TOOLS TO ASSESS THE ECOHYDROLOGICAL IMPACTS OF WATER SYSTEM INNOVATIONS

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ABSTRACT

Water scarce countries such as South Africa are subject to various hydrological constraints, particularly within resource poor farming communities that are reliant on rainfed agriculture. Recent initiatives to address this issue have shifted focus to explore more efficient alternatives to water supply. Adoption of water system innovations through the use of runoff harvesting is one such alternative that provides a means to supplement water use for increased food production. However, increasing the implementation of runoff harvesting, without encountering unintended impacts on downstream hydrological and ecological systems, requires better understanding of the hydrologic and environmental impacts at catchment scale. The objective of this dissertation was to gain knowledge to the ecohydrological impacts that are likely to occur with the adoption of water system innovations as a means for upgrading rainfed smallholder farming systems. To fulfil this objective, a research component was developed whereby tools were utilised to facilitate this process on the basis of two broad aims. The first aim entailed developing a method for locating areas that are most suitable for the adoption of runoff harvesting using Geographical Information Systems (GIS). This was achieved by spatially modelling physical properties of the landscape which influence runoff response. Combining potential runoff with socio-economic factors produced a runoff harvesting map of sites with low, medium and high suitability. This is illustrated by a case study at the Potshini catchment, a small sub-catchment in the Thukela River basin, South Africa. The second aim involved modelling the impacts that runoff harvesting would have on the downstream hydrology and ecology based on the alteration of the flow regimes. To accomplish this, the *ACRU* Agrohydrological model which was configured to represent runoff harvesting, was used to simulate streamflow for quaternary catchments within the headwaters of the Thukela River basin. Simulated streamflows from *ACRU* was input into the IHA model to generate ecologically relevant hydrological parameters. Alteration of the flow regime due to runoff harvesting was mostly a reduction in high and low flows however the impacts were insignificant. This suggests that, depending on the intensity of runoff harvesting, downstream ecological impacts are insignificant.

PREFACE

The work described in this dissertation was carried out in the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg under the supervision of Professor Graham Jewitt.

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

Chapter 3 and Chapter 4 in this dissertation are written in the form of research papers based on research work done of which Chapter 3 has been published in the Journal, Physics and Chemistry of the Earth.

DECLARATION

I, ………………………………………….. declare that:

1. The research reported in this dissertation, except where otherwise indicated, is my original research.

2. This dissertation has not been submitted for any degree or examination at any other university.

3. This dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

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   a. Their words have been re-written but the general information attributed to them has been referenced
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5. 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 thesis and in the References sections.

Signed: ……………………………………

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1. INTRODUCTION

A contemporary issue in water resources planning and management is the adoption of new innovative methods within agricultural systems, particularly rainfed systems. Understanding the impacts that are likely to occur with adopting these various methods is an important matter that needs to be addressed, especially if the intention is to execute innovations in a controlled and sustainable manner, without undermining hydrological and ecological processes.

The world population is growing rapidly, especially in water scarce regions, and this has a direct influence on the global food requirements (Falkenmark, 1997). Consequently population pressure has led to increased withdrawals and deterioration of water, as a result of agricultural, urban and industrial development. But it is agriculture that has been responsible for the largest withdrawals of water for direct human use. The result is a growing pressure to increase agricultural production through increased yields per unit soil and unit water (Rockström *et al.*, 2002). Hence many have highlighted the need for a "changing water paradigm", which has many components that include a shift away from reliance on finding new sources of supply to address perceived new demands, a growing emphasis on incorporating ecological values into water policy, a re-emphasis on meeting basic human needs for water services, and a conscious breaking of the ties between economic growth and water use (Gleick, 2000). These principles need to be addressed, particularly within the rainfed agricultural sector which supports a significant proportion of the human population.

Today, 55 percent of the gross value of our food is produced under rainfed conditions which makes up nearly 72 percent of the world's harvested cropland (Comprehensive Assessment of Water Management in Agriculture, 2007). In water scarce regions, such as sub-Saharan Africa (SSA), rainfed agriculture forms more than 95 percent of the crop lands, and will continue to be the dominant source of food for growing populations of the tropics in the future (Rockström, 1999; Rockström *et al.*, 2004). Here agriculture is the major economic activity, engaging between 75 percent and 85 percent of the people of those countries (Ngigi, 2003). However, the majority of these people rely on subsistence ways of life, with individuals supplementing their livelihoods from small-scale plots of land that quite often produce unsatisfactory yields. A particular contribution to the productivity problem in SSA lies in the fact that large tracts of the arable land are located in water scarce areas subject to recurrent dry spells (SIWI, 2001). Therefore being subjected to unreliable rainfall as well as low soil fertility, food production is continually under threat in the SSA, thus making food security a major concern (Ngigi, 2003).

The extent of such concerns has been exacerbated further due to land degradation and desiccation that has in many areas resulted in diminishing crop yields, with average yields oscillating in the range of one ton per hectare (Bhatt *et al.*, 2006).

Consequently water productivity in rainfed agriculture will have to increase dramatically over the next generation if food production is to keep pace with population growth (Rockström *et al.*, 2002). Likewise, further degradation of the available land and water resources will need to be minimised if humans continue to intensify production and utilisation. Hence the main challenges to improving the livelihoods of the small-scale farmers are how to upgrade rainfed agriculture to improve rural livelihoods and how to conserve ecosystems, and upgrade upstream landuse in balance with water needs for human and ecosystems downstream (Ngigi, 2003).

An increase in pressure exerted upon the available water resources often corresponds with new ways of thinking regarding how to improve productivity without negatively impacting other water resource users. Runoff Harvesting, a topical water system innovation, is one such approach. However the extent to which such development can take place is limited by the availability of natural resources, especially water and land. Additionally there are negative impacts that corresponding development has on ecosystems and society which depends on these natural resources. Thus the ultimate challenge of sustainability-oriented environmental management is to find a proper balance between human needs and the impacts caused to the environment (Falkenmark, 2003b). To fulfil this, food production needs to be sufficient but still take into account the importance and existence of natural ecosystems to ensure the well being and functioning of these ecosystems particularly, in the context of integrated water resources management. However major threats to sustainability are likely to persist due to pressures emanating from a poverty stricken rural sector, as more and more people attempt to make a living out of dwindling resources (Alexandratos, 1995). This has been a major realisation by the "Smallholder System Innovations in Integrated Watershed Management" (SSI) Programme.

1.1 SSI Background

SSI is a research programme adopted to address the challenges of increasing food production, improving rural livelihoods, while safeguarding critical ecological functions (Rockström *et al.*, 2004). The programme aims at filling research gaps to enable unanswered questions to be answered regarding how far rainfed smallholder land management can go in securing human livelihoods in semi-arid regions; what the upstream-downstream implications of upgrading of rainfed agriculture are; how scales interact from field to river basin; and what the trade-offs are between water for food and water for the environment (Bhatt *et al.*, 2006). The work reported herein forms one aspect of a multi-disciplinary project aimed at developing smallholder system innovations in the context of integrated water resources management. Increasing pressures arising from population growth and expansion worldwide, more specifically developing African countries necessitates the need for such an approach. The SSI research is carried out in two river basins in Southern Africa; the Pangani basin in Tanzania, and the Thukela River basin in South Africa (Bhatt *et al.*, 2006). Lessons from the study are associated with all areas within sub-Saharan Africa as expanded upon in Chapter 5, however, this study is focused more on the Thukela River basin, in particular a sub-catchment, the Potshini catchment, and Quaternary Catchments in the headwaters of the basin as detailed in Chapters 3 and 4.

1.2 Research Aims and Objectives

The primary aim of research described herein is to add knowledge, through the use of various tools, about the ecohydrological[1] impacts that are likely to occur should there be widespread adoption of water system innovations for upgrading rainfed smallholder farming systems. To fulfill this, the objectives of this study were;

a) to identify areas that are suitable for the adoption of runoff harvesting in the Potshini catchment; and

b) to assess the potential impacts on downstream ecosystems resulting from large-scale implementation of runoff harvesting.

[1] Ecohydrology is used here from a water perspective to describe the interactions between hydrological and ecological processes to better understand the connections and responses leading to catchment degradation.

1.3 Document Structure

This dissertation is structured whereby the main body comprises three chapters, the first highlighting background literature and the later two written essentially as research papers, preceded by an overall introduction and followed with a final discussion. Although the research chapters are intended for specific journals, they are written in a format that is consistent with that of this dissertation.

Chapter 2 is based on the relevant literature that brings to light perceptions of rainfed agricultural systems, the limitations that are experienced, possible water system innovations that can be introduced into rainfed systems to improve the current situation while emphasising the likely ecohydrological constraints associated with the adoption of water system innovations. This forms the basis for the two research chapters that are to follow; Chapter 3 describes a possible solution for locating sites that will be most suitable for harvesting runoff through spatially explicit modelling of physical and socio-economic characteristics of a catchment, the Potshini catchment. Subsequently, Chapter 4 presents a modelling study that quantifies the reduction imposed by large-scale runoff harvesting and using this information to illustrate the downstream impacts to aquatic ecosystems through the alteration of the flow regime upon which vital ecosystem functioning is dependent.

2. REVIEW OF RAINFED AGRICULTURAL SYSTEMS WITHIN AN ECOHYDROLOGICAL CONTEXT

The connections between water and food are receiving increasing attention as concerns begin to encompass the realities of water availability (Gleick, 2000). According to the Comprehensive Assessment of Water Management in Agriculture (2007) it will be possible to produce food for a growing population, however, if the current food production and environmental trends are continued, many parts of the world will face crises. Climatic and hydrologic variations will continue to dominate the challenges faced by water resource managers in balancing the demands of water for humans and their social systems with those of ecological systems (Taylor, 2006). Unfortunately it is the poor developing countries, such as those in sub-Saharan Africa (SSA), where concerns as to achieving such a balance are considered to be most critical. Most of SSA faces difficulties caused by low, variable rainfall which results in limited and poorly distributed water resources (Ngigi, 2003). Furthermore, the majority of the farmers in this region depend on rainfed agriculture for their livelihoods (SIWI, 2001). At present 97 percent of the agricultural land in sub-Saharan Africa is under rainfed agriculture (Rockström *et al.*, 2004). Thus an enormous potential exists to improve the viability of site-specific techniques to improve crop productivity (Fox and Rockström, 2000) particularly regarding more efficient and sustainable use of water resources. It is therefore important to realise the value of improving the management of water resources, particularly in regions such as SSA, because of the dominant role that rainfed agriculture plays in food production in this region. However, there is also an imperative to balance this need with those of ecosystems.

2.1 Problems Associated with Rainfed Agriculture in Semi-Arid Regions

Rainfed agriculture dominates in SSA and worldwide it produces some 55 percent of the gross value of crop production from 75 percent of harvested land (Comprehensive Assessment of Water Management in Agriculture, 2007). Despite efforts to improve crop production systems, rainfed production systems in semi-arid regions (e.g. SSA) have been very much neglected (Twomlow, 1994). It is clear that in these regions water scarcity is one of the major threats to agricultural development (Nasri *et al.*, 2004). Rainfall patterns are unpredictable, both in quantity and timing (Vorhauer and Hamlett, 1996; Mbilinyi *et al.*, 2005) and this has major implications for crop production within the rainfed agricultural sector. An additional difficulty that contributes further to the problem of water scarcity is poor rainfall partitioning, i.e. that is only a small fraction on rainfall reaches the root zone (Rockström, 2000). Consequently smallholder farming systems in SSA are continuously subjected to pressures as a result of the rainfall variability and the lack of adequate soil water that is associated with the poor partitioning of rainfall.

2.1.1 Limited water resources

Many people dependant on rainfed agriculture are highly vulnerable to both short-term (two to three weeks) dry spells and long-term (seasonal) drought (Comprehensive Assessment of Water Management in Agriculture, 2007). SSA is characterised by a high risk of periods of below optimal cumulative rainfall, which leads to poor soil water availability during the growing season, and a poor rainfall distribution (Rockström, 2000). The average annual rainfall varies from 400 to 600 mm in the semi-arid zone, and between 200 and 1 000 mm from the dry semi-arid to the dry sub-humid zone (Rockström, 1999; Rockström, 2000; SIWI, 2001). Incorporating the cumulative evapotranspiration of 600 to 900 mm over the growing period constitutes a major contributing factor to the dryness of these water scarce regions (Rockström, 1999; SIWI, 2001; Ngigi, 2003). In spite of this, the limited availability of water still needs to supply domestic, agricultural, industrial and ecosystem requirements and as a consequence, water scarcity is seen as the greatest threat to food production (Seyam *et al.*, 2002).

The overall result of unpredictable and variable spatial and temporal rainfall patterns is a common occurrence of meteorological droughts and an even greater chance of intra-seasonal dry spells (Rockström *et al.*, 2002). These events are particularly significant due to their probability of occurring during critical growth phases of the crop. However, Gowing (2003) highlighted that excessive yield reduction or total crop failure could occur even where seasonal rainfall is reasonable, a situation that has mainly been attributed to inadequate moisture in the root zone due to poor rainfall partitioning. As a consequence, concerns relating to problems of food security and famine need urgent solutions, especially in semi-arid environments where environmental degradation has further decreased agricultural productivity, making inhabitants even more susceptible to drought and other natural disasters (Ngigi, 2003).

2.1.2 Rainfall partitioning

In dry environments, one of the most important aspects of the hydrological cycle is the partitioning of rainfall into surface runoff and infiltration (Parsons, 2005) and this is termed by Rockström (2000) as the "first partitioning point". A second partitioning takes place as infiltrated water (i.e. soil moisture) is divided into evaporation from soil, transpiration from plants, and groundwater recharge (Falkenmark and Rockström, 2004). Rockström (2000) highlighted that poor rainfall partitioning, where only a small fraction of rainfall reaches the root zone, is a major contributing factor to the problem of water scarcity in semi-arid regions of SSA. Figure 2.1 shows a conceptual overview of the partitioning of rainfall that relates specifically to rainfed agriculture in semi-arid regions of SSA. Typical to these regions, high evaporative demands result in large proportions of non-productive water flows in the water balance whereby 30 – 50 percent of the rainfall is appropriated to soil water evaporation (Rockström, 1999). Of the 75-90 percent of rainfall that infiltrates into the soil, crops transpire only about 15-30 percent i.e. productive or "green water flow" (Falkenmark and Rockström, 2004). The remaining water, after productive and non-productive evaporation demands are met, contributes to "blue water" or runoff as detailed in section 2.2.1. Arguably, this partitioning is the key to understanding and enhancing water productivity in a dry environment (Parsons, 2005). A study conducted by Kosgei *et al.* (2007) in semi-arid conditions revealed that land use practices e.g. conservation tillage influences water partitioning by encouraging infiltration and retention of soil moisture through out the crop growing period. This is vital from a rainfed agricultural perspective where inadequate infiltration and soil moisture have been shown to dramatically reduce crop yields.

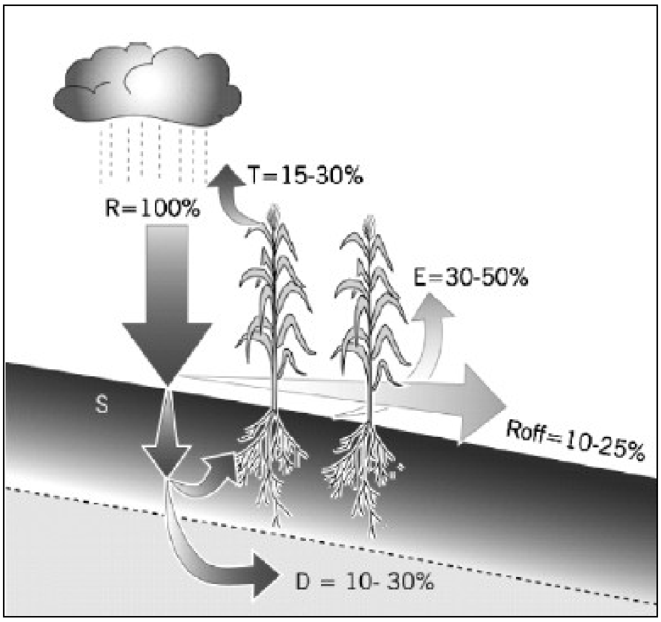

Figure 2.1 General overview of rainfall partitioning in farming systems in the semi-arid tropics of sub-Saharan Africa. R = Rainfall, T = Transpiration, E = Evaporation from soil and interception, Roff = Surface runoff, S = Soil moisture and D = deep percolation (Rockström *et al.*, 2002).

Consequently, poor rainfall partitioning has led humans to search for ways of capturing, storing, cleaning, and redirecting freshwater resources in efforts to reduce their vulnerability to irregular river flows and unpredictable rainfall (Gleick, 2000). Traditionally, increasing food production to meet growing food demands tended to concentrate on irrigated agriculture (Fox and Rockström, 2000). However many of these projects have proven to be unnecessary, costly and environmentally unsustainable (Ngigi, 2003). The neglect of other, more economically viable solutions has been the main cause of agricultural development particularly for the regions with deficient water resources. Only in recent times has it been acknowledged that an important challenge, especially in semi-arid regions of SSA, is to improve rainwater use efficiency by maximising infiltration and root water uptake in agriculture (Rockström, 1999).

2.2 Understanding Water in the Landscape

Water both sustains and constrains land use, which in turn, influences catchment hydrological functioning by partitioning incoming precipitation into runoff, ground water recharge and evaporation (Hope *et al.*, 2004). All these processes take place within the catchment where rainfall is shared between terrestrial and aquatic systems, and between the environment and society (Falkenmark, 2003b). Hence the role that water plays within the landscape is intricate and such complexities are more pronounced in water stressed environments (i.e. SSA) where the limited availability of water resources may be restricted further by land use impacts. Biophysical processes that influence the movement of water at the land and water interfaces as runoff, baseflow and groundwater recharge, as well as the flow of water vapour as transpiration, all of which need to be better understood, spatially, temporally and organisationally (Taylor, 2006).

2.2.1 Hydrological flow paths: The Green Water Context

The “Green Water Context” highlights that rainwater represents the ultimate water resource, part of which vaporises or is stored in the soil (green water), while the rest forms runoff or groundwater (blue water) (Falkenmark, 2003a). Green water flow refers to the commonly used term evapotranspiration, which combines the transpiration from plants and trees (productive green water) and the evaporation flows from soil and interception (non-productive green water) (Falkenmark and Rockström, 2004). In effect “Green water” flows are sources from soil moisture storage. “Blue water” flow is the total runoff including the sum of surface runoff, produced from the partitioning of rainfall at the land surface, and groundwater recharge, produced from the partitioning of soil water in the soil profile (Rockström, 1999). Differentiation of these flow paths is important for understanding the links between the various components of the landscape. The hydrological cycle links the different ecosystems of rivers, wetlands, lakes and groundwater, with terrestrial ecosystems beyond the stream channel and floodplain through its energy, sediment and water flows (Taylor, 2006). Figure 2.2 shows that the linkages and inter-relationships between green and blue water flows in aquatic ecosystems and the broader environment can be explored via the hydrological cycle (Ashton *et al.*, 2005). Hence rainfall is shared between terrestrial and aquatic systems and between the environment and society and any human induced impacts within one ecosystem can become indirectly manifested within other ecosystems.

2.2.2 Integrating water flows

For many years, the water resource management focus has been on blue water flow which is used for irrigated agriculture, industry and households (Rockström *et al.*, 1999). Gleik (2000) attributed population growth, changing standards of living, and expansion of irrigated agriculture as being three major drivers to the enormous expansions of water resources infrastructure during the twentieth century. However, this past "blue revolution" is becoming less favourable and there is tendency towards a present and future green water phenomenon where efforts are concentrated in other areas where humans benefit, such as the dominant rainfed agricultural sector. This has mostly been due to the growing realization that such an approach to water resource management, which considers accessible blue water flow as the only freshwater involved in societal development, needs to be widened to involve functions of both green and blue water flows (Bhatt *et al.*, 2006). The dominant role that green water flow has on the hydrological cycle has led to much interest, particularly in semi-arid and arid regions, where small changes in green water flows have a major impact on downstream blue water flows (Jewitt, 2006). Understanding the green/blue water concept within water resources management is a fundamental approach for assessing water flows to be appropriated for future food production (Falkenmark, 2003a). In South Africa, the National Water Act (Act no.36 of 1998) recognises that integrated management of water resources in needed in order to achieve sustainable use of water because of the different components of the hydrological cycle (Ashton *et al.*, 2005). Hence, there is provision to improve the way in which South Africa's water resources are managed through better knowledge of blue and green water flows.

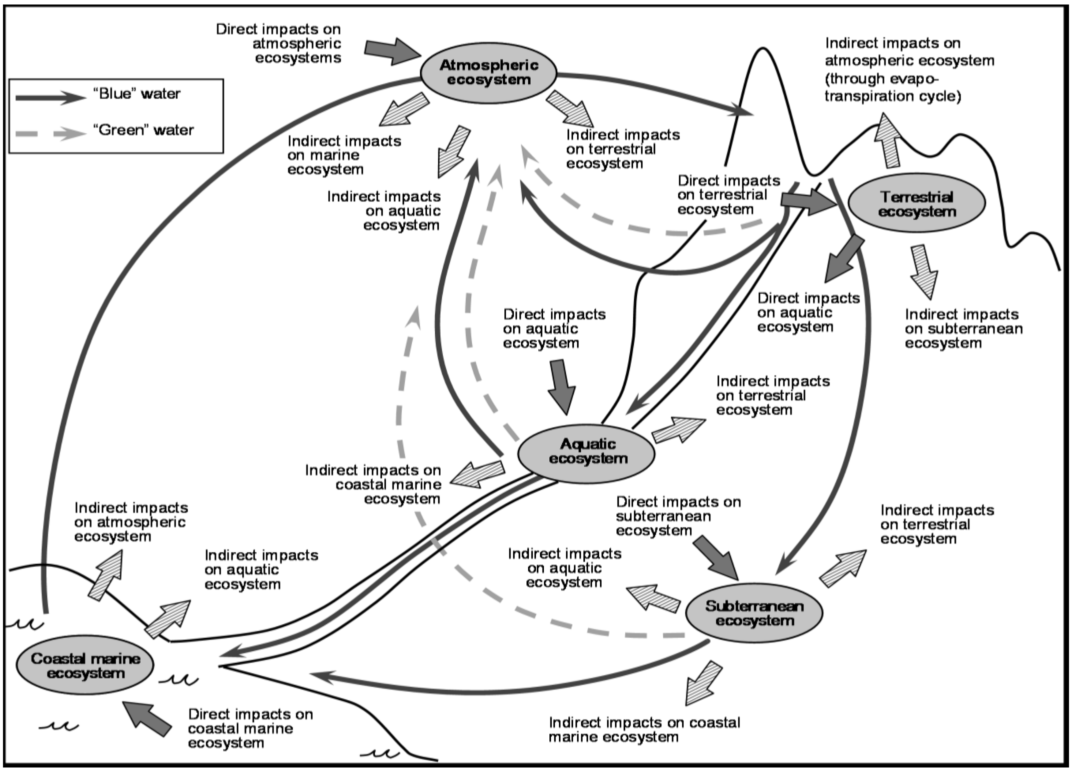

Figure 2.2 Phases of the hydrological cycle (Ashton *et al.*, 2005).

2.3 Linking Ecosystems with Water and Society

As indicated, catchments form the fundamental unit in hydrological cycle (*c.f. Section 2.2*). It is within the catchment that all water-dependent human activities and ecosystems are enclosed (Falkenmark and Rockström, 2004). Thus there is a closely linked relationship between human societal systems and ecological systems both of which depend largely on water for their existence.

The integrity of natural systems is valued by society mostly because of the goods and services that are provided for production and consumption uses (Hope *et al.*, 2004). Of particular significance are the goods and services generated by the movement of water through the landscape that have been assumed to make significant contributions to the livelihoods of rural communities (Hope *et al.*, 2004). This movement of water through the landscape, as shown in Figure 2.2, contributes to production (e.g., crops, timber, livestock), information (e.g., nature experiences), regulation (e.g., formation of topsoil, carbon dioxide sequestration), and functions of the environment (Jewitt, 2002).

Functioning ecosystems maintain ecosystem services and biodiversity and therefore ecological health and well-being, which therefore maintain an array of ecosystem goods for the benefit of humans and society (Taylor, 2006). Threats to ecosystem services and biodiversity result from a wide variety of human activities and from a lack of value given to ecosystem services to ensure long-term, social well-being (Daily, 1999). However the global human demand for ecosystem goods and services continues to intensify as agricultural, domestic and industrial uses increase to meet the desires of burgeoning populations (Taylor, 2006). Thus a key step to the sustainable development of ecosystem services is to facilitate further understanding into the use of water for human benefit, both directly and indirectly, and to ensure that the gains resulting from ecosystem services are viable.

2.3.1 Supply of goods and services

Both blue and green water flows support ecological functions and delivery of ecosystem goods and services and both are also a precondition for human survival and societal development (Falkenmark and Rockström, 2004). Services provided by ecosystems are processes that produce, or support the production of, ecosystem goods, regeneration processes, stabilising processes and preservation of options needed for future supply (Daily, 1999). These services are generated by a complex interplay of natural cycles, powered by solar energy and operating across a wide range of space and time scales, and incorporating both biotic and abiotic components (Jewitt, 2002). Ecosystem goods are physical elements that are directly, or indirectly, consumed by humans.

Human society benefits from aquatic ecosystem services by using freshwater from rivers, springs, wetlands and lakes for many different agricultural, industrial, urban, household and recreational activities (Baron *et al.*, 2002). In the agricultural sector ecological goods and services are produced and utilised as a result from using the environment in a way that is valued by society (Gerowitt *et al.*, 2003). Unfortunately, aquatic ecosystems are facing the greatest threats that poses much concern, probably because the condition of these systems has direct impacts on the lives of people (Taylor, 2006). This presents a major problem in that aquatic ecosystems essentially drive the blue water flow domains thus affecting the generation of ecosystem goods and services from which human society benefit.

2.3.1.1 Water flow domains

Fulfilling the shift towards an ecohydrological paradigm requires the integration of water flows that support the various uses and functions from which humans may benefit. Four ecohydrological domains exist within which freshwater functions are sustained as a result of partitioning rainfall into green and blue water flows. Table 2.1 conceptualises the role played by both green and blue water flows in sustaining direct and indirect ecological functions and services that benefit humans as part of the integrated approach to freshwater management (Falkenmark and Rockström, 2004; Rockström *et al.*, 2004). The water flow domain is divided into green and blue water flows, and the use domain, into direct uses and indirect uses. The conventional focus of water resources management has been on the direct blue water use (Bhatt *et al.*, 2006). However humans also benefit directly from green water flow which sustains rainfed agriculture, as well as other water dependent ecosystems, such as forests, woodlands, grazing lands, grasslands, and wetlands (Rockström *et al.*, 2002). Indirect use of green and blue water fulfils the supportive role to maintaining biodiversity and ecological resilience. This benefits humans in an indirect way, such as green water flow supporting biomass growth in grasslands, natural forests, wetlands, meadows etc., that forms the habitat for a vast biodiversity of flora and fauna (Falkenmark and Rockström, 2004; Bhatt *et al.*, 2006).

Humans are direct beneficiaries of the green and blue water flows from which they receive economic biomass growth. It is the indirect benefits, however, that are equally, if not more, important to societies and should receive greater attention to better understand the relationships with ecosystem functions (i.e. indirect blue water flows). It is useful that distinction can be made between functions generated by green and blue water flows, and between direct and indirect uses of water. However quantifying human dependence on water flows is not easy and very few attempts have been made to quantify the volumes of direct and indirect green flows and indirect blue flows (Falkenmark and Rockström, 2004).

Table 2.1 The four freshwater use domains for an integrated approach to freshwater management indicating (After Falkenmark and Rockström, 2004).

Use Domain	Water flow domain	
	Green	**Blue**
Direct	**Economic Biomass Growth**	**Economic Use In Society**
	Rainfed food, timber, fibres, fuel wood, pastures, etc. (Direct human consumption)	Irrigation, industry, domestic/municipal (Direct human consumption)
Indirect	**Ecosystem Biomass Growth**	**Ecosystem Functions**
	Plants and trees in wetlands, grasslands, forests and other biotopes. Habitats for fauna and flora (Biodiversity, resilience)	Aquatic freshwater habitats for plants. (Biodiversity, resilience)

2.3.1.2 Aquatic ecosystem functioning

Aquatic ecosystem functioning within the water resources system is an integral component for the provision of various, water related services that society depends on to support the well being and livelihoods of people and to promote socio-economic development (Taylor, 2006). It is in this context that the productive function of water, used for economic development, requires serious attention (Falkenmark, 1997). However it is important to acknowledge that the production and utilisation of ecological goods and services is not only considered for its productive value (Gerowitt *et al.*, 2003) but also for its intrinsic value.

Aquatic habitats and wetlands fall within the indirect blue use domain within which ecological functioning and ecosystem services are secured (Falkenmark and Rockström, 2004). As a consequence to their positioning within the landscape, aquatic ecosystems are subjected to numerous impacts that arise indirectly from upstream aquatic and terrestrial systems as a result of human alterations, including the regulation of flow, pollution and consumption (Figure 2.2). This means that to secure correct ecosystem functioning in aquatic environments, adequate volumes of river water of suitable quality need to be sustained to ensure that biodiversity and resilience are conserved. Unfortunately, unsustainable use of freshwater has overlooked its value in supporting the aquatic environment (Baron *et al.*, 2002) to the extent that in many cases, biodiversity and ecosystem functioning can only be recovered through restoring natural hydrological responses to some degree (Strange *et al.*, 1999). The intricate connections between water and land are likely to become more important into the future especially with the advent of changing land uses that conform to the requirements of humans and societies. This has already led to quests to ascertain how much water aquatic systems need to maintain their physical and biological functioning and ensure that thresholds of ecosystem sustainability and resilience are not exceed through over utilisation (Taylor, 2006).

2.3.2 Significance of the natural flow regime

The flow regime is regarded as a key driver of river and floodplain wetland ecosystems (Bunn and Arthington, 2002). In assessments of environmental water requirements, a dominant view that emerged in recent years is the allocation of flow to the environment, specified as a minimum flow (Smakhtin and Shilpakar, 2005). However this contradicts the need to maintain flow variability in a river. Since flow variability maintains various ecological processes, which in turn generate ecosystem goods and services; there is a need for consideration of how to secure a sustainable flow regime that is suited to maintaining ecological processes.

Temporal variation of the natural flow regime includes wet and dry years, timing and duration of flood pulses, frequency of floods and droughts, and rates of change on rising and falling river levels (Taylor, 2006). Spatial variation of the natural flow regime takes into consideration any climatic, geological and topographical regions as well as the heterogeneity of stream ecological organizations (e.g., catchments, river reaches, riffles and pools) (Taylor, 2006). Bunn and Arthington (2002) reviewed four key principles to highlight important mechanisms linking hydrology and aquatic biodiversity, in space and time, and the consequent impacts of altered flow regimes (Figure 2.3). Each flow event, making up the natural flow regime, has specific ecological functions to fulfil. The four principles, driven by various hydrological mechanisms, as illustrated in Figure 2.3, indicate how vital spatial and temporal variations in flow events are to aquatic biodiversity.

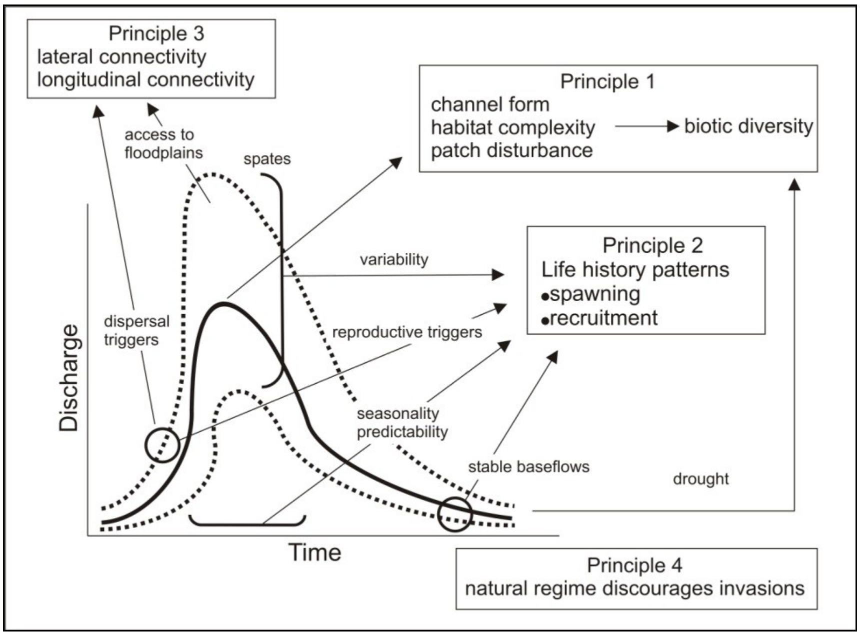

Figure 2.3 Mechanisms of the natural flow regime influencing aquatic biodiversity over different spatial and temporal scales (Bunn and Arthington, 2002).

Subsequent to alterations in the natural flow regime, the hydrological regime determines the riverine habitat availability and seasonal changes provide the necessary cues for the life cycles of specific organisms (Taylor, 2006). More specifically, high flows of different frequency are important for channel maintenance, wetland flooding and maintenance of riparian vegetation while moderate flows may be critical for cycling of organic matter and fish migration (Smakhtin and Shilpakar, 2005). Extremely important to the natural flow regime are low flows. Different magnitudes of low flows are important for algae control, water quality maintenance, etc. (Smakhtin and Shilpakar, 2005). The resulting influences of spatial and temporal variations in the flow regime are on the abundance and distribution of benthic macroinvertebrates (Smakhtin, 2001).

2.3.3 Balancing the needs of water

It has been highlighted that tradeoffs will be required if future water demands by humans are to be met and at the same time to ensure that ecosystem functions and services are maintained. Falkenmark (2003a) suggests that huge additional amounts of green water flow (some 3.1 times the present amount for SSA) will have to be appropriated in order to feed future populations at acceptable nutritional levels. Any modifications to natural systems result in a trade-off between the additional (artificial) benefits gained and those which are lost as human regulation negatively impacts on some natural functions (Jewitt, 2002). Land use changes in a catchment directly affect water flow availability to sustain ecosystems (Falkenmark and Rockström, 2004). Semi-arid and arid regions are affected the most, as the burgeoning populations lead to expansion of agricultural lands to produce even the smallest of yields from the complicated growing conditions. Additionally, unintended impacts from agricultural developments (e.g. runoff harvesting) may result in impacts on flow variability, ecological requirements and functions being unnoticed (Taylor, 2006).

Complete restoration of natural hydrology is generally not an option in human-dominated river systems highlighting the need to determine specific flow manipulations that are necessary to restore species-dependent ecosystem services in particular systems (Strange *et al.*, 1999). Furthermore, in the context of green water flows, the issue is not just equitable sharing of blue water in the rivers, but rather how to share the precipitation falling over the river basin (Falkenmark, 1997). Here the relationship between the hydrological cycle and ecological goods and services is an important realisation in water resources management and it should be acknowledged that land management and river management go hand in hand (Taylor, 2006). To do so it is important to have an understanding of the role of different components of the hydrological regime and their relationship with the ecosystem functions.

Falkenmark and Rockström (2004) called for a new approach to ecohydrology with adequate focus on both green and blue water through an integrative approach that includes all water flows in the hydrological cycle, as well as the ecological functions of water. In rainfed agricultural systems, Falkenmark (1997) suggests that non-productive water losses be minimised, the equivalent of maximising green water productivity, as a strategy for sustainable man/land/water interaction. Equally important to ensuring sustainability is to conserve biodiversity, arising from functional, structural and compositional diversity, at multiple scales within a landscape, along with the ecological processes within it (Jewitt, 2002). Suggestions like these need to be integrative where water requirements of both the environment and humans can be balanced to ensure sustained societal development.

2.4 Water System Innovations for Rainfed Agriculture

Rainwater harvesting, defined as the collection of water for productive use, is an appropriate method for adding extra water through supplementary irrigation to compensate for soil water deficiency and to reduce the risk of plant damage during dry spells (SIWI, 2001). It includes all methods of concentrating, diverting, collecting, storing, and utilising and managing runoff for productive purposes (Ngigi, 2003). Historically, many rainwater harvesting techniques have been developed, only to be neglected, giving way to modern irrigation techniques. However, a resurgence of interest from the beginning of the 1990s, has resulted in traditional systems being restored in many places e.g. Tunisia (Nasri *et al.*, 2004).

Rockström (2000) described many techniques of conservation tillage, runoff farming, flood irrigation and supplemental irrigation that have been put into practice throughout arid and semi-arid regions of Africa. Such rainwater harvesting systems do not necessarily focus on improving the water-use efficiency (water used per biomass output), but primarily to reduce the huge variability in potential and actual yield gaps over time (Fox and Rockström, 2000).

2.4.1 *In situ* water harvesting

Within the context of rainfed agriculture, attention has been focused on ways to limit surface runoff and improve soil water infiltration in the crop fields (soil conservation approach). This gave rise to various soil conservation technologies that retain water and improve infiltration, such as mulching, reduced tillage, terracing, bunds and pitting (SIWI, 2001). *In situ* systems dominate in SSA and are methods used, on-farm as water conservation, to enhance soil water infiltration and water holding capacity (SIWI, 2001) thereby extending the water availability to the crop and hence improve yields (Kosgei *et al.*, 2007). These methods are mostly devised as a result of land preparation techniques (Kosgei *et al.*, 2007). Ultimately they aim to conserve the rainfall where it falls in the cropped area (Ngigi, 2003).

Most commonly practiced in rainfed agriculture is conservation tillage, which helps to store more water in the soil profile and reduce evaporation from the surface and has potential to greatly increase productivity (Molden and Falkenmark, 2003). Rockström (2000) defined conservation tillage as any tillage sequence having the objective to minimize the loss of soil and water, and having an operational threshold of leaving at least 30 percent mulch or crop residue on the surface throughout the year.

In situ water conservation is one of the simplest and cheapest methods and can be practiced in almost all rainfed systems. However the risk of crop failure is only slightly lower compared to using no measures (Ngigi, 2003). A project conducted by the Department of Soil Science at the University of the Free State where runoff plot data was used in an attempt to determine the effects of crop management and tillage practices on the accumulation of water in the root zone (Bennie *et al.*, 1994). From measurements of the water balance and of soil and crop characteristics it was concluded that the amount of runoff was dependent on the degree of soil disturbance, which increased the soil infiltrability, and the amount of mulch cover was ineffective in reducing runoff for different tillage practices (Bennie *et al.*, 1994). In a South African study, Kosgei *et al.* (2007) found that nearly twice as much runoff was generated from plots planted under maize when using conventional tillage methods compared to plots with zero tillage. Despite the extensive presence of water harvesting systems in SSA, these are predominantly *in situ*; potential improvement is still required because of the limited use of runoff storage water harvesting (Rockström, 2000).

2.4.2 Runoff based storage systems

Traditional water harvesting techniques, aiming at diverting surface water flows to the crop fields, are quite rare in SSA (Fox and Rockström, 2000). However rainwater collected from hillslopes and manmade catchments upstream from crop lands can create new supplies by providing water for regions where other water sources are too distant, or too costly and limited (Nasri *et al.*, 2004). In runoff-based systems, surface runoff from small catchments (1-2 ha) or adjacent roads/foot paths runoff is collected and stored in manually and/or mechanically dug structures, such as tanks, reservoirs, dams, etc. (50-1 000 m^3 storage capacity), and used for supplemental irrigation (Ngigi, 2003). Figure 2.2 shows the principle of rainwater harvesting which is common for different classifications of runoff-based rainwater harvesting that depend on:

- Source of runoff (external or within-field catchments);
- Methods of managing the water (soil infiltration, storage, flood inundation); and
- Use of water (domestic, livestock, crop production, etc.) (Ngigi, 2003).

Runoff storage systems act as the farmer’s tool for water stress control by helping to reduce risks of crop failures caused by poor rainfall distribution (SIWI, 2001). But the level of investment is high and requires some operational knowledge especially on water management (Ngigi, 2003).

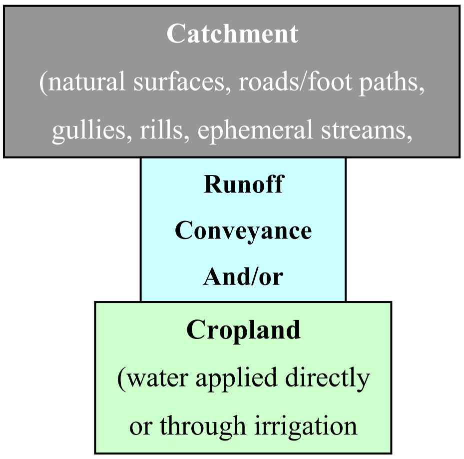

Figure 2.4 The principle of runoff-based rainwater harvesting technology (After Ngigi, 2003).

2.4.3 Potential for improving rainfed agriculture

Rainwater harvesting technologies in semi-arid regions are credited as a cost-effective and ultimately viable means to improve rural livelihoods among resource-poor farmers. However perceptions of the high risks attributed to rainfed agriculture requires a change of attitude, as currently little or no effort is given to supplement low soil moisture content as well as nutrient deficiencies. Should the availability of water be improved, farmers could be driven to invest more into crops, such as through fertiliser application, to further improve the prospects of obtaining a good harvest (Fox and Rockström, 2000). Supplemental irrigation combined with rainwater harvesting contributes to water productivity by protecting crops from yield reductions caused by dry spells to obtain “more crop per drop” (Molden and Falkenmark, 2003). However this form of irrigation differs from commercial irrigation in that the farmer has little control over timing, as runoff can only be harvested during a rainfall event (Ngigi, 2003).

Erosion control measures have made farming on hill slopes more profitable and less destructive and by introducing rainwater harvesting it will be possible to earn a more sustainable living in semi-arid areas (Bunch, 2000). Synergies are likely to occur as benefits from rainwater harvesting generate a cascade of further potentially beneficial effects. Progressive increases in biomass production will result in higher restitution of crop residues, resulting in increased contents of organic matter, which in turn would increase the long term nutrient and water productivity of the soils (Rockström, 1999). Additionally rainwater harvesting minimises some of the problems associated with conventional irrigation such as competition for water between various uses and users, low water use efficiency, and environmental degradation (Ngigi, 2003).

2.5 Implications of Adopting Runoff Harvesting

In order to feed humanity at acceptable nutritional levels, an enormous amount of water is required. However given the environmental constraints the most appropriate way for the demands to be met is through the increased 'crop-per-drop' concept (Falkenmark, 2003a). An appropriate approach is the adoption of runoff harvesting techniques. However, diverting more water for agriculture may have serious implications for other water users and water using activities and systems (Bhatt *et al.*, 2006). This is largely because the majority of the water collected through runoff harvesting will not be made available for reuse via rivers and aquifers and merely return to the atmosphere as green water flows. Semi-arid regions are faced with further problems, as a significant amount of green water is lost as non-productive flows to the atmosphere (i.e. through soil water evaporation) due to limited soil water conservation and large proportions of exposed soil surfaces. Falkenmark (1997) found that for Southern Africa an average of 65 percent of the rainfall returns to the atmosphere through evaporation (non-productive) and only 20 percent enters the root zone for green water use, while the remaining 15 percent recharges the aquifers and rivers as blue water.

The widespread adoption of runoff harvesting technologies may be held up by the challenge to determine how much water river systems need to maintain their physical and biological functioning and to ensure that the thresholds of ecosystem sustainability and resilience are not exceeded through over utilisation. Understanding the response of water within catchments provides an indication of the likely affects that rainwater harvesting technologies could have on downstream hydrologic and ecologic processes.

2.5.1 Downstream hydrological impacts

Land use influences catchment hydrological responses by partitioning rainfall between return flow to the atmosphere as evaporation and transpiration (green water) and flow to aquifers and rivers (blue water) (Hope *et al.*, 2004). Beyond the stream channel and floodplain, land based activities (i.e. agriculture) influence the hydrological cycle by altering the natural flow-paths of precipitation and streamflow generating mechanisms (Taylor, 2006). With conventional irrigation blue water is redirected during the growing season which is converted into consumptive green water (Falkenmark, 2003a). This results in reduced flood flow, during the wet season, and more problematic reductions of dry season flow (Falkenmark, 2003a). Depending on the scale of adoption, runoff harvesting could have similar impacts to conventional irrigation.

Although supplemental irrigation using stored surface runoff is considered favourable for improving crop production, the downstream impacts are not well known. Runoff harvesting, as in conventional irrigation, involves abstraction of water in the catchment upstream and may have hydrological impacts on downstream water availability and up-scaling could have hydrological impacts on river basin water resources management (Ngigi, 2003). It is possible that supplemental irrigation will increase the recharge of water to the root zone and then beyond the root zone to groundwater. In this case, any return flows from agricultural fields contribute to additional sub-surface flows and/or base flows to the river channel and consequently contribute to the river's water balance (Smakhtin, 2001). However, Jewitt (2006) cautioned that the water that is stored in the soil may not necessarily move beyond the root zone, to contribute to groundwater, and then is not available to downstream users.

It is important to analyse the downstream effects on water availability before introducing a technique which captures surface water upstream (Rockström, 1999). Nasri *et al.* (2004) highlighted that few studies have focused on such hydrological aspects. As a result studies such as the one by Nasri *et al.* (2004) have been undertaken to obtain measurements, including rainfall, runoff and infiltration, to investigate how a traditional runoff harvesting scheme influences catchment water balance. In their study in Tunisia the harvesting systems significantly reduced runoff peaks within the catchment and total runoff was reduced to zero (Nasri *et al.*, 2004). Such studies are critical for understanding the hydrological affects of small-scale developments and results caution that impacts of runoff harvesting on the hydrology, especially if applied to larger spatial scales (i.e. catchment/river basin).

2.5.3 Possible impacts on ecosystems

In recent years it has become more and more evident that large-scale increase of irrigation is not a favourable solution towards agricultural development, particularly from an ecological perspective. This is mostly due to the negative effects that intensive irrigation practices have on downstream aquatic ecosystems; these impacts are exacerbated even further with continued expansion of irrigated lands (Falkenmark, 2003a). In particular is the increasing green water flow associated with intensified crop production which alters the water balance resulting in an impact on ecological performance (Rockström, 1999). Consequently, runoff harvesting systems that are used for supplementary irrigation are becoming more accepted as an approach to improve agricultural production, particularly in the subsistence sector. Here systems may operate at different scales (household, field and catchment/basin), and have the potential to affect water availability and management for downstream ecosystems, due to reduced catchment yields (Rockström, 2000; Ngigi, 2003).

Natural disturbances, such as fires, floods, droughts, etc., have always played an integral role in most intact ecosystems by regulating population size and species diversity across a range of spatial and temporal scales (Lytle and Poff, 2004). It is because of disturbances such as these that organisms have become adapted, to the extent that they depend on the occurrence of these events for their survival. More recently the natural flow regimes of most river systems have been altered by human interventions, of which agriculture has had a major influential role. This has led to the processes of aquatic ecosystems becoming influenced by the utilisation of ecosystem goods and services that are provided (Taylor, 2006). As a result, free-flowing rivers, natural riparian systems, and many aquatic species have become increasingly rare and even valued (Gleick, 2000). This raises concerning questions that relate to both the evolution and conservation of biodiversity in aquatic ecosystems (Lytle and Poff, 2004) as well as the realisation of the value that ecosystems have to society.

Every aquatic ecosystem requires a certain amount of water, especially varied patterns and timing, to maintain its ecological integrity (Smakhtin, 2002). However, improved agricultural production from supplemental irrigation converts blue water to green water (vapour), leading to reduced river flows downstream or depleted ground water reserves (Molden and Falkenmark, 2003). Thus, increasing use of water in rainfed and irrigated agriculture may have negative implications on water availability to sustain downstream ecosystem services (Ngigi, 2003). Unfortunately the impact of changing the land use, particularly in regions where green water dominates the hydrological cycle, on the generation of goods and services flows is rarely considered explicitly (Hope *et al.*, 2004). Therefore an important component for the planning and management of water resources is to determine the potential impacts that runoff harvesting could have on downstream river systems especially in terms of sustaining the flows required aquatic ecosystem functioning. The maximum extent that runoff harvesting can be implemented within a catchment system needs to be assessed and quantified. This will ensure that river systems are not altered to levels that are detrimental to ecosystems as well as to fulfill improved livelihood development through benefits attained by runoff harvesting and supplementary irrigation.

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As highlighted in this review, rainfed agriculture is restrained by difficult growing conditions particularly in arid and semi-arid regions; poor crop yields are testimony to this. However, rainfed agriculture holds the greatest potential to close the gap of projected food shortages. Harvesting rainwater has consequently been identified as a valuable enterprise to improve crop water availability and hence productivity, however, at a cost of potentially depleting downstream water resources which may be detrimental to aquatic ecosystems. The following chapter (i.e. Chapter 3) presents a methodology for identifying areas that would be most suitable for runoff harvesting, which would be useful for assisting future decision making processes. Subsequently, Chapter 4 investigates the possible impacts that large-scale runoff harvesting could have and downstream hydrological and ecological regimes.

3. A GIS-BASED APPROACH FOR IDENTIFYING POTENTIAL RUNOFF HARVESTING SITES IN THE THUKELA RIVER BASIN, SOUTH AFRICA

Abstract

Water scarce countries such as South Africa are subject to various hydrological constraints which can often be attributed to poor rainfall partitioning, particularly within resource poor farming communities that are reliant on rainfed agriculture. Recent initiatives to address this have shifted focus to explore more efficient alternatives to water supply and the recognition of numerous opportunities to implement runoff harvesting as a means to supplement water availability. However, increasing the implementation of runoff harvesting, without encountering unintended impacts on downstream hydrological and ecological systems, requires better understanding of the hydrologic and environmental impacts at catchment scale. In this paper the representation of spatial variations in landscape characteristics such as soil, land use, rainfall and slope information is shown to be an important step in identifying potential runoff harvesting sites, after which modelling the hydrological response in catchments where extensive runoff harvesting is being considered can be performed and likely impacts assessed. Geographic Information Systems (GIS) was utilised as an integrating tool to store, analyse and manage spatial information and when linked to hydrological response models, provided a rational means to facilitate decision making by providing catchment level identification, planning and assessment of runoff harvesting sites as illustrated by a case study at the Potshini catchment, a small sub-catchment in the Thukela River basin, South Africa. Through the linked GIS, potential runoff harvesting sites are identified relative to areas that concentrate runoff and where the stored water will be appropriately distributed. Based on GIS analysis it was found that 17 percent of the Potshini catchment area has a high potential for generating surface runoff, whereas an analysis of all factors which influence the location of such systems, shows that 18 percent is highly suitable for runoff harvesting. Details of the spatially explicit method that was adopted in this paper are provided and output from the integrated GIS modelling system is presented using suitability maps. It is concluded that providing an accurate spatial representation of the runoff generation potential within a catchment is an important step in developing a strategic runoff harvesting plan for any catchment.

3.1 Introduction

Water scarce countries such as South Africa are subject to various hydrological constraints particularly within resource poor farming communities that are reliant on rainfed agriculture. Rainfall patterns in semi-arid areas are unpredictable, both in amount and time. Consequently, the ability to successfully manage the resulting runoff is extremely important (Vorhauer and Hamlett, 1996; Mbilinyi *et al.*, 2005). Furthermore pressures, such as poor crop production and even crop failures leading to malnutrition and loss of well-being, experienced in semi-arid areas can be attributed to poor rainfall partitioning, i.e. only a small fraction of rainfall reaches the root zone, which contributes further to the problem of water scarcity (Rockström, 2000). Another factor, associated with poor rainfall distribution, is the frequent occurrence of mid-season dry spells that consequently result in poor soil water availability during the growing season (Rockström, 2000). Milder forms of dry spells reduce yield potentials, and in more severe instances increase the risk of crop failures. Due to these circumstances runoff harvesting is particularly significant because rainwater-runoff can be captured and efficiently utilised to maintain agricultural production in an economically and environmentally sustainable manner (Ziadat *et al.*, 2006). In response people who rely completely on rainfall have over the centuries developed indigenous knowledge systems to harvest runoff that is generated and exploit niches within the landscape (Mbilinyi *et al.*, 2005). However there are consequences that may occur downstream of sites where runoff harvesting is taking place. This may include the loss of water to rivers downstream to the detriment of ecosystem services and other water users.

Rainwater harvesting in the broad sense describes all methods for concentrating, storing and collecting runoff from rainwater, for domestic and agricultural uses (Rockström, 2000; Sutherland and Fenn, 2000). These water harvesting systems can be grouped into three main types, namely; in-situ moisture conservation (soil and water conservation), concentration of runoff to crops in the field, and collection and storage of runoff water (from roofs and land areas) in different structures for both domestic and agricultural use (Falkenmark and Rockström, 2004). Specific to harvesting runoff are the different forms of surface runoff that are utilised, namely; sheet, rill, gully and stream flow (Rockström, 2000). In response to the various types of runoff are a number of options that can be chosen for storing harvested runoff, such as farm dams or reservoirs, groundwater recharge systems, check dams, tanks and bunds (which confine water in fields) (Durga Rao *et al.*, 2001).

Various harvesting systems exist throughout sub-Saharan Africa, however these are predominantly soil water conservation techniques and therefore potential improvements are still possible for adoption of runoff storage type water harvesting systems due to limited application (Rockström, 2000). In South Africa the potential of runoff harvesting has not yet been fully explored and it has been suggested that implementation could alleviate spatial and temporal water scarcity for productive use (Mwenga Kahinda *et al.*, 2005). Furthermore, attempts made to store rainwater-runoff could reduce the restrictive needs of having to grow only rainfed crop varieties due to the lack of irrigation facilities (Padmavathy *et al.*, 1993). This is particularly significant because most rural communities of South Africa are subject to a lack of land and water resources to support agricultural practices.

There is a growing need for cost effective and time saving methods for locating and identifying areas that are suitable for introducing harvesting technologies in the areas where such innovations are needed most, i.e. rainfed rural agro-ecosystems. A particularly useful approach is the application of a Geographical Information System (GIS). GIS is effective in providing a framework for collecting, storing, analysing, transforming and displaying spatial and non-spatial data for particular purposes (Padmavathy *et al.*, 1993; Coskun and Musaoglu, 2004). Advances in computer technology and GIS packages have allowed users access to the spatial management and interpolation of data without requiring specialist skills to manage and analyse large spatial datasets. Thus integrating spatial characteristics of catchments has become more efficient, allowing for improved understanding and representation of hydrological processes in the landscape. Thus the potential for applying GIS to hydrological modelling is considerable (Stuebe and Johnston, 1990) particularly when modelling accuracy is affected by estimations of spatial and temporal distributions of the water resource parameters (Gangodagamage and Clarke, 2001). As a result numerous studies have been conducted using GIS interfaces for hydrological modelling (Gangodagamage and Clarke, 2001). Durga Rao *et al.* (2001) showed that GIS can be used to identify runoff potential zones and locate suitable sites for rainwater harvesting innovations in India. Within the context of Southern Africa, Mwenga Kahinda *et al.* (2006) developed a decision support system on a national scale using a GIS interface system that aims to determine areas for rainwater harvesting. However, the approach is limited by the level of detail of the datasets that the decision support systems uses (i.e. national soils and land cover) and thus is only appropriate for application at the national scale.

In this study, potential runoff generating sites, and thus priority areas for runoff harvesting, in a small rural community at Potshini in the upper Thukela River basin are identified with the use of GIS. To achieve this objective it was necessary to identify and obtain the relevant data, develop the required databases and specify how these data are to be utilised in a GIS working environment, in order to meet the goal of reflecting the spatial extent of runoff and to prioritise sites for runoff harvesting.

3.1.1 Study area

Potshini is predominantly a smallholder farming area and forms a sub-catchment of the South African Quaternary Catchment[2] number V13D (Emmaus catchment) in the Thukela River basin in the foothills of the Drakensberg Mountains in South Africa (Kongo and Jewitt, 2006). The Potshini catchment is drained by first and second order streams that enter the Lindeque Spruit, an important tributary of the Thukela River, an important river of the KwaZulu-Natal Province (Figure 1). Topographically, the Potshini catchment has gentle slopes, suited for agronomic purposes, surrounded by steeper slopes in the upper reaches of the catchment which are predominantly used for livestock grazing. The elevation ranges from a minimum of 1219 to a maximum of 1483masl. The major crops grown are *Zea mays* (maize) and *Glycine max* (soya beans) with occasional small-scale vegetable gardens. The natural vegetation for the area is tall grass dominated by tall, but seasonally dormant grasses.

[2] The SA Department of Water Affairs and Forestry sub-divides the country's catchments into quaternary catchments for water resources management purposes.

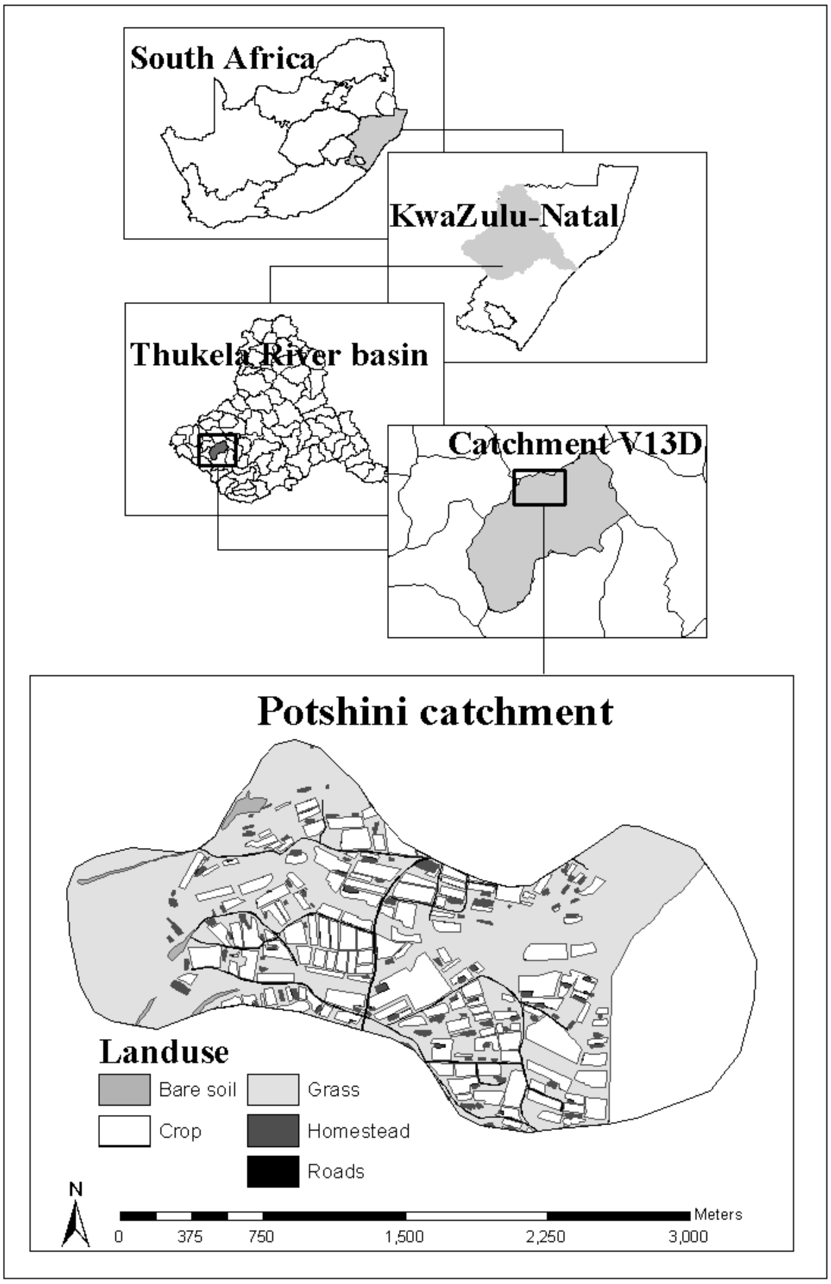

Figure 3.1 Spatial position of the Potshini catchment relative to the Thukela River Basin. Also shown is the landuse detail for the Potshini catchment.

3.1.2 Mapping criteria for runoff harvesting

The objectives and allied technologies for runoff harvesting are highly location-specific, and dependent on physiographic, environmental, technical and socioeconomic conditions. Therefore appropriate technologies are specifically developed for particular regions and cannot simply be replicated in other areas (Durga Rao *et al.*, 2001). Although most runoff harvesting systems in Potshini are subterranean storage systems, the methods described in this paper are appropriate for any form of harvesting that utilizes small reservoirs to store runoff. Rainwater-runoff is harvested from rill or sheet flow generated from small catchment areas near to the storage systems. The catchment or watershed is considered the fundamental hydrological unit in which all rainfall-runoff processes should be considered. Thus developing a site-specific approach for locating suitable runoff harvesting sites requires an integrative process at the catchment scale whereby various catchment conditions are taken into account. Hydrologically, the response of a catchment depends on rainfall characteristics, on initial moisture conditions and also on landscape characteristics (topography, soil, geology, land cover and hydrography) (Chow *et al.*, 1988). Landscape characteristics are particularly important to generate rainfall-runoff output and thus GIS technologies become increasingly significant because of their ability to present spatial data accurately (Coskun and Musaoglu, 2004).

Determining criteria to support a strategy for identifying suitable runoff harvesting sites requires a biophysical approach where information based on physically derived catchment characteristics is used for understanding the catchment's hydrological response. Such an approach is likely to save considerable amounts of the time that is required for identifying runoff harvesting sites given the availability of data. Stormflow, usually in the form of surface runoff, is the major contributing factor for runoff harvesting systems. Thus, these and the rainfall thresholds that generate them are considered to be the primary hydrological component used to identify potential runoff harvesting sites. Vorhauer and Hamlett (1996) suggested several biophysical criteria that are useful for selecting runoff harvesting sites and these include soil suitability, slope suitability, landuse, and harvesting potential for the upstream catchment. Slope steepness is considered an important criterion for selecting and implementing water harvesting interventions (Ziadat *et al.*, 2006) especially in the context of surface runoff generation. From a topographical perspective hilly areas are significant in terms of rainfall-runoff response in that high rainfall amounts are considered as a loss from the system as a significant contribution of rainwater simply runs off. This rapid runoff response from steep slopes consequently results in non-availability of water in peak demand periods, even if average rainfall remains quite high (Durga Rao *et al.*, 2001). In relation to this, the capacity of the soil to absorb, retain and release water suggests that soil is a prime regulator of the hydrological response of a catchment (Schmidt and Schulze, 1987). Soils with a high clay content, that are poorly drained, with a shallow water table, and that have a surface crust tend to produce a high stormflow response. Comparatively, soils with a low clay content, that are well drained, and deep generally have a lower stormflow response unless restrictions in the soil horizons are present (Schulze *et al.*, 1992). Impervious surfaces and soil crusting and/or surface sealing, typical of semi-arid and arid regions, are important in that they may generate Hortonian overland flow (Lycon *et al.*, 2006) rather than surface runoff generated as a result of saturation in the soil profile. In the South African rural landscape impervious areas make up a significant portion of the surface area. These impervious areas form as a result of soils being subjected to compaction and are typically characteristic of homesteads, foot paths and dirt roads. Landcover properties also play an important role in runoff generation in that vegetative cover controls how much rainwater/surface runoff is intercepted, which directly influences the partitioning of water into infiltration and surface runoff.

Criteria used for identifying potential sites for the implementation of runoff harvesting technologies should also include socio-economic factors. Sites most suitable for harvesting surface runoff are influenced by factors such as gravitation effects, potential pumping distance and conveyance costs. These and other socio-economic aspects such as distance from croplands and homesteads are also important components for locating optimal sites for runoff harvesting. Close proximity to homesteads is a key factor for harvesting surface runoff to supply subterranean tanks, as storage facilities are most likely to be constructed in and around homesteads. A secondary factor is that surface water nearest to the tanks is most suited for harvesting through the reduced need of having to direct surface water to the tanks over long distances using diversion structures. Similarly, the further the distance from croplands the less suitable the area is for runoff harvesting because of the greater need for conveyance systems.

3.2 DATA ACQUISITION

In this study, the input data required to characterise the biophysical and socio-economic parameters of the catchment were derived using available data as well as information obtained from in-field surveys. An elevation dataset obtained for the catchment was derived from a Digital Elevation Model (DEM) of KwaZulu-Natal, which was generated by the GIS group at the School of Environmental Sciences at the University of KwaZulu-Natal. The DEM has a 20 m horizontal resolution and was generated in ARC/INFO using 20 m contours from 1:50 000 scale topographical maps. Digital image processing of 1:30 000 scale aerial photographs that were captured in 2002 was undertaken using ArcGIS version 8.2. Various land uses were identified and digitised from aerial photographs and these were classified into five categories; namely two artificial themes (residential areas and roads), one agricultural theme (crop) and two natural themes (bare soil and grasslands). Digitising the land uses was done on-screen in

ArcInfo 8.2 and followed up with ground truth mapping using a Trimble Pro-XRS GPS. The resultant landuse map is shown in Figure 3.1 and consists of five dominant landcover classes; namely bare soil, crop, grass, homes, and roads. In Potshini the cropped area makes up a large proportion (approximately 40 %) of the catchment with the average size of crop fields being 1 ha. Due to the lack of readily available detailed soils data, a soil survey to assess the runoff potential and spatial variation of the Potshini catchment was requested and was undertaken by the KwaZulu-Natal Provincial Department of Agriculture. The survey sampled 58 sites (14 pits, 44 augered samples) in the Potshini catchment and assessed various soil parameters (soil form and family, effective rooting depth, clay percentage, surface crusting etc) which were then incorporated in the GIS database and coverage. Based on the detailed soils coverage, four textural classes were identified in the Potshini catchment; loam (69 %), sandy loam (17 %), clay loam (12 %), and loamy sand (3 %).

In the case of the landuse map, where each category was digitised separately, the roads (represented as line features) were buffered to create polygons in order to define the areal extent of the road feature. The categorised features were combined to create a final coverage to be used in the analytical processes. Both the landuse and soils coverage generated initially as vector type formats, each containing their related attribute files, were converted into raster (grid) datasets to conform to the data requirements of ArcGIS Spatial Analyst. Figure 3.2 shows the various steps taken in utilising the acquired datasets to generate useful output information (i.e. runoff potential, suitable runoff harvesting) in the form of grid surfaces. Essentially, Figure 3.2 presents a conceptual basis for the modelling process undertaken in this study where each step is described in further detail according to the relevant data processing.

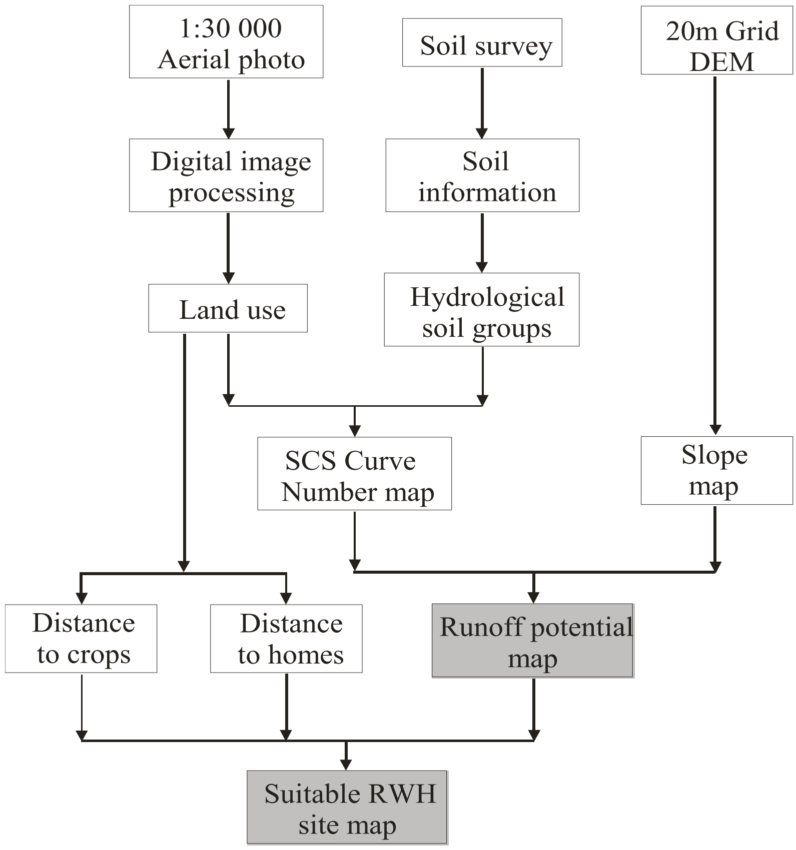

Figure 3.2 Conceptual framework for generating runoff potential and suitable runoff harvesting sites for the Potshini catchment.

3.3 DATA PROCESSING

Input datasets were integrated and analysed using ArcGIS Version 8.2 (ESRI, 2001; Gangodagamage and Clarke, 2001) as part of the process for locating potential runoff zones and suitable sites for runoff harvesting. A variety of Spatial Analyst tools were utilised to solve various spatial problems, i.e. calculating slope and distance, reclassifying values, and the raster calculator.

3.3.1 Slope

Slope is derived from a relief ratio, which is the ratio of the elevation difference between two points to the horizontal straight distance between the two points (Mishra and Singh, 2003). A slope map, expressed as percentage slope, for the Potshini catchment was derived from the acquired DEM (elevation dataset). Figure 3 shows that the Potshini catchment consists of undulating topography with the upper reaches of the catchment dominated by steep slopes exceeding 12 %. For analytical purposes the slopes were grouped into three classes; namely, less than 4 %, 4 to 12 %, and greater than 12 % and represent gentle, medium, and steep slopes respectively (Figure 3).

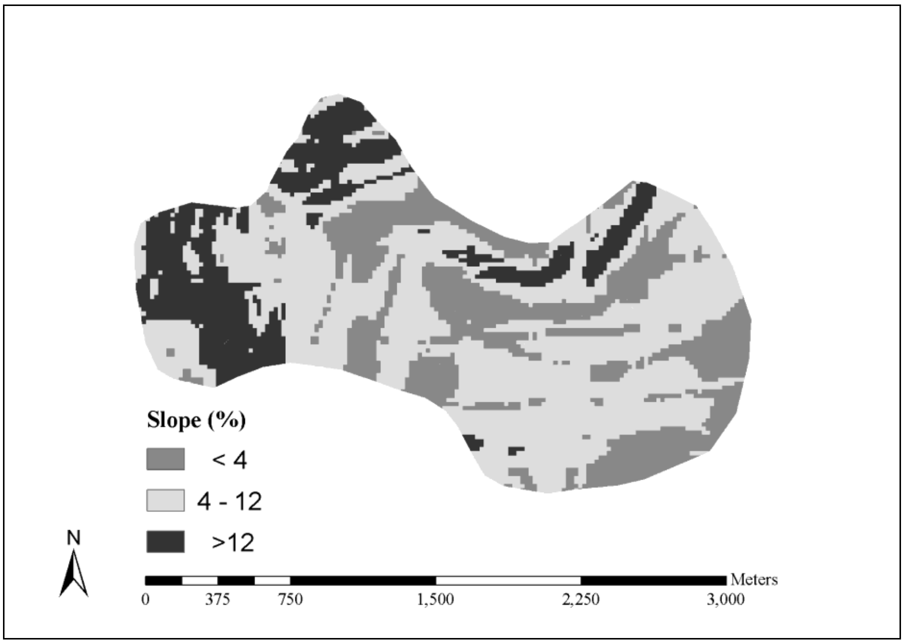

Figure 3.3 Output map showing the three slope categories within the Potshini catchment.

3.3.2 SCS curve number

The Soil Conservation Services (SCS) method is the most widely used technique for estimating surface runoff for a given rainfall event from small catchments (Das and Paul, 2006). The SCS method considers the relationship of land cover (cover type, land treatment and hydrologic condition) and hydrologic soil group, which together make up the curve number (Schulze *et al.*, 1992; Gangodagamage and Clarke, 2001). The curve number is an index expressing a catchment's runoff response to a rainfall event (Schulze *et al.*, 1992) and therefore indicates the proportion of rainwater that contributes to surface runoff (Stuebe and Johnston, 1990). Curve numbers vary from 0 to 100 where greater curve numbers represent a greater proportion of surface runoff (Stuebe and Johnston, 1990; Schulze *et al.*, 1992). The SCS-SA method has been adapted for southern Africa and has become an accepted and widely used technique throughout the region (Schmidt and Schulze, 1987). Concepts used for deriving curve numbers that are developed within the SCS method provided the basis for mapping runoff potential in this study.

The SCS method requires information on soil form and family to classify the hydrological soils groups (A, B, C, and D). The SCS version adapted for southern African conditions includes three intermediate soil groups (A/B, B/C, and C/D) in the soil classification to account for the wide spectrum of properties found in southern African soils (Schmidt and Schulze, 1987). Following the detailed soil survey described in section 2 a taxonomic classification approach was used to determine the SCS soil groupings based on soil form, family and textural class information. Curve numbers were calculated for each of the hydrological soils groups when combined with the various land covers. Both the hydrological soils classification and curve number determination were carried out according to the procedures described by Schmidt and Schulze (1987). A map of curve numbers was generated based on the hydrological soil groups and land cover grid surfaces. Figure 4 shows the curve number grid map at the 1x1 meter pixel resolution that was used in the suitability modelling exercise used to determine potential runoff zones.

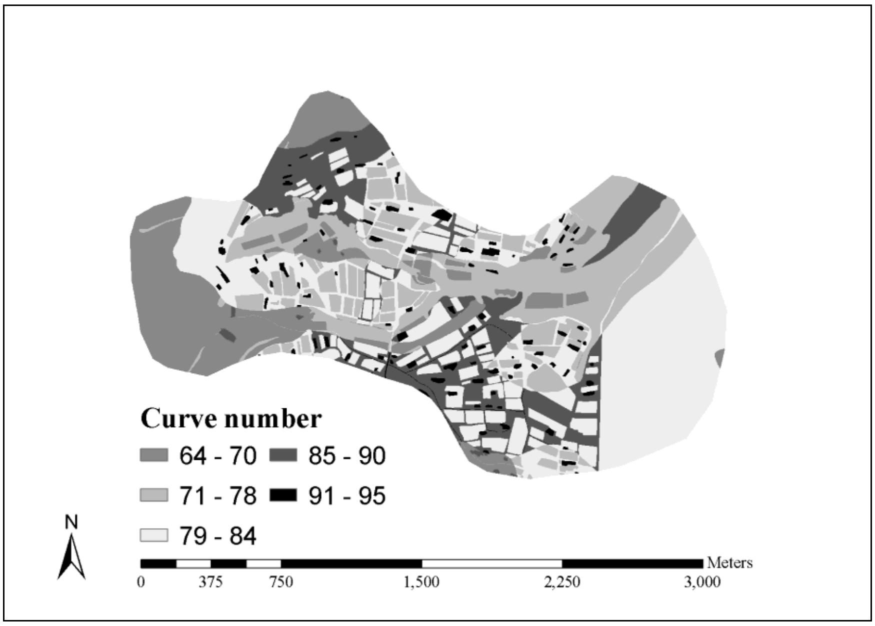

Figure 3.4 Output map showing the number of different curve number classes for the Potshini catchment.

3.3.3 Distance from homesteads and crop fields

The homesteads and crop grids were classified into five categories of varying distance intervals taken as a straight-line (Euclidean) distance (Table 1, Figure 5a and 5b). Depending on the criteria each interval class for the homestead and cropland map were allocated a suitability rank to facilitate the suitability analysis. Higher rankings represent areas of higher suitability for runoff harvesting. Generally there is a decrease in suitability with increasing distance from homesteads and croplands with the exception of croplands (0m interval class) having a low suitability (Table 3.1). The areas utilised for cropping were given a low suitability, as this land is valued more for producing crop rather than developing runoff harvesting systems. Additionally, high interception rates during the maize growing season, which corresponds with the rainy season when most runoff is generated, is most likely to hinder the potential surface runoff.

Table 3.1 Suitability rankings associated with each distance interval class for homesteads and crops, low rankings characterise areas with a high suitability.

Interval class (straight line distance)	**0 m**	**0-25 m**	**25-50 m**	**50-100 m**	**>100 m**
Homestead suitability rank	1	2	3	4	5
Crop suitability rank	5	1	2	3	5

3.4 SUITABILITY MODELLING

The final step was to combine the various factors in order to identify the most suitable sites for runoff harvesting. Suitability maps were developed in which the necessary datasets to create a single ranked map of either potential runoff or suitable runoff harvesting sites were combined. This suitability modelling approach was adopted due to its simplicity and the minimal time that is required for transforming and analysing the datasets. Numeric values, such as the suitability rankings shown in Table 3.1, were assigned to the classes within each map layer in order to facilitate the suitability analyses. The map layers used to perform the suitability analyses included the slope, SCS curve number, distance to homestead and distance to cropland maps. The values from each map layer were ranked on a scale of most suitable to least suitable based on the criteria of each dataset, with each layer being assigned an equal weighting.

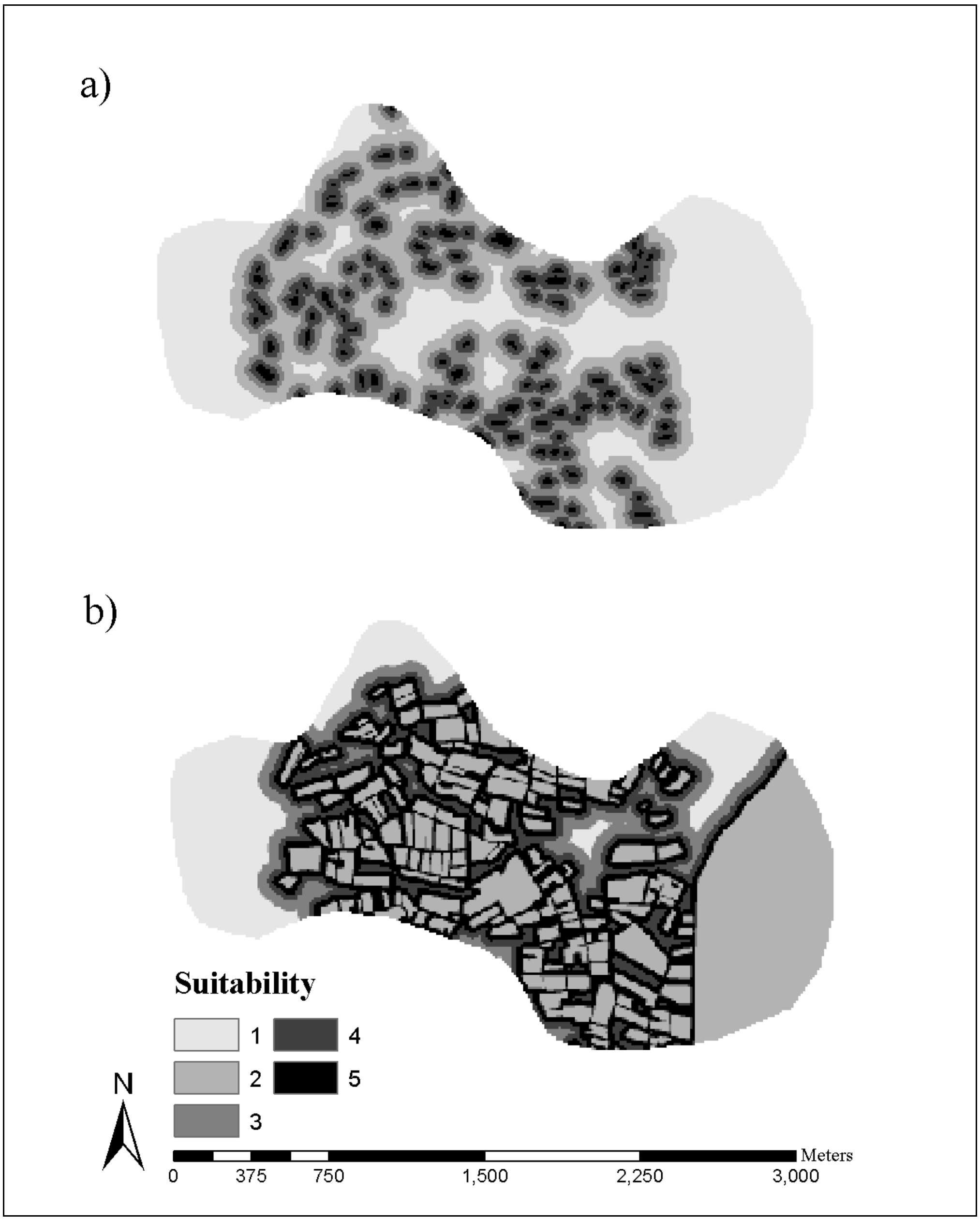

Figure 3.5 Suitability rank maps for distance to homesteads (a) and distance to croplands (b).

3.4.1 Potential runoff areas

Slope, derived from the DEM, and the SCS curve numbers were used to determine the runoff potential. Before combining the slope map with the curve number map, ranked suitability values needed to be assigned to the respective classes for each map. Conforming to the slope-based criteria for surface runoff generation, the three slope categories were ranked from least suitable to most suitable, where the steeper the slope category, the higher the potential runoff generation. For the curve number map, higher curve numbers are indexed as having a high proportion of surface runoff and are therefore potentially most suitable for runoff generation. The potential runoff map derived as a result of combining the aforementioned parameters was a three-class qualitative grid map as shown in Figure 6. In essence this runoff potential map was derived from physical catchment information that controls catchment runoff response and was utilised as input information for locating suitable sites for runoff harvesting. To support the suitability modelling the three qualitative categories were reclassified into numeric values ranked in order of most suitable to least suitable for harvesting surface runoff. Figure 6 illustrates that a fair proportion (17 %) of the Potshini catchment has a high potential to generate surface runoff during a rainfall event and much of the catchment has a moderate runoff generation potential. This is useful from an initial planning perspective as further analysis can be performed to determine the upstream (run-on) area that is utilised for runoff harvesting.

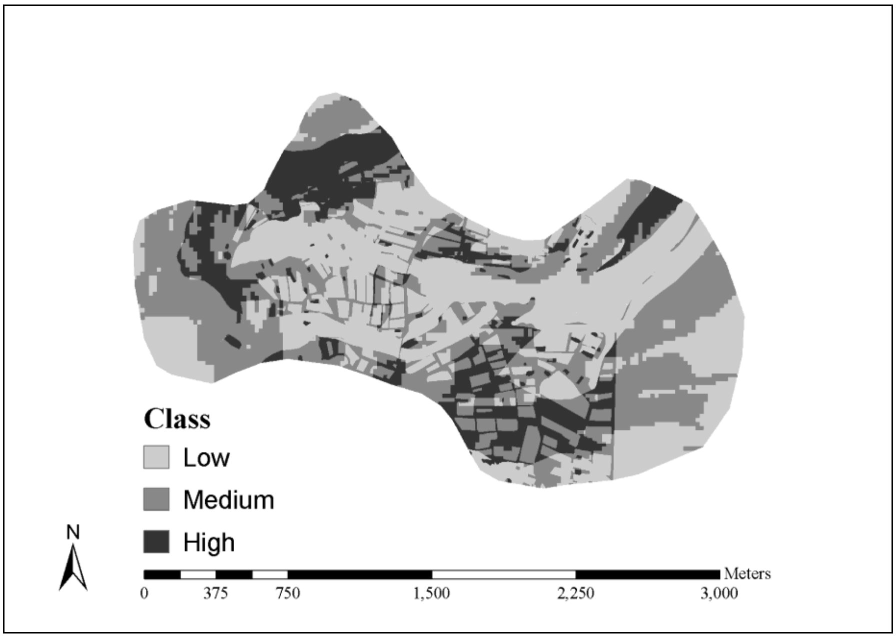

Figure 3.6 Runoff potential map partitioning the Potshini catchment into three runoff zones; low, medium and high that respectively make up 44, 39, and 17 % of the catchment area.

3.4.2 Suitable runoff harvesting sites

Locating optimal sites for runoff harvesting was based on the physically derived potential runoff map as well as socio-economic factors influencing system innovations required for runoff harvesting, distance to homesteads and croplands. Both maps, consisting of five suitability values ranked accordingly, were combined with the runoff potential map comprising three suitability rankings. Combining these grid surfaces resulted in a map generated that indicates suitable zones for harvesting surface runoff within the catchment (Figure 7). According to Figure 7, 18 % of the Potshini catchment is highly suitable for developing runoff harvesting system innovations.

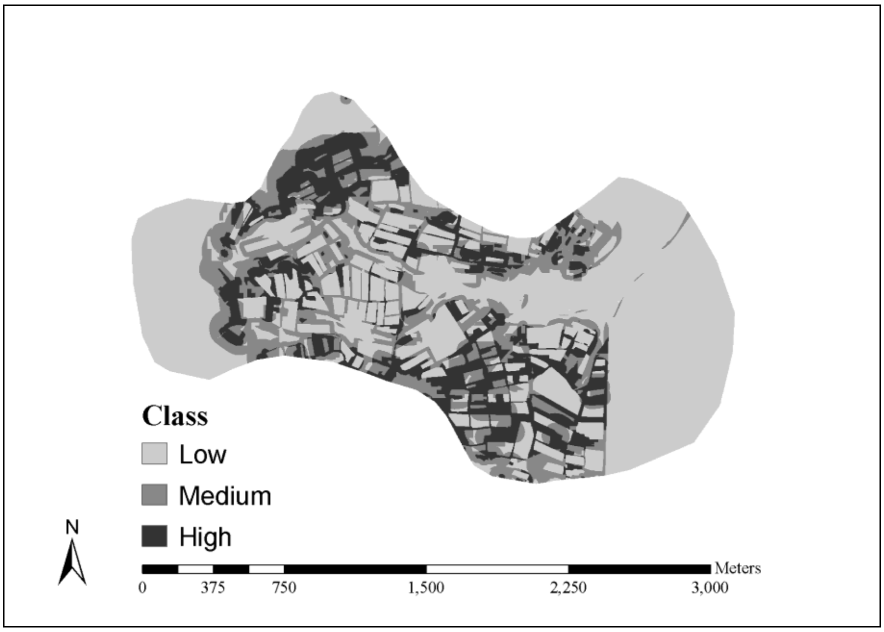

Figure 3.7 Suitability map ranking the Potshini catchment into three zones based on their runoff harvesting suitability. The relative proportions of the catchment these zones make up are 60 (low), 22 (medium) and 18 % (high).

3.5 THRESHOLD RAINFALL ASSESSMENT

Now that the most suitable runoff harvesting sites were identified, an assessment of rainfall thresholds was undertaken to determine the number of runoff producing events that are likely to occur within a high rainfall year compared to a low rainfall year and therefore the allied risks associated with planning runoff harvesting systems.

To facilitate design flood estimation in South Africa, four design rainfall distributions have been identified of which the “Type 4” distribution produces the highest intensities and “Type 1” the lowest intensities (Schulze *et al.*, 1992). The Potshini catchment falls within the “Type 4” distribution area and is therefore designated as being an area where high rainfall intensities are likely. With a small catchment size (3.5 km^2) it can also be assumed with a fair amount of confidence that the uniformity of rainfall is high. Rainfall patterns for the Potshini catchment and a nearby farm (Broadacres) are distinctly seasonal, with rainfall exceeding 800mm in the wet season while the dry season experiences less than 100mm (Table 3.2).

Table 3.2 Mean monthly rainfall and mean annual precipitation (MAP) for Potshini, taken from 2004 to 2006, and Broadacres farm, from 2002 to 2006. Average monthly rainfall was calculated from the mean monthly values from both sites.

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**MAP**
Potshini (mm)	297	191	164	29	14	6	4	31	12	104	148	108	1107
Broadacres (mm)	149	156	137	28	13	8	3	25	16	54	102	97	789
Average (mm)	223	173	151	29	13	7	4	28	14	79	125	102	948

Daily rainfall events exceeding threshold amounts of 10 and 25mm/day were assumed to represent suitable events for generating surface runoff, based on hydrological analyses performed by Kongo and Jewitt (2006). The number of rainfall events exceeding these thresholds was calculated for the Potshini catchment and Broadacres farm. However, it should be noted that the available rainfall data is limited in terms of record length and is considered to be insufficient for making statistically reliable decisions of rainfall based on long-term trends. Consequently, rainfall data from the Potshini catchment were patched through the derivation of monthly correction factors from concurrent rainfall data from a long term rainfall record (125 years) supplied by the Bergville meteorological station situated ten kilometres away (Table 3), following the approach developed by Schulze *et al.* (1992). These correction factors were applied to the long term Bergville dataset generating a rainfall record representative of the Potshini catchment. The same procedure was applied to the Broadacres farm rainfall record to improve the spatial availability of rainfall data. Dry years and wet years were determined from determining the 10th and 90th percentiles for the entire rainfall record. The Broadacres farm had an equal number of daily rainfall events exceeding the 10mm and 25mm thresholds of the Potshini catchment. Analysis of the 125 years of record show that annual rainfall variations are considerable and that the risks associated with runoff harvesting are high for a dry year when the number of rainfall events is low (Table 4). In a wet year, large amounts of surface runoff can be captured when the number of days of rainfall above the 10 and 25mm/day threshold is high. Some surface runoff would also be harvested during the dry season.

Table 3.3 Concurrent median monthly rainfall values for the Bergville meteorological station, recorded from 1882 to 2006, and the manual rain gauges at Potshini, from 2004 to 2006. Calculated monthly correction factors used to patch the Potshini rainfall data.

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Bergville	215	145	112	30	13	2	0	50	15	85	93	90
Potshini	297	191	164	29	14	6	4	31	12	95	148	108
Correction factor	0.73	0.76	0.68	1.03	0.95	0.33	0.00	1.59	1.28	0.90	0.63	0.84

Table 3.4 Number of daily rainfall events exceeding 10mm and 25mm thresholds for wet and dry seasons distinguished between wet and dry years for Potshini.

Season	**10mm events**		**25mm events**	
	Wet year	**Dry year**	**Wet year**	**Dry year**
October - March (Wet)	27	10	16	3
April - September (Dry)	5	1	2	0

3.6 Discussion and conclusion

A method for identifying potential sites that supports runoff harvesting interventions was developed through utilising GIS. Being site-specific, assessing the suitability of the land for runoff harvesting therefore requires quantitative data and involves integration of specific criteria (Ziadat *et al.*, 2006). The GIS approach that was used for locating suitable sites for runoff harvesting helps to reduce the aerial extent of a catchment through identifying specific areas that are potential sites for runoff harvesting, and which then can be verified in the field. A similar study was undertaken by Gupta *et al.* (1997) to estimate water harvesting potential by using topographical, soils and land cover information to derive SCS curve numbers. However this study differed in that the water harvesting potential was based on actual runoff depth over a much greater spatial scale covering several river basins. Particular to this study was that spatial and temporal rainfall data was not taken into consideration as a runoff controlling mechanism allowing for this approach to remain simple and straightforward whilst conserving reliability. In a study undertaken by Sekar and Randhir (2007), a temporal steady state was assumed whereby temporal variability was excluded from the model allowing specific focus on spatial variability in the model. Hence the representation of the potential runoff response is based on physical attributes for any given rainfall event, given that the rainfall supports assumptions of uniform rainfall distribution and intensity.

The proportion of the Potshini catchment that is highly suitable for runoff harvesting was found to make up 18 % of the entire catchment area. This information is a valuable step towards implementing a runoff harvesting strategy that is unique to the catchment, as it allows planners to identify the source areas that generate high amounts of runoff. These upstream (run on) areas that produce high amounts runoff can be used to assess the total amount of runoff that can be harvested and used to supplement a particular cropping (command) area. With further analysis, it is possible to determine how often a tank of a certain size, or storage structure, can be filled within a season and ascertain how many days of dry spell can be overcome with using the stored water (Kosgei *et al.*, 2007). Alternatively, the size of the run on area can inform planners as to what size tank would be most suited to the runoff producing area.

The ideal scenario for Potshini would be to implement a runoff harvesting strategy that supports small-scale, high-value vegetable gardens where stored surface water, captured during the rainy season, provides supplemental irrigation during the dry season. The existing major crops' (i.e. maize) growing period coincides with the rainy season and is largely rainfed. Therefore it is not considered viable to invest large amounts of harvested water to supplement the maize, especially if there is an existing vegetable garden that utilises water from the same storage structure. Furthermore, maize has a relatively low cash value in the area.

In the Potshini catchment runoff is usually generated when daily rainfall exceeds 10 mm/day and for most rainfall events, runoff is expected because Potshini is situated within a high intensity rainfall distribution area. The rainfall analysis (table) shows that this happens during a dry year 10 times and during a wet year 27 times. However dry spells may persist even during the wet season and should a dry spell occur during a critical growth stage, maize crop failure is likely. Thus, supplemental irrigation of maize during such dry periods may greatly improve the chances of producing a good crop, should this be considered a priority. Capturing excess surface runoff using harvesting tanks can thus be viable for coping with dry spells during the rainy season. During the dry season it is only possible to harvest surface runoff in wet years, when about 5 occasions excess rainfall can be recorded.

Providing information of runoff that is spatially relevant is a vital step for locating runoff-generating areas and determining areas within a catchment where surface water is generated is an important step in promoting runoff harvesting technologies. The extension of this methodology to larger areas will provide a useful strategic planning tool for water resources managers especially in the context of downstream impacts. However, as highlighted above, runoff harvesting approaches are highly location-specific and obtaining data at the level of detail reported in this study will be extremely difficult for large areas. Therefore in comparing this more detailed approach with the large-scale desktop approach developed by Mwenga Kahinda *et al.* (2006), it is obvious that this method would have issues if applied on a national scale as it relies, to a large extent, on field surveys and detailed site specific information. Nevertheless, the methodology described herein does offer some broad guidelines for such large-scale studies. For example, the use of GIS as a tool to facilitate this process has been shown to improve the level of accuracy for pin-pointing areas for runoff harvesting due to the ability of GIS to utilise spatial information in an integrative manner and to display this spatially through maps. Therefore there is potential to incorporate large-scale datasets, such as those used for the decision support systems developed by Mwenga Kahinda *et al.* (2006), i.e. the national soils and land cover datasets of South Africa.

Adopting an approach to determine areas suitable for runoff harvesting is essential to ensure optimal functionality of water system innovations once they have been implemented, especially when the risks associated with rainfall are taken into consideration. If not, then those efforts undertaken to utilise available rainwater-runoff in an efficient and sustainable manner will be less effective and water scarcity will continue to be a major problem facing smallholder rainfed agriculture. Surface water resulting from rainfall-runoff responses within a catchment is a potential water resource, which, if managed correctly, can be utilised to supplement high demands. Thus runoff harvesting is a suitable option to capture and store surface runoff for later utilisation, especially during periods when there is limited water availability.

4. ECOHYDROLOGICAL IMPLICATIONS OF RUNOFF HARVESTING IN THE HEADWATERS OF THE THUKELA RIVER BASIN, SOUTH AFRICA

Abstract

Hydrological regimes have an important influence on biodiversity, structure, and functioning of aquatic ecosystems. Unforeseen circumstances, both hydrologically and ecologically, caused by potential adoption and expansion of runoff harvesting innovations is of particular concern to water resource planners as downstream river systems are likely to be adversely affected. This paper offers a plausible method for determining the influence that large-scale adoption of runoff harvesting could have on downstream flow regimes by using a scenario-based approach, with the *ACRU* Agrohydrological model, to simulate the probable alteration of streamflow regimes. Runoff harvesting scenarios were based entirely on the spatial extent of impervious surfaces associated with rural homesteads, estimates of which were taken from current population data used to establish the density of hypothetical runoff harvesting systems within a catchment setup. Daily streamflow simulation from nine Quaternary Catchments in the Thukela River basin provided suitable data series' for analysis using the IHA method to compute ecologically relevant hydrological parameters. The outcome of this ecohydrological study demonstrated that a relatively simple modelling exercise offers the potential to determine impacts caused by large-scale runoff harvesting. Results established that magnitudes for high and low flows were reduced when runoff harvesting uptake was high. In most scenarios the results showed that the impacts were insignificant despite modelling scenarios being based on unrealistically high proportions of runoff harvesting systems. However, increasing the spatial extent of runoff harvesting is expected to have a much greater impact at smaller spatial scales; water resources of small sub-catchments may become appreciably depleted where such catchments host excessive numbers of runoff harvesting systems. Therefore it would be equally important to understand the more localised level of impacts of runoff harvesting on aquatic ecosystems particular emphasis towards the alteration of low flow regimes.

4.1 Introduction

There is increasing consensus of the need to improve agricultural productivity and water resources management to meet new challenges posed by increasing demands and diminishing water supply (Ngigi *et al.*, 2007) especially so that food and livelihood requirements will be fulfilled for the years to come in a sustainable manner. More food will be necessary, and more food translates into more water for agriculture, which will in many cases result in less water for the environment (Molden and de Fraiture, 2004). Achieving this is particularly challenging especially when 97 percent of the agricultural land in sub-Saharan Africa is under rainfed agriculture (Rockström *et al.*, 2004) and it is most likely that rainfed agriculture will remain the dominant source of food production for the foreseeable future in this region (Woyessa *et al.*, 2006). Contemporary initiatives are investigating ways to introduce innovations such as runoff harvesting as a means to supplement productivity for rainfed agriculture. In South Africa the possibilities for runoff harvesting have not yet been fully explored, but it has been suggested that its implementation could alleviate spatial and temporal water scarcity for productive use (Mwenga Kahinda *et al.*, 2005). In order for runoff harvesting to be successful, sites where appropriate amounts of water, supplied from surface runoff, are necessary to sustain the storage structures used for harvesting runoff. Such surface runoff is generated locally when a pulse of water flow is produced from degraded foot paths, homesteads and marginal grazing areas, often lasting no longer than a couple of hours after each large rainfall event (Rockström *et al.*, 2002).

Despite the anticipated socio-economic impacts, up-scaling of runoff-harvesting, may beyond a certain limit, lead to hydrological and environmental impacts (Ngigi, 2003). Several hydrological studies have shown that upstream shifts in water-flow partitioning may result in complex and unexpected downstream effects, both negative and positive, in terms of both water quantity and quality (Vertessey *et al.*, 1996; Rockström *et al.*, 2002). However in a recent study, Ngigi *et al.* (2007) hypothesised that, adoption of runoff harvesting will increase due to its tangible benefits to farmers and that increased retention of runoff upstream will then reduce river flow. Hence it is vital to consider the potential impacts of runoff harvesting on downstream hydrological and ecological systems, for both water resources management and planning purposes, as a fundamental step towards Integrated Water Resources Management (IWRM). Most definitions identify that IWRM should meet human requirements for the use of freshwater, whilst maintaining hydrological and biological processes and biodiversity which are considered essential for the functioning of ecosystems, the sustainable use of water resources and the maintenance of goods and services provided by them (Jewitt, 2002). Within South

Africa, IWRM is supported by the National Water Act (NWA) (Act No. 36 of 1998) which serves as the principle legal system relating to water resources management in South Africa. In terms of the NWA all existing and future water users will eventually have to be licensed and this licensing process must account for the water requirements of both the basic human needs and Ecological Reserve (Hughes, 2006). Regulating the use of water through the allocation of licences is important in order that the Reserve may be used on a sustained level. Unless a water user is listed in Schedule 1, is an existing lawful use, or permissible under general authorisation, a water use license is required. Since its promulgation in 1998, attempts have been made to quantify the water requirements needed to support both human and environmental components of the Reserve.

Aquatic ecosystems are complex, with many interlinked components, and are susceptible to human alteration resulting from a range of human activities (Taylor, 2006). Streamflow regimes support these ecosystems through controlling key habitat parameters such as flow depth, velocity, and habitat volume (Richter *et al.*, 1998). Modification of natural flow regimes alters the abundance of composition of biodiversity thus affecting the provision of ecosystem services (Strange *et al.*, 1999). Deciding how much water should be reserved for the maintenance of ecosystems to provide “natural” goods and services and how much water should be used by agriculture and industry to provide “artificial” goods and services necessitates some measure of environmental flow assessment (Taylor, 2006). However difficulties exist due to inabilities to distinguish direct effects of modified flow regimes from impacts associated with land-use changes that often accompanies water resources development (Bunn and Arthington, 2002).

In the context of IWRM the question needs to be asked; should runoff harvesting be classed as a streamflow reduction activity (SFRA) or a specified water user, in which case a licence is required, due to potential influences on the Reserve, in particular the Environmental Reserve, under the NWA. A stream flow reduction activity as defined in the South African NWA is “… any activity (including the cultivation of any particular crop or other vegetation) 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” (NWA Section 36(2)). This requires appropriate studies to establish whether runoff harvesting should be declared a SFRA due to its potential for diverting considerable amounts of surface water, depending on the scale, from river systems (Mwenga Kahinda *et al.*, 2005). A summary prepared by Bosch (2005) suggests that rainwater harvesting (including runoff harvesting) does not meet all criteria for declaring it a

SFRA under Section 21 (i.e. reduce mean annual runoff, reduce low flows, effect class of the Reserve, National and catchment management strategies) and therefore regulations should be implemented according to Section 22 and 27 of the NWA (Table 4.1). As a water user, rainwater harvesting would therefore be controlled by policy of permissible water use and general authorisation, which allows for limiting the use of water should it become detrimental to other users (e.g. environmental systems).

Hence the objective of this study is to assess the possible impacts of large-scale runoff harvesting, a potential method for supplementing agricultural water demands, on downstream flow regimes and the implications that flow alterations may have on aquatic ecosystems, and so to provide a more quantifiable input to Bosch's (2005) assessment, preferably regarding the impact on hydrological regime and the Reserve.

Table 4.1 Criteria for defining land based activities as a streamflow reduction activity (SFRA) affecting the degree of water use regulation (after Bosch, 2005).

Criteria for <u>including</u> activity as SFRA	**Current available evidence**	
	Forestry	**RWH**
An activity that occurs outside the boundaries of a watercourse, and is located upslope of the watercourse	yes	yes
Reduce mean annual runoff (increase evaporation relative to base line)	yes	no
Reduce low flows for a watercourse	yes	no
Effect class of the Reserve, National and catchment management strategies	yes	no
Criteria for <u>excluding</u> activity from SFRA		
Activity is best regulated through a different statute than the NWA	no	yes
Activity pollutes the water resource, but is best regulated under Section 21 of the NWA but not 21(d)	no	?

4.2 Methods

4.2.1 Study area

The Thukela River basin covers an area of 29 036 km^2 and is one of South Africa's 22 Primary Catchments. It is highly diverse, with valuable aquatic and terrestrial ecosystems, mixed with subsistence and commercial farming activities (Kosgei *et al.*, 2007). As defined by the South African Department of Water Affairs and Forestry, the Quaternary Catchment (QC) is the breakdown of a Primary Catchment used for water resources management purposes. Nine of the 86 QCs that make up the Thukela River basin were used in this study for hydrological modelling and provided spatial scales apt for the purpose of the investigation. These QCs are located in the Upper Thukela and form a sub-basin with an areal extent of 1876.64 km^2 (Figure 4.1). The nine QCs include V11A to V11H and V11J, the respective catchment areas of which are shown in Table 4.2. The flow in the rivers of the QCs is highly variable with mean daily flow rates and coefficient of variation ranging from 0.52 to 16.30 $m^3.s^{-1}$ and from 1.76 to 26.70 $m^3.s^{-1}$ for V11F and V11J respectively. The majority of the sub-basin is dominated by unimproved (natural) grassland (79.8 %) followed by dryland subsistence agriculture (6.8 %) and commercial agriculture (6.0 %). Spread throughout the Upper Thukela are informal residential areas that are essentially rural in character. They include scattered plots or smallholdings and dwellings that retain some cultivation in the form of plots associated with the settlements and subsistence farming (Figure 4.2). It is within these circumstances that people are most likely to adopt a runoff harvesting strategy and thus these areas are a key consideration for purpose of this study.

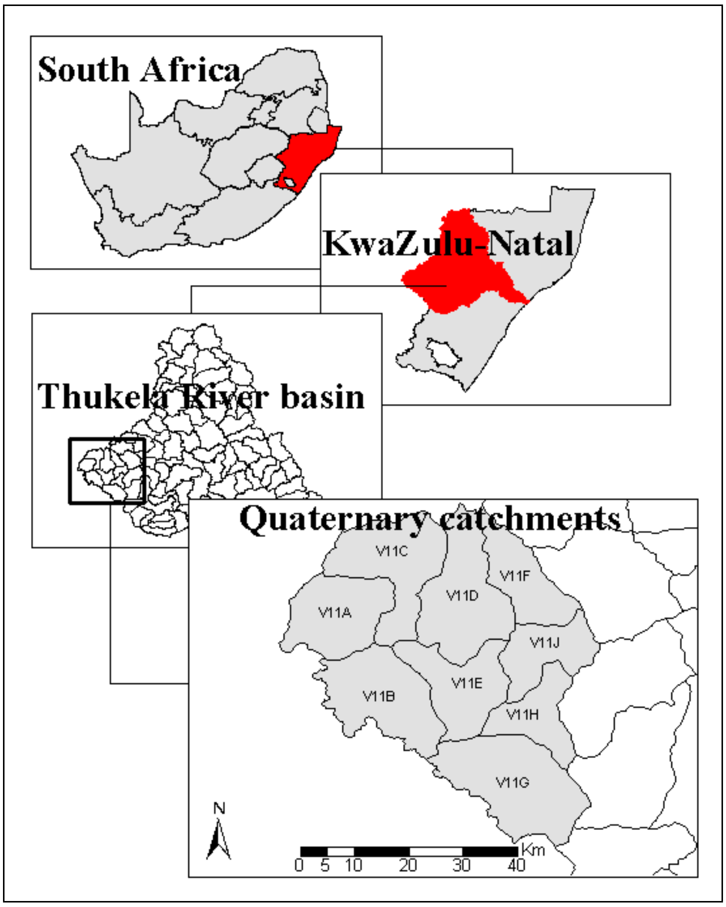

Figure 4.1 Spatial position of the sub-basin comprising the nine quaternary catchments situated in the headwaters of the Thukela River basin.

4.2.2 Simulating runoff harvesting

A scenario-based modelling approach was undertaken to provide insight into the ecohydrological circumstances that could arise due to widespread adoption of runoff harvesting. The *ACRU* Agrohydrological model was utilised to simulate the streamflows for a 50 year period (1 January 1950 to 31 December 1999) based on present land use conditions. *ACRU* is a daily time step, physical-conceptual and multi-purpose model with the option to output daily values of total streamflow (Schulze and Smithers, 2003). The model revolves around a multi-layer soil water budgeting and is therefore structured to be hydrologically sensitive to changes in land use and management (Schulze and Smithers, 2003). Thus *ACRU* is capable of modelling the impacts of land use changes associated with up-scaling runoff harvesting. An *ACRU* configuration generated by (Schulze *et al.*, 2007), for the nine QCs, was adapted for use in this study and reconfigured to comply with the runoff harvesting scenarios. Delimitation of sub-catchments, determining the hydrological characteristics of soils, generating information of land cover and land use for the *ACRU* configuration is as described in (Schulze *et al.*, 2007).

4.2.3 Likely extent of runoff harvesting

Typical situations within the rural regions of the Upper Thukela include homesteads comprising of impervious ground surfaces and rooftops. The type of structures most likely to be used for runoff harvesting, and considered in this study, include tanks for capturing runoff from rooftops, and subterranean tanks that collect surface runoff from the impervious micro-catchments that make up the homesteads. Runoff collection by the latter can be made in many small reservoirs storing less than 50 m^3 and is more likely to support small-scale agriculture. Based on the study by de Winnaar *et al.* (2007) (Chapter 3) in Potshini, a small village in an adjacent area, these impervious areas were determined to be approximately 800m^2 per homestead. Figure 4.2 shows the homesteads in Potshini and how they are scattered throughout the landscape. A simple analysis using the population data taken from the 2001 census (StatsSA, 2001) was performed to determine the potential for runoff harvesting and a likely number of runoff storage tanks for the study area represented by the nine QCs identified. An average number of persons per household was calculated (i.e. 5.77 ± 0.75) from ward information encompassing the sub-basin. Population data for the QCs of the Thukela River basin, produced by Dlamini (2006), was multiplied by the StatsSA "persons per household" estimate to determine the number of households for each QC (Table 4.2). Three hypothetical runoff scenarios were then generated based on the area of impervious ground surface, which was calculated by multiplying the homestead area estimate with the number of households within each QC (Table 4.2). The three scenarios were designed assuming 50 % (50 % E_{pop}), 100 % (100 % E_{pop}) of the current effective population and a future 200 % (200 % E_{pop}) of the current effective population adopting runoff harvesting. Results are compared with a baseline scenario representing the potential to utilise runoff generated from existing impervious and future impervious area, i.e., because the extent of impervious areas is delimited as being dependant on the number of homesteads in the catchment, the baseline for the first two scenarios is based on the runoff potential for existing catchment population, but for the third scenario, a doubling of population implies a doubling of impervious areas. Hence the time that the later scenario represents differs in comparison to the the first two scenarios. A description of the scenarios is summarised in Table 4.3.

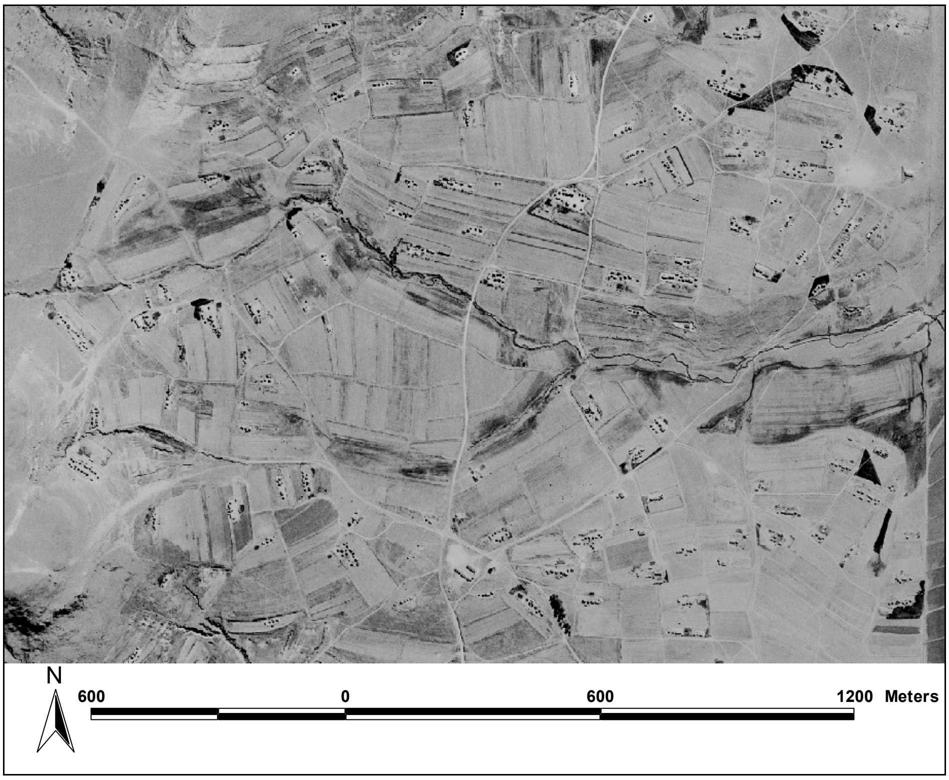

Figure 4.2 Areal view of the homesteads and croplands in Potshini, a rural village situated in the headwaters of the Thukela River basin.

Table 4.2 Details of area, population, and household numbers used to determine impervious areas of each scenario for the Quaternary Catchments.

Quaternary Catchment	Area (km^2)	Population	No. of Households	Impervious area (km^2)		
				50 % E_{pop}	100 % E_{pop}	200 % E_{pop}
V11A*	206.95	12982	2250	0.90	1.80	3.60
V11B	252.77	4691	813	0.33	0.65	1.30
V11C*	249.64	15043	2607	1.04	2.09	4.17
V11D*	239.64	29385	5093	2.04	4.07	8.15
V11E	184.07	8813	1527	0.61	1.22	2.44
V11F	157.76	9257	1604	0.64	1.28	2.57
V11G	313.72	2671	463	0.19	0.37	0.74
V11H*	132.77	8596	1490	0.60	1.19	2.38
V11J	139.32	3591	622	0.25	0.50	1.00
Sub-basin	1876.64	95029	16469	6.59	13.18	26.35

* QCs with the greatest population densities
E_{pop} = Effective population

Table 4.3 Description of runoff harvesting scenarios and the corresponding baselines.

Scenario	**Description**
50 % E_{pop}	Half the number of homesteads of the effective population harvest runoff.
Baseline	All the impervious areas of the effective population homesteads generate runoff NOT used for harvesting.
100 % E_{pop}	All homesteads of the effective population harvest runoff.
Baseline	All the impervious areas of the effective population homesteads generate runoff not used for harvesting.
200 % E_{pop}	Double the number of homesteads of the effective population harvest runoff. Accounts for population growth.
Baseline	Double the impervious areas of the effective population homesteads generate runoff not used for harvesting.

4.2.4 Accounting for runoff harvesting in the *ACRU*

ACRU is capable of simulating surface stormflow from impervious ground surfaces following a rainfall event, and this gives the model the ability to imitate runoff harvesting. Surface areas suitable for runoff harvesting can be input into the model's configuration by adjusting the fraction of the catchment occupied by impervious areas that are not adjacent to a watercourse (Smithers *et al.*, 1995). However in this study, instead of the stormflow draining from impervious areas on to pervious areas where infiltration can take place, the model was configured whereby the surface runoff produced from stormflow is extracted from the catchment and stored in a pseudo catchment. This pseudo catchment essentially imitates the storage structures used for runoff harvesting where stormflow is generated, captured and stored. The approach assumes, however, that all runoff produced from impervious areas of the homesteads is harvested and that the pseudo catchment ultimately does not have a fixed capacity. Given the nature of the *ACRU* Model, this method allows for a realistic representation of runoff harvesting systems whereby storage water is utilised for supplementary irrigation, of which it has been found that hand-watering is most effective in the study region (Sturdy *et al.*, 2008). It is unlikely from this situation that storage water will contribute to downstream streamflow following irrigation as it will either be evaporated directly from the soil surface or be taken up by the crop, via the soil, only to be used by transpiration.

Daily streamflow values for the QCs were simulated in *ACRU* using the aforementioned approach with each runoff harvesting scenario supported by the impervious areas shown in Table 4.2. A simulation of each runoff harvesting scenario was compared against its respective baseline simulation, which excludes runoff harvesting processes, to determine the difference in streamflow. Simulated daily streamflow data is considered useful for determining hydrological indices that are then used for assessing the characteristics of the streamflow regime (Richter *et al.*, 2003). Hence it was possible to assess the effects of runoff harvesting on the streamflow regime using daily streamflow output from *ACRU* as input for the Indicators of Hydrological Alteration (IHA) method. Developed by the United States Conservancy, the IHA method provides a means to determine the extent that anthropogenic influences alter streamflows through statistical analysis of daily streamflow data (Richter *et al.*, 1996; 1998).

4.2.5 Indicators of Hydrological Alteration

IHA is an increasingly well used software package for the analysis of changes in flow regimes from an ecological perspective (Richter *et al.*, 1996). The IHA method provides for a statistical analysis of 32 ecologically relevant hydrological parameters (Table 4.4) which characterise intra-annual variability in the streamflow regime (Taylor, 2006). IHA software is then able to compute inter-annual statistics (central tendency and dispersion) for the 32 parameters. The natural variation of IHA parameter values before a system is altered is used as a reference for comparing the hydrological regimes to, after it has been altered (Richter *et al.*, 1996). Thus in order to determine impacts caused by runoff harvesting, statistics for the IHA parameters needed to be calculated for a data series that reflects the situation before runoff harvesting with the same process repeated for a data series comprising runoff harvesting. Hence data for a runoff harvesting period followed on from data obtained for a pre-runoff harvesting period, essentially creating a continuous dataset from which the IHA software may compute the degree of alteration taking place between the two periods. Annual time series for several IHA parameters over the 50 year period, set with no runoff harvesting and a constant land use, were first plotted for the QCs to identify any long term trends. Distinct long term trends were evident and are attributed to various extreme rainfall driven hydrological events (e.g. floods and droughts) that occurred during the time series. This determined that the 50 year time period should not be split into equal 25 year periods of pre-runoff and post-runoff harvesting as results from IHA analyses would be influenced by these noteworthy events resulting from the aforementioned long-term discontinuities. Rather, the approach followed was that the pre-runoff harvesting situation incorporated the entire 50 year period (i.e. 1950 to 1999). This data series was then duplicated to create an additional 50 year period, which was then used as input to the model for the different scenarios to create an effective 100 year record. Hence the data set (pre- and post-runoff harvesting) comprised a 100 year period that includes a 50 year baseline followed by 50 years of post impact.

Daily streamflow data for each scenario, both for pre- and post-runoff harvesting situations, output from *ACRU* provided the input data required for the IHA method. Within the IHA software high and low flow thresholds were set to the recommended default values (i.e. the median plus or minus 25 percent). Using the IHA software, for each year in each data series (i.e. pre- and post-runoff harvesting) values for the 32 ecologically relevant hydrologic parameters were calculated and this was done for each of the three scenarios. Based on these values, medians and coefficient of dispersion were computed with the decision to use median values to account for the skewed distribution of hydrological data. These inter-annual statistics were then compared for the different scenarios between the pre- and post-runoff harvesting situations to determine the percentage deviation from pre- to post-runoff harvesting with the results presented spatially in the form of maps using ArcView for the QCs.

Table 4.4 Summary of hydrologic parameters used in the Indicators of Hydrologic Alteration and their characteristics (After Richter *et al.*, 1996).

IHA statistic group	Regime characteristic	Hydrologic parameters
Group 1: Magnitude of monthly conditions	Magnitude Timing	Mean value for each calendar month
Group 2: Magnitude and duration of annual extreme water conditions	Magnitude Duration	Annual minima 1-day means Annual maxima 1-day means Annual minima 3-day means Annual maxima 3-day means Annual minima 7-day means Annual maxima 7-day means Annual minima 30-day means Annual maxima 30-day means Annual minima 90-day means Annual maxima 90-day means
Group 3: Timing of annual extreme water conditions	Timing	Julian date of each annual 1 day maximum Julian date of each annual 1 day minimum
Group 4: Frequency and duration of high / low pulses	Magnitude Frequency Duration	No. of high pulses each year No. of low pulses each year Mean duration of high pulses within each year Mean duration of high pulses within each year
Group 5: Rate and frequency of water condition changes	Frequency Rate of change	Mean of all positive differences between consecutive daily means Mean of all negative differences between consecutive daily means No. of rises No. of falls

4.3 Results

4.3.1 Impact on streamflow yields

An increase in runoff harvesting practices reduced the streamflow volumes downstream with reductions to streamflow being more pronounced between 100 % E_{pop} and 200 % E_{pop} (Table 4.5). With these two scenarios the percentage reduction of streamflow increased proportionately with the area of impervious land surfaces where a doubling in impervious area results in the percentage reduction of streamflow being doubled. However an increase in impervious area results in streamflow yields increasing when the situation does not include runoff harvesting relative to the decrease in streamflow resulting from runoff harvesting. Thus even though reduction in streamflow between pre- and post-runoff harvesting situations increases due to increasing impervious areas, the actual reduction in streamflow yields caused by increasing runoff harvesting is fairly small. Hence a feedback relationship exists between the size of human population and the extent of impervious areas where as a consequence of population growth is an increase in the area of impervious surfaces. This then results in more runoff whereby streamflow yields will increase, more as a result of increasing stormflow response relative to the decrease in streamflow yields caused by harvesting the entire impervious areas stormflow.

Table 4.5 Mean annual flow between simulations with and without runoff harvesting and percentage reduction in flow for each scenario within the sub-basin and four Quaternary Catchments.

Quaternary Catchment	**Mean Annual Flow (m^3 x 10^6)**					
	Scenario 1 (50 % E_{pop})		**Scenario 2 (100 % E_{pop})**		**Scenario 3 (200 % E_{pop})**	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**
V11A	51.49	50.26	51.49	49.99	52.72	49.50
V11C	47.63	46.89	47.63	46.76	48.27	46.21
V11D	30.74	28.98	30.74	28.65	32.44	28.21
V11H	26.34	25.65	26.34	25.50	26.92	25.30
Sub-basin	519.55	512.83	519.55	511.41	525.91	509.03
	Flow Reduction (%)					
V11A	2.39		2.91		6.12	
V11C	1.55		1.83		4.28	
V11D	5.73		6.79		13.04	
V11H	2.62		3.19		6.02	
Sub-basin	1.29		1.57		3.21	

4.3.2 Alteration of streamflow regimes

Comparing daily streamflows produced from the *ACRU* simulations reflects temporal changes in the hydrological regime. Assessment of the time series in Figure 4.3 shows how the peak flows are reduced as a result of runoff harvesting. The difference between peak flows is minor for 50 % E_{pop} (Figure 4.3a) but as the intensity of runoff harvesting increases, so too does the reduction to the peak flows (Figure 4.3b and c). The magnitude of the reduction in peak flows for QC V11A using 200 % E_{pop} was approximately 1.5 $m^3.s^{-1}$ per day.

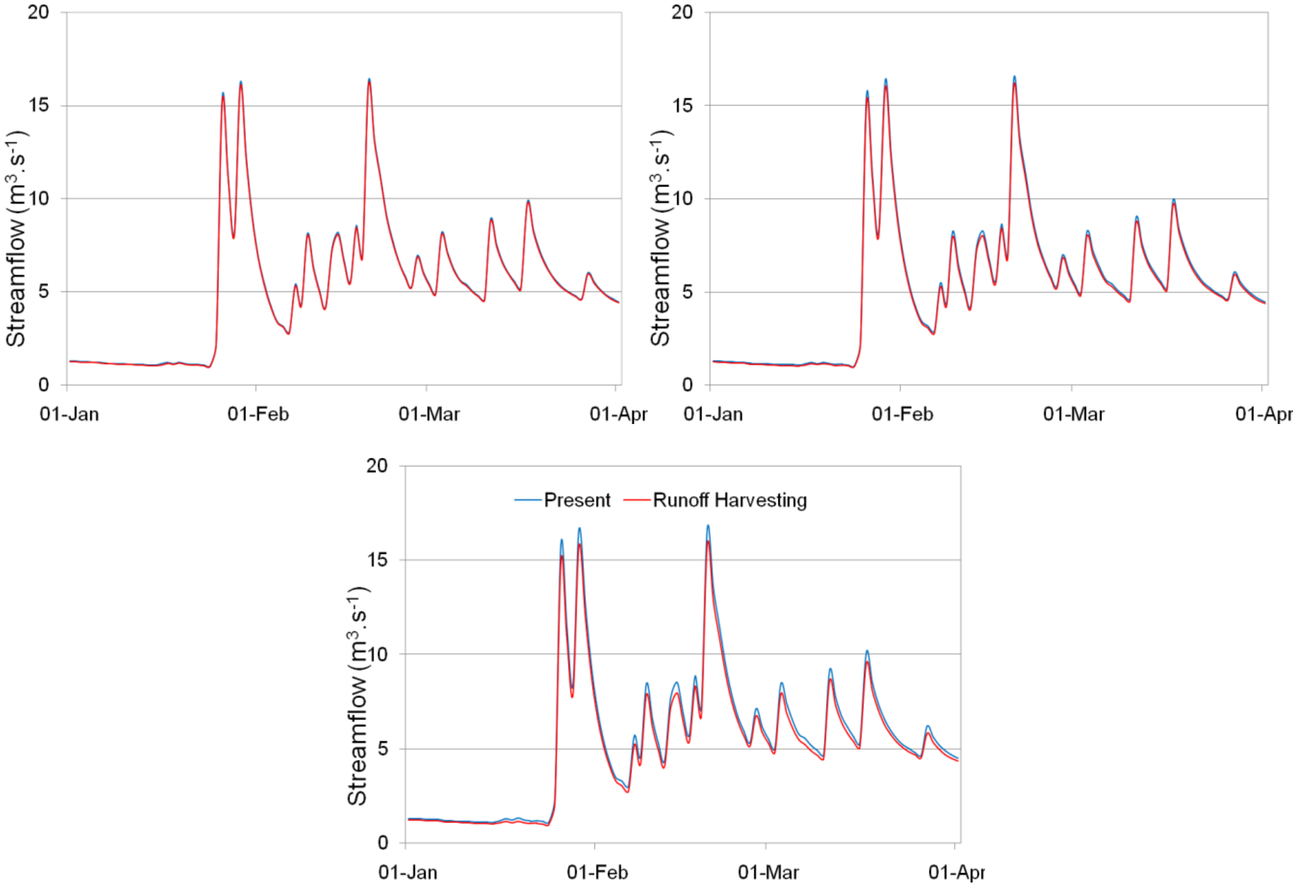

Figure 4.3 Time series comparison of pre- and post-runoff harvesting for 50 % E_{pop} (a), 100 % E_{pop} (b), and 200 % E_{pop} (c) from V11A over a three month period (1 January to 1 April 1975).

Results from the IHA analysis revealed the potential impact that runoff harvesting could have on streamflow regimes specifically on high and low flows. However the effect that runoff harvesting had on the hydrological regime in terms of changing Group 4 IHA parameters between scenarios was minor. 50 % E_{pop} and 100 % E_{pop} showed no changes to the frequency of low pulses for each of the QCs with an increase in the number of low pulses becoming evident only in 200 % E_{pop} where deviations of 20 % and 50 % recorded from QCs V11A and V11D respectively (Figure 4.4). Similarly, the median number of annual high pulses did not show considerable deviation between the different scenarios, except for one or two of the QCs where a decrease in the number of high pulses was noted (Figure 4.5).

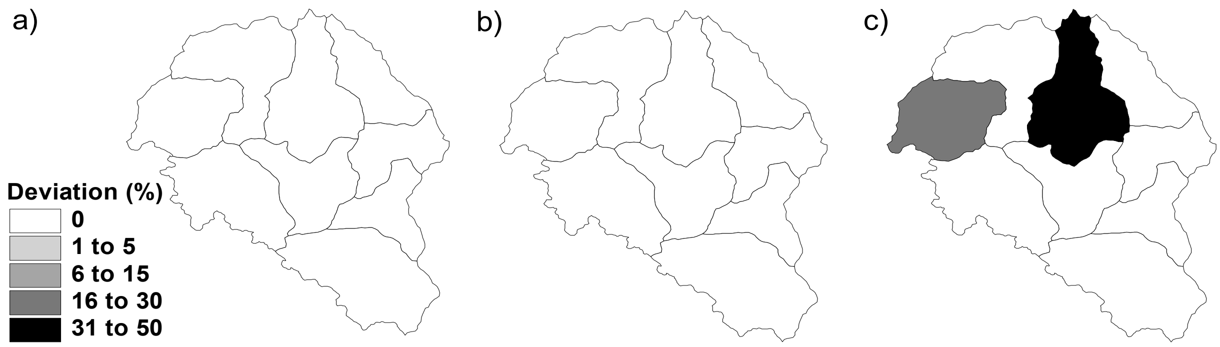

Figure 4.4 Percent deviation of the frequency of median annual low pulses (IHA Group 4) from pre- to post-runoff harvesting within the QCs for 50 % E_{pop} (a), 100 % E_{pop} (b), and 200 % E_{pop} (c).

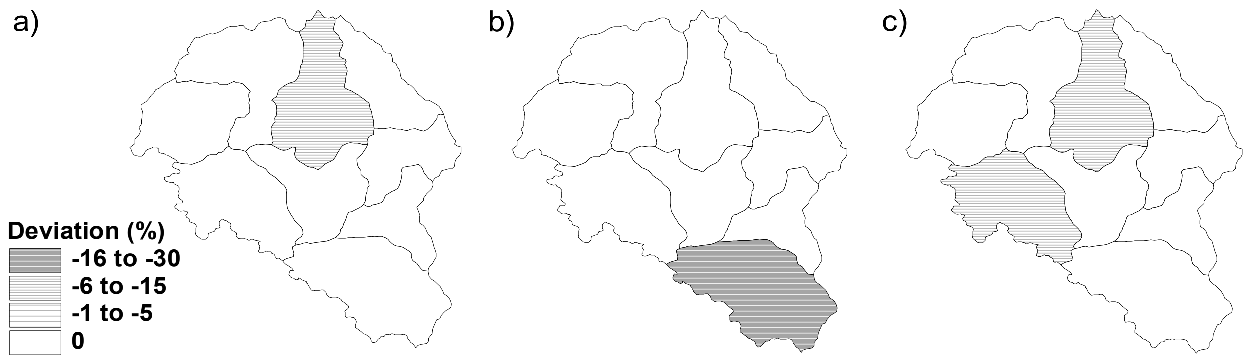

Figure 4.5 Percent deviation of the frequency of median annual high pulses (IHA Group 4) from pre- to post-runoff harvesting within the QCs for 50 % E_{pop} (a), 100 % E_{pop} (b), and 200 % E_{pop} (c).

IHA Group 2, both minimum and maximum, decreased as a result of runoff harvesting. 7 day minimum and 1 day maximum values represented the other durations of annual extremes (i.e. 1 day to 90 day values) with similar outcomes being recorded. The relative differences between medians ranged from -1 % to -29 % and 0 % to -12 % for 7 day minimum and 1 day maximum values respectively.

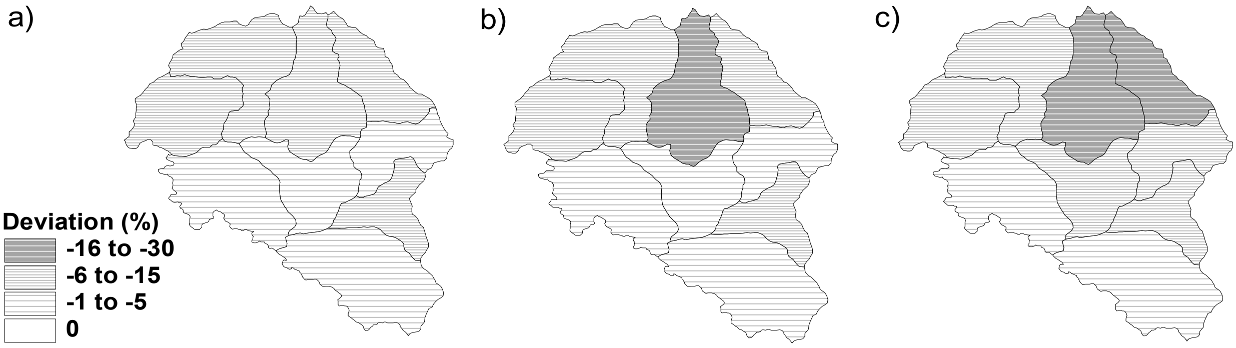

Figure 4.6 Percent deviation of the median annual minimum 7 day values (IHA Group 2) from pre- to post-runoff harvesting within the QCs for 50 % E_{pop} (a), 100 % E_{pop} (b), and 200 % E_{pop} (c).

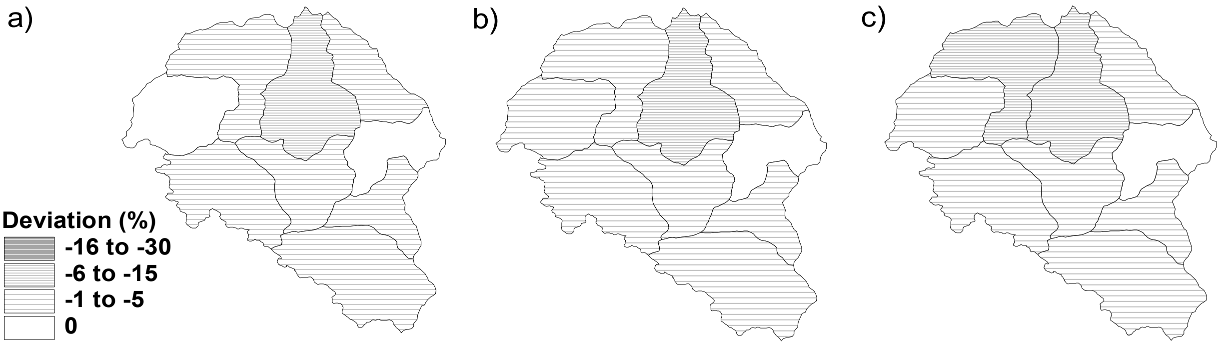

Figure 4.7 Percent deviation of the median annual maximum 1 day values (IHA Group 2) from pre- to post-runoff harvesting within the QCs for 50 % E_{pop} (a), 10 % E_{pop} (b), and 200 % E_{pop} (c).

4.4 Discussion and conclusions

To support the drive towards intensification of rainfed agricultural practices through the adoption of runoff harvesting systems, it is important to address how much water can be retained without negative implications on the hydrological and ecological regimes. This study offers a preliminary investigation in this regard, by providing a suitable approach into modelling the likely impacts of runoff harvesting on downstream river systems, and more specifically, how such impacts may affect river ecosystems.

Runoff harvesting at a QC scale was found to have little influence on total streamflow yields, even when the entire effective population for 2001 was assumed to be harvesting runoff. However, runoff harvesting may be more influential on specific components of the flow regime from the perspective that ecological functioning supports the structure and functioning of river ecosystems and their associated flow regimes (*c.f. Section 2.3*). Use of the IHA method demonstrated that certain components of the flow regime (i.e. extreme low and high flow magnitudes) were affected more than others as a consequence of runoff harvesting and this could have a strong influence in water resources management decisions regarding the maximum extent of runoff harvesting within river catchments. Simulating runoff harvesting processes using the *ACRU* model, however, did not account for continual depletion and refilling of storage structures that would be the case in reality. Instead the runoff harvesting systems replicated in the modelling exercises were simplified whereby storage structures were capable of capturing stormflow continuously, regardless of the number of rainfall events. However, in reality, the situation is different as once the storage structure is filled it cannot capture any more water unless water is abstracted and any surplus contributes to the downstream streamflow. Ultimately the actual situation, with the same amount of runoff harvesting as defined in this study, would have more runoff contributing to streamflow as a consequence of storage structures being filled. Furthermore, all runoff water that was captured was stored permanently and not utilised for supplemental irrigation. This approach is therefore based on the assumption that contributions of water from supplemental irrigation to downstream water resources as return flow is negligible as majority of this water will be lost as part of green water flow (i.e. due to evapotranspiration). Thus, the findings of the modelling exercise are extremely conservative, which suggests that even with large-scale runoff harvesting, the influences on streamflow regimes are likely to be insignificant. Hence findings from this study support the suggestion made by Bosch (2005) that rainwater harvesting should not be considered as a SFRA under the NWA and therefore should be regulated through another statute other than the NWA (Table 4.1). Rather, rainwater harvesting should be regarded as a Schedule 1 activity where water that is harvested may be used for purposes such as reasonable domestic use and irrigating small gardens.

However, despite the possible negative impacts that are possible as a result of large-scale introduction of runoff harvesting systems (i.e. reduction of downstream flows) there are also benefits. For example, managing rainfall where it falls not only increases the likelihood of reduced erosion and enables more energy-efficient water management; it also increases flexibility in ecohydrological landscape management (Falkenmark and Rockström, 2004). Reduced erosion due to controlled surface runoff is likely to influence physical habitats and biota of aquatic environments positively due to the decrease in suspended sediments, thus enhancing the overall integrity and functioning of riverine ecosystems. Additionally, runoff storage systems reduces the need for abstractions for irrigation, particularly during dry periods (Ngigi *et al.*, 2007) directly affecting the water availability for aquatic ecosystems. Therefore the spatial distribution of water management is more flexible, with an almost unlimited number of options for small-scale rainwater management, compared to very few options for large-scale water management using reservoirs (Falkenmark and Rockström, 2004). Furthermore the possibilities of integrating the conservation of biodiversity, and the ecosystems that they support, into water resources planning and management, will be much easier. Although supplemental irrigation is coupled with important synergies where farmers are expected to become more inclined to utilise fertilisers and pesticides (SIWI, 2005). Therefore understanding the possible negative impacts caused by pollution to surface water resources and aquatic ecosystems needs to be investigated, within the rainfed agricultural context, prior to excessive adoption and utilisation of runoff harvesting systems.

Runoff harvesting is an effective method for storing excess runoff for subsistence purposes particularly for during the dry seasons and therefore is considered a viable option to meet increasing agricultural demands. However benefits form harvesting runoff will need to be weighed up against the benefits for conserving ecosystems and the goods and services that they provide, in order for a decision to be made and unfortunately a compromise may be the only option. Based on the outcomes from this study the benefits that are potentially possible from large-scale adoption of runoff harvesting are likely to outweigh the impacts on downstream river systems.

5. FINAL DISCUSSION

For most rainfed agricultural lands the issue of "enough rainfall for crop production" is not a particular problem. Instead, the problem is due to poor rainfall distribution, whereby too little rainfall occurs during critical growth periods of crops. However, many such rainfed agricultural areas have considerable potential for increasing yields through runoff harvesting, but the key to achieve such increases is careful water management with consideration for different spatial and temporal scales (Comprehensive Assessment of Water Management in Agriculture, 2007). The following decades will no doubt experience major advances in the improved use of water. Small-scale irrigation projects are likely to become more common, as will the extent of adoption of an increasing variety of techniques for water harvesting (Bunch, 2000). Upgrading rainfed systems by providing supplemental irrigation, along with improving soil moisture conservation, is regarded by the Comprehensive Assessment of Water Management in Agriculture (2007) as a route to alleviating large numbers of people from poverty and increasing water productivity, especially in semi-arid regions. This builds on suggestions by many researchers over the past performance of rainfed agricultural systems (*c.f. Section 2.1*). For example, Senay and Verdin (2004) suggest that average maize yields could potentially increase to three tons per hectare, a much greater contribution to food supply than the current one ton per hectare average experienced in Africa, although, additional gains in crop production are also possible through soil pH control and fertilisation. Runoff harvesting is one particular avenue that small-scale rainfed farmers could adopt to attain these kinds of improvements, thereby increasing crop productivity. The majority of this potential lies in the capacity that runoff harvesting has to supplement crops with water when it is most required, for example, during critical growth phases, and hence would allow greater opportunities for attaining higher yields at the end of the cropping season. Subsequent to that, if farmers have water available more frequently, but in limited quantities, a demand for approaches to utilise water more economically will develop (Bunch, 2000), as will the urge to invest more into their crops through additional practices such as fertiliser application.

Current human induced transformations of the earth's landscape are, however, unprecedented in scale, altering important characteristics of terrestrial and aquatic systems, though the rates and directions of these changes are not believed to be sustainable, posing a serious threat to human well-being (Daily, 1999). This is especially the case in most sub-Saharan African (SSA) countries, where there is a lack of policy and legislation for implementing environmentally sound planning and management of water resources (Ngigi, 2003). In some countries, namely

South Africa, Tanzania and Zimbabwe, such policy is in place as it has been legislated in revised water laws (e.g. South Africa's National Water Act). The role of these, and similar national policies, is to facilitate Integrated Water Resources Management (IWRM) in the light of principles and provisions described in the water laws (Schulze *et al.*, 2004). However, the manner in which national policy is implemented will determine the overall effectiveness for addressing future water resources management issues. Therefore, the need to assure suitable quality and quantity of water supply required to protect basic human needs and aquatic ecosystems in order to secure ecologically sustainable development and utilisation is paramount (NWA, 1998).

Central to water resources planning and management is the process of determining the likely outcomes of human related activities on downstream hydrological regimes, and the implications that these activities may have on other water users, such as the Ecological Reserve. Within this context, the introduction of water system innovations (e.g. runoff harvesting) to rainfed agriculture requires both the identification of potential sites for runoff harvesting as well as an assessment of the associated impacts. Therefore it is crucial that investigative studies are undertaken to assess the full range of possible impacts that runoff harvesting may have on downstream water resources and to establish whether any negative impacts could arise as a result of widespread adoption. Although pre-emptive, such tasks are valuable in the sense that problems could develop due to excessive adoption and the identification and attempts to quantify these provide guidelines for catchment planning. For this reason it is imperative to determine the spatial constraints for future adoption where, provided runoff harvesting is implemented within acceptable limits, detrimental repercussions can be avoided whilst safeguarding the enhancement of rainfed agriculture. The research work highlighted in this dissertation aimed to achieve these objectives, as well as providing useful answers to research questions into the topic of runoff harvesting, by investigating the likely consequences prior to runoff harvesting becoming a dominant manifestation of catchment systems (*c.f. Section 1.2*). In doing so, modelling tools were successfully used to quantify potential impacts on downstream hydrology by determining the relative effects on the river flows that are required to support aquatic ecosystems. To compliment these investigations into large-scale adoption of runoff harvesting, a GIS-based spatial model that identifies upland areas within a catchment that would be suitable for runoff harvesting was developed.

Worldwide, various spatial models have been developed specifically for rainwater/runoff harvesting (Gupta *et al.*, 1997; Durga Rao *et al.*, 2001; Ziadat *et al.*, 2006), however, the GIS model devised for this study was developed using localised information for the Thukela River Basin, as well as methods that have been developed specifically for South African conditions (e.g. SCS-SA). Subsequently, this GIS modelling approach was found to be particularly effective for identifying high runoff generating areas for a representative catchment within the Thukela River Basin. Where these areas are situated in close proximity to croplands and homesteads, they offer more advantageous sites for runoff harvesting systems; opportunities therefore exist to reduce the need for complex diversion structures and pipe networks directing runoff water to storage tanks, and from tanks to croplands. Given the current motivation towards the introduction of water system innovations to rainfed agriculture, such an approach presents a valuable tool for identifying optimal sites within catchments for future runoff harvesting initiatives. Justifiably, the spatial model is useful for application in South Africa; hence the data inputs are relatively accessible. Furthermore, the approach is not data intensive, enabling an easy to use method, as well as limiting the likelihood of erroneous outputs that are generally associated with complex methods. Thus, as a result, the confidence that can be attributed to the runoff potential and rainwater harvesting (RWH) suitability maps is high.

The main aim for this dissertation, highlighted in Chapter 1, was fulfilled to the extent that ecohydrological methods were devised that utilise tools, relatively simple to use, but more importantly, that provide valuable information for water resource planning and management. However, the spatial modelling procedure highlighted in Chapter 3 describes an approach that is reliant on specific data needs in order to attain results with high confidence and the quality of the results is dependent on the quality of the data that is used. This presents an inherent weakness of the method, however, more and more spatial datasets are being generated, especially at national scales, with a high level of detail, and such datasets will continue to improve with further advances in data capture technology. Therefore the future prospect of using such an approach will be complimented by the enhanced development of datasets. An additional, potential shortfall with the spatial modelling exercise presented in this dissertation is that the method was applied to a fairly small sized catchment, which therefore brings to light issues attributed to “scaling”. At different scales the spatial and temporal variability of hydrological processes differ as do the distribution patterns and sensitivity (Schulze, 2000), so too do other processes that respond to hydrological variations (e.g. aquatic ecosystems). Thus it is important that attempts are made to apply these kinds of modelling tools at greater spatial scales where potential for runoff harvesting may be assessed at a scale that has a more regional context. Application at larger spatial scales (e.g. Quaternary Catchments) would, undoubtedly, require data that is appropriate for use at larger scales. However, as already highlighted, this may then compromise the accuracy of the results due to insufficient detail of available spatial data. Preliminary work by Mwenga Kahinda *et al.* (2006) has commenced which aims to develop a rainwater harvesting decision support system (DSS) that determines the potential impacts for wide scale adoption of rainwater harvesting as well as to determine which areas are suitable for rainwater harvesting. This approach is based on data derived from three broad categories; namely, physically based data, "dynamic" data (i.e. land use and socio -economic), and boundary data defining the spatial extent of interest. Although there is little provision for ecological impacts associated with rainwater harvesting, the DSS will be developed for the entire country (i.e. South Africa) and will essentially utilised data sets that are available on a national scale. Such data sets, for example, include spatial information such as the land use data derived from the National Land Cover database (NLC, 2005) and Land Type maps of soils information available on a national scale (Institute for Soil, Climate and Water, 2005). Although a national scale approach may be limiting in terms of the level of detail for identifying suitability sites, it would initially assist the process of selecting large areas or even catchments, where in runoff harvesting would be most suitable. Subsequent, more detailed approaches could then be carried out within priority areas to enhance the level of detail for locating potential sites. Therefore there is potential to merge small-scale, detailed spatial modelling with a more broad-scale approach particularly when scaling down from regional to more local planning.

An obvious limitation of this dissertation is a result of some lack of integration between Chapter 3 and Chapter 4, despite their independent aims complimenting each other in the within the greater context of this study. The difficulty of linking the former approach more directly with that of the later was as result of their contrasting spatial scales with which each method was based. Idealistically, it would be far more coherent to utilise the information generated from the spatial model in terms of suitable runoff harvesting sites and use this information as input to the later, i.e. to determine the potential impact of adoption towards downstream water resources and aquatic ecosystems. This would ensure that areas that are effectively most suitable for RWH would be used to determine the density of harvesting systems. Such an approach arguably would be far more realistic in terms of taking the probable RWH scenario into account, and thus would be a more accurate determination of the density of harvesting systems within a catchment as apposed to simply assuming the density of storage structures based on human population numbers. Therefore, had the two methods been devised for comparable spatial scales then this would have been possible. The question, however, would then be which scale would be most appropriate? Using a large-scale approach for locating suitable runoff harvesting sites would result in the compromising of spatial detail, i.e. through using national soils and land use coverages, which would then reflect unfavourably in the results for determining the impacts of runoff harvesting on aquatic ecosystems. Furthermore, and based on the outcomes from Chapter 4, adopting the aforementioned method would no doubt highlight minor downstream impacts, and likely to be much less than the least impacting scenario (i.e. Scenario 1) that was presented in Chapter 4. On this note, a useful recommendation would be to simulate the effects of runoff harvesting for a smaller spatial scale thus allowing for more realistic account on the possible density of storage structures.

Further research into the topic of spatial modelling of suitable runoff harvesting sites has the potential to enhance the usefulness of the GIS method described in Chapter 3. The inclusion of elevation data associated with homesteads and croplands, in particular, would be useful for determining suitable runoff harvesting sites that are situated upslope offering more affordable circumstances for delivery of storage water to crops by means of gravity. Through the use of gravity there are options to utilise low pressure irrigation technology (e.g. drip irrigation), which are favoured from a “more crop per drop” perspective. In addition to improved water application efficiency, the use of gravity allows for a supplemental irrigation system to be put in place that avoids, to some extent, the reliance of high-maintenance, costly pumps. Done independently or in parallel with the above, determining the minimum runoff generating area that would be required to support an area of crop could be incorporated into the model to exclude areas that are too small, thus identifying sites with greater priority for runoff harvesting. Furthermore, from a crop production point of view, these sites offer the most sustainable options for ensuring water supply. Finally, and for completeness of the spatial modelling, it would be useful to undertake a verification study that involves relatively straightforward ground-truthing of sites in the field that have been identified by the model. Additional field assessments valuable for verification purposes include quantitative methods to measure the surface runoff generation from these sites of interest, for example using runoff plots, a particularly useful procedure to carry out prior to designing and implementation of a runoff harvesting system to ensure adequate supplies of water will be definite from runoff harvesting sites.

In conclusion, our actions bear consequences reflecting the manner in which we will utilise our future water resources, particularly in the context of ecological and societal systems. Avoiding detrimental circumstances to these systems, however, is only possible with knowledge of possible outcomes. Various modelling tools have the ability to generate such information and provide valuable insight into what can be expected, a basis from which future water resources planning and management endeavours may be assisted. Within the context of this dissertation, the objectives (*c.f. Section 1.2*) developed to achieve this overall goal were accomplished, closing the knowledge gap pertaining to ecohydrological impacts of, as well as identifying suitable sites for, runoff harvesting. These findings highlight that future tradeoffs between water for livelihoods and water for ecosystems, specifically in terms of supporting ecologically important flow regimes, are possible through large-scale adoption of such water system innovations. This is an important progression towards achieving sustained future development of rainfed agriculture; however, the question is how much water can be traded between societies and ecosystems? Although the tools and methods developed and described herein provide a useful contribution to addressing this question, further investigations into additional perceived impacts is required, particularly in terms of water quality issues that may develop as a consequence of advancing water system innovations.

6. REFERENCES

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