# Exploring the Potential for the use of Remote Sensing Technology and GIS to aid the Upscaling of Rainwater Harvesting in Sub-Saharan Africa

**by**

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## PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Hydrology, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The research was financially supported by the European Community's Seventh Framework Programme [FP7/2007–2013], under the WHaTeR project (Water Harvesting Technologies Revisited) Grant Agreement No. 266360.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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Signed: Prof. Graham Jewitt

Date:

## DECLARATION 1: PLAGIARISM

I, Lauren Michelle Bulcock, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been re-written but the general information attributed to them has been referenced;

b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

(vii) this dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

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Signed: Lauren Michelle Bulcock

Date: 18 August 2016

## DECLARATION 2: PUBLICATIONS

My role in each paper and presentation is indicated. The * indicates corresponding author.

### Chapter 2

1. Bulcock, L.M.* and Jewitt, G.P.W. 2013. Key physical characteristics used to assess water harvesting suitability. Physics and Chemistry of the Earth 66 (2013) 89–100.

This review paper takes the place of the literature review. I collected the data through an extensive literature review, analysed the data and wrote the paper.

### Chapter 3

2. Bulcock, L.M.*, Schulze, R.E. and Jewitt, G.P.W. Global change and Rainwater Harvesting: A southern Africa case study. Poster presentation at XXV IUGG General Assembly (Melbourne, Australia, 28th June to 7th July 2011) and oral presentation to 16th SANCIAHS Conference (Pretoria, South Africa, 1st to 3rd October 2012).

This paper is an analysis of the potential impacts of climate change on domestic rainwater harvesting yields in southern Africa. Downscaled climate change scenarios were supplied by the CSAG at University of Cape Town. I designed the methodology, analysed the data and wrote the paper.

### Chapter 4

3. Bulcock, L.M.*, Chetty, A.S. and Jewitt, G.P.W. Exploring the Potential for using Remote Sensing Technology to Identify Existing Water Harvesting Sites. Oral presentation to the 6th World Water Forum (Marseilles, France, 12th to 17th March 2012) and oral presentation to 17th SANCIAHS Conference (Cape Town, South Africa, 1st to 3rd September 2014).

This paper is an analysis of remote sensing data collected until 2015. I designed the methodology, processing of images was done with the assistance of Chetty, AS and I analysed the data and wrote the paper.

### Chapter 6

4. Bulcock, L.M.* and Jewitt, G.P.W. 2015. Exploring the Potential for using Remote Sensing and GIS to Identify Potential Water Harvesting Sites.

This work is an analysis of remote sensing and GIS data collected until 2015. I designed the methodology, analysed the data and wrote the paper.

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Signed: Lauren Michelle Bulcock

Date: 18 August 2016

**ABSTRACT**

Increased strain on water resources across the globe, and particularly in Sub-Saharan Africa, has resulted in increased vulnerability of those communities who rely directly on rainfall to sustain their livelihoods, through crop production, water for drinking and domestic purposes and other economic activities. This dynamic interface between people and the environment is central to the current decadal research theme of the International Association of Hydrological Sciences (IAHS) "*Panta Rhei*" – everything flows, emphasises that greater recognition and understanding of the interconnection between human action and water resources, and how in order for development plan to be sustainable they must take greater cognisance of the dynamic interface between people and the environment.

Applying this philosophy to the subject of RWH suggests an alternative approach to the traditional guidelines for assessing RWH suitability approach. A review of the conditions under which RWH currently take pace was done and found that guidelines often only prescribe optimal conditions for RWH which results in many sites which may be suitable being over looked. Results show that RWH is taking place under a much broader range of conditions than those recommended by the guidelines. An alternative approach was investigated which rather aims to assess how much water a selected RWH system can supply in any location, applied at a regional scale across the whole of South Africa, under both present and shifting climate conditions as well as optimising the water storage tank to secure a certain level of supply. Results showed that the eastern portions of South Africa were best suited to RWH with supply being secured for 100 -200 days of the year. However this also highlighted that a multiple source water supply system, which can dynamically adjust to supply water from different sources depending on water supply, will be more sustainable. This will allow water demand for different uses to be satisfied for different supplies, rather than a conventional piped water supply system which provides one quality of water, often drinking water standard, for domestic consumptions where up to 70% of water use is not used for direct consumption.

In order to design a dynamic sustainable system, continuous monitoring is needed to understand the constant changes in the system. One such monitoring tool gaining popularity in water resources is remote sensing (RS). RS technology was used to calculate total evaporation (ET) and the normalized difference vegetation index (NDVI) as indicators of the

current implementation of RWH. This allows for a census technique to monitor the extent and uptake of RWH systems as well as evaluate the performance of different systems in increasing soil water or water available to plants. Results show that large scale techniques such as the spate irrigation in Tanzania or mass implementation of smaller techniques, such as the "Zai Pits" and contour bunds in Burkina Faso were visible from calculated ET maps. The contour bunds were the most successful in storing water, in the soil profile, for plant use with higher ET being measured from the bunded system compared to the surrounding landscape well into the dry season. However, the fields irrigated by micro-basin plastic storage tank systems in South Africa were not visible from ET maps but were visible from NDVI maps in summer. RS is also used to monitor the extent of less transient factors, such as slope and soil types, which influence the runoff potential that can be generated and then stored. Using RS at a catchment or sub-catchment scale will allow planners to evaluate the runoff potential of a landscape and design a RWH system that can sustainably capture and utilise that runoff. RS can also be used to monitor the impacts of the RWH system on the landscape by continuously monitoring the changes in ET, NDVI, soils and slope over time. RS provides a cost and time effective method for doing this from a remote location.

## ACKNOWLEDGMENTS

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# CHAPTER 1: INTRODUCTION

## 1.1 Rationale for the research

Growing population have placed increased strain on water resources across the globe, and particularly in Sub-Saharan Africa, and have resulted in increased vulnerability of those communities who rely directly on rainfall to sustain their livelihoods, through crop production, water for drinking and domestic purposes and other economic activities. These anthropogenic strains are in turn impacting how ecosystems function and altering the balance of biodiversity and ecosystem functioning. This dynamic interface between people and the environment is central to the current decadal research theme of the International Association of Hydrological Sciences (IAHS) - "*Panta Rhei*" everything flows. Panta Rhei emphasises that greater recognition and understanding of the interconnection between human action and water resources, and how in order for development plan to be sustainable they must take greater cognisance of the dynamic interface between people and the environment. Panta Rhei was perhaps the most famous view of philosopher Heraclitus of Ephesus, who died approximately age 60 in 535 BC, and is popularised today in the saying "No man ever steps in the same river twice". This philosophy emphasises that everything in the world is constantly changing and all processes are constantly changing and so our understanding needs to encompass this change. Many regional hydrological modelling studies rely on regional or global datasets as inputs. However these datasets lack the spatial resolution required to represent the spatial variability in the datasets such as vegetation and soil types which will greatly influence the accuracy of a model (Andersson et al., 2015). Andersson et al. (2015) also found that refining inputs such a catchment delineation or meteorological inputs had a notable impact on model results, hence the need for methods to access data as fine spatial and temporal resolution is paramount. Heraclitus explains further that the act of stepping into the river, changes not only the man who steps into it, but also changes the river. This philosophy, when applied to the very suitable topic of hydrology, requires not only a recognition that hydrological cycle is dynamic in its own right, then both changed by and changing of human population but also requires that development plans incorporate ways to assess and monitor this dynamic change constantly, and that plans be readjusted to limit environmental degradations while still allowing sustainable human development. Andersson, et al. (2015) notes that large river basins are often highly impacted by human activity. Data which monitors this impact is seldom available at a regular enough spatial scale to make a meaningful impact to modelling studies however new technology such as remote sensing technology is rapidly improving this.

Broadly, RWH can be defined as the concentration, collection and storage (in different structures or in the soil) of rainwater or runoff for use either on-site or at a different location, immediately or at a later time (Siegert, 1994). RWH aims to improve the efficient use of rainfall by capturing it on the site where it falls or capturing the runoff it generates and storing it for later use to supplement plant water requirements (Rockström, 2000; Agarwal, 2001; Ziadat et al., 2006). RWH is limited to in-field or small scales ex-situ catchments and water is generally not available throughout the dry season. It differs from conventional irrigation in that water is not normally available throughout the dry season from RWH structures (Mbilinyi et al., 2005). In the case of crop production, RWH aims to decrease the amount of rainfall "lost" through unproductive evaporation, namely soil evaporation, litter and canopy interception and through runoff and to increase the amount of water available to the plant for productive crop transpiration and as a result increase crop growth and production.

Rainwater harvesting (RWH) has been promoted as an alternative water supply strategy to increase water security, help safeguard the livelihoods of these vulnerable communities, reduce and even reverse anthropogenic induced landscape degradation and provides an adaptation strategy against climate change. Lebel et al. (2014) evaluated RWH as a climate change adaptation strategy at a continental scale and found that RWH could improve the yield deficient of maize by 40% under current conditions and 31% under climate change conditions expected in the 2050's.

The United Nations (UN) state that approximately 795 million people are undernourished and more than 90 million of these are children (UN, 2008). Furthermore, agriculture is the single largest employer in the world, with 40% of the world population engaged in agricultural activities as employment or to sustain their livelihoods (UN, 2015). Target 1C of the Millennium Development Goals (MGDs) aimed to halve the number of people who suffer from hunger (UN, 2008). The Sustainable Development Goals (SDGs) Goal 2 aims to reach the other half and have zero hunger by 2030 by focusing on people centred rural development and agricultural opportunities and systems that will help halt or reverse degradation of the environment (UN, 2015). RWH for agricultural application has been widely studied. Jägermeyr et al. (2016) investigated how improved crop water management, including RWH, would improve crop yields and found that overall improved water management could increase productivity by 41% at a global scale, with 26% of this increase being attributed to low-tech irrigation solutions. Rost et al. (2009) suggested that global crop production could increase by 19% under future climate conditions which is similar to the improvements in yield which have resulted from the implementation of irrigation system under current climate conditions. The impact is even more relevant when considering that global yields are predicted to decrease by 9% under climate change conditions, if no water saving adaptations are implemented. If agricultural practice and strategies do not adapt to more water smart strategies, then more people might be unemployed in the future, further exasperating other development challenges such as the estimated 1 billion people living in extreme poverty such SDG 1 aims to address (UN, 2015).

Approximately 2.6 billion people worldwide still do not have access to improved drinking water sources and 2.4 billion are still using unimproved sanitation facilities, with 946 million of these having no access to improved and enclosed sanitation facilities at all (UN, 2008). Water scarcity, poor water quality and inadequate sanitation threaten the livelihoods of people in many ways. Drinking and cooking with contaminated water can cause a variety of disease leading to poor health and death. Unicef reports that in 2013 up to 1800 children died from water related diseases everyday (Unicef, 2014). Target 7C of the MDGs aimed to reduce by half, the number of people without access to clean drinking water (UN, 2008). Goal 6 of the SDG aims to reaching the remaining half and to provide access to water and sanitation for all (UN, 2015). Closely link to this is MDG 3 and SDG 5 focused on achieving gender equality and empowerment for women and girls. Since household chores, such as fetching water is often a female responsibility, many women and girls spend a large proportion of their day collecting water. This means rural girls sometimes are not able to attend school which reduces their education levels, the future employment opportunities and traps them in the poverty cycle (UN, 2008, UN, 2015). RWH is one strategy that can held society to reach the MDGs and SDGs. RWH provides a source of water close to people's homes, improving their access to water and helping to secure their livelihoods. This can help achieve the MGD goal 7C and SDG goal 6 by providing an improved source for water. Chapter 3 discussed the potential for RWH for providing a domestic water source in a case study of South Africa.

As such many sub-Saharan African governments are including RWH in their policies and programmes. However, currently there is no global census of the extent of RWH practices, no comprehensive understanding of the full range of conditions under which RWH can take place, few measurements of the effectiveness of RWH at field scale and no true understanding of the potential for RWH in a catchment. Uptake of RWH is usually on an ad-hoc or user driven basis. However if governments want to promote RWH as an alternative, sustainable water supply solution, a more comprehensive approach which draws on existing knowledge and new techniques is required. This thesis aims to demonstrate how GIS, remote sensing (RS) and statistical analysis can be used as tools to assess the current extent of RWH, the full range of conditions under which RWH can take place, assess the potential of an area to support RWH structures and assess the potential volume of water that can be harvested for a RWH structure. It also aims to show that technology such as remote sensing and GIS can be used to monitor dynamic hydrological systems and monitor both positive and negative changes caused by RWH systems to the environment.

### 1.2 Justification

The key aim of most hydrological studies and one of the missions of the International Association of Hydrological Sciences and the UNESCO IHP-VIII is to advance the science of hydrology for the benefit of society, with a key focus being placed on parts of the world which experiences severe water problems. The World Economic Forum highlighted water as the number one global risk in the next ten years in the 2015 Global Risk Report. In addition, The World Bank identifies climate change as a major threat the development of countries and people, with the poor being the most vulnerable. They warn that 1.5°C increase in global temperature from the pre-industrial times is now unavoidable and will result in increasingly extreme weather, increased risk to food and water availability and increased energy insecurity. The impacts of rapidly changing human systems often have the greatest impact on already water scarce areas.

Panta Rhei in the context of rainwater harvesting requires an approach that allows for learning from already existing RWH systems, to understand which type of system is best suited to each environment, rather than what type of environment is suited to a RWH system. Traditional RWH criteria are too rigid and do not allow for the examination of the natural and human induced fluxes of the landscape. Landscapes may be discounted as not suitable under this approach, when potential does exist for RWH and where RWH could improve the landscape. Human activities, for example intense, low input agriculture, can deplete top soil therefore reducing the depth, removal of organic matter and remove natural vegetation. However, good agricultural practices can increase top soil depth, increase organic matter and promote the growth of natural vegetation between crop fields. This “reversal” of suitability assessment would allow for site specific examination of the interconnections between the people using that RWH system and its impact on the environment. Some of the criteria used assess RWH suitability, such as soil depth texture and vegetation are dynamic. Implementing a RWH system will change the environment, much like Heraclitus theory of stepping in the river changes the river, and so an approach which rather looks at which system would work better in each landscape, would be better suited to ensuring sustainable development and supplying water to people who need it. This approach is discussed in Chapter 2.

Often, the argument come up that if a system is dynamic, and constantly changing, how can a development plan be designed that can account for and adapt to this. Decentralised systems are often more flexible and allows for system changes more than large centralised one. In terms of water supply, small decentralised systems which combined multiple water sources for different uses are increasingly being considered as more sustainable solution to large centralised dams. Large dams can cause considerable impact of river systems and are inflexible to environmental change and supply one quality of water, often to drinking water standards, for uses that often don’t require water to this standard. Chapter 3 looks at the potential for supplying water form a rooftop RWH system for none potable supply. Gleick (1996) showed that up to 70% of domestic water supply is used for non-potable uses such as cleaning and sanitation. However all piped water to domestic households is cleaned to drinking water standards, requiring considerable cost and infrastructure layouts. A multiple source water supply system, which can dynamically adjust to supply water from different sources depending on water supply, will be more dynamic and allow water demand to be satisfied while limiting the demand on potable water supplies. Chapter 3 explores a method for determining how large a rooftop RWH tank is needed to fulfil different levels of supply surety at the study site and how often that tank would be able to supply water to domestic needs.

In order for a development plan to adapt to dynamic systems, a system for monitoring the performance of plan and its impact on the environmental needs to be implemented and plans need to adjusted according to these monitored changes. As the world and society changes, so does the technology we can use to monitor and analyse data. Advancements in technology allow us to study the world in ways that were not possible before and to answer questions that we were unable to before. One of the advancements gaining popularity for application in the field of hydrology and water resources is remote sensing. Satellite technology allows scientists to study and monitor water issues across a much broader range of spatial scales and from a remote location. This has alleviated many of the issues of traditional data collection and monitoring in remote locations which has made studies laborious, costly and time consuming. A core component of this study is to explore the potential for using remote sensing to identify existing and potential RWH sites, to assist in future water resources monitoring and planning. Chapter 4 and 5 investigates the use of remote sensing and GIS as methods to monitor the transient environmental factors, such a moisture and vegetation dynamics as well as more gradually changing factors such as slope and soils, respectively. Utilising technologies such as RS, which allows for monitoring at large spatial scales and at regular temporal intervals and from a desktop in a location often less remote than the site being studied, will allow for a greater understanding of the dynamic system in which the RWH system is being implemented as well as allow for the monitoring of change that the RWH system introduces to the landscape. Continuous monitoring will allow for fine tuning of the system to reduce negative environmental impacts. It will also allow for the monitoring of how the RWH system may be positively impacting the environmental, for example through increased soil moisture.

## 1.3 Aims

The aim of this research was to explore the potential for using statistical analysis, remote sensing and GIS technology as an approach to promote and monitor the uptake of RWH. Exploring the potential of using this technology to assess the capacity of a landscape for the implementation of additional RWH structures allows for the monitoring and implementation plans to be carried out over a large spatial scale which is useful to planners in their efforts to upscale RWH in sub-Saharan Africa. The approach of this thesis was to move away from guidelines which restrict the possibility of implementing RWH systems and rather focus on ways to assess the potential of a landscape to sustain a successful RWH system and supply water where it is needed by people, for domestic purposes or agriculture.

## 1.4 Objectives

The objectives of this thesis were:

- To assess whether current, commonly used, guidelines for RWH encompass the full range of condition under which RWH currently takes place and whether these still provide a useful framework for RWH planning in a shifting social, environmental and hydrological cycle (Chapter 2, Paper 1).

- To explore the potential for an alternative approach which aims to assess how much water a selected RWH system can supply in any location in South Africa under both present and shifting climate conditions (Chapter 3, Paper 2).
- To explore the role remote sensing and GIS can play in identifying existing RWH structures, as well as the performance of these systems with the landscape, to allow planners to fully understand the current scale of RWH implementation and to assess where RWH has already gained societal acceptance (Chapter 4, Paper 3).
- To explore the potential for using remote sensing and GIS to assess the potential harvesting capacity of a selected location (Chapter 5, Paper 4).

### 1.5 Outline of dissertation/thesis structure

Each chapter is mostly self-contained, containing a literature review, methodology, results and discussion, and conclusions. The concept of exploring how RWH can help address water needs and how remote sensing, GIS and statistical analysis can help assess this is central to all the papers.

Chapter 2 is a review paper which explores whether commonly used guidelines, the current framework for assessing RWH suitability, encompass the full range conditions under which RWH can take place. This paper aims to assess whether a new framework is needed, which aims to find the best system to be implemented in each location rather than a guideline framework, which aims to classify only suitable locations.

Chapter 3 is a case study on South Africa and how global drivers are promoting the uptake of RWH. It highlights the importance of incorporating RWH into a water supply system and provides a study of the potential in South Africa for a certain type of RWH, i.e. roof collection into plastic storage tanks, to supply all or a portion of domestic water needs across South Africa.

Chapter 4 explores the potential of remote sensing for identifying existing RWH sites in several locations in Africa. This can help planners to understand the current scale and level of societal acceptance of RWH. It can also further help understand how successful certain types of RWH structures are in certain landscapes.

Chapter 5 explores the potential for remote sensing and GIS to calculate the capacity of a landscape to generate runoff which can be harvested in RWH system. This allows planners to place a RWH structure in the best location within a landscape and to understand the potential harvest that system can capture.

The final chapter, Chapter 6, integrates the work, provides conclusions and documentation of the contributions of this research.

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# CHAPTER 2: REVIEW PAPER - KEY PHYSICAL CHARACTERISTICS USED TO ASSESS WATER HARVESTING SUITABILITY (PAPER 1)

Bulcock, L.M.* and Jewitt, G.P.W. 2013.
Physics and Chemistry of the Earth 66 (89-100).

**Abstract**

Water harvesting (WH) techniques, which aim to increase water availability to crops, have long been used in arid and semi-arid areas to decrease the risk of reduced yields and crop failures due to dry spells. The landscape conditions dictate the type of WH system that can be implemented as well as the quantity and quality of water that will be collected. The measurement and understanding of how these landscape characteristics influence the hydrological function of WH systems is important and essential for further studies which seek to understand and enhance efficiency, extend uptake and model the impacts of WH within a catchment. However, commonly used guidelines often only prescribe optimal conditions for WH which results in many sites which may be suitable being over looked. Various statistical analyses was performed on 28 WH sites gathered from the available literature to try and identify whether the landscape conditions under which WH is currently taking place differs to the recommended guidelines. The results show that WH is taking place under a much broader range of conditions than those recommended by the guidelines. The recommendations for minimum and maximum slope in particular are too restrictive, with examples of successful WH taking place on slopes much steeper than the stipulated guidelines. A new set of guidelines are suggested, which take into account not only optimal conditions but also a range of suitable conditions on either side of the optimal range.

***Keywords:*** *Water harvesting, site characteristics, upscaling, statistical analysis, site guidelines*

## 2.1 Introduction

Approximately 70% of the world's poor live in rural areas where they have little option but to rely on rainfed agriculture to sustain their livelihoods (CAWMA, 2007). The spatial and temporal distribution of rainfall in semi-arid regions varies greatly. When rainfall is characterised by few, high intensity events, water may not be available for crops during critical growth periods (Rockström, 2000). Dry spells during critical crop growth periods and drought further exacerbate the vulnerability of poor people relying on rainfed agriculture (CAWMA, 2007). Dry spells and mid-season droughts, rather than an overall reduced mean annual precipitation (MAP) can, and often do, cause crop failures (Rockström, 2000).

### *2.1.1 The Context of Water Harvesting*

As a result, the adoption and development of water harvesting (WH) strategies to ensure the efficient use of water and sustain human livelihoods, both for domestic and agricultural purposes, has evolved over centuries (Rockström, 2000; Vohland and Barry, 2009; Bossio et al., 2011).

Broadly, WH can be defined as the concentration, collection and storage (in different structures or in the soil) of rainwater or runoff for use either on-site or at a different location, immediately or at a later time (Siegert, 1994). WH aims to improve the efficient use of rainfall by capturing it on the site where it falls or capturing the runoff it generates and storing it for later use to supplement plant water requirements (Rockström, 2000; Agarwal, 2001; Ziadat et al., 2006). WH is limited to in-field or small scales ex-situ catchments and water is generally not available throughout the dry season. It differs from conventional irrigation in that water is not normally available throughout the dry season from WH Structures (Mbilinyi et al., 2005). In the case of crop production, WH aims to decrease the amount of rainfall "lost" through unproductive evaporation, namely soil evaporation, litter and canopy interception and through runoff and to increase the amount of water available to the plant for productive crop transpiration and as a result increase crop growth and production.

Whilst the Sharm el Sheik commitment's highlight the intention to increase the portion of domestic water provided by WH systems in Africa to 15%, there are also continued efforts to expand the use of these small scale systems, particularly in areas not considered suitable for conventional irrigation development, but also an alternative thereto (AMCOW, 2008; AMCOW, 2012). Modern WH systems have often evolved from traditional or indigenous systems and coupled with improved agronomic practices have been shown to have much potential in enhancing crop production (Falkenmark et al., 2001; Mbilinyi et al., 2005). There remains much to be learned from the indigenous systems, however, such improvements often include the use of more modern materials, different seed types and the application of fertiliser and herbicides. Such investment requires a sound site suitability assessment but this is an aspect where knowledge needs to be improved. Recommendations regarding, which WH system is best suited to a potential site, how it could be implemented or where it should be sited requires through analysis of existing successful systems.

Water harvesting techniques can be divided into two main categories, namely in-situ and ex-situ. In-situ WH involves capturing runoff generated in the field or cultivation sites where the crops are grown. Examples include pitting (Figure 2.1a) and semi-circle or contour bunds (Figure 2.1b). Ex-situ WH collects runoff from a larger area and stores it in a storage area that is not adjacent to the runoff generation area. The water may then be transported to the cultivation area via channels or ducts (Gowing et al., 1999). Examples of techniques used include terraces and dead level terraces (Figure 2.1d, e and g) and runoff storage tanks (Figure 2.1f) (Rockström, 2000; Agarwal, 2001; Desai and Ghose, 2001; Gandhi and Kirtane, 2001; Oweis et al., 2004; Nissen-Petersen, 2006). Other examples of macro-catchment WH include sand and sub-surface dams, small earthen dams with in-flow channels which are often built in existing depressions (Figure 2.1c), flood irrigation and stone lines (Figure 2.1h).

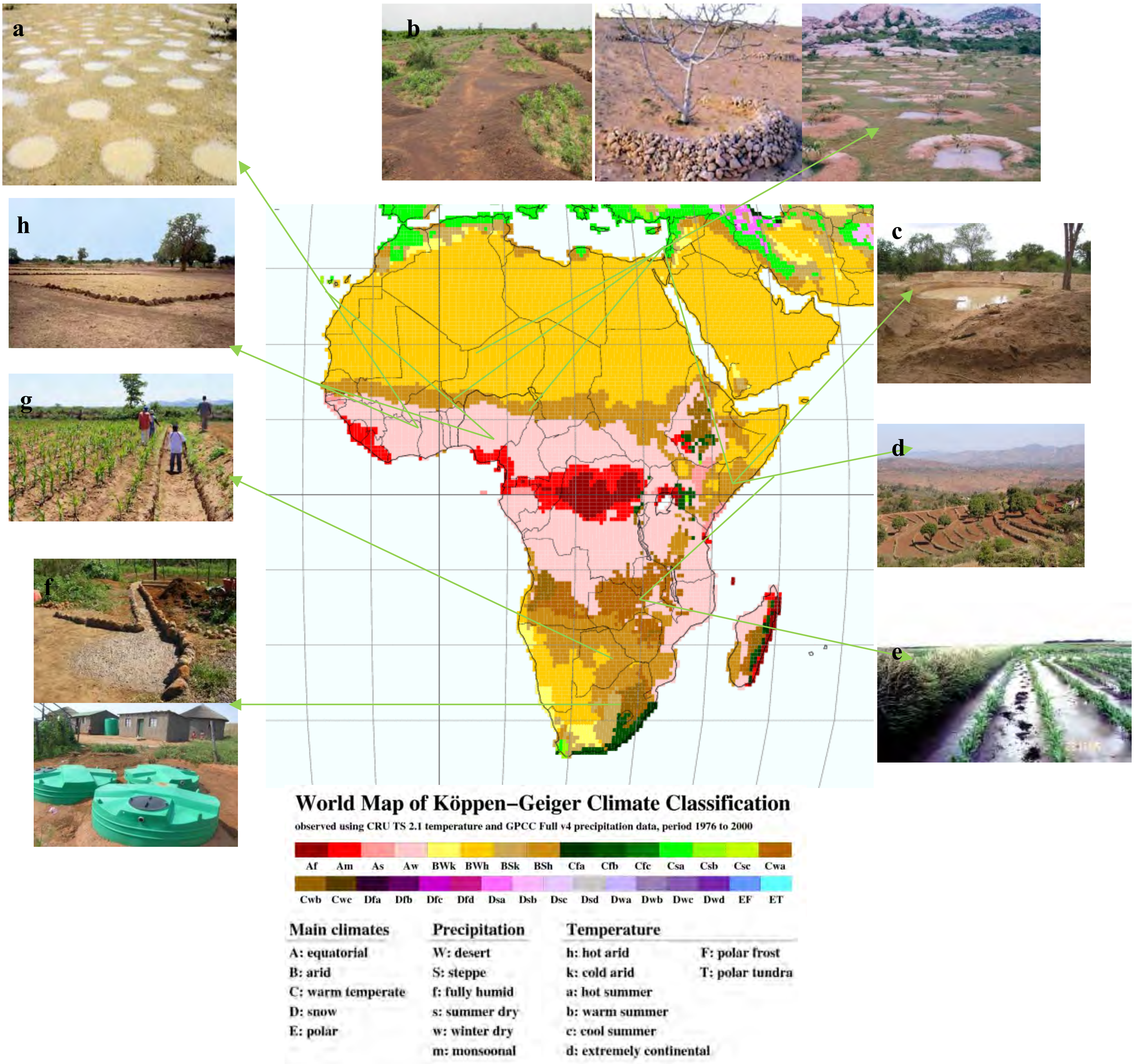


**Figure 2.1 (clockwise from top left) a- Zai Pitting in Burkina Faso and Niger (rainwaterhavesting.org), b- Contour bunds/demi lunes in Kenya, Mali, Niger Burkina Faso (rainwaterhavesting.org) , c- micro runoff dames in Kenya (Nissen-Petersen, Kenya), d and e- contours with borders of stone or grass in Kenya and Zambia (Hanspeter Liniger, WOCAT), f- surface runoff collection into tanks in South Africa (SSI project, UKZN), g- dead level contours in Zimbabwe (Mupangwa, Waternetonline) and h- stone lines in Burkina Faso and Niger (ICRISAT).**

## 2.2 The Key Physical Characteristics of Water Harvesting Sites

### *2.2.1 Criteria used to determine the suitability of water harvesting sites*

Extensive literature exists on the social and economic value of WH sites and how they benefit the communities that use them (Warren et al., 2003; Mbilinyi et al., 2005; Kessler, 2006; Kessler, 2007; de Graff et al., 2008). Research has also been done to assess the suitability of selected research catchments for the siting of WH structures. Most of these studies (which are discussed in Section 2.2.2 below) use one of three sets of criteria (or derivative thereof) developed by Critchley et al. (1991), Oweis et al. (1998) or the Integrated Mission for Sustainable Development (IMSD) for devised to determining the physical suitable of sites for WH technologies in India (in Singh et al., 2009). These guidelines are described in Table 2.1 The guidelines of Oweis et al., (1998) are the most encompassing through consideration of the often difficult terrain WH system can exist in and can operate under. They determine criteria for different types of WH structures and set ideal and suitable limits for factors such as soil texture, soil depth, slope and vegetation and stoniness. Oweis et al. (1998) specify requirements specific to different types of agriculture, i.e. the requirements for trees are different to field crops and to rangelands grazing. For example, trees require deeper soils (>100cm) with a heavy texture, field crops require a medium depth soils (50 – 100cm) with a medium texture while rangeland grazing can have shallow soils (<50cm) with a medium texture. The ranges for slope are also more encompassing with contour benches being suitable to steep slopes (>12%) while contour ridges and small basins are suitable for gentle (<4%) to medium slopes (4 –12%). These criteria are used by Ziadat et al. (2012) in assessing WH investment potential in Jordan using data collected through field survey and analysed in a GIS system.

**Table 2.1 Commonly used guidelines for determining water harvesting site suitability**

| | Author | | |
|---|---|---|---|
| | Critchley *et al*. (1991) | Oweis *et al.* (1998) | IMSD (in Singh *et al.*, 2009) |
| **Mean Annual Precipitation (mm/a)** | <150 – 750 | 50- 300 | Not defined |
| **Slope (%)** | Runoff generation: short, steep slopes<br>Runoff collection: <5% | <4% | <15% |
| **Soil Texture (class)** | Medium textured loamy soils are best, otherwise all which are suitable for agriculture. | Not defined | System dependant: percolation tanks suited to sandy soils, ponds suited to clay soils |
| **Soil Depth** | <1m is unsuitable, 2m is ideal but rarely found | <50cm | Not defined |
| **Other** | Not defined | Not defined | Land use should be barren, scrubland or bare soil |

### *2.2.2 Methods used to determine the suitability of water harvesting sites*

Malesu et al. (2007) uses criteria, largely governed by the FAO standards, for creating index maps of Africa for the suitability for 4 different types of WH systems, rooftop runoff tanks, ponds and pans, flood diversion and flow storage (i.e. sand dams) and in-field techniques such as zai pitting and terracing. They indicate that rainfall >200mm/annum is sufficient for all methods, slopes of <2% were best suited to most techniques however ponds could be situated on slopes up to 8%. Soils with low permeability are indicated, except for sand dams where fluvial soil must be present. However, saline soils are not suitable for in field techniques. One of the major constraints to the study of Malesu et al. (1997) is the lack of data. Some assumptions, such as that all agricultural land is suited to infield WH, will result in an over estimation of land suitability for WH. Furthermore, an exclusion of all other land currently not under agriculture will also skew results as this land may be underutilised for other reasons such as restrictions due to conservation areas, transport infrastructure, political or social reasons.

Singh et al. (2009) use the water balance approach together with the Integrated Mission for Sustainable Development (IMSD) guidelines for determining WH site suitability. These guidelines are specific to different types of WH systems and are more lenient in their site specifications than the Critchley et al. (1991) guidelines. Slopes up to 15% are considered suitable for some systems, while soil texture characteristics are specific to the type of systems, e.g. soils in the ponds should have low infiltration rate while soil around the percolation tanks should have a high infiltration rate. These guidelines are more encompassing of the difficult climates under which WH systems are often founds. The land use guidelines present many challenges. Singh et al. (2009) recommends land use classes such as shrub land, barren land or bare soils. These are often not used for agriculture, therefore suitable sites may be identified which are located far from where the water is needed. Water harvesting structures are often small and can be fitted within the farm lands/cultivated areas therefore to exclude this land use is restrictive.

Some practitioners and authors have amended the available guidelines to be more encompassing of local conditions. Al-Adamat et al. (2010) researched WH suitability in Jordan and ranked characteristics on a scale of 1-4 (with 4 being the most suitable) to develop a multi-criteria decision support system. MAP was ranked with <100mm/a being least suitable and >500mm/a most suitable, slope <3% most suitable while slopes >10% least suitable, soils with clay content <10% as least suitable and clay content >35% most suitable. This allows marginal areas which may have only 2 of the 3 criteria regarded as suitable to be still be considered. For example, an area with clay soils >35% and a slope of <3% but MAP of <100mm/a can still be ranked as suitable, even though not all the selection criteria have been meet. Al-Adamat et al. (2012) also altered the criteria so that MAP >50mm/a, slope <5% and soil texture classified as silty loam, loam and silty clay loam were all considered suitable for WH. However, the rankings in a multi-criteria decision support system such as that utilised by Al-Adamat et al. (2010), can be somewhat subjective. Al-Adamat et al. (2010) acknowledge that in reality soil texture can be the deciding factor in determining site suitability; however they only rank soil texture as the third most important factor (3 out of 6). Rainfall has the highest ranking, even though they describe it is the least determinate factor. Furthermore, how the ranking of the criteria was determined is not well explained and can have a great influence on the results.

The SCS-Curve Number (SCS-CN) approach has been used by many authors as an alternative approach to determining catchment suitability for WH. Land use, slope, soil class and anticedal soil moisture conditions are used to assess how much runoff can be generated from a runoff area. This is often overlaid with drainage patterns within the catchment and the areas with the highest runoff generation capacity and closest to existing drainage lines are considered most suitable location for a WH structure. This approach is used by De Winnaar et al. (2007) in South Africa; Munyao (2010) in Zanzibar; Wang et al. (2012) in China and

Gupta et al. (1997); Ramakrishnan et al. (2009); Kadam et al. (2012) and Sharma and Singh (2012) in India. Senay and Verdin (2004) used the SCS-CN approach to produce low resolution index maps for the whole of Africa.

Jasrotia et al. (2009) used a water balance approach for determining the suitability of WH sites. Remote sensing data from the Indian satellite IRS-1D (LISS+PAN) and GIS techniques were used to determine the runoff potential (using the Thrornthwaite and Mather (1955) (TM) Model) of various land use types in Jammu Himalaya in India. Runoff potential was determined using rainfall and temperature data. THE IRS-1D data was used to create a land use map which was intersected with a soil texture map. A topographical map was used to create a slope map using a Digital Elevation Model (DEM). Runoff potential was ranked on a scale from low to high and then overlaid with a drainage channel map to confirm water availability. Lastly, settlements were given a 500m exclusion buffer. This method determined that 11% of the Devak-Rui catchment in Jammu Himalaya, India was suitable for WH (Jasrotia et al., 2009).

Elewa et al. (2012) mapped the potential of the Sinai peninsula in Egypt for WH. A watershed modelling system was combined with a multi-criteria decision support system using 9 thematic layers related to catchment hydrological characteristics such as the volume of annual floods, drainage frequency, maximum flow distance basin slope and area. They found that between 5 – 12% of the catchment was considered highly suitable for WH while 64% was considered moderately suitable. This is despite the annual MAP of the Sinia peninsula being <100mm/a in most areas, with only 5 to 15 rainfall days per year. This suggests that the criteria set out by many authors is too limited and that redefining the criteria used to assess the suitability of an area for WH may identify much greater potential for WH than most approaches predict.

With so many guidelines and derivatives being used to determine suitability, it is difficult to assess which are the best methods for site selections. Water harvesting often takes place in less than optimal conditions as it is in these areas where it is most needed. However it appears that by applying the criteria set by some authors, especially the FAO guidelines, many sites currently under WH would not be classified as suitable.

### *2.2.3 Data Sources*

Several studies have used GIS and/or remote sensing to locate sites suitable for both macro- and micro-catchment rainwater harvesting schemes based on these criteria (Al-Ahmed et al., 2008; Sekar and Randhir, 2006 and 2007; De Pauw et al., 2006; Bodhankar, 2004; Durga Rao and Bhaumik, 2003; Oweis et al., 2001; Patrick, 1997; Mwenge Kahinda et al., 2009; Mbilinyi et al., 2005). The FAO guidelines for the siting of rainwater harvesting ponds as well as other FAO documents on WH are also based on the Critchley et al. (1991) criteria (FAO, 2003).

One of the major constraints in the curve number approach is the resolution and quality of available input data. Ramakrishnan et al. (2009) used data from the Indian Remote Sensing Satellite (IRS-LISS-III) to prepare land use maps, a digital elevation model (DEM) derived from the Shuttle Radar Topographic Mission (SRTM) to derive the slope map and drainage lines and a 1:50000 hydrological soil group (HSG) map generated by the Indian National Bureau of Soil Survey and Land Use Planning (NBSSLUP) to provide a WH suitability map. Kadam et al. (2012) used Landsat Thematic Mapper to identify landuse. These high resolution data resulted in more accurate input data and more accurate results. However, Senay and Verdin (2004) used SCS-CN to create index maps for Africa for pond suitability using 10km resolution data. This coupled with inaccuracies in the model meant that the absolute values for runoff amounts could not be used and only a relative comparison between the suitability of areas for ponds could be done. Arguably, a 10km data resolution for identifying areas for relatively small scale structures such as WH structure is not useful. Furthermore, some assumptions made in the SCS-CN studies are bold and unsubstantiated. For example Gupta et al. (1997) assume that all areas with slopes <5% are under agricultural production and therefore can be defined as suitable to WH, this may result in an over estimation of suitability for WH. Conversely, Kadam et al. (2012) identify agricultural land as unsuitable for a WH structure, which contradicts the design and purpose of a WH structure. This results in the sites suitable for WH being located far from the fields and areas where the water is needed. Lastly, assumption in the antecedent soil moisture calculations often result in an over assumption in the runoff generation potential of the site.

A study was done to examine under what conditions WH is currently taking place, to see if there is indeed a strong correlation between the actual sites and the guidelines. Without a proper understanding or inventory of the physical characteristics of WH sites we cannot begin to understand how and why WH systems function and studies into the potential for upscaling, understanding catchment and environmental responses to WH, modelling the local and regional impacts or any other physically based studies are futile.

## 2.3 Methodology

### *2.3.1 Data Collection*

Twenty eight site reports were analysed, of which fifteen were from the World Overview of Conservation Approaches and Technologies (WOCAT) database (https://www.wocat.net/en/knowledge-base.html), eleven from peer reviewed scientific papers and two from research project reports (Table 2.2). Additional papers and reports would have been useful, however many lack proper descriptions of the study sites or are not readily available. Data regarding the physical characteristics of the site which may affect the hydrological functioning of the WH system were extracted. These include slope, soil texture and depth and mean annual precipitation. Other data extracted were latitude, longitude and altitude. Data regarding drainage patterns types, land cover and mean annual evaporation may have also been valuable but were generally not available. Even scientific papers which focus on runoff related characteristics lacked a good description of key hydrological influencing characteristics and these needed to be in-filled. The most difficult data to gather were the percentages of clay, sand and loam respectively. When this data was not available from the paper/report the authors of the papers were emailed and asked to verify the characteristics of the site. Very few responded but those that did were able to provide updated soil data or alternative references. Often a general description of the soil texture was available (e.g. sandy loam) or a ranking of the textures classes was available, (i.e. more clay than sand and more sand than loam). In these cases the percentages were estimated using the soil texture triangle (Saxton et al., 1986). Table 2.2 show the 28 sites used and their characteristics. When no information was available, the site was discarded. Sites were classified as either in-situ or ex-situ according to the definition in Section 2.1.1 above.

> Since the publication of this paper in 2013, the Africa Soils Information Service has been published (http://africasoils.net/). This database offers soils data at a 250 m resolution across most of Africa. This dataset would significantly improve this analysis and any subsequent rainwater harvesting suitability analyses.

## Table 2.2 Database of WH sites used for the PCA analysis

| Site No | Country | Catchment Name/Site location (Reference) | Latitude | Longitude | Altitude (masl av) | Type of WH System | WH Type | MAP (mm/a) | Slope Minimum | Slope Maximum | Soil Depth (cm) | %Sand | %Loam | %Clay |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | *Ethiopia | Bilate watershed (Pretorius, 2001) | 7.07 | 38.07 | 1950 | Micro catchments/ ponds | 2 | 900 | 2 | 8 | 50 | 60 | 32 | 8 |
| **2** | *Chad | Eastern Chad (Zähringer, 2012) | 11.58 | 15.46 | 550 | Water-spreading weirs | 2 | 275 | 0 | 5 | 85 | 8 | 9 | 83 |
| **3** | *China | Gansu Province, Zhuanglang County (Wang, 2006) | 38.98 | 110.94 | 1250 | Terraces | 1 | 500 | 16 | 30 | 150 | 41 | 40 | 19 |
| **4** | *Ethiopia | Bilate watershed (Danano, 2011) | 7.07 | 38.07 | 1750 | Earth checks | 1 | 875 | 5 | 8 | 100 | 41 | 40 | 19 |
| **5** | *Ethiopia | Alaba special woreda (Pretorius, 2011) | 7.49 | 38.19 | 1950 | Grass strip, bunds, contours | 1 | 900 | 2 | 8 | 100 | 69 | 26 | 5 |
| **6** | *India | Madhya Pradesh, Ratlam, Mohanpada (Gandhi, 2002) | 23.31 | 75.03 | 750 | Sand wells in stream bed | 2 | 800 | 0 | 8 | 25 | 80 | 4 | 16 |
| **7** | *India | Bijapur district, Hadalsang village, Karnataka (Metri, 2004) | 16.81 | 75.71 | 594 | Farm Ponds | 2 | 550 | 2 | 5 | 30 | 42 | 17 | 41 |
| **8** | *Kenya | KiMuiki, Kitise, Mburo, Kwa Kauisi (Pretorius, 2003) | 2.23 | 37.85 | 1000 | Retention/infiltration ditch | 1 | 350 | 6.5 | 12 | 50 | 59 | 28 | 13 |
| **9** | *Nepal | Kavrepalanchowk district/ Lamdihi, Patalekhet, Chiuribot (Dhakal, 2006) | 27.68 | 85.68 | 1000 | Plastic lined ponds | 2 | 1070 | 5 | 16 | 100 | 7 | 51 | 42 |
| **10** | *Philippines | Nueva Ecija (Pretorius *et al*., 2000) | 15.79 | 120.82 | 250 | Micro Dams | 2 | 1980 | 5 | 30 | 115 | 1 | 43 | 56 |
| **11** | *Philippines | Pangasinan, Nueva Ecija, Tarlac, Isabela, Bulacan, Ilocos Norte (Labois *et al*., 2000) | 14.79 | 120.88 | 250 | Micro Dams | 2 | 1867 | 8 | 16 | 35 | 29 | 47 | 24 |
| **12** | South Africa | Botshabelo, De Wetsdorp, Bloemfontein, Thaba Nchu (Botha, 2001) | 29.21 | 26.83 | 1508 | Micro Basins | 1 | 600 | 0 | 2 | 100 | 28 | 12 | 60 |
| **13** | *Senegal | Tabanding, Tambacounda (Ndiaye, 2010) | 13.91 | 13.41 | 50 | Concrete barrier | 1 | 750 | 2 | 8 | 35 | 20 | 9 | 71 |
| **14** | *Syrian Arab Republic | Hannaser Valley Turkelboom, 2004) | 36.28 | 37.66 | 300 | *Zai* mixed with drainage ditch | 1 | 250 | 5 | 16 | 65 | 40 | 37 | 23 |
| **15** | *Tajikistan | Kabodion / Khudoikulov, Khatlon (Firdavs *et al*., 2011) | 37.21 | 68.21 | 300 | Flood irrigation/water spreading | 2 | 100 | 0 | 2 | 35 | 94 | 3 | 3 |
| **16** | *Zambia | Southern Province (Zähringer and Maimbo, 1970) | 16.72 | 26.53 | 750 | Small earthen dams | 2 | 700 | 2 | 40 | 65 | 66 | 23 | 11 |
| **17** | South Africa | Thukela, KwaZulu-Natal (de Winnaar *et al*., 2007) | 28.81 | 29.35 | 1351 | JoJo Tanks | 1 | 1800 | 4 | 16 | 250 | 17 | 69 | 12 |
| **18** | Burkina Faso | Gampela (Spaan *et al.,* 2005) | 12.33 | 1.33 | 275 | Stone Lines | 1 | 600 | 0 | 5 | 100 | 78 | 11 | 11 |
| **19** | Mali | Kaniko, Koutlala Region (Bodnár *et al*., 2007) | 12.32 | 5.36 | 351 | Stone rows /water spreading, grass strips | 2 | 1200 | 0 | 5 | 100 | 37 | 42 | 21 |
| **20** | Jordan | North-East Jordan - S1 (Abu-Zreig and Tamimi, 2011) | 32.56 | 36.02 | 520 | Sand ditch | 1 | 211 | 10 | 12 | 750 | 22 | 48 | 34 |
| **21** | Jordan | North-East Jordan - S2 (Abu-Zreig and Tamimi, 2011) | 32.56 | 36.02 | 520 | Sand ditch | 1 | 211 | 10 | 12 | 200 | 14 | 48 | 38 |
| **22** | China | Gaolan County, Lanzhou, Gansu Province (Li and Gong, 2002) | 36.22 | 103.78 | 1780 | Micro compacted plots | 1 | 263 | 7 | 8 | 100 | 12.3 | 66.9 | 20.8 |
| **23** | South Africa | Thohoyandou, Limpopo (Mzezewa *et al*., 2011) | 22.97 | 30.43 | 596 | Micro-catchments | 1 | 450 | 2 | 8 | 180 | 27 | 24 | 49 |
| **24** | India | Udhagamandalam, Tamil Nadu (Madhu *et al*., 2011) | 11.40 | 76.68 | 2217 | Furrow contours | 2 | 1204 | 25 | 25 | 100 | 45 | 20 | 35 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **25** | India | Aravalli hills, Banswara (Singh, 2009) | 23.42 | 74.41 | 280 | Trenches | 1 | 990 | 3-53 | 53 | 100 | 13 | 5 | 82 |
| **26** | Ethiopia | Kushet – Gobo Deguat (Hengsdijk *et al*., 2005) | 13.66 | 39.42 | 2575 | Stone bunds | 1 | 538 | 0-50 | 50 | 78 | 78 | 14 | 8 |
| **27** | Kenya | Kalalu, Diaga, Laikipia (Ngigi *et al*., 2006) | 0.10 | 37.14 | 1900 | Micro-dams | 1 | 1024 | 4 | 4 | 125 | 20 | 30 | 50 |
| **28** | South Africa | Baynesfield, KwaZulu-Natal (Everson *et al.,* 2011) | 29.75 | 30.34 | 1150 | Micro catchments | 1 | 900 | 5 | 16 | 150 | 19 | 35 | 46 |

[1] Code for type of Water Harvesting system 1=*in-situ*, 2= ex-situ

* Indicates soil texture inferred as opposed to reported

### *2.3.2 Statistical Analysis*

In order to assess the current status of WH knowledge available through published (including informal publication) literature and data, a principal components analysis (PCA) was undertaken to evaluate the relationships between the characteristics of the reported WH sites. A PCA is a type of cluster analysis which groups variables according to the variance within the dataset (Morell et al., 1996). The PCA converts a set of possibly correlated variables into a set of values of linearly uncorrelated variables i.e. principal components so that each is homogenous (Sârbu and Pop, 2005; Chaplot et al., 2010; Chaplot et al., 2011). The principle components describe the variance in the data set with the first principle component being accountable for the majority of variance, the second principle component for the second largest and so forth (Selle et al., 2013). Together the variables should account for most of the variance within the dataset. The PCA aims to expose trends and relationships between variables in the data, which represent a common process/impact and may not be apparent otherwise (Selle et al., 2013). It identifies patterns in data, and expressing the data in such a way as to highlight the similarities and differences. The base equation underlying the PCA method is:

$$Z_{ij} = \sum_{i=1}^{m} b_{ji} PC_{il} \quad (2.1)$$

where Z is the observed data, which was standardized by subtracting the mean and dividing by the standard deviation for each of the measured water quality variables; b denote 'loadings' representing coefficients of correlation between observed variables and principal components; PC are the 'scores' reflecting the relationship between samples and the principal components; i represents an index of samples indexing both locations and time of sampling; j is an index of m variables that were measured for each sample; and l is an index of m principal components.

A correlation matrix PCA was applied to the data using the Ade-4 software to evaluate the relationship between the environmental variables (Chessel et al., 2004). PCA is used to identify whether two variables measure the same characteristics, thereby showing which variable have a greater impact on the location of WH sites and should be prioritised for measurement, and which variable is less important. PCA groups variables, along the principle component axes, thereby classifying measured variables according to their importance to WH. The PCA also illustrates how the characteristics of the site are similar or where they differ and reveals relationships not always apparent by just looking at the data. Descriptive statistics (Minimum, Maximum, Mean, Mode, Median, Standard deviations, skewness testing and kurtosis) were computed for MAP, Altitude, minimum slope (%), maximum slope (%), soil depth (cm) and the percentages of sand, loam and clay in the soil. These results were displayed and are presented in the next section.

## 2.4 Results and Discussion

### *2.4.1 Determining the most important factors in positioning an in-situ WH site*

The correlation circle in Figure 2 illustrates the results of the PCA. There is a clustering of soil characteristics around the first principle component, which accounts for 28.51% of the variability in the data for micro-catchment WH (Figure 2.2). Therefore soil characteristics accounts for most of the variance in the data. This is further supported by the large standard deviation seen in the soil characteristics in Table 2.3. This implies that in-situ WH is taking place under a wide variety of soil conditions. Figure 3a shows that in-situ WH is taking place in soils with clay content across the spectrum therefore clay content does not limits WH. No in-situ WH is taking place in very sandy soils (>80%) or soils with a high loam content (>70%). Most WH takes place when loam content is between 10-50% and sand content is between 20-30% and 40-49%. According to this analysis, the % of sand and loam has an influence on the location of in-situ WH sites. Minimum slope (%) and Longitude are closely aligned with the 2nd principle component which accounts for 20.25% of the variability in the data. Climate zones are closely linked to their position relative to the Equator, i.e. tropical, sub-tropical, arid and semi-arid regions. The distribution of the location of in-situ WH sites, across the longitudinal zones indicated that there is no direct relationship between in-situ WH and climate zones and therefore in-situ WH can be utilised under a wide range of climatic zones. The variability in the minimum and maximum slope angle (in %) varies greatly, evident in a standard deviation of 4 and 14% respectively (Table 2.3) however analysis of skewness of the data (Figure 2.3 b and c) illustrates that minimum and maximum slope is skewed towards the left, around the more gentle slopes. This shows that more gentle slopes are better suited to in-situ WH with most occurring on gentle slopes with a minimum and maximum range of ≤7 - 20%. However examples are present of in-situ WH taking place on slopes of 18% - 53%, so these potential sites with steep slopes should not be excluded. This suggests that the recommendation by all three guidelines are too restrictive as the steepest slope recommendation, by IMSD, is <15%. Altitude and MAP are all highly variable and so it appear that in-situ WH can take place at any altitude and across many MAP regions (Table 2.3).

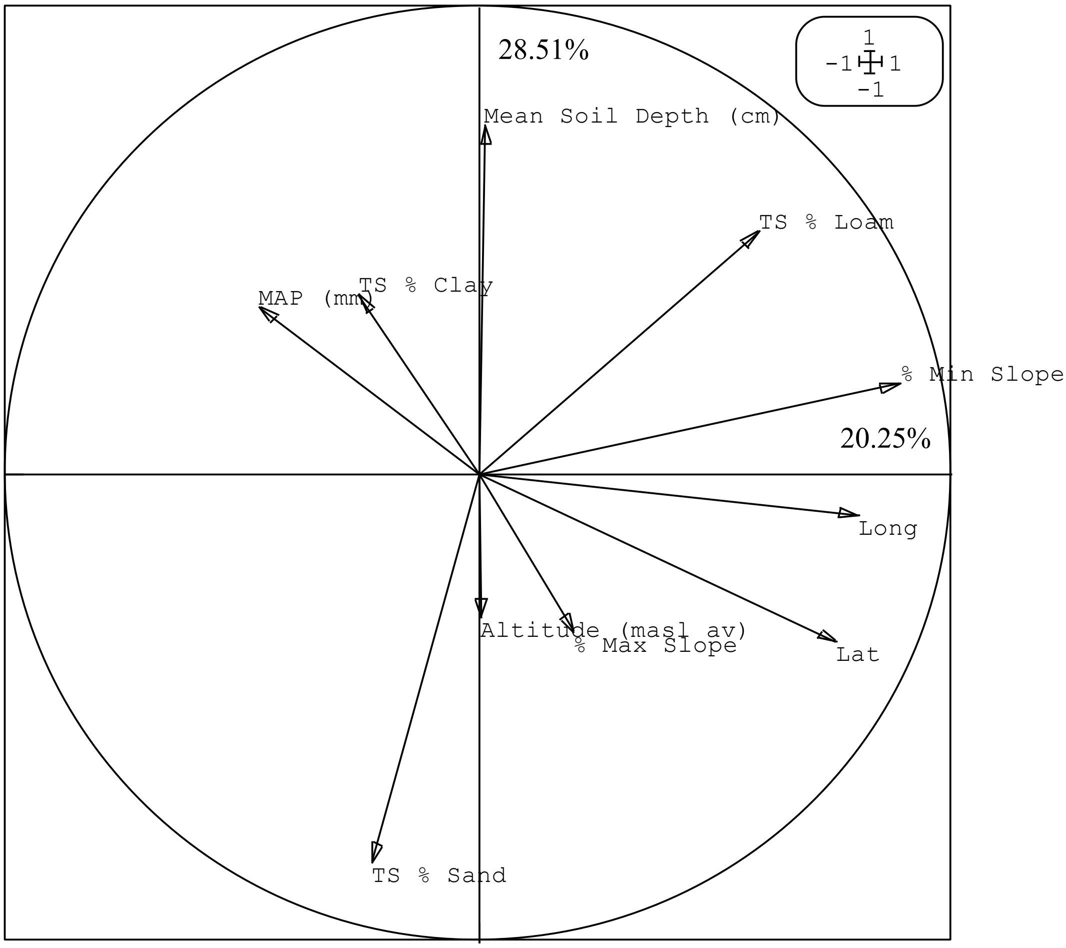


**Figure 2.2 Correlation circle PCA which expresses the relationship between variables of *in-situ* WH sites.**

**Table 2.3 Statistical analysis of the site characteristics of *in-situ* WH sites**

| **WH Type 1 – *In-situ*, n=17** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | MAP (mm/a) | Altitude (masl) | Min Slope (%) | Max Slope (%) | Soil Depth (cm) | % Sand | % Loam | % Clay |
| **Mean** | 659.53 | 1103.2 | 4.7 | 15.8 | 155 | 35.2 | 31.9 | 32.9 |
| **Min** | 211 | 50 | 0 | 2 | 35 | 12 | 5 | 5 |
| **Max** | 1800 | 2575 | 16 | 53 | 750 | 78 | 69 | 82 |
| **Median** | 600 | 1150 | 4 | 12 | 100 | 27 | 30 | 23 |
| **Mode** | 900 | 520 | 2 | 8 | 100 | 41 | 40 | 19 |
| **Std Dev** | 405.2 | 737.8 | 4.2 | 14.9 | 162.9 | 22.7 | 19.1 | 23.3 |
| **Skew** | 1.3 | 0.3 | 1.3 | 1.9 | 3.4 | 0.9 | 0.5 | 0.7 |
| **Kurt** | 2.7 | -0.9 | 1.9 | 2.7 | 12.6 | -0.4 | -0.3 | -0.5 |

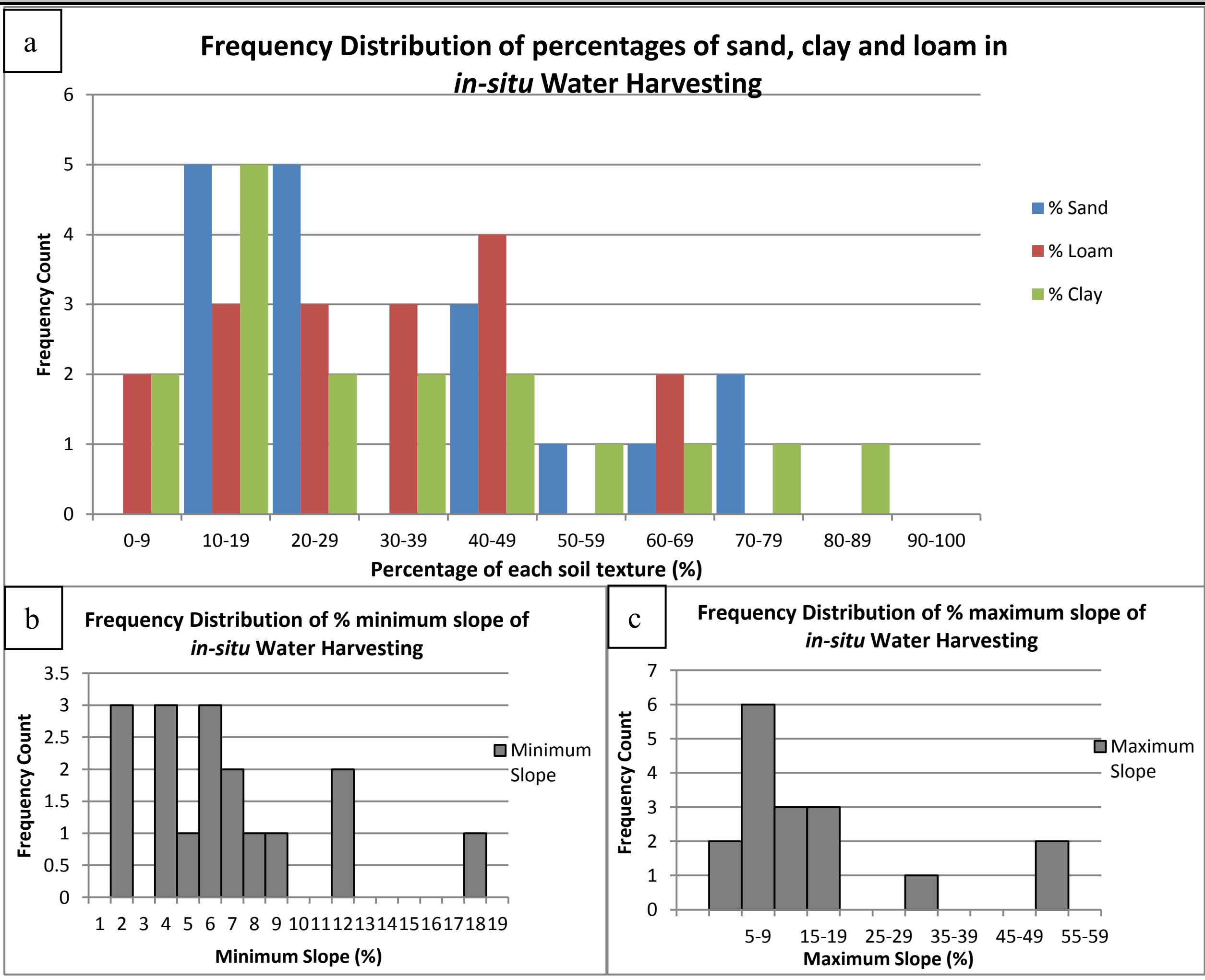


**Figure 2.3a- Frequency distribution of soil texture classes of in-situ WH sites, 2.3b and c- Frequency distribution of minimum and maximum (respectively) slope classes for in-situ WH sites.**

### *2.4.2 Determining the most important factors in positioning ex-situ WH site*

The results of the PCA show that the first principle component accounts for 36.33% of the variance in the data while the second principle component accounts for 19.41% of the variance in the data. In ex-situ WH there is a strong relationship between the soil depth, MAP and the % of loam in the soil (Figure 2.4). Deeper soils (≥1m) were found in areas with a higher MAP and had a higher percentage of loam. These represent the most ideal conditions for WH as suggested by all three sets of guidelines. The standard deviation of the macro-catchment mean soil depth is much lower than the in-situ WH (34 cm as opposed to 163 cm) indicating that ex-situ WH is taking place in mostly shallow soils as compared to in-situ WH which is taking place in a wide range of soil depths (Table 2.4). This is again confirmed by the skewness test which shows little variation from the mean of the ex-situ WH (skewness = 0.063) (Table 2.4). There is a strong inverse relationship between the amounts of clay and sand in the soil, which is to be expected (Figure 2.4). The soil texture frequency distribution (Figure 2.5a) shows that no ex-situ WH is taking place in soils with a loam content >60% however ex-situ WH is taking place across the full range of sand and clay contents, indicating that the clay and sand are not limiting factors in location of ex-situ WH. The minimum and maximum slope lines are not closely aligned with either principle component indicating that there is not much variability within the data. The lines are also positioned very close to each other indicating that there is not much variability between the two characteristics (Figure 2.4). Examination of the frequency distribution of the slope shows a strong clustering around the gentle slopes for the minimum slope (except for one outlier) (Figure 2.5b) and most of the sites having a maximum slope of <20%, except for 3 sites (Figure 2.5c). This again confirms the recommendations by the three sets of guidelines that more gentle slopes are best suited to WH, but evidence of ex-situ WH taking place on steeper slopes indicates that the guidelines are restrictive and perhaps ex-situ WH can take place on more steep slopes.

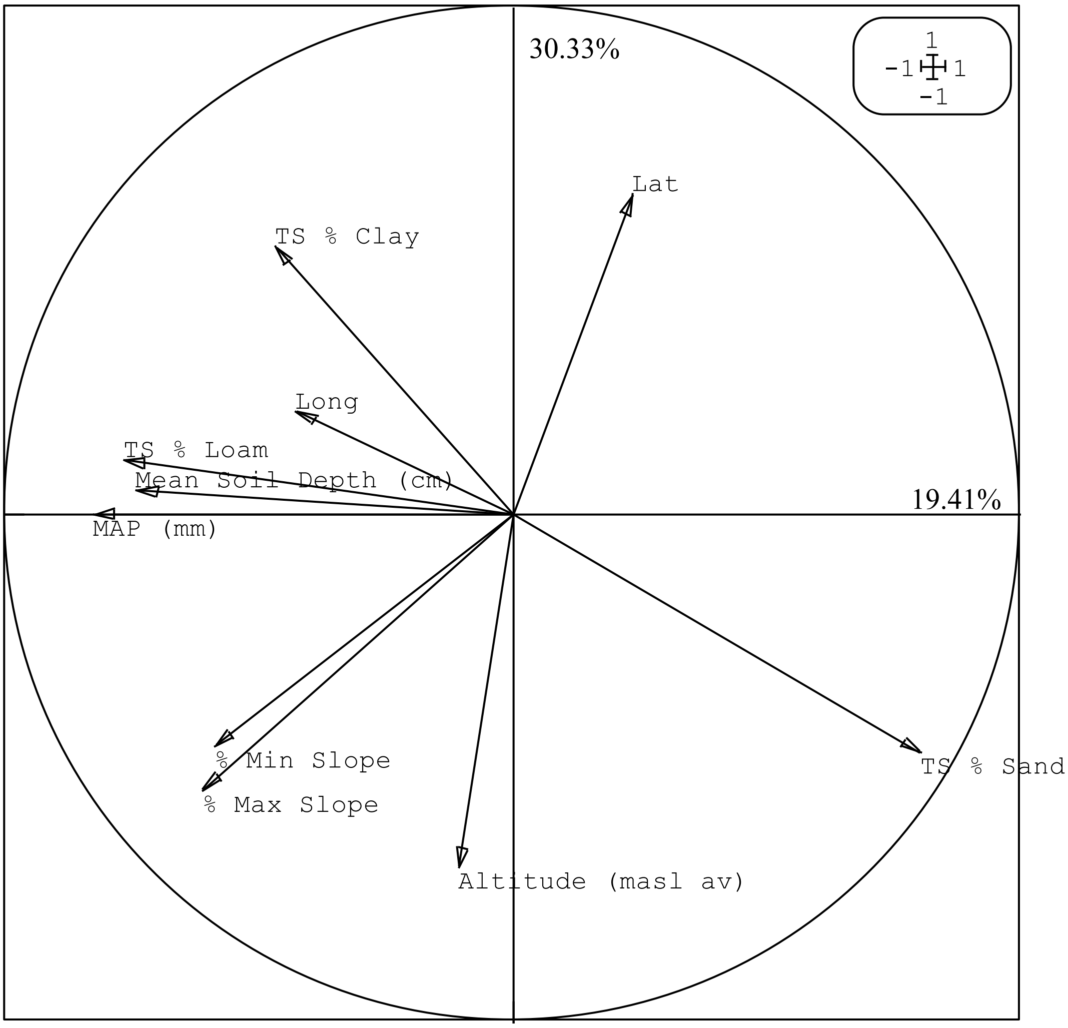


**Figure 2.4 Correlation circle PCA which expresses the relationship between variables of *ex-situ* WH sites.**

**Table 2.4 Statistical analysis of the site characteristics of *ex-situ* WH sites.**

| **WH Type 2 – *Ex-situ*, n = 11** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | MAP (mm/a) | Altitude (masl) | Min Slope (%) | Max Slope (%) | Soil Depth (cm) | % Sand | % Loam | % Clay |
| **Mean** | 967.8 | 814.7 | 4 | 14.5 | 67.3 | 42.6 | 26.5 | 30.9 |
| **Min** | 100 | 250 | 0 | 2 | 25 | 1 | 3 | 3 |
| **Max** | 1980 | 2217 | 20 | 40 | 115 | 94 | 51 | 83 |
| **Median** | 900 | 594 | 2 | 8 | 65 | 42 | 23 | 24 |
| **Mode** | N/A | 750 | 0 | 5 | 100 | N/A | N/A | N/A |
| **Std Dev** | 588.7 | 673.4 | 5.9 | 12.3 | 33.7 | 30.5 | 17.5 | 23.8 |
| **Skew** | 0.4 | 1.4 | 2.3 | 1.1 | 0.1 | 0.2 | 0.1 | 1.1 |
| **Kurt** | -0.3 | 1.1 | 5.8 | 0.2 | -1.9 | -0.9 | -1.6 | 0.9 |

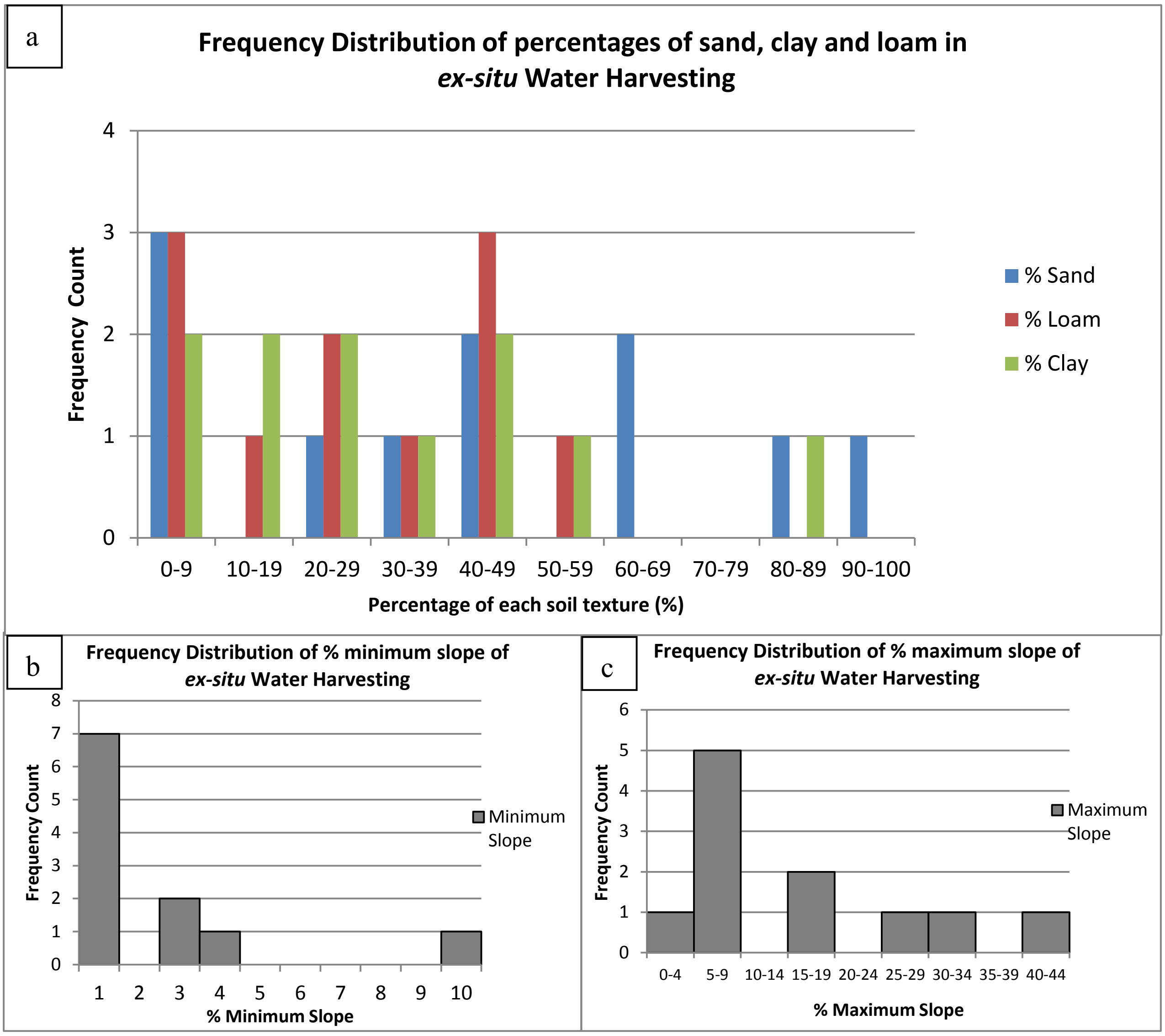


**Figure 2.5a Frequency distribution of soil texture classes of *ex-situ* WH sites, 5b and c- Frequency distribution of minimum and maximum (respectively) slope classes for *ex-situ* WH sites.**

### *2.4.3 Consequences for the guidelines*

The results of the statistical analysis have shown that while most of the WH sites are situated in landscape characteristics similar to those recommended by the three sets of guidelines, some sites have characteristics quite different to those specified in the recommendations. The guidelines may be described as the optimal conditions for WH, but a second set of recommendations should be made to allow for conditions that may still be suitable, even if they are not optimal. Furthermore, separate recommendations for in-situ and ex-situ WH are necessary. Table 2.5 presents a new set of guidelines for the positioning of both optimal and suitable conditions for in-situ and ex-situ WH sites based on the results of this study.

**Table 2.5 New guidelines for WH site requirements based on a statistical analysis of existing WH sites.**

| *In-situ* **WH Site Requirements** | | | |
|---|---|---|---|
| **Criteria** | Low Limit Suitability | Optimal | Upper Limit Suitability |
| **Altitude** | | No restrictions | |
| **Latitude** | | No Restrictions | |
| **Longitude** | | No Restrictions | |
| **MAP (mm/a)** | | No Restrictions | |
| **Slope** | No Lower limit | <20% | Up to 53% proven to work |
| **Soil Texture** | Loam: No Lower Limit<br>Sand: 10%<br>Clay: No Lower limit | Loam: 0-50%<br>Sand: 10-30%<br>Clay: 0-50% | Loam: <70%<br>Sand: <80%<br>Clay: No Upper Limit |
| **Soil Depth** | 35 | 100 | No Upper Limit |
| *Ex-situ* **WH Site Requirements** | | | |
| **Criteria** | Low Limit Suitability | Optimal | Upper Limit Suitability |
| **Altitude** | | No restrictions | |
| **Latitude** | | No Restrictions | |
| **Longitude** | | No Restrictions | |
| **MAP (mm/a)** | 100 | 900 | No upper limit |
| **Slope** | No Lower Limit | <10% | Up to 40% proven to work |
| **Soil Texture** | Loam: No Lower limit<br>Sand: No Lower Limit<br>Clay: No Lower Limit | Loam: 0-50%<br>Sand: 20-50%<br>Clay: 0-50% | Loam: 60%<br>Sand: 95%<br>Clay: 90% |
| **Soil Depth (cm)** | 25 | 100 | 115 |

## 2.5 Conclusion

Detailed information on the physical characteristics of WH sites is imperative to understand the hydrological functions of these sites within the catchment. Localised soil, slope and land cover condition will have an influence on how runoff is generated, how much is generated and how it naturally moves through the landscape. These conditions will also dictate the extent and what type of WH can be sustained within a catchment and the quantity and quality of water that can be harvested. It will also have an effect on the environment, downstream and upstream users, at a local scale, at catchment sale and potentially even a regional scale. Without a good understanding of the physical characteristics of existing and potential WH sites, we cannot begin to model or understand the possible impacts of existing WH sites nor can we explore the potential for expanding and upscaling of WH within a catchment.

The results of the statistical study show that the existing guidelines which are most commonly used to determine suitable locations for WH only represent the optimal conditions for WH. WH can, and currently does, take place under an much wider range of conditions. This implies that many more sites may be suitable for WH than currently acknowledged. Therefore the strict application of existing guidelines is too limiting. Evidence from existing WH sites shows that a new set of guidelines, taking into account not only optimal conditions but also upper and lower limits of suitability need to be developed. The ranking of conditions may allow for many more potential WH sites to be identified and allow WH to make a greater impact in supplying water for agricultural, livestock and domestic uses.

## 2.6 Recommendations

One of the limits to this study was the availability of data. Site descriptions often left out important details such as land use, drainage patterns and mean annual evaporation which have all been identified in previous studies as being important in determining WH site suitability. Several other authors such as Malesu et al. (2007) highlighted a lack of data as a constraint on their mapping exercises. Malesu et al. (2007) also highlighted that their study on sand dams was further compromised by poor slope data and so slope had to be discarded, weakening the study. Prinz et al. (1998) highlighted that large scale planning and implementation of WH structures, requires quantitative information of the spatial distribution of physical land characteristics which is often not available in arid or semi-arid areas at the resolution required for accurate land suitability assessments for small scale structures such as WH structures. Traditional soil and land surveys (1:10 000) do give sufficiently accurate information however these are often only available over limited areas, are expensive and time consuming to produce (Prinz et al., 1998).

Unfortunately there are few guidelines for the describing the minimum accepted sample size for PCA (Osborne and Costello, 2004). Some authors recommend an absolute minimum sample number (N) of 50, while others suggest a ratio between the number of cases per variable (N/p) with recommendations range from 3:1–6:1(Cattell, 1978). Later studies by Arrindell and Van der Ende, (1985); Jackson, (2001) and MacCallum et al. (1999) show that recommendations on absolute N and the N/p ratio can be misconceiving. MacCallum et al. (1999) developed a theoretical framework for testing the effects of sample size on factor recovery and concluded that there are no absolute thresholds for a minimum sample size however it is accepted that the smaller the sample size, the less confidence can be placed in a result (de Winter et al., 2009).

In this study the sample size of N=28, means that caution should be applied when examining the results. Rather than concluding that the ranges and recommendations for new guidelines be regarded as absolute truth, the trends in the data should be considered. It is apparent that WH is taking place under a much wider range of conditions than those currently considered suitable. This should be the basis or motivation for future work to improve the availability of WH data, to allow for more robust analysis of existing data and also to expand WH research and more rigorously analysis of existing WH sites so that researchers can learn under what full range of conditions WH can take place. Developments in techniques such as GIS, remote sensing, geo-information and a more common acceptance of the role of indigenous knowledge can allow for more wide spread data collection. Remote sensing has proven to be successful in identifying potential WH sites by various authors as discussed above. Further use of this technology to collect data about existing WH sites and analysed through statistical analysis as presented in this paper (but with a larger sample size) will further strengthen the guidelines for WH site suitability.

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# CHAPTER 3: DOMESTIC RAINWATER HARVESTING AS AN ADAPTATION STRATEGY FOR WATER SCARCITY AND CLIMATE CHANGE: A SOUTH AFRICAN CASE STUDY (PAPER 2)

Bulcock, L.M., Jewitt, G.P.W. and Schulze, R.E.

**Abstract**

Global change can be defined as anthropogenic related changes that have resulted from human exploitation of the Earth's natural resources in the quest for development and advancement of the human race. Global change includes climate change, population growth, economic development, urban sprawl and land use change. Global change places increasing pressure on water resources and consequently over 1.2 billion people worldwide do not have access to safe drinking water or adequate sanitation. Rainwater harvesting (RWH) is one solution being promoted to help supply water for both domestic and agricultural purposes and so reduce strain on conventional water supplies while still ensuring access to water. Water scarcity affects people at a household level and on a daily timescale. Therefore there is the need for a small scale, daily analysis of the potential suitability for domestic RWH which takes into account not only the patterns of rainfall, intensity and distribution but also storage capacity and daily household demand.

A daily water harvesting model was developed to analyse the suitability of southern Africa for domestic RWH at a quinary level. Fifty years of historical climate data was used to assess a baseline of suitability and then global circulation models were used to predict how changes in rainfall pattern may influence the long term sustainability of proposed RWH suitability. Results showed that the east coast of South Africa was the most suited to RWH, with eastern demands being met 50-100 days of the year from a 3000 litre RWH tank. Under projected climate change conditions, the east coast become more suited to RWH, with demand being meet 100-150 days of the year and some areas even having demand met 150-200 days of the year. The central regions of southern Africa are marginally suitable for RWH under historical climate conditions, with at least a portion of the daily demand being met up to 100 days of the year. Under climate change conditions, up to 100 days a year can be fulfilled by RWH and an additional 50 days a year receive a portion of the daily water requirement from RWH. This suggests that there is great potential for domestic RWH in southern Africa, where at least a

portion of daily household water requirements can be met by RWH technologies. This can increase household water security and help alleviate some of the pressure on municipal water supply and treatment.

### 3.1 Introduction

Anthropogenic change can be described as change induced indirectly or directly for the benefits of humans. Climate change (Bates et al., 2008; Pittock, 2009), population growth (Doos, 2002; Parnell and Walawege, 2011), economic development and decline (Ewers, 2006; World Bank, 2010), urban migration and land use change (Veldkamp and Verburg, 2004; Foley et al., 2005; Dams et al., 2008 and Tu, 2009) are all factors contributing towards global change. Global change is placing increasing pressure on water resources, particularly in water scarce regions such as Sub-Saharan Africa. Increasing demand for water at various spatial and temporal scales is placing increased pressure on water supply systems, while poor implementation of water quality legislation, lack of monitoring and poor water reticulation infrastructure results in pollution of water resources which greatly affects downstream users.

Projected increases in water demand are placing increased pressure of governments and water service providers in many countries. Many developing countries in Africa and Asia cannot supply enough water for current demands. The 1980's and 1990's saw a shift in focus away from large scale dams and reservoirs towards water use efficiency. The World Commission on Dams (2001) recognised the social and economic implications of large scale water infrastructure projects, which result in one group losing access to resources, land and livelihood security for the benefit of another group's access to water, are becoming harder to justify. The World Bank (2010) however highlighted that in cases where water availability is characterised by high variability, water management strategies has little or no impact. Therefore the water resources strategy focuses on investments in physical interventions aimed at increasing water availability at household, community or society levels. As a result, governments are increasingly looking towards small scale solutions for helping to alleviate the growing water demands of communities and small scale agriculture and to help alleviate the pressure of the water treatment system.

Over the centuries and throughout Sub-Saharan Africa, indigenous knowledge systems have developed various ways of collecting and storing water for later use (Rockström, 2000; Mbilinyi et al., 2005). However, the full potential of this type of water supply has not been fully exploited in Southern Africa to date. It has been suggested that water harvesting could be implemented to alleviate the temporal water supply problems and to supplement the conventional water supply systems as demand increasingly grows (van der Zaag and Gupta, 2008; Mwenga Kahinda et al., 2005). RWH collectively refers to all methods used to collect, store and utilise rainfall for domestic and agricultural uses (Rockström, 2000; Sutherland and Fenn, 2000). RWH aims to reduce the scarcity of water by increasing supply at a decentralised scale. McCartney et al. (2013) and van der Zaag and Gupta (2008) both discuss the criteria for choosing between large scale centralized water storage infrastructure or decentralised storage and distribution systems within communities. The added pressures of climate change and growing environmental awareness have also prompted governments and individuals to look for more decentralised and sustainable solutions to alleviate the demand on scarce resources, such as water. One such solution gaining popular attention is rainwater harvesting for the provision of domestic water in both rural and urban settings.

## 3.2 Global change as a driver of rainwater harvesting technologies uptake

The effects of global change are experienced through highly localised impacts (Vincent, 2011; Paavola, 2008; Reid and Vogel, 2006) and are seldom the result of a single global change driver (Ngcobo et al., 2013). Adoption and promotion of RWH is influenced by many aspects of global change.

### *3.2.1 Population dynamics and access to water*

The world's population has grown to over 6 billion people (UNFPA, 2011) while urbanisation has increased tenfold since 1950's (Steffen et al., 2005). Pastures and crop lands account for 40% of current land cover (Foley et al., 2005). Approximately 1.2 billion people worldwide do not have access to safe drinking water (40% of these people lived in Sub-Saharan Africa), 2.6 billion people lack access to adequate sanitation and approximately 2 million people, most of them children, die every year from issues arising from a lack of clean water (Watkins et al., 2006).

Although population growth is predicted to slow by 2030, increased standards of living and the associated increases in resources may still result in water shortages (Hoff, 2011; WRC, 2002). Add to this the complexity of strains placed on many people in the developing world brought about by a reliance on increasingly impacted natural resources, economic practices driven by development, the emergence of new threats brought about by a rapidly changing environment (Ncgobo et al., 2013) including persistent socio-economic issues such as poverty, unemployment and HIV/AIDS, it is not difficult to see why the issue of access to safe and clean water has been labelled a crisis (Descheemaeker et al., 2010; Pollard and Du Toit, 2011).

Water scarcity in developing countries places considerable strain on communities which rely directly on rainfall to sustain their livelihoods both in rural and urban settings. Irregularity in timing and distribution of rainfall may leave many communities without access to water for even the most basic daily requirements. Amongst the most vulnerable are poor communities living in low income houses with little access to services and resources. Most developing countries in the world are still experiencing a population growth and as standards of living increase, so does the demand and consumption of water. This means that issue of access to water continues to increase even as development of infrastructure which improves access increases.

### *3.2.2 Economic development and decline*

Many of the world food insecure and impoverished people live in Sub-Saharan Africa. Although economic growth and development is most rapid in developing countries, little emphasis is placed on protecting natural resources and as a result short and long term degradation results in reduced livelihood security for the region's poor. Economic development through commercial farming, mining and infrastructure development often results in loss of access to land and resulting livelihood securement for poor rural populations. These activities often fuel demands from foreign markets rather than improving the livelihoods of local people (Döös, 2002). Ausubel et al. (2013) argues that innovations in yield and production technologies will result in less land being needed to sustain future populations. However Ausubel et al. (2013) do not considering that the water requirements needed under more intensive agriculture and that this level of agricultural efficiency cannot be realised under the rainfed agricultural systems found across most of the developing world (Ngcobo et al., 2013).

Sub-Saharan subsistence agriculture is characterised by reliance on rainfall, lack of investment in fertilisers and depleted soil nutrients. The reestablishment and promotion of indigenous knowledge practices such as conservation agriculture, rainwater harvesting and seed saving is the key to greater food and water security and reduced environmental degradation (Bossio et al., 2011). Some argue urbanisation is driven by lack of security in rural areas as a result of crop failures (Sullivan and Sibanda, 2010). Therefore water storage is needed to buffer livelihoods and secure crops against water shortages (Zaag and Gupta, 2008). Innovative technologies are needs to secure water on a day to day basis to secure and improve crop yields (Zaag and Gupta, 2008).

Large dams, inter-basin transfer schemes, trans-boundary transfer schemes and ground water abstraction are the main water supply infrastructure in southern Africa. This water requires treatment and as a result of human activities, eutrophication from farming fertilizers, mine water drainage and inadequate sewerage systems, the requirements and associated costs of treating water are increasing to ensure this water is fit for human consumption. The price of water in South Africa is determined by individual municipalities and the while the price and average increases in the price of water are not uniform across the country, in most municipalities, water users have experienced an increase in water prices of between 20 and 50% between 1996 and 2004 (Bailey and Buckley, 2004). Most of the water, used in a domestic household is used for showering, irrigating gardens and washing cars, flushing toilets and in mashing machines, while as little as 6% is used for direct human consumption, i.e. drinking and food preparation. Gleick (1996) showed that the 50 litre (ℓ) per capita per day breakdown recommended by the FAO could be broken down into 15 ℓ of bathing, 10 ℓ of cooking, 5 ℓ for drinking and 20 ℓ of sanitation and hygiene per day. This means that 35 ℓ (or 70%) of the daily water requirements is not for direct human consumption and does not need to be treated to drinking water standards. It is argued that considerable costs are invested in treating water to the level fit for human consumption (drinking and food preparation) are being wasted when a majority of domestic water use is not human consumption (Li, 2010). However the cost of infrastructure layout to provide different quality of water through different municipal supplies is not considered feasible.

There is discussion around even more water price hikes, hoping that the increased cost of water will make consumers more conscience of efforts to limit wastage. However others argue that the municipalities, which are responsible for water supply infrastructure, account for more loss through poorly maintained infrastructure and that this wastage should be addressed before increasing the costs to consumers. Increasing the costs of water will also impact the poorer sectors of society the most and may impede their basic rights to water for drinking and sanitation. Although the free basic water (FBW) policy is South Africa should guarantee access to water for all, including the poorest members of society, the implementation of this policy often allows those who can afford to pay for water free access while failing to deliver to those who are most in need. Often the devices and measures used to ensure that the basic daily quotes are not exceed do not work efficiently and reduce access so much, that the basic daily requirements are not meet and quality of life and dignity is impeded (Smith, 2010).

### *3.2.3 Climate variability and projected climate change*

Rainfall is highly variable across the region with high daily, monthly and annual coefficients of variability (Nicholson, 2000). River streamflow is also variable. Africa, along with Australia, has the world lowest rainfall and the region is often described as being "hostage to its hydrology". This implies that development is directly limited as a result of variable access to water. People relying directly on rainfall to sustain their livelihoods are impacted more by daily variations in rainfall and streamflow than by long term trends in climate (Kandlikar and Risbey, 2000). In order to understand the hydro-climatic impacts of variability at a local scale, rainfall data needs to be available at small spatial scale at daily intervals (Ngcobo et al., 2013). Rainfall information at broad regional and annual scales is not useful. So far climate change vulnerability and adaptation studies have mostly focused flood and drought frequencies and magnitudes, however issues surrounding water storage are rapidly gaining attention with a host of storage alternatives being investigated (McCartney and King, 2011). Label et al. (2015) investigated how RWH could help bridge the maize yield gap in Africa and found that RWH could reduce the yield gap by 40% under current climate change conditions and 31% under predicted climate conditions in 2050.

There is still uncertainty regarding the magnitude and specific impacts of climate change, however there is consensus on the patterns of change that can be expected. Predicted trend in precipitation under climate change indicate that the central and eastern parts of the Southern Africa will experience increased rain days and increased rainfall intensity, while the south western regions will experience decreased rainfall events and intensity (Hewitson et al., 2005). Runoff and streamflow in the central and eastern regions were projected to increased two to three times relative to rainfall under climate change scenarios (Warburton et al., 2012; Hewitson et al., 2005). Variability in events may result in more extreme low flows and more flood events and may result in even greater irregularities in the availability of water for daily use. The impacts of this may threaten the livelihoods and wellbeing of the already vulnerable communities the most.

Rainwater harvesting is one of the specific climate change adaptation strategies mentioned several times in the South African National Climate Change Response (White Paper) (DEA, 2011). RWH is highlighted as potential adaptation strategy for small scale farmers and the white paper mentions the aim to rollout RWH strategies for these farmers. The intention to accelerate the provision of RWH tanks for rural and low income households are also mentioned (DEA, 2011).

### *3.2.4 Legislation and international commitments*

The global water crisis has received much attention from the international community and policy makers. The United Nation's (UN) Millennium goals aimed to decrease, by half, the proportion of people without access to safe drinking water and basic sanitation. By 2012, the UN reported that it had achieved this goal however it has noted that 2.5 billion people in developing countries are still without access and that over 40% of these people are in Sub-Saharan Africa.

As part of its commitments under the Sharm El Sheikh Declaration on Water and Sanitation, the African Union, has committed to promoting RWH and use, with the aim to increase RWH's share of total water use to 10% by 2015. There are also continued efforts to expand the use of these small scale systems, particularly in areas not considered suitable for conventional irrigation development (AMCOW, 2008; AMCOW, 2012). While a lot of government and international funding is still focused on large scale reservoirs, increased interest and awareness is being given to installing or upgrading traditional water harvesting systems, where large dams and irrigation schemes are not possible (Lankford, 2003).

Some countries are starting to incorporate decentralised RWH systems into their building codes and regulations (Mankad et al., 2010). For example in Queensland, Australia, all new houses built after 2007 are required to install a water collection devise that enables the collection of 70 kℓ of water per year. This water is pumped into the house for use in washing machines, flushing toilets and other non-potable needs (DPI, 2010). This legislation was supported by substantial rebates to encourage new and existing home owners to invest in water storage structures (Mankad and Tapsuwan, 2011).

There may be some contradiction in legislation which has resulted in the perception that RWH is actually illegal in some contexts. In various stage of history, RWH has been deemed illegal in Australia, due to concerns over the quality of harvested water for human consumption (Coombes and Kuczera, 2002). In South Africa, there was concern that RWH could be a potential streamflow reduction activity as it may have the ability to reduce the availability of water in a water course and as a result may require a license (NWA Section 36(2)). However, Bosch (2005) concluded that RWH did not met all the requirements to be classified a streamflow reduction activity as it did not reduce the mean annual runoff and did not decrease the low flows of a water course. RWH is considered to be better managed under a different statute of the National Water Act (NWA) in South Africa because it transcends the boundaries of basic human needs for survival. RWH has the potential to supply water for human consumption (drinking water and sanitation) as well as subsistence agriculture, which are considered basic human rights and protected by the South African Constitution (the highest law in SA) (de Winnaar and Jewitt, 2010). As a result, the potential of RWH as a streamflow reduction activity will not hamper adoption and uptake in SA.

However, the large scale implementation of RWH may become a driver of global change. Mass implementation may result in changes in the runoff related components of baseflow and stormflows, reducing river recharge and impacting on water availability for downstream users. In addition, water quality may be affected by the type of land cover used as a collection areas and the storage of water in different mediums. While general consensus agrees that RWH will have little impacts on catchment hydrology (de Winnaar and Jewitt, 2010), greater research is required to explore the potential impacts of large scale RWH implementation before wide spread implementation occurs.

It is evident that there are many factors driving RWH adoption in Sub-Saharan Africa. In order for initiatives aimed at upscaling RWH to be successful, it is important that the areas which can support the most sustainable RWH systems, both now and under potential climate change scenarios, are prioritised for upscaling projects.

Mwenge Kahinda et al. (2010) investigated the potential for domestic RWH in 4 selected study sites in South Africa under climate change conditions. They found that the humid area areas provided the most water security, of approximately 30%. The semi-arid, arid and dry sub-humid areas all achieved a water security rating of approximately 15%. The size of the tank had little effect on improving the water security except in the semi-arid area where water security increased to 20% using a $10m^3$ tank. Water security was determined by calculating the number of times the daily household water requirement (of 100 ℓ) was met. The household water requirement is vastly underestimate in this study. The FAO recommends a daily water use of 50 ℓ per person. If the average number of people per household is taken to be 4 (as per the statistics used by Mwenge Kahinda et al., 2010) then the daily household water use should at least be 200 ℓ per day. This would halve the water security figures. In addition, the water security is calculated as an absolute figure, the number of days when the tank will be able to partially fulfil the household needs is not considered. This is extremely important in areas that receive a lot of small rainfall event which still produce runoff. Lastly there is no indication as to whether the 4 selected sites are representative of the whole of South Africa and whether policy recommendations can actually be made based on these four, relatively small study sites.

The added complexity of climate change also presents a planning challenge. RWH needs to be sustainable in the long run. Any changes in rainfall patterns will affect the amount of water that can be harvested. Increases in intense, high event thunderstorms may result in the tanks overflowing more often and less water becoming available, whereas decreases in rainfall mean less water is available overall, and more small events, means more water is lost to initial abstraction. This means systems could become less effective. A case study was needed to examine the practical threshold for RWH implementation (Pandey et al., 2003). This case study aims to assess which areas in South Africa are most suited to RWH by calculating how often a RWH tank will be able to supply the household daily requirements (based on the FAO standard of 50 ℓ per person per day) and by considering the capacity of the tank. This includes how many days the tank will be able to partially supply the daily household requirement and allowing to tank to overflow in cases of extreme events.

### 3.3 Methodology

The research focuses on collecting rainfall running off from the roof surface of a typical sub-economic house constructed through South Africa government initiatives for low income households. Such houses are frequently termed 'RDP houses' after the post-1994 Reconstruction and Development Programme. Collection of the water would be in a water tank.

Rainwater yield depends on roof size, tank capacity and the frequency and magnitude of rainfall, but also on the daily water requirements of the household. According to the FAO, the daily per capita water requirement for basic domestic and sanitation functions is 50 ℓ (Gleick, 1996; Diouf, 2007). For this study an assumption of 6 people per house was made, which is slightly higher than most statistics show for urban households. However, low income households frequently have higher than average numbers of people inhabiting them and therefore a conservative figure of 6 people was taken (Statistics SA, 2012). RDP houses in South Africa typically have roof sizes in the range of 30 to 50 $m^2$, with an average around 40 $m^2$.

Tank size optimisation was done using the method suggested by van der Zaag (2000). In this method relative storage capacity is optimised by examining daily water demand, roof (or catchment) area, and satisfaction level. This analysis is always site specific and requires at least 3 years of daily data. In this case study, 20 years of historical daily data was used at quinary level in South Africa. Once relative storage capacity is determined, it is multiplied by the roof area to give the actual storage tanks size in litres.

$$\textit{Tank Size } (\ell) = \textit{relative storage capacity (mm) x roof area } (m^2) \qquad (3.1)$$

The daily water supply and demand model used daily rainfall values which were extracted from data files from a historical 50 year rainfall database and of the multiple GCMs used in this study (Schulze et al., 2011a and b) for the two 20 year periods representing the intermediate future (2046 - 2065) and the more distant future (2081 - 2100) climate scenarios. An initial abstraction (i.e. loss, Ia) of 1 mm was assumed as a detention loss due to evaporation from and adhesion to the roof, and this was then subtracted from the day's rainfall. The remaining rainfall was available for collection in the 3 000 ℓ, 4000 ℓ and 5000 ℓ tank. The amount of water that can be harvested from the roof was then calculated as

$$\textit{Harvested Water } (\ell) = \textit{(rainfall (mm) - Ia) x roof area } (m^2) \qquad (3.2)$$

Household water requirements were calculated according to FAO specifications, viz.

$$\textit{Household requirements } (\ell) = \textit{Number of people x daily requirements per capita } (\ell) \qquad (3.3)$$

The daily water balance of the tank was calculated as

$$W = dV - dEa + F_{in} - Eov \qquad (3.4)$$

Where W is the daily water balance in the tank (ℓ), dV is the stored water balance from the previous day (ℓ), dEa (ℓ) is the daily extraction of water for household use (it is assumed that the total daily requirement is abstracted at the beginning of the day, before any rainfall occurs,

$F_{in}$ is the flow of water into the tank due to rainfall (ℓ) and Eov is the overflow of water in the case that the tank is full and more rainfall occurs causing the tank to overflow (ℓ).

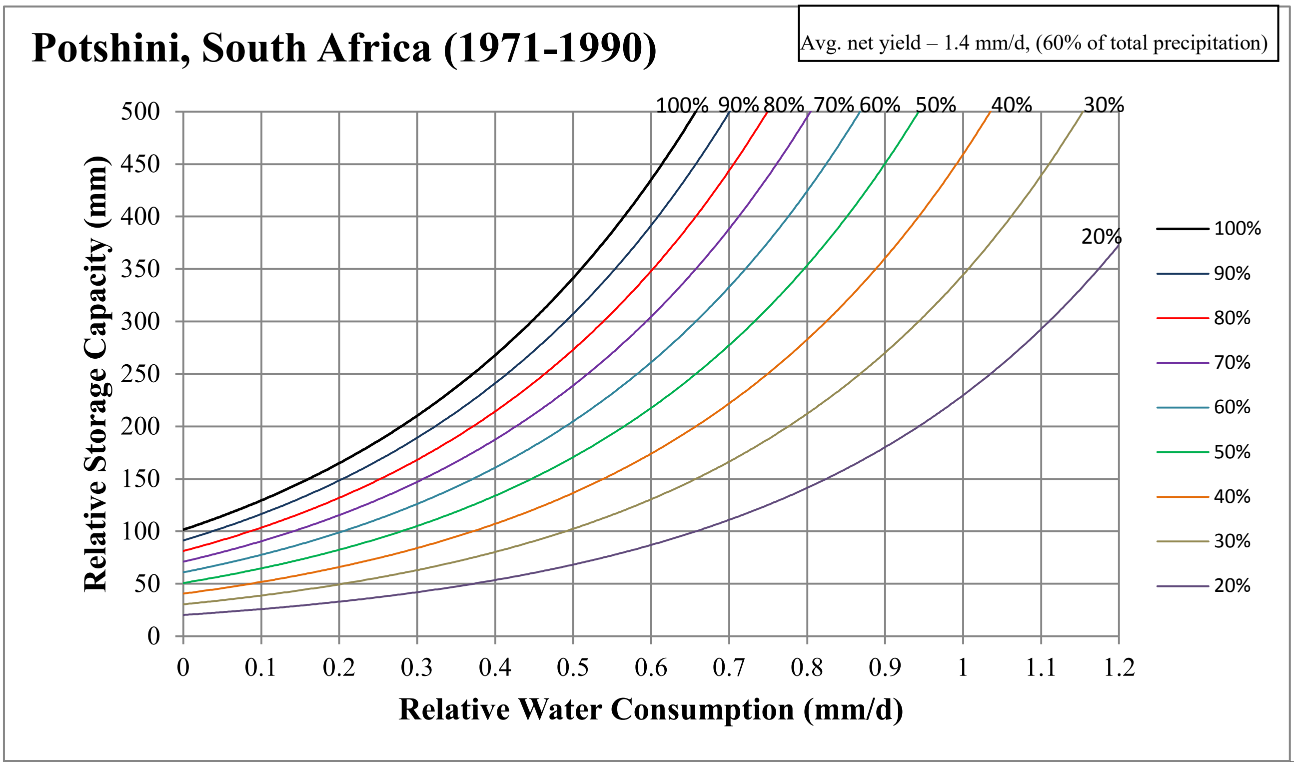
Based on the water use assumptions, a model was set up to calculate the daily inflows into the tank from rainfall (on days when it rained more than 1 mm) and the daily abstractions for the household requirements, for the whole of South Africa using the quinaries catchment database. The model calculated how often the tank:

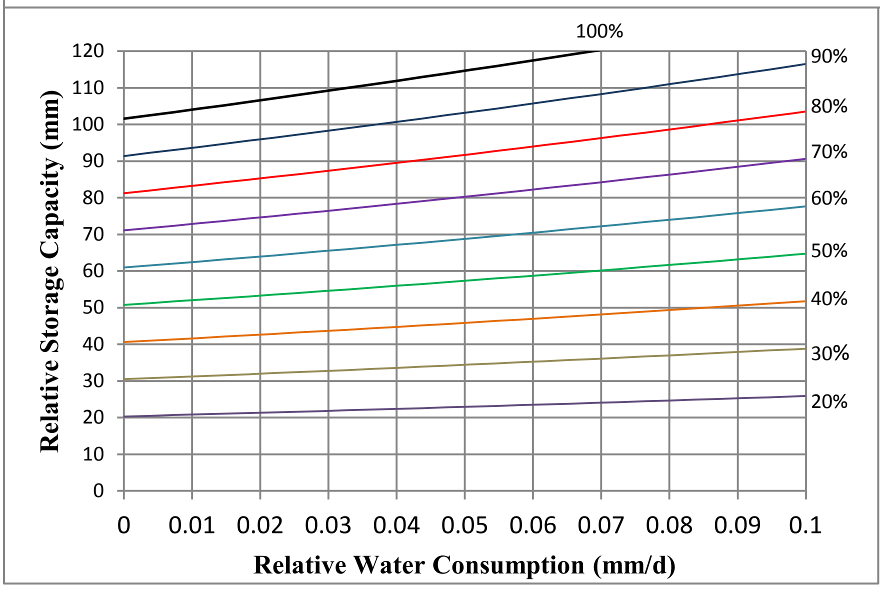
- was able to supply all of the daily household water requirements,
- was able to supply some* of the daily household water requirements , and
- overflowed.

*This category was added as sometimes there is just a little bit of water left in the tank, after the previous day's abstraction or it rained just a small amount (between 1mm and 7 mm, which would provide some of the daily water requirements, but not all of it.

### 3.4 Results and discussion

The results of the tank optimisation methods suggested by van der Zaag (2000) for the Potshini area in South Africa showed that a relative storage capacity of 104 mm and an actual tank size of 4160 ℓ for 100% assurance of supply, while a 3000 ℓ tank would supply a 80% assurance supply level (Figure 3.1). Van der Zaag described satisfaction level as being the number of days when the daily water requirements will be met and gives the example that 50% satisfaction level will means that daily water demand will be fully satisfied for 50% of all days. Therefore two sizes were used to assess the daily supply and storage potential for rainwater harvesting across the whole of South Africa. A 3000 ℓ tank was used to represent 80% assurance supply and a 5000 ℓ as the most common commercially available tank which would supply 100% assurance of supply. A comparison between these two tank sizes also allowed for the analysis of the overflow from the tank on water losses.




| RSC and tank capacity at RWC 0.02 mm/d | | |
|---|---|---|
| Supply Assurance (%) | RSC (mm) | Actual Tank Capacity (ℓ) |
| 100 | 104 | 4160 |
| 90 | 95 | 3800 |
| 80 | 83 | 3320 |
| 70 | 73 | 2920 |
| 60 | 64 | 2560 |
| 50 | 54 | 2160 |
| 40 | 43 | 1720 |
| 30 | 32 | 1280 |
| 20 | 21 | 840 |

**Figure 3.1a- Relative Storage Capacity graphs for various satisfaction levels (%) Potshini, South Africa; b- zoomed in on lower relative water consumptions and c- converted to actual tank capacities for an RWC of 0.02 mm/d.**

Figure 3.2 shows that historically the eastern part of South Africa and a small area around the city of Cape Town in the Western Cape have the greatest potential to support a RWH system. A low income household of 6 people, using 50 ℓ of water per person per day will be able to meet their daily needs from a 3000 ℓ RWH tanks between 50 and 100 days of the year, under historical climate conditions. This means that the African Unions goal of 10% of water supply coming from domestic RWH is easily achievable in these areas. The western and central part of SA is not as suited to RWH, with less than 50 days of the year having the daily requirement meet.

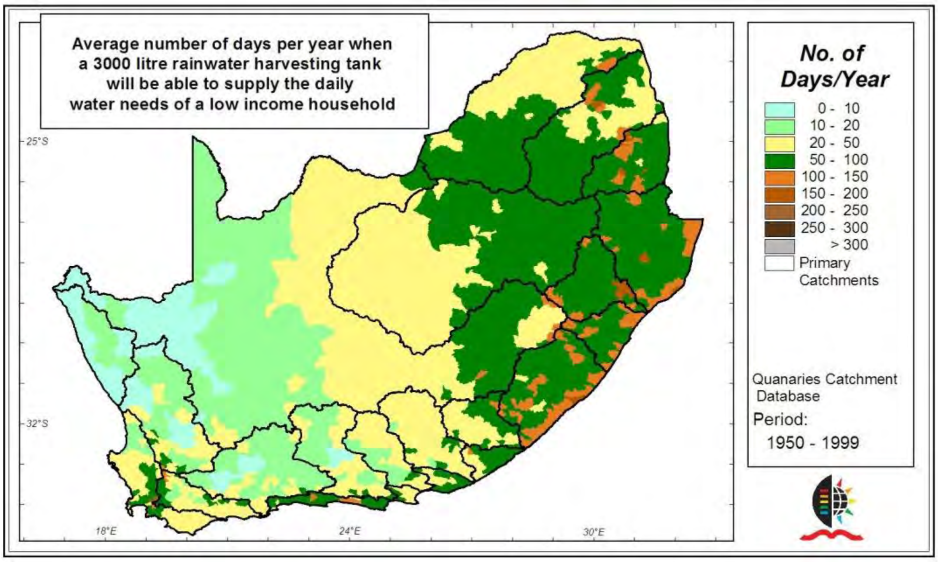



**Figure 3.2 Domestic rainwater harvesting tank (3000 ℓ) potential to meet a daily household requirement of 300 ℓ per day, for the period 1950-1999 for South Africa.**

Figure 3.3 shows the percentage of days per year when at least a portion of the daily household requirement can be met by a 3000 ℓ RWH tank. It shows that under historical climate conditions, a further 20-50 days of the year will have some water available from the RWH tank in most of the central and eastern parts of southern Africa, while some areas along the east coast will have part of their daily requirements met on 50-100 days. The number of days with partial supply is lower than the number of days with full supply across most of the eastern parts of South Africa as rainfall in this area is generally characterised by high intensity and volume events (generally thunderstorms) rather than low intensity, "drizzle" events. The rainfall events more often exceed 7 mm and therefore provide at least 1 day's water requirements of 300 litres (based on the roof size of 40 $m^2$ used in this study). On the days when only partial water supply is available, the average amount of water that is available is 132 ℓ. This is approximately half of the daily requirement. Using Gleick's (1996) breakdown of water use in a low income household, the daily requirements for sanitation and hygiene (20 ℓ per person per day) or the daily requirement for bathing (15 ℓ per person per day) could be meet by the RWH tank up to half of the year. This will reduce the demand and strain on traditional water supplies which treat water to drinking standard at a considerable cost.

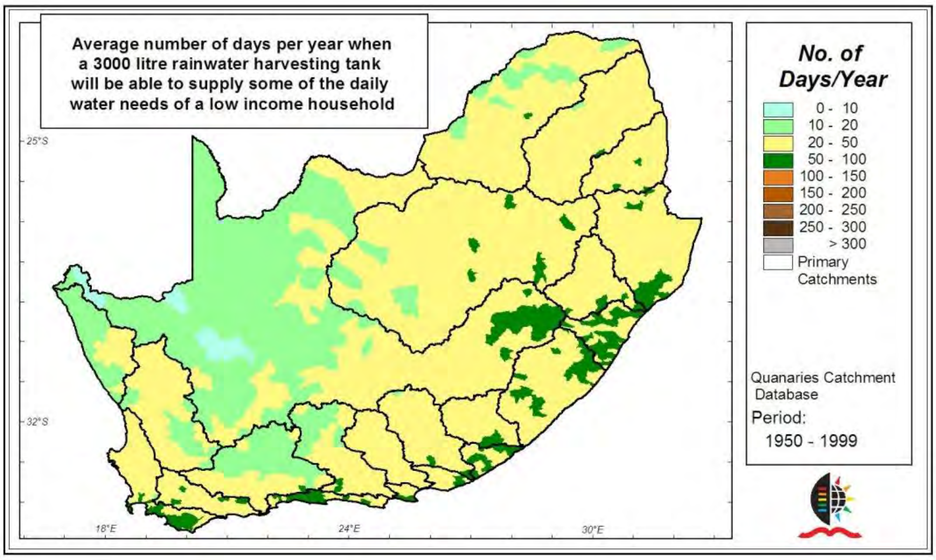



**Figure 3.3 Domestic rainwater harvesting potential to meet a portion of daily household requirement of 300 ℓ per day, for the period 1950-1999 for South Africa.**

Table 3.1 also shows that the on average a RWH tank with a 3000 ℓ capacity will over flow an average of 6.75 times per year in the eastern part of the region. The average amount of water lost during an overflow event due is 1,760 ℓ per year. Increasing the tank capacity to 5000 ℓ will reduce the number of overflows to 3.37 resulting in an average loss of water of just 1,653 ℓ per year. However the increased cost of a 5000 ℓ does not significantly increase the number of days when the tank can supply water for domestic needs. This suggests that climatic limitation in the rest of South Africa limit the actual yield of water that can be selected in the tanks. A 3000 ℓ tank seems to be an optimal size for most of South Africa as suggested by van der Zaag's (2000) method.

**Table 3.1 Comparison of the number and amount of water lost between a 3000 litre and 5000 litre rainwater harvesting tank.**

| | **3000 litres** | | | **5000 litres** | | |
|---|---|---|---|---|---|---|
| | Historical climate (1950-1999) | Intermediate future climate (2046-2065) | Distant future climate (2081-2100) | Historical (1950-1999) | Intermediate future climate (2046-2065) | Distant future climate (2081-2100) |
| **Average no. of overflows/year** | 6.75 | 7.76 | 11.14 | 3.37 | 5.08 | 7.66 |
| **Max amount of water lost in a single overflow** | 12,583.72 | 1,961.70 | 2,265.21 | 13,128.52 | 961.70 | 1,265.21 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **event (ℓ)** | | | | | | |
| **Average amount of water lost per overflow event(ℓ)** | 1,760.18 | 870.69 | 2,265.21 | 1,653.84 | 885.99 | 1,026.37 |
| **Average total water lost/year(ℓ)** | 25,490.64 | 14,552.69 | 22,350.1 | 15,953.75 | 10,984.23 | 16,455.09 |

Figure 3.4 and 3.5 shows the ability of a 3000 ℓ tank to supply all or some of the daily water requirements of a low income household under intermediate climate change conditions (for the period 2046-2065). Figure 3.4 shows that all of the east coast could receive its daily requirement at least 50 – 100 days of the year and many areas have increased to 100-150 days per year. The areas suitable for RWH around Cape Town have increased, with many more areas now able to meet their daily requirement between 50-100 days of the year. The central regional of SA will also be able to meet their daily water requirements using RWH, 50-100 days of the year. This means that the AU goals will become more achievable under intermediate climate change conditions. The western parts of SA are still not suited to RWH, with less than 10 days of the year having water available.

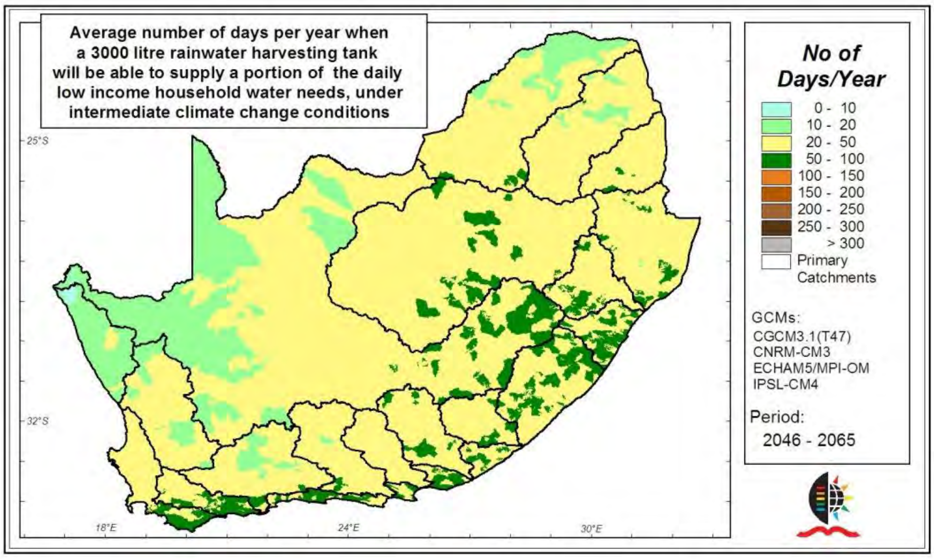



**Figure 3.4 Domestic rainwater harvesting tank's potential to meet a daily household requirement of 300 ℓ per day, for the period 2046-2065 for South Africa.**

Figure 3.5 shows a significant increase in the areas where RWH can supply at least some of the daily water use requirements of a low income household. On average 133 ℓ of water is available on these days which will still provide the daily requirements for sanitation and hygiene or for bathing according Gleick's (1996) breakdown of daily water use in a low income household. This could be especially important in the dry western part of the country, where water delivery cost are not only associated with the high cost of treatment but also the high costs of transporting water from high rainfall areas to low rainfall areas. However the cost of the tanks may still outweigh the benefits of receiving only a partial supply of water on less than 100 days of the year. The 3000 ℓ tank will overflow more often in the eastern part of SA under intermediate CC conditions (increasing from an average of 4.26 to 7.76 times per year) and losing on average per year 14,553 ℓ of water. Increasing the tank size to 5000 ℓ will decrease the number of overflows by an average of 2.7 events per year and decrease the average amount of water lost per year by 3568 ℓ.

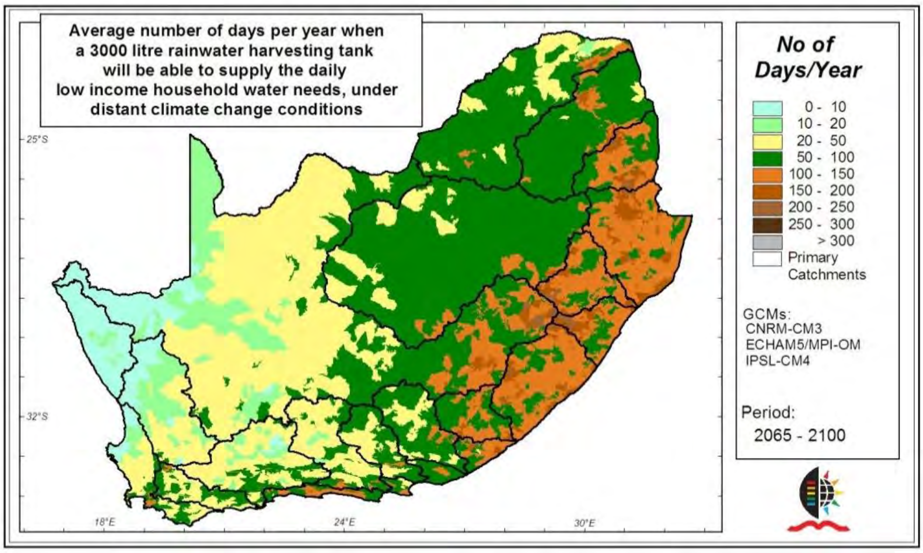



**Figure 3.5 Domestic rainwater harvesting tank's potential to meet a portion of daily household requirement of 300 ℓ per day, for the period 2046-2065for South Africa.**

Figure 3.6 and 3.7 shows the ability of a 3000 ℓ tank to supply all or some of the daily water requirements of a low income household under distant climate change conditions (for the period 2081-2100). Figure 3.5 shows an increase in the ability to meet the daily household requirement in the east from 50 – 100 to 100 – 150 days while the areas which will receive partial supply (with an average of 132 ℓ available) will increase across the central regions of South Africa. Generally the eastern part of SA will become more suitable for domestic RWH under climate change conditions while the western part of SA remains less suitable.

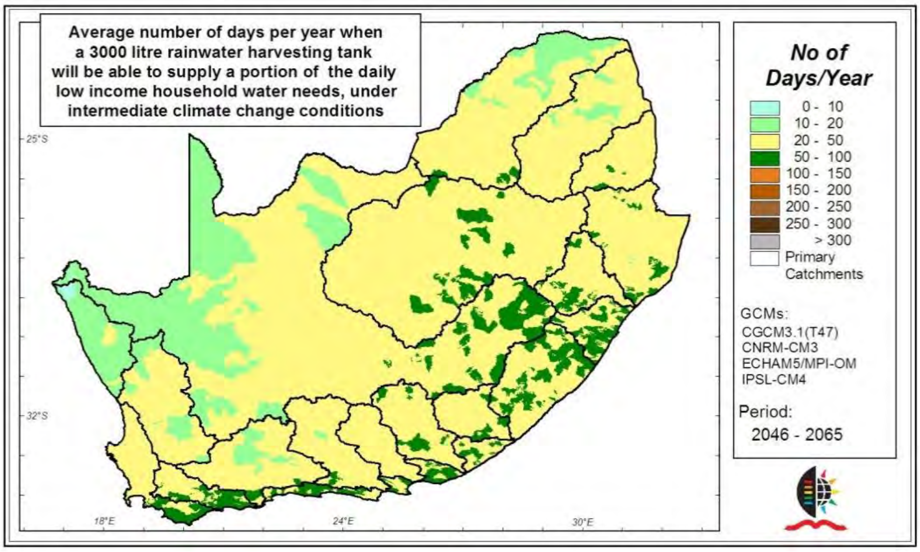



**Figure 3.6 Domestic rainwater harvesting's potential to meet a daily household requirement of 300 ℓ per day, for the period 2081-2100 for South Africa.**

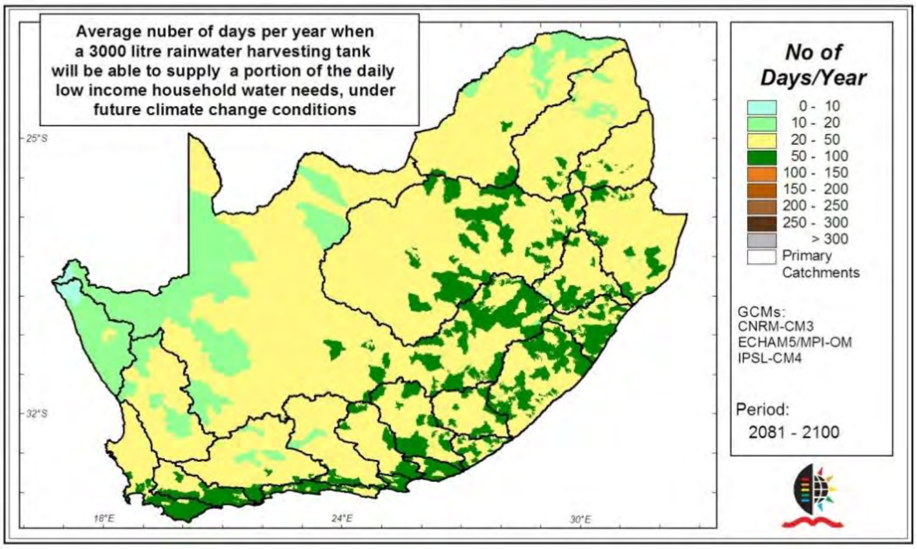



**Figure 3.7 Domestic rainwater harvesting's potential to meet a portion of daily household requirement of 300 ℓ per day,** for the period 2081-2100 **for South Africa.**

In summary, the eastern part of SA is most sustainable for RWH investment and should be prioritised for the implementation of domestic RWH programs. The AU goals of 10% of water supply being provided by RWH are easily achievable in this region. However it is obvious that RWH can only be viewed as a supplementary water supply solution, as almost half of the year there is no water in the tanks and an alternative water supply need to be available. Water quality issues also need to be taken into account. According to Gleick's (1996) breakdown of water use in a low income household 10 ℓ of water is used per day for cooking and 5 ℓ for drinking. This water need to be high quality to prevent waterborne diseases and so if RWH is intended for drinking purposes, additional infrastructure, such as first flush systems, water filters and water purification need to be installed which increase the cost of a domestic RWH system.

A 3000 litre RWH tank currently costs at US$ 205, while a 5000 litre tank costs US$ 295 (priced on 17 July 2016, where the South African R 14.58 equalled US$ 1). A first flush system cost approximately US$ 30 and standard 125 mm guttering US$ 8.6 per meter.

### 3.5 Conclusion

Rainwater harvesting is increasingly being identified as water supply solution both under present and project climate conditions. This research has shown that the eastern part of South Africa and a small area around the city of Cape Town in the Western Cape are currently most suited to domestic RWH and will become even more suited under intermediate and distant future climate change conditions. However, RWH can only even be seen as a supplementary water supply solution as the tanks would be empty up to half the year even in the most suitable areas in the east. The cost of implementing a RWH that can provide potable water is quite high, and so RWH may be best prioritised for non-potable uses, such as bathing and sanitation or for large scale uses such as irrigation and commercial application.

The perceived risk of using harvested water is one of the greatest limitations to RWH adoption. In a study by (Mankad and Tapsuwan, 2011) the general view of the public was that most harvested water was not suitable as a source of potable water and was generally only accepted as source of water for non-potable uses. This means that government is still mandated to supply water for potable use, as it is this use that is prioritised as a basic human need. Therefore investment in RWH may not be enough or prioritised if governments still need to supply the infrastructure or means to supply potable water. Water harvesting is still often viewed as a “soft” solution, only sustainable for small scale interventions (Gleick, 2003). However its greatest benefit may be in collection of water for large scale, non- potable use such as commercial buildings and irrigation (even of small urban gardens). Instead of using potable water, which has been purified at a high cost, for non-potable uses, investment in RWH to supply water at the local scale for non-potable use may be more economic and relieve the pressure of conventional water supply systems.

Hard activities, such as focus on technology and infrastructure verses soft activities such as governance and management are needed in collaboration. Evidence from the field shows that the RWH fails to bring about the desired livelihood adaptations as not enough emphasis is focused on social acceptance of RWH and the wants and needs of a community in securing livelihoods not just acceptance of the technologies before the inception phase. In the framework of “Panta Rhei” everything flows, there must be greater focus on community driven adaptation rather than trying to fit solutions onto communities. A useful strategy is to identify which RWH systems are already implemented, gaining social acceptance and proving to be effective within a society. Utilising systems which have already proven successful in within a landscape allows for a more spontaneous uptake of the system, which has already proven successful. Communities can learn from each other how and why the system works, reducing the input form “external” implementing agencies, which may not identify with the challenges of each community. In the following chapter, a method for identifying the extent of existing RWH on a large spatial scale is explored with the aim of providing a method to undertake such a study.

In turn, large scale implementation of RWH may become a driver of global change. Mass implementation may result in changes in the runoff related components of baseflow and stormflows, reducing river recharge and impacting on water availability for downstream users. While general consensus agrees that RWH will have little impacts on catchment hydrology (de Winnaar and Jewitt, 2010), greater research is required to explore the potential impacts of large scale RWH implementation. In the following chapter, remote sensing is used to try identifying the current extent of current for 4 different RWH systems as well as evaluate how effective these systems are in storing water during the dry season.

### 3.6 Acknowledgements

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# CHAPTER 4: EXPLORING THE POTENTIAL FOR USING REMOTE SENSING TECHNOLOGY TO IDENTIFY EXISTING WATER HARVESTING SITES (PAPER 3)

Bulcock, L.M.*, Chetty, A.S. and Jewitt, G.P.W.

**Abstract**

Increasing demand for improved agricultural production, as a direct result of a rapidly growing world population, is leading to the intensification of production on existing crop land as well as the expansion of crop lands into new area. Sometimes, these areas are only marginally suited to crop production, and without proper land and water management degradation could occur. There is increasing interest in rainwater harvesting (RWH) which could ease the burden of water shortages for agricultural and domestic purposes and coupled with soil/land management reduce land degradation. However, currently there is no global census of the extent of current RWH practices and very few water balance studies at field or catchment scale to support this assumption. This paper explores the potential for using remote sensing technology to calculate total evaporation (ET) and the normalized difference vegetation index (NDVI) as indicators of the current implementation of RWH. This will allow for a census technique to monitor the extent and uptake of RWH systems as well as evaluate the performance of different systems in increasing soil water or water available to plants. Four Different RWH techniques were assessed at sites in South Africa, Tanzania and Burkina Faso. Results show that large scale techniques such as the spate irrigation in Tanzania or mass implementation of smaller techniques, such as the "Zai Pits" and contour bunds in Burkina Faso were visible from calculated ET maps. The contour bunds were the most successful in storing water, in the soil profile, for plant use with higher ET being measured from the bunded system well into the dry season. However, the fields irrigated by micro-basin plastic storage tank systems in South Africa were not visible from ET maps but were visible from NDVI maps in summer. The implementation of this technique is not as widely spread as in the other three case studies; therefore the impact on the spatial and temporal distribution of ET is not great enough to make a measurable difference in the landscape. It is concluded that remote sensing is a useful technique for calculating ET and NDVI as an indicator of agricultural land, however ground truthing or expert knowledge is needed to confirm that sites identified are part of WH systems as opposed to rainfed agriculture.

### 4.1 Introduction

Growing populations, economic development, climate variability, projected climate change as well as legislation and international commitments are the main drivers of rainwater harvesting (RWH) adoption around the world and in Sub-Saharan Africa. Approximately 70% of the world's poor live in rural areas where they have little option but to rely on rainfed agriculture to sustain their livelihoods (CAWMA, 2007). However, when agricultural intensification expands into areas considered marginal for crop production, the risk of anthropogenic induced land degradation can have an impact on the natural vegetation, watercourses, biodiversity, socio-economic stability and food security (Brink and Eva, 2009; Kalama et al., 2014; Ouedraogo, et al. 2015). To prevent or reverse land degradation in agricultural systems in marginal areas, soil and water conservation techniques need to be implemented. As a result, the adoption and development of rainwater harvesting (RWH) strategies to ensure the efficient use of water, reduce storm runoff and associated top soil loss as well as sustain human livelihoods, both for domestic and agricultural purposes, has evolved over centuries (Rockström, 2000; Vohland and Barry, 2009; Bossio et al., 2011).

In recent years, RWH (as defined in section 2.1.1 above) has been gaining interest as an alternative water supply solution, especially in rural areas where traditional piped water may be expensive and unfeasible to implement at an adequate spatial scale to ensure fair access to water for all. The Africa Union, through Sharm El-Sheikh Commitments for Accelerating the Achievement of Water and Sanitation Goals in Africa (AMCW, 2008), committed to increase the RWH share of total water supply to 10%. Conservation tillage, planting system in which at least 30 % of the soil surface is covered by plant residue after planting has been well documented to reduce soil erosion and thus reduce degradation (FAO, 1993; Evans et al., 2000; Carthy, 2001; Veenstra et al., 2006; Nyagumbo, 1999). RWH can also improve crop production and improved plant cover (and associated root growth) is well known to reduce soil erosion. McCool et al. (1995) found a reduction of 40-80% in water runoff and soil erosion by practicing conservation tillage.

However, currently uptake and upscaling of RWH is ad-hoc and user or research driven. There is little census of the current scale of RWH across Africa. In addition, as the results in Chapter 2 showed, guidelines for assessing the suitability are too narrow to account for the full range of conditions under which RWH can take place. Instead, it is recommended that by evaluating the extent of existing systems and the landscape characteristics in which they operate the most appropriate system can be implemented in almost any site.

However, there were no tools or techniques available to undertake such a large scale spatial study until recent years. The availability of increasingly high resolution satellite images and associated advancements in analysis provides a useful tool for the assessment of the scale and extent of RWH as well as the success of upscaling efforts. Quantification of the scale of evaporation from RWH as a measure of its effectiveness, identification of water crop deficient by comparing actual and potential ET and the associated food security issues could be ways of and assessing the human induced impacts of up-scaled RWH on fresh water supplies (Anderson et al., 2012).

This paper tests the potential of using remote sensing imagery to calculate total evaporation (ET) using the water balance approach and NDVI of the landscape where RWH systems are implemented to test whether it is a viable method for identifying the existence of RWH sites within a landscape.

### 4.2 Study Sites

This study was carried out at four sites (Figure 4.1). These are the Potshini area of South Africa, using Landsat and MODIS to compare the efficiency of medium (30m) and low (250m) resolution images (respectively) for identifying RWH sites, Makanya in North Central Tanzania and, two areas around Ouagadougou and Linongen in Burkina Faso using Landsat images only.

The Potshini sub-catchment (part of Emmaus catchment, quaternary catchment number V13D - 28°48'42.78"S; 29°22'45.92"E) is located in the Bergville district, in the foothills of the Drakensberg Mountains in the KwaZulu-Natal province of South Africa and forms part of the Thukela River catchment. The Thukela river basin has an area of 29,036 km$^2$, while the areas of QC V13D and Potshini sub-catchment are 280 km$^2$ and 1.2 km$^2$ respectively. Potshini is at an altitude of about 1250 m.a.s.l, and with a mean annual precipitation estimated to be 700 mm/a and mean annual potential evaporation (PET) between 1600-2000 mm/a (Guy and Smith, 1995). The mean annual temperature ranges between 16 and 18 °C. Frost is severe to very severe during winter (May to September) and hail is sporadically severe in summer (October to April). It is a predominately smallholder subsistence farming areas with rainfed maize being the major crop. Some vegetable gardening also takes place with cabbage, spinach, tomatoes and beans forming the main crops. Rainwater harvesting schemes were implemented in 2005 through the Smallholder Systems Innovation (SSI) project to irrigate vegetable gardens (Sturdy et al., 2008; Kosgei et al., 2007). Fifty RWH schemes were installed consisting of 3 x 5000 ℓ storage tanks harvesting runoff from around the homesteads or from the roads and 1 x 5000 ℓ rooftop runoff storage from the homestead roofs. Harvested rainwater is used to supplement irrigation of the vegetable gardens but is also used to water livestock and for limited domestic purposes.

Makanya catchment (4°21'33.37"S; 37°49'20.12"E), located in Same district within the Pangani river basin in Tanzania is divided into two altitudinal regions. The northern highlands have a mean altitude of 2500 m.a.s.l whereas the southern lowlands have a mean altitude of below 600m.a.s.l. The catchment is dominated by a convective rainfall which is characterised by its low, erratic and unreliable nature (Mutiro et al., 2006; Kinoti et al., 2010; Fischer et al., 2013). The shortest rainy season, known as “Vuli” occurs in November-January and the longest, “Masika”, between March and May. The average rainfall in the highland ranges between 800-1200 mm/a and it is below 500 mm/a in lowland (Makurira et al., 2009; Tumbo et al., 2011). The high rainfall variability in time, space and altitude is also associated with long and frequent dry spells (Enfors and Gordon, 2007; Pachpute, 2010). The vegetation cover varies from forest to dense bushland in the highland, and sparse bushland to degraded land in the lowlands. Spate irrigation, as described in Section 2.1.1 is practiced here, and without it crop production would be severely limited due to the low rainfall in the lowlands. RWH is received wide spread acceptance and uptake throughout the catchment and is considered to be prevalent in the catchment (Pachpute et al., 2009). The SSI project also operated in the Makanya area and aimed to improve the livelihoods of the rural poor through improvements in rainfed and RWH irrigated agriculture (IWMI, 2007).

Two study sites were explored in Burkina Faso, in the region known as the plateau-central. The first is in the area of Katabtenga (12°29'25.92"N; 1°33'49.63"W), which is approximately 15km north of the capital Ouagadougou, where the “*Zai*” pits RWH method is practiced. The second is just outside of Linongen (12°24'45.87"N; 1° 8'28.67"W), approximately 43km east of the capital Ouagadougou, where the contour bunding is practiced. Traditionally RWH systems are mostly implemented in the northern regions of Burkina Faso, however researcher have recently been promoting the practice and encouraging adoption in the middle and south-west of the country (Bouma nd Lasage, 2013). Both areas have a mean altitude of 298 m.a.s.l and are characterised by degraded soils. Low levels of mechanisation are implemented on both sites. The mean annual rainfall is 747mm/a, with most rain falling between June and September. Mean annual PET is 2000mm/a. Minimum temperature range between 13-15°C while maximum temperature range between 40-45°C. Vegetation in this region is dominated by semi-desert savanna and desert shrub (Kagone, 2001).

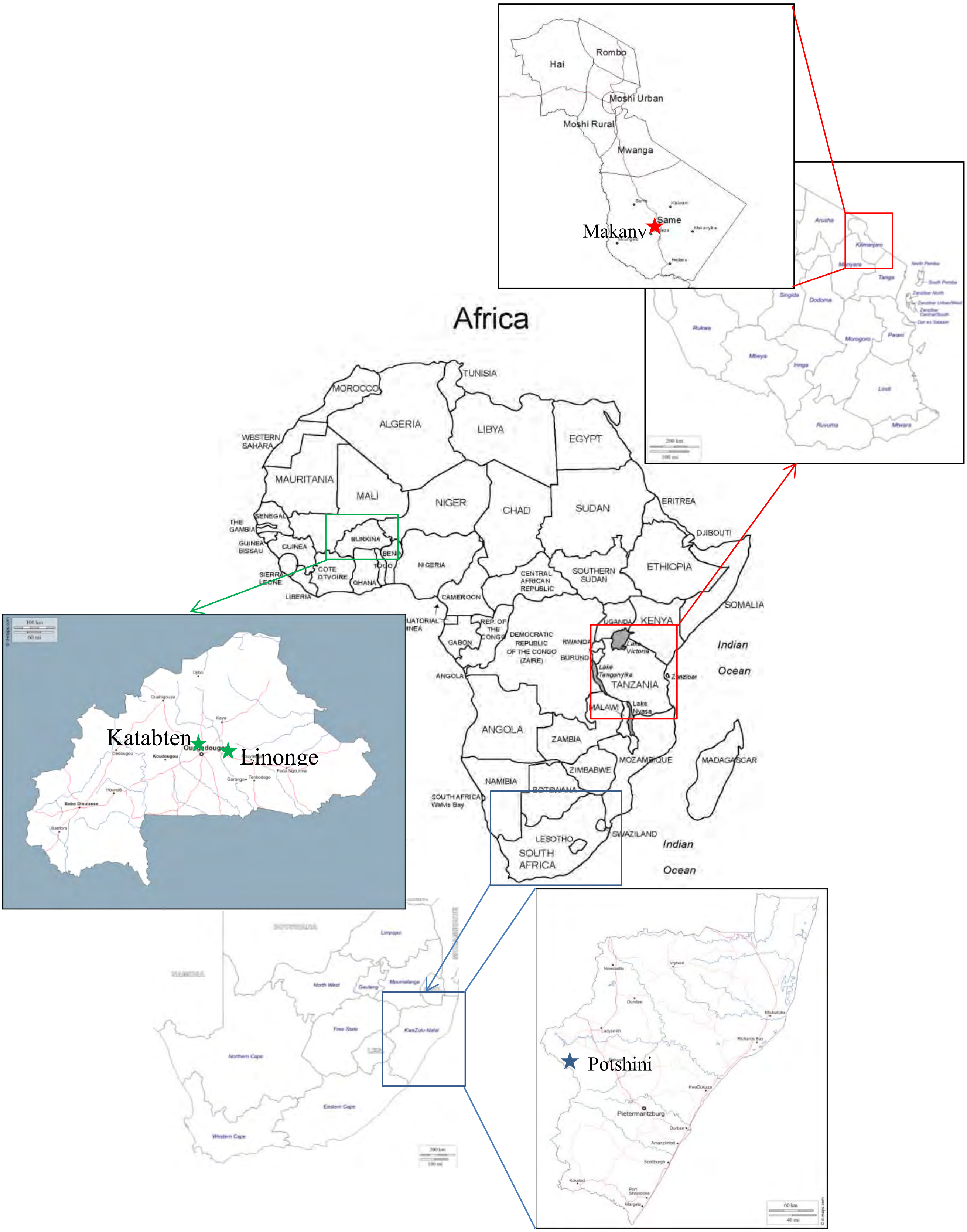



**Figure 4.1 Site layouts for each of the four study sites**

## 4.3 Theory and Methods

Remote sensing satellites that contain both visible and thermal bands can measure energy emitted from the Earth's surface. Using surface energy balance models, such as SEBS (Su, 2002), total evaporation (ET) of the land surface can be calculated across a landscape at a variety of different scales. The SEBS model estimates atmospheric turbulent fluxes using remote sensing imagery, which allows for the better estimation of ET across large areas than other energy balance models that cannot account for these atmospheric fluxes.

SEBS composes of three steps to calculate ET. Firstly pre-processing involves atmospheric corrections and calculation of physical parameters such as albedo, emissivity, temperature and vegetation cover. These are derived from RS imagery together with additional information regarding the land surface (such as altitude). Secondly, an extended model for calculating the roughness length for heat transfer (Su et al., 2001) which requires air pressure, temperature, humidity and wind speed at reference height. Finally, a formula for calculating the evaporative fraction based on the energy balance using limited cases is applied and requires the input of downward solar and longwave radiation which can either be measure directly, parameterised and calculated using a separate model. In order to assess whether ET from RWH could be distinguished, cloud free images from LandSat7 TM/ Landsat 8 (Table 4.1) and MODIS Level 1 (Table 4.2) images were downloaded for the period 2005 to 2014, during summer and winter.

**Table 4.1 Landsat Images used for ET and NDVI calculations.**

| Potshini, South Africa | | Makanya, Tanzania | | Burkina Faso | |
|---|---|---|---|---|---|
| Dry Season (May – Sept) n=30 | Wet Season (Oct – April) n=20 | Dry Season (June – Oct) n=9 | Wet Season (Nov – May) n=15 | Dry Season (Oct - May n=28 | Wet Season (June - Sept) n=10 |
| 01/06/2005 | 23/10/2005 | 22/08/2005 | 29/01/2006 | 02/02/2006 | 08/06/2014 |
| 17/06/2005 | 01/04/2006 | 08/07/2006 | 03/01/2008* | 06/03/2006* | 24/06/2014 |
| 19/07/2005 | 28/02/2006 | 15/10/2007 | 05/01/2009 | 07/04/2006 | 10/07/2014 |
| 04/08/2005 | 11/11/2006 | 02/10/2008 | 24/01/2010 | 15/01/2014 | 11/08/2014 |
| 05/09/2005 | 13/12/2006 | 03/07/2015 | 09/02/2010 | 31/01/2014 | 28/09/2014 |
| 21/09/2005 | 14/01/2007 | 27/09/2015 | 13/03/2010 | 04/02/2014 | 11/06/2015 |
| 06/07/2006 | 15/02/2007 | 13/10/2015 | 30/01/2012 | 16/02/2014 | 27/06/2015 |

| Potshini, South Africa | | Makanya, Tanzania | | Burkina Faso | |
|---|---|---|---|---|---|
| Dry Season (May – Sept) n=30 | Wet Season (Oct – April) n=20 | Dry Season (June – Oct) n=9 | Wet Season (Nov – May) n=15 | Dry Season (Oct - May n=28 | Wet Season (June - Sept) n=10 |
| 07/08/2006 | 03/03/2007 | 23/10/2015 | 22/05/2012 | 20/03/2014 | 13/07/2015 |
| 06/05/2007 | 19/03/2007 | 26/10/2014 | 04/02/2014 | 05/04/2014 | 14/08/2015 |
| 23/06/2007 | 01/01/2008 | | 11/01/2014 | 21/04/2014 | 15/09/2015 |
| 09/07/2007 | 18/02/2008 | | 27/11/2014 | 23/05/2014 | |
| 26/07/2007 | 06/01/2010 | | 13/12/2014 | 15/11/2014 | |
| 08/05/2008 | 08/10/2011 | | 14/01/2015 | 01/12/2014* | |
| 27/07/2008 | 24/10/2011 | | 04/05/2015 | 02/01/2015 | |
| 13/09/2008 | 11/11/2011 | | 22/05/2015 | 14/01/2015 | |
| 27/05/2009 | 10/10/2012 | | | 18/01/2015 | |
| 12/06/2009 | 11/11/2012 | | | 03/02/2015 | |
| 28/06/2009 | 14/01/2013 | | | 19/02/2015 | |
| 14/07/2009 | 14/11/2013 | | | 07/03/2015 | |
| 17/07/2010 | 30/11/2013 | | | 23/03/2015 | |
| 02/08/2010 | | | | 24/04/2015 | |
| 18/08/2010 | | | | 10/05/2015 | |
| 18/06/2011 | | | | 26/05/2015 | |
| 20/07/2011 | | | | 01/10/2015 | |
| 21/08/2011 | | | | 17/10/2015 | |
| 06/09/2011 | | | | 30/10/2015 | |
| 24/09/2012 | | | | 02/11/2015 | |
| 06/05/2013 | | | | 18/11/2015 | |
| 22/05/2013 | | | | | |
| 26/07/2013 | | | | | |

* Images displayed in analysis below

**Table 4.2 MODIS Images used for ET and NDVI calculations.**

| MODIS Images used at Potshini, South Africa | | |
|---|---|---|
| Wet Season (Oct – Apr) n=12 | Dry Season (May – Sept) n=21 | |
| 24/10/2005 | 01/06/2005 | 29/06/2009 |
| 01/04/2006 | 18/06/2005 | 14/07/2009 |
| 04/01/2007 | 20/07/2005 | 18/07/2010 |
| 06/02/2007 | 04/08/2005 | 02/08/2010 |
| 01/01/2008 | 05/09/2005 | 19/08/2010 |
| 18/02/2008 | 22/09/2005 | 19/06/2011 |
| 08/10/2011 | 06/07/2006 | 21/07/2011 |
| 25/10/2011 | 07/08/2006 | 22/08/2011 |
| 11/11/2011 | 08/05/2007 | 06/09/2011 |
| 10/10/2012 | 24/06/2007 | |
| 11/11/2012 | 09/07/2007 | |
| 14/01/2013 | 27/07/2007 | |

MODIS images were orthorectified and bands of importance extracted using Modis Swath Tool. All pre-processing and the application of SEBS were done using in built functions or script writer in the open source software Ilwis 3.3. The sections below describe the detailed methodology applied, while Figure 4.2 and 4.3 summarises the process in a flow diagram.

### *4.3.1 Preprocessing MODIS and Landsat for SEBS*

Pre-processing Landsat and MODIS images requires a sequence of steps to convert raw data into georeferenced and atmospherically corrected data that can be input into SEBS. Figure 4.2 and 4.3, presents a graphic representation of the entire pre-processing and application of SEBS for MODIS and Landsat respectively. A different process is required for pre-processing Landsat and MODIS (delineated by the grey square in Figure 4.2 and 4.3) and the pre-processing equations used for each can be found in Chapter 11 of the Landsat 7 Science User Data Handbook (2002) or in the MODIS Level 1B Product User's Guide (2006), which is also described in the help section of ILWIS SEBS 3.0. The pre-processing and SEBS processing steps for MODIS are already programmed into Ilwis, however Ilwis had to be programmed to preprocess Landsat images and run the SEBS model on the Landsat images.

MODIS data is generally not atmospherically corrected and so the data needs to be atmospherically corrected to account for the thickness of the atmosphere over the site, the air pressure, the water content vapor at the time of the image as well as the angle of the sun and sensor at the time the image is taken. Landsat images which have already been atmospherically corrected can be downloaded (and were for this study) however if only uncorrected images are available then a similar atmospheric correction process is needed.

Spectral radiance is the outgoing radiate energy of each band observed by the satellite at the top of the atmosphere. Spectral radiance for each band was calculated using the raw data and corresponding coefficient value for correction for each band. The coefficient value can be found in the metadata file which accompanies each image. Surface reflectivity or surface albedo is defined as the ratio of reflected radiation flux to incident radiation flux for both the Earth and the atmosphere. The reflectivity calculations take into account the angle and distance of the Earth to the sun for a representative central pixel. Top of the atmosphere (TOA) albedo was calculated using the reflectivity bands and sensor specific coefficient which relate to blackbody constant emissivity.

Solar and satellite zenith and azimuth angle maps were generated to correct differences in the distance and angle of the Earth in relation to the sun for each pixel in a MODIS image. This is important in MODIS imagery which has a swath of up to 2330 km but is not as important in a Landsat 7 image which has a swath of 185 km. It was assumed that it is safe to use a representative pixel in a Landsat image for zenith and azimuth angle as the variation over the 185 km swath of a Landsat image will not be so great. A digital elevation model was generated for the MODIS images whereas a representative average elevation for the area of interest was used for the Landsat images. The MODIS solar and satellite bands were calibrated using the sensor specific coefficients.

TOA albedo was atmospherically corrected to calculate surface albedo. The correction of the atmospheric absorption and scattering in the visible channels is essential for any approach which makes use of the energy balance equation. The Simplified Method for the Atmospheric Correction (SMAC) model, developed by Rahman and Dedieu (1994) was used for MODIS imagery. The SMAC technique uses semi-empirical formula to describe and account for the interactions of solar radiation, such as absorption and scattering, as the solar energy travels through the atmosphere. SMAC requires parameters such as water vapor, surface pressure, aerosol optical thickness and ozone content. Such data was accessed from maps obtained from NASA'sEarthObservatory webpage [http://earthobservatory.nasa.gov/GlobalMaps/view.php]. This process is perhaps the most difficult in the entire SEBS application. Parameters such as aerosol optical thickness and ozone water content change hourly. Unless sophisticated and expensive machinery is available to measure these values (in which case it may be easier and cheaper to measure ET and NDVI directly), daily values need to be abstracted from the NASA Earth Observation page, which may introduce inaccuracies in the ET calculation of the SEBS model. Furthermore, the SMAC calculation becomes less reliable when applied to solar zenith angles greater than 60 degrees and/or satellite zenith angles greater than 50 degrees, which may introduce a margin of error in the calculations during winter time (Rahman and Dedieu, 1994).

The Landsat atmospheric correction uses a less detailed process based on atmospheric transmissivity which is defined as the fraction of incident radiation that is diffused by the atmosphere and reflects the absorption and scattering effects of the atmosphere (Bastiaanssen, 2000). The transmissivity equation assumes conditions of clear skies and relatively dry condition, which may introduce errors especially in the wet rainfall season.

Surface emissivity was required for the accurate calculation of land surface temperature. Land surface emissivity was estimated from the visible red band (Bred) and the near infrared bands (Bnir). Firstly, NDVI values were calculated using the Rouse et al. (1973) equation. After which fractional vegetation cover ($f$c) was calculated using the Carlson and Ripley (1997) Method. Three different sets of equations are used to calculate emissivity (e) and emissivity difference (dE) based on the NDVI value as described in Table 4.3 below. The emissivity of water pixels is assumed to be e = 0.995, based on surface albedo < 0.035.

**Table 4.3 Formula used to calculate emissivity and emissivity difference for different NDVI pixels based on Sobrino (2003).**

| Land cover represented | **Bare soil pixels** | **Mixed pixels** | **Vegetation pixels** |
|---|---|---|---|
| NDVI value | < 0.2 | 0.2 =< NDVI < = 0.5 | > 0.5 |
| Emissivity (e) | = 0.9825 - 0.051 * Bred | = 0.971 + 0.018 * $f$c | = 0.990 |
| Emissivity difference (dE) | = -0.0001 - 0.041 * Bred | = 0.006 * (1 - $f$c) | = 0 |

After emissivity had been calculated, land surface temperature ($T_S$) was calculated using the split window technique for MODIS and the modified Plank equation for Landsat (Figure 4.2 and 4.3). The split window technique applied to MODIS uses the derived emissivities (e and dE) and the band brightness temperature to calculate $T_S$. The advantage of the SWT is the cancellation of the effect of the atmospheric components, with exception of the atmospheric water column. A formula by Sobrino and Raissouni (2000) was used:

$$T_S = btm2 + (1.97 + 0.2 * W) *(btm2 - btm1) - (0.26 - 0.08 * W) * sqrt(btm2 - btm1) + (0.02 - 0.67 * W) + (64.5 - 7.35 * W) * (1 - e) - (119 - 20.4 * W) * dE \quad (4.1)$$

where $T_S$ is the land surface temperature, btm1, btm2 is brightness temperature (MODIS band 31 and 32 respectively), W is water vapour content, e is surface emissivity and dE is surface emissivity difference.

Landsat has only one thermal band therefore the split window technique was not suitable. Instead $T_S$ for Landsat was calculated using a modified Plank equation. This requires three steps before $T_S$ can be calculated:

1. LAI is calculated as a function of NDVI,
2. emissivity is calculated from the narrow band 6 of Landsat (10.4 to 12.5 µm) , and
3. corrected thermal radiance (Rc) from the surface is calculated using the equation defined by Wukelic et al (1989) as:

$$Rc = \ -(1-\varepsilon_{NB})R_{sky} \quad (4.2)$$

where $R_{sky}$ is the downward thermal radiation of clear sky in band 6 and $\varepsilon_{NB}$ is the transmissivity of air. Land surface temperature ($T_S$) can then be calculated for Landsat images using the modified Plank equation:

$$T_S = \frac{K_2}{\ln\left(\frac{\varepsilon_{NB} K_1}{R_c}+1\right)} \quad (4.3)$$

where, K1 and K2 are constants and for Landsat images (666.09 and 1282.71 W/$m^2$/sr/µm respectively (Landsat 7 Science User Data Handbook (2002)).

### *4.3.2 Application of SEBS to MODIS and Landsat images*

The simplified energy balance model, which is the basis of the SEBS model, is written as:

$$R_n = G_o + H + \lambda E \tag{4.4}$$

Where $R_n$ is the net radiation flux, $G_o$ is the soil heat flux, $H$ is the sensible heat flux and $\lambda E$ is the latent heat flux ($\lambda$ is the latent heat of vapourisation and $E$ is the actual evapotranspiration).

Net radiation flux is calculated as:

$$R_n = (1 - \propto) \cdot R_{swd} + \varepsilon \cdot R_{lwd} - \varepsilon \cdot \sigma \cdot T_0^4 \tag{4.5}$$

Where $\propto$ is the albedo, $R_{swd}$ is the downward solar radiation, $R_{lwd}$ is the downward longwave radiation, $\varepsilon$ is the emissivity of the surface, $\sigma$ is the Stefan-Boltzmann constant and $T_0^4$ is the land surface temperature. The equation to calculate soil heat flux is expressed as:

$$G_o = R_n \cdot [\Gamma_c + (1 - f_c) \cdot (\Gamma_s - \Gamma_c)] \tag{4.6}$$

Where $\Gamma_s$ and $\Gamma_c$ are the ratio of soil heat flux to net radiation and are assumed to be 0.315 for bare soil and 0.05 for a full vegetation canopy respectively Landsat 7 Science User Data Handbook (2002). Interpolation is performed using fractional vegetation cover ($f_c$) and based on $\Gamma_s$ and $\Gamma_c$ as the limiting cases (Su, 2002).

Sensible and latent heat flux are calculated using the similarity relationship in the atmospheric surface layer (ASL) where wind speed ($u$) and the mean potential temperature difference between the surface and the air ($\theta_0 - \theta_a$) is expressed in integral form as:

$$u = \frac{u*}{k}\left[\ln\left(\frac{z - d_0}{z_{0m}}\right) - \Psi_m\left(\frac{z - d_0}{L}\right) + \Psi_m\left(\frac{z_{0m}}{L}\right)\right] \tag{4.7}$$

$$\theta_0 - \theta_a = \frac{H}{ku*\rho Cp}\left[\ln\left(\frac{z - d_o}{z_{0h}}\right) - \Psi_h\left(\frac{z - d_0}{L}\right) + \Psi_h\left(\frac{z_{0h}}{L}\right)\right] \tag{4.8}$$

Where $z$ is the height above the land surface, $u*$ is the fraction velocity, $Cp$ is the specific heat of air at a constant pressure, $\rho$ is the density of air, $k$ = 0.4 as per the von Karman's constant (Sheppard, 1947), $d_0$ is the zero plane displacement height, $z_{0m}$ is the roughness height or momentum transfer, $\theta_0$ is the potential temperature at the surface, $\theta_a$ is the potential temperature at the height z, $z_{0h}$ is the scalar roughness height for heat transfer, $\Psi_m$ and $\Psi_h$

are the stability correction functions for momentum and sensible heat transfer respectively and $L$ is the Obukhov length (Businger et al., 1971) and can be calculated as:

$$L = \frac{\rho C p u_*^3 \theta_v}{kgH} \tag{4.9}$$

Where g is the acceleration due to gravity and $\theta_v$ is the virtual potential temperature near the surface. Using a combination of equations 4.10 and 4.11 in an iterative method, sensible heat flux can be estimated (Su, 2002). In order to calculate the evaporative fraction, SEBS applies the energy balance at dry and wet limiting cases so that relative evaporative ($\Lambda_r$) can be derived as:

$$\Lambda_r = 1 - \frac{H - H_{wet}}{H_{dry} - H_{wet}} \tag{4.10}$$

Where $H_{wet}$ is the sensible heat flux at the wet limit and $H_{dry}$ is the sensible heat flux at the dry limit, the calculations of which are detailed in Su (2002). The evaporative fraction ($\Lambda$) is estimated by:

$$\Lambda = \frac{\lambda E}{R_n - G} = \frac{\Lambda_r \cdot \lambda E_{wet}}{R_n - G} \tag{4.11}$$

Where $\lambda E_{wet}$ is the latent heat flux at the wet limit. Latent heat flux ($\lambda E$) can be calculated as:

$$\lambda E = \Lambda(R_n - G_0) \tag{4.12}$$

Finally, daily ET is calculated using (Su, 2002):

$$ET = 8.64 \times 10^7 \times \Lambda_0^{24} \times \frac{\overline{R_n} - \overline{G_0}}{\lambda \rho_w} \tag{4.13}$$

Where $\rho_w$ is the density of water (1000kg m-3) and $\overline{R_n}$ is the average daily net radiation and $\overline{G_0}$ which is average daily soil heat flux and is assumed to be negligible as most of the heat gained by the soil during the day is lost at night and therefore the flux in average daily soil heat are so slight they have little impact on the energy balance .

| Symbol | Meaning | Symbol | Meaning |
|---|---|---|---|
| $\propto_{TOA}$ | Top of atmosphere albedo | H | Sensible heat flux |
| $Bred$ | Satellite Red band | $kB^{-1}$ | Van Kármán constant and Stanton number |
| $Bnir$ | Satellite near infrared band | $d_0$ | Zero plane displacement height |
| $NDVI$ | Normalised Difference Vegetation Index | $u$ | Friction velocity |
| α | Surface albedo | $T_a$ | Air Temperature (°C) |
| $dE$ | Surface emissivity difference | $\Psi_m$ | Stability correction function for momentum heat transfer |
| $Eo$ | Surface emissivity | $\Psi_h$ | Stability correction function for sensible heat transfer |
| $T_0^4$ | Land surface temperature | $Rn$ | Net Radiation Flux |
| $fc$ | Fractional Vegetation Cover | $Go$ | Soil Heat Flux |
| $LAI$ | Leaf Area Index | λ$E$ | Latent Heat Flux |
| $Z_{0m}$ | Roughness length for momentum | $ET$ | Evapotranspiration |

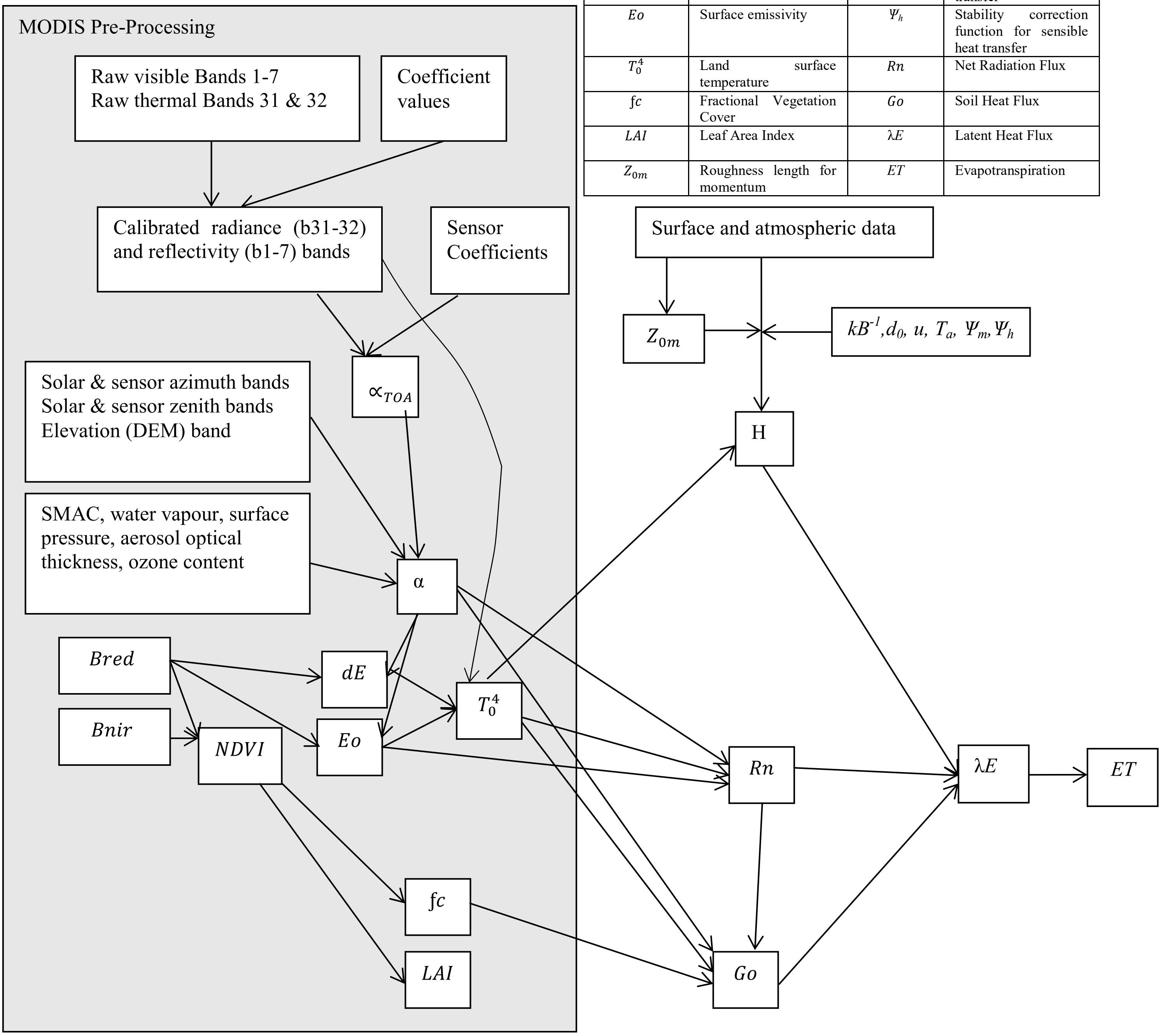
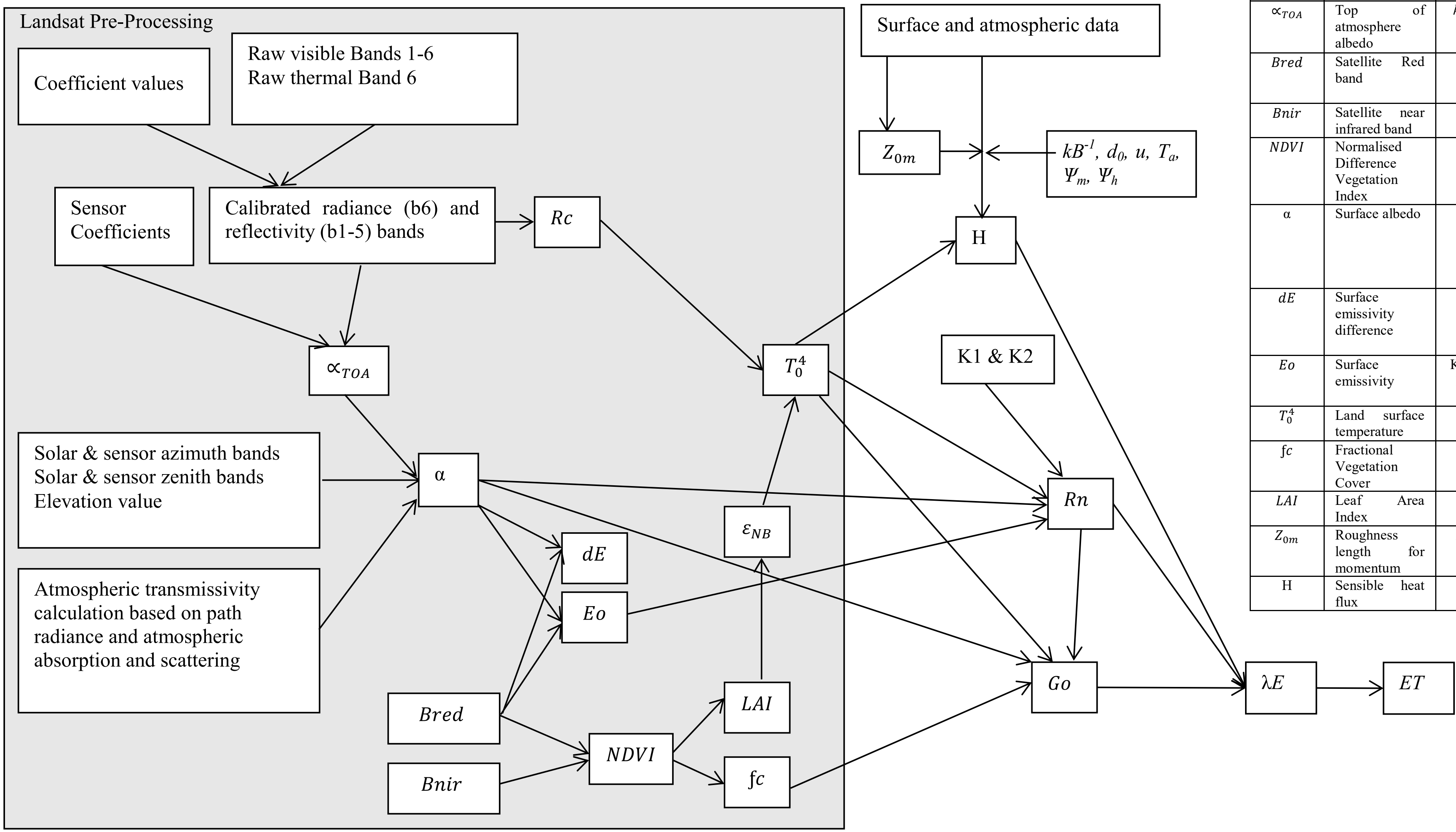



**Figure 4.2 Schematic diagram of methodology used to pre-process MODIS images and run the SEBS model**




| Symbol | Meaning | Symbol | Meaning |
|---|---|---|---|
| $\propto_{TOA}$ | Top of atmosphere albedo | $kB^{-1}$ | Van Kármán constant and Stanton number |
| $Bred$ | Satellite Red band | $d_0$ | Zero plane displacement height |
| $Bnir$ | Satellite near infrared band | $u$ | Friction velocity |
| $NDVI$ | Normalised Difference Vegetation Index | $T_a$ | Air Temperature (°C) |
| α | Surface albedo | $\Psi_m$ | Stability correction function for momentum heat transfer |
| $dE$ | Surface emissivity difference | $\Psi_h$ | Stability correction function - sensible heat transfer |
| $Eo$ | Surface emissivity | K1& K2 | Landsat constants |
| $T_0^4$ | Land surface temperature | $Rn$ | Net Radiation Flux |
| $fc$ | Fractional Vegetation Cover | $Go$ | Soil Heat Flux |
| $LAI$ | Leaf Area Index | $\lambda E$ | Latent Heat Flux |
| $Z_{0m}$ | Roughness length for momentum | $ET$ | Evapotranspiration |
| H | Sensible heat flux | | |

**Figure 4.3 Schematic diagram of methodology used to pre-process Landsat 7 images and run the SEBS model**

Once daily ET for both MODIS and Landsat was calculated, the daily ET and daily NDVI values for RWH sites and other land use sites, including non-irrigated agriculture, wetlands, grasslands/grazing lands and trees were analysed. These landcover types were classified using a visual classification from a Google Earth image and was ground truthed during field visits. Statistical analyses, including the determination of the median, quartiles and extremes of data for these sites were conducted in order to determine distribution of the data and whether RWH showed a noteworthy difference compared to other landcover types in daily ET or NDVI values during a) the entire year, b) the summer months or c) the winter months. A comparison between the resolutions of the two satellites used at the Potshini study site was also performed.

## 4.4 Results and discussion

### *4.4.1 Potshini Catchment*

Figure 4.4 a-f, displays an analysis of the variation in total evaporation values for 5 different land cover types including crops irrigated from water harvesting structures at the study site in Potshini for the period 2005 – 2013. Generally, Landsat derived estimates had higher ET values than MODIS, especially in summer. Rainwater harvesting sites do not evaporate at a notably different rate to the surrounding different types of land cover. Therefore, using ET calculation to distinguishing water harvesting sites of this nature is not possible. It was expected that the the winter ET of the WH would be higher than surronding land cover types however this has not been observed. The reason may be that the the surrounding landscape is comparatively less disturbed that the cultivation areas, therefore the soil water holding capacity has not been disturbed and retained soil moisture compensates for any increased ET as a result of WH irrigation. It was also expected that wetands would be more distiguishable and show higher ET than the surronding landscape but this has not been observed. The reason may be that the wetlands at this site are relative small, most less than 60m by 60m, which would constitue less than 4 pixels in a Landsat image making wetlands indistinct on the images. The wetlands are also used by cattle for watering which compromises the integrety of the wetlands and the surronding wetland vegetation meaning that they may not be functioning properly and may be quite dry in winter.

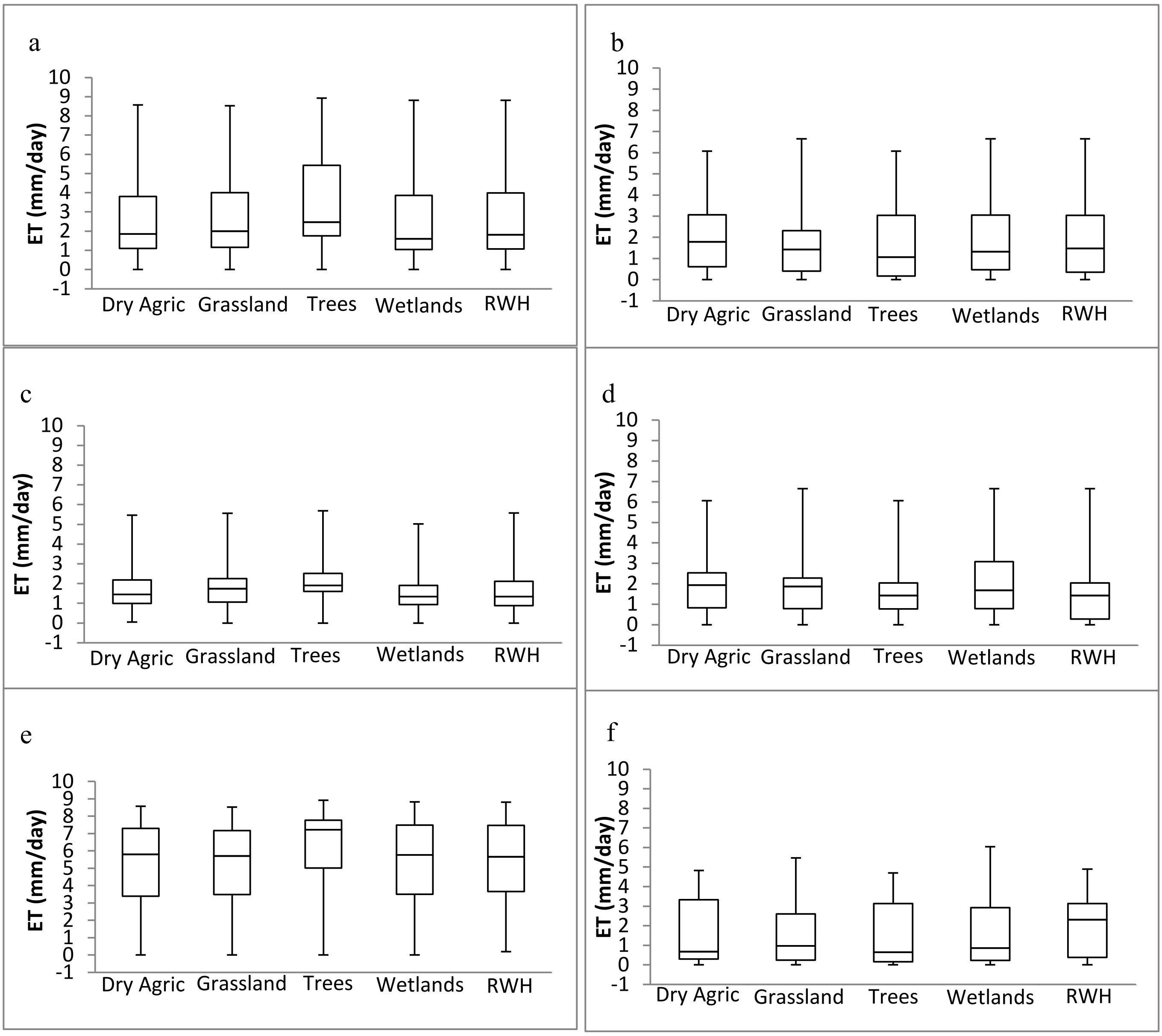



**Figure 4.4 a, c and e, shows the annual, winter and summer trends in total evaporation from 5 different land cover types at Potshini, including RWH calculated using the SEBS model and 30m Landsat images. Figure 4.4 b, and f, shows the annual, winter and summer trends in total evaporation from 5 different land cover types at Potshini, including RWH calculated using the SEBS model and 250m MODIS images.**

Figure 4.5 a-f, displays a statistical analysis of the variation in NDVI values for 5 different land cover types including crops irrigated from water harvesting structures at the study site in Potshini for the period 2005 – 2014. Generally, MODIS calculated higher NDVI values than Landsat. However this may be because of the larger pixel size which makes it difficult to distinguish the fine detail of vegetation cover differences that would be found between crops, grasslands and wetlands. In the summer NDVI calculation from the Landsat images, RWH sites did display noticeable higher NDVI values than other land cover types at Potshini. This shows that crops irrigated from water harvesting are producing higher crop cover than any surrounding vegetation during the summer months.

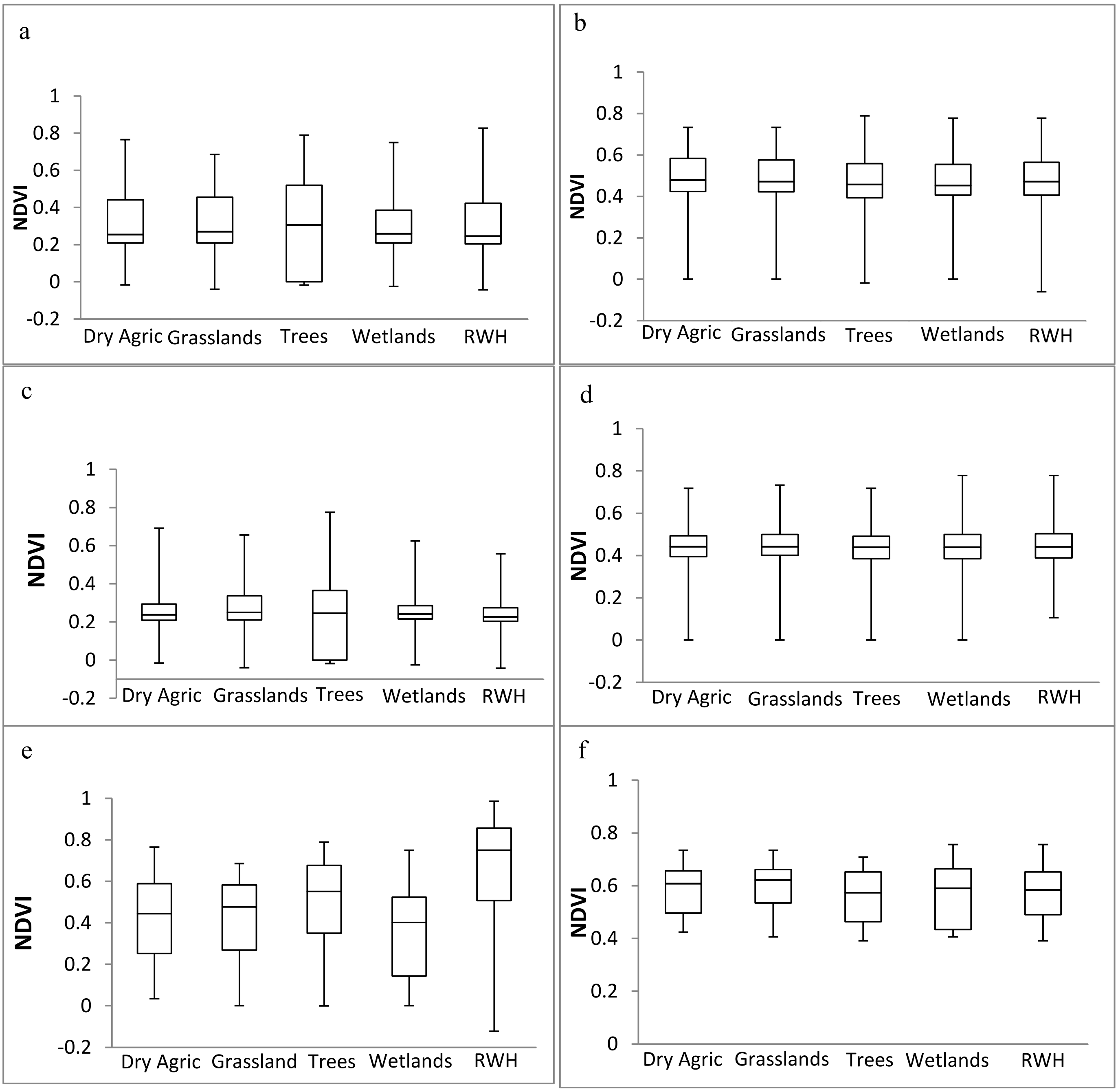



**Figure 4.5 a, c and e shows the annual, winter and summer trends in NDVI values from 5 different land cover types at Potshini, including RWH calculated using the SEBS model and 30m Landsat images. Figure 4.5 b, d-f, shows the annual, winter and summer trends in NDVI from 5 different land cover types at Potshini, including RWH calculated using the SEBS model and 250m MODIS images.**

Using remote sensing technology to assess the small scale RWH implemented at Potshini has provided limited success. The reason may be that the field size irrigated by this type of RWH systems is often not much larger than 30m, which means that only one pixel, in the case of Landsat, represents each field, or that the field crosses over 2 pixels and so the pixels represent mixed land use. Results show that low resolution sensors, such as MODIS, might be thought to be sufficient for small-scale hydrological catchment assessments, it is in fact not suitable for understanding the variability present in these small catchments, which often play out at a field scale which is smaller than the resolution of MODIS at 250m. At this stage it can be concluded that only summer month NDVI is suitable indicator for identifying RWH sites, such as the ones found at Potshini, using medium resolution remote sensing imagery such as 30m Landsat. MODIS images, at a resolution of 250m are simply too coarse to identify small-scale RWH such as the ones found at Potshini.

### *4.4.2 Makanya Catchment*

The application of Landsat to measure ET and NDVI at Makanya in Tanzania provide results that are more promising than the Potshini results. Figure 4.6 a-b and 4.7 a-b shows the ET and NDVI images from 30 January 2012, along with the associated histograms. In Figure 4.6 a-b the irrigated areas, which are solely irrigated by the spate system with very little MAP at the site, are clearly visible compared to the surrounding lowland vegetation. The daily evaporation values for the RWH irrigated crops on the 30$^{th}$ January 2012 are between 3.5-5 mm/day while the surrounding landscape has a maximum ET of 1.9 mm/day, as seen in Figure 4.6a. However long term trends of ET from the various landcover surfaces throughout the wet season (Figure 4.8) shows that while ET was distinct for the spate irrigated fields compared to the surrounding landcover surface (mountain forests to sparse bushland, the canal system linked to the spate system and the sparse bushveld surroundings) it is distinctly lower. The variance graph (Figure 4.8) shows that most of the ET measurements from the irrigated area to be between 0.78-2.9 mm/d. However Figure 4.9 shows the variance of measured ET values during the dry season at Makanya. In this figure the ET from irrigated fields is between 2.5-3.5 mm/d whereas the surrounding landscape is 1.8-2.5 mm/d. This confirms that the spate irrigation is successfully retaining water which is being used by the crops in the dry season, when the surrounding landscape (not irrigated) is drying out. This shows that ET calculated from Landsat images is a useful indicator and method for identify spate irrigation systems, especially during the dry season. However, the NDVI is less clear as vegetation in the highlands has a similar NDVI, of about 0.3, to the irrigated crops and so the fields are not clearly visible compared to the highlands natural vegetation cover even though they are clearly distinct to the non-irrigated lowland land cover. Therefore, NDVI is not a useful indicator for identifying spate irrigation systems in this landscape, even though the scale of the Landsat images is suitable.

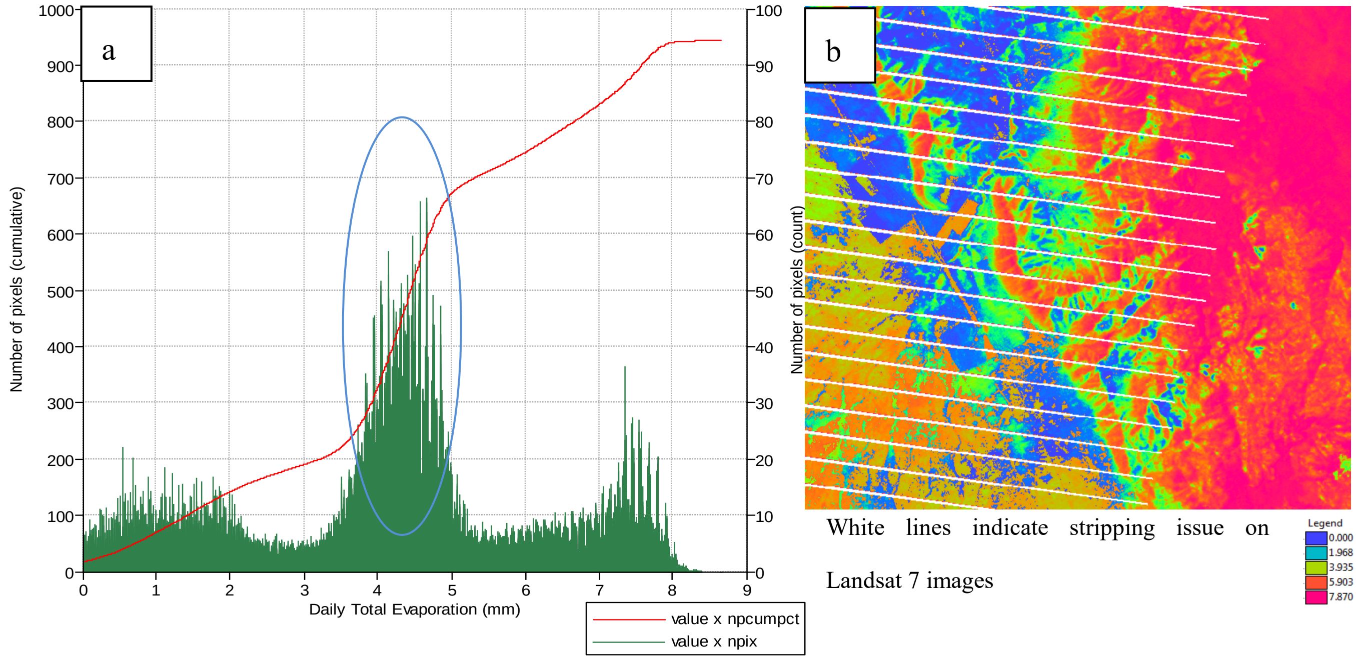



**Figure 4.6a shows the histogram of the image from 30 January 2012 which is displayed in Figure 4.6b which is the calculated daily total evaporation from the site at Makanya in Tanzania. The orange irrigated area (which is solely irrigated via the spate irrigation system) is visible in the image and in the histogram with ET values of between 3.5-5 mm daily.**

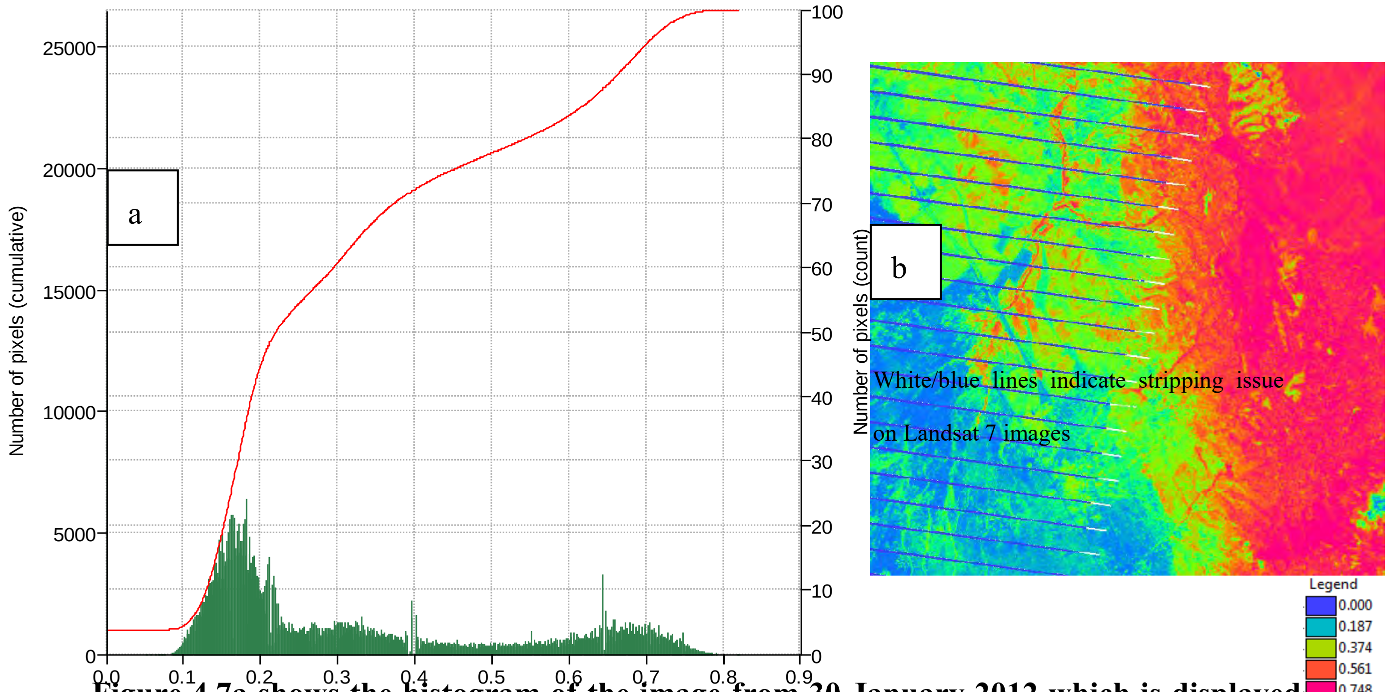



**Figure 4.7a shows the histogram of the image from 30 January 2012 which is displayed in Figure 4.7b which is the calculated NDVI from the site at Makanya in Tanzania. The NDVI distinguishes the fields from the non-irrigated landscape on the lowlands however, the NDVI of the vegetation of the highlands appears similar.**

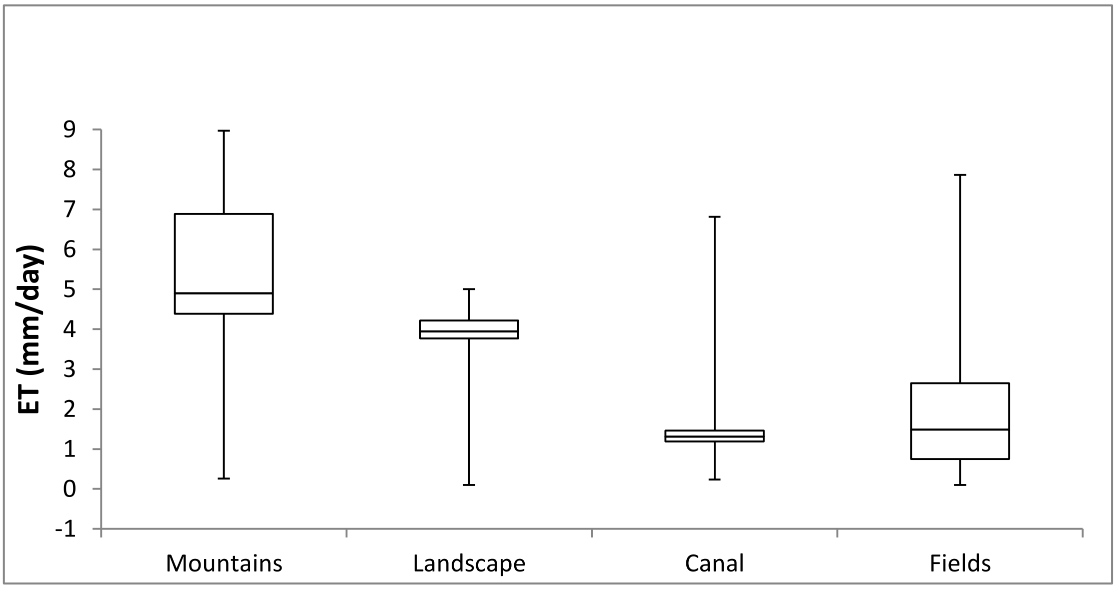



**Figure 4.8 shows the wet season variation in total evaporation from 4 different land cover types at Makanya, including the spate irrigated RWH calculated using the SEBS model and 30m Landsat images.**

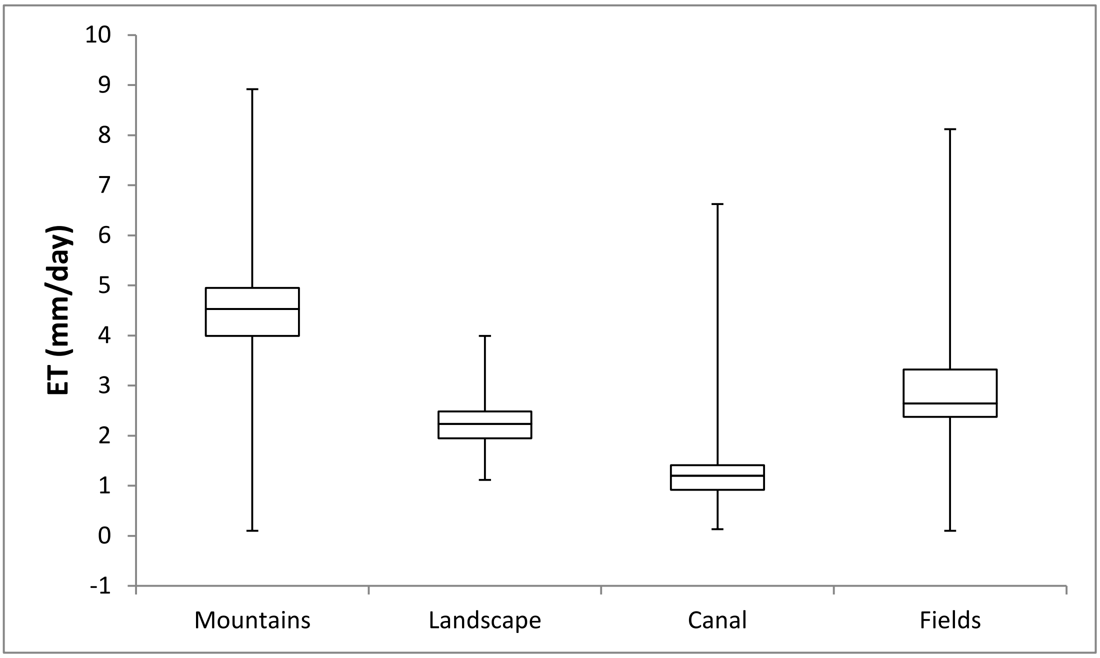



**Figure 4.9 shows the dry season variation in total evaporation from 4 different land cover types at Makanya, including the spate irrigated RWH calculated using the SEBS model and 30m Landsat images.**

### *4.4.2 Burkina Faso Sites*

Figure 4.10, shows the ET for 6 March 2006 calculated over the central regions of Burkina Faso. Results show that the "*Zai pits*" (various sites within the black circle) evaporate more than surrounding areas (point a in Figure 4.9) however the amount is marginal (<1mm/day). Figure 4.11 shows the evaporation from the bunded fields, which combine contours with agroforestry, (fields outlines in black) are evaporating much higher than the surrounding landscape, during the wet season season (Image date 14/08/2015). Analysis of the long term trends in evaporation from the central region of Burkina Faso during the wet and dry seasons (Figure 4.12 and 4.13 respectively) show that both RWH systems are producing higher ET than the surrounding landscape. The areas not under RWH were evaporating between 0.5-1.5mm/d during the wet season while the *"Zai"* recorded average ET of between 3-5mm/d and the bunded fields between 3.2-5.5mm/d. This shows increased plant growth in areas under RWH how effective the RWH systems are in storing water and making it available for plant use. During the dry season the areas not under RWH recorded ET of 0.5-1.3mm/d, while the *"Zai"* recorded ET of 1-1.5mm/d and the bund system 3.2-4.5mm/d. This shows that the bund system is improving the storage of moisture in the soil profile or supporting health vegetation into the dry season. This is a very effective RWH system in this landscape. In addition, the landscape surrounding the RWH systems is fairly degraded, making the differences between the RWH vs non-RWH sites more noticeable. It is possible to use RS to identify RWH agricultural areas in Burkina Faso, however further knowledge or ground verification is needed to verify that the findings are in fact due to RWH and not conventional irrigation or due to improvement practices such as fertilization alone.

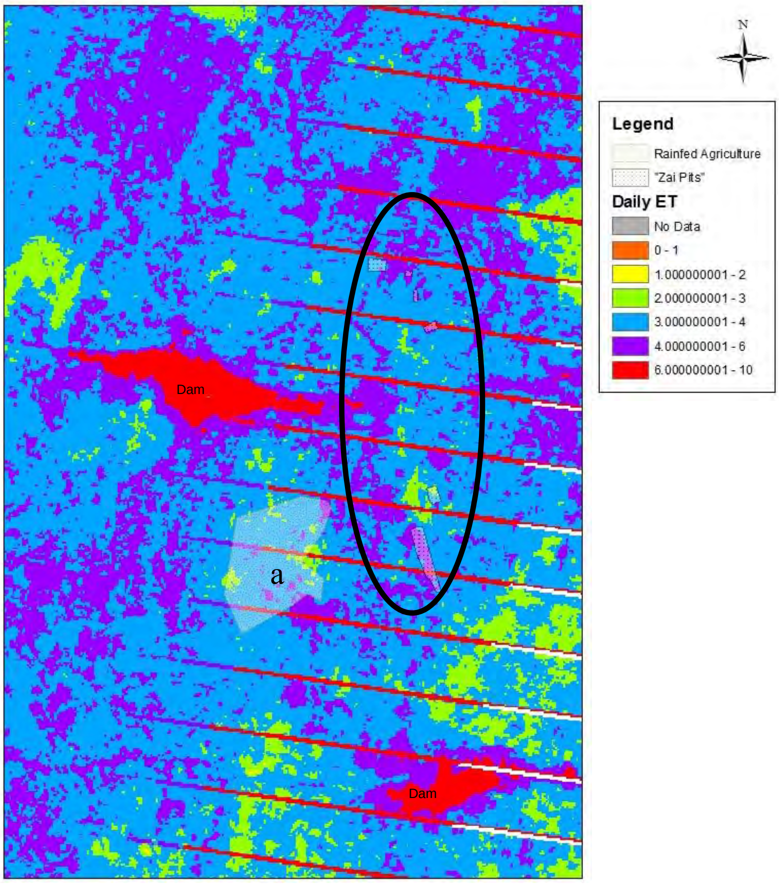



**Figure 4.10 Total evaporation the "*Zai Pits*" in the central region of Burkina Faso illustrating that agricultural areas evaporate more than the surrounding areas.**

The ET measured from the agroforestry/contour bounded fields is significantly higher and spatially distinct from the surrounding systems. The RWH system intercepts the storm runoff and increases the time for infiltrations and increases the amount of water in the soil profile which has benefits beyond the extent of the agricultural fields and is increasing water availability to the surrounding local landscape, even into the dry season. This is the type of "normal" landscape response that is expected for a pristine ecosystem, where non degraded soils slow the runoff of stormwater, retaining it in the soil, making it available for plant use and releasing it slowly for baseflow, which sustains waterways. This shows that this RWH system has the potential to combat and perhaps even reverse the impacts of anthropogenic land change.

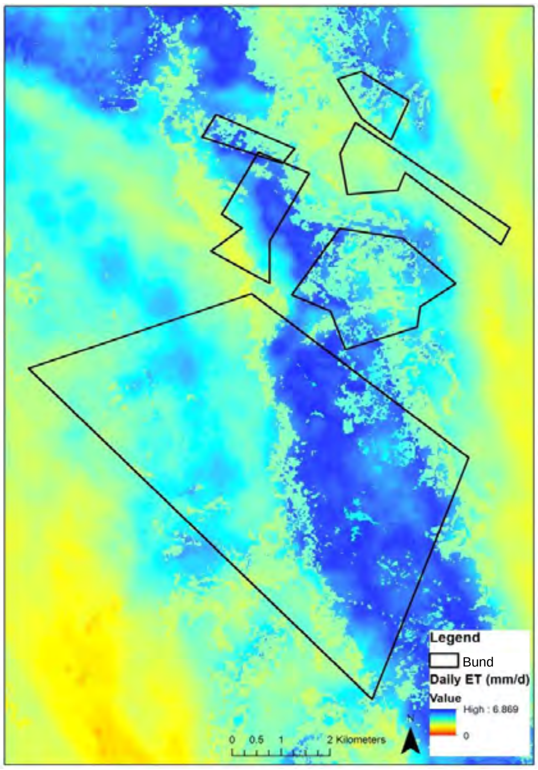



**Figure 4.11 Total evaporation the bunded fields in the central region of Burkina Faso illustrating that agricultural areas evaporate more than the surrounding areas.**

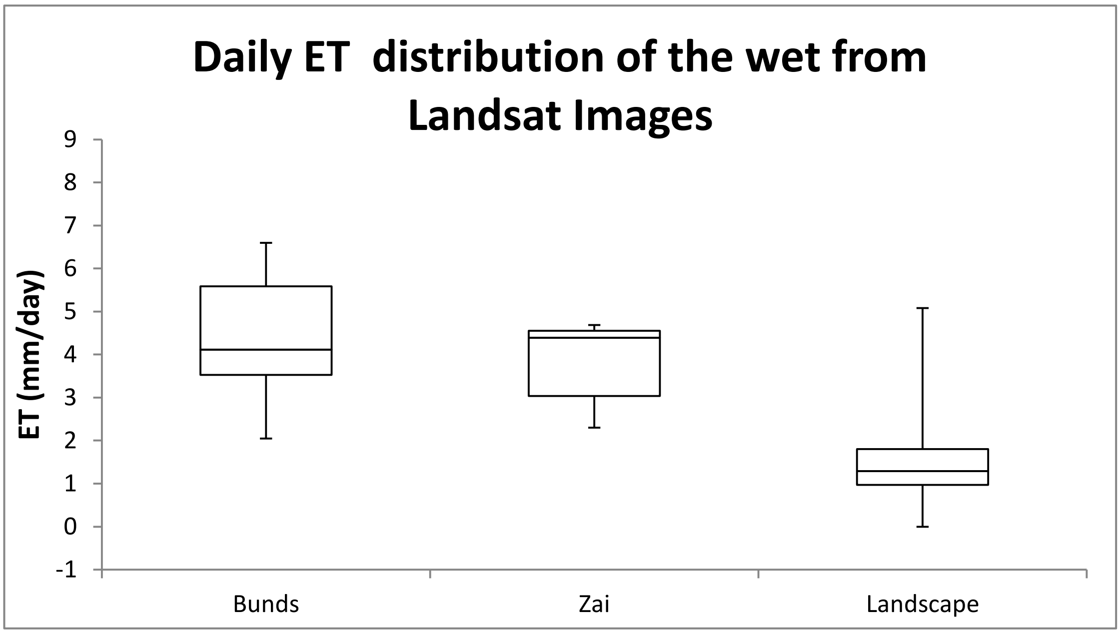



**Figure 4.12 shows the wet season variation in total evaporation from 3 different land cover types at the 2 study areas in Burkina Faso, including the bund systems and the "*Zai*" system RWH systems calculated using the SEBS model and 30m Landsat images.**

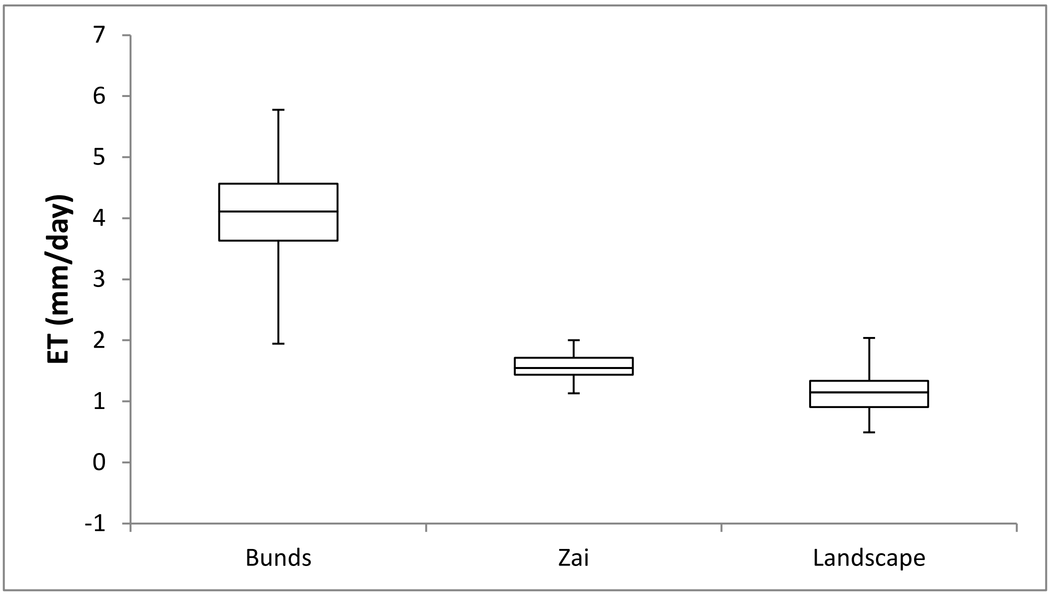



**Figure 4.13 shows the dry season variation in total evaporation from 3 different land cover types at the 2 study areas in Burkina Faso, including the bund systems and the "Zai" system RWH calculated using the SEBS model and 30m Landsat images.**

NDVI results for Burkina Faso did not show noticeable differences between RWH sites and surrounding landscapes. This may be because the planting strategy in the bund system results in sparsely distributed crops and as a result mixed pixels (Figure 4.14). The increased vegetation cover that would be measured using the NDVI would be diluted by the bare soil surrounding the crops. The ET is still noticeable as the water is absorbed into the soil all around the bund system.

**Figure 4.14 Bund RWH system showing dispersed planting system (www.ifad.org).**

## 4.5 Conclusions

Growing human populations and the associated demand on natural resources is one of the leading causes of global change. The intensification of food production can cause land degradation as crop production moves into more marginal areas unless proper land and water management is practiced. Conservation tillage has been proven to decrease soil erosion. RWH aims to store water where it falls and make it available for plant growth. This can increase the soil moisture and prevent erosion. The identification of existing RWH systems will allow for a census of the scale of implementation of RWH sites across Africa. This will assist planners and policy makers who aim to increase RWH efforts in an attempt to secure water for livelihoods and agriculture.

Remote sensing technology provides a tool for identifying RWH systems across large spatial scales. In this study, total evaporation and NDVI were used as indicators of RWH systems based on the premise that a site irrigated with harvested water would evaporate more than the non-irrigated surroundings and the vegetation would produce a higher NDVI than surrounding areas. These two indicators were calculated using 250m MODIS images and 30m Landsat images.

Statistical analysis showed that ET calculated from Landsat images produces indistinct differences for very small scale RWH sites in South Africa compared to the surrounding landscape, while the NDVI did show distinct responses from RWH sites. However, because the field size of small-scale, dispersed RWH systems is often equal to the resolution of medium resolution (30m), freely available satellite data, the confidence in identifying the structures without additional knowledge or data of the site is low.

ET provided a more reliable indicator for RWH sites that were either large in scale, such as a spate irrigation system or implemented at a large scale, such as the "*Zai pitting*" and the contour bunds in Burkina Faso. The bund system in Burkina Faso shows higher evaporation in areas with bunding even into the dry season. This shows that RWH is effective in improving plant available water, which contributes towards either the high evaporation or high transpiration from plants which is being recorded in these satellite images. . This can improve crop production in marginal areas and reduce the anthropogenic impacts on the landscape. Implementing contour bunds in degraded areas may prove useful in restoring degraded landscapes, by increasing soil moisture which will allow plants to re-establish. Further studies into the effectiveness of contour bunds together with agroforestry are recommended to assess whether this system is as effective in other landscape. This highly effective RWH system is easily identifiable from the surrounding landscape and remote sensing can provide a useful tool for identifying this type of RWH system at a large spatial scale.

Evapotranspiration and NDVI should be used together to analyse the landscape and proved to much more successful that just using NDVI or a landcover classification. In these cases, some RWH systems were clearly distinguishable, however in all cases ground truthing, either through a formal process of using training sets and supervised classification or through a more ad-hoc visual verification process on the ground, or expert knowledge of the sites is required to confirm whether the site are in fact RWH systems. It is evident that not only do RWH systems need to be implemented on a large scale to be identified, but also to have a meaningful impact on the large landscape. Only the spate irrigation system in Makanya and the contour bunds in Burkina Faso showed a noticeable impact on soil moisture within the general landscape surrounding the systems. Therefore, if RWH systems are to have an effect on reducing the anthropogenic impacts of increase crop production, not only does the suitable system need to be implemented in each landscape, but at a large enough scale to make an impact. This suggests that planner should aim to expand RWH intensively in an area, rather than on an ad-hoc distributed basis for it to have a meaningful impact on livelihoods and the ecosystems. Chapter 5 explores the role RS and GIS can play in identifying potential RWH sites at a sub-catchment scale, to assist with the large scale, co-ordinated upscaling that is required.

As mentioned in the conclusion to Chapter 3, large scale implementation of RWH may result in changes in the runoff related components of baseflow and stormflows, reducing river recharge and impacting on water availability for downstream users. This study has shown a positive increase in soil moisture and while general consensus agrees that RWH will have little impact on catchment hydrology (de Winnaar and Jewitt, 2010), greater research is required to explore the potential impacts of large scale RWH implementation on the landscape. More specifically, greater research into whether RWH systems such as the ones studies here can have positive effect on soil erosion by decreasing runoff velocity and increasing crop cover and root cover is needed.

Further research into the role remote sensing can play into identifying soil moisture, as result showed that RWH in conjunction with improved soil management is improving soil moisture, may strengthen this analysis. The SEBS model is a suitable tool for this as it does contain a soil moisture model add-on.

### 4.6 Acknowledgements

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# CHAPTER 5: EXPLORING THE POTENTIAL FOR USING REMOTE SENSING FOR IDENTIFYING POTENTIAL RAINWATER HARVESTING SITES IN SUB-SAHARAN AFRICA (PAPER 4)


## Abstract

Growing populations and the associated increase in demand for food has resulted in renewed attention on methods such as rainwater harvesting (RWH) for bridging dry spells and reducing the risk of poor crop yields due to short term water shortages. However it is important to determine the best locations and optimal size of a harvesting system to ensure it captures sufficient runoff to be effective and provide a sustainable water source for its users, as well as ensuring that it can be implemented at a large enough spatial scale to have a positive impact on soil moisture in the surrounding landscape. For this, potential runoff needs to be calculated which requires data on land cover and hydrological soil grouping. This information is often not available in remote locations at the scale needed for input into flow generation models or is cumbersome to calculate at the large spatial scales necessary for planning roll out of RWH systems. Remote sensing has proven useful for collecting this information in remote locations and at the spatial scale required. In this study, Shuttle Radar Topography Mission (SRTM) was used to determine the drainage catchments while Landsat 8 was used to determine landcover and hydrological soil groupings at Potshini, a small rural catchment in KwaZulu-Natal, South Africa. The soil conservation services (SCS) method was applied at both pixel scale and drainage catchment scale to determine the best location and potential yield for both small household systems (collecting runoff from an area of 30m x 30m) and medium scale systems such as community ponds. Satellite RS was highly suitable for collecting the information needed as inputs into the model which calculates runoff potential in the case study. SCS also allows for the calculation of potential overflows in extreme rainfall events and the planning of how to deal with the overflow to reduce impact on households down slope or downstream. Further research into better classification of soils using remote sensing is needed to improve the accuracy of this method.


## 5.1 Introduction

In recent years RWH (as defined in Section 2.1.1) has been gaining interest as an alternative water supply solution, especially in rural areas where traditional piped water may be expensive and unfeasible to implement at an adequate spatial scale to ensure fair access to water for all. The Africa Union, through the Sharm El-Sheikh Commitments for Accelerating the Achievement of Water and Sanitation Goals in Africa (AMCW, 2008), committed to increase the RWH share of total water supply to 10%.

Chapter 3 describes a method for assessing the current scale of RWH, which would allow planners to understand the current scale of RWH implementation. However for successful upscaling of RWH an in-depth analysis of the landscape is required to identify which areas within a selected landscape will be most suited for the expansion of RWH and to determine the optimum RWH reservoir size. This requires an analysis of factors which influence runoff potential, including flow direction and accumulation, drainage patterns, catchment, land cover type/use and soil types. This information is often not available or difficult to access in data poor environments, typical of sub-Saharan Africa. In these cases satellite remote sensing and GIS may prove useful in supplying this data at a wide spatial scale. Additional information such as location to settlements and fields, access via paths and road, recreational and proximity to culturally significant sites can also be accounted for using GIS.

This study aims to demonstrate the role remote sensing of the catchments biophysical characteristics may have in determining the potential of a site for a RWH structure. These characteristics are more constant, such as soil type and slope and therefore don't require evaluation that contrasts the season like the NDVI and ET measured in Chapter 4. These characteristics require a once off assessment to determine how they influence runoff potential in the catchment area. Medium resolution (in this case 30m) satellite data has become more readily available to users relatively cheaply or even free. NASA's Shuttle Radar Topography Mission (SRTM) mission took place in 2000 and produced high-resolution topographical data from across the globe. Initially only 3 arc-second data was available for areas outside of the USA. However in September 2014, NASA released the 1 arc-second (30m) data for Africa for public download free of charge. This allows for in-depth topographical analysis of landscapes that do not have active surveys or orthophotos.

Landsat 8, launched in February 2013, consists of 8 spectral bands (bands 1-7 and 9) with a spatial resolution of 30 meters as well as a panchromatic band (band 8) at a resolution of 15m and two thermal bands (band 10 and 11) at a resolution of 100m and provides an opportunity to identify landscape landcover and soil information (Table 5.1). It has a 16 day return (temporal resolution) and swath of approximately 170km. It replaced Landsat 7 which had overrun its intended lifespan and had developed a stripping problem which could not be rectified.

**Table 5.1 Band designation and descriptions of Landsat 8 (USGS, 2015)**

| Band | Wavelength | Application |
|---|---|---|
| **Band 1 – Coastal aerosol** | 0.43 – 0.45 | Coastal and aerosol studies |
| **Band 2 – Blue** | 0.45 – 0.51 | Lake or ocean floor mapping, distinguishing soil from vegetation and deciduous from coniferous vegetation |
| **Band 3 – Green** | 0.53 – 0.59 | Emphasises peak vegetation and plant growth vigour |
| **Band 4 – Red** | 0.64 – 0.67 | Emphasises vegetation slopes |
| **Band 5 – Near Infrared (NIR)** | 0.85 – 0.88 | Emphasises biomass content and shorelines |
| **Band 6 – Shortwave Infrared (SWIR)1** | 1.57 – 1.65 | Discriminates soil and vegetation moisture content and is able to penetrate thin clouds |
| **Band 7 – Shortwave Infrared (SWIR) 2** | 2.11 – 2.29 | Improved soil and vegetation moisture content and is able to penetrate thin clouds |
| **Band 8 – Panchromatic** | 0.50 - 0.68 | 15 meter resolution, sharper image definition |
| **Band 9 – Cirrus** | 1.36 – 1.38 | Improved detection of cirrus cloud contamination |
| **Band 10 – Thermal Infrared 1** | 10.60 – 11.19 | 100 meter resolution, thermal mapping and estimated soil moisture |
| **Band 11 – Thermal Infrared 2** | 11.5 – 12.51 | 100 meter resolution, Improved thermal mapping and estimated soil moisture |

In order to identify potential RWH sites, site data needs to be collected to determine the potential runoff. The soil conservation services (SCS) method is one of the most widely used methods for estimating surface runoff from a rainfall event (Das and Paul, 2006). The SCS method takes into consideration the hydrological soil grouping and surface land cover to determine a curve number (Schulze et al., 1992; Gangodagamage and Clarke, 2001). The curve number represents how much runoff the land surface will generate in relation to the amount of rainfall that falls in an event or for a particular design criterion. The SCS method has been adapted for southern African conditions (SCS-SA) and is commonly used throughout the region (Schmidt and Schulze, 1987) and has been applied in other studies to investigate RWH potential (De Winnaar et al., 2007).

### 5.2 Study Site

The Potshini sub-catchment (part of Emmaus catchment, quaternary catchment number V13D) is located in the Bergville District, in the foothills of the Drakensberg Mountains in the KwaZulu-Natal Province of South Africa and forms part of the Thukela River Catchment. The Thukela river basin has an area of 29,036 km$^2$, while the area of QC V13D and Potshini sub-catchment are 280 km$^2$ and 1.2 km$^2$ respectively. Potshini is at an altitude of about 1250 m.a.s.l, and with the mean annual precipitation estimated to be 700 mm/a and mean annual potential evaporation between 1600 and 2000 mm/a (Guy and Smith, 1995). The mean annual temperature ranges between 16 and 18 °C. Frost is severe to very severe during winter (May to August) and hail is sporadically severe in summer (September to April). It is a predominately smallholder subsistence farming areas with rainfed maize being the major crop. Some vegetable gardening also takes place with cabbage, spinach, tomatoes and beans forming the main crop.

Approximately 50 households already practice RWH in the Potshini catchment through the implementation of diversion of runoff from rooftops and around the homesteads into a system of sunken plastic storage tanks. Community members generally report a positive livelihood benefit from the RWH systems, with increased crop yield and increased diversity of crops being the main benefit (Sturdy et al., 2008). Other community members would like to implement RWH systems however spontaneous uptake is slow as individual systems are expensive and often beyond the financial reach of the typical low income household found in such communities.

### 5.3 Methodology

The SCS-SA method was used to determine stormflow potential from a landscape with the intention of determining the runoff potential that can be harvested by a RWH system which can supply a sustainable water source to the surrounding community. In order to design for both larger systems, such as community dams which collect runoff from larger catchment areas, as well as small systems (collecting from an area of 30m x 30m, the equivalent of 1 Landsat 8 pixel), it was necessary to determine the drainage catchment areas within the landscape. SCS requires information about slope, soil type and landcover to calculate stormflow. To do this the SRTM 30m DEM was used to calculate catchment areas and slope. SRTM was used to calculate slope and flow paths while Landsat 8 was used to calculate landcover and soil type for each pixel. Stormflow was estimated using SCS-SA for each pixel, each drainage catchment as well as cumulative stormflow for the drainage catchments.

The newly released SRTM 30m DEM was downloaded and imported into the free RS processing platform Ilwis. Alternatively, if 30m images were not yet available, the 90m images could be imported into ArcGIS and resampled to 30m using the bilinear method. Slope was calculated as percentage of the elevations differences between the centre of two pixels on a horizontal straight line difference (Mishra and Singh, 2003). Following this the catchment drainage was calculated using the process described in Figure 5.1.

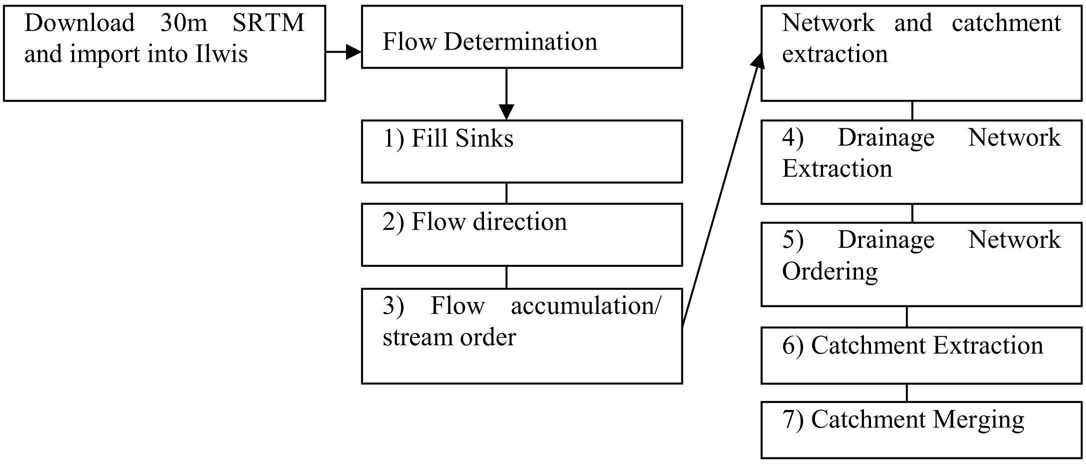


**Figure 5.1 Flow diagram of the process followed to delineate drainage catchments using SRTM images.**

The flow determination process involved 3 three steps. First the fill sink operation was applied which removed any local depressions in the DEM. Single cell depressions are filled by raising the height of that pixel to equal the lowest value of the surrounding 8 pixels. If a depression consists of multiple pixels then the height of those pixels are raised to the lowest value pixel adjacent to the outlet for the depression to ensure the flow would discharge from the depression. Next the flow direction operation determined which direction water would flow from a pixel into its neighbours according to the steepness of the slope (greatest difference in pixel height). This function also examines each pixel in relation to its surrounding 8 neighbours. Lastly, the flow accumulation operation calculates the number of pixels that contribute to the cumulative hydrologic flow path or outlet of water.

The next procedure was network and catchment extraction which involves 4 steps. First the drainage network extraction operation applied a threshold value which determined the minimum number of pixels which should drain into a pixel for it to remain as a drainage pixel on the map. In this case a minimum of 10 pixels was selected as this represents an area of $30m^2$, which is the average minimum size of the cleared area around a homestead in Potshini. The output was a map showing drainage lines. Step 2 was the drainage network ordering operation. This step applied a Strahler stream order number to each segment of the drainage network. When using medium resolution DEMs, some redundant streams or flow paths were determined. In this step a minimum drainage length was input to remove superfluous streams and reduce calculation times. A minimum drainage length of 250m was used. Step 3 was the catchment extraction operation. This step used the drainage network ordering map, the flow direction map and the original DEM to create catchment areas for each segment of the drainage network. The output included the area and perimeter for each drainage catchment as well as the total upstream area of each catchment, i.e. the total area that drains into each catchment which allows for accumulated runoff to be calculated. The final step was the catchment merge function which allowed the user to determine the minimum drainage size and merge adjacent catchment to meet this requirement.

Landsat 8 images were then used to classify landcover and soil types. A supervised classification was performed on a composite image of band 4, 3 and 2 representing the red, green and blue bands respectively. Eight training classes were defined according to Table 5.2. A maximum likelihood classifier was applied to the image. Landcover was classified as it is required to determine the SCS curve number.

**Table 5.2 Description of land cover classes used in supervised classification process**

| Class # | Land cover type |
|---|---|
| **1** | Water/Dams |
| **2** | Alien Trees |
| **3** | Commercial Irrigated Maize |
| **4** | Newly planted Maize |
| **5** | Impervious (Building, compacted bare soil, roads) |
| **6** | Fallow Crop Land |
| **7** | Subsistence Crops |
| **8** | Grazed Grasslands |

Bare soils were detected using the NDVI vegetation index:

$$NDVI = \frac{NIR-R}{NIR+R} \tag{5.1}$$

Yoshino et al. (2012) used Landsat 7 to detect the mineralogy of soils in arid areas, while Aksoy et al. (2009) developed an approach to mapping soils using Landsat 7 and slopes calculated from a digital elevation models to generate a 3D model of the landscape which is used to predict soil characteristics. These methods are only suited to areas where the soil types are largely homogenous which is not the case at the Potshini study site. Landsat 8 has several bands (bands 5-7) which were designed to measure soil characteristics (Table 5.1). Reflectance values of all bare soil pixels (NDVI$\leq$ 0.2) for all Landsat 8 bands were calculated and mapped. The greatest distinction between soil types was evident in bands 5 and 6 (Figure 5.3). This is expected as band 5 was designed to discriminate coastal beaches so would be sensitive to identifying sandy soils, while band 6 was designed to discriminate soil moisture so is useful for identifying more clay type soils with a higher water holding capacity (Table 5.1 (above). The reflectance signatures of the soil types showed 3 distinct runoff rating groups, namely low, medium and high classified through a simplification of the hydrological soil groups determined in the SCS-SA method (Table 5.3).

**Table 5.3 Grouping of hydrological soil groups into 3 runoff rating groups.**

| **Soil Runoff Rating** | **Hydrological Soil Group** |
|---|---|
| **Low** | A |
| **Medium** | A/B, B, B/C |
| **High** | C, C/D |

Validation of the remote sensing spectral curves was done by classifying pixels using bands 5 and 6 and the three rating groups. This was compared to the detailed soil survey data from de Winnaar et al. (2007) where 58 soil samples were taken using pit and augured samples and incorporated into a GIS database using interpolation techniques.

Figure 5.2 shows the reflectance curves of the hydrological soil groupings determined using bands 5 and 6 of the Landsat 8 imagery. Sandy soils reflected more brightly due to a lower iron content which reflects more of the near infrared reflectance (NIR) band 5 and 6 (Demattê et al., 2002). Clay soils (generally black and grey in colour) absorb more of the near infrared light and therefore have lower reflectance values.

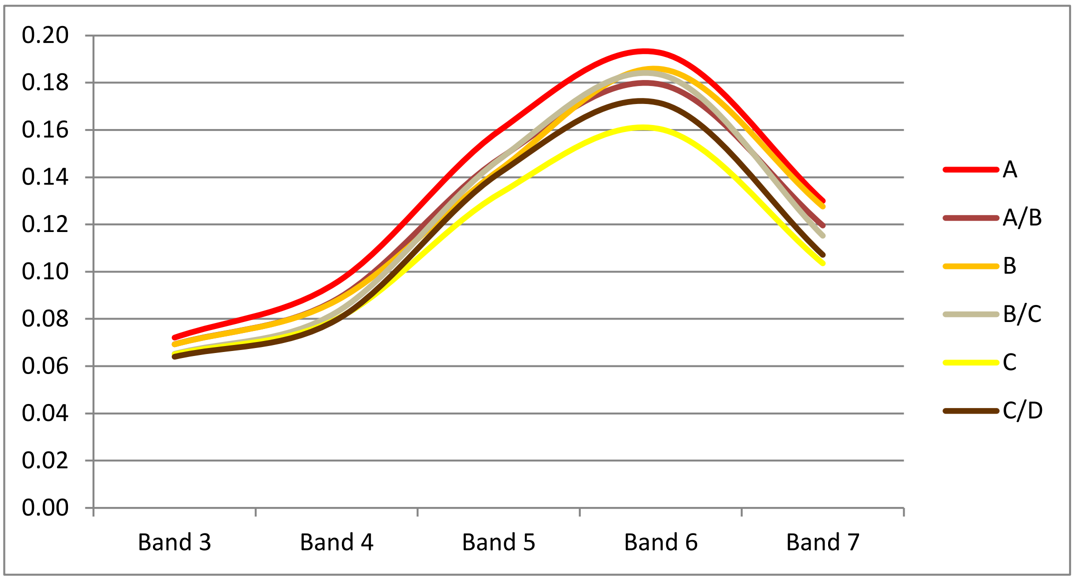


**Figure 5.2 Soil reflectance curves for hydrological soil groupings**

SCS curve numbers were assigned to each pixel based on the land cover and soil runoff calculated in the steps above and using the rating in Table 5.1 of Schulze et al. (2004). Design rainfall events (Table 5.4) were extracted from Smithers and Schulze (2003) for the Bergville rainfall station (station number 0299614_W) which is located approximately 10km from the Potshini study site.

**Table 5.4 Design rainfall from station 0299614_W**

| | Return Periods | | | | | |
|---|---|---|---|---|---|---|
| | 2 Year | 5 Year | 10 Year | 20 Year | 50 Year | 100 Year |
| **1 Day Design Rainfall (mm/day)** | 59.5 | 79.5 | 93.3 | 107 | 125.3 | 139.5 |

Runoff depth for each return period in Table 5.4 for each pixel was calculated using the stormflow volume equation:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \qquad (5.2)$$

Where $Q$ = stormflow depth (mm), P is one day daily design rainfall (mm) for a given time period, $S$ is potential maximum soil water retention (mm) and $Ia$ is initial abstraction losses (mm) such as depression storage, interception and initial infiltration before stormflow is generated:

$$S = \frac{25400}{CN} - 254 \tag{5.3}$$

$$Ia = S \times 0.1 \tag{5.4}$$

Stormflow volumes for each return period were also calculated for each drainage catchment and a cumulative stormflow was calculated to account for the accumulation of runoff down the slope. Daily rainfall could also be used to model daily runoff yields of proposed systems if this data is available, although the SCS-SA method was intended to be used for design purposes using particular design criteria.

### 5.4 Results and discussion

High resolution SRTM and Landsat images proved highly useful in determining the runoff potential of the landscape of Potshini. Figure 5.3 below shows the slope classification described in Section 5.3. above.

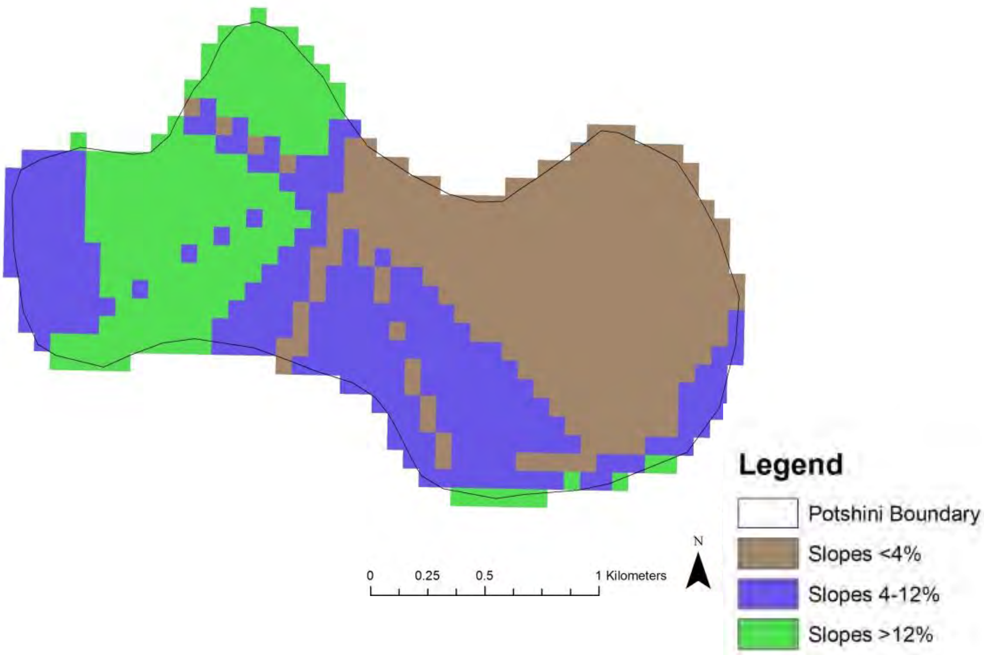


**Figure 5.3 Slope map (%) derived from 30 meter SRTM images.**

An accuracy assessment was conducting to assess how well the SRTM slope classification compared to slopes derived by de Winnaar et al. (2007) for the same site using 20 m contours from 1:50000 scale topographical maps and a detailed soil survey. Table 5.5 shows that over 50% of the slopes which fall into the <4% and 4-12% category were correctly classified. However slopes >12% were largely misclassified as being <4%. This highlights a common problem with satellite images where elevation measurements on slopes facing away from the satellite sensor can report higher errors (Kääb et al., 2002) .

**Table 5.5 Accuracy assessment of slope classified using Landsat 8 vs. slope survey done by de Winnaar e al. (2007).**

| | | SRTM Slope Classification | | |
|---|---|---|---|---|
| | | <4% | 4-12% | >12% |
| Topographic derived Slope | <4% | 57% | 32% | 11% |
| | 4-12% | 14% | 54% | 32% |
| | >12% | 57% | 15% | 28% |

The drainage network (Figure 5.4) shows the low points within each drainage catchment and where water would flow during a rainfall event. It is important to note that this drainage network is based at the accumulated lowest point within the drainage catchment as it represents the path of runoff flow. It is not necessarily a river network (although some perennial and non-perennial river may be present). The drainage catchment boundaries show the catchment area of each of the drainage segment. The catchment delineation using the 30 m SRTM differs only slightly from the more detailed surveyed catchment delineation done by de Winnaar et al (2007).

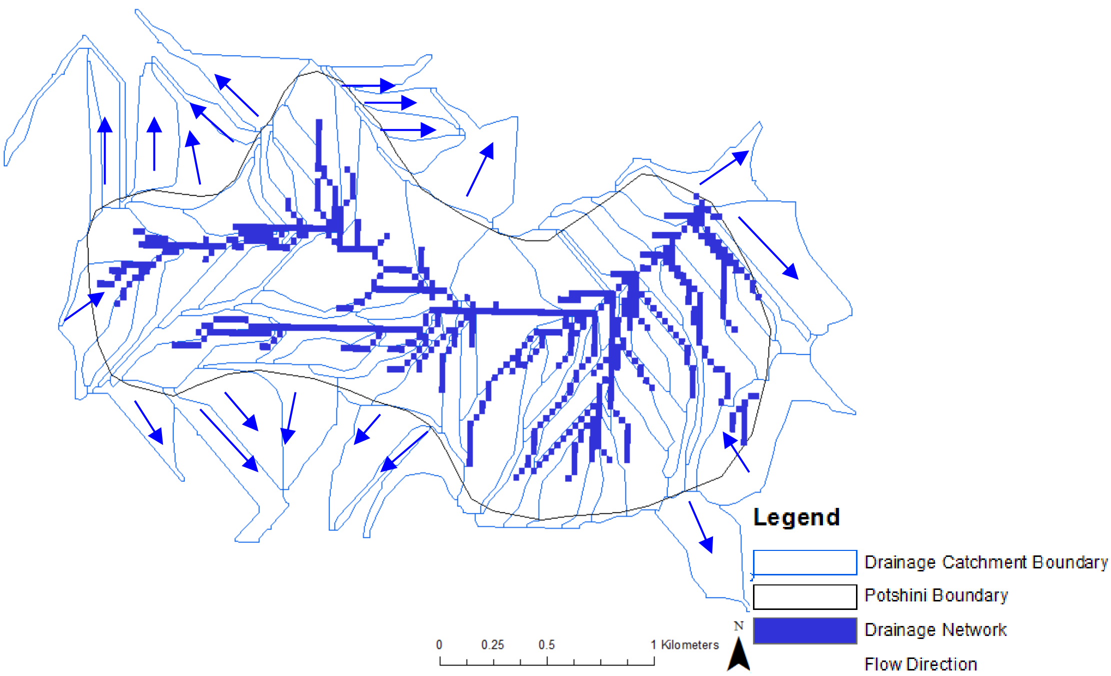


**Figure 5.4 Runoff catchments delineated from 30 meter SRTM images.**

Figure 5.5 shows the classification of soils at Potshini using Landsat 8 according to the soil runoff rating.

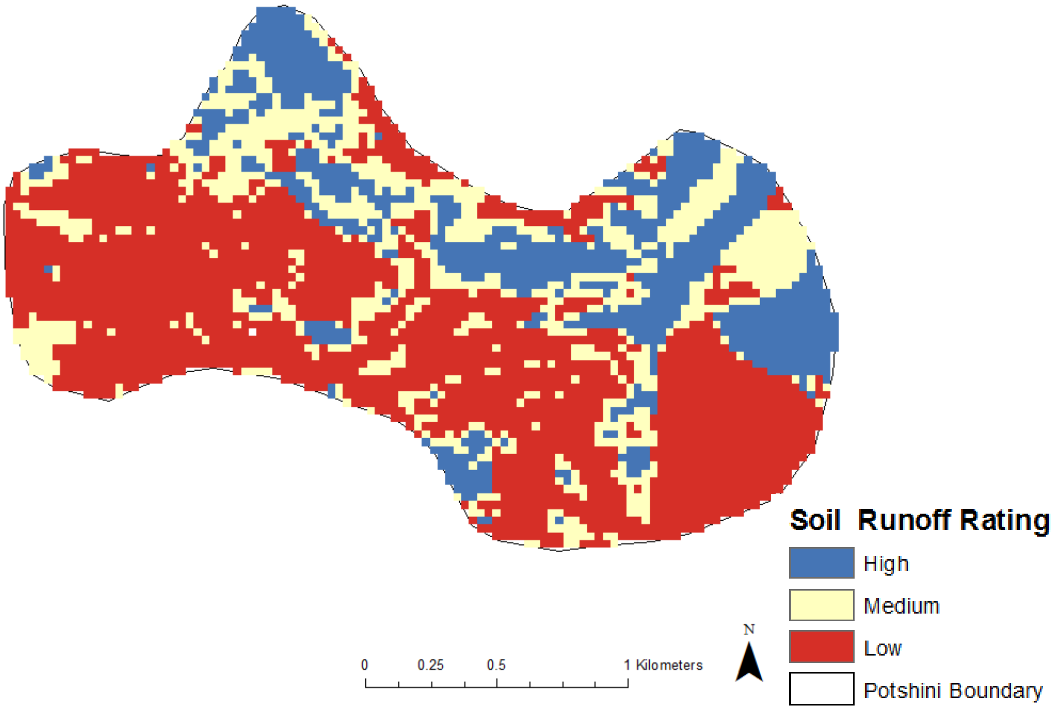


**Figure 5.5 Soil runoff rating groups classified using bands 5 and 6 of Landsat 8.**

An accuracy assessment was conducting to assess how well the Landsat 8 soil rating group classification, described in Table 5.5, performed when compared to soils classified by the field study of de Winnaar et al. (2007). Table 5.6 shows that 68.25% of soils in the "low" runoff rating group were correctly classified, while only 32.91% and 39.04% of the "medium" and "high" runoff rating group were correcting classified. While the accuracy of the medium and high groups are lower than ideal, it is concluded that using this technique where detailed soil survey data is not available would provide a reasonable indication of the texture of the soil using remote sensing.

**Table 5.6 Accuracy assessment of soil classified using Landsat 8 vs. soil survey done by de Winnaar et al. (2007).**

| | | Satellite Reflectance Classification | | |
|---|---|---|---|---|
| | | Low | Medium | High |
| Observed Soil Samples | Low | 68.25% | 18.67% | 13.09% |
| | Medium | 48.61% | 32.91% | 18.48% |
| | High | 33.62% | 27.34% | 39.04% |

Figure 5.6 displays the per pixel stormflow values which have been calculated. This shows which areas of the catchment produce the highest amount of runoff and would produce the maximum yield for a RWH. The individual pixel volumes could be useful to planners who want to build small RWH systems at a household level. It gives a good indication of the amount of runoff that could be collected from around a homestead which typically is close to 30mx30m similar to the pixel size used in this study. A map such as Figure 5.6 would help planners identify which areas are most suited to RWH by illustrating which areas produce the highest amount of runoff and prioritising these areas for implementation of RWH. Designers could also use this information to determine the optimal size of the RWH system by deciding whether they want a system that would capture e.g. a two year flood or a five year flood etc. They would also be able to determine how often and by how much the system would overflow in a high rainfall event. The amount of overflow must also determine the location of the system to ensure overflow does not affect other households situated downslope or downstream.

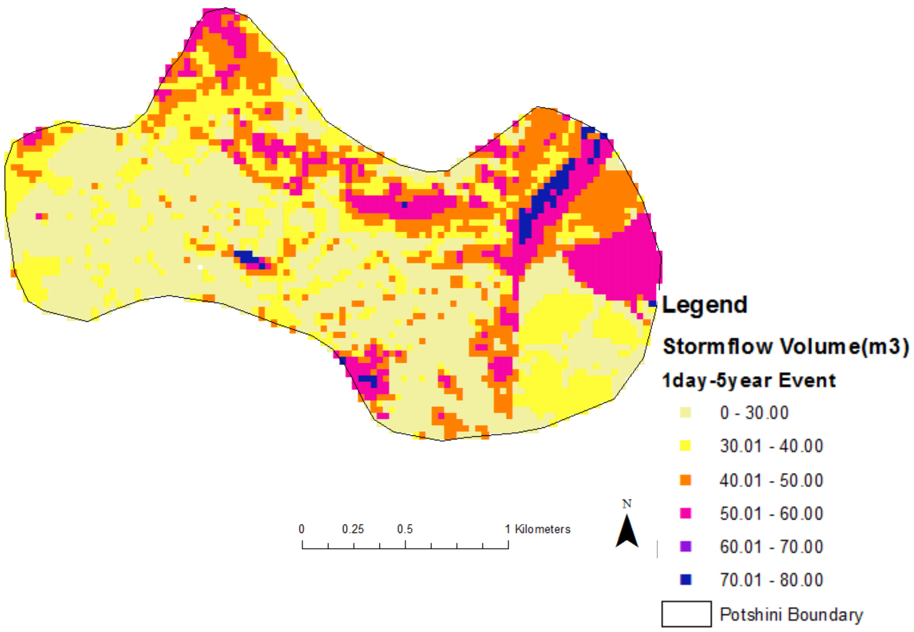


**Figure 5.6 Stormflow volumes per pixel for a 1 day-5 year design flood event.**

Figure 5.7 shows the accumulated stormflow for each drainage catchment in Potshini. The catchment stormflow is an accumulation of the stormflow of the individual pixel which contribute to that drainage catchment. Figure 5.8 indicates the cumulative catchment stormflow as per the catchment delineation in Figure 5.4 above, which include the stormflow from the catchment above which drain into the lower catchments. It is important to note that the volume is calculated for the lowest point of the catchment, and any system planned for that catchment should be located at the outlet to realise the volumes indicated. This map could be useful for the planning of larger community systems such as community ponds or small dams. Again, planners could determine the size of the system by deciding which design event they hope to capture, e.g. 2 year event or 5 year event. The planner will also be able to determine by how much the system will overflow in a large event, e.g. a 20 year rainfall event and incorporate this information into the planning of the location of the system so as to minimise impact of downslope or downstream communities. It will also allow planners to plan infrastructure such as the appropriate spillway and storm overflow design. This is more important with large systems such as community dams than small household systems as the volume of water is much greater and overflows have the potential to cause more damage.

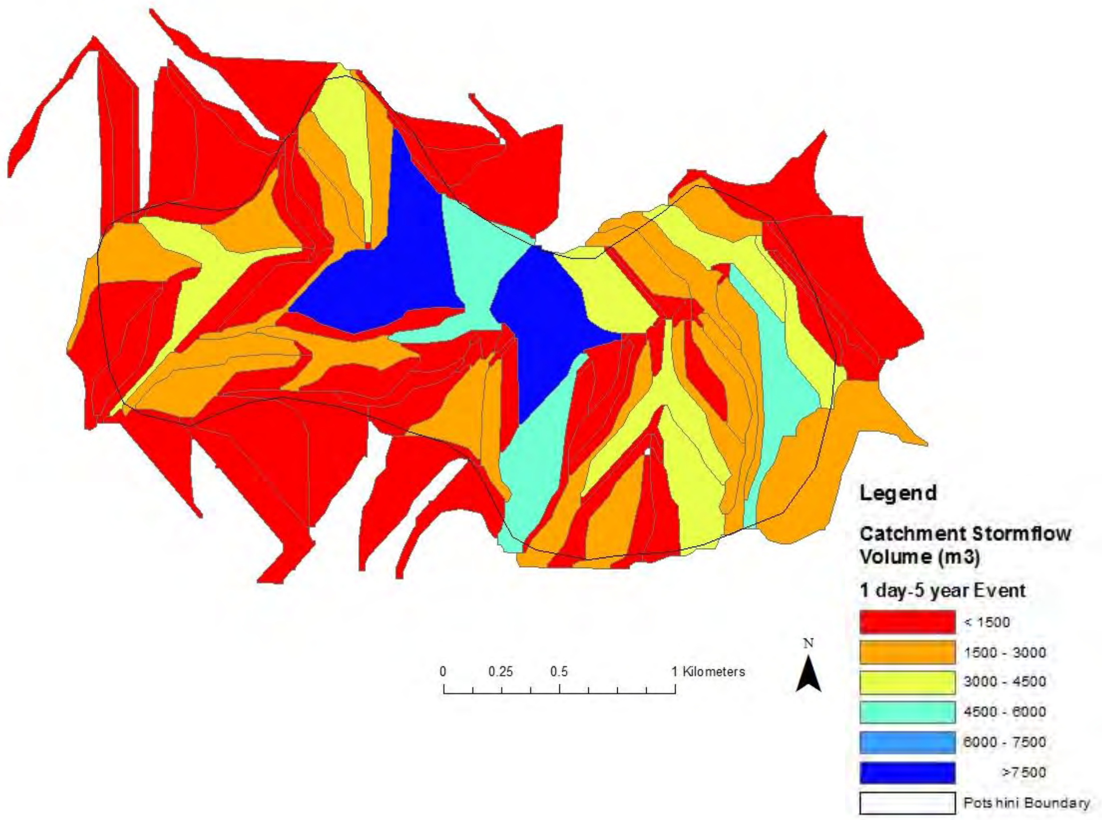


**Figure 5.7 Stormflow volumes per drainage catchment for a 1 day-5 year design flood event.**

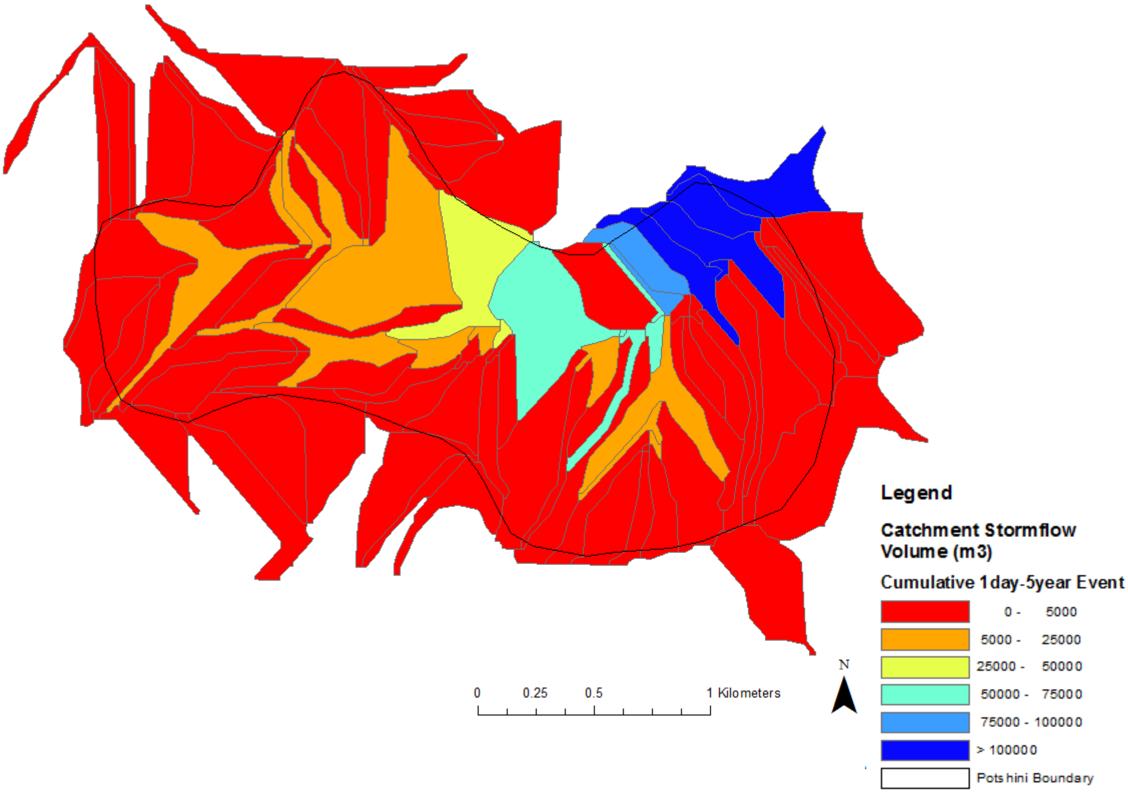


**Figure 5.8 Cumulative stormflow volumes per drainage catchment for a 1 day-5 year design flood event.**

de Winnaar et al. (2007) also included other factors to determine the suitability of sites for a RWH system, such as distance to houses and crop fields. De Winnaar et al (2007) used 1:30000 scale aerial photographs to identify and digitize landcover types. Both supervised and unsupervised land cover classification was undertaken in this study; however both methods proved unsuccessful as the small and dispersed rural the houses and small scale crop fields were not distinguishable using the Landsat 8 classifications. Only larger scale, homogenous features, such as the large irrigated commercial fields and the grazing land on the upper slopes of the catchment were accurately classified. This identifies a weakness in the satellite imagery, where detailed imagery of small scale features is not viable using 30m resolution Landsat 8 images.

Inaccuracy in the classification of soil and slopes will decrease the accuracies of the stormflow volumes calculated. RS is an effective tool for a catchment wide comparison of the most effective place to put a RWH system, however on the ground evaluation will be required to validate data and confirm expected stormflow volumes before the RWH system is designed and implemented.

### 5.5 Conclusions

Remote sensing has proven to be a useful tool to collect data about a landscape to determine the optimal location of a RWH system. SRTM DEM data can be used to determine the slope, flow path and direction as well as the drainage catchments. Landsat 8 proved useful in determining the large scale, homogenous landcover types and hydrological soil grouping, even though the accuracy of groups “medium” and “high” is less accurate than ideal.

Landsat satellite images proved useful as a decision support tool to determine catchment runoff which will allows planners and designers to determine the best location for a RWH system based on which areas which produce the highest amount of runoff. The SCS-SA method is used to determine peak flow as well as the volume of water associated with that peak. This gives an indication of the amount of runoff generated during rainfall events. Planners and designers can use this relatively straightforward method, which does not require many inputs, to understand how the landscape characteristics translate into runoff potential. This is important when designing large RWH systems, such as community ponds, as overflows can cause local flooding downstream and cause other impacts such as soil erosion. Planners can adopt a conservative approach by using the SCS-SA method to determine the optimum size of the system by deciding whether they want to design a system which will only overflow once every 5 years, 10 years etc. Remote sensing allows the SCS-SA method to be applied to areas where accurate soil and landcover is not available or not easy to collect. Design rainfall is essential for determining the stormflow but when this data is not available, then daily or artificially generated rainfall can be substituted.

Once the ideal location is determined using the SCS, it is advisable for planners to conduct a more in-depth study, either by conducting site visits or using higher resolution data, such as the aerial photos and or more detailed topographical maps such as the 1:50000 scale topographical maps used by De Winnaar et al. (2007) to determine the acceptability of the location in terms of human convenience, such as the distance to homesteads or crop fields. Therefore, using remotely sensed data for assessing the ideal location of potential RWH sites is best suited to sub-catchment and catchment planning and will allow the designers of the system to determine by how much the system will overflow in a large rainfall event and so ensure that plans or infrastructure (such as diversion channels) are put into place to ensure overflow does not adversely affect downslope households or downstream communities. However, local ground work is needed to determine the acceptability of the final location to ensure that is can be successfully used by the intended users.

### 5.6 Acknowledgements

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# CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

## 6.1 Introduction

This detailed study of how statistical analysis, GIS and remote sensing can contribute towards a comprehensive plan for the upscaling of RWH has shown that there is great potential for RWH in Sub-Saharan Africa. The first objective of this thesis, as outlined in Section 1.4 was to assess whether current, commonly used, guidelines for RWH encompass the full range of condition under which RWH currently takes place and whether these still provide a useful framework for RWH planning in a shifting social, environmental and hydrological cycle. Typically, one of three sets of RWH guidelines would have been consulted to assess whether a site was suitable for RWH. However Chapter 2 showed that many existing RWH are situated, and function, in sites that would not be considered suitable through the application of these guidelines. The range of conditions under which RWH currently takes place is vast. This demonstrates the need to rather consider which RWH system is best suited to a site of interest, rather than the traditional view of trying to find the best site for a RWH system. Therefore objective one was met by showing that the current set of RWH guidelines are no longer an adequate framework to guide RWH upscaling and allowing this technique to be fully exploited as an alternative water source. Limiting the expansion to RWH to those sites deemed suitable according to the guidelines, would hamper initiatives aimed at improving water security, especially in Sub-Saharan Africa and may result in objectives such as the African Union's Sharm El Sheikh Declaration on Water and Sanitation being met.

The second objective outlined in Section 1.4 was to explore the potential for an alternative approach which aims to assess how much water a selected RWH system can supply in any location under both present and shifting climate conditions. Chapter 3 demonstrates, in a case study of South Africa, that a simple RWH system could be implemented anywhere in South Africa. However the capacity of that system to supply water to a household on a daily basis (in this case a domestic case study) would vary across the country. The eastern part of South Africa would yield the most consistent water supply, with daily water supply being met up to half the year from a 5000 litre RWH tank. This study also investigated how climate change may impact RWH in the future in South Africa. The results showed that most of South Africa, particularly the East, would experience increasingly favourable conditions for RWH in the future, with fewer days of the tank being empty and fewer days of the tank only supplying partial household requirements and more days when the total household requirements could be met by the RWH tank. This chapter met objective two. It supports the framework of Panta Rhei, showing how human induced climate change will impact water resources, and how RWH as an alternative water supply solution will become more sustainable in the future. Panta Rhei aims to understand the interconnection between society's requirement for access to water resources and the simultaneous impact on water resources. Decentralised water supply solution may have less impact than traditional dams while still supply water to people who need it most. This chapter highlights that implementation of RWH upscaling project need to take into account which RWH systems are currently successfully implemented and benefiting the communities and the ecosystem they are situated in. In order to do this a method which can be applied at large spatial scale, is needed to identify existing RWH systems.

Chapter 2 and 3 proved that RWH can take place under many different climatic and biophysical conditions and supports the idea that a shift in thinking about RWH is needed. In Chapter 4, the use of GIS and RS as a tool to identify existing RWH sites was explored as per objective 3 in Section 1.4. This is important as it could allow planners and government to conduct a census of existing RWH which can help identify which RWH technologies are already present and successful in an area as well as assess potential for new systems This is useful as it means similar systems can be implemented as they have been proved to work in an area and have community acceptance.

Chapter 4 showed that using NDVI as an indicator of areas irrigated by RWH was successful in identifying small scale RWH sites, while using ET as an indicator was more successful for large scale RWH sites. The bund system which is implemented in conjunction with agroforestry practices in Burkina Faso was not only the most easily identifiable using RS and GIS but also showed how successful this system was in this landscape at storing water for use by crops into the dry season. This system was implemented at a large scale and the benefits of increase soil moisture availability extended beyond the boundary of the fields into the local surroundings. This shows that this RWH system may be useful in restoring areas degraded due to anthropogenic activities. However RWH is itself an anthropogenic activity and the large scale implementation may alter catchment responses. Using these methods to identify already existing RWH structures can help planners develop strategies to upscale these systems already in use and accepted within a community. It also allows planners and scientists to see what systems work best under certain climatically and biophysical conditions and better develop a set of best practices for RWH to prevent unintended negative impacts on catchment responses.

Chapter 5 presented a methodology which used RS and GIS to assess the runoff potential of a catchment to demonstrate the potential water which could be harvested, and meets objective 4 from Section 1.4. This shows that the main physical criteria that influence the runoff potential can be identified using RS. While these factors change more gradually, they have a great influence on the ability of the landscape to produce runoff. RWH systems, which aim to reduce runoff, have the ability to change the landscape in which they operate. RS provides a cost and time effective method that can be used to monitor how RWH may be influencing the environmental system overtime, from a remote location. Likewise, the method presented in Chapter 4 which monitors the more transient factors of ET and NDVI, which can be used to monitor the performance of the RWH systems at increasing soil moisture but also how it is influencing the surrounding landscape. This is evident in the Burkina Faso study site where soil moisture increased in the landscape surrounding the RWH systems, introducing a more transient change to the dynamic system.

This means that RS and GIS can be used to do a once off assessment of the potential runoff and storage capacity of an area for RWH, whereas the method presented in Chapter 4 can be used on a continuous basis to identify existing RWH systems and monitor the expansion of these systems. This methodology could be very useful for planners to calculate the potential and capacity of a landscape to sustain a RWH system. This will allow catchment level planning to support upscaling efforts within a landscape. It also allows for the optimisation of the design of the RWH systems to capture runoff. It also allow for detailed impact studies to determine the potential effect of harvesting a certain volume of water from the landscape and allow for mitigation plans to deal with potential impacts and overflows from a proposed RWH structure. However, RS was not able to successfully identify the sparsely distributed homesteads typical of the rural landscape of the study site. It is therefore recommended that once catchment level plans have identified the sites with the most potential to support RWH in a catchment, that a site visit and more detailed study be done to determine if the location is acceptable in terms of distance to house and fields, to ensure that the system will effectively and adequately service the people it is intended for. An oversight in this regard may result in the failure of the system if it does not fit into the lives of its intended users. This study has shown that great potential exists for RWH as an alternative water supply system.

The main aim of the research was to explore the potential for using remote sensing and GIS technology to identify existing RWH sites, the success of these systems in their respective landscapes and explore the potential for using RS and GIS to assess the capacity of a landscape for the implementation of potential RWH structures. GIS and RS are useful tools which can be implemented to identify existing RWH sites, which provides insight into which RWH technologies are already accepted, practiced and proving successful in an area. However medium to high resolution images are required. Low resolution images, such as MODIS images at 250 m have an insufficient resolution to identify small scale systems such as RWH systems which operate at field scale. RS is also useful for collecting data at a large spatial scale and in remote locations, which can be integrated with a GIS system to conduct catchment level assessments of the potential runoff from the landscape. This will allow for the evaluation of the best type of system to be installed and the optimisation of the amount of water that can be harvested from the system. This provides a useful tool which can assist in the upscaling of RWH and improving access to water in rural and under-resourced areas. The Panta Rhei philosophy helps to challenge the traditional mind set of suitability analysis and rather encourages an acknowledgement of the integrated relationship between water and people. Improving water and livelihood security of people, especially in rural sub-Saharan Africa, relies on better utilisation of whatever water resources are found within a community, and RWH aims to do this. The Panta Rhei philosophy also requires an understanding of how anthropogenic activities have caused impacts to the landscape and highlight how increasing demand on natural resources can further damage these ecosystems. The bund RWH system in Burkina Faso showed the potential positive impact of improved water availability during the dry season extended beyond the fields where it was implemented in addition to improved agricultural practices and improved plant rooting depth as land is restored. This highlights how anthropogenic intervention may prevent or even reverse past damage to the environment.

RS would provide a useful tool for the catchment level assessment plans needed to identify and prioritise upscaling efforts of RWH systems. This is necessary to improve access to water for people who need it most and reduce the strain on conventional potable water supplies by supplying an alternative water sources for non-potable needs and helping countries and regions met their international commitments.

### 6.2 Challenges

The greatest challenge was the labour intensive and data intensive analysis of satellite images. Multiple images were analysed to test the methodology in different season across different years and different study sites to ensure there was no bias in the analysis. This required a lot of data storage, time for analysis and field visits to confirm results. The most difficult data to source was site specific weather data which is still sparsely distributed across most of Africa. As such several potential sites which were originally considered for analysis had to be discarded. Often site-specific weather data is only available from sites located at research sites such as Potshini and Makanya or near commercial airports such as the Burkina Faso sites. While this highlights just how valuable RS data is in conducting analysis of physical characteristics in remote areas, it also presents a challenge to studies such as these which require site-specific data inputs. RS can help fill the data void across Africa however access to data still remains a challenge. Available finances were also a challenge and as a result, free data had to be used which limited the resolution of images to 30m at best. Access to high resolution images (10 m or less) across Africa would assist in providing the data to provide detailed analyses of the potneial for upscaling RWH. This would provide the first step in assisting in upscaling effort which would improve food security and reduce poverty, helping to achieve the sustainable development goals (SDG).

Ground truthing of results is still required unless higher resolution imagery proves to be more successful in the identification of existing RWH. Ground truthing is also essential once identification of the potential for RWH has been established as Andersson et al. (2015) found that refining inputs such a catchment delineation or meteorological inputs had a notable impact on model results.

### 6.3 Future possible research

The field of remote sensing and water resources is a relatively new one and holds great potential for future research. Further research using increasingly available and high resolution data may result in better identification of existing RWH sites and better classification of soil types. The development of an integrated RWH mapping tool, which provides up-to-date and high resolution analysis of the parameters discussed in Chapter 4 and 5, would allow any user with access to the internet to assess which RWH system is best suited to their site and how much water they could potentially yield.

Further research into the role remote sensing can play into identifying soil moisture, as result showed that RWH in conjunction with improved soil management is improving soil moisture, may strengthen this analysis. The SEBS model is a suitable tool for this as it does contain a soil moisture model add-on.

A comparison between the traditional guidelines presented in chapter 2 and the wider criteria suggested through this study would be an interesting study. The resultant gain in potentially arable land and how this can contribute towards increased food security could provide a useful basis for examining how RWH can help contribute towards the sustainable development goals.

This thesis presents a method for evaluating the potential for upscaling of RWH however successful upscaling is multi-faceted and will still depend on many other factors, such as societal acceptance and the ability to see how investment in RWH will make a tangible benefit to food security and livelihood security. The ability and means to invest both money and labour into implementation and maintenance of RWH systems. Access to fertilizers, mechanisation and secure food storage facilities which will complement RWH and allow the users to invest in soil nutrition, harvest increased yields and store food safely from pests and diseases.

Further studies into the potential impact of wide scale adoption and implementation of RWH are needed to ensure that the capacity of the catchment is not exceeded causing further anthropogenic impacts both upstream and downstream which may in return reduce runoff potential and undermine the harvesting potential of the RWH system.

### 6.4 Final comments and summary conclusions

This study fulfilled the aims and objectives set out in Chapter 1. It shows that a mind-set shift, in lines with the philosophy of Panta Rhei, is required to assist in the upscaling of RWH in Sub-Saharan Africa. Great potential exists for RWH to provide some or all of a households daily water requirements and great potential also exists for the capture of runoff for agricultural irrigation while improving the soil moisture of the surrounding landscape and so reducing or reversing the anthropogenic impacts of expanding agriculture. This study sets a framework and highlights some of the GIS and remote sensing tools which can help planners and scientists to develop a strategy and a catchment level plan to upscale RWH across southern Africa and improving access to water. Access to high resolution image as a tool for collecting data over Africa is paramount in the quest to use remote sensing to assist the upscaling of rainwater harvesting in sub-Saharan Africa.

# Appendix A