THE POTENTIAL IMPACTS OF UP-SCALED RAINWATER HARVESTING ON ECOSYSTEM GOODS AND SERVICES IN THE POTSHINI AND MAKANYA CATCHMENTS

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PREFACE

The research contained in this dissertation 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 Campus, South Africa. The research was financially supported by Water Harvesting Technologies Revisited (WHaTeR) a four-year collaborative project funded by the European Commission.

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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DECLARATION

I, AS Chetty, 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) 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.

Signed: AS Chetty

Date: July 2016

ABSTRACT

Water scarcity is fast becoming a global concern, with at least each continent facing water-related issues regarding quantity, quality and delivery. An estimated 8.8% of South Africans do not have access to potable water, according to the World Wildlife Fund's 2011 South African census (2016). The inaccessibility to water for domestic, agricultural or economic activities directly impacts on food security and poverty. Communities living in rural surroundings and depending directly on the environment to support their livelihoods are most affected by water shortages. The 1.2 km^2 Potshini Catchment, located in the foothills of the Drakensburg Mountains in South Africa, and the 300 km^2 Makanya Catchment, situated on the western side of the South Pare Mountains in Tanzania, provide good case studies to assess how communities, vulnerable to poverty and food security, cope with water shortages. Both catchments have well-established rainwater harvesting (RWH) networks that supplement the rainfed subsistence crops. RWH is a method of capturing, conveying and storing rainwater and runoff for future use. It is a valuable practice in agriculture, intended to improve the availability of water to crops towards the end of high rainfall months and during dry-spells. The conservation of water, in these instances, has the potential to secure and improve livelihoods, and to lessen the pressure placed on ecosystem goods and services. Albeit that RWH is an alternative water innovation, supporting the ideals of integrative water resource management, the impacts of up-scaled RWH on streamflow are still to be determined. Little is known about how ecosystem goods and services will respond to the expansion of RWH, as well as the presence of a feedback mechanism.

Therefore, the aim of this study was gain a better understanding of the nature of RWH and its potential impacts on the environment in the form of a literature review. Secondly, a hydrological method or tool was developed to understand the impacts of RWH on ecosystem goods and services, in order to improve the catchment management of upstream and downstream communities alike. This was achieved by determining the relevant ecosystem goods and services within each catchment. Thereafter, the impacts of RWH on streamflow and soil moisture were determined by hydrological modelling of each catchment, using the ACRU Model. Using a scenario-based approach, the limits to RWH may be determined by increasing the level of water harvested in each case. Once the significance of this has been determined, the impact on related ecosystem goods and services can be understood.

The Makanya and Potshini Catchments are located in rural settlements, whose population relies mostly on the environment for daily survival. Ecosystem goods and services, such as water supply and regulation, are high priority benefits. Water is supplied, filtered and purified through natural processes in the environment, whilst floods and droughts are regulated. Through the promotion of infiltration and reduced flow velocities by vegetation, the ecosystem controls the harsh effects of natural variability. Soil formation and retention assists the growth of crops through the facilitation of soil water infiltration and the transport of nutrients from the topsoil. Other basic goods and services within the catchments are the provision of food (fauna and flora), raw materials, and natural habitats for breeding, as well as cultural and recreational areas.

The ACRU Model was successful in simulating daily streamflow and soil moisture in the Makanya and Potshini Catchments. A general reduction in streamflow as a result of increased RWH was modelled over the 56-year study period between 1952 and 2007, for both catchments. A virtual dam within the ACRU model is created to capture rainfall. Increased RWH scenarios are based on 30%, 60% and 90% of the current RWH conditions. It has been estimated that harvesting runoff in the drier months of the year could have the greatest impact on the environment, as low flows are initially reduced by a lack of rainfall. As RWH was increased, a gradual reduction in baseflow was modelled for the Potshini Catchment, whilst baseflows were reduced to zero mm in the Makanya Catchment, as rivers ran dry in low rainfall seasons. When compared to the baseline, the cumulative streamflow over the study period was reduced by 50% and 30%, respectively, in the Makanya and Potshini Catchments. This reduction was significant at all levels (30%, 60% and 90% increase in RWH relative to current conditions) of RWH in Makanya, whilst scenarios up-scaling RWH over 60% had a significant impact on the ecosystem in Potshini (95% confidence interval based on a t-test). The introduction and up-scaling of RWH had a positive impact on soil moisture, increasing total soil water content values far above the baseline values. Harvested water is allocated for irrigation to improve crop yields. Increased water availability improved crop yields up to 50% (assuming no other crop stress occurred), particularly in the Potshini Catchment, thus potentially improving food security within rural communities. Improved soil moisture through RWH acts a means of mitigating the reduction of streamflow downstream. Water is reallocated in the ecosystem and used to improve the delivery of goods and services for human benefit.

Whilst, the environment may have the ability to absorb the initial shock, the continual expansion of RWH has the potential to reduce the resilience of the environment and the goods and services they provide. The large-scale employment of RWH over a long period can attest to a portion of the degradation found in the Makanya Catchment. This is commonly known as a negative feedback mechanism. As a result of improved crop yields, greater expanses of the catchment are converted to runoff generation areas, to increase the opportunities for harvesting water. As agriculture expands and population densities increase, further threats to the environment are created.

Although future predictions cannot be accurately made, it is necessary to attempt to understand the possible outcomes of various theories. The accuracy of this scenario-based research is limited by the accuracy by which each scenario represents RWH, the accuracy with which ACRU represent all key processes and quality of historical data used. However, this study presents a method to determine the likely limits to up-scaling RWH in water-scarce regions, in order to safeguard the integrity of the environment for future generations.

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1. INTRODUCTION

As a result of the exploitation of the earth's natural, non-renewable resources, small-scale water storage schemes are fast becoming the preferred short-term solution to increase the availability of water in the arid and semi-arid areas of sub-Saharan Africa (van der Zaag and Gupta, 2008). Global change trends, such as rapid population growth, urbanisation and economic development, increase the risk of water insecurity, which is further exacerbated by a limited and highly variable rainfall pattern (Gleick, 2000). Securing water for agriculture, the biggest water consumer, has become extremely difficult, especially in the developing countries of sub-Saharan Africa, where 95% of the world's population growth occurs (Rockström, 2004). Rain water harvesting (RWH) is an ancient water storage method, practised in many countries around the globe. It aims to reduce the stress imposed on people, communities and industries as a result of the variability of rainfall. RWH systems captures, convey and store water, during high rainfall periods, from land or rooftop catchments, and is used for a variety of purposes during months that experience low rainfall or during inter-seasonal dry spells (Helmreich and Horn, 2009).

Together with low and variable rainfall, the success of rainfed agriculture is also inhibited by degraded and infertile land, which threatens food security (Ngigi, 2003). This has caused many rural communities to utilise RWH methods for their survival. Tanks and pits, among others, are used to collect water, in order to carry out daily domestic activities such as cooking, cleaning, bathing and flushing toilets. Harvested water is also used by subsistence farmers to irrigate crops, in order to improve yields between the wet and dry seasons. RWH is especially effective in relieving the stress imposed on plants at critical growth stages during dry spells within a season (Rockström, 2000). In order to maintain or improve their livelihoods, it is essential that these rural communities maximize the potential to collect and store rainwater. RWH is a sustainable practice (Kahinda *et al.*, 2007) that could help governments meet their MDG targets and remains an important strategy under Sustainable Development Goals (SDGs) (UN, 2016; Sachs, 2012).

RWH can have both positive and negative impacts on the surrounding landscape. The environment has the ability to absorb negative disturbances and recover. However, environmental resilience has a limit, where a disturbance beyond a particular scale or magnitude can cause irreversible damage. Therefore the limit to upscaling RWH needs to be defined, in order to maintain proper ecosystem functioning, as natural ecosystems provide the essential goods and services necessary for human health and survival. Ecosystem goods and services directly or indirectly benefit humans (Costanza *et al.,* 1997; Jewitt, 2002). These benefits are roughly categorized as regulation, control and production functions. Air, climate and water regulation, water supply, erosion, biological control and food production are a few examples of the ecosystem goods and services necessary for human survival (Costanza *et al.*, 1997). Added pressure from a rapidly-increasing population, as well as food and fibre production, places stress on the water supply which, in turn, negatively impacts the dependant aquatic biodiversity and natural ecosystems (Rockström *et al.,* 2000; 2004). According to Jewitt (2002), it is essential that ecosystems are managed in a sustainable manner, as they are not regarded as water users, but rather the resource from which water and other necessary goods and services are derived. Ecosystems form the platform for social and economic development within communities, which spurs development within the country.

1.1 Rationale for the Research

As RWH intensifies, some ecosystem goods and services are expected to improve at the expense of others (i.e. enhanced food production versus streamflow reduction), but what does that mean for future up-scaling? How does an already degraded landscape impact on up-scaled RWH and how does it compare to studies using pristine baselines? These questions are yet to be answered, as existing research has not focused on the feedback mechanism between up-scaled RWH and ecosystem goods and services. For instance, does RWH, which acts as a soil conservation practice, have the potential to create water-logged soils, mitigating erosion or will it result in the loss of fertile topsoil needed for efficient crop yields? RWH studies lack this focus on the knock-on-effects within the environment.

As a result, tipping points need to be understood and identified, to enable water resource managers to implement up-scaled RWH in a sustainable manner, limiting the negative impact on ecosystem goods and services. Such research is essential in defending the integrity of ecosystems, the goods and services of which are considerably depended upon by humans (Jewitt, 2002). Providing guidance on the limits of up-scaled RWH within a catchment enables water to be equitably shared between the environment and society, which is essential for the maximization of benefits in a water-scarce region.

1.2 Justification

Rainfed agriculture is the basis of rural livelihoods in sub-Saharan Africa, but is highly sensitive to changes in the ecosystem. In many parts of southern Africa, there has been a shift from a centralized water management approach, to a more decentralized, Integrated Water Resource Management (IWRM) approach. These are supportive of RWH as a method of reaching sustainable resource consumption, focusing on rural agriculture and decreasing vulnerability towards climate change and population growth (Kahinda *et al.*, 2007; Rockström *et al.*, 2010; Gupta, 2011). However, there is a large gap in research regarding the effects of RWH on streamflow and ecosystem goods and services, as much attention has traditionally been placed on dam and reservoir construction for water storage, which was the decentralized management approach pre IWRM (Ngigi, 2003; van der Zaag and Gupta, 2008). A wealth of information is available on the effects of large dams on streamflow and ecosystems, as large-scale water storage developments are usually the initial solution to water shortage issues. In South Africa, the introduction of the National Environmental Management Act (NEMA) in 1998 means that, all construction needs an environmental impact assessment. This has forced the conception of innovative ideas for water storage that promotes RWH, yet studies on intensive RWH are few (de Winnaar and Jewitt (2010); Andersson *et al.,* (2011); Andersson *et al.,* (2013), as most pilot projects focus only on small-scale implementation, such as the Smallholders Systems Innovations Project (SSI) carried out in two river basin in Southern Africa; the Thukela River Basin in South Africa and the Pangani River Basin in Tanzania (Bhatt *et al.,* 2006; Mul, 2009). Research conducted through the SSI project concentrated in vulnerable, semi-arid tropical and sub-tropical watersheds (Bhatt *et al.,* 2006). The SSI research focused in the Makanya Catchment (approximately 300 km^2) located in the South Pare Mountains of the Pangani River Basin and in the Potshini Catchment (approximately 1.2 km^2), located in the foothills of the Drakensburg in the Thukela River Basin. Developing countries, such as those mentioned above, have the highest population growth rates in the world and the largest regions prone to water scarcity. A lack of water and food creates several food security and malnourishment concerns. The SSI's aim was to contribute to the achievement of the MDG's by halving the population living in poverty and malnourishment, through agricultural and water innovations. One of the main aims was to maximize the productivity of current agricultural activities through innovative tools and strategic agricultural water management, whilst safeguarding the environment and its functions. The outcomes of this initiative have been successful with the formations of Farmer Learning Groups which promotes information sharing and learning amongst farmers. Farmers and communities have been educated and trained in the use of innovative water technologies. Overall the engagement with local and basin-level institutions has improved allowing the opportunity to educate people on the ground creating long-lasting partnerships (Humphries *et al.*, 2015; Hilmy, 2009).

A lack of large-scale implementation and research could be the result of RWH potentially being contested as a Streamflow Reduction Activity (SFRA). A SFRA is an activity that reduces the amount of water available for the Reserve. An activity capable of reducing streamflow requires a water license and needs to declare and pay for the volume of water required for its operation. Without the proper management of SFRA, the Reserve cannot be met, resulting in unhealthy river systems and poor functioning ecosystems (Dye and Versfeld, 2007). Researchers are intimidated by the conflict that could result, as many livelihoods are dependent on RWH for survival. Therefore, investigation in this field is vital, to determine the advantages and disadvantages of up-scaled RWH.

As the population grows, more and more people are becoming dependent on RWH, however little is known about its potential hydrological and environmental impacts should its uptake become widespread (Gleick, 2000; Ngigi, 2003; van der Zaag and Gupta, 2008). RWH may provide an alternative solution to supplying basic water needs, but its up-scaled impacts have not yet been adequately documented by scientists. Assumptions have been made on the potential impacts, but the literature lacks modelled examples of large-scale RWH uptake and its consequences. The same can be said for the environment's ability to support the up-scaling of RWH, where this two-way relationship has not been adequately investigated. Essentially, for an environment to support RWH, it has to subscribe to a number of prerequisites, which have been the focus of many scientists through suitability mapping and GIS (Kahinda and Taigbenu 2011;

Kahinda *et al.,* 2007; de Winnaar *et al*., 2007). The crucial unknown is the environment's current ability to promote RWH and to sustain large-scale RWH. Determining a threshold or "tipping point" within sensitive ecosystems is a proactive approach, supported by IWRM, which ensures equity amongst all users, by highlighting the points of potential impact and integrate the management of the system to benefit the stakeholders . This however, is yet to be defined in the literature. This research project promotes the understanding of ecosystem functions and their socio-economic role within the rural communities of Potshini and Makanya, and showcases the potential impacts of up-scaled RWH on ecosystem goods and services, and vice versa.

Some regions within sub-Saharan Africa are arid to semi-arid, prone to dry humid conditions and receive little rainfall. Rivers flow intermittently, during extreme events, making it difficult for communities to survive dry-spells. Some areas in rural Tanzania rely heavily on RWH for the supplemental irrigation of their crops. This occurs during approximately two flooding events per year, making the downstream effects significant for the dependant community. RWH has become a water supply concept that is "pro-human", as it can easily be adopted within various households to the benefit of humans. What this really means is that the environment has become less of a priority and compromised, with the assumption that it will adapt and continue to support human activities. Pushing an environment past its point of resilience will cause irreparable harm. More studies need to be ecologically driven, to enable the environment to sustainably support humans for years to come. Determining the up-scaled impacts of RWH will benefit rural communities in South Africa and Africa alike, in communities such as Potshini and Makanya, whose daily survival relies on the amount of water they harvest. Promoting the uptake of RWH in rural communities may potentially increase crop yields and improve their standard of living in an environmentally-sustainable manner, thereby decreasing rural vulnerability, whilst bridging the gap between pro-human and pro-environment philosophies.

It is a common practice for modelling exercises to run catchment simulations, based on pristine baselines. These baselines are based on years of historical data, during which the environment remained relatively undisturbed. However, pristine baselines are unrepresentative of the current condition of the environment, which are altered by human activities (i.e. urbanisation). Catchments respond differently under these new conditions and in order to understand the true impact on RWH on the environment it is necessary that the baseline be revised. Important decisions are influenced by model outputs, therefore this Masters project addresses how important it is to use current and more realistic baselines in hydrological modelling, in order to make accurate predictions. This will be done by comparing pristine baselines with current baselines, taking into account land-use change and degradation, in order to predict the most accurate results.

1.3 Aims and Objectives

This master’s project forms part of a larger research project funded by the European Union called Water Harvesting Technologies Revisited (WHaTeR). The underlying deliverable aims to contribute knowledge on RWH and modelling in aid of formulating tools and methods to determine the impacts and trade-offs of RWH techniques, both upstream and downstream focusing on the Potshini and the Makanya Catchments. This component of the project aims to determine the potential impacts of up-scaled RWH on ecosystem goods and services within the Potshini and Makanya study catchments. This will take the form of two papers, the first being a comparative assessment of traditional RWH methods, whilst the second highlights the feedback relationship between up-scaled RWH and ecosystem goods and services, and provides an analysis of potential tipping points. In order to ascertain the above, the following questions need to be answered:

- What ecosystem goods and services are relevant in the Potshini and Makanya Catchments? Chapter two focuses on this objective which includes how ecosystem goods and services can be measured.
- Does intensive RWH have the potential to impact ecosystem goods and services, how does the state of the environment affect the potential for up-scaling RWH and is there a feedback between these? This review can be found in Chapter 2.
- What is an appropriate baseline for modelling studies which aim to address the potential impacts and benefits of RWH on catchment hydrology?

- How does up-scaling RWH impact on the hydrological cycle, particularly streamflow and soil moisture? The methodology in Chapter three outlines the process used to determine the impact on streamflow and soil moisture.
- Are there thresholds or tipping points to the extent of RWH up-scaling where the generation of ecosystem goods and services are permanently affected? Results of this modelling study, which highlight the tipping points, can be found in Chapter three.
- The following literature review paper describes the concepts of RWH, including the associated ecosystem goods and services that are related to aquatic ecosystems. This paper also seeks to give a comparison of the unique research catchments in South Africa and Tanzania that incorporate RWH practices daily.

1.4 Structure of Dissertation

The body of this dissertation is comprised of two chapters, written as journal papers in accordance with the guidelines approved by the University of KwaZulu-Natal. Chapter 2 is a review paper which forms part of the literature review for this dissertation. It includes the nature of RWH, as well as its potential impacts on the environment, and it highlights the approach of assessing downstream impact. Chapter 3 is a modelling study, which illustrates the use of the Agricultural Catchments Research Unit (ACRU) Model in determining the impact of RWH on streamflow in the Potshini and Makanya Catchments. The final outcome of Chapter 3 highlights the impact of RWH on ecosystem goods and services, whilst quantifying the limit to RWH expansion, which can be found in the concluding Chapter 4.

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2. AN ECOSYSTEM PERSPECTIVE OF RAINWATER HARVESTING

Abstract

This review firstly defines RWH and introduces the different types through two catchment case studies. The Potshini Catchment is located in the foothills of the Drakensburg Mountains in South Africa, whilst the Makanya Catchment is situated on the western side of the South Pare Mountains in Tanzania. The communities situated in these catchments are rural to peri-urban, relying on the environment to provide food, fuel and shelter for survival. Both catchments utilize RWH technologies daily, in order to perform essential livelihood tasks, including the irrigation of subsistence crops. RWH has become a necessity, to maintain crop yields in dry spells and low rainfall seasons. Furthermore, this review outlines the positive and negative impacts of RWH and offers methods to measure these impacts. Expanding the RWH network may seem like a viable option to improve livelihoods through increasing water accessibility; however, it is necessary to explore and measure the negative impacts that it will place on the environment, including the ability to sustain the goods and services it provides. The alteration of natural river flows, expansion of agriculture, degradation and conflict among stakeholders, are but a few of the concerns that arise from up-scaled RWH. Furthermore, feedback mechanisms may further exacerbate these issues. It is therefore, recommended that an activity with the potential to threaten the delivery or sustainability of these goods and services, be modelled and understood, before implementation and expansion.

Keywords: Rainwater harvesting, up-scaled, ecosystem goods and services, impacts thresholds.

2.1 Introduction

In the arid and semi-arid regions of sub-Saharan Africa, water is fast becoming a luxury, as climate change threatens water security (Scheffran and Battaglini, 2011). Many rural communities are struggling to survive, as the changing climate alters rainfall patterns, and increases its variability in space and time (Bulcock and Schulze, 2011). Only a small fraction of rainfall is converted to runoff (blue water), which recharges rivers and lakes (Rockström and Falkenmark, 2015). Under desert-like conditions, where high temperatures speed up the process of evaporation, up to 95% of sub-Saharan agriculture relies on soil moisture (green water) for crop water supply alone. The rural and peri-urban communities that are marginalized to the outskirts of towns and cities often do not have access to potable drinking water and rely heavily on the river system for their daily water requirements (Aladenola and Adeboye, 2010). Often women and children walk long distances to collect water for domestic chores, as well as livestock and to irrigate crops. Such communities rely on the health of these river systems and the related ecosystem goods and services, for their wellbeing and survival. Rainwater harvesting (RWH) is the process of capturing and storing rainfall or runoff for later use. It offers relief in areas that do not have access to water. Tanks, pits, terraces and dams serve as water storage options to make rainwater and runoff more readily available. RWH systems are considered an integrative technology, reducing the natural stresses imposed on different stakeholders, such as agriculture, domestic and livestock (Ngigi 2003).

However, the potential negative implications of RWH need to be investigated, in order to maintain the natural balance of the environment. When natural systems are in equilibrium they are able to provide society with goods and services sustainably. Through its natural processes, the environment provides the essential resources to ensure the basic health and well-being of society. The provision of food, water and timber are well known goods which provide necessary resources for survival. Introducing unnatural systems into the environment or over exploiting natural systems disturbs the natural order and increases vulnerability (Daily, 1997; de Groot *et al.,* 2002; Rockström *et al.,* 2004). Thresholds and parameters need to be determined in order to limit the potential negative impact imposed on ecosystems by such developments and maximize the benefits they provide. Therefore, the focus of this review aims to define RWH within each catchment, while determining the relevant ecosystem goods and services provided by environment, as well as highlighting not only the positive implications of RWH, but also the negative impacts felt by the ecosystem. Furthermore, the potential consequences of up-scaled RWH are also discussed.

2.2 Defining Rainwater Harvesting

People have practised RWH for many centuries and their traditional, indigenous methods have evolved over the years (Mbilinyi *et al*., 2005). It has been argued to be a means of benefitting humans, whilst nurturing ecosystems, in order to sustainably perform its necessary functions (Patil *et al.*, 2013).

RWH systems are designed and built to capture, convey and store rainwater from a structure, such as a rooftop or safeguarded land surface. Water that is stored, either in tanks, pits, trenches, soil or small dams, can be used at a later stage for a variety of purposes (Kahinda *et al.*, 2007). These uses differ between urban and rural homesteads, but general uses include watering the garden, flushing toilets, washing cars and depending on the quality, for drinking purposes, if properly treated. RWH is effective in reducing crop failures caused by mid-season dry spells during the critical growth stages of plants (Vohland and Barry, 2009). Water that has been stored during a rainy season can be used in drier periods of the season to improve crop yields (Rockström, 2000).

Studer and Liniger (2013) have considered the ecosystem in their definition of RWH, namely, the collection and management of floodwater or rainwater runoff to increase water availability for domestic and agricultural use, as well as ecosystem sustenance. They argued that captured water is made accessible to people, whilst ecologically destructive floods are mitigated, highlighting the importance of maintaining social and environmental equity. This concept is especially important when considering the upscaling of RWH in a particular community and should be further explained by considering other aspects of ecosystem sustenance.

Upscaling refers to intensifying the use of RWH within a community or even expanding the territory in which RWH is used. Additional homesteads practise RWH, therefore increasing household benefits, but also environmental impact. This motivates studies such as this, to determine the limit to upscaling and to understand how the environment can limit RWH expansion or benefit from it.

2.3 Rainwater Harvesting Methods

RWH is generally categorized into three different types, based on the scale, namely, *in-situ*, micro-catchment and macro-catchment WH (Prinz and Singh, 2000; Helmreich and Horn, 2009).

In-situ RWH includes techniques similar to that of soil or water conservation and involves capturing runoff wherever it falls. The aim is to reduce runoff and increase infiltration in the root zone (Mbilinyi *et al*., 2005: Helmreich and Horn, 2009). Examples include deep tillage, ridges, borders, terraces and trash lines. Micro-catchment RWH captures and stores water from a runoff generation plot, which is a distinctly separate area next to the cultivation plot. Pits, contour bunds and semi-circular bunds are common micro-catchment techniques. Macro-catchment RWH is similar to the technique employed in a micro-catchment, except that it occurs on a much larger scale. The runoff generation area occurs off-site, where water is captured, stored and then transported for agricultural use. Sub-surface dams and small earthen dams are known as examples of such RWH (Mbilinyi *et al*., 2005; Prinz and Singh, 2000; Helmreich and Horn, 2009). For a particular technique to be regarded as RWH, rainfall needs to be captured and stored in the wet seasons, as water is not available all year round (see Table 2.1 for illustrations).

2.4 Rainwater Harvesting Practices in the Potshini and Makanya Catchments

A considerable number of the world's rural communities are located in sub-Saharan Africa and of these communities, the majority rely on rainfed agriculture to sustain basic livelihoods (Rockström *et al.*, 2004; Pachpute *et al.*, 2009: Rockström and Falkenmark, 2015). The Potshini Catchment in Southern Africa and the Makanya Catchment in Tanzania are typical communities where rainfall is supplemented with RWH for the irrigation of their crops. The most common forms include domestic RWH (micro-catchment) from ground or rooftop catchments, as well as flood harvesting (macro-catchment).

2.4.1 Case study: Introduction to the Makanya Catchment

The Makanya Catchment (300 km^2) is situated on the western portion of the South Pare Mountains in the Kilimanjaro region within the Pangani River Basin, Tanzania. This Catchment consists predominantly of smallholder subsistence farmers, with rainfed agriculture supporting the livelihoods of up to 40 000 people (Enfors *et al.*, 2008; Pachpute *et al.*, 2009; Mzirai and Tumbo, 2010). Rainfall in Tanzania is characterized by two distinct rainy periods from October to December, commonly known as the “Vuli”, and from March to June, known as the “Masika”. Rainfall is highly variable across Tanzania, making dry spells inevitable. The higher slopes are too steep for cultivating crops, which has resulted in the lower, gentler slopes becoming highly degraded due to the extensive utilization for agriculture. Natural vegetation present includes wooded grasslands, shrubs and acacia tree species (Mbilinyi *et al.*, 2005; Pachpute *et al.*, 2009).

The RWH technique most commonly used in the catchment for research purposes is flood diversion, including, amongst others, micro-dams, dug out ponds, spate irrigation sub-surface runoff harvesting tanks and rooftop RWH systems. Flood water harvesting captures and stores water from short-term streams and rivers during peak flows in high rainfall seasons, notably in regions where a number of flooding events occur annually. Water is captured in a distinctly separate area away from the cultivated area and is diverted, when irrigation is necessary (Ngigi, 2003). In the case of spate irrigation (flood diversion), water is diverted from a riverbed (wadi) to a cultivated area. Alternatively, a plot used for planting is flooded, promoting the infiltration of water to the root zone, below the evaporative zone, where it is stored in the soil for future use (Prinz and Singh, 2000; Studer and Liniger, 2013). Due to large amounts of water being stored in the root zone, it is common for flood water harvesting to contribute to groundwater recharge. Eight percent of rural communities within the Makanya Catchment are reliant on flood diversion (and other RWH techniques) for irrigation, as rainfall in the lowland areas is limited to 200-400 mm over two seasons (Mbilinyi *et al.*, 2005; Mul, 2009). It is estimated that this number will increase as the population rapidly grows. Thus far, farmers are able to ensure crop yields to sustain their families, by incorporating RWH into their agricultural practices. Despite this, land degradation, erosion and decreased pollination, amongst others, is an escalating concern as provisioning ecosystem services increase, causing a decrease in regulatory, supporting and cultural ecosystem services (Gordon and Enfors, 2008).

2.4.2 Case study: Introduction to the Potshini Catchment

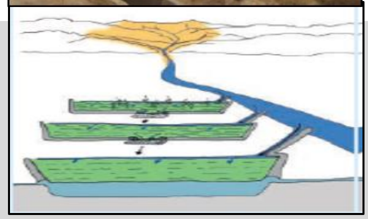
Potshini is a rural, smallholder farming community situated in the foothills of the Drakensburg Mountains in the Thukela River Basin, in the Bergville District of KwaZulu-Natal, South Africa (Kongo and Jewitt, 2006; de Winnaar *et al*., 2007). The Potshini Catchment (1.2 km^2) is a sub-catchment within the South African Quaternary Catchment V13D, also known as the Emmanus Catchment. It is characterised by gentle slopes used for agriculture, whilst steeper slopes in the upper reaches are mainly used for grazing livestock (de Winnaar *et al.*, 2007). Maize and soya bean are the main cash crops grown within the catchments, while small-scale vegetable gardens are individually maintained by roof-top and ground catchment RWH. Natural vegetation within the catchment consists mainly of tall grass species. Precipitation occurs in the warmer summer months in the form of thundershowers, in contrast to the cold, dry conditions experienced in winter (de Winnaar *et al.*, 2007).

A hydrological monitoring network was established in Potshini, in conjunction with the Smallholder Systems Innovations (SSI) research programme, to involve the rural community and other stakeholders in the monitoring process at catchment scale, in order to improve water resource management practices (Bhatt *et al*., 2006; Kongo *et al.*, 2010). The RWH methods involve the collection of water from rooftops or groundwater catchments for domestic use. This is typical of domestic RWH, where water that falls on rooftops, courtyards or gardens is collected and stored in tanks either above-or underground. Domestic RWH is characterised by the use of the stored water for household chores, sanitation, drinking or watering garden crops (Helmreich and Horn, 2009; de Kwaadsteniet *et al*., 2013). The ongoing monitoring in the Potshini Catchment highlights effective stakeholder integration and communication and furthers the understanding of hydrological processes within the Catchment. RWH has been successful in the area, in that households have increased crop yields by improving land productivity and have safeguarded crops in drier winter periods with stored rainwater. The sustainable use of ecosystem goods and services are encouraged, as crop yields improve due to RWH. This results in less land being required and lower quality water being re-used (Sturdy *et al.*, 2008).

Table 2.1 provides an illustration of some basic RWH methods, of which ground, rooftop and flood diversion are common to the above study catchments.

Table 2.1 Description and illustration of various rainwater harvesting techniques (after FAO, 2003; Kahinda and Taigbenu, 2011; Studer and Liniger, 2013)

Type of RWH	Name of RWH	Description	Illustration
In-situ	Terrace	Embankments are graded into the slope and grassed to reduce the downward velocity of runoff and increase infiltration	
Micro (Domestic)	Roof-top (tank)	Water harvested from the rooftops of houses,schools etc and channeled into storage tanks	
Micro (Domestic)	Ground surface (tank)	Water harvsted from a plot of land in homestead. Water drains into and is stored in underground tanks	
Micro	Contour bunds/ half moons	Earth shaped into half moons and stabilized with stones upslope, capturing runoff and increasing infiltration to the root zone	
Micro	Pits	Water stored in small planting pits/zai pits. Plant has direct access to water in root zone	

Macro	Sub-surface dam	Water harvested from uncultivated hillslope, stored in an earthen dam and transported for irrigation	
Flood water harvesting (Macro)	Spate irrigation/ Flood water diversion	Water from flood events is captured diverted from a river-bed (separate area) to a cultivated field.	

2.5 Defining Ecosystem Goods and Services

The ecosystem is dynamic, multifaceted and constantly adapting to the current climate and global drivers (Jewitt, 2002). Natural capital is the core resource for all development, making it highly exploited and vulnerable. The importance of the conservation of ecosystem goods and services is growing, as societal dependence increases and the inability of technology to substitute them is recognised (Daily, 1997; Brown *et al.*, 2007; Egoh *et al.*, 2009). Ecosystem goods and services are the result of ecosystem functioning that provides humans with the benefits they need for health and well-being (Daily, 1997; de Groot *et al.*, 2002; Rockström *et al.*, 2004). Ecosystem goods and services comprise intrinsic biotic and abiotic relationships that maintain the earth's natural cycles in equilibrium. Thorp *et al.*, (2010) describe ecosystem services as a qualitative/quantitative benefit to the overall environment, including products and services which benefit humans. Ecosystem goods include products, such as food and raw materials provided by nature, and ecosystem services are represented by the processes and physical, biochemical cycles that the environment facilitates, such as nutrient cycling and carbon sequestration (Constanza *et al.*, 1997; Brown *et al.*, 2007). Humans are direct or indirect benefactors of ecosystem goods and services; however, their actions directly influence the state of the environment, impacting its ability to deliver necessary goods and services (Constanza *et al.*, 1997; Jewitt, 2002). The abundance of goods and services provided by the ecosystem is a reflection of how well the environment is maintained. It has been emphasized by authors, such as Constanza *et al.* (1997) and de Groot *et al*, (2002), that ecosystem functions are interdependent and not isolated. For instance, water regulation and supply ensures that rivers channel sufficient water through the watershed for waste assimilation and dilution. Not only does water quality improve, directly benefitting the health of humans, but aquatic ecosystems are healthier, promoting fauna breeding, pollination and diversity.

Based on work of Constanza *et al.* (1997), de Groot *et al*. (2002) and the MEA (2005), ecosystem goods and services can be roughly categorized into four main functions, namely, regulating, provisioning, supporting and cultural (see Figure 2.1 below for illustration).

Figure 2.1 Four main functions of ecosystem goods and services (source: Ecosystem services diagram, www.metrovancouver.org [Accessed: 12 September 2014])

Regulatory functions include the facilitation of ecological processes that support all living organisms and systems on earth, whilst maintaining the health of the biosphere and providing human benefits. Regulatory functions include gas, climate, water and hazard/disturbance regulation. Ecosystem goods and services, referred to as provision/production, constitute products manufactured by photosynthesis including food, fibre and raw materials. The ecosystem also provides habitats for plants and animals. These habitats provide shelter, security and food for organisms and, most importantly, an environment for reproduction. Lastly, humans benefit from the information/cultural function of ecosystem goods and services by providing landscapes for recreation, aesthetic pleasure and for religious practices. In addition, the environment offers scientists the opportunity to study and investigate processes, organisms and habitats in an effort to discover new concepts and to advance scientific research (Constanza *et al.*, 1997; de Groot *et al.*, 2002; Jewitt, 2002; Egoh *et al.*, 2012).

RWH can be considered as an example of humans altering the environment to extract further benefits. This has the potential to harm the environment's natural ability to deliver goods and services i.e. a trade-off. Whilst a portion of the ecosystem thrives due to an increased water supply, it is possible the downstream portion is faced with altered flow regimes, reduced streamflow and a decline in available opportunities (McCartney *et al.*, 2000).

Figure 2.2 illustrates the long-term impacts of altering a natural environment. An undisturbed, pristine environment naturally offers sustainable, long-term benefits. Altering the natural order of the environment results in substantial short-term, benefit which eventually stabilizes at the point where the environment is either negatively impacted or where its careful management allows for continued long-term benefits (McCartney *et al.*, 2000). The aim of IWRM is to develop and utilize a catchment sustainably, in order to maximize the total benefits from the environment over the long-term. RWH is a method of abstracting rainfall and runoff, with potentially positive long-term benefits for people and the environment, if implemented correctly. However, the inability to determine whether there is a threshold to RWH could result in a negative feed-back mechanism, which would decrease sustainability. Section 2.8.2 details examples of a negative feed-back mechanism.

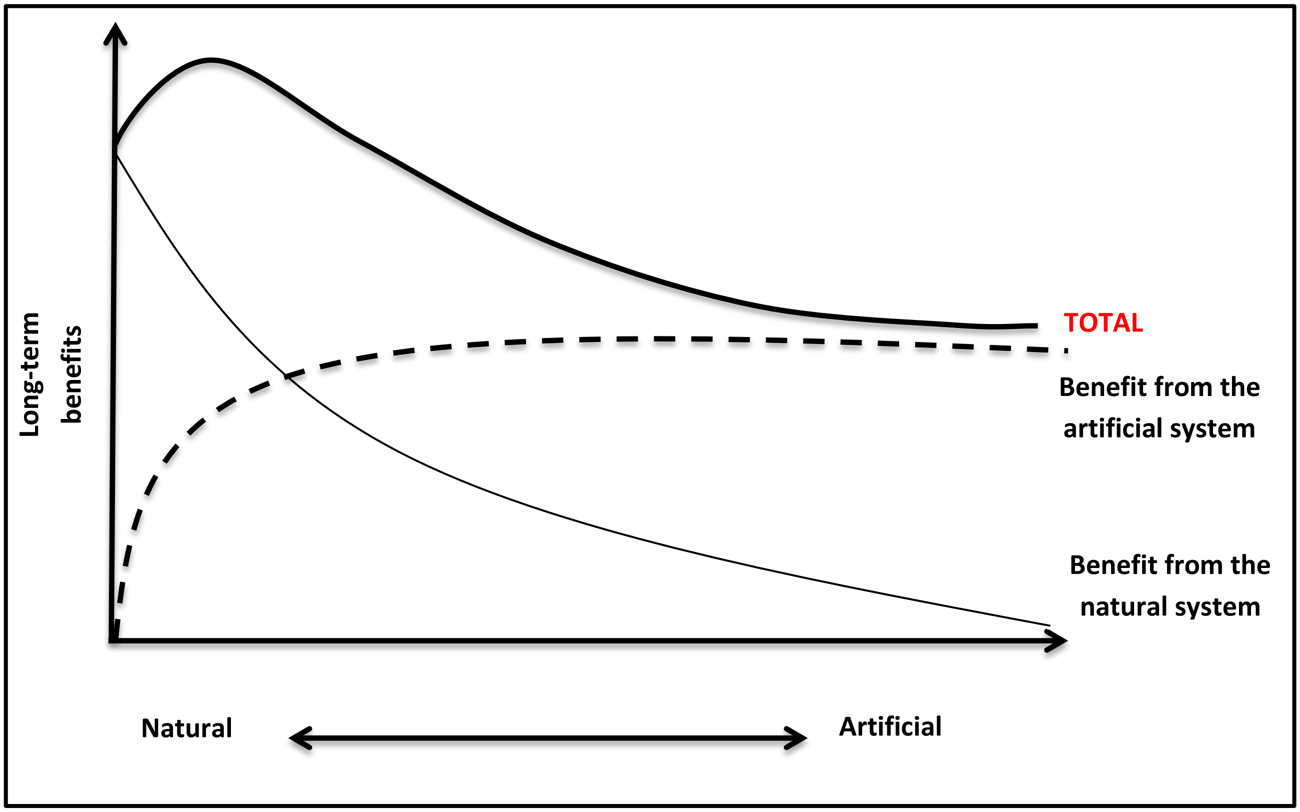


Figure 2.2 Maximizing the benefits from a freshwater ecosystem (after McCartney *et al.*, 2000)

2.6 The Importance of Ecosystem Goods and Services in Sub-Saharan Africa

Two-thirds of the population of sub-Saharan Africa live under rural conditions, with half its population facing extreme poverty, malnutrition and water shortages (Enfors and Gordon, 2007; Rockström and Falkenmark, 2015). Most livelihoods in this region are dependent on ecosystem goods and services. Water provision and purification are two of the most important ecosystem functions that humans depend on, in addition to soil fertility for agriculture, pollination and the provision of natural resources, such as timber, for fuel and shelter (Egoh *et al*., 2012). RWH is fast becoming a popular technique to increase accessibility to water and to decrease the spread of water-borne diseases.

In arid, humid climates common to sub-Saharan Africa, water supply is essential for survival and development, as most agriculture is rainfed. In low rainfall areas, communities tap into ground water as an alternate source of water. Harvesting and hunting, as well as gathering and collecting, are daily norms for many rural African people. Having access to fibre allows the construction of homes, shelters, fences and fuel for fires (Egoh *et al.,* 2012). Maize is the staple food source in many parts of Africa, which most farmers cultivate, including subsistence farmers, whilst timber products, fruit and sugar cane are grown for trade and export. The natural environment provides the necessary goods and services, such as erosion and pest control, soil and nutrient fertility, sediment loss reduction, water purification and hazard control, to support the livelihoods of humans. See Table 2.2 for descriptions.

Many people in Africa lack access to proper health care, making them vulnerable to diseases and illnesses, such as diarrhoea, fever and flu symptoms, and they are therefore highly dependent on traditional medicines (Egoh *et al.,* 2012). For this, they rely on raw materials, such as leaves, plants, roots and bark provided by the landscape, to manufacture a variety of traditional medicines (Egoh, 2002). Natural resources also allow religious rituals to take place, satisfying people spiritually. Portions of the landscape are priority areas for worship, particularly in traditional African cultures. This, for example, is true for many Tanzanians, where roughly eight-percent of the North Pare Mountains are used exclusively for sacred rituals, while plants and animals native to the forests are used as sacrifices and medicines (Egoh, 2002; Sheridan, 2008).

The socio-economic development of the continent is heavily reliant on the ability of the ecosystem to continually provide goods and services (van Wyk *et al.,* 2007). Raw material and services offered, allow expansion of rural areas and also a shift towards urbanisation. Based on the interpretation of the environmental Kuznets curve by Ngcobo *et al.* (2013), the initial degradation of environmental goods and services is inevitable in a developing country. However, once economic growth has stabilized, sustainable boundaries are established, to protect and conserve the environment.

2.7 Practical Examples of Ecosystem Goods and Services in the Potshini and Makanya Catchments

The ecosystem is a complex and dynamic network of processes that work towards keeping the earth's systems in equilibrium (Jewitt, 2002; MEA, 2005). The functions listed in Table 2.2 are intricately linked and dependent on each other for the successful functioning of a variety of ecosystems (Brauman *et al.,* 2007). Water sustains all life in a natural ecosystem, therefore altering the integrity of the hydrological cycle causes a knock-on-effect, as water flows through the landscape (Jewitt, 2002; Rockström *et al*., 2004). RWH has the potential to affect majority of these functions in both a positive and negative way, a consequence of interconnectedness of the goods and services of each ecosystem. Table 2.2 includes ecosystem goods and services common to the Potshini and Makanya Catchments that have been adapted from Constanza *et al.* (1997), de Groot *et al*. (2002) and Brown *et al.* (2007). The potential RWH impact is the author's own interpretation based on literature reviewed, observation in the field and discussions with stakeholders and scientists active in RWH.

Table 2.2 Ecosystem goods and services potentially impacted by RWH

	Function	Process	Ecosystem Illustration	Potential RWH impact
Regulation	Gas regulation	Maintaining chemical balance of the atmosphere: O_2/CO_2	Cleaning/filtering the air for breathing. UV protection	RWH prevents erosion of topsoil. Organic matter = CO_2 sink
	Disturbance control	Safeguarding humans by buffering impacts of natural disasters	Vegetation reducing the velocity of flood water, promoting infiltration	Water capture and storage is promoted reducing flood/drought impacts on livelihoods
	Water regulation	Maintaining natural flows, facilitates quantity of flow	Ensuring water for transport and downstream irrigation. Flood and drought regulation	Less water for society. diverted/abstracted Commercial/ subsistence farmer conflict
	Water supply	Storage, supply and filtering/purification	Water filtered through vegetation, soil and organisms in wetland	Less water for aquatic systems
	Climate regulation	Controls atmospheric circulation patterns contributing to climate	Regulating climate for human health, comfort, crop growth	Crop expansion increases the carbon sink (photosynthesis)
	Soil retention and formation	Rocks fragment, nutrient inputs from organisms. Soil stabilized by tree/vegetation roots	Crop and vegetation productivity. Soil erosion prevention. Soil fertility maintained. Improved infiltration	Water diverted to plant root zone, improving infiltration and groundwater recharge. RWH doubles as soil conservation, limiting erosion, increasing soil moisture

Category	Function	Process	Ecosystem Illustration	Potential RWH impact
	Nutrient cycling	Recycling elements; O, H, C, N, P, S, Fe, Zn, making them available for important processes	N essential for plant growth. Elements improve soil fertility. Maintains life of organisms	Stored water carrying nutrients concentrated in roots
	Pollination	Reproduction of plants, increasing diversity. Provision of pollinators	Essential for agriculture, food and preservation of rare/ extinct species	Decreased river flows reduce the transport of vectors. Crop expansion attracts more pollinators
	Biological control	Feed-back mechanisms employed to control pest/disease spread. Maintains predator-prey balance	Reduces over population of a species, limits the outbreak of pests destroying agriculture	RWH stores water creating a breeding ground for pests such as mosquitos spreading malaria
	Waste treatment	Store, filter, purify, recycle wastes through dilution, adaptation etc.	Wetlands purify/filter human waste in water naturally	Reduction in streamflow reduces the ability of wetlands to perform
Habitat	Habitat	Homes and shelter to protect and feed plants and animals	Animals and insects burrow in the ground, birds nest in trees. Feed off fruit and vegetation	Aquatic biodiversity decreased as water levels and natural flows are reduced
Habitat	Nursery	Breeding and nursery areas, promoting the survival of young	Wetlands and estuaries provide safe environments for reproduction	RWH limits the safe aquatic habitats as a result of water abstractions
Provision	Food	Food collected and gathered in nature, hunting and subsistence farming	Wild fruit, vegetables. Hunting wild animals and fishing. Small-scale farming	Natural vegetation is threatened as croplands expand. Crop yields increase as stored water is used to irrigate
Provision	Raw materials	Non/Renewable resources; timber and fibre, including bi-products for trade and construction	Wood, gum, wax, tannins, certain organic oils. Fossil fuels such as coal, gas and oil (non-renewable)	Growth of timber and fibre used for shelter and fuel wood is enhanced by additional stores of water
Provision	Medicinal resources	Nature provides material for making drugs and medicine to cure human illnesses.	Chemicals from roots and leaves can heal sores, diarrhoea and flu (traditional medicines and pharmaceutical drugs)	Increased abstractions upstream limits the natural distribution of water downstream necessary for growth of indigenous vegetation

	Function	Process	Ecosystem illustration	Potential RWH Impact
Information and culture	Aesthetic	Providing picturesque landscapes for inspiration and encouragement	Mountain and ocean views. Scenic garden routes	Decreased river health and water quantity may restrict richness of biodiversity
	Spiritual	Nature provides places to worship, and animals to sacrifice	Sacred ancestral lands, graves, worship areas. Animals and rivers for sacrificial ceremonies	Scared lands become increasingly vulnerable as natural flows decrease
	Recreational/ tourism	Economic development. Offering relaxation and recreation	Hiking, swimming, fishing, camping, canoeing. Leisure and rest	Biodiversity decreases limiting the ability to fish/swim and enjoy the natural landscape
	Scientific/ educational	Ecosystems are field laboratory's needed for education and monitoring change for human safety	Leading to publications, implementation of mitigation strategies, expanding knowledge and awareness	Increased scope and opportunities for nature studies. Catchment modelling and management. Innovative water solutions.

2.8 Potential Impacts of Up-scaled Rainwater Harvesting on the Hydrological Cycle and Further Impacts on Ecosystem Goods and Services

Within the philosophy of IWRM, RWH has been proposed as the ideal approach to ensure that water is managed sustainably, whilst taking into account the needs of all stakeholders (Ngigi, 2003; Rockström *et al.*, 2010). This method also promotes the values of IWRM, by aiming to curb the demands of the population and attempt to supply water equitably to all its stakeholders (Ngigi *et al.*, 2007; Gupta, 2011). Building from Studer and Liniger (2013) the expansion of RWH, water storage systems could pose a shift from an engineering challenge towards a conservation solution (Rockström and Falkenmark, 2015). RWH has a less devastating impact on the environment than large dams, as rivers and streams are not impounded, thus reducing the impact on environmental flows, and decreasing nutrient loading and transport. The pressure placed on ground water through extractions is alleviated, as RWH allows access to "free" water (Prinz and Singh, 2000). Climate change places huge pressure on ecosystems to provide water.

Up-scaled RWH can be seen as an adaptive climate change strategy that relieves this pressure, by storing water when rainfall is abundant, for use when water is scarce (Pandey *et al.*, 2003).

Up-scaled RWH has the potential to provide relief in areas that are vulnerable to water scarcity (MEA, 2005; Ngigi *et al.*, 2007). However, the ecosystem has the potential to be impaired by negative trade-offs, which need to be addressed in order to maintain resilience (Enfors and Gordon, 2007). In this context, an ecosystem threshold is a term used to describe a point in nature where even slight changes beyond that threshold can cause large responses, triggering serious and, in many instances, irreparable damage (Groffman *et al.*, 2006).

Figure 2.3 illustrates the introduction of a stress factor into the environment, based on Dinda (2004). From this it can be seen, that the initial inception of the stressor does not fatally harm the environment or reduce the systems functions. Each ecosystem has the ability to absorb the stress and adapt to the new conditions (Groffman *et al.*, 2006). However, a limit is reached (as indicated by the red arrow) where the accumulative impacts of the stressor cannot be absorbed by the environment, which tips the balance of the ecosystem and its functions into a region of unsteadiness. Environmental resilience is decreased, so that the ecosystem is potentially irreversibly damaged, decreasing its ability to deliver goods and services efficiently. However, according to McCartney *et al.* (2000), the environment does have the ability to continue to provide goods and services in a modified system, provided it is properly managed. It can be seen from Figure 2.3 that, if the limit to RWH is known, the maximum benefits can be extracted from the environment before reducing environmental resilience, whilst further promoting the long-term provision of benefits.

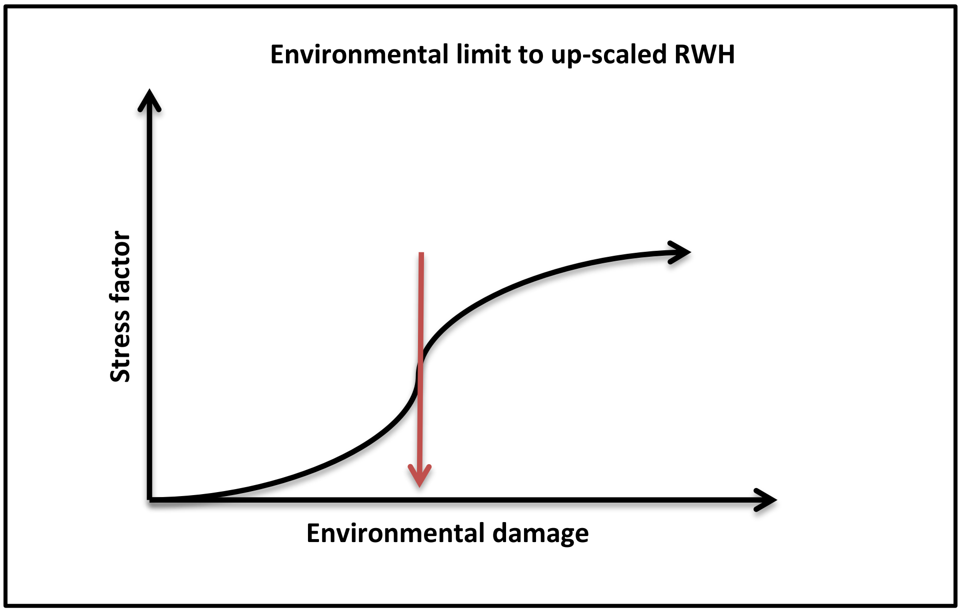


Figure 2.3 S-curve depicting the tipping-point of environmental resilience based on the Kuznets Curve Hypothesis (after Dinda, 2004)

Reductions in streamflow, due to increased RWH (de Winnaar and Jewitt, 2010), are an example of such a stress factor that has the potential to reduce the ability of the environment to absorb the disturbance and adapt, therefore increasing the vulnerability of the environment and the people who depend on its goods and services.

De Winnaar and Jewitt (2010) conducted a similar study in the Thukela River basin. The aim was to determine the eco-hydrological impacts of large-scale RWH on streamflow regimes using the Agrohydrological Model (ACRU). Using census data and determining the impervious runoff generation areas the potential for runoff harvesting was established (de Winnaar *et al.*, 2007). Here a scenario-based approach was enlisted, to determine the impacts of up-scaled RWH. The scenarios were designed assuming 50%, 100% and 150% of the current effective population adopting RWH. The project found that an increase in RWH activities decrease streamflow downstream, which was significant in the 100% and 200% scenarios. However, the expected increase in streamflow expected from impervious area without RWH was disproportionate to streamflow reductions with RWH. Therefore the reduction in downstream streamflow yields both pre and post RWH was relatively small. Using the Indicators of Hydrologic Alteration (IHA) model, it was found that although the reduction in streamflow was minimal, the impact of high and low peaks were affected. This could have future implications on sensitive ecological functions in the catchment. In order to, maintain stability within ecosystems, and to limit potential harm within ecosystems, it is necessary to predict and understand these thresholds.

As the population continues to increase at an exponential rate and the climate starts to change faster than the earth's ability to adapt, the harder it will be to abstract water (Gleick, 2000). RWH has the potential to be adopted and up-scaled at a rapid rate to mitigate water scarcity, but these negative impacts will be up-scaled too (Ngigi, 2003; Ngigi *et al.*, 2007). Inexperience and a lack of knowledge, with regard to site and RWH method selection, could result in ecological ruin, where large abstractions occur in water-sensitive environments. In addition, different types of RWH may have different effect on the water regime of a catchment (Kahinda *et al.*, 2009).

2.8.1 Potentially positive implications of rainwater harvesting

People rely on many essential hydrological ecosystem services, such as, water supply, flood and drought mitigation, soil water conservation and water regulation. The impacts of up-scaled RWH on the hydrological cycle and ecosystem goods and services are both positive and negative, often occurring simultaneously in different locations. In addition, the degree of impact may vary in terms of the spatial extent of RWH, climatic conditions (rainfall intensity) and catchment conditions (degraded or pristine). Comparing upstream and downstream environments highlights this juxtaposition, emphasizing how downstream users endure the consequences of the entire watershed's experience (Ngigi *et al.*, 2007). As a result of water moving through the landscape, any diversion directly impacts the ecosystem, and vice-versa (Brauman *et al.*, 2007).

RWH plays a complementary role in improving the availability and access to water, which ranks highly on the list of the SDG goals set by the United Nations (UN, 2016). Improved water storage and accessibility allows subsistence farmers to intensify agriculture and improve the health of livestock, as water is available for irrigation and animal-use in dry periods, promoting yields (Ngigi *et al.*, 2007) (Table 2.2). Studies conducted by Andersson *et al.*, (2015) and Andersson *et al.*, (2011) illustrate how a combination of improved soil water and fertility can improve subsistence crop yields. Both studies were conducted in a similar fashion using the same methodology at differ spatial scales (Thukela River Basin vs South Africa). The soil and water assessment tool (SWAT) was used to model potential impacts on maize yields as consequence of increases in soil moisture from RWH and improved nutrient levels as a result of fertilization with stored human urine (Ecosan). The Curve Number (CN) with the SWAT model responsible for partitioning water into the soil was adjusted to increase infiltration (a form of water harvesting). This project also used a scenario based approach allowing RWH to be modelled alone, in-conjunction with Ecosan and based on an unlimited water supply. The impact of RWH alone on crop yield is minimal. In order to achieve an increase in crop yield of 5%, a runoff reduction of 80% would be estimated. RWH is helpful in reducing spatial yield variability and buffers the impact of dry spells which leads to low soil moisture. RWH coupled with Ecosan improve crop yields by up to 30%. Unsurprisingly, unlimited nutrients and available water drastically improve crop yields. The project found that the impact of RWH on river flows is likely to be minimal which is a result of lateral flows contributing to discharge rather that surface runoff (which is harvested). Contrary to de Winnaar and Jewitt (2010), the projects found that the impacts to low-flows were consistent and limited. The key issue highlighted by Andersson *et al.,* (2015) and Andersson *et al.,* (2011), is the dual effort of RWH in-conjunction with soil fertility to improve crop yields, which has little baring on streamflow reduction.

Senkondo *et al.,* (2004), modelled the profitability of the use of RWH in the Makanya Catchment. With simple field experiments, staple crops such as maize, onions and rice were planted. The control only received water when it rained, whilst the remaining plots received supplemental irrigation from stored water made available by RWH. Results indicated that 70% of the maize plots that did not receive water from RWH did not harvest anything, whilst those that benefitted from supplemental irrigation recorded an average yield of 1.97 t/ha. This simple experiment highlights the potential for increasing the uptake of RWH for subsistence agriculture.

Sub-Saharan Africa relies heavily on rainfed agriculture for economic activities; therefore increasing crop yields through RWH could stimulate economic growth and improve food security (Ngigi, 2003). It can also be seen as a method of informing rural communities and transferring skills and knowledge to improve their standard of living. Initiating workshops amongst small farmer networks provides a platform to share experience, as well as to offer support and technical assistance to newer farmers (Studer and Liniger, 2013). Based on the poor response to community programmes highlighted by Sturdy *et al.* (2008), improving the understanding of the farmers in terms of socio-economic value and practicality would benefit the adoption of RWH and the positive impacts associated with it.

RWH allows water to be more accessible within a homestead, which promotes the growth and diversity of biomass, and increases the health and chances of habitation within an area. RWH techniques, such as terraces and contours, assist in retarding high velocity flows of runoff down hillslopes. These can be regarded as soil conservation techniques, and as a method of increasing the infiltration of water to the root zone of plants (Table 2.2). This highlights the ability of up-scaled RWH to support ecosystem functions (Ngigi *et al.*, 2007). Ecosystem services, such as erosion control, retaining sediments and flood control, are maintained through up-scaled RWH, as water is captured and stored when it is available, particularly in high rainfall seasons or in the instance of floods, mitigating their devastating consequences. Depending on the storage capacity of the RWH infrastructure, flood waters can be diverted and stored for future use and, in doing so, sediments and nutrient-rich topsoil that would have been eroded and transported by fast-moving waters, is conserved (leRoy Poff *et al.*, 1997). As a result, soil fertility is positively affected and, in turn, agriculture thrives, directly benefitting humans. The growth of some alien invasive vegetation in the riparian zones is restricted as streamflow is reduced. Floods, transporting seeds and promoting the pollination of alien vegetation, is also limited, therefore reducing the chances of colonization and invasion. As a result, natural vegetation has the ability to adapt to the river conditions and thrive.

2.8.2 Potentially negative implications of up-scaled rainwater harvesting

According to Jewitt (2002), freshwater ecosystems overlap and have an influence on almost all other ecosystems on the earth. Any alteration, negative or positive, will have a knock-on effect, the impact of which will be felt among all dependant ecosystems. Aquatic ecosystems have adapted their life cycles to the natural flow of a river, making them vulnerable to changes in streamflow (leRoy Poff *et al.*, 1997)**.** Unfortunately, up-scaled RWH has the potential to result in numerous drawbacks, which are highlighted in this section.

While some studies indicate a negligible impact on streamflow (Andersson *et al.,* 2011) others show that water retention that occurs upstream has the potential to reduce the natural river flow and affect the ecosystems downstream (Ngigi *et al.,* 2007; de Winnaar and Jewitt, 2010). Communities that rely on RWH downstream may escape the negative impacts, but those who rely on natural water sources will experience limited water supplies and poorer water quality, as the ecosystem is unable to provide its water regulation and purification services, illustrated in Table 2.2. Conflicts are bound to ensue, to the frustration of downstream water users, thus reducing social cohesion. Increased downstream water scarcity threatens the livelihoods of stakeholders, making it harder to grow crops, secure an income, maintain livestock health and perform daily tasks (Ngigi, 2003). It is possible that downstream users will be in continual competition with upstream users for water, which could potentially result in conflict, due to the serious threat of water security in water scarce countries. Tension could arise between commercial farmers and the subsistence farmers in the area due to the reduction of river flow resulting from the practise of water harvesting. Such conflict will be heightened in dry seasons (low flows) when ephemeral streams and rivers run dry, which is common in sub-Saharan Africa climates (Ngigi, 2003).

In South African water law, there is legislation intended to control such circumstances. A stream flow reduction activity is a form of water use "… [that] ... is likely to reduce the availability of water in a watercourse to the Reserve, to meet international obligations, or to other water users, significantly", based on Chapter 4, Part 4, Section 36 (2) to (3), of the National Water Act, (NWA, 1998). Depending on the scale of expansion, RWH practices have the potential to be deemed a streamflow reduction activity. RWH project does not require an environmental impact assessment, but according to, the National Environmental Management Act of 1998, in the event of widespread use, an initial assessment of the watershed needs to occur. Furthermore, the management of RWH needs to take into account its impact on low flows, as well as equitable share of water resources amongst social, economic and environmental sectors (NWA, 1998; NEMA, 1998; Kahinda and Taigbenu, 2011). Proper management can ensure the efficient functioning and provision of ecosystem goods and services (de Winnaar and Jewitt, 2010). Furthermore, the concept of up-scaled RWH evolving into a streamflow reduction activity under Section 36 of the NWA (1998) has the potential to be contested. This is based on a paper by de

Winnaar and Jewitt (2010), who argue in favor of supplementing irrigation with up-scaled RWH. They argue that RWH alleviates poverty and increases the access to water which is a basic human necessity. They also agree show that relative to an existing, modified landuse, RWH had a negligible impact on downstream users.

Freshwater habitats decline as recharge to them decreases (Ngigi *et al.*, 2003), limiting the number of fish and aquatic organisms breeding in the rivers. Fish are not only a source of food for humans living near rivers, but also to birds of prey and a variety of carnivorous animals within the ecosystem. Microscopic organisms and a variety of soils filter river water, benefiting those who utilize the river as a source of water. In addition, disturbing the hierarchy of aquatic species may result in an over-population of pest species that could be detrimental to agriculture. In order for, certain species to migrate or cross flood plains for breeding or survival, flooding is often a necessity (leRoy Poff *et al.,* 1997). In regions of up-scaled macro-catchment RWH, such as flood diversion harvesting in Tanzania, crucial migratory processes are hindered, disturbing ecological balances. With the potential to decrease streamflow, up-scaled RWH alters a river's ability to act as a transport medium for nutrients and organic material. Water is also a transport medium for pollen, i.e. hydrophily, hence a limiting factor in the pollination process (Ackerman, 2000).

In the case of recreation, aesthetic pleasure and cultural practices, downstream users may be at a disadvantage, especially in drier seasons, when water levels in rivers are substantially lower. Sacred rituals and ceremonies are hindered because landscapes are drier, limiting the amount of resources necessary for sacrificing and worship. These sites are semi-degraded due to the drier conditions that are exacerbated by up-scaled RWH. Contributions to the economy through tourism is reduced, as more land is converted to agriculture due to increased water availability (Balmford *et al.,* 2002).

2.9 How are Impacts on Ecosystem Goods and Services Quantified?

The past 50 years have seen the most drastic changes to ecosystems according to, the MEA (2005). This is largely due to the increased need for water, food, fibre and timber. Human well-being, the economy and climate change are among the many factors that have contributed to the degradation of ecosystems and the exploitation of their goods and services. Rapid population growth has stressed the environment's natural ability to provide necessities (Gleick, 2000). A lack of clear housing policies has contributed to the hasty urbanisation and degradation of land. In these cases basic human rights meet a lack of environmental law enforcement, allowing both agricultural and urban expansion beyond their limits, to provide food and shelter. Advances in technology, transport and trade have increased the consumption and dependence on non-renewable resources, contributing to global warming (Omer, 2008). The severity of climate change can be seen from how sensitive ecosystems fail to adapt to their environments rapidly enough to survive. With the death and extinction of species, so too are the regulating, provisioning and aesthetic functions of our ecosystem lost.

In order to protect the environment from the ongoing evolution of mankind, it is necessary to measure the impact that humans have on the environment, in order to limit or mitigate them in future. Figure 2.4 provides is a framework that describes the link between the economy, society and the environment, which influences the way environmental resilience is measured and managed.

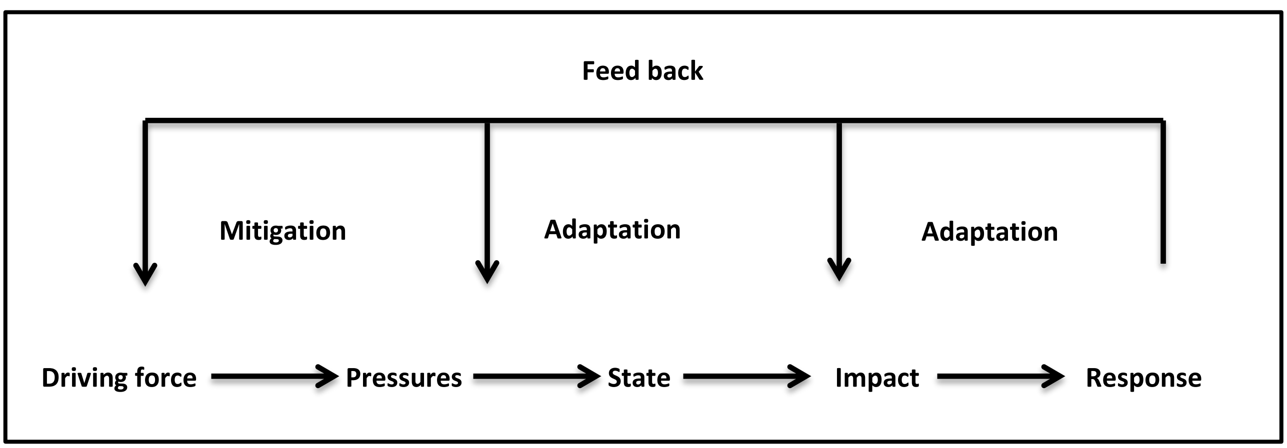


Figure 2.4 Simple conceptual model of interaction within social-economic-environmental systems, highlighting the mitigation and adaptation feedback strategies of management (after McCartney *et al.*, 2000)

Global change factors are the key components (drivers) that place a large amount of pressure on the ecosystem (current-state). The nature and severity of these pressures influences the vulnerability of the ecosystem, which impacts the environment, economy and society. The response of society at large contributes to a feedback mechanism, which can further impact the state of the environment (McCartney *et al.*, 2000). Therefore, it is essential to monitor and incorporate these responses into management strategies (mitigation/adaptation), to ensure and sustain long-term environmental benefits. As an illustration, the exponential growth of the population has placed greater pressure on the agricultural sector to provide food. Currently oceans are being over-fished in order to keep up with the demands. The impact can be seen in more fish species becoming extinct. A mitigating response would ensure that all endangered species be put on a high risk list prohibiting them from being caught. In order to adapt to the current situation, farmers should ensure that the most abundantly found fish is caught and consumed. This promotes sustainability and improves the resilience of the environment.

Environmental benchmarks need to be established for research, the MEA (2005) being an example. Baselines need to be reassessed in order to obtain a realistic understanding of the environment. It is necessary to shift away from natural, pristine environments and move towards including degraded landscapes and urbanisation as an increasingly common reality. Impacts can then be modelled, using various models specific to several facets of the environment. For example, Enfors and Gordon (2007) describe an ecosystem resilience framework, which enables the current state of the ecosystem to be mapped. The framework graphically depicts how a current system deviates from a baseline over time. Figure 2.5a illustrates the condition of a landscape along a trajectory. The environmental management choices shift the landscape towards either a productive or degraded state through what is known as a feedback mechanism. Figure 2.5a illustrates a fairly high production potential. Figure 2.5b shows how social and environmental management strategies can shift thresholds, in order to improve the vulnerability and sustainability of the environment (Enfors and Gordon, 2007). Variable rainfall, incorrect land management, population growth and resource management has pushed the landscape past its threshold, into a degraded state.

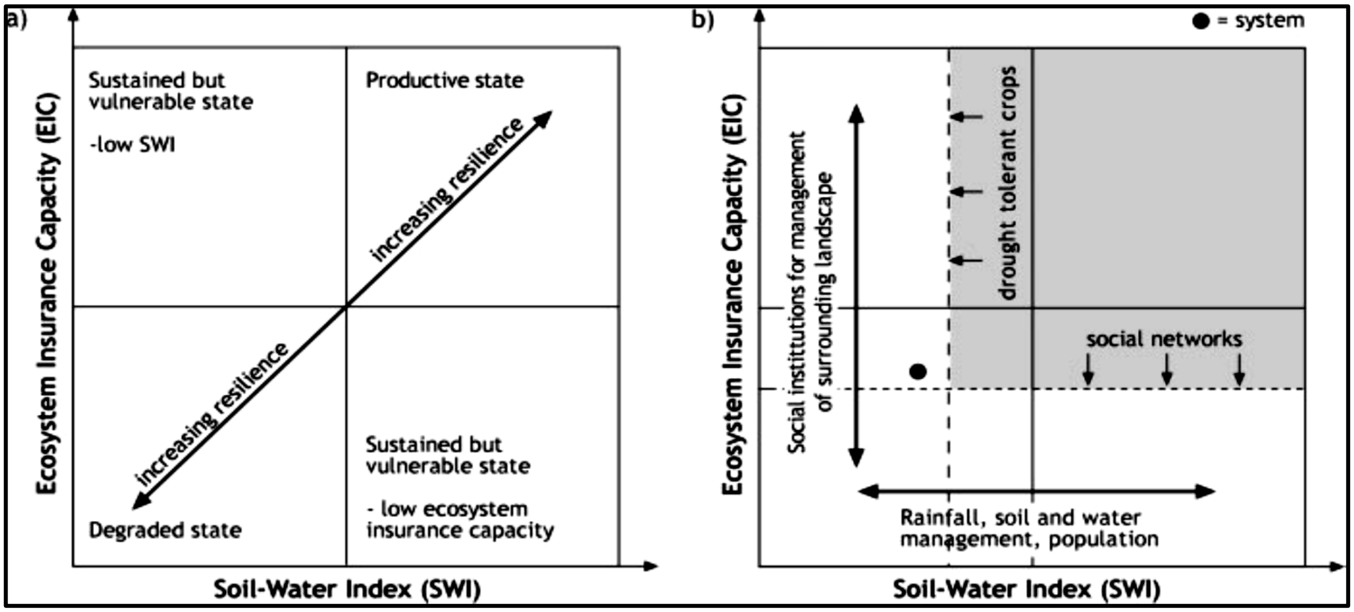


Figure 2.5 Ecosystem resilience framework mapping the productivity of the Makanya Catchment using EIC (capability of the environment to insure provision) and SWI (an indication of moisture in the soil for agricultural productivity) (after Enfors and Gordon, 2007). Figure 2a) shows two stability domains. A productive state as a result of good environmental practises improves ecosystem resilience ensuring continual provision of goods and services. The degraded state shows how mismanagement can cause a decrease in resilience. The feedback response is the inability of the environment to provide goods and services. Environmental thresholds can be shifted by efficiently managing variables such as rainfall, soil, water and populations, as seen in the altered trajectory in 2b).

Figure 2.5 incorporates a framework to showcase the trend in ecosystem resilience over the last 50 years in the Makanya Catchment (Enfors and Gordon, 2007). Soil water was the variable used to determine the state of the ecosystem. Between the 1950's and 2000's, a steep drop in ecosystem capacity was mapped, moving from a productive to a degraded state. Land management practices, i.e. long fallows, were restricted, in order to maximize agriculture to meet the demand from a growing population.

This pressure resulted in reduced soil fertility, encroachment on protected land/natural ecosystems and low crop yields. Taking Figure 2.4; into account (McCartney *et al.,* 2000), the vulnerability can be related to the pressures of global change drivers and societal responses. In order to improve the current state (Figure 2.6), resource management strategies need to be addressed. Soil and water system innovations, such as conservation tillage and RWH can be incorporated to reverse the degradation, thereby increasing ecosystem functioning (capacity). Increased soil moisture from RWH enables farmers to irrigate crops during critical growth stages, safeguards (within reason) crops during dry spells and improves the overall yield. A result of increased soil moisture is the reduction in bare soils. Larger extents of the catchment sprout vegetation preventing the loss of fertile topsoil and further improve the infiltration of rainfall and runoff. This contributes towards improving the productive state of the catchment.

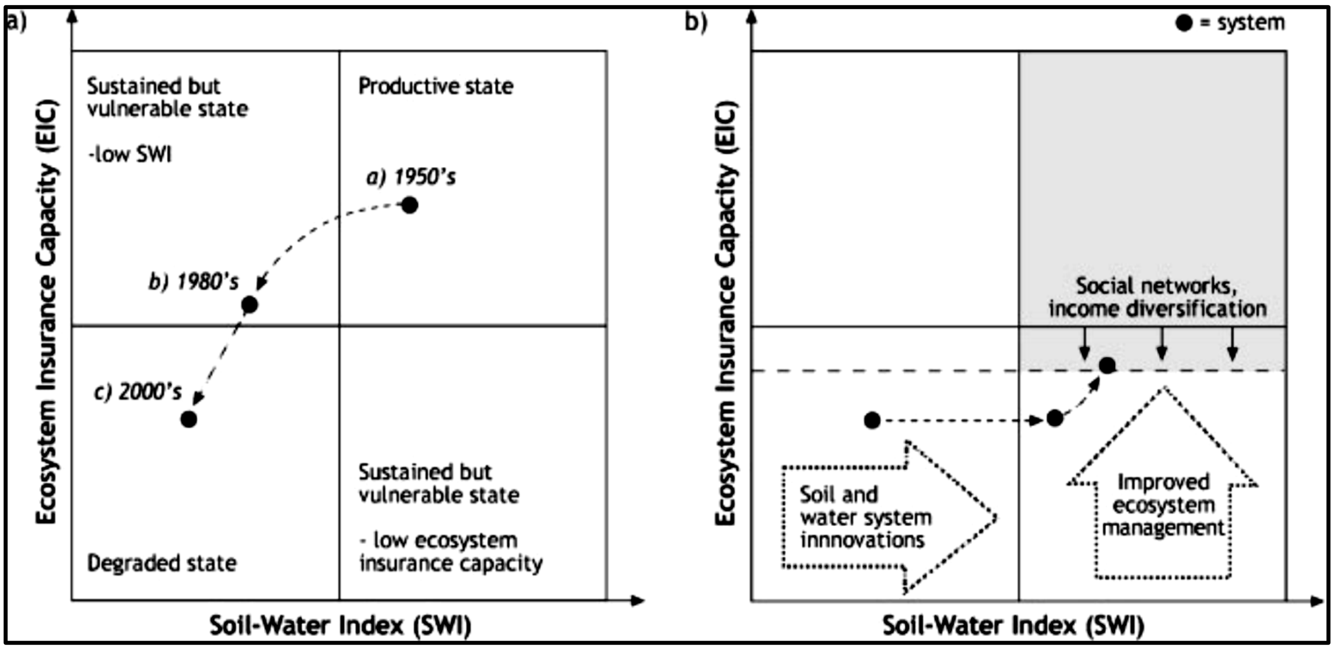


Figure 2.6 Ecosystem resilience framework mapping the productivity and mitigation of the Makanya Catchment (after Enfors and Gordon, 2007)

Indicators of Hydrologic Alteration (Richter *et al.,* 1996), ACRU (Schulze and Smithers, 2003), and statistical ecological modelling (Qian *et al*., 2003) are among the models suggested to assist in determining environmental impacts. The ACRU model in particular, is a multi-layer soil water budget that offers the user the opportunity to model the impacts of soil moisture on crop yields, which can be useful in understanding how soil and water innovation systems can be used as conservation tools within an ecosystem. The use of remote sensing, orthophoto's and Geographic Information Systems (Chen *et al*., 2009) allows an efficient desktop analysis of any changes in catchment over a period of time. The above-mentioned methods require a certain degree of data acquisition, which is essential in developing a long-term data record for effective ecosystem monitoring.

2.10 Conclusion

As highlighted, the impacts of up-scaled RWH have both positive and negative implications. Essentially, individual households have access to water, which directly influences the quality and quantity of their crop yields. This, however, may impact the environment, as many ecosystem goods and services are closely linked to water resources. More often, regions where RWH expansion is considered are already degraded due to dense population, overgrazing, erosion and compaction attributed to rural settlements and agriculture. Degraded areas will be placed under further pressure from the negative impacts of RWH, known as the feedback response. For instance, increased soil moisture could promote water-logging and increase soil erosion. Instead of limiting the loss of fertile topsoil, large amounts of soil are washed away. Further up-scaling will be limited or stopped altogether, as a result. Nutrients are diluted due excess water and the soil's ability to act as a carbon sink decreases. Up-scaling RWH could be ineffective, as streamflows decrease and the quality of the remaining water is poor, when wetlands reach their thresholds. More water may not always be the solution, as it increases water-logged areas, acts as a breeding ground for pests and disease and hinders plant growth.

It is essential that the limit to up-scaling be realised (Ngigi, 2003), in order to prevent the degradation to indispensable ecosystem goods and services. As a result, the main focus of Chapter 3 aims to understand the consequences of up-scaled RWH. The impacts on streamflow and soil moisture are vital to recognizing the influence that RWH has socially and environmentally, as they are the foundation for food production and survival of rural communities. A scenario-based, modelling approach to harvesting rainwater and maize production would allow these consequences to be simulated and understood. Thereafter, mitigation/adaption can be incorporated into a response strategy, in order to efficiently manage this integrated system of stakeholders. Therefore, RWH thresholds will be investigated in order to sustainably alleviate poverty in rural sub-Saharan Africa, whilst protecting the integrity of the ecosystem and its goods and services.

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3. DETERMINING THE IMPACTS OF UP-SCALED RAINWATER HARVESTING ON ENVIRONMENTAL RESPONSES IN THE POTSHINI AND MAKANYA CATCHMENTS

Abstract

Rainwater harvesting (RWH) has the potential to improve rural livelihoods by increasing the yield of subsistence farming. When stored water is made available to crops during critical growth stages, it decreases the chance of low yields. This may well be the key driver to up-scaling RWH in rural communities. This project aims to understand the environmental responses to up-scaled RWH and the limits beyond which the uptake cannot be sustained.

Two rural catchments, dependent on RWH as a form of irrigation were selected for this project namely, the Makanya Catchment (300km^2) in Tanzania and the Potshini Catchment (1.2km^2) in KwaZulu-Natal. The objectives were to simulate daily streamflow (the simulation period from 1952 through 2007) using the ACRU model and accurately represent the impacts of abstractions caused by RWH. A scenario-based approach was used to illustrate how varying degrees of RWH influenced streamflow and soil moisture. Each scenario up-scaled RWH by 30% of the current, total RWH in each catchment i.e. 30%, 60% and 90%. Runoff generated from hardened land surfaces flowed into a storage dam, representative of the current volume of harvested water. Each scenario was simulated in both wet and dries seasons.

Under maximum RWH (+90%), ACRU outputs indicated a gradual decrease in streamflow by 50% and 30% in the Makanya and Potshini Catchments, respectively. Low-flows, in the driest months were the most effected based on the 10th and 90th percentile indicators. The reduction in streamflow was deemed significant for all up-scaled RWH scenarios in the Makanya Catchment and RWH greater than 60% in the Potshini Catchment, at a 95% confidence interval. In an effort to understand the relationship between RWH and soil water content, soil moisture was modelled based on three different scenarios namely; minimum, current and an unlimited water supply. A proportional relationship was noticeable whereby; an increase in RWH resulted in an increase in soil moisture.

The significant impact of RWH in the Makanya Catchment can be attributed to an erratic rainfall regime providing for a large catchment area. It's low mean annual precipitation (MAP) (200-400 mm/year), variable rainfall and a high population density increase the pressure placed on the environment to provide ecosystem goods and services. RWH is intensely practised in this catchment already, which could be the reason why additional up-scaling has a significant impact. Increased amounts of RWH increase the pressure on an already sensitive environment. Potshini is less vulnerable due to its higher MAP, smaller catchment area and lower population density. Due to the immediate response of improving soil moisture, RWH can also be recognized as a mitigating measure to offset downstream streamflow reductions. Utilizing soil and water innovations such as RWH supports efficient ecosystem management, with its benefits noticeable in the productive state of the environment as well as improved food security.

Keywords: Up-scaled rainwater harvesting, ACRU, streamflow

3.1 Introduction

Rainfed agriculture is the basis of rural livelihoods in sub-Saharan Africa, with 90% of the staple food production being cultivated amongst the poor communities, who are highly sensitive to changes in the ecosystem (Cooper *et al.,* 2008). Governments in the region have promoted the shift from a centralized water management approach to a more decentralized IWRM approach, which is generally supportive of alternate water supply methods (Ngigi, 2003; Vohland and Barry, 2009). RWH is such a technique, which enables sustainable resource consumption and focusses on rural agriculture, with the intention of decreasing vulnerability to climate change and population growth (Kahinda *et al.,* 2007; Rockström *et al.,* 2010; Gupta, 2011). However, a large gap in knowledge exists, regarding the impacts of RWH on streamflow and associated ecosystem goods and services, because much attention has been traditionally placed on dam and reservoir construction for water storage (Ngigi, 2003; van der Zaag and Gupta, 2008). A wealth of information is available on the impacts of large dams on streamflow and ecosystems, as large-scale water storage developments are typically the preferred solution to water shortage issues. For example, after the introduction of the National Environmental Management Act (NEMA) (1998) in South Africa, the construction of a dam above a certain size needs the approval of an environmental assessment committee. One outcome of this is the consideration of innovative ideas regarding small-scale water storage, such as RWH. The mismanagement of the ecosystem affects both societal and environmental benefactors, leading to increased water security threats (Gleick, 2000). In water stressed regions, a conflict can easily be provoked by any factor that increases their vulnerability to water, hence it is imperative that these impacts be realised, in order to reduce “upstream-downstream” conflicts (local and trans-boundary) and to capitalize on the contributions made by the environment, on which most of nature and society depend (Taylor, 2006). Research into these innovative practices supports efficient water resources management.

As the population grows, more and more people are becoming dependent on RWH; however, little is known about its up-scaled impacts (Gleick, 2000; Ngigi, 2003; van der Zaag and Gupta, 2008). Despite the contributions of de Winnaar and Jewitt (2010) and Andresson et al., 2011 and 2015, literature still lacks practical examples of the limits to large-scale RWH and its immediate consequences (Kumar *et al.,* 2006). The same can be said for the environment’s ability to sustain up-scaled RWH for long periods of time, as well as future consequences resulting from environmental feedbacks. Essentially, for an environment to support RWH, it has to meet a number of prerequisites, and this has been the focus of many scientists through suitability mapping, GIS and remote sensing (Kahinda *et al.*, 2009). The crucial unknown is the environment's ability, in its current state, to provide opportunities for RWH and its ability to sustain large-scale uptake, thereof. Arguably, a pristine environment offers optimal goods and services. Water supply and regulation, including the purification and maintenance of natural flows, disturbance control, which buffers the impact of natural disasters, such as floods, as well as soil retention and formation for crop development, are essential services that are limited by the state of the environment, as shown in Table 2.2 (*cf. Section 2.7*). The addition of RWH has the potential to supplement and improve the provision of these services, but the limits to up-scaling need to be determined. A system will reach its threshold when a force or action pushes the system past its normal state of operation and from which it cannot easily recover (Lenton *et al.*, 2008). In the context on IWRM, determining this threshold or tipping point is a proactive approach, which ensures equity amongst all users. It would be ideal if it could be anticipated when a system will reach its threshold, so that early warning systems can be implemented and the chance of irreversible harm can be reduced.

This paper aims to explore the potential impacts of up-scaled RWH utilizing the Agricultural Catchments Research Unit (ACRU) hydrological model. Various scenarios based on varying degrees of RWH are run, in order to determine the impacts on streamflow and ecosystem functions. A statistical analysis thereafter, determines the significance of the result.

The Makanya and Potshini Catchments have been incorporated into research conducted by the Smallholder System Innovations in Integrated Watershed Management (SSI) programme. Thus far, issues concerning the increase of food production, the improvement of livelihoods and the safeguarding of the environment have been addressed (Rockström *et al.*, 2004, Bhatt *et al.*, 2006). IWRM approaches, such as RWH, were incorporated into previous research, with the aim of better understanding the impacts on ecosystem functions. The Makanya Catchment, situated in the Pangani River Basin in Tanzania, utilizes macro-dam and spate irrigation, a form of flood water harvesting, whilst the Potshini Catchment, located in the Thukela River Basin in South

Africa, employs rooftop and ground water harvesting. Therefore, continuing the theme of smallholder water system innovations, both catchments were utilized as a part of the WHaTeR EU Project (www.whater.eu). Each catchment is hydrologically modelled using the Agricultural Catchments Research Unit (ACRU) Model. Herein, an adjacent impervious area captures and conveys rainfall and runoff to a dam representing a RWH storage structure. Thereafter, varying degrees of up-scaled RWH was utilized to understand the impact on streamflow and soil moisture and the effects on the environment. The up-scaling of RWH increased by 30% to 90% of the current RWH in each scenario. The threshold used to determine the impact on ecosystem goods and services depended on the success of a maize crop, under the condition of RWH providing the minimum amount of water necessary for maize to survive.

3.2 Methodology

The following section consists of site descriptions of the Makanya and Potshini Catchments, as well as the methods and materials used in determining the impact on ecosystem goods and services.

3.2.1 Study area

Two catchments were selected for the purpose of this study, namely, the Makanya Catchment in Tanzania and the Potshini Catchment in South Africa.

3.2.1.1 The Makanya Catchment

Located in the mid-to-upper reaches of the Pangani River Basin in Tanzania, and represented by semi-arid to dry humid conditions, the Makanya Catchment (4°21′32,34″S 37°49′19,35″E), is found nestled in the South Pare Mountains (Rockström *et al.*, 2004). Four main tributaries flow within the catchment and drain into the Makanya River, which drains into the larger Pangani River, exiting the river basin into the Indian Ocean. The Makanya Catchment covers an area of roughly 300 km^2, with altitudes varying between 600-2000 masl (Mul, 2009). The landscape is dominated by natural forest, wooded grassland and shrubs in the higher altitudes, whilst thickets, wooded grass and shrub-lands populate the lower regions (Mzirai and Tumbo, 2010). Soils in the area are of folded and weathered metamorphic igneous rock. Continual weathering shows layers of meta-sedimentary and meta-igneous rock, similar to the granite soils in the Mozambican belt (Mul, 2009). The average rainfall for this water-scarce country ranges from 400-800 mm/a, varying with season and altitude. Rainfall is bimodal, with heavier rains occurring from March to June, locally known as the *Masika*, whilst the shorter season, referred to as the *Vuli*, occurs between October and December (Makurira *et al.*, 2009).

Between 35000 and 40000 people have settled in the lower reaches of the Makanya Catchment (Enfors *et al.*, 2008) (see Figure 3.1). Ecosystem goods and services, especially provisioning and regulating services, drive the livelihood activities within the catchment. The provision of water for RWH and the regulation of nutrient and soil processes for agriculture, work together to benefit those living within the catchment. Subsistence farming is the predominant form of livelihood, with maize and legumes being the main source of food. Cattle, sheep and goats are also kept within the homesteads (Pachpute *et al.*, 2009). The catchment has a well-established RWH network that has been in operation for centuries (Mbilinyi *et al.*, 2005). Flood water is diverted through distribution canals, where needed, primarily for the purpose of irrigation. The Makanya Catchment is ideally suited for the nature of this study, as villagers are directly dependent on macro-catchment RWH for the irrigation of crops. Communities within the catchment rely heavily on the harvested water for daily operations. Large portions of the catchment are degraded, due to continual agricultural expansion, frequent dry spells and intensive population growth over the past 50 years, causing the landscape to move towards an increasingly degraded state (Enfors and Gordon, 2007). Degradation is also the result on the migration of pastoral communities from other heavily degraded lands such as the maasailand.

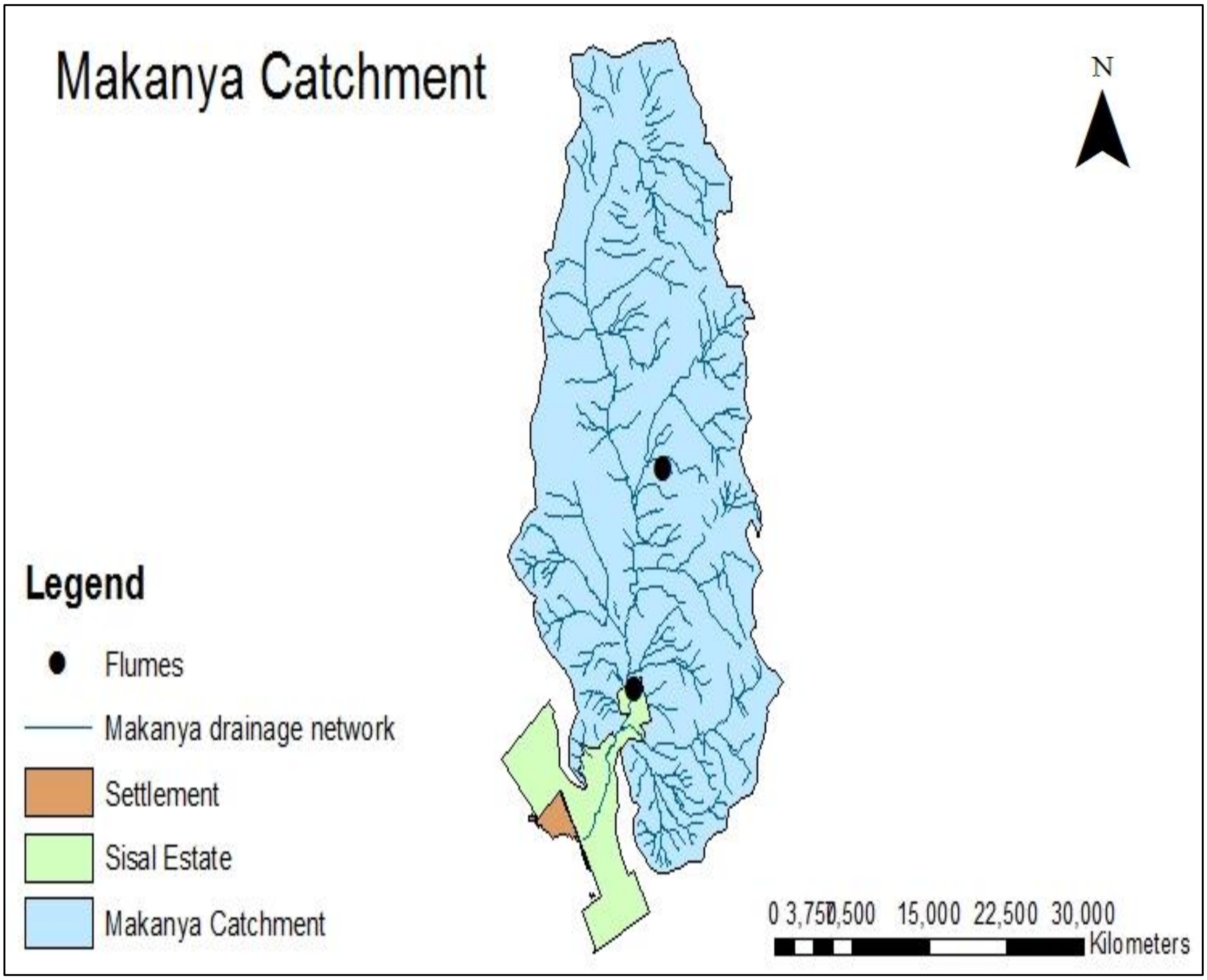

Figure 3.1 Location of the Makanya Catchment and overview of sub-catchment components

3.2.1.2 The Potshini Catchment

The Drakensberg Mountains form the headwaters of the Potshini Catchment (29.37°E, 28.82°S) and are located in the Bergville region of the Thukela River Basin in KwaZulu-Natal (Kongo and Jewitt, 2006). The Lindequespruit is the main tributary that drains the catchment, eventually flowing into the Thukela River. The Potshini Catchment falls within the Emmaus quaternary catchment (V13D) and has an area of 1.2 km^2 and an average altitude of 1250 masl. Soils are of an acidic nature, where sandstone and mudstone are most common, originating from the

Tarkastad Formation, Beaufort Group, and shale and sandstone from the Estcourt Formation, Beaufort Group (Kongo and Jewitt, 2006). Grasslands, burnt annually, are the common vegetation type found within the Potshini Catchment. Precipitation occurs in the form of thundershowers in the summer months, between November and March (unimodal rainfall regime), at an average of 700 mm/a (de Winnaar *et al.*, 2007).

Smallholder subsistence farming and grazing (goats and cattle) are the dominant landuses, allowing rural communities to farm maize and soya bean to maintain their livelihoods. Roof and ground water catchments are used for harvesting water within the catchment, which was one of the focal research components of the Smallholder System Innovation (SSI) study (Rockström *et al.*, 2004; Bhatt *et al.,* 2006). The basis of that project was to understand water flows and land management practices, such as water harvesting, in order to intensify such practices and to supplement irrigation, without hindering downstream functions, and to determine its impact on ecosystem functions (Kosgei *et al.,* 2007). Research by Malinga *et al.* (2013) indicates that provisioning services of the ecosystem, such as food and water, are prioritized in an agricultural landscape, and they are therefore the basis of this study.

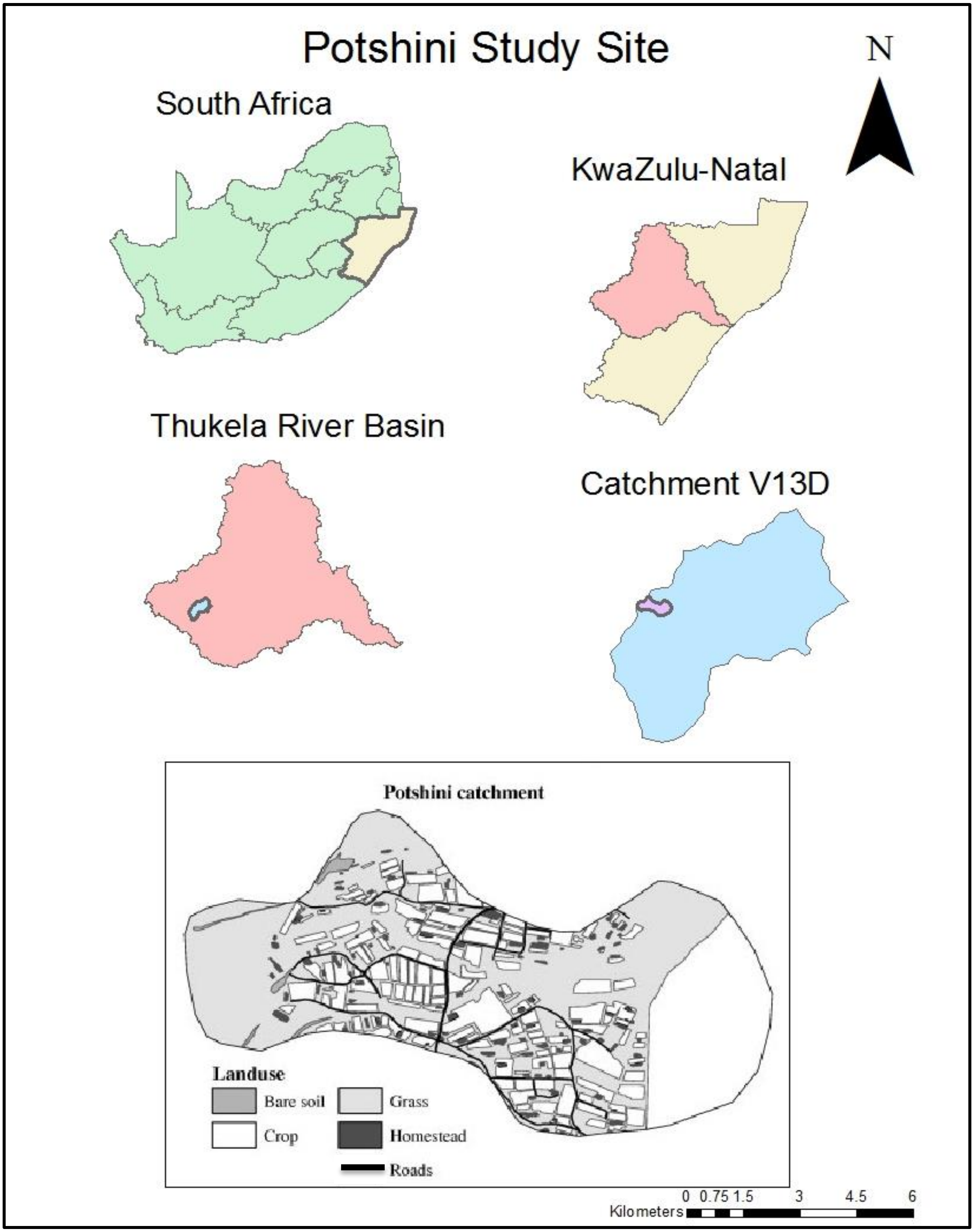

Figure 3.2 Location of the Potshini Catchment and overview of sub-catchment components, (after de Winnaar *et al.*, 2007)

3.2.2 Modelling with ACRU

The ACRU Model (Schulze and Smithers, 2003) is a daily time-step, physical, conceptual, multi-purpose model which was utilized for the purpose of modelling catchment hydrology in the Potshini and Makanya Catchments, following a similar configuration as in de Winnaar and Jewitt (2010). The ACRU Model is an agro-hydrological model sensitive to changes in the landscape (management), allowing the state of environmental goods and services to be represented. The model also incorporates a multi-layer soil water budget, which is necessary when considering RWH as a soil water conservation practice. Although ACRU does not directly account for RWH, its ability to simulate runoff allows the model to be adapted for this study. The ACRU Model has diverse applications and was successfully used as the modelling tool in related studies (de Winnaar and Jewitt, 2010; Warburton *et al.*, 2012). For this study, a virtual dam is included in the model configuration to represent RWH storage in both catchments. Runoff is harvested off an impervious land area (adjunct impervious) and stored in the dam under conditions of minimal evaporation and seepage, mimicking RWH tanks and canals, assumed to be in good condition. From here, water can be diverted for scheduled irrigation. Figure 3.3 gives a systematic overview of the model structure. See the Appendix for details on model configuration.

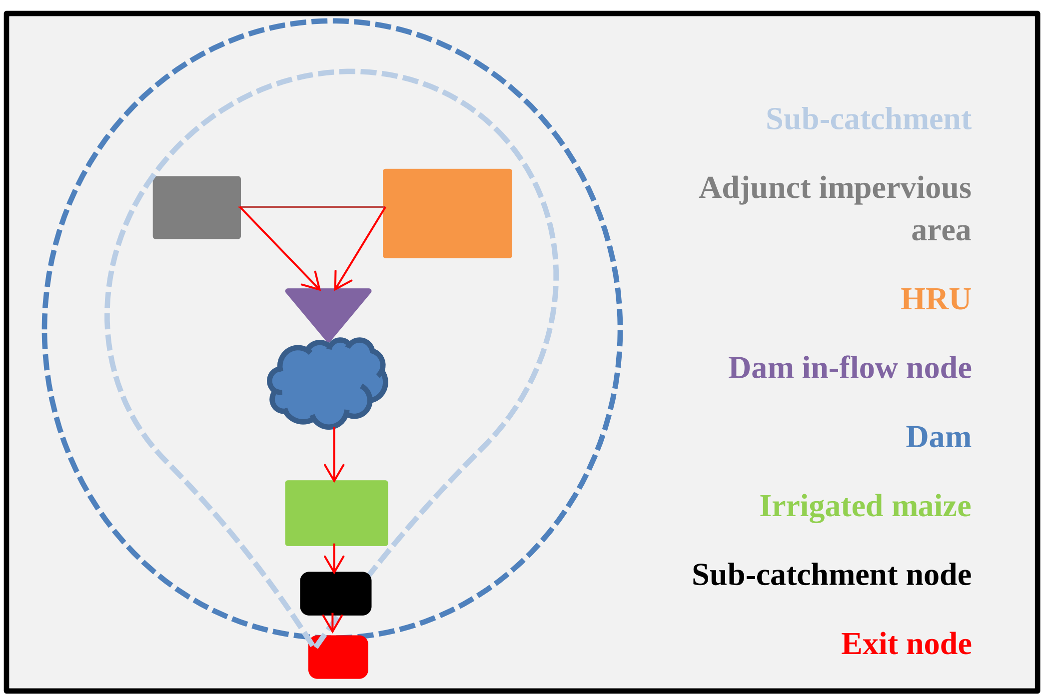

Figure 3.3 Systematic ACRU configurations for the Makanya and Potshini Catchments

3.2.3 Data inputs

Data for the Makanya Catchment have been acquired from ongoing research at the Stockholm Environment Institute under the WHaTER project, which added to the dataset developed under the aforementioned SSI project. This included a variety of parameters, such as daily rainfall, streamflow and landuse. Further input data, such as soils data, temperature and evaporation, were sourced from journal papers, past research projects and national GIS databases at the University of KwaZulu-Natal (Bhatt *et al.*, 2006). Research by Mul (2009) also contributed many parameters for this study.

Climate data for the Potshini Catchment, such as rainfall, streamflow, landcover and soil information, were readily available on the GIS national database at the University on KwaZulu-Natal, as well as from previous studies conducted in the catchment (Bhatt *et al.*, 2006; de Winnaar *et al*., 2007). Climate files containing daily rainfall, streamflow and temperature were created and linked to the ACRU Model. For the purpose of this project, rainfall and streamflow data was patched based on a visual inspection and the nearest neighbour method.

The length of the rainfall record acquired for both catchments was insufficient. Therefore, the Stochastic Climate Library Ver 2.2, containing a climate generation model, was used to generate a representative stochastic, daily rainfall record of 56 years for each catchment. The longer rainfall record improves the generation of simulated streamflow, facilitating easier trend detection. Stochastic data also decreases the uncertainty associated with short climate records and climate variability, by generating data based on historical records (SCL, 2007). See Siriwardena and Srikanthan (2002), Zhou *et al.* (2002) and Siriwardena *et al.* (2002) for details on stochastic daily rainfall generation.

3.2.4 Approach

A scenario-based approach was adopted in each catchment, allowing a systematic method for understanding uncertainties and researching complex, future outcomes (Malinga *et al.*, 2013). Each scenario is based on current conditions, factored in with future possibilities (Enfors *et al.*, 2008). The thought behind scenario-planning is that it highlights possible relationships between the environment and the management approach taken. This will enable informed decision-making, in order to limit ecological destruction in areas, where communities are highly dependent on the environment for survival, which is particularly important in this study.

RWH scenarios of 30%, 60% and 90% increase, as described in Table 3.1, were simulated for the Makanya and Potshini Catchments, in order to determine its impacts on streamflow and related ecosystem goods and services. Each catchment was configured to contain an adjunct impervious area, representing the runoff generation regions within the catchment, a dam which stores rainfall and runoff, representing a RWH storage system, and an irrigated area, containing subsistence maize and natural vegetation (see Tables 3.2 and 3.3). A baseline scenario mimicked a pristine environment. In order to understand the catchment's natural behaviour, no storage, agriculture or impervious areas were included in the baseline. Current conditions within the catchments, which include RWH and maize production, are also represented as a scenario (see Table 3.2, Run 2). For the purpose of this study, it is assumed that water was the only limit to plant growth. In the context of this study, up-scaling refers to an increase in the capture and storage of water by RWH. Thus, in each up-scaled run within ACRU, the capacity of the dam was increased. In addition, the size of the irrigated area needs to increase in order to correctly mimic the expansion of agriculture under improved water availability conditions. Conversely, to remain within the actual catchment boundary, the area of the grassland/bush thicket was decreased accordingly. For instance, Run 3 (Table 3.1) includes a hydrologic resource unit (HRU) (an area of natural vegetation), an impervious area and with 30% more RWH and maize than Run 2 (i.e. 130%). Up-scaling was capped at 90% (almost double), in order to realistically model both catchments by remaining within their boundaries. In order to determine the effect of RWH on soil moisture, each Run outputted soil moisture based on conditions of minimum, current and an unlimited supply of harvested (irrigation) water. Irrigation under minimum, current and unlimited water supply corresponds to minimum, current and up-scaled RWH conditions. The irrigation cycle within the ACRU Model was configured to apply 5 mm of water every 5 days for 5 months. In doing so, an indication of the impact of RWH on streamflow and soil moisture could be realised. Apart from its impact on the water supply, the impact on other ecosystem goods and services, such as disturbance control, water regulation, natural habitat and breeding grounds, food production, soil retention and formation and the overall aesthetic value, can also be identified *(cf. Section 2.7, Table 2.2).*

Table 3.1 Scenario descriptions for up-scaling

Runs	Scenario
Baseline	HRU land type (Thicket and bushland - Makanya/ grassland #64 Acocks - Potshini)
1	HRU, impervious areas, no storage
2	HRU, impervious areas, current storage (RWH) and irrigated maize
3	HRU, impervious areas, 30% up-scaled storage and irrigated maize
4	HRU, impervious areas, 60% up-scaled storage and irrigated maize
5	HRU, impervious areas, 90% up-scaled storage and irrigated maize

The baseline for storage in the Potshini Catchment was the number of tanks per household. Located at each of the 40 homesteads are 4x5000l tanks, which cumulatively equates to 800m^3, the initial dam capacity. Google Earth was used to estimate the size of the impervious region, by calculating the average impervious area per household and multiplying it by the average number of homesteads within the catchment. Data derived from Mul (2009) were used as a guideline to model the RWH in Makanya. A total of 75 micro-dams have been identified in the area (Makurira *et al.,* 2007; Mul, 2009). On average, a dam of 1620 m^3 can irrigate an area ranging from 2 ha – 400 ha. By, multiplying the number of dams by the average size of the dam, an initial dam capacity of 120000 m^3 was applied. Based on land classification maps, impervious regions were represented by the amount of degraded land in the catchment. The maize and grassland were then proportionally allocated sizes.

Table 3.2 Up-scaled scenario inputs for the Makanya Catchment

(Km^2)	**Baseline**	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
Catchment area	300	300	300	300	300	300
Adjacent impervious area	-	150	150	150	150	150
Dam surface area	-	-	0.12	0.156	0.192	0.228
Dam (m^3)	-	-	120000	156000	192000	228000
Irrigated maize	-	-	49	63.7	78.4	93.1
HRU (bush/thicket)	300	150	100.88	86.14	71.42	56.67

Table 3.3 Up-scaled scenario inputs for the Potshini

(Km^2)	Baseline	Run 1	Run 2	Run 3	Run 4	Run 5
Catchment area	1.2	1.2	1.2	1.2	1.2	1.2
Adjacent impervious area	-	0.14	0.14	0.14	0.14	0.14
Dam area	-	-	0.0008	0.001	0.002	0.007
Dam (m^3)	-	-	800	1040	1280	1520
Irrigated maize	-	-	0.15	0.19	0.24	0.28
HRU (grassland)	1.2	1.07	0.91	0.87	0.82	0.78

The simulations were run over the 56 year study period, for both the wet and dry seasons (summer versus winter), to determine the impacts of RWH on high-flows and low-flows and to illustrate the impacts within a season. In order to determine how the catchment has been affected, a number of output indicators within ACRU were selected. Simulated streamflow, dam storage, soil moisture and crop yield were among the outputs to consider, with respect to ecosystem functioning.

The provision of water is seen as one of the most important variables linked to the provision of ecosystem goods and services (FAO, 2000; Jewitt, 2002). Streamflow is a significant aspect of the hydrological cycle, impacting water supply and water regulation. Not only would water quantity be influenced, but also the quality and timing of floods and droughts. Natural filtration and purification of water is an essential process, especially for people relying directly on river systems for water. Altered flows influence the efficiency of natural purification (i.e. dilution) processes. A change in water quantity impacts the amount of water available for irrigation, as well as nutrients available for uptake, thus impacting on crop yields and ultimately livelihoods. The manipulation of natural flows also affects seasonal flow patterns and flood pulses (Reinfelds *et al.*, 2006). This in turn impacts sensitive species that are reliant on specific flow regimes for reproduction and migration.

Changes in streamflow may also limit species diversity and survival as habitats within the ecosystem are altered *(cf. Section 2.7, Table 2.2).* As a result, the ability to hunt and gather food is affected. These outputs are best suited, as they directly influence the standard of daily living amongst rural communities. In addition, streamflow availability is a concern facing both countries, limiting RWH expansion.

In order to, interpret the findings of this study, a limit is required, for up-scaling purposes. As an indicator, simulated catchment streamflow was selected. Streamflow is a limiting variable, in terms of crop yields, as a particular amount of water must be harvested to irrigate and maintain a plot of maize. The FAO (2015) stipulates that *zea mays* typically requires 500-800 mm of water per growing season, yielding an average of 1.6 kg/m^3 of maize. According to Zwart and Bastiaanssen (2004), the agricultural production of maize can be maintained by using 20-40% less water and yielding 1.8 kg/m^3. Furthermore, according to Evans (*et al.*, 1997) a reduction in soil moisture between 20%-40% in an agricultural ecosystem has the potential to reduce plant biomass by 10%-25%. Such a reduction can adversely affect crop yields and species diversity (Heywood, 1995; Evans *et al.*, 1997; Walsh and Rowe, 2001; Pimentel, 2006). The tipping point for the degree to which RWH can be practised in the Makanya and Potshini Catchments was therefore set at a 40% reduction in streamflow, based on the median value for the driest month.

Potential crop failures are higher beyond a 40% reduction in streamflow. This increases the community's vulnerability to poverty and food insecurity, thereby threatening daily survival. Larger efforts would be made to capture and store water for irrigation, hence reducing the amount of water available for the environment. According to (Arthington *et al.*, 2005; Hamilton *et al.*, 2005; Arthington *et al.*, 2006; Bunn *et al.*, 2006), extracting or reducing a rivers annual discharge by a third to a half, will indeed change the natural timing and flow variations, vital for ecosystem functions. Acute ecological impact and dewatering of streams and rivers are a result of streamflow reductions at this threshold. In the absence of site-specific ecological data, the general "rule of thumb" based on Cullen (2001), i.e. a 40% reduction, is accepted to provide protection for ecosystem functions and ultimately improve management of the environment. A reduction in streamflow and soil moisture beyond a 40% limit has the potential to create to an imbalance in the provision of ecosystem goods and services. Should a reduction of greater than 40% occur, an assessment on ecosystem goods and services is necessary, in order to safeguard sensitive facets within the environment, as the potential for harm is greater. Whilst modelling environmental thresholds can assist in understanding environmental responses, they cannot be accurately predicted. The uncertainty related to the assumptions made in this approach to modelling streamflow is acknowledged and requires further research to improve the outcome.

Services, such as water supply and regulation, are impacted by RWH uptake. Less amounts of water are available for downstream irrigation. This, in turn, impacts the amount of water that infiltrates through the soil to the root zones of crops. This, together with soil crusting, restricts the emergence of seedlings in the initial stages of crop growth (Constantin *et al.*, 2015). The loss of fertile top-soil, by means of erosion, hinders the potential of maximum crop yields, placing added pressure on the environment to provide food. Fishing, hunting and gathering are also reduced, due to the lack of water to sustain life-cycles (see Table 2.2).

3.2.5 Statistical analysis

As a result of the reduction in streamflow, a potential limit to up-scaling RWH can be determined. In addition to determining the threshold, streamflow will be analysed in terms of the statistically-determined 10^{th} and 90^{th} percentiles. This enables a comparative analysis of wet and dry seasons, and similarly, high and low-flows. Lastly, a t-test is applied to test the significance of the difference. The percent difference in soil moisture is calculated and graphs are used to illustrate the effect on crop yields.

The pristine environment has been significantly modified over the past five decades in the Makanya Catchment, transforming much of the natural forests and grasslands into compacted, impervious regions (Enfors and Gordon, 2007). Comparing the pristine catchment against a scenario containing RWH, will show a positive increase in streamflow, as a result of this degradation. While this may be theoretically true, it may not be the most effective may of illustrating the impacts of RWH (RWH not in isolation). In order to effectively portray the significance of this impact, Run 2 will be used as the basis for statistical analysis *(cf. Section 1.2).*

3.3 Results

The results for each catchment are reported separately, which will be followed by a comparative analysis of both catchments. These results include cumulative streamflow, whereby the 10^{th} and 90^{th} percentile values, median threshold and t-test were analysed, followed by soil moisture and crop yield illustrations.

3.3.1 Makanya Catchment

Streamflow is mainly used for the domestic and irrigation of crops, such as maize and cassava. Water is diverted further to irrigate sisal plantations.

3.3.1.1 Cumulative streamflow

To test the streamflow response to RWH, the simulated streamflow output for the 56-year stochastic rainfall record from ACRU, was plotted in a cumulative graph (see Figure 3.4), illustrating the daily cumulative streamflow for the Makanya Catchment. For the study period, the baseline scenario yielded the least streamflow of 9760 mm. Run 1 (under maximum impervious areas, no storage, no maize production – see Table 3.1) yielded the greatest streamflow of 23404 mm. Streamflow in Run 2, under current RWH conditions, is less than that of Run 1, at 22284 mm over the entire study period. As seen in Figure 3.4, a gradual decrease in streamflow is noticeable with each up-scaled scenario. However, this response is non-linear. Runs 3, 4 and 5 yielded 19869, 19275, and 18736 mm, respectively. An overall reduction of 3548 mm was estimated between the current RWH scenario and the 90% up-scaled scenario over the study period.

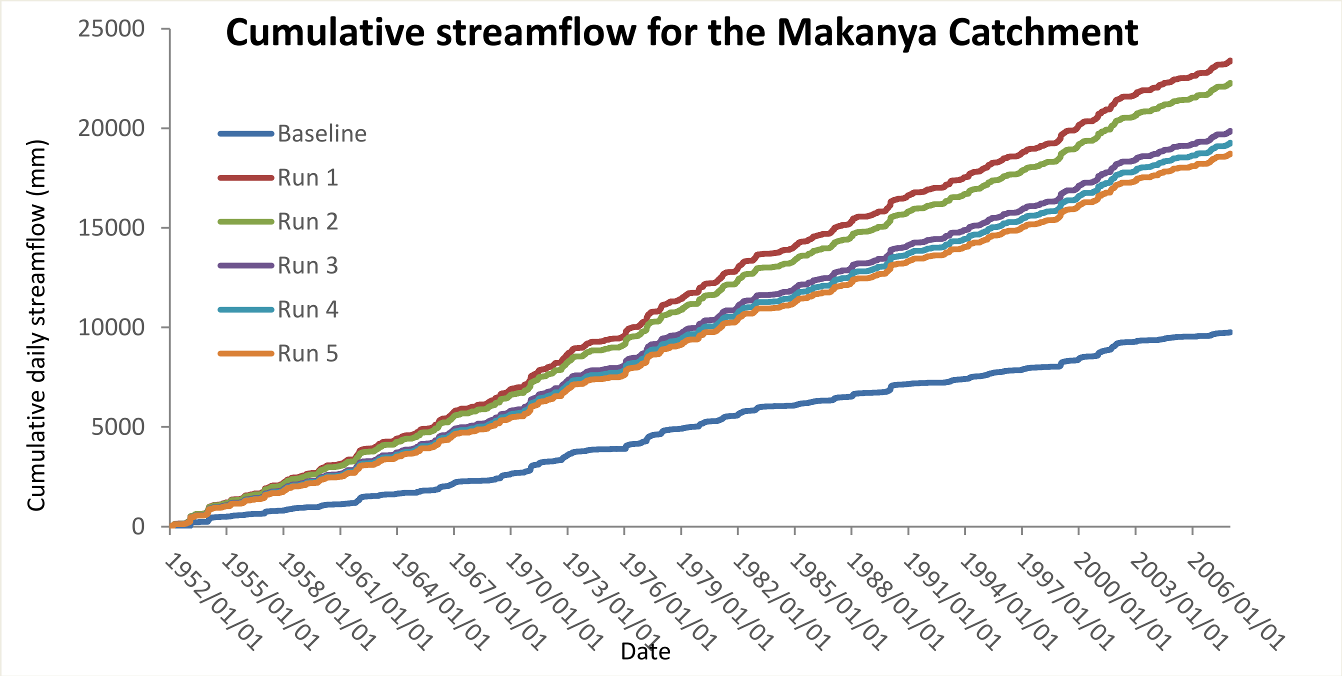

Figure 3.4 Cumulative daily streamflow within the Makanya Catchment

3.3.1.1.1 Impact on high and low flows

The 10th and 90th percentiles represent the statistically-determined low and high streamflow values, respectively. The 50th percentile value (i.e. the median) is also included, in order to understand how the catchments respond 50% of the time. The baseline has the smallest 10th, 50th and 90th percentile values for both wet and dry seasons, as seen in Table 3.4. As expected, Run 1, comprising primarily of an impervious region and no storage or maize production, generated the highest percentile values. As a result of no water storage occurring in this scenario, a larger amount of runoff contributed to streamflow. Overall, flow values are seen to decrease with up-scaled RWH. The 10th percentile value for December under current RWH is 7.3 mm (for Run 2), 6.7 mm for Run 3, 6.5 mm for Run 4 and 6.4 mm for Run 5. The same decreasing tendency is noticeable at the 50th and 90th percentiles for March and September. Streamflow decreases from December through to September, as seasonal rains subside. This can be seen in Run 2, where low flow values of 7.3 mm, 6.6 mm and 0.4 mm were recorded for December, March and September, respectively. The greatest impact of RWH can be seen in dry months, such as September, where low flows are substantially small (see Figure 3.5). Similarly, as seen in Figure 3.6, the baseflow is also reduced to zero mm in drier months, which can be attributed to the extreme climatic conditions of the region.

Table 3.4 Percentile values reflecting high and low-flows for the Makanya Catchment

	Dec (Wet)			Mar (Wet)			Sept (Dry)		
Percentile	**10th**	**50th**	**90th**	**10th**	**50th**	**90th**	**10th**	**50th**	**90th**
Baseline	1.9	0.3	0.1	1.7	0.4	0.1	0.4	0.1	0
Run 1	7.6	0.5	0	6.7	0.3	0	0.8	0.5	0
Run 2	7.3	0.3	0	6.6	0.2	0	0.6	0.4	0
Run 3	6.7	0.1	0	5.9	0.1	0	0.5	0.3	0
Run 4	6.5	0	0	5.7	0	0	0.4	0.3	0
Run 5	6.4	0	0	5.5	0	0	0.3	0.2	0

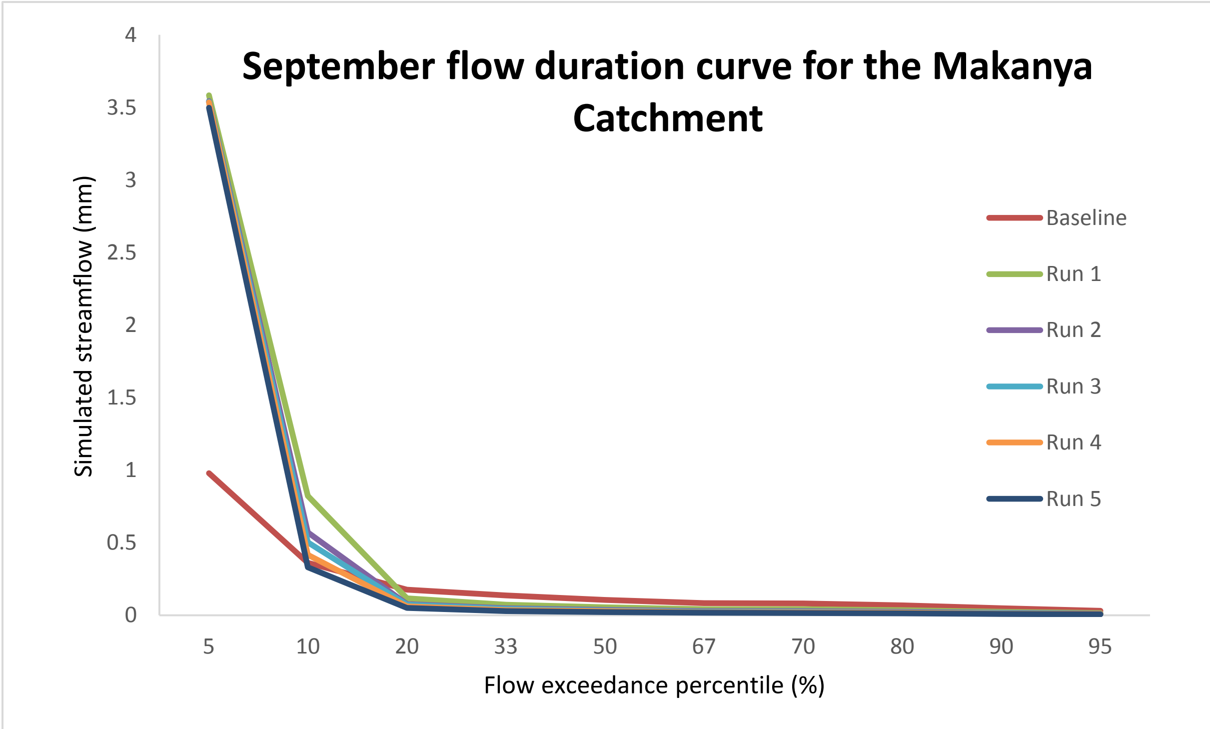

Figure 3.5 September flow duration curve for the Makanya Catchment

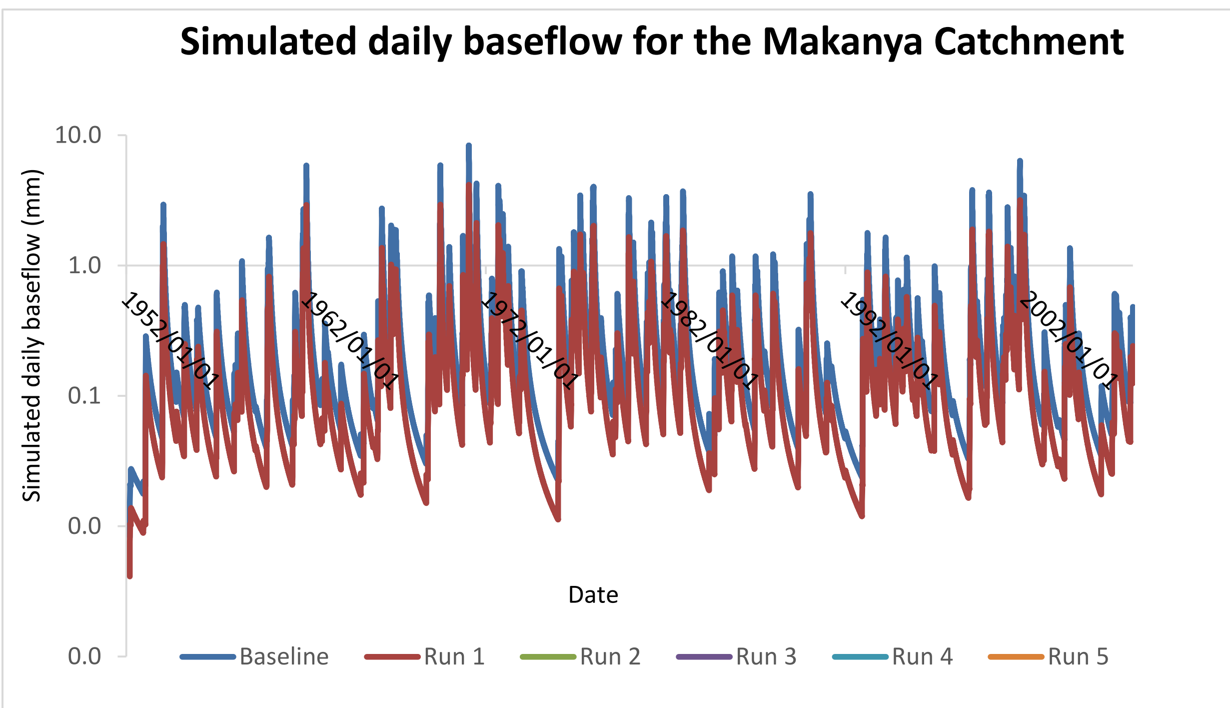

Figure 3.6 Simulated daily baseflow for the Makanya Catchment

3.3.1.1.2 Median threshold

The growing season occurred over a period of 140 days beginning each year in October. This allows the maize to acquire enough water at all critical growth stages, in order to maintain a satisfactory yield. This equates to 680 mm per harvest, in accordance with the FAO (2015) maize water requirements of between 500-800 mm. The median streamflow variable for the driest month was selected, in order to determine the percentage reduction in streamflow brought about by this irrigation scenario. Table 3.5 shows the median values for the driest month of the hydrological year i.e. September. Results show a 150% difference in streamflow between the baseline and Run 2 (current RWH scenario) (see Figure 3.4 for an illustration). Run 1 yielded 25% more streamflow than Run 2, whilst the remaining up-scaled RWH scenarios show a steady streamflow decrease of 25%. Run 5, which included a 90% higher up-take of RWH, resulted in a streamflow reduction of 50%.

Table 3.5 September median daily streamflow value for the Makanya Catchment

	September		
	Median (mm)	**Median Vol (m^3)**	**% Difference**
Run 2	0.04	12000	-
Baseline	0.10	30000	+150
Run 1	0.05	15000	+25
Run 3	0.03	9000	-25
Run 4	0.03	9000	-25
Run 5	0.02	6000	-50

3.3.1.1.3 T-test

Based on the streamflow output of the model, reported in the preceding sections, it is understood that RWH has a decreasing influence on streamflow. The significance of this influence is now determined by performing a t-test analysis on cumulative streamflow at a confidence interval of 5%. The null hypothesis for this test states that RWH has no significant impact on streamflow. In order to accept this hypothesis, the calculated t-value (t-stat) needs to be smaller than the t-critical value (minimum t-value). In addition, the P-value generated from this test needs to be higher than 0.05. If this is true, there will not be a significant difference and the null hypothesis will be true.

Listed in Table 3.6 are the outputs from the t-test for different scenarios in the Makanya Catchment. Run 2, the current RWH scenario, is the baseline for comparison. A t-stat value of 0.2.78 was generated in the test between Runs 2 and 3, whilst the value for t-crit was 1.96. The p-value for this run was 0.005. The calculated t-stat value is greater than the t-crit value and the p-value generated is lower than 0.05, therefore the null hypothesis can be rejected. RWH has a significant impact on streamflow at the 95% confidence level. This is true for Runs 1 to 5, which include up-scaling RWH to 90%. Here the t-stat value of 4.03 is below the t-crit value of 1.96. The p-value remains smaller than 0.05 at 5.61E-5. RWH has no significant impact on streamflow in Run 1, under conditions of maximum impervious regions. The t-stat value of -1.32 is smaller than the t-crit value of 1.96 and the p-value of 0.19 is greater than 0.05.

Table 3.6 T-test statistic values for the Makanya Catchment

	Run 2		
Variable	**t-stat**	**t-crit**	**p-value**
Baseline	19.54	1.96	2.21E-84
Run 1	-1.32	1.96	0.19
Run 3	2.78	1.96	0.005
Run 4	3.44	1.96	0.0006
Run 5	4.03	1.96	5.61E-5

3.3.1.2 Soil moisture and crop yields

Soil moisture under minimal irrigation resulted in the driest soils, whilst the maize irrigated under unlimited water conditions had the greatest soil moisture content, as seen in Figure 3.7. Soil moisture outputs for all RWH Runs shared the same upward trend. It can also be seen that soil moisture in the drier winter months, although low, continues to be higher under conditions of up-scaled RWH, depicted in green on Figure 3.7.

As a result of RWH, water is made available to crops during critical growth periods which keeps soil moisture in the region of (or greater than) field capacity rather than close to the wilting point, which places crops under water stress.

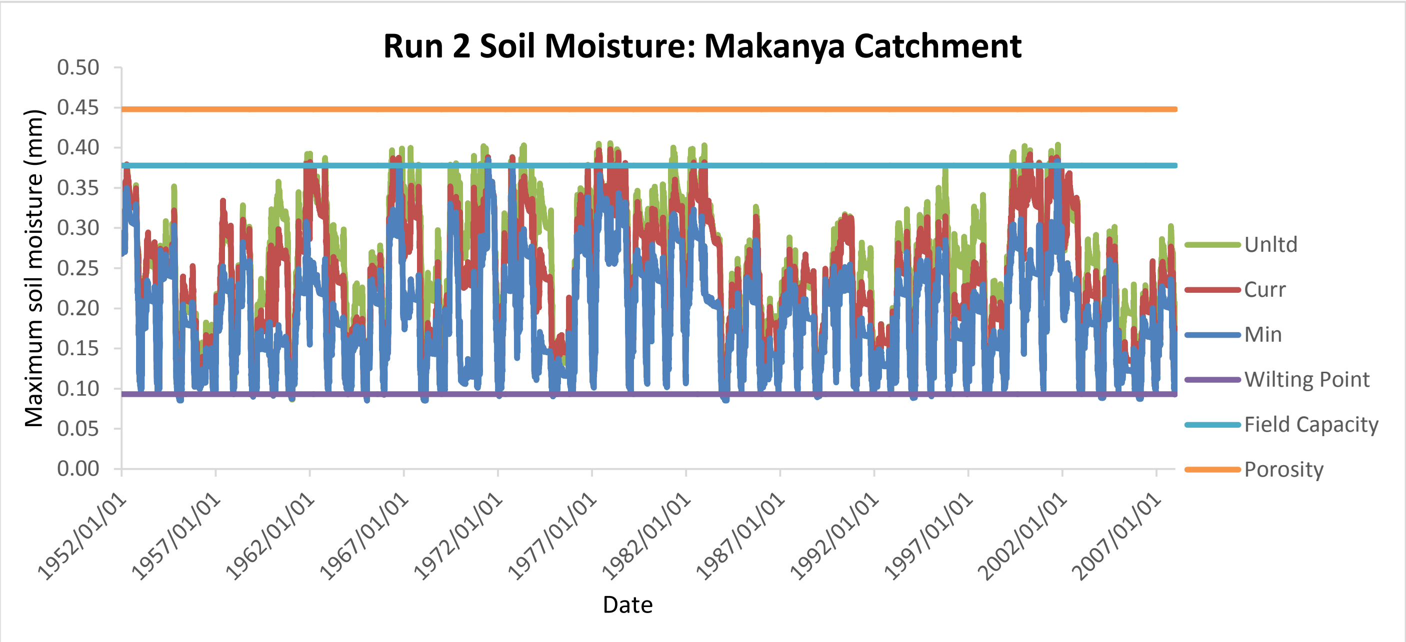

Figure 3.7 Soil moisture under conditions of minimum, current and unlimited water supply.

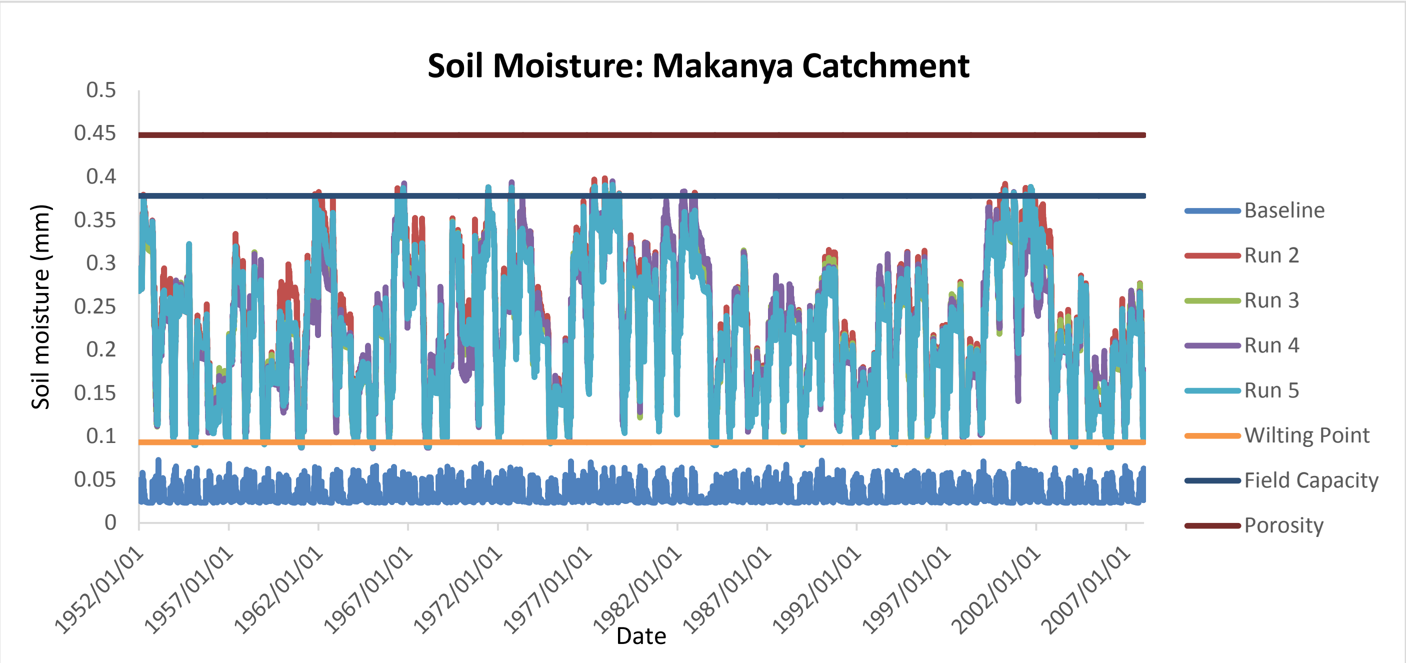

Figure 3.8 Total soil moisture in the Makanya Catchment.

Up-scaled RWH increased soil moisture greater than that of soil moisture in the baseline scenario as seen in Figure 3.8. Soil moisture remains relatively low below field capacity at an average of 0.05 mm, while the introduction of RWH increases soil moisture to an average of 0.25 mm. In some instances RWH has improved soil moisture such that the water content of the soil lies beyond field capacity. Continual RWH expansion results in a slight decline of soil moisture over time as seen in Run 5. Greater volumes of stored water encourages agricultural expansion causing a greater distribution of water across the landscape which may lead to a proportional decline in soil moisture.

Corresponding to the increase in soil moisture, from a minimum supply to an unlimited supply, as a result of up-scaled RWH (mimicked by the unlimited water supply) is the increase in crop yields per ha per Run. Conditions within the catchment support an average maize yield of 2 t/ha. Figure 3.9 indicates this increase in maize yield. Future research that takes into consideration greater up-scaling and plant growth limitation factors may show greater variations in maize yield.

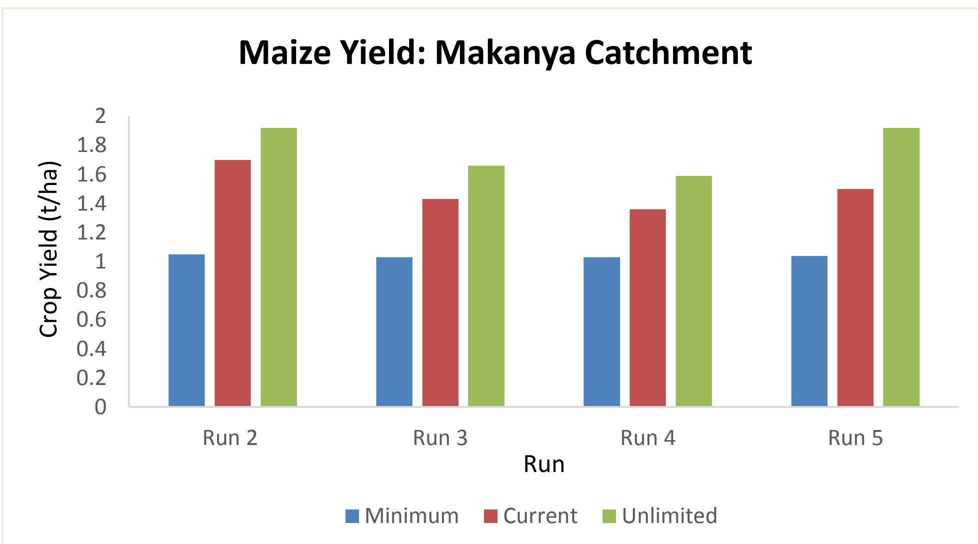

Figure 3.9 Maximum maize yields per Run in the Makanya Catchment.

3.3.2 Potshini Catchment

Water in the Potshini Catchment is stored and later used for domestic activities and irrigation. Crops include maize and soya beans, whilst herding goats and cattle is also a common practice.

3.3.2.1 Cumulative streamflow

The cumulative streamflow graph for the Potshini Catchment in Figure 3.10 shows a decreasing trend in streamflow, with the introduction of increasing amounts of RWH. Similar to the Makanya Catchment, the baseline scenario mimicked a pristine environment, by modelling the catchment with a natural grassland (Acocks 64). This generated a cumulative streamflow value of 11392 mm. A total of 13718 mm was generated in Run 2 over the modelling period. The catchment yielded 11622 mm in Run 2, under current RWH conditions. 11101 mm, 10515 mm and 10145 mm of streamflow were generated once RWH was up-scaled by 30, 60 and 90%, respectively. A total reduction of 1477 mm of streamflow occurred between the current RWH scenario and the 90% up-scaled scenario.

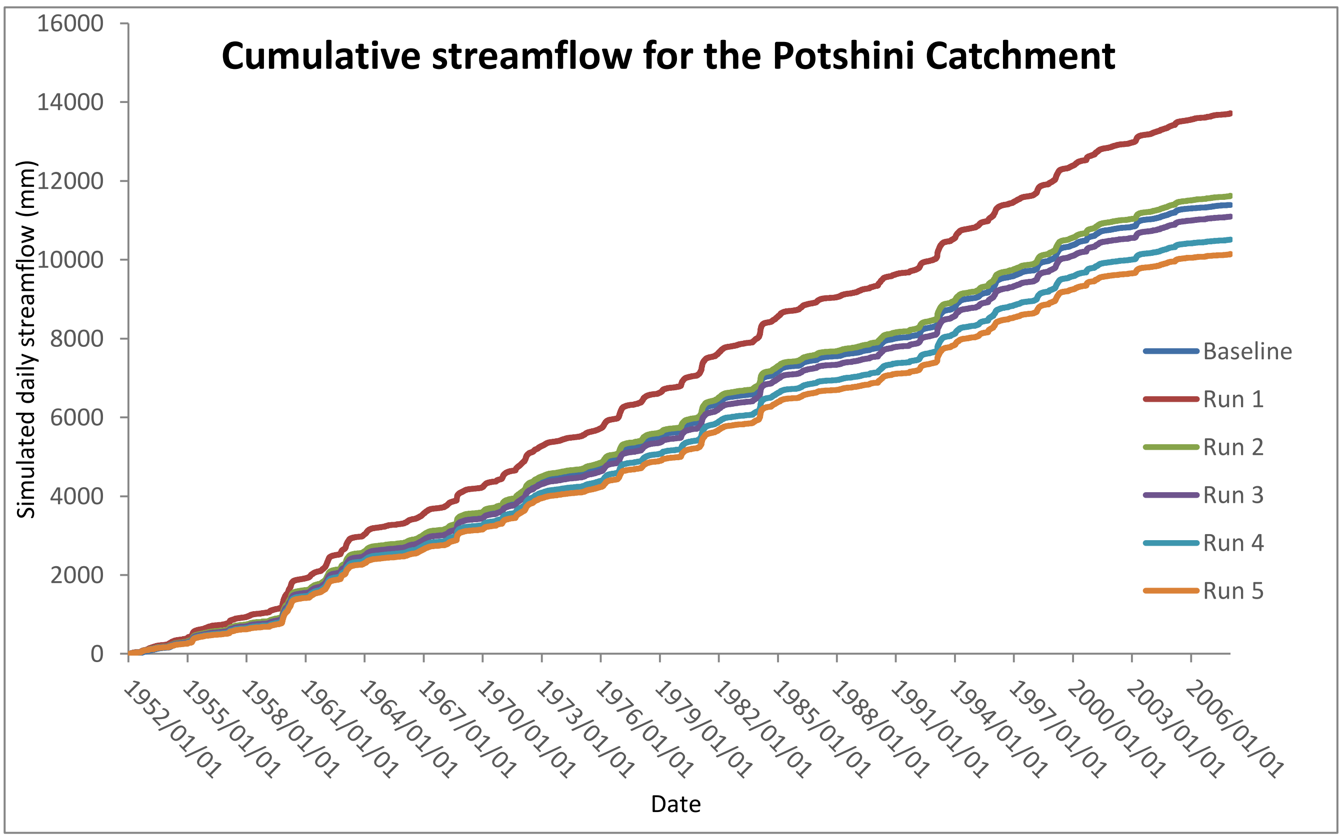

Figure 3.10 Cumulative daily streamflow within the Potshini Catchment

3.3.2.1.1 Impact on high and low flows

The baseline yielded 2.85 mm of streamflow at the 10^{th} percentile in the wettest month, compared to 0.28 mm in the driest month, as seen in Table 3.7. The 10^{th} percentile values for February and August are 2.80 mm and 0.30 mm in Run 5, highlighting that the lowest overall flows occur amidst the greatest degree of RWH. A value of 3.13 mm is calculated in Run 2 at the 10^{th} percentile in February, dropping to 2.80 mm in Run 5. This same decreasing tendency is seen in August, where values drop from 0.32 mm in Run 2 to 0.30 mm in Run 5. Essentially, a reduction of 0.33 and 0.02 mm is recorded between the baseline and 90% up-scaled scenario in February and August. Low-flows occurring in winter are lower in comparison to the summer months, decreasing further with each increasing RWH. Figure 3.12 illustrates the impact of the various RWH scenarios on the baseflow. Using the years 2006 – 2007 as indicators, it can be seen that a steady decrease in baseflow occurs as RWH expands. The environmental impact will be greater in the drier seasons when, streamflow is already low, compared to the rainy seasons. High flows are minimal in summer as a result of large amounts of runoff being captured and continually being used for irrigation. High flows are apparent, yet minor, in August, decreasing from the baseline (see Figure 3.11).

Table 3.7 Percentiles reflecting high and low-flows for the Potshini Catchment

	Feb (Wet)			**Aug (Dry)**		
Percentile	**10^{th}**	**50^{th}**	**90^{th}**	**10^{th}**	**50^{th}**	**90^{th}**
Baseline	2.84	0.56	0.17	0.28	0.17	0.09
Run 1	4.37	0.76	0.15	0.34	0.15	0.08
Run 2	3.13	0.48	0	0.32	0.14	0.07
Run 3	3.05	0.41	0	0.32	0.13	0.07
Run 4	2.89	0.30	0	0.31	0.13	0.07
Run 5	2.80	0.22	0	0.30	0.12	0.06

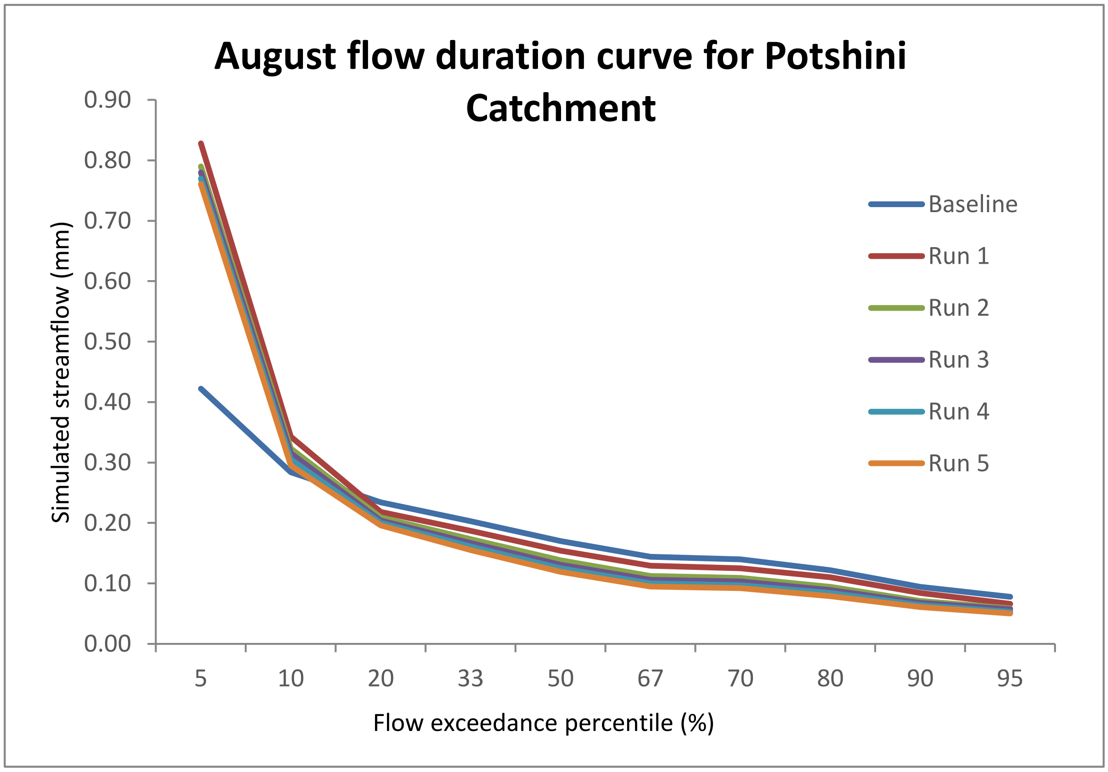

Figure 3.11 August flow duration curve for the Potshini Catchment

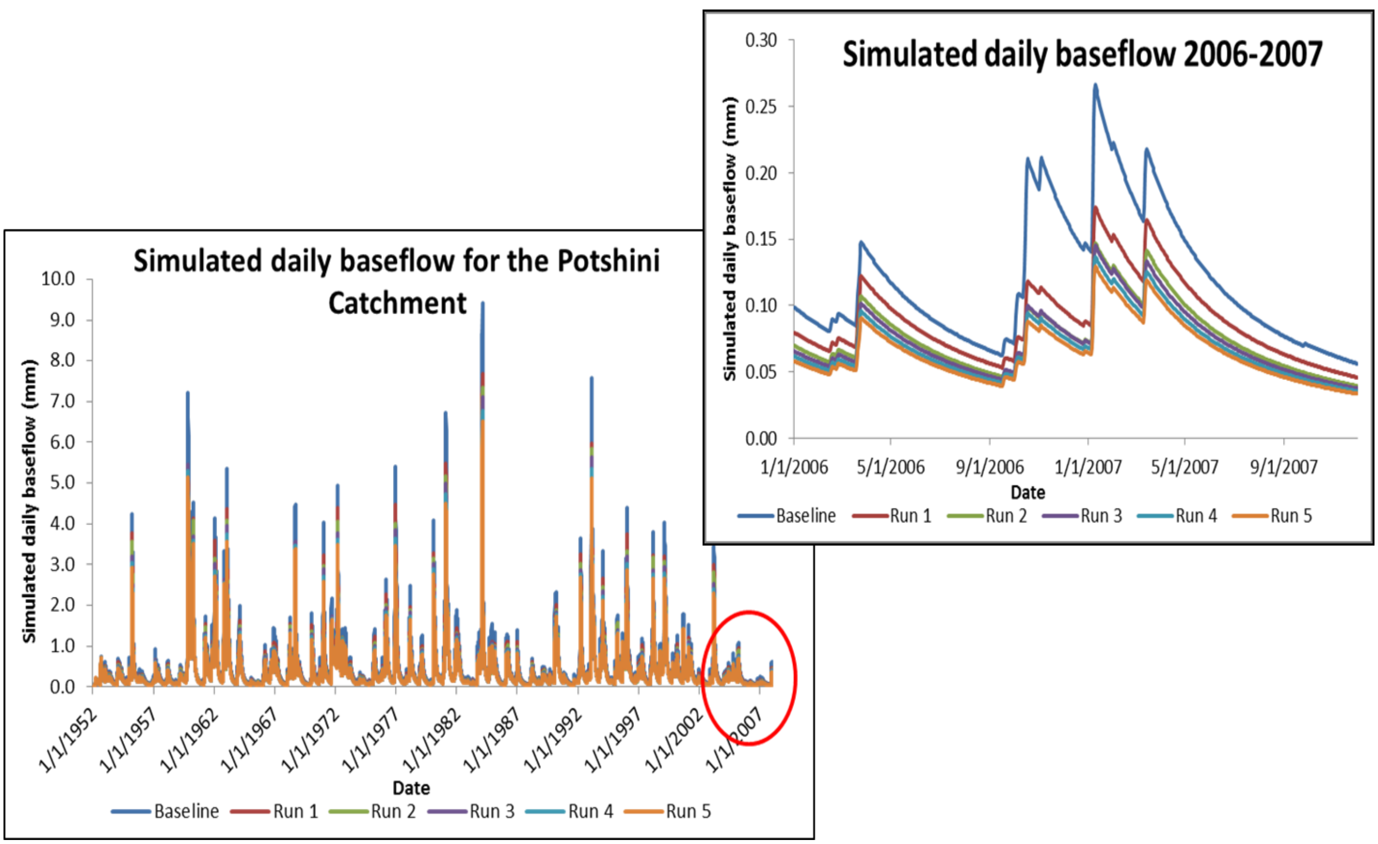

Figure 3.12 Simulated daily baseflow for the Potshini Catchment

3.3.2.1.2 Median threshold

August is the driest month in the Potshini Catchment and will be used as a control month, to determine whether it can supply the minimum required water for irrigation. Table 3.8 lists the percent reduction in streamflow from the baseline and not the current RWH conditions, as in the Makanya Catchment, as it is still a relatively new concept that has been introduced to the community, with uptake remaining relatively low, as part of the research under the SSI project (Bhatt *et al.*, 2006). Run 1 is the only scenario in which streamflow is shown to increase by 9.4%. Thereafter, each scenario shows a progressive decrease in streamflow, from a 19% reduction at current RWH, to a 30% reduction in the scenario with 90% more RWH.

Table 3.8 August median daily streamflow values for the Potshini Catchment

	August		
	Median (mm)	**Median Vol (m^3)**	**% Difference**
Baseline	0.170	204	-
Run 1	0.154	184.8	+9.4
Run 2	0.138	165.6	-19
Run 3	0.131	157.2	-23
Run 4	0.125	150	-26
Run 5	0.119	142.8	-30

3.3.2.1.3T-test

The results from the t-test for the Potshini Catchment can be found in Table 3.9. The null hypothesis can be accepted on the basis that the t-stat values are below the t-crib values for Runs 1 to 3. The p-values for Runs 2 and 3 are also high, suggesting no significance at the 5% confidence interval. T-stat values of 4.28 and 6.05 for Runs 4 and 5, respectively, are greater than the t-crit values of 1.96. In addition, the p-values for the same runs are 1.89E-05 and 1.48E-09, which are smaller than 0.05. The null hypothesis cannot be accepted and therefore RWH, up-scaled by 60% or more, will have a significant impact on the Potshini Catchment. Run 1 has a significant impact, on the basis that the p-value of 6.96E-28 is much smaller than 0.05. The significance is positive, in that an increase in streamflow was recorded, unlike the decrease found in Run 4 and 5.

Table 3.9 T-test statistic values for the Potshini Catchment

	Baseline		
	t-stat	**t-crit**	**P-value**
Run 1	-10.95	1.96	6.96E-28
Run 2	-1.12	1.96	0.26
Run 3	1.14	1.96	0.16
Run 4	4.28	1.96	1.89E-05
Run 5	6.05	1.96	1.48E-09

3.3.2.2 Soil moisture and crop yields

As was the case in the Makanya Catchment *(cf. section 3.3.1.2)*, soil moisture under conditions of minimum irrigation resulted in the lowest moisture content. Figure 3.13 illustrates the increase in soil moisture as water is made more available (through RWH). Under unlimited water conditions, soil moisture is higher, denoted by the green line, which is more pronounced in winter months. Figure 3.14 illustrates the soil moisture for all scenarios modelled in the Potshini Catchment. Soil moistures for Runs including RWH are greater than that of the baseline. Stored water is made available to crops, especially in drier periods increasing the water content of the soil. RWH has the ability to supplement rainfall and improve soil moisture such that crops are not under stress or reach wilting point, improving crop yields, as seen in Figure 3.15. As indicated in Run 5 of Figure 3.14, soil moisture decrease slightly in greater cases of up-scaling. This is largely in lieu of communities intensifying their subsistence agriculture to maximize the benefits of stored water. This in turn proportionally reduces soil moisture as a wider distribution of water needs to occur.

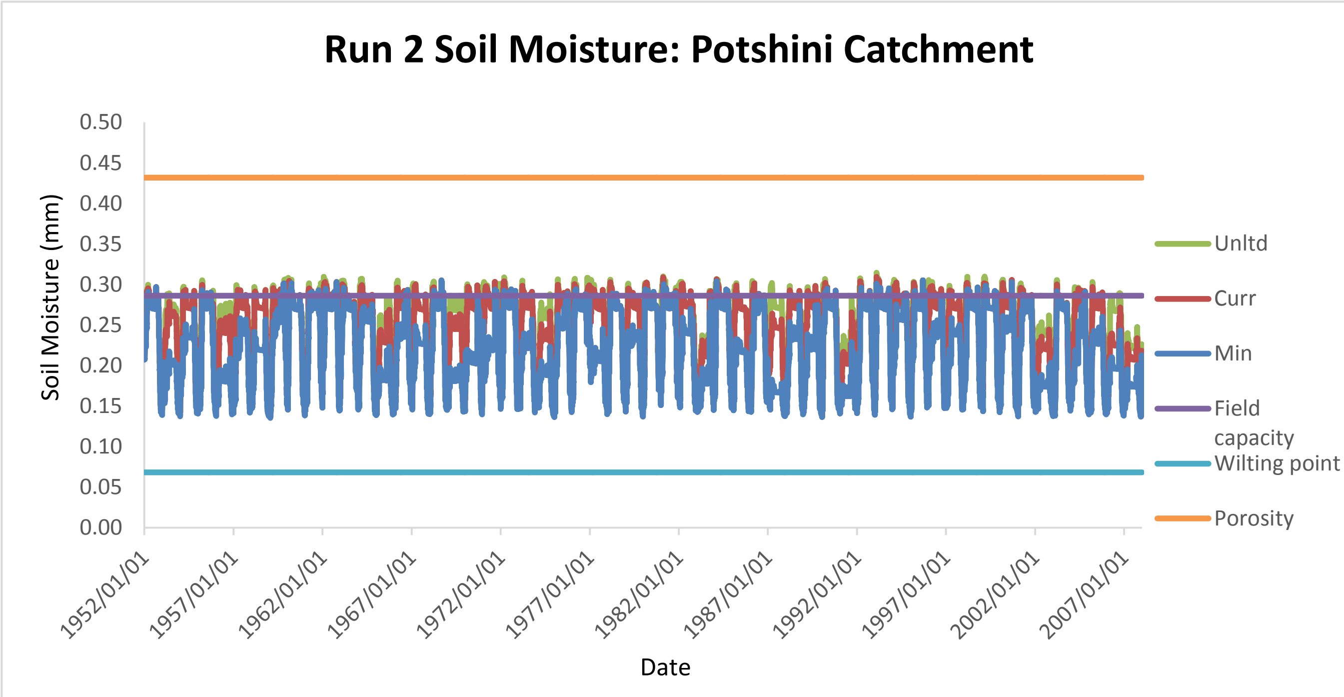

Figure 3.13 Soil moisture under minimum, current and unlimited water conditions

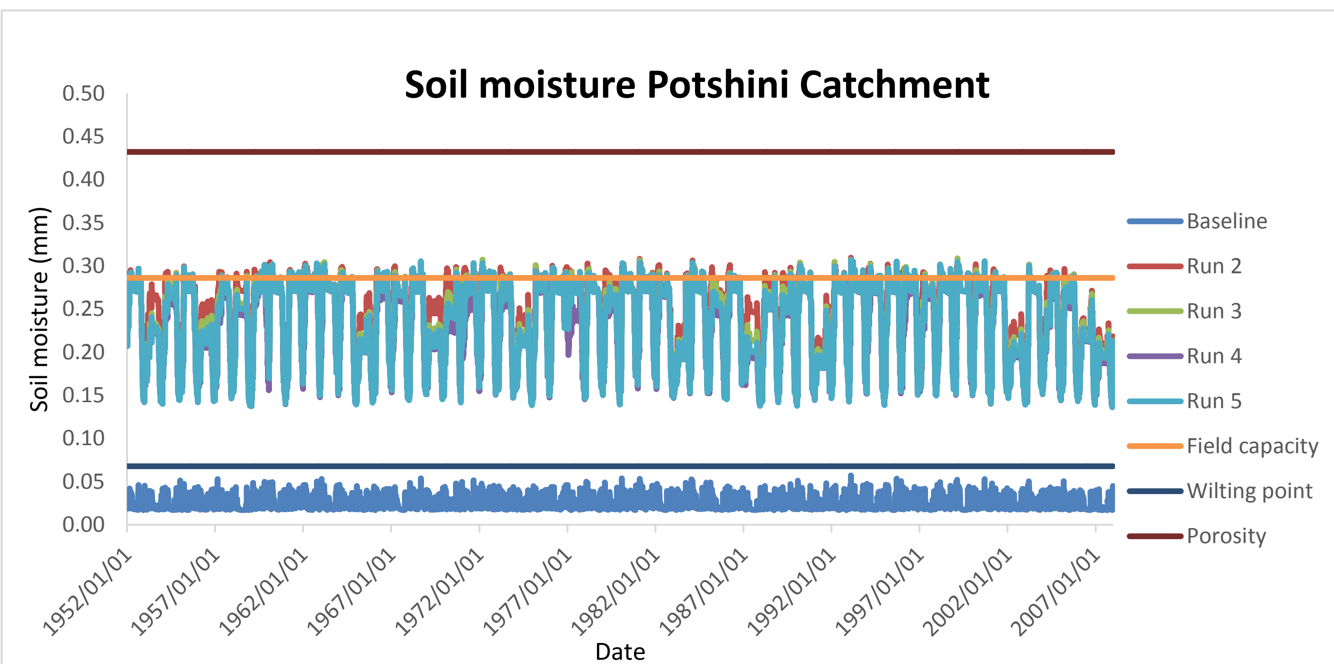

Figure 3.14 Total soil moisture in the Potshini Catchment

An increase in RWH has a positive effect on crop yield. All Runs with up-scaled RWH have greater yields than that of Run 2, the current scenario, as seen in Figure 3.15. Crop yield scenarios were also run on minimum, current and unlimited water supplies. An increase in water for irrigation contributes to the soil moisture content which improves crop yields as illustrated.

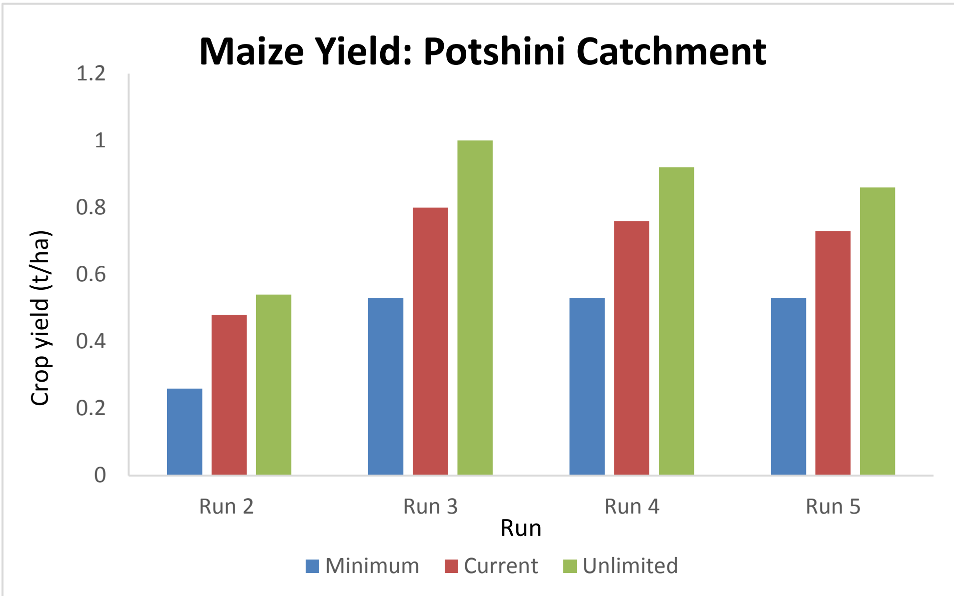

Figure 3.15 Maximum maize yields per Run in the Potshini Catchment

3.4 Discussion

The following discussion compares both catchments, based on each statistical output variable described in Section 3.3.

3.4.1 Cumulative streamflow

The (pristine) baseline scenario in the Makanya Catchment yielded the lowest streamflow due to an abundance of naturally vegetated areas. The catchment has since been modified, with the introduction of agricultural, grazing animals, RWH intensification and settlements. Larger degraded portions of the catchment create an increase in runoff generation areas, which is why Run 1 generated the greatest runoff. Streamflow continually decreased with each increase in RWH over a period. Conversely, less modification has occurred in the Potshini Catchment, allowing much of the rainfall to naturally infiltrate the grassland. Therefore the pristine baseline and current RWH behaved similarly. Run 1 yielded the highest as a result of no storage, whilst for up-scaled RWH scenarios over 30% saw a progressive reduction in streamflow.

A greater uptake of RWH in the Makanya Catchment resulted in larger regions of the catchment becoming modified. It is possible that the large scale use and type of RWH (spate irrigation) caused a higher reduction in streamflow (Kahinda *et al.*, 2009). A small-scale uptake of RWH in the Potshini catchment yielded similar results to de Winnaar and Jewitt (2010), which saw a less significant reduction in streamflow. RWH in this project is represented by households listed in the SSI project, while de Winnaar and Jewitt (2010) used a population density census to approximate household RWH, which may have resulted in different outcomes.

3.4.1.1 Impact on high and low flows

The annual rainfall for Makanya is bimodal, split over two seasons and often associated with flooding events (Bhatt *et al.*, 2006). The lack of rainfall has an impact on low-flows, the environment and the downstream users. High flows in drier months are unsurprisingly non-existent. High and low flows for the baseline run remain relatively low, due to the natural environment's ability to retain more runoff. Low flows continue to decrease thereafter, with the addition of RWH (spate irrigation / flood irrigation). Medium flows are reduced in both seasons and baseflows are not common, as rivers dry up once the rainfall season passes/ends. Ephemeral rivers are recharged by surface flows, which have been restricted by RWH hence the overall reduction in flows.

Low-flows in the Potshini Catchment behave in a similar manner. Wetter months, such as February, recorded higher low flows than those for August, due to the summer rainfall. High flows are recorded more often in August than in February. The seasonal senescence of vegetation could increase the runoff potential in drier months, with unseasonal rainfall. Low, medium and high flows decrease with increasing amounts of RWH. Harvesting water during the rainy season is less detrimental to natural flow. Impacts to low flows are similar to the outcomes recorded by de Winnaar and Jewitt (2010) who indicate that low flows are reduced (minor) in the Upper Thukela District. Interestingly, Andersson *et al.*, (2011), noted that their simulations enhanced low flows, as a result of the SWAT model considering lateral flows as the major contributor to streamflow (not surface runoff = RWH).

3.4.1.2 Median threshold

The median streamflow value for the driest month of the hydrologic year was the variable selected to identify the limit of RWH. For each streamflow output, the percent difference was calculated and compared to a threshold limit, set at 40%. The initial increase in streamflow in the Makanya Catchment can be accredited to the continual change in landuse. Thereafter the introduction of agriculture, water storage and the expansion of human settlements spur degradation, creating an enabling environment for increased runoff. As a result streamflow decreases as the opportunity for RWH increases. The scenario enlisting the most RWH exceeds the threshold limit by 10%. This is a minor reduction as can be managed. A maximum target yield of 2 ton/ha was maintained from the 67th percentile in Run 2 and Run 5, with both decreasing to a reasonable 1.7 and 1.5 ton/ha respectively at the 50th percentile (see Appendix). The fair maize yields are comparable to Andersson *et al.,* (2015) and Andersson *et al.,* (2011), where maize yields are small, improving only by a few percent from the baseline. Despite having a larger amount of stored water crop yields also depend on the fertility of the soil. Studies in Burkino Faso and Ethiopia indicate that crops cultivated in nutrient poor soils cannot profit from increased water made available through RWH, if the soil fertility issues are not addressed (McHugh *et al.,* 2007; Brenman *et al.*, 2001).

An increase in water storage resulted in a steady decrease in streamflow. A maximum reduction of 30% occurred where storage increased by 90%. The maximum target yield of 2 ton/ha was not reached in Potshini. At the 95th percentile (for maximum RWH), 1.39 ton/ha of maize was generated with 0.73 ton/ha at the 50th percentile, greater than that of the yield under current RWH conditions. Less water needs to be abstracted for irrigation in the smaller Potshini Catchment, thereby reducing the likelihood of exceeding the threshold. The potential of water being the limiting factor in the maize yield in these scenarios is small, considering the quantity of water made available by up-scaled RWH. Therefore, other factors, such as soil quality, pest control or climate regulation, need to be considered. Furthermore, the higher MAP in the Potshini Catchment enables the environment to obtain the necessary amounts of water.

The potential for crop lands to expand is high, under increased RWH adoption. However, the overall efficiency of spate irrigation in the Makanya Catchment is very low. Conveyance losses average around 80%, whilst maintenance on canals is limited to each farmer's financial contribution (Makarira *et al.*, 2007: Biazin *et al.*, 2012). Over time this translates to greater crop failures, due to low rainfall and inefficient RWH systems. Crop lands, once rich in biodiversity, are now left fallow, increasing the potential of erosion. In order to, maximize the potential of harvested water, famers would need to reduce the number of fields they irrigate, thereafter concentrating farming upstream near the source (Makariru *et al.*, 2007). The resultant impact on water quantity and quality increases the vulnerability of downstream users. In the Potshini Catchment, water-logged soils, as a result of excessive water harvesting may inhibit crop growth, in addition to limiting other natural processes within the ecosystem.

3.1.4.3 T-test

The outcome of the t-test analysis for the Makanya Catchment shows that RWH does have a significant impact on streamflow at the 0.05 confidence level. Therefore, the null hypothesis cannot be accepted. The removal of natural vegetation, for the introduction of intensive agriculture and homesteads, has significantly increased the runoff potential of the catchment. Whilst the opportunity to harvest more water arises, the effectiveness of highly essential ecosystem goods and services are decreased.

A reduction in streamflow is clear with each increase in RWH for all scenarios. P-values steadily decrease with each increase in storage, confirming the significance. Increased compaction and degradation within the catchment promotes runoff. This, in turn, persuades farmers to capture more water, which reduces the natural streamflow within the catchment. A reduction in streamflow generates an array of issues within the ecosystem, impacting downstream users the most. A reduction in water reduces the abundance of biodiversity and organisms, as flows regulate breeding and facilitates habitats.

Similarly, in the Potshini Catchment, the null hypothesis is rejected for RWH scenarios greater than 30%. The t-test results show that increasing the harvesting of water by 30% may not significantly hinder the delivery of ecosystem goods and services. Harvesting beyond this point, may influence the ability of the environment to effectively supply and regulate flows and to maintain the natural balance of downstream. The fast response times of smaller catchments need to be considered, when altering natural processes. Gradual application of RWH in Potshini will allow the environment time to naturally adapt.

3.4.2 Soil moisture and crop yields

Results indicate that an increase in RWH does increase the soil moisture within each individual Run for both the Makanya and Potshini Catchments. More water is made available to irrigate crops throughout the growing season, especially during drier periods of the season. RWH also makes water more readily available during low rainfall months (i.e. winter months in the Potshini Catchment). Though crops yields were not drastically improved, increased soil moisture during temporal variations in rainfall reduced crop stress and assisted in maintaining a yield. This too can be said for crop yields in Andersson *et al.,* (2011) where RWH stabilized yields during critically dry months rather than vastly increasing yields overall. A dry spell can have devastating effects on the livelihoods of subsistence farmers. The benefits of harvesting water, is the ability to reduce crop stress during these drier periods and maintain a harvest. A negligible reduction in downstream soil moisture of up to 4.9% over a period on 56 years was recorded, equating to a 0.08% reduction per year, well below the threshold value of 40%.

The impact of RWH on soil moisture should not hinder the productivity of plant biomass and animal diversity within the ecosystem of each catchment. Therefore, RWH should be seen as a soil conservation tool in order to mitigate its impacts resulting from a reduction in streamflow (*cf. section 2.9*). It is recognized that while ecosystems need to be protected, they also need to be utilized and it is essential that the balance between the two be established. Consider Figure 2.5, in the past communities unsustainably abstracted from the environment, decreasing its resilience and forcing it into an unproductive state. Fortunately, as seen in Figure 2.6, it is possible to utilize the ecosystem whilst protecting it through strategic management. The introduction of RWH as an innovative soil conservation strategy allows communities to abstract water and redistribute in back into the environment.

3.5 Conclusion

The result of this study shows that up-scaled RWH gradually decreases streamflow. This reduction is significant in all RWH scenarios in the Makanya Catchment at a confidence level of 0.05. The reduction in streamflow is significant at 60% and 90% up-scaled RWH in the Potshini Catchment. RWH has a greater impact on low-flows in the winter months, when streamflow is naturally low, as is the case in the Potshini Catchment. RWH has no influence on low-flows in the Makanya Catchment, due to the climatic regime and the ephemeral nature of rivers. The t-test cautions against up-scaling RWH by more than 60% of the current storage within the Potshini Catchment, due to the small catchment area. The variability of seasonal rainfall and its distribution over a large surface area, the low MAP and the extent of degradation, make the Makanya Catchment more vulnerable to change. This study also shows that an increase in RWH improves soil moisture in both catchments, the advantages of which are numerous. Soils with greater moisture contents have lower erodibility potentials and are less likely to experience soil crusting. This limits the amount of fertile top soil that could be eroded, as well as providing an enabling environment for seed emergence, both of which improve crop growth. Careful consideration needs to be taken when up-scaling RWH, despite the predetermined limit to RWH not being overly exceeded in both catchments.

An initial stressor will not immediately have a substantial impact on the environment, but rather only after the accelerated or prolonged use thereof. Therefore, the initial impact of RWH will be absorbed and thereafter unsupervised expansion will upset the natural order of the environment and inhibit the provision of ecosystem goods and services, decreasing environmental resilience. Freshwater systems overlap and influence several other ecosystems. A reduction in streamflow will have a knock-on effect, the impact of which will be felt by numerous stakeholders.

However, RWH has been proven to increase soil moisture, which sustains agriculture. In this instance RWH now acts as a conservation tool which aims to mitigate the initial abstraction of water. Harvesting water in rainy seasons maximizes the storage capacity, enabling farmers to improve irrigation efficiency. Agricultural activities upstream are likely to expand, increasing the pressure on ecosystem goods and services within the catchment. However, RWH can also be used within definable limits to improve ecosystem insurance. The use of RWH as a mitigation tool will not only manage the ecosystem from a vulnerable state to a productive state, but it will also improve the social networks and diversification of the communities it's utilized in.

The negative feedback impacting ecosystem goods and services needs to be managed in conjunction with up-scaling. The marginal reduction in soil moisture across both catchments enables RWH to be used as an adaptive strategy to mitigate negative impacts and improve ecosystem functioning. Water that has been abstracted can be redistributed back into the soil and changed into food, benefitting people. This can be accomplished through up-scaling within the advisable limits, which aims to sustainably manage the environment and improve planning through integrative management.

3.6 References

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4. CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

4.1 Introduction

Every day across the globe, everyone depends on ecosystem goods and services, not only for survival, but also to improve their quality of life. Hydrological services, such as water supply, water quality regulation, flood attenuation and the maintenance of aquatic habitats, encompass human dependence on ecosystem goods and services (Brauman *et al.,* 2007). However, as the population grows at an exponential rate, an increased demand is placed on the ecosystem to provide more services and produce more goods. Taking into consideration further, the current pressures of water scarcity are pushing global ecosystems to their limit, in order to meet demands (Gleick, 2000). In order to limit the stress imposed on the environment it is essential to understand what ecosystem goods and services are significant to a certain catchment, how these ecosystems are inter-linked and what their thresholds are. Understanding these aspects of the environment promotes an integrative management approach within the catchment, which aims to support ecosystems by sustainably providing goods and services, both today and in the future.

RWH is an innovative water storage concept that has the potential to improve the delivery of water to communities that are vulnerable to water scarcity, in an effort to cope with the rapidly increasing food demands (Ngigi, 2003). Water that is easily accessible can be used for domestic purposes, as well as supplemental irrigation in catchments such as Makanya and Potshini, that rely on subsistence farming for survival. The positive implications are numerous; however, the environment has the potential to be exploited through the extensive use of RWH practices. The integrity of the ecosystem and its goods and services is largely dependent on the efforts of its stakeholders, to research, understand and implement appropriate conservation practices, thereby improving environmental resilience and sustaining the delivery of environmental benefits to humans and other ecosystem services benefactors.

4.2 Aim and Objectives

The main focus of this research project involved improving the understanding of RWH and modelling, so as to formulate tools and methods to determine the impacts and trade-offs of RWH techniques. In doing so, the environment and the communities within a catchment can be managed holistically *(cf. Section 1.3).* The main research questions of the study are as follows:

- What ecosystem goods and services are relevant in the Potshini and Makanya Catchments?
- What is an appropriate baseline for modelling studies which aim to address the potential impacts and benefits of RWH on catchment hydrology?
- How does up-scaling RWH impact on the hydrological cycle, particularly streamflow and soil moisture?
- Does intensive RWH have the potential to impact ecosystem goods and services, how does the state of the environment affect the potential for up-scaling RWH and is there a feedback between these?
- Are there thresholds or tipping points to the extent of RWH up-scaling where the generation of ecosystem goods and services are permanently affected?

A list of ecosystem goods and services was generated, based on catchment characteristics and community dependence, of which; water supply and regulation, soil fertility and food production were the most important. The overall rural nature of the Makanya and Potshini Catchments, as well as the low income generation per household increases the dependency on the environment to provide basic needs. The abstraction of water from rivers and streams is used for domestic and agricultural purposes. Fertile soils and improved water availability for irrigation have the potential to increase crop yields, thus reducing the vulnerability of the community. The acquisition of wide-ranging catchment data enabled the development of an appropriate baseline for both catchments. Valuable knowledge was gathered, by running various scenarios of up-scaled RWH through the ACRU Model. Ultimately, it was established that RWH does decrease streamflow, whilst the application of water through irrigation improved soil moisture and had the potential (with further research) to mitigates the loss of water through the system. Thus, the impact on ecosystem good and services is maintained at an acceptable limit.

The current state of the catchment plays an important role in how extensively RWH can occur, because the ecosystem directly impacts hydrological processes as water moves through the landscape. This is evident in the Makanya Catchment, where a large degree of degradation has occurred, transforming natural landscapes into compact, runoff generation areas and increasing the runoff potential. However, while this may seem viable in a water-stricken catchment, this limits the natural infiltration of water into the soil and reduces soil fertility through the loss of top soil, which further impacts the ecosystem. These trade-offs are inherent in the supply of hydrological services.

4.3 Challenges

The ACRU Model was selected for the purpose of modelling the catchment hydrology of Makanya and Potshini. While its sensitivity to land-use change and its ability to simulate streamflow are suited for this study, the model cannot accurately predict future outcomes. Models should not be used to validate a study, but rather to enhance, or strengthen, a hypothesis (Orekes *et al.*, 1994). Therefore, its use in a scenario analysis such as this requires further in-field research, using empirical data to eliminate the uncertainty common to model predictions. In addition, ACRU does not directly account for RWH within its structure. Therefore, dams were used as temporary storage structures, representing tanks and diversion canals. This decreases the accuracy of the study, as dams have input variables that need consideration, but which may not entirely reflect a RWH system. For instance, the large surface area of a dam requires the input of an evaporation coefficient, whilst evaporation from a RWH tank is effectively nil.

In reality, RWH supplements rainfed agriculture in the Makanya and Potshini Catchments. Within the model, maize is irrigated solely by means of the dam. Therefore, the maximum maize yield is limited by the storage capacity of the dam. The length of the data records used for both catchments were inefficiently short and contained large amounts of missing data. This led to the use of a stochastic rainfall generator, which simulated 56 years of rainfall data. The Stochastic Climate Library, developed for the Australian climate is not entirely transferable to an African climate, despite both continents being located in the southern hemisphere. The uncertainty linked to patched data records needs to be considered.

4.4 Future Research Needs

This study focused on an array of ecosystem goods and services, which benefits the rural communities and on which they depend. Future research should determine the impact of up-scaled RWH on one particular aspect of the environment at a time. These aspects could include the effects on water quality, the timing of flows or even the impact of up-scaled RWH on the breeding of fish species. Research will therefore be more concentrated and the results more focused. This should improve the understanding of catchment function, including how inter-linked various facets of the ecosystem are, essentially leading to improved integrative catchment management. Furthermore, in addition to determining that RWH has the ability to decrease streamflow, future research should investigate to what extent this reduction can occur, before it is deemed a streamflow reduction activity. The output of future studies should also highlight the impact of RWH, specifically high, low and base flows. Lastly, in order to accurately model infield RWH, necessary additions to current models need to be made, to include RWH as a method of water storage. The inclusion of a non-evaporating tank would complement the adjacent impervious region (representing roofs) used to capture and convey runoff. Lastly, future research should model the influence of RWH on maize yield by including plant growth limitations such as nutrients, which was a limitation of this study.

4.5 Final Conclusion

Ecosystem goods and services play a vital role in the survival of humans and other living organisms in nature. The introduction and intensification of RWH have the potential to positively and negatively impact these goods and services, varying at different catchment scales. This project shows that RWH increases water for supplemental irrigation, which improves soil water and thereby increases crop yields (assuming water was the only limiting factor). Unfortunately, RWH also inhibits natural processes downstream, such as water purification, biodiversity and habitat support. The ACRU Model was successful in determining the potential impact of RWH on river flows. A general reduction in streamflow was recorded for the Makanya and Potshini Catchments. This reduction was significant in all up-scaled RWH scenarios (30 – 90%) in the Makanya Catchment, whilst an up-scaling RWH between 60 – 90% denotes a significant reduction in the Potshini Catchment, at a 5% confidence interval, based on the 40% streamflow reduction threshold that had been set. Based on median daily streamflow values, it has been determined that low flows in September and August, the driest months of the year, are most affected by up-scaled RWH, in the Makanya and Potshini Catchments, respectively. Up-scaled RWH, improved soil moisture which is significant in low rainfall months. Soil moisture was seen to decrease marginally as more land was taken over by agriculture. This however has little influence on the functioning of the ecosystem as this reduction was 4.9% and 4.5% in the Makanya and Potshini Catchments respectively, far from the threshold limit, promoting an increase in successful crop yields.

Results show that the Makanya Catchment is more sensitive to alterations in the environment, which can be attributed to a number of variables. These include the low MAP of the catchment, as well as the variability of seasonal rainfall, the distribution thereof, over a large surface area and the greater intensity of harvesting. The degree of degradation prevalent within the catchment also reduces the resilience of the ecosystem and its ability to provide ecosystem goods and services. In comparison, the Potshini Catchment has a higher MAP and a smaller catchment boundary. Coupled with a lower population density, less pressure is placed on the ecosystem. Hence, the opportunity exists to up-scale RWH to a greater degree within this catchment.

The prospect of converting natural landscapes to agricultural land is high, as a result of stored water. Rapid landuse change, without the correct management, has the potential to create a negative feedback mechanism, influencing the amount and quality of water harvested in the future. The state of the environment plays an important role in determining the suitability of RWH. Less water is available for harvesting in a pristine catchment, in comparison to a degraded one, as hydrological process work in unison with the natural vegetation to retain larger amounts of water. A degraded catchment increases the velocity and timing of flows, ultimately increasing the potential to harvest more water, rich in sediments. RWH can be used as a soil conservation tool, providing an adaptive approach to safeguarding the environment. Water that is abstracted through RWH can be redistributed back into the soil, thus allowing for the expansion of agricultural land, whilst addressing social necessities, through an integrated management approach.

Undeniably, it is obligatory to utilize the environment for basic human survival. How we utilize it will determine how long it will benefit us for. Whilst, RWH does reduce streamflow downstream, locally that water is used for crop irrigation which contributes to soil moisture, providing a direct benefit to humans in the form of food. This project offered a catchment scale comparison of the effects of RWH on runoff, soil moisture and interrelated ecosystem goods and services. In order to sustain the long-term benefits from the environment and improve societal resilience, it is essential to maintain a balance between the benefits offered by the natural landscape and the benefits generated by artificial systems through sustainable limits.

4.6 References

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5. APPENDIX A

Table A1: Baseline ACRU data for the Makanya Catchment

	Pangani River Basin			Thukela River Basin
	Makanya Catchment	Sisal Estate	Makanya Settlement	Potshini
Quickflow response	0.3	0.3	0.3	0.3
Elevation (m)	1500	700	640	1250
MAP (mm)	800	600	500	700
Soil	Sandy Clay	Sandy Clay	Sandy Clay	Loamy sand
Latitude (°)	4.36	4.36	4.36	28.82
Evaporation	Hargreaves & Samani	Hargreaves & Samani	Hargreaves & Samani	Hargreaves & Samani
Baseflow response	0.009	0.009	0.009	0.009
Critical stormflow depth (m)	0.3	0.3	0.3	0.3
Vegetation	Thicket & Bushland	Maize Mvoti	Informal residential rural	Northern tall grasslands & Maize Mvoti

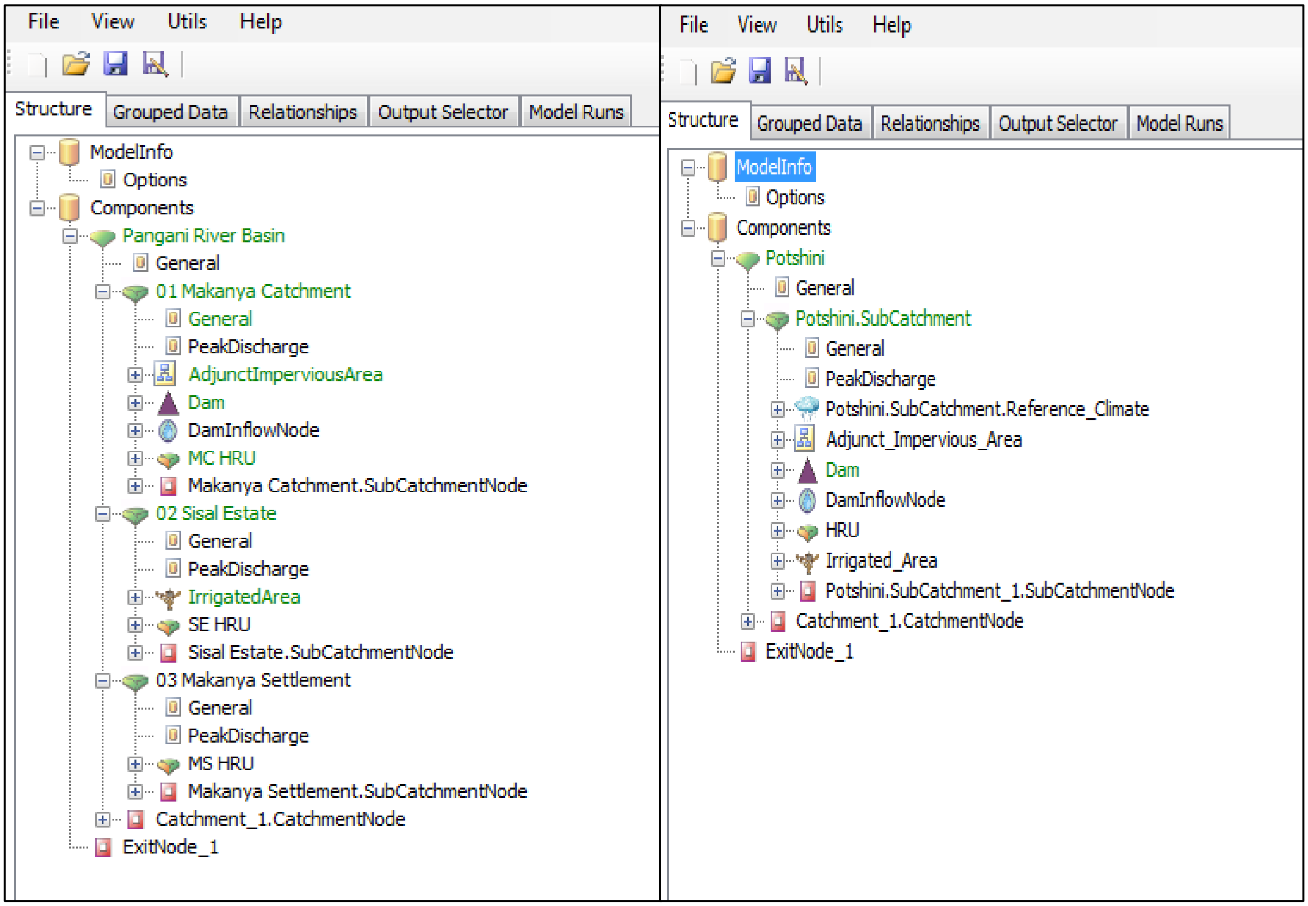

Figure A1: ACRU model configuration for the Makanya and Potshini Catchments

Table A2: Maize yield in the Makanya Catchment

Percentile	Run 2 Yield (t/ha)	Run 5 Yield (t/ha)
10.00%	0.81	0.68
20.00%	1.10	0.95
33.00%	1.34	1.14
50.00%	1.70	1.50
67.00%	1.98	1.88
80.00%	1.99	1.99
90.00%	1.99	1.99
95.00%	2.00	1.99

Table A3: Maize yield in the Potshini Catchment

Percentile	Run 2 Yield (t/ha)	Run 5 Yield (t/ha)
10.00%	0.27	0.44
20.00%	0.32	0.52
33.00%	0.40	0.59
50.00%	0.48	0.73
67.00%	0.59	0.89
80.00%	0.75	1.19
90.00%	0.84	1.33
95.00%	0.96	1.53

Table A5: Makanya Maize Yield (Run 2) considering various water quantities

Percentile	Min Yield (t/ha)	Current Yield (t/ha)	Unlimited Yield (t/ha)
10.00%	0.46	0.81	1.13
20.00%	0.66	1.10	1.37
33.00%	0.80	1.34	1.67
50.00%	1.05	1.70	1.92
67.00%	1.33	1.98	1.98
80.00%	1.80	1.99	1.99
90.00%	1.99	1.99	1.99
95.00%	2.00	2.00	2.00

Table A6: Makanya Maize Yield (Run 5) considering various water quantities

Percentile	Min Yield (t/ha)	Current Yield (t/ha)	Unlimited Yield (t/ha)
10.00%	0.46	0.68	0.87
20.00%	0.66	0.95	1.29
33.00%	0.79	1.14	1.54
50.00%	1.04	1.50	1.92
67.00%	1.32	1.88	1.98
80.00%	1.79	1.99	1.99
90.00%	1.99	1.99	1.99
95.00%	2.00	1.99	2.00

Table A6: Potshini Maize Yield (Run 2) considering various water quantities

Percentile	Min	Current	Unlimited
	Yield (t/ha)	Yield (t/ha)	Yield (t/ha)
10.00%	0.18	0.27	0.31
20.00%	0.20	0.32	0.37
33.00%	0.22	0.40	0.44
50.00%	0.26	0.48	0.54
67.00%	0.34	0.59	0.67
80.00%	0.43	0.75	0.92
90.00%	0.49	0.84	0.99
95.00%	0.56	0.96	1.00

Table A7: Potshini Maize Yield (Run 5) considering various water quantities

Percentile	Min	Current	Unlimited
	Yield (t/ha)	Yield (t/ha)	Yield (t/ha)
10.00%	0.37	0.44	0.49
20.00%	0.40	0.52	0.59
33.00%	0.45	0.59	0.66
50.00%	0.53	0.73	0.86
67.00%	0.69	0.89	1.04
80.00%	0.87	1.19	1.43
90.00%	0.99	1.33	1.72
95.00%	1.11	1.53	1.84