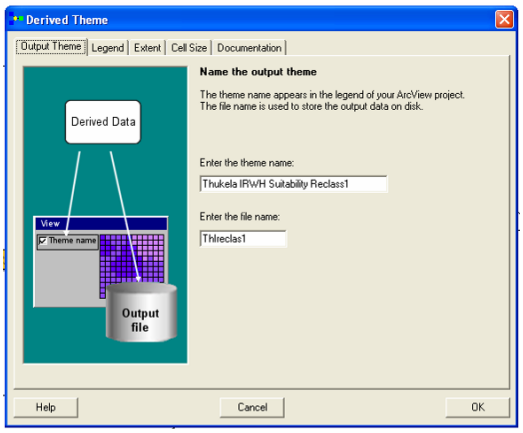
3. Make some changes to the influence weights and scale values. Experiment by making the changes as shown in the table below. If necessary resize the weighted overlay window by dragging the right corner in order to view the entire weighted overlay table.



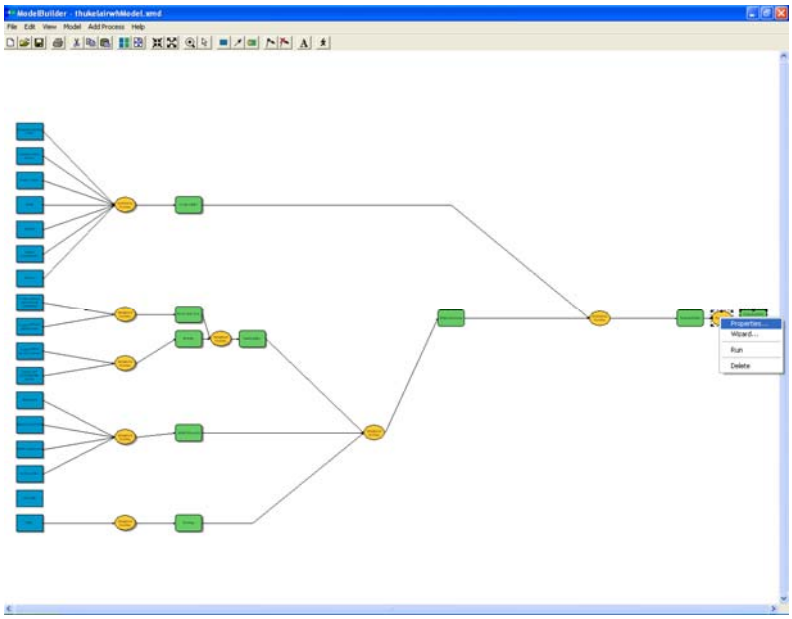
4. The new version of the IRWH suitability reclassified (Output Grid) overwrites the old one. Hence, the Output grid must be renamed to enable any comparison. Right-click the IRWH suitability node and click Properties.



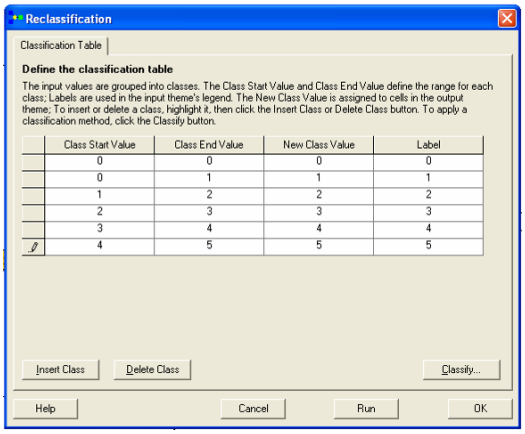
5. Change the theme name to Thukela IRWH Suitability Reclass1. Also change the file name to Threclass1 (Note that the file name must be less than 13 characters). Press Ok.



6. Right-click the reclass function and click Properties.

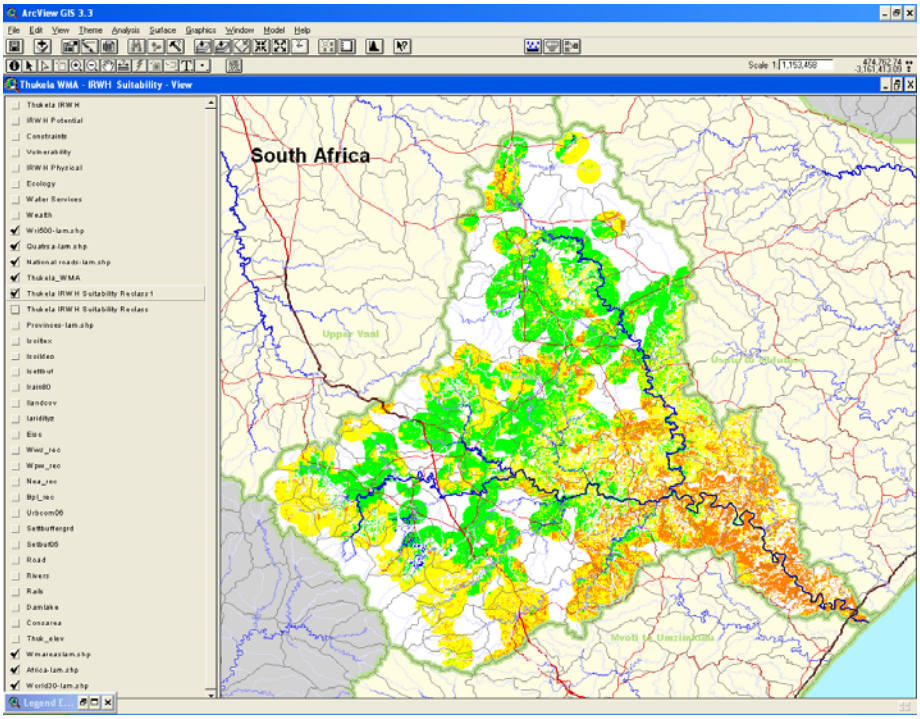


7. Insert a class in the classification table to obtain the following result.

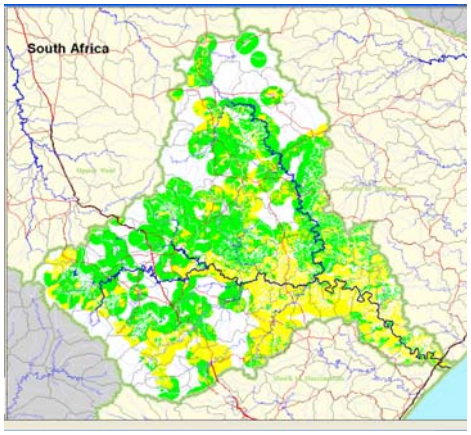


8. Click the Run button to run the Model and follow the procedure described previously to clean and see the final result.

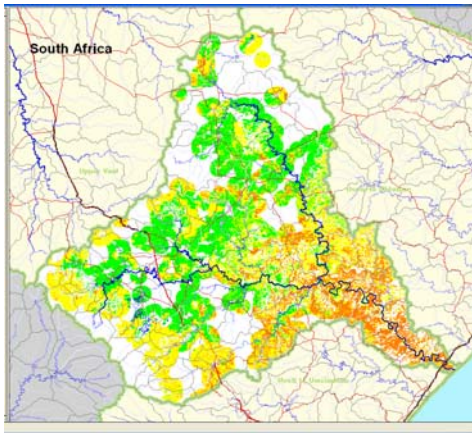
9. Cleanup following follow the procedure described previously (See 4.3 8-9) and see the final result. Only leave the IRWH Suitability Reclass1 Grid on.



10. Observe the change in Areas suitable for IRWH.



Thukela IRWH Suitability Reclass

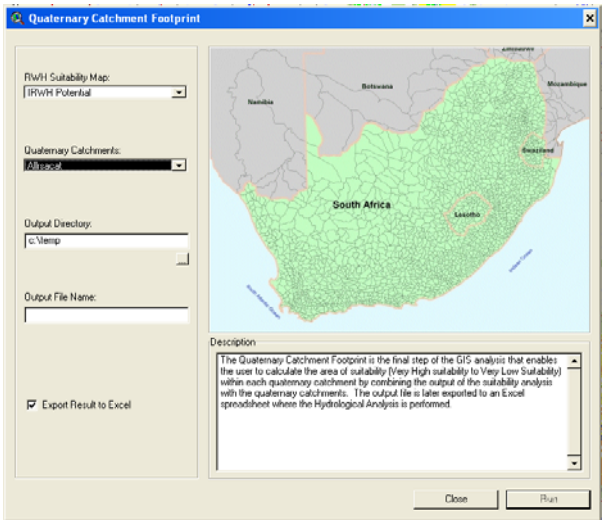


Thukela IRWH Suitability Reclass1

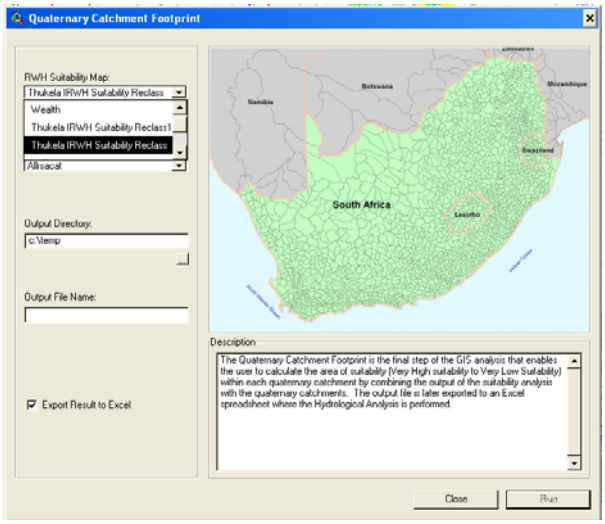
To quantify the change, the RWH footprint at quaternary catchment level should be viewed.

4.5 FOOTPRINT

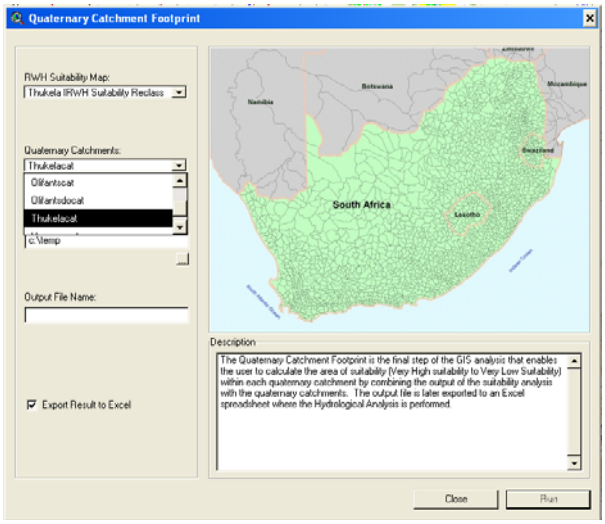
1. Press the Quaternary Catchment Footprint button to open the Quaternary Catchment Footprint Interface.



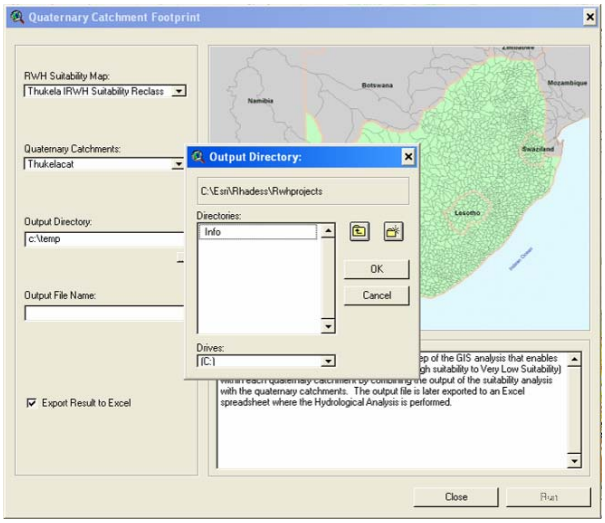
2. Press the dropdown menu arrow below RWH Suitability Map and select the IRWH Suitability Reclass.



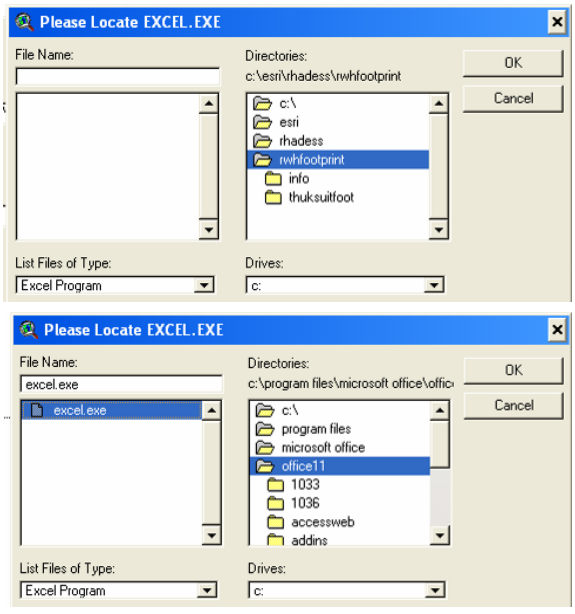
3. Next, press the dropdown menu arrow below Quaternary Catchments and select Tukhelacat



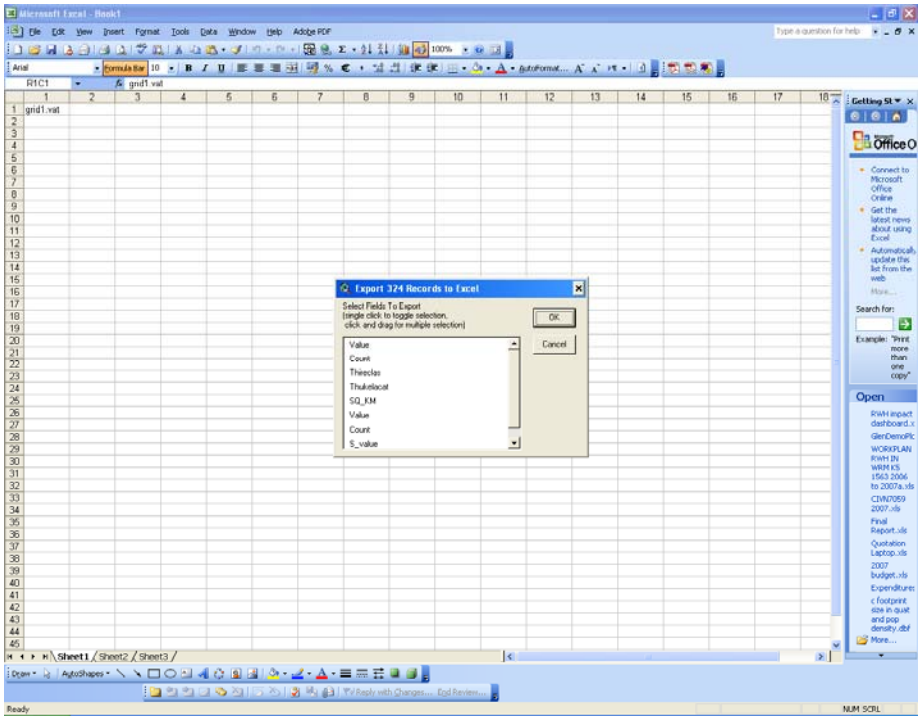
4. Click browse button  to select an output directory (for this exercise, save under c:\Esri\Rhadess\Rwhfootprint) and name the output file thuksuitfoot. Tukhelacat Leave the export Result to Excel selected and press Run.



When used for the first time, RHADESS will ask to locate Excel.exe. For Windows 2003, it is located in C:\Program Files\Microsoft Office\OFFICE11.



5. An Excel spreadsheet is open. Following the instruction on the Export to Excel window, select all the fields (keep the shift button pressed for more than one selection) and click ok.

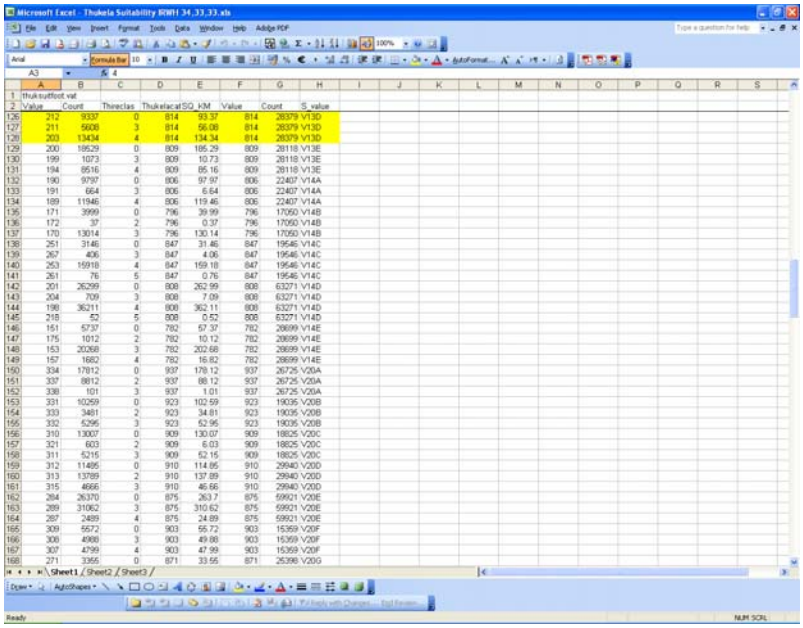


6. Save the Excel file as Thukela Suitability IRWH 34,33,33 under the directory C:\ESRI\RHADESS\RwhDuments\RwhExcel.

7. Do the same operation to get the footprint of IRWH Suitability Reclass1. Note that the following needs to be changed:
   - Select the IRWH Suitability Reclass1
   - Name the output file thuksuitfoot1
   - Save the Excel file as Thukela Suitability IRWH 10,80,10 under the directory C:\ESRI\RHADESS\RwhDocuments\RwhExcel.

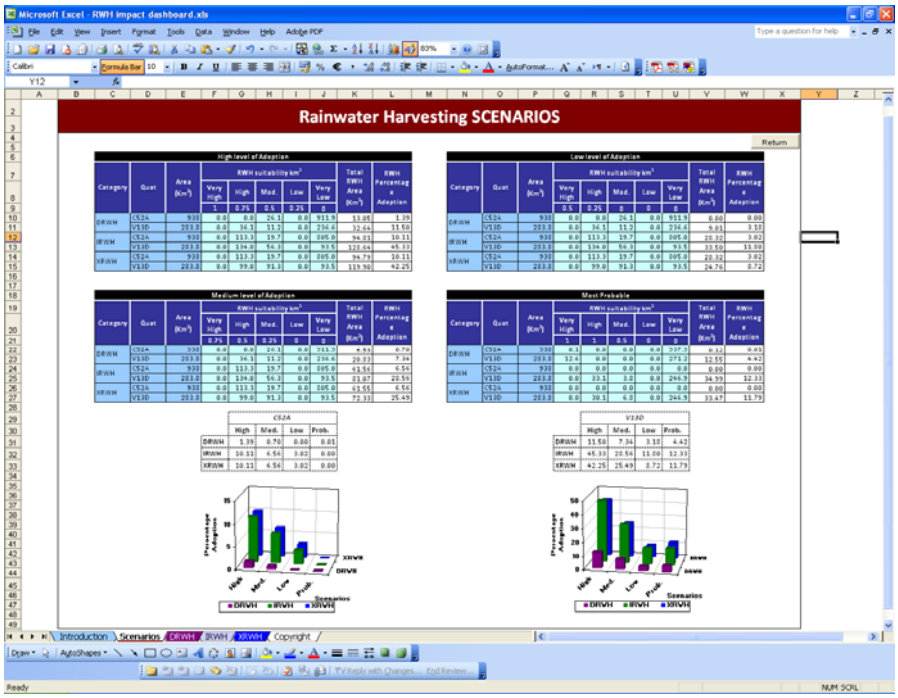
4.6 HYDROLOGICAL IMPACT

1. Open the Thukela Suitability IRWH 34,33,33 file located in C:\ESRI\RHADESS\RwhDuments\RwhExcel and determine the land area of each suitability class (5 = very high, 4 = High, 3 = Moderate, 2 = Low while 0 and 1 =Very low) for the Emmaus quaternary catchment.

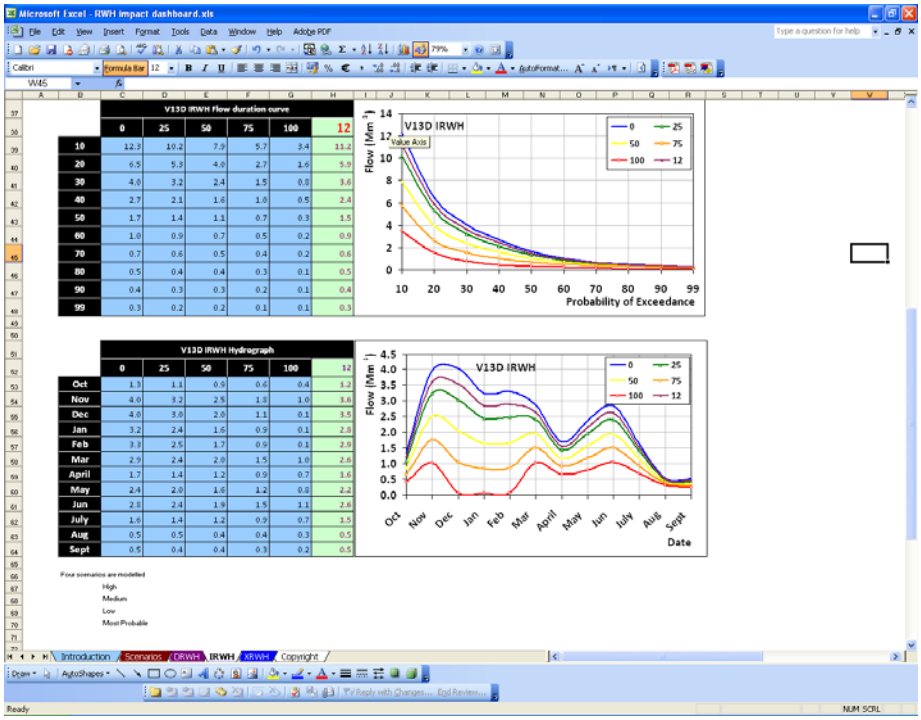


The third column (C) gives the suitability class while the fifth (E) and eighth (H) columns gives the area in km^2 and the quaternary catchment.

2. Open the folder "C:\ESRI\RHADESS\RwhDocuments\RWH Impact", open the RWH impact dashboard file and insert the different suitability class area in the Scenario worksheet. Once the percentage of each suitability class is selected, the percentage adoption of RWH in V13D is determined.



3. The impact can be seen on the IRWH worksheet on the IRWH flow duration curve and the hydrograph.

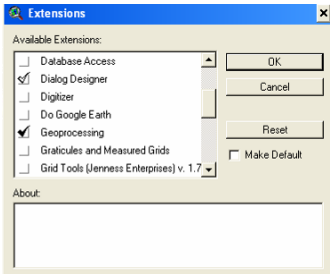


If the following screen appears, click the ok button 



Do the following:

- Open the extension and tick Geoprocessing



- Save the project
- Open the extension and untick geoprocessing
- Once again save the project.