THE EFFECTS OF RAINWATER HARVESTING ON AGROHYDROLOGICAL ECOSYSTEM GOODS AND SERVICES IN THE SMALLHOLDER FARMING COMMUNITY OF POTSHINI, SOUTH AFRICA

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ABSTRACT

Water harvesting techniques offer subsistence farming communities the ability to enhance water supply and management, leading to increased food and water security and health. Though the benefits seem obvious, a lack of understanding surrounds the local effects of these activities on natural systems, and the increasing prevalence of water harvesting practices invites a closer look. This study employs agrohydrological modeling to simulate changes in land use and water management and uses the outputs to assess the potential impact of upscaling rainwater harvesting on selected agricultural and hydrological ecosystem goods and services. Potshini, a well-studied rainwater harvesting community in the foothills of the upper Drakensberg range in KwaZulu-Natal, South Africa, was used as a case study. A detailed land cover map was created in order to accurately simulate the small scale of the Potshini catchment (9.643 km^2) and subcatchment boundaries were delineated according to streamflow monitoring instrument locations. Model scenarios were developed according to current and realistic future expansion of rainwater harvesting practices which were used to assess the effects on ecosystem goods and services. Selected goods and services include water supply and water regulation (in terms of quantity, quality, location, and timing), food production (by harvested rainwater fed vegetable gardens), and raw materials (natural grassland primary production of grass roofing materials). Indicators included water flow rates, timing, and distribution, crop yields, irrigation demand, plant stress factors, reservoir storage, and net primary production of grasslands. Results suggest that water supply is enhanced for crops while environmental water flows are reduced. Water quality indicators imply a decline in surface and shallow ground water resources, though harvested rainwater provides an alternative and flexible option for fresh water. Distribution of water is altered to increase relative surface flow, though overall decreases also suggest additional evapotranspiration and soil water retention. Timing of extreme flow events is adjusted and dry season low flow periods are extended, although rainwater storage enables flexibility in irrigation schedules. Food production is increased, while production of grass roofing materials is slightly reduced. In several cases indicators of water supply and regulation under rainwater harvesting trend towards those of the historical undeveloped scenario, suggesting a hydrological regime shift approaching the natural environmental state. Contributions are made towards a more accurate understanding of small catchment impacts of rainwater harvesting, and the tools and methods developed hold potential for future use in investigating other aspects of natural processes or alternative future scenarios in Potshini, as well as application to other locations with under similar conditions.

CONTENTS

I. INTRODUCTION

Climate change and increasing populations are challenging natural resources and communities worldwide (Hansen and Sato, 2001; Parry et al., 2007; Rosenzweig et al., 2008). Rainfed agriculture in arid and semi-arid lands is particularly susceptible to increasingly varying precipitation (Goswami et al., 2006; Jones et al., 2007) and is a vital source of food for many people across rural areas of sub-Saharan Africa (Cooper et al., 2008). Improvements in agricultural practices can help mitigate negative impacts of changing rainfall distribution, providing benefits in the form of increased food and water security, reduced poverty, and improved quality of life (Pandey et al., 2003; Hope et al., 2008; FAO, 2012).

Agricultural productivity is subject to many variables, including timing of planting and harvest, crop varieties, fertilizer and pesticide application, tillage techniques, water management, and environmental conditions (Rockström et al., 2004; Makurira et al., 2011). Of these, water management holds a particularly significant potential to contribute to agricultural development, and the implementation of water harvesting techniques, where suitable, provides a flexible source for irrigation. This is especially important in regions where low, erratic rainfall and high evaporation leads to frequent dry spells and low soil moisture which can devastate crop yields (Falkenmark et al., 2001).

(1) *Water harvesting*

Water harvesting techniques offer benefits across the world and in many regions of sub-Saharan Africa as they hold potential to enhance soil infiltration in agricultural zones and provide water for supplemental irrigation to bridge dry spells. Such innovations provide a much needed opportunity for communities to combat food and water insecurity, earn income, and improve wellbeing (MA, 2005; Ngigi et al., 2005; CAWMA, 2007; Baiphethi et al., 2009; Makurira et al., 2011; Mwenge Kahinda and Taigbenu, 2011).

Rainwater harvesting is described as *the collection and storage of rainwater runoff for agricultural or domestic use* (Gould, 1999). Techniques are classified by Mwenge Kahinda and Taigbenu (2011) into three types: *in-situ, ex-situ,* and *domestic*. With *in-situ* rainwater harvesting, water is collected directly at the site of use (*i.e.* on the field) and often consists of reshaping the soil surface to slow runoff and enhance infiltration. *Ex-situ* rainwater harvesting consists of water collection from an off-farm location, for example from a nearby hillside or adjacent runoff plot, which is collected and transported to crops for irrigation as desired. *Domestic* rainwater harvesting involves water collection from rooftops or other constructed surfaces primarily for household uses such as drinking, cooking, and washing.

In order for these systems to be effective, they must be applied such that they suit the local socioeconomic context as well as the technical characteristics of the site (Critchley and Siegert, 1991). Specific designs and concepts for water harvesting systems are diverse and a detailed discussion of the available techniques can be found in Falkenmark et al. (2001) and Critchley and Siegert (1991). Several studies have also focused on evaluating the suitability of locations for rainwater harvesting, identifying important contributors to successful rainwater harvesting sites including physical parameters such as slope, soil properties, runoff, proximity to farms, land cover, rainfall, and flow extremes (de Winnaar et al., 2007; Mbilinyi et al., 2007; Mwenge Kahinda et al., 2008; Mwenge Kahinda et al., 2009), as well as ecological sensitivity, land use constraints, and socioeconomic factors such as sanitation, water infrastructure, poverty, and economic activities (Mwenge Kahinda et al., 2008; Mwenge Kahinda et al., 2009). Under these considerations, suitable locations in South Africa in particular appear to be widespread and thus rainwater harvesting holds the potential to benefit a large population in need.

In addition to the ability of agricultural innovations such as water harvesting to improve food production and quality of life, they have a number of effects that extend to the surrounding environment. Many impacts result from altered hydrodynamics, where some water is redistributed from wet to dry periods, improving infiltration, soil fertility, and groundwater recharge while decreasing peak runoff flows and thus reducing erosion and sediment transport (Li et al., 2000; Vohland and Barry, 2009). This can result in higher groundwater recharge rates and overall increases in biomass production (Andersson et al., 2011; Glendenning and Vervoort, 2011; Welderufael et al., 2011), although tradeoffs occur between the abundances of cultivated crops and wild vegetation. Improvements in land and water use efficiency reduce the need for agricultural expansion and environmental water abstraction during the dry season, but also depend on management practices (Li et al., 2000; de Winnaar and Jewitt, 2010). Studies have shown significant reductions in local streamflow, but only relatively minor impacts on river flow downstream (Andersson et al., 2011; Glendenning and Vervoort, 2011). This suggests that impacts are more significant on the local scale with buffering exhibited on the regional level, although this is also affected by site-specific factors and the limited scale of water harvesting practices that are currently implemented (de Winnaar and Jewitt, 2010; Warburton et al., 2012).

(2) *Ecosystem services*

Rural subsistence farming communities have an especially local dependence on the environment. Ecosystem goods and services are depended upon for daily life and sustenance, and their sustainable management is vital (Le Maitre et al., 2007; Reyers et al., 2009). In such communities, the close relationship between people and their environment highlights the importance of establishing and maintaining an awareness of the impacts of local activities on the environment, and illuminates the interconnectedness of ecosystems as they encompass human activities and natural processes.

Ecosystem goods and services (EGS) provide a framework by which ecological integrity and processes can be evaluated and communicated, often for communication purposes in conservation and land management decision-making (Burkhard et al., 2010; De Groot et al., 2010). Ecosystem goods and services can be defined and categorized in a variety of ways (Fisher et al., 2009), depending on the goals of the research. Much debate and development has occurred over this in recent years, with various systems being accepted for use with different scenarios and goals (MA, 2005; Brauman et al., 2007; Egoh et al., 2007; De Groot et al., 2010). In this study, EGS serve a practical purpose to evaluate linkages between human activities and the surrounding environment. As such, EGS are defined here as *the elements of ecosystems utilized by people to improve and support wellbeing* (Boyd and Banzhaf, 2007; Fisher et al., 2009).

The interactions between humans and the surrounding environment are complex, and an understanding of relevant outcomes in the form of goods, services, and benefits will be enhanced by taking a holistic perspective that integrates the tradeoffs and synergies between these two aspects of a single complex system (Ngigi et al., 2007). Such an understanding can inform policy and management development in order to maximize the long-term benefits of impactful projects (Jewitt, 2002).

From a biological perspective, EGS represent the anthropocentric outcomes of natural processes which support vital ecosystem functions and maintain their integrity. Thus, EGS can be used to guide the assessment of both environmental support of human livelihood (Corvalan et al., 2005) and of general ecosystem health (Rapport et al., 1998; Balvanera et al., 2006). Further, observed changes in ecosystem goods and services can be used to inform a detailed investigation into specific underlying dynamics in which water plays a fundamental role (Rockström et al., 2004; Brauman et al., 2007; Le Maitre et al., 2007). Hydrological ecosystem services are well understood, and readily quantified and modeled, and so also provide communicable insight into relevant changes in ecological systems (Brauman et al., 2007; Kandziora et al., 2013).

Agricultural activities also play a complex role in ecological systems, as they constitute a cultivated component of the ecosystem and provide goods and services that support the vast majority of the global human population. These activities require resources such as land, water, and nutrients, that have significant effects on other ecological functions and EGS (Metzger et al., 2006; Dale and Polasky, 2007; Gordon et al., 2010; Power, 2010). Conversely, the surrounding natural systems have effects on agriculture both supporting and detracting from agricultural productivity through mechanisms such as evapotranspiration, water storage and transfer, soil production, and pollination (Zhang et al., 2007). In order to fully understand these interactions, analyses must consider aspects of land use, hydrology, and nutrient flows that result from natural processes, human activities, and feedbacks between the two.

II. STUDY AREA

(1) *Potshini*

The Potshini catchment is the site of multiple ongoing collaborative research projects designed to comprehensively assess the benefits and drawbacks of water harvesting. As part of the Water Harvesting Technologies Revisited (WHaTeR) project, Potshini is one of several locations involved in an interdisciplinary examination of environmental and socioeconomic tradeoffs associated with water harvesting. Potshini was originally selected for this research due to a combination of previous collaboration with researchers, and its suitability for rainwater harvesting (Andersson et al., 2011).

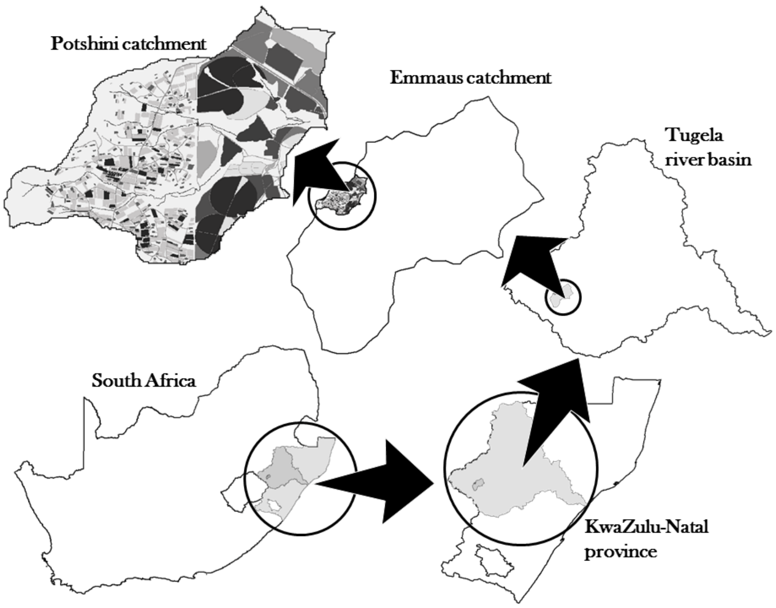

Figure 1. Location of the Potshini catchment

Potshini is a rural smallholder farming village with a population of around 1200 people, located in the foothills of the Drakensberg Mountains in the Emmaus Quaternary Catchment (V13D) in the western reaches of the Tugela river basin in the province of KwaZulu-Natal, South Africa (28°48'50"S, 29°22'51"E, Figure 1). Land use in the Potshini catchment is by area 11.5% subsistence farming, on the gentle lower slopes of the catchment, 6% grazing land for goats, cattle, and sheep on the steeper upper slopes and among farms, and 28.5% commercial farming downstream of the village. Major smallholder crops include maize (*Zea Mays*) and soybeans (*Glycine max*), and vegetables, legumes, and fruits are farmed in small gardens to provide nutritional diversity and some supplemental income (Greeff and MacGregor, 2011). These gardens are irrigated by hand on each day with low or no rainfall, and are the primary recipient of rainwater which is collected from rooftops and surface runoff.

Altitude ranges from 1239 to 1466 masl, sloping gradually away from the low lying mountains in the southwest. Perennial streams run down each side of the catchment with flows decreasing severely during the dry winter. Water from streams is used locally for domestic purposes and livestock, and downstream to recharge reservoirs used for irrigation of commercial farms (Kongo and Jewitt, 2006; de Winnaar et al., 2007).

Precipitation varies seasonally (Figure 2) with a mean annual rainfall of 870 mm. Average temperatures range from a lows of near freezing in the winter months of June and July, to nearly 30°C in February. Mean annual evaporation potential has been estimated at 1750 mm (Rockström, 2000; Kongo and Jewitt, 2006; Kosgei et al., 2007), so water must be carefully managed in order to maintain healthy crops and provide sufficient food each year.

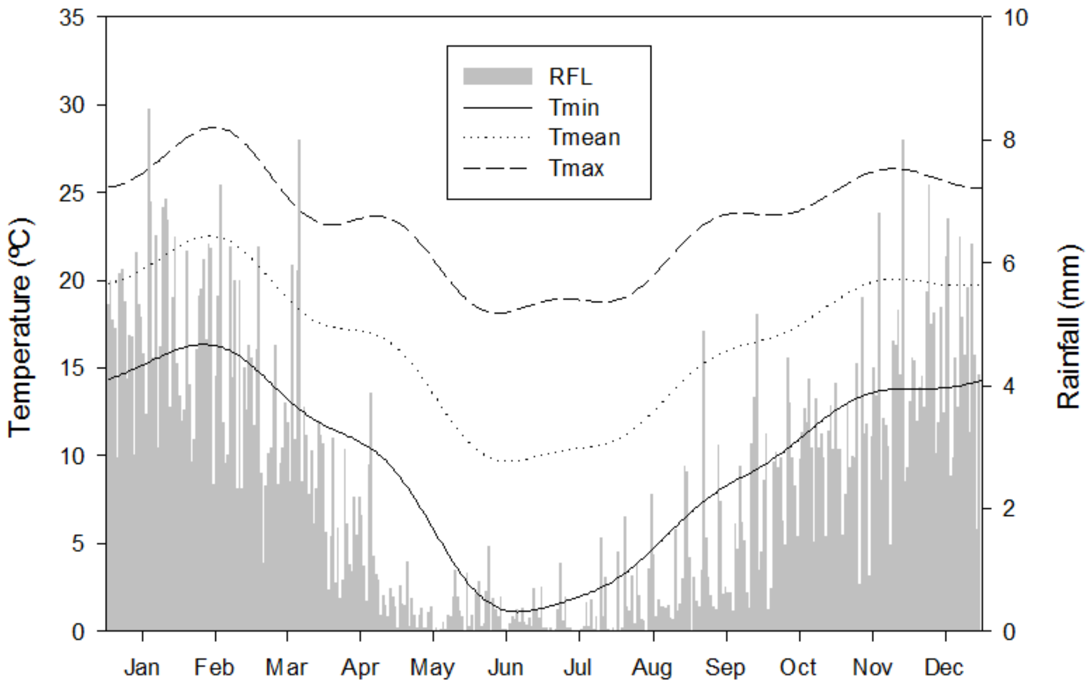

Figure 2. Mean daily temperature ranges and rainfall averages for Potshini

46 homesteads in Potshini have been equipped with rainwater harvesting equipment through development projects over the last 10 years. Most houses have at least one above ground tank harvesting rooftop runoff for domestic use, and two to three underground tanks harvesting surface runoff from the compacted bare soil surrounding the house. Apart from two older underground farrow cement tanks of considerably higher volume (30000 L and 50000 L), all tanks are 5000 L polyethylene plastic JoJo brand tanks, 2.275 m in height and 1.81 m in diameter (JoJo, 2013).

Researchers have fostered a culture of experimentation and development among the farmers and many employ additional agricultural innovations in order to improve crop production and water use efficiency. These include *in-situ* rainwater harvesting, where trenches are constructed to divert and collect water that infiltrates into cropped soils; *tower gardens*, which percolate grey water through ash and rock to provide clean water to plants grown at their base; *drip irrigation*, which brings water efficiently, directly to the roots of the plants; and *rain gauges*, which inform farmers about the water available for irrigation (Prolinnova, 2008).

Farmers have also shown initiative in improving their own rainwater harvesting systems, in one case by digging a trench across a hillside to collect additional runoff, and in another case by taking advantage of a nearby spring as an additional water source (Bulcock, 2012). One farmer has created channels around his homestead to direct spillage from his rooftop tank and grey water from his household waste into his agricultural tanks. He also utilizes traditional methods for fertilization and pest regulation in his vegetable garden, using diluted cow dung for fertilizer and for pesticides uses a combination of water and one of the following: crushed chili and garlic, low concentration dish soap, or crushed bodies of the pests themselves. Taking this use of mainly organic resources together with efficient rainwater harvesting and nutritional benefits to the community, and combining that with the potential for diverse agriculture to improve yields and at least reduce negative environmental impacts if not bolster ecosystem service provision (Kremen and Miles, 2012), these vegetable gardens promise a significant and healthy shift towards sustainability.

Significant effects of climate change have been observed in the region, including decreased mean precipitation on rainy days and increased warm spell durations (New et al., 2006). Further forecasts call for increases in autumn rainfall and seasonality, strengthening the need for acute attention to adaptive crop timing for maximizing productivity (Nel, 2009). These changes highlight the potential benefits of innovations such as rainwater harvesting in order to increase crop yields and establish food security in the region.

Potshini has been the site of much research over the years; the ongoing WHaTeR project and the previous Smallholder Systems Initiative (SSI) (Rockström et al., 2004), both concerned with agricultural innovation, have maintained a significant research presence in the community for nearly 20 years. This work has sought to combine research with the needs of local populations, focusing on practical improvement of water use efficiency in the area while investigating the effects on underlying social and natural processes.

Previous work has included a comparison of agricultural techniques that demonstrated the benefits of conservation tillage practices, where reducing soil tillage improved infiltration, soil moisture, and crop production relative to traditional tillage practices (Kosgei et al., 2007). Quantitative work has been supported by an ecohydrological assessment of the area and the establishment of a hydrological monitoring network (Kongo and Jewitt, 2006). This infrastructure was developed in collaboration with local farmers, who have actively participated in management of the systems and recording of data (Kongo et al., 2007). The monitoring network supports the collection of quantitative data on surface runoff, streamflow, water quality (sediment load), rainfall, humidity, and temperature (Kongo and Jewitt, 2006).

An investigation by de Winnaar and Jewitt (2010) assessed the ecological impacts of rainwater harvesting in the area on a multiple quaternary catchment scale spanning some 1900 km^2. This study utilized modeling tools to investigate the ecohydrological effects as indicated by the Impacts on Hydrological Alteration (IHA) framework (Richter et al., 1996; Richter et al., 1998; Gao et al., 2009), revealing only minor impacts on downstream flow regimes, and suggested that the benefits from rainwater harvesting practices would detract from ecological welfare at such a scale (de Winnaar and Jewitt, 2010).

Ongoing work continues to pursue a comprehensive understanding of activities and environment in the area, with researchers investigating such parameters as water quality, both in streams and rainwater tanks; carbon cycles, including both dissolved organic carbon in the streamflow and respiration levels in the soil; sediment transfer and erosion; differences in surface runoff on scales from 1 m^2 microplots up to the 30000 km^2 Tugela river basin scale; and a participatory investigation of ecosystem services.

III. RESEARCH QUESTIONS

(1) *Motivation*

Ecological effects of rainwater harvesting are poorly understood and susceptible to the changes in water and nutrient flows caused by water harvesting. Tradeoffs and benefits extend beyond local communities and crops, as downstream farmers see reduced river flow and surface runoff (Kongo and Jewitt, 2006; Ngigi et al., 2007). This has subsequent effects on climate, nutrient availability, plant and animal biodiversity and abundance, and downstream water availability (Vohland and Barry, 2009).

The study of de Winnaar and Jewitt (2010) highlights the need for smaller scale evaluation of the impacts of rainwater harvesting. Further improvements on their study can be made by incorporating agricultural considerations, specifically by incorporating reservoir capacity, recharge, and irrigation into models. These adjustments permit a realistic comparison of different scales of implementation, and the expected associated benefits in terms of improved crop yields and water supplies. A multi-scale approach can further add to insights on the scale-dependency of observed effects, providing useful information for development planners and stakeholders considering rainwater harvesting expansion.

The ecosystem goods and services framework (Fisher et al., 2009) provides an integrated perspective on both development needs and those of natural systems, as they require sufficient levels of ecosystem integrity in order to benefit human populations. In particular, hydrological and agricultural goods and services concern the population of Potshini and similar communities around the world, and are responsive to perturbations due to rainwater harvesting innovations (Falkenmark et al., 2001; Rockström et al., 2004; de Winnaar and Jewitt, 2010). Hydrological dynamics are integral to both ecological and social development throughout the world, and agricultural production is the driving force behind changes in land use. Together, these amenities dictate the sustainability of ecosystem support systems and so their potential responses to human activity demand close scrutiny before any significant development decisions can be reliably justified (Le Maitre et al., 2007; Nelson et al., 2009; de Winnaar and Jewitt, 2010; Power, 2010).

Small systems innovations in Potshini have placed local farmers at the cutting edge of rainfed agriculture, yet comprehensive understanding of the environmental impacts of these changes requires further research. The site provided a unique opportunity for an integrative approach that combines social, hydrological, and environmental impacts (Falkenmark et al., 2001; Ngigi et al., 2007). The present research enhances scientific understanding through development and application of a model-based approach to quantifying hydrological and agricultural tradeoffs between rainwater harvesting activities and the provision of EGS. The case study allowed for a detailed consideration and delineation of site-specific sensitivities, such as land cover and harvesting practices , which can have significant effects on outcomes (Ngigi, 2003).

While many effects of water harvesting are conceptually understood, there remain significant gaps in understanding of ecological impacts on small scales (Ngigi, 2003; Vohland and Barry, 2009). These include effects on local and downstream wetlands (Falkenmark et al., 2001; Andersson et al., 2011), and feedbacks with local native vegetation due to water and nutrient cycling (Glendenning and Vervoort, 2011), each resulting from changes in water flows. Analysis of the effects on agrohydrological ecosystem services provides the ability to assess these dynamics while preserving a focus on the benefits to local populations. This provides a better understanding of the potential ecological impacts, and better predictive tools for assessing the effects of expanded adoption of rainwater harvesting (Makurira et al., 2011; Mwenge Kahinda and Taigbenu, 2011).

(2) *Questions*

The present study improves the understanding of the potential effects of expanding rainwater harvesting practices in the context of ongoing agricultural development using Potshini as a case study, answering the central research question: ***What are the effects of rainwater harvesting on ecosystem goods and services in the Potshini catchment?***

This was achieved by evaluating changes in the local environment and hydrological system under the use of water harvesting, focusing specifically on local ecosystem services in the context of food and water security in Potshini. Exploration of the main question involved answering several sub-questions, each specific to the Potshini catchment:

(i) What is the current state of land use and water harvesting?
(ii) What ecosystem goods and services are most important locally?
(iii) What quantitative indicators can be used to assess the state of EGS?
(iv) What are the effects of rainwater harvesting on EGS?
(v) What are the anticipated effects of upscaling rainwater harvesting on local EGS?

IV. METHODS

This research examines the effects of rainwater harvesting using a modeling approach, employing the ACRU agrohydrological model and selecting indicators for EGS from its outputs. Scenarios were developed for several scales of expanded use of rainwater harvesting in the catchment, and relied on current practices to realistically model potential changes. Supporting information was gathered from researchers and community members to determine which EGS are most relevant in Potshini. A literature review illuminated the relevance of EGS to the expected effects of rainwater harvesting and dry season irrigation. Analysis of outputs was performed using a selection of indicators for relevant EGS, which were calculated from aggregated daily values of hydrological and agricultural data for interpretation of the expected effects.

(1) *Modeling*

Extensive data collection and curation was performed in order to obtain the information necessary for accurate simulations. This came through various channels, including a land cover survey, conversations with farmers, public data sources, and collaboration with fellow researchers. The modeling approach allows simulation of several scenarios for Potshini, both past and present, to investigate the effects of different land use and water management activities on EGS.

The field survey of land cover was necessary in order to provide data of sufficient detail for the relatively fine scale of application. A literature review was conducted to select locally relevant ecosystem services and respective quantitative indicators from model outputs. Significance of differences in output data were established by performing linear regression on time series data between parallel simulations.

To translate the effects on indicators into effects on EGS, a qualitative interpretation was performed, concluding with the expected consequences and tradeoffs associated with observed changes drawn from the direction and relative magnitude of changes.

(1.1) *A tool for decision-making*

In order to make decisions for management, policy, and development, scientific understanding provides people with much needed and reliable information. These decisions can drastically alter land cover and use, leading to complex ecological changes that affect human wellbeing. Theoretical understanding is well-established for many processes, but applications require a knowledge of state and performance variables specific to the area of interest. Though these parameters can be measured, a model provides the ability to expand knowledge beyond current scenarios, utilizing easily obtained datasets for local applications.

For example, a South African municipality considering whether and where to install a dam can take advantage of national scale climate, rainfall, soil, and elevation datasets to predict how quickly it would fill up, what the downstream impacts would be, and even how the resulting reservoir could be used to irrigate crops. This information provides vital scientific insight into the ramifications of human activities, without requiring a comprehensive understanding of the underlying principles. Further, it provides quantitative output that can be used to communicate impacts in concrete terms.

(1.2) *Model selection*

The agrohydrological model ACRU (Schulze, 1984; Schulze, 1995) was selected for numerical simulations, as it provides sufficient detail for quantification of processes pertaining to wild vegetation, agriculture, hydrology, and land use, and does so with an accuracy conducive to small scale evaluations. The model was previously developed and validated for use in the study area, and many data input requirements were readily available from public and in-house sources at the collaborating institute.

The ACRU model also includes native databases pertaining to local vegetation types and climate, and has been validated for application to the region many times. Additionally, advice and consultation with experienced users and developers of the ACRU model were possible throughout the course of the research. The detailed outputs available from the model provide sufficient detail to adequately assess the parameters of interest in this study, as its specific tailoring to integrate hydrological and agricultural would suggest.

(1.3) *Flexibility and repeatability*

Another advantage of modeling involves the tremendous opportunity for detailed examination of the many interwoven parameters once the model has been set up. Many questions that come out of simulation results can be further explored by altering parameters and rerunning simulations for additional analysis.

(2) *ACRU*

(2.1) *Model description*

The ACRU model constitutes a physical conceptual model, utilizing multi-layer water budgeting to quantify water flows (Figure 4) and vegetative production on a daily time scale (Schulze, 1995). It thus encapsulates agrohydrological theory and presents a flexible platform for investigation of the effects of parameters such as climate, land cover, soil, and management practices on the agrohydrological system.

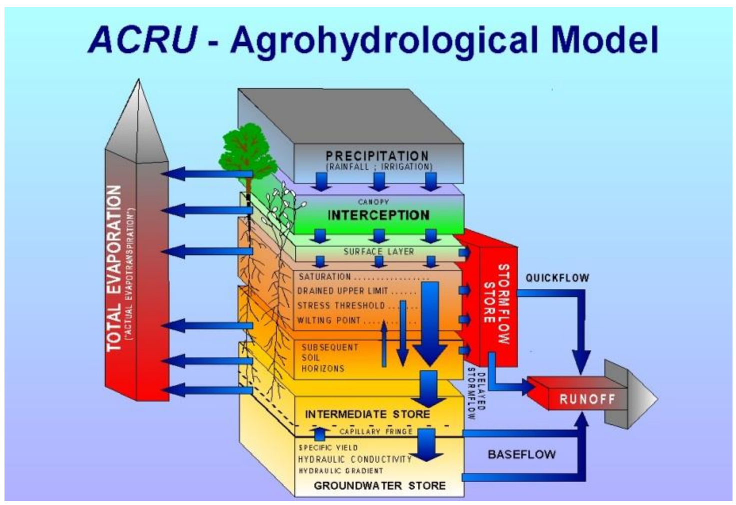

Figure 3. ACRU agrohydrological model flows (Schulze, 1995)

ACRU, originally developed by Schulze (1984; 1989; 1995), comprises a detailed and robust tool with which to explore the environmental effects of water harvesting. The ACRU model has been developed, verified, and applied specifically for research in southern Africa (Tarboton and Schulze, 1991; Tarboton, 1992; Jewitt and Schulze, 1999; Jewitt et al., 2004; de Winnaar and Jewitt, 2010; Warburton et al., 2012), and has since been adapted for use in a variety of agrohydrological settings around the world (Bekoe, 2005; Kienzle and Schmidt, 2008; Forbes et al., 2010).

The model is divided down into a system of layers, with water flows moving between the atmosphere, surface vegetation, soil horizons, and groundwater zones. Major flows include evapotranspiration and runoff, and major storage occurs in soils and shallow groundwater. A visual representation of the ACRU inter-layer flows is illustrated in Figure 3 above.

Data requirements for running the model are flexible, and functions are included to work around or interpolate data where necessary. Core data requirements comprise physical and climatic data pertaining to the catchment, specifically rainfall, reference potential evaporation, soil data, and land cover. Optional modules are also available for analyzing several other relevant parameters including groundwater flow, peak discharge, reservoir yield, sediment yield, irrigation supply and demand, crop yield, and forest responses. For a more detailed description of the model, please refer to the theory or user manuals (Schulze et al., 1989; Schulze, 1995).

(2.2) *Model setup*

Establishing a reliable baseline simulation requires the acquisition and curation of a wide range of data, including climatic inputs in terms of temperature, rainfall, and evaporation; land cover parameters in terms of vegetation, soil properties, and human activities; location data in terms of elevation and latitude; and water flow data in terms of management, irrigation, dams, and observed streamflow. Further, a mechanism for incorporating rainwater harvesting into the model had to be devised, incorporating the methods and suggestions of de Winnaar and Jewitt (2010).

The existence of a hydrological monitoring network at the study site was beneficial to the development of inputs, as rainfall and temperature data could be locally evaluated and streamflow data were available to validate outputs. Rainfall and temperature data were originally collected by automated weather stations at two central locations within the catchment, and streamflow data were collected from H-flumes equipped with pressure transducers and automatic data loggers.

Land cover parameters had to be built from the ground up, as previous maps by van den Berg et al. (2008) and de Winnaar et al. (2007) were too coarse in resolution (20 m x 20 m) and too narrow in scope, respectively. Mapping of the catchment was performed based on satellite imagery and field observations.

Baseline scenarios were developed as described by Warburton et al. (2012), employing *Acocks veld types* (1988), as parameters pertaining to these vegetative classes were native in the ACRU software. Future scenarios were developed based on information obtained from a household survey done by a student at UKZN, which included per household data on water tank storage capacity, current volume, water use, number of people, number of animals, and collection surface types. Expansion levels of rainwater harvesting were based on per household averages and the number of households currently not equipped with storage tanks.

Lastly, areas for runoff collection and vegetable gardens were computed using GIS data, creating polygons around satellite images in Google Earth at confirmed locations of each and using ArcMap and ArcGIS XTools to project and calculate areas.

(3) *Data*

(3.1) *Elevation*

Several digital elevation maps (DEMs) were assessed for suitability to the current application, including ASTER (Abrams, 2000), SRTM (Jarvis et al., 2008), and another obtained from UKZN (Weepener et al.). The SRTM 90 m version 4.1 dataset was selected due to its documented low error and gap rates, hydrological improvements, and availability

(Wolf et al., 2009; Hirt et al., 2010). This data was interpolated to approximately 20 m resolution using the bicubic algorithm included in the ArcMap raster resample tool in order to smooth the surface for subsequent watershed delineation.

Delineation of subcatchments was performed for three scales with outlets located at continuous flow monitoring points, and at points corresponding to two large-scale commercial dams in the catchment. This was done using the Arc Hydro Tools extension for ArcMap which uses the digital elevation map as the input (Maidment, 2002). Details of the process are described in Appendix (1), and resulting subcatchment divisions and outlets are shown in Figure 4. **Delineated subcatchments for flow monitoring points and dams in the Potshini catchment**Figure 4.

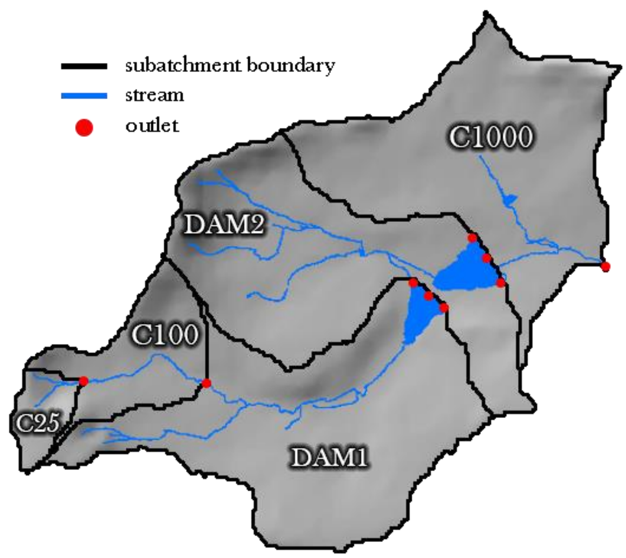

Figure 4. Delineated subcatchments for flow monitoring points and dams in the Potshini catchment

(3.2) *Land cover*

Land cover for the smallest scales was delineated manually using a combination of satellite imagery from Google Earth (2009) and ground observations, and was compared against coarser datasets (20 m x 20 m) derived from satellite data on a provincial scale (Ezemvelo). Land type classification was determined by input requirements of the ACRU model (Schulze et al., 1989), and consisted of the following classes:

- Grassland
- Degraded grassland
- Bare soil and rock
- Impervious surfaces (homesteads, roads)
- Smallholder crops (dryland maize and soybeans)
- Commercial crops (irrigated and dryland maize, soybeans, vegetables, cabbage, and wheat)
- Commercial plantations
- Streams
- Reservoirs

The steps involved in this process were iterative, consisting of first constructing a digital map of polygons for contiguous distinguishable land cover areas, and polylines for features such as roads and streams, using the feature construction tools and satellite images included with the Google Earth software (2009). These maps were then exported as KMZ files and imported into ArcMap, where they were projected, preliminarily classified, and used to produce a printed version of a land cover outline map for the Potshini catchment. This map was taken into the field and, using a combination of landmarks and GPS waypoints, features on the map were correlated with features on the ground and their classes were confirmed. Landmarks consisted of homesteads, trees, streams, roads, and the central school, and are indicated along with reference GPS waypoints in Figure 5.

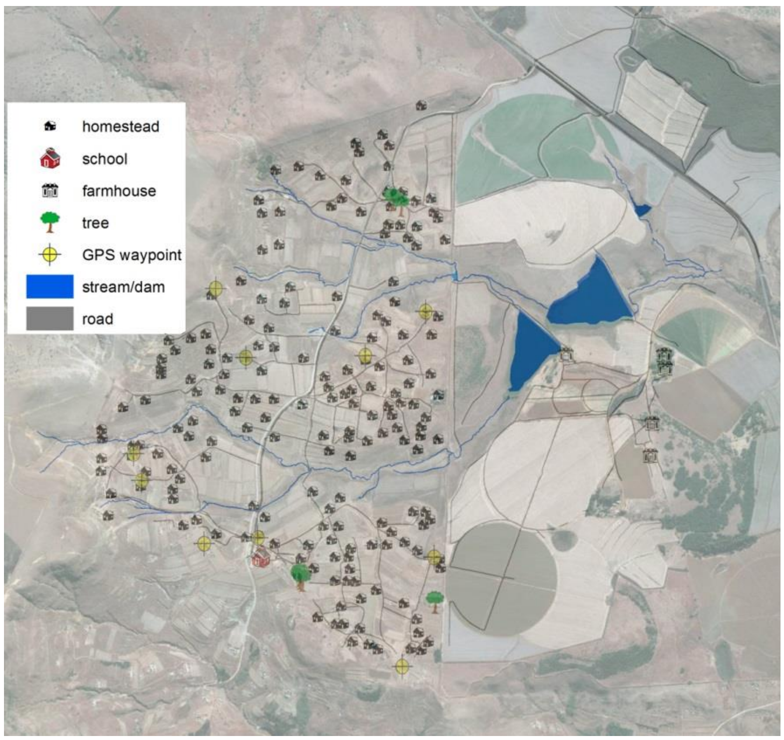

Figure 5. landmarks and GPS points used for land cover mapping. Image © AfricaGIS (2009)

Smallholder crop identification was carried out in consultation with the local community liaison and residents, who indicated that major crops consisted of only maize and soybeans, which are easily distinguishable from each other during the growing season. Maize, or mielie as it is known locally, is a tall grass which reaches between 1-4 m in height, has broad, flat blades, and at the time of the investigation was in a growth stage where orange-hued anthers were visible (Courteau, 2012; FAO, 2013). This facilitated identification from a distance, as illustrated in Figure 6 taken from the top of the hills in the upper reaches of the catchment. Soybeans typically grow to around 30-90 cm in height, and have a dark green colour with flat leaves, allowing for reliable identification from a distance (Courteau, 2012).

Figure 6. Maize (foreground) and soybean crops (background)

Homesteads were clearly identifiable from satellite images, allowing them to be used as additional landmarks by which to identify and map smallholder crops. Roads and streams were similarly easy to identify, and also served as useful landmarks. Commercial crop identification was supplemented with irrigation data obtained from the Water use Authorisation Registration Management System (DWAF, 2013) national database maintained by the Department of Water Affairs, Republic of South Africa (DWAF).

Undeveloped portions of the land cover were not delineated, i.e. this mapping effort did not seek to distinguish between degraded and healthy grassland boundaries or the extent of bare rock and soil outcrops in the upper hills of the watershed. Instead these distinctions were made by proportionally dividing up a single land class (termed *Grass*) into subclasses of healthy grass, degraded grass, and bare rock and soil, according to the land cover dataset developed for Ezemvelo KwaZulu-Natal Wildlife by GeoTerraImage in 2008 (Ezemvelo).

An overlay of the two datasets using ArcMap exhibited alignment of distinct features including roads and commercial crops and side-by-side comparison between the two datasets illustrates good overall agreement (Figure 7).

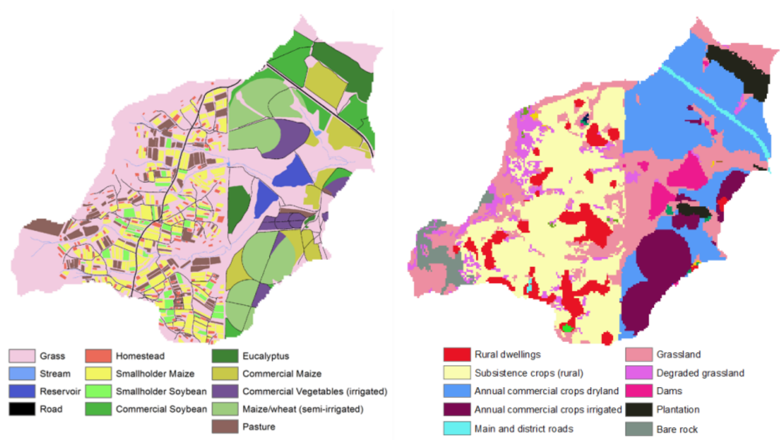

Figure 7. Newly mapped land cover (left) vs. satellite derived data (right) (Ezemvelo)

The resulting land cover map (Figure 8) was used to compute areas for input into the model. This was done in ArcMap by taking pixel counts from clippings of the raster land cover layer for the extent of each subcatchment as previously delineated.

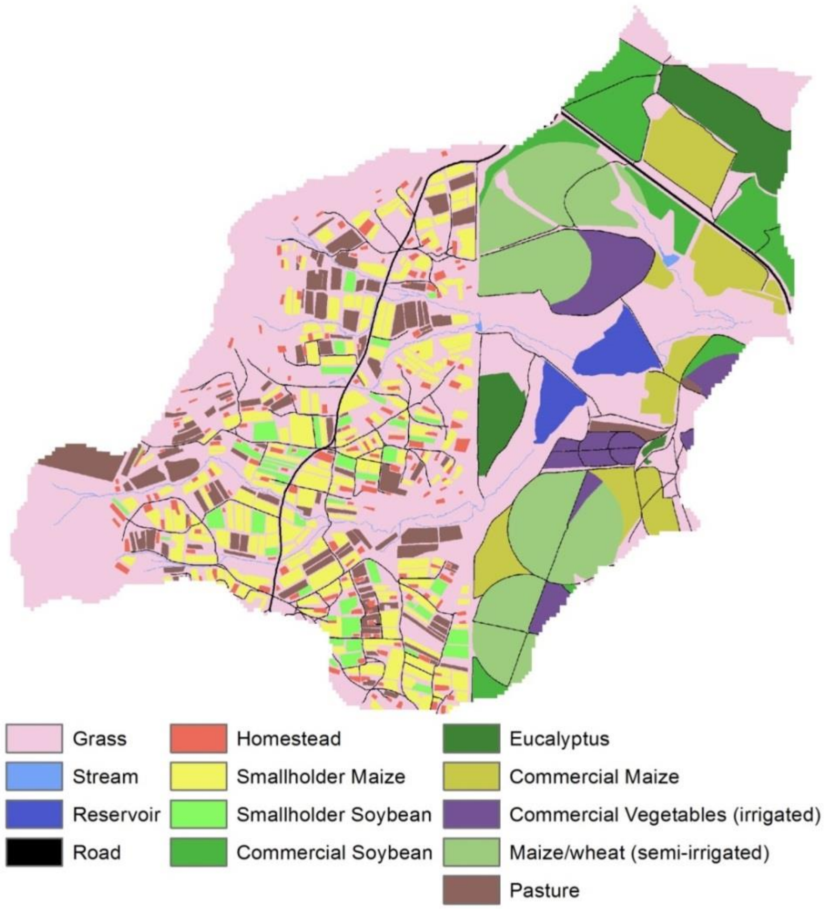

Figure 8. Newly mapped land cover map (with detail)

(3.3) *Climate*

Historical temperature data, including monthly averages of daily minima and maxima, were taken from the South African Atlas of Climate and Agrohydrology (SA Atlas) (Schulze and Horan, 2008) which contains average values from the 50 year period from 1950-1999 represented on a national grid with 3 km x 3 km resolution. These values were taken for a central location at median altitude in the Potshini catchment and altitudinal correction factors appropriate to the region were built into the model (Schulze, 1995).

Daily rainfall data were acquired from the Department of Water Affairs, South Africa (DWAF, 2013) for the period from 1980-2013 from three nearby weather stations (V1E006, V1E008, and V1E010) selected for their proximity and similarity in altitude. This data was interpolated using inverse distance weighting with $p = 2$ (Chen and Liu, 2012), and compared to rainfall data collected at automatic rain gauges situated at locations in Potshini. Correction factors were calculated using the period from 2006-2013, and calibrated using historical rainfall data to fit mean annual precipitation (MAP) values obtained for each Potshini subcatchment from the SA Atlas (Schulze and Horan, 2008). Correction factors and MAP values for each subcatchment are given in Table 1.

Table 1. Model input correction factors and mean annual precipitation for each subcatchment

	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec	**MAP**
C25	0.83	1.01	1.08	0.81	0.81	0.55	0.63	1.05	0.98	0.87	1.13	0.65	**790**
C100	0.88	0.87	0.94	0.88	0.63	0.80	0.50	0.91	1.20	1.00	0.94	0.91	**799**
DAM1	0.95	0.95	1.02	0.95	0.69	0.87	0.55	0.99	1.31	1.09	1.03	0.99	**869**
DAM2	0.97	0.96	1.04	0.97	0.70	0.88	0.55	1.00	1.33	1.10	1.04	1.00	**882**
C1000	0.97	0.96	1.04	0.97	0.70	0.88	0.55	1.00	1.33	1.10	1.04	1.00	**882**

Long-term A-pan equivalence evaporation data were obtained from DWAF as collected at the nearby Eendracht/Driel Barrage weather stations (V1E008). Monthly totals were calculated and averaged over the period 1992-2013 and put into the model. Ratios of monthly A-pan equivalence at Potshini to that of the V1E008 weather station were calculated from corresponding values in the SA Atlas (Schulze and Horan, 2008) and used as correction factors in ACRU. Corresponding average monthly simulated values are shown in Table 2.

Table 2. Model input corrected monthly A-pan equivalent evaporation for each subcatchment

	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec
C25	184.1	157.4	150.4	125.3	108.2	84.5	101.9	141.9	169.8	174.9	192.0	203.1
C100	188.1	160.9	152.0	126.6	108.2	84.5	101.9	143.4	171.6	176.8	194.1	205.3
DAM1	190.2	164.4	155.2	127.9	108.2	85.4	101.9	143.4	173.4	180.7	198.3	209.8
DAM2	192.2	166.2	155.2	127.9	108.2	85.4	101.9	143.4	175.2	182.6	198.3	209.8
C1000	194.3	166.2	156.8	127.9	109.3	86.2	101.9	143.4	175.2	184.5	200.4	212.0

(3.4) *Soils*

Soil parameters were also acquired from the SA Atlas (Schulze and Horan, 2008), as well as some regionally typical values obtained from the ACRU Theory Manual (Schulze, 1995). Parameters calculated from the Atlas include A and B soil horizon depth, and values for corresponding permanent wilting point, field capacity (drained upper limit), porosity, and interlayer flow response fractions. These were calculated separately for each subcatchment, taking the raster layer from the SA Atlas, resampling, clipping it to the boundaries, and taking the mean pixel value for each parameter. Resulting values used for model inputs are shown for each subcatchment in Table 3.

Table 3. Model input soil parameters calculated SA Atlas by subcatchment

horizon	parameter	C25	C100	DAM1	DAM2	C1000
A	depth	0.45	0.45	0.45	0.45	0.45
	wilting point	0.145	0.133	0.129	0.13	0.134
	field capacity	0.229	0.221	0.217	0.218	0.222
	porosity	0.433	0.433	0.434	0.434	0.432
	A-B response fraction	0.37	0.44	0.47	0.46	0.45
B	depth	0.34	0.59	0.7	0.66	0.68
	wilting point	0.187	0.197	0.203	0.201	0.204
	field capacity	0.262	0.268	0.274	0.271	0.278
	porosity	0.406	0.406	0.405	0.405	0.407
	baseflow response fraction	0.37	0.44	0.46	0.46	0.46

(3.5) *Irrigation and yields*

Maize yields were assessed by the KwaZulu-Natal Provincial Department of Agriculture as part of a previous study (de Winnaar et al., 2007), from which average values of 6 t/ha were computed for use in the model. Soybean yields were estimated based on conversations with farmers in Potshini, who estimated them to be approximately one third the volume of their maize yields, or 2 t/ha.

Irrigation schemes for both smallholder vegetable gardens and commercial farms were assumed to be efficient, and are modeled with demand mode scheduling to apply irrigation just before soil water drops to the critical level of 50% of plant available water in order to avoid plant stress. Though in reality irrigation systems may be less efficient, modeling with a demand mode schedule creates yield outcomes that are more responsive to irrigation, and thus provides a better indication of the potential benefits of rainwater harvesting. A less efficient fixed daily irrigation would cause reservoirs to deplete more quickly and thus depend more on rainfall during the dry season.

(3.6) *Streamflow*

Streamflow data has been collected over several years using automatic data loggers attached to pressure transducers in flumes at each of the three scales. However, some data collected in past years was not properly calibrated and was deemed unreliable. The reliable portion of the data was calibrated by adjusting water depth values with the mean difference between the logged value and measured values, and calculating flow rates based on equations developed for each of the flumes.

(3.7) *Rainwater harvesting data*

Data on the locations and number of rainwater tanks were obtained from UKZN and supplemented with observations in the field. Printed maps were used to record the number of tanks observed at each homestead and later compared with the supplied list. Average vegetable garden and runoff harvesting areas were calculated from GIS data created using Google Earth following on-site observations.

(4) *Rainwater harvesting in ACRU*

Rainwater harvesting was incorporated into the model in a manner similar to De Winnaar (2010), by creating a separate subcatchment in the model containing runoff collection sites which are simulated as impervious areas. Each runoff collection site corresponds to an aggregate of areas for homesteads harvesting rainwater, and is subjected to the reference climate of its respective subcatchment. Runoff is directed into an aggregated rainwater reservoir representing the collection of tanks distributed among homesteads. A single vegetable garden is included to represent one vegetable garden of average size for each homestead, which draws irrigation water from the rainwater reservoir. Evaporation and other water losses for the reservoir were minimized to simulate the closed nature of the rainwater harvesting tanks.

(5) *Model validation*

The model was validated according to procedures outlined in the ACRU User Manual (Schulze et al., 1989).

The first measure was a comparison of rainfall frequencies and mean annual precipitation levels. Simulated and observed values were compared over the same period for which correction factors were originally generated. Daily rainfall differed slightly in simulations with the mean, standard deviation, and variance each around 10% higher than that of observed values (see Appendix (2)). Frequency distributions show higher extreme values in simulations, and higher frequency of very low values in observed data. These difference are partly explained by the fact that observed data were averaged across two separate weather stations, and so daily values are systematically reduced if they do not coincide.

With respect to mean annual precipitation (MAP), simulations exhibited a value slightly lower than that which was obtained from the SA Atlas and used in calibration. Simulated MAP was equal to 840 mm/y where the expected observed value was 869 mm/y. This could be due to one of several factors: i) the simulation period from 1980-2013 was below the long term average rainfall of the SA Atlas' period from 1950-1999, ii) the calibration period of 2006-2013 exhibited greater rainfall difference between weather stations and Potshini than occurs on average, or iii) rainfall measurements at the local monitoring station were underreported for some reason. In any case, the difference of 3.3% is small enough to accept rainfall simulations as reliable.

For flow data, the User Manual stresses that any parameter changes be justified and logical, and that agreement between model fit and efficiency as measured by the Nash-Sutcliffe coefficient is more important than direct agreement with observed values (Schulze et al., 1989). Such an agreement is an indication that the model is responsive in both timing and magnitude to the degree to which r^2 and E approach unity.

Streamflow validation was performed at two scales as limited by data availability. Linear regression of 25 ha data revealed an initial oversimulation of baseflows and simultaneous undersimulation of stormflows (intercept > 0, slope < 1). According to the ACRU User Manual, this trend is to some extent to be expected in areas with dry winters such as Potshini. To correct the disagreement, the A-horizon and stormflow response depths were each increased, and the quickflow response fraction was reduced. A number of other parameter changes were also investigated but were not able to achieve satisfactory fits without drastic or unrealistic changes. The adjusted model achieved an efficiency coefficient of E = 0.677 and a goodness of fit of r^2 = 0.762 (see Appendix 0), which is satisfactory as it exceeds the ACRU user manual's recommended minimum target of r^2 = 0.65. One additional note about the linear regression plot is that points seem to waver around the regression line in three segments. This could be a result of someone having used a suboptimal height to flow rate formula for the flume, as many instances require three separate relationships to accurately calculate all levels of flow (Kilpatrick and Schneider, 1983).

The 100 ha scale was validated in a similar manner, with flow data aggregated to monthly totals and compared over a period of four years from 2007-2011. Parameters were subjected to the same adjustments as the 25 ha scale, after which the model achieved an efficiency coefficient of E = 0.627 and a goodness of fit of r^2 = 0.725, again satisfying the targets outlined in the ACRU user manual.

(6) *Ecosystem service assessment*

Ecosystem goods and services were considered both in terms of relevance and measurability. Relevance was assessed using a combination of literature reviews, expert opinions, and resident perceptions. Measurability was determined from the available modeling capability of ACRU, as well as appropriate quantitative indicators gleaned from the literature. A list of ecosystem goods and services along with the appropriate indicators was compiled to be investigated under the effects of rainwater harvesting by using the ACRU model.

(6.1) *Selection process*

For the compilation of a preliminary list of EGS, sources of information included literature, from both UKZN and the greater academic community, and informed observations in Potshini. The primary criterion is relevance; as the study site is well studied there is facility to investigate those goods and services most pertinent to this case.

Following a thorough literature review and numerous field trips, a comprehensive list of local ecosystem goods and services was defined (Table 4), based off a combination of definitions and classifications including those of De Groot et al. (2010), Costanza et al. (1997), Boyd and Banzhaf (2007), Fisher et al. (2009), and Wallace (2007).

Table 4. List of ecosystem goods and services with locally relevant items in **bold**

PROVISIONING	REGULATING	SUPPORTING
food (crops, grass for livestock)	**local climate regulation**	**biodiversity**
water supply (for drinking, washing, irrigation)	**water regulation (seasonal)**	*natural habitat*
raw materials (fuel wood, grass for roofing)	**water treatment**	**CULUTURAL**
genetic materials	**erosion control**	**nature (for tourism, recreation)**
medicinal plants	**soil regulation (formation, quality)**	**cultural value (spaces, species)**
cultural materials (ornamental, sacred)	*pollination (crops, wild plants)*	**education**
	pest regulation	*aesthetics*
	air quality (oxygen, particulates)	*practical inspiration*
	hazard mitigation	*spiritual inspiration*

Using knowledge of the capabilities of the ACRU model, the investigation was further specified to agrohydrological EGS, which represent some of the most important elements that the people of Potshini utilize from their surrounding ecosystem. Though environmental hydrology is complex and deeply interwoven, it is also the basis for the most fundamental, physiological needs for human survival (Maslow, 1943): food and water. Food production also represents one of the most valuable ecosystem services globally for both grasslands and croplands (Costanza et al., 1997), and offers the possibility of economic benefits for the families in Potshini.

Two other important categories of EGS, culture and biodiversity, are certainly vital to the community (van Jaarsveld et al., 2005) but their assessment requires a completely different approach and their benefits are not as easily quantifiable (Heink and Kowarik, 2010; Chan et al., 2012; Hernández-Morcillo et al., 2013). However, many arguments support the idea of tradeoffs between multiple ecosystem services (Bennett et al., 2009; Zavaleta et al., 2010; Egoh et al., 2012), and that agricultural ecosystem services often come at the cost of regulatory and cultural services (Dale and Polasky, 2007; Swinton et al., 2007; Gordon et al., 2010; Kremen and Miles, 2012). Therefore it is imperative that cultural ecosystem services and biodiversity be assessed to provide a comprehensive picture of the associated benefits and tradeoffs. Though it falls outside the scope of this study, there is ongoing work developing understanding on these topics in Potshini (Ouedraogo et al., 2011; Malinga, in press).

Several other ecosystem services fall beyond the capabilities of the ACRU model, including climate regulation, erosion control, and soil regulation. Of these, erosion and sediment yield are currently being studied by several researchers in the catchment, and carbon and other nutrient cycles are being monitored. There is still a need for better assessment of climate change and regulation in Potshini. Also worth noting is the healthy state of educational services provided by the Potshini catchment, as several teams of scientists have been studying the site for upwards of 10 years. This has resulted in the publishing of dozens of articles and has contributed to the knowledge of local farmers in the process.

(6.2) *Indicators*

The subset of ecosystem goods and services which are both relevant to the community and can be modeled using ACRU include water-related services and production of food and raw materials. Numerical indicators were identified for each of these services, and methods for calculating them using outputs from the ACRU model were subsequently devised. Ecosystem services and corresponding indicators are listed in Table 5, along with supporting literature sources and methods of calculation.

Table 5. Agrohydrological EGS and indicators (De Groot et al., 2002; Brauman et al., 2007; Kandziora et al., 2013)

Service	Aspect	Indicator	ACRU outputs	units	Source
Water supply	quantity	crop demand	REQIR	m^3/year	Kandziora *et al.* , 2013
		plant stress	PSIND	#days/year	
		quick:baseflow	(URFLOW-UBFLOW)/UBFLOW	ratio	Brauman *et al.* , 2007
		net primary production	NPP	t/ha/year	
		unit runoff	URFLOW	mm/year	
		unit streamflow	USFLOW	mm/year	
		channel outflow	CHOUTF	m^3/year	
		rwh storage	DAMPER	% capacity	Brauman *et al.* , 2007; de Groot *et al.* , 2002
Water treatment	quality	days surface>baseflow	(URFLOW-UBFLOW)>UBFLOW	# days/year	Brauman *et al.* , 2007
		surface:baseflow ratio	(URFLOW-UBFLOW)/UBFLOW	ratio	
		quantity (dilution)	CHOUTF	m^3/year	
Water regulation	location	quick:baseflow	(URFLOW-UBFLOW)/UBFLOW	ratio	Brauman *et al.* , 2007
		unit runoff	URFLOW	mm/year	
		channel outflow	CHOUTF	m^3/year	
Water regulation	timing	min flow date	CHOUTF	date	Brauman *et al.* , 2007
		max flow date	CHOUTF	date	
		mean low flow duration	CHOUTF	# days	
		mean peak flow duration	CHOUTF	# days	
		seasonality	CHOUTF	m^3/month	
		crop yields	yield	% potential	
		net primary production	NPP	t/ha/year	
Food supply	crops	crop yields	yield	% potential	Kandziora *et al.* , 2013; de Groot *et al.* , 2002
Raw materials	building	wild grass	NPP	t/ha/year	Kandziora *et al.* , 2013; de Groot *et al.* , 2002

CHOUTF - channel outflow (m^3); URFLOW - unit runoff (mm); USFLOW - unit streamflow (mm); UBFLOW - unit baseflow (mm); RFLA - rainfall (mm); DAMPER - dam fill level (%); REQIR - irrigation requirement (m^3); PSIND - plant stress indicator (0,1); NPP - net primary productivity (t/ha, % potential)

Most data pertaining to flow characteristics and distribution were assessed as average monthly flows to allow for seasonal comparison, as were plant stress indicators and crop water demand for the vegetable plots. Peak and low flow timing data were taken as the dates corresponding to annual maxima and minima, respectively, and thresholds were set at values corresponding to the mean upper and lower 5^{th} percentiles as calculated from annual frequency analyses. Average annual low and peak flow durations were assessed by determining the length of each sequence of 5 or more consecutive days on which high or low flows occurred, which were then averaged between years. Crop yields and net primary productivity data are output on an annual basis with corresponding statistics. Coincidence of rainfall and growing season was calculated by taking the total rainfall occurring during the growing season for each crop year.

(7) *Scenarios*

Several scenarios were developed in order to investigate the relationships between rainwater and runoff collection, vegetable crop yields, and environmental water flows. The progression begins with a historical baseline scenario with completely natural land cover, and works gradually towards the physical upper limits of the Potshini catchment. In this way the effects of current and future rainwater harvesting projects could be explored in a realistic context and evaluated against future needs of the community.

(7.1) *Historical*

The historical baseline, *RWHhist,* uses a simple, healthy grassland cover of Southern Tall Grassveld as classified by Acocks (1988). The only portions of land not covered by grass were sections of bare soil, impervious areas representing stream beds and rocks, and baseline adjunct (streamside) and disjunct impervious area values obtained from the national soil map (Dijkshoorn, 2003).

(7.2) *Present day*

The present day scenario, *RWHnow*, relied heavily on the land cover dataset developed in this research, modeling crops as they appear in Figure 8, roads and homesteads as disjunct impervious areas, and a portion of grassland as degraded using ACRU's inbuilt parameters. The extent of rainwater harvesting was estimated based on calculations of total storage tank volume and runoff collection areas using average per homestead values extended to the current number of 34 homesteads currently harvesting rain within the catchment. Total storage volume is equal to 585 m^3, which includes two large underground water tanks (total 80 m^3), and 110 of the 5000 L plastic JoJo tanks. For irrigated vegetable gardens, the planting area would correspond to approximately 0.6 ha, but ACRU is limited to a minimum irrigated crop size of 1 ha, so yield data was not expected to be representative or very high.

A very similar scenario, *RWHless*, was adjusted to represent the current scenario without rainwater harvesting. The only difference was the removal of the rainwater harvesting areas (which were reclassified as homesteads) and the rainwater reservoir. The vegetable garden was left in the model in order to assess baseline yields for a rainfed scenario.

(7.3) *Upscaling*

Many scenarios were developed for the simulation of scaled up rainwater harvesting implementation in Potshini. First, with *RWHplus,* a modest increase in homesteads and proportional harvesting areas was done to increase the vegetable garden size to the minimal 1 ha, corresponding to 60 homesteads with gardens and a total of 970 m^3 in storage capacity. Next, *RWHall* was developed to simulate the case if all homesteads in the catchment, 187, were to adopt rainwater harvesting practices. This scenario corresponds to a vegetable garden size of 3 ha and a water storage capacity of 2790 m^3. Lastly, *RWHdub* was developed to represent water collection from as yet unused disjunct impervious areas to double water harvesting capacity (both area and tank size), but leaving the vegetable planting area static at 3 ha.

(7.4) *Gardening*

In the interest of optimizing crop yields, several scenarios were adapted from the *RWHplus* scenario to explore the relationship between water storage capacity and vegetable planting area. For these scenarios, termed *RWHplusX2*, *RWHplusX5*, and *RWHplusX10*, rainwater storage capacity was increased to 2000, 5000, and 10000 m^3, respectively, while water collection and vegetable planting areas were held constant.

(8) *Outputs*

For each simulation, model outputs consisted of around 550 parameters listed in a database on a daily basis for the period of 1980-2013. To negate sensitivity to the initial conditions of the model, the first two years of data were removed. Hydrological parameters were aggregated by summing on a monthly basis, and averaging each month over the course of the 30 year simulation so that seasonal trends could be investigated. Other parameters such as crop yields and flow extremes were taken on an annual basis.

For comparisons between scenarios, data for the present day *RWHnow* were compared to those of the natural landscape in *RWHhist*, as well as the case without rainwater harvesting, *RWHless*. Each of the expanded scenarios, *RWHplus*, *RWHall*, and *RWHdub* was compared with the present situation in *RWHnow*. Finally, the impact of water storage capacity on vegetable yields was explored by comparing the outputs of *RWHplus*, *RWHplusX2*, *RWHplusX5*, and *RWHplusX10*, as well as outputs from the previous simulations.

V. RESULTS AND DISCUSSION

(1) *Water quantity*

The results of simulations of the various scenarios exhibit varying trends in water quantity on different scales (Table 6). The smallest scale (25 ha) showed no difference and data are not shown here. The 100 ha scale shows gradual reductions in surface water flows, although the ratio of surface to baseflow is increasing. This suggests that shallow groundwater stores are reduced at this scale, which is logical since the model simulates collection in each subcatchment but redistributes water through irrigation, as well as dam overflow, in the DAM1 subcatchment, effectively cutting the supply in the 100 ha subcatchment. Though trends are consistent throughout the scenarios, significantly larger effects are apparent in the *RWHall* scenario. In this case, declining primary production indicates more water available for human use.

Table 6. Relative changes in indicators of water quantity, taken from ACRU simulations of rainwater harvesting

Scale	indicator	***RWHnow/hist***	***RWHnow/less***	***RWHplus***	***RWHall***	***RWHdub***
100 ha	surface:baseflow ratio	-36.2%	2.7%	2.4%	15.8%	31.0%
	net primary production	-20.7%	-0.5%	-0.4%	-2.4%	-5.6%
	unit runoff	30.4%	-1.6%	-1.3%	-6.9%	-12.6%
	unit streamflow	22.5%	-1.1%	-0.9%	-4.9%	-8.8%
	channel outflow	29.7%	-2.1%	-1.8%	-9.2%	-17.4%
1000 ha	crop demand	-	-	-18.9%	-19.1%	-46.5%
	plant stress	-	-	-63.1%	-63.1%	-78.2%
	surface:baseflow ratio	-73.9%	-33.2%	70.7%	119.4%	208.7%
	net primary production	-50.6%	-0.1%	-0.1%	-1.2%	-2.4%
	unit runoff	58.7%	0.4%	-0.2%	0.3%	1.3%
	unit streamflow	-19.6%	2.7%	1.9%	13.1%	29.9%
	channel outflow	56.7%	-0.3%	-0.1%	-1.0%	-0.5%
	rwh storage	-	-	20.8%	20.4%	45.4%

At the 1000 ha scale, surface flow effects are basically reversed, and both relative and absolute levels of surface flow are increased. With respect to rainwater harvesting and vegetable garden cultivation, both predictably improve with higher levels of rainwater harvesting indicating larger volumes of water appropriated to the needs of people. Interestingly, there is a correlation between the availability of supplemental irrigation from rainwater and the total water demand of vegetable crops. This suggests that irrigation to bridge dry spells might not only keep plants from becoming stressed, but would also require less water overall, meaning that under supplemental irrigation, lighter levels of rainfall could end periods of stress associated with dry spells and reduce recovery periods; having more water available could reduce the total water demand.

(2) *Water quality*

Indicators of ecosystem services supporting water quality suggest a declining trend with increasing prevalence of rainwater harvesting (Table 7). As surface flows increase relative to baseflows, a greater proportion of streamflow originates from overland flow, leading to greater concentrations of surface-sourced contaminants such as agricultural fertilizer, pesticides, petrochemicals, or manure. It is possible for rainwater to provide an alternative source of clean domestic water for consumptive purposes, but a detailed analysis of its quality first needs to be performed and adequate precautions taken. The combination of lower surface flow quantities and higher surface to baseflow fractions also warrants caution when it comes to shallow groundwater stores, as such conditions could put additional stress on these resources.

Table 7. Relative changes in indicators of water quality, taken from ACRU simulations

Scale	indicator	*RWHnow/hist*	*RWHnow/less*	*RWHplus*	*RWHall*	*RWHdub*
25 ha	days surface>baseflow	-4.9%	0.0%	0.0%	0.0%	0.0%
	surface:baseflow ratio	-5.2%	0.0%	0.0%	0.0%	0.0%
	quantity (dilution)	5.1%	0.0%	0.0%	0.0%	0.0%
100 ha	days surface>baseflow	-27.1%	2.1%	2.4%	13.1%	22.4%
	surface:baseflow ratio	-36.2%	2.7%	2.4%	15.8%	31.0%
	quantity (dilution)	29.7%	-2.1%	-1.8%	-9.2%	-17.4%
1000 ha	days surface>baseflow	-48.6%	-7.0%	21.5%	46.6%	76.4%
	surface:baseflow ratio	-73.9%	-33.2%	70.7%	119.4%	208.7%
	quantity (dilution)	56.7%	-0.3%	-0.1%	-1.0%	-0.5%

(3) *Water distribution*

Resulting data on indicators for water distribution suggest that rainwater harvesting scenarios reduce both baseflows and surface flows, suggesting that water is either retained as soil moisture, lost through evapotranspiration, or both, indicating some degree of redistribution of water from blue to green water flows (Table 8). The coincidental decrease in baseflow suggests that shallow groundwater storage is also reduced. Reductions in surface flow represent a local confinement of water, although the 1000 ha scale exhibits very little change. The slight increase in runoff suggests an enhanced soil moisture level in the *RWHdub* scenario, possibly due to increased irrigation which is especially significant during the dry season. Also of note is the lack of changes at the 25 ha scale, indicating that it is certainly a combination of land cover and rainwater harvesting responsible for the observed effects. Lastly, it is important to recognize that increases in rainwater harvesting are in several cases counter to the changes in the *RWHnow/hist* comparison column due to land cover changes. Especially on the 100 ha scale, and with respect to surface flow : baseflow ratios on the 1000 ha scale, rainwater harvesting provides a redistribution of water flows that corresponds more closely with the natural hydrology of the landscape.

Table 8. Relative changes in indicators of water distribution, taken from ACRU simulations

Scale	indicator	*RWHnow/hist*	*RWHnow/less*	*RWHplus*	*RWHall*	*RWHdub*
25 ha	surface:baseflow ratio	-5.2%	0.0%	0.0%	0.0%	0.0%
	unit runoff	5.1%	0.0%	0.0%	0.0%	0.0%
	channel outflow	5.1%	0.0%	0.0%	0.0%	0.0%
100 ha	surface:baseflow ratio	-36.2%	2.7%	2.4%	15.8%	31.0%
	unit runoff	30.4%	-1.6%	-1.3%	-6.9%	-12.6%
	channel outflow	29.7%	-2.1%	-1.8%	-9.2%	-17.4%
1000 ha	surface:baseflow ratio	-73.9%	-33.2%	70.7%	119.4%	208.7%
	unit runoff	58.7%	0.4%	-0.2%	0.3%	1.3%
	channel outflow	56.7%	-0.3%	-0.1%	-1.0%	-0.5%

(4) *Water supply timing*

Flow changes associated with rainwater harvesting scenarios alter flows consistently throughout the year. Absolute changes in flow are greater during the wet season, as more precipitation is available to be intercepted (Figure 9)

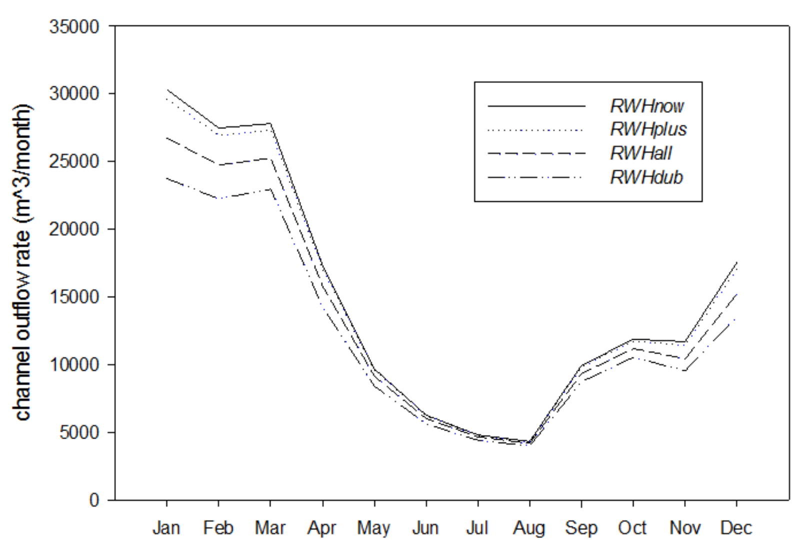

Figure 9. Channel outflow at the 100 ha subcatchment scale as modeled under rainwater harvesting

Outputs pertaining to extreme events follow the same trend. Looking at minimum and maximum flow timing, the 100 ha scale exhibits a tendency towards returning to the natural state (*RWHhist*, Table 9). Where the difference between the historical and present day scenarios comprises a 41 day delay in the minimum flow date, the most extreme case of rainwater harvesting brings it back by almost a month. Similarly, the initial four day delay in peak flow date is returned to its original state by the *RWHall* scenario. This suggests that the process of retaining rainwater in tanks and distributing it gradually as irrigation mimics the original hydrology of the catchment and helps to overcome the decrease in infiltration and residence time associated with previous development of the area for human activities.

When it comes to extreme flow duration, increased rainwater harvesting and irrigation tends to extend dry seasons at the 100 ha scale. At the 1000 ha scale, apart from the initial increase in peak flow duration under the current rainwater harvesting extent, expanded scenarios have only small effects on the timing and duration of extreme flow events.

Table 9. Relative changes in indicators of water supply timing, taken from ACRU simulations

Scale	indicator	*RWHnow/hist*	*RWHnow/less*	*RWHplus*	*RWHall*	*RWHdub*
25 ha	low flow date	-7	0	0	0	0
	peak flow date	0	0	0	0	0
	low flow duration	-20.1%	0.0%	0.0%	0.0%	0.0%
	peak flow duration	17.2%	0.0%	0.0%	0.0%	0.0%
	net primary production	-2.0%	0.0%	0.0%	0.0%	0.0%
100 ha	low flow date	41	-8	0	-20	-29
	peak flow date	4	0	0	-4	-3
	low flow duration	-50.9%	8.5%	2.9%	12.5%	40.1%
	peak flow duration	95.2%	29.4%	-1.3%	-8.3%	-21.8%
	net primary production	-20.7%	-0.5%	-0.4%	-2.4%	-5.6%
1000 ha	low flow date	25	0	0	0	0
	peak flow date	3	-1	0	0	-1
	low flow duration	-64.1%	0.8%	0.1%	2.3%	3.6%
	peak flow duration	251.7%	86.3%	-0.3%	-2.9%	-1.3%
	net primary production	-50.6%	-0.1%	-0.1%	-1.2%	-2.4%
	crop yields (vegetables)	-	86.1%	9.5%	9.5%	20.7%

Rainwater harvesting provides clear improvements in the timing of water availability as it retains water to be distributed at the user's will. In the model, with vegetable garden irrigation this corresponds to a 86.1% increase in yield over a completely rainfed system (without water harvesting), and further increases of 10-20% for higher scales of rainwater harvesting.

(5) *Food and materials*

As was just mentioned, improvements in temporal availability of water associated with rainwater harvesting enable farmers and gardeners to increase their yield substantially. However, a closer look at the data reveals additional questions. In the *RWHplus* and *RWHall* scenario inputs, ratios between runoff collection areas, storage capacity, and planting area remain constant. In the scenario of *RWHdub*, rainwater harvesting capacity is doubled (both collection area and storage capacity), while the planting area remains the same size. This improves yields by over 20% (Table 10), however it requires a doubling of infrastructure from the case in which every house is already equipped with 3 x 5000 L tanks. This means not only are an additional 550 storage tanks purchased and installed, but that corresponding runoff plots are available and constructed. Additionally, this 20% increase is as compared to the *RWHnow* scenario, and so constitutes only a 10% increase over the case with 550 fewer tanks. More intensive scenarios may not even be practical, as the benefits to food production, as compared with purely rainfed agriculture, are available at relatively low rates of rainwater harvesting infrastructure. A slightly deeper investigation into this concept is discussed in the next section.

Table 10. Relative changes in indicators of food and raw material production, taken from ACRU simulations

Scale	indicator	***RWHnow/hist***	***RWHnow/less***	***RWHplus***	***RWHall***	***RWHdub***
25 ha	wild grass	-2.0%	0.0%	0.0%	0.0%	0.0%
100 ha	wild grass	-20.7%	-0.5%	-0.4%	-2.4%	-5.6%
1000 ha	crop yields (vegetables)	-	86.1%	9.5%	9.5%	20.7%
	wild grass	-50.6%	-0.1%	-0.1%	-1.2%	-2.4%

Production of raw materials in the form of grass suffers slightly under high levels of rainwater harvesting (Table 10). Certain grasses are used in Potshini by some residents to build roofs for their houses, which must be replaced annually. The presence of inter-crop zones and undeveloped land likely maintains a high enough level that a 5.6% decrease in grass production will not threaten this activity, however, if population increases, farmland expands, or livestock grazing intensifies, then this could become an issue in the future.

(6) *Vegetation*

Plant stress in the vegetable gardens as modeled is only partially alleviated by irrigation from harvested rainwater. Although yields improve markedly, and dry spells can be bridged, the dry season eventually becomes too much to overcome as significant periods of stress persist in all classic scenarios (Figure 10). When looking at the figure below, keep in mind that the *RWHnow* scenario is not proportional to reality, and has an oversized vegetable plot relative to the other scenarios.

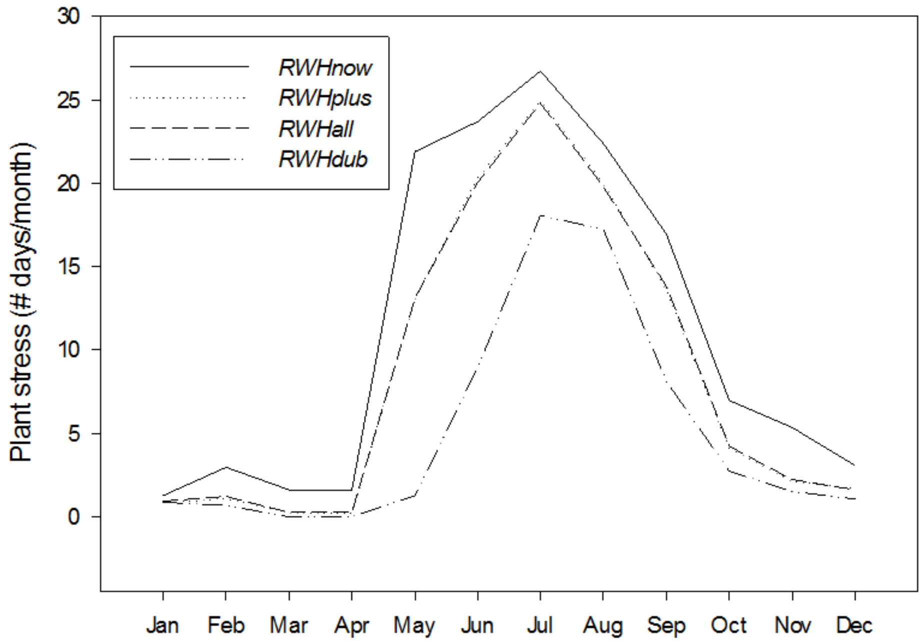

Figure 10. Monthly plant stress modeled in vegetable gardens under rainwater harvesting scenarios

This winter stress results from a high crop water demand during this period, in combination with a relatively low rainwater reservoir capacity. To further explore this question, model simulations were run for several scenarios while varying the capacity of storage tanks and the area for collecting runoff.

A comparison between additional rainwater harvesting scenarios with varying tank capacities, runoff areas, and crop sizes, illustrates a clear relationship between crop productivity and the ratio of rainwater tank storage volume to garden plot area (Figure 11).

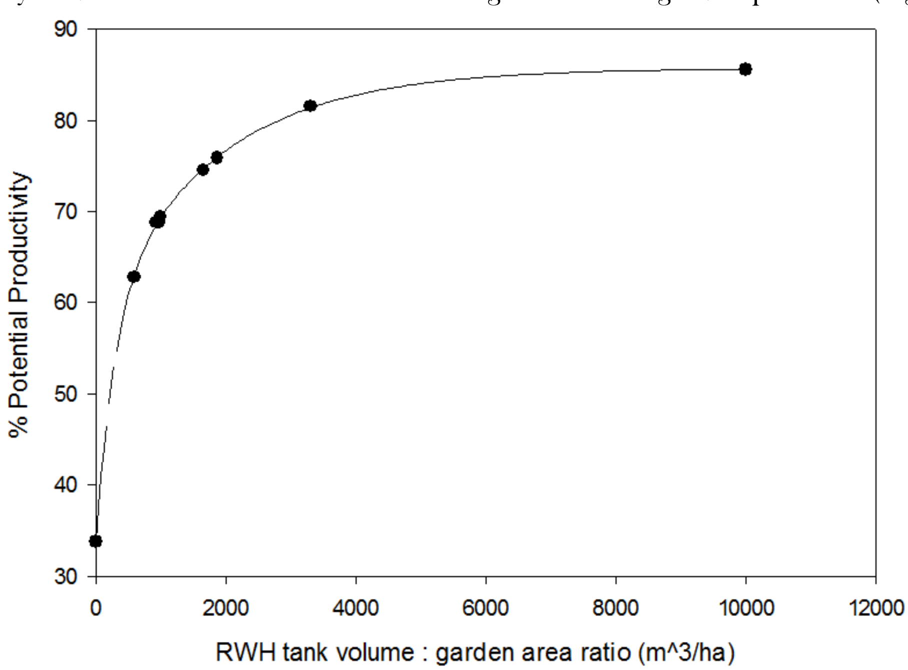

Figure 11. Vegetable crop productivity vs. ratio of water storage capacity : crop area

This relationship was fitted using a double exponential rise to maximum equation in SigmaPlot software, and achieved an $r^2 = 0.9997$ with $p < 0.0001$. The resulting empirical formula is as follows:

$$\%P = 33.756 + 24.5109(1 - e^{-.0036x}) + 27.4538(1 - e^{-.0006x}),$$

where $\%P$ is the fraction of potential crop yield and x is the ratio of water storage capacity to crop size in m^3/ha. This formula is included here because it represents a potentially useful tool for planning the efficient upscaling of rainwater harvesting in order to temper the potential negative effects on ecosystem services and the environment.

(7) *Discussion*

The described effects of rainwater harvesting on indicators of ecosystem services exhibit trends consistent with previous research (Kongo and Jewitt, 2006; Kosgei et al., 2007), particularly with respect to reductions in surface runoff and streamflow. The model is most sensitive to rainwater harvesting on the 100 ha scale, and on the 1000 ha scale effects are buffered by the downstream presence of commercial dams. Since the 25 ha scale is located on a steep upper hillslope that would not realistically experience developments in rainwater harvesting, and so no significant changes were observed.

Although the benefits of rainwater harvesting are clear, promising improved food production and water availability with only mild negative consequences, the increased adoption of these practices for agricultural expansion could increase the prevalence of pesticides and fertilizer use, leading to imbalances in biodiversity, decreases in natural water quality, and associated land use changes.

In the case of Potshini, the location upstream of relatively large commercial dams also reduces the magnitude of any potential downstream effects, and so tradeoffs between water users remain largely confined to villagers and the adjacent commercial farmers.

(8) *Future directions*

In addition to the results presented, the methods and tools developed here also hold potential to benefit future research efforts, including contributions to ongoing studies of ecosystem services, sedimentation, and nutrient cycling in the catchment, and the scale specificity of the model provides the potential for direct adaptation by hydrologists already studying related effects (Chaplot and Poesen, 2012; Orchard et al., 2012).

Further considerations that could be incorporated into the model include the addition of rainwater harvesting at the 25 ha scale, to quantify more accurately the small scale impacts. The model could also be adjusted, either for Potshini or another catchment, to simulate without the commercial dams in order to quantify larger scale impacts. Indicators for Hydrological Alteration could also be assessed using the outputs of the simulated scenarios, so that impacts on ecohydrology could be quantified and compared with other research, e.g. (de Winnaar and Jewitt, 2010).

Climate change is another variable which could easily be explored, by generating altered temperature, rainfall, and evaporation data for possible future scenarios, in order to understand the extent of associated that the local population are likely to face.

ACRU also has the capacity to model nitrogen and phosphorus levels and cycles, which could be input to get a better idea of how soil and water quality are affected by rainwater harvesting or other changes.

Lastly, a fairly straightforward question arises out of the heavy dependence on maize crops in the catchment, that is by how much yields could be improved by using rainwater to supplement irrigation during dry spells, and what water storage capacity would be required for the scale present in the Potshini catchment. The application of the tools and methods developed here to these and other questions holds the potential to provide deeper insight into local processes, thereby allowing for more sustainable water management and development planning in the community.

VI. CONCLUSIONS

Rainwater harvesting has great potential to alleviate a variety of pressures on communities such as Potshini in variable rainfall areas relying on smallholder farm production for subsistence and livelihood. Compared with historical conditions, the impact of rainwater harvesting on environmental hydrology, is relatively small while the benefits are significant. One particular improvement can be achieved by increasing storage capacity to more reliably bridge dry spells and improve annual vegetable yields, thereby providing income, nutrition, and health to the community.

Impacts on EGS as they were assessed suggest that, even at high levels of rainwater harvesting there is an overall beneficial impact on people. However, associated reductions in surface flows could have negative impacts on biodiversity and aquatic ecosystems which are not as easily predicted.

Water supply services, in terms of quantity, distribution, and timing were all enhanced by rainwater harvesting. Crop water demand was reduced, water availability and vegetable yields were increased, and hydrological regimes trended back towards the historical natural scenario, both in the distribution of water above and below ground, and in the timing of annual peak and low flows. Enhancements of soil moisture and evapotranspiration were also suggested.

Surface water quality, due to overall reductions, is likely to decline as contaminant concentrations increase and baseflow contributions reduce. Further research is addressing the quality of harvested rainwater as it could potentially mitigate these impacts.

Food production was increased for the modeled vegetable garden, though the upper limits of such benefits still need to be explored.

Lastly, productivity in natural grasslands exhibits a slight decline, suggesting that resources for raw materials such as grass for thatched roofs is under mild threat. This also holds relevance for livestock grazing, as the two could produce reinforcing detriments not only to grasslands as resources, but as local biodiversity, habitat, and pollination.

The scenarios modeled constitute a range of realistic levels of upscaling rainwater harvesting, and exhibit pronounced benefits with only mild drawbacks. The adoption of rainwater harvesting provides clear overall improvements to the benefits of ecosystem goods and services in semi-arid regions and enhances water and food security with reduced reliance on external resources.

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IX. APPENDICES

(1) *Subcatchment delineation*

Arc Hydro Tools subcatchment delineation process:

1. *Build walls* – Polyline shapefiles representing dam walls are used to elevate the DEM to form barriers to water flows for subsequent delineation of watersheds contributing to each dam.
2. *Fill sinks* – Sinks in the DEM are filled in order to provide a hydrologically consistent surface for flow analysis. Stream burning was not performed as it interfered with the point delineation tool, likely due to interrupted flow routes.
3. *Flow direction* – Each cell in the DEM is compared to surrounding cells to determine which direction water will flow in and out of a cell, i.e. in the direction of steepest descent.
4. *Flow accumulation* – A value is calculated for each cell based on the number of cells upstream that flow into it.
5. *Stream definition* – Using the flow accumulation data, a threshold is set to determine areas where streams will form: if the flow accumulation value of a cell is above the threshold, it is characterized as part of a stream which continues downhill to the subcatchment outlet. A threshold of 125 cells representing 5 ha was chosen to maintain sufficient detail for accurate delineation of the 25 ha catchment.
6. *Stream segmentation* – streams are broken up into a number of segments.
7. *Catchment grid delineation* – A catchment grid is created to indicate which cells drain into each stream segment.
8. *Catchment polygon processing* – the catchment grid is converted to the polygon feature class to create catchment shapes for each stream segment.
9. *Drainage line processing* – creates a polyline feature class based on the segmented stream grid.
10. *Adjoint catchment processing* – for each subcatchment, a polygon is created representing the entire upstream catchment contributing to its inlet.
11. *Point delineation* – a catchment outlet of interest is indicated by clicking on the map, and is used to delineate the final subcatchment.

Arc Hydro Tools process:

- `Terrain Processing>DEM Manipulation>Build Walls`
- `Terrain Processing>DEM Manipulation>Fill Sinks`
- `Terrain Processing>Flow Direction`
- `Terrain Processing>Flow Accumulation`

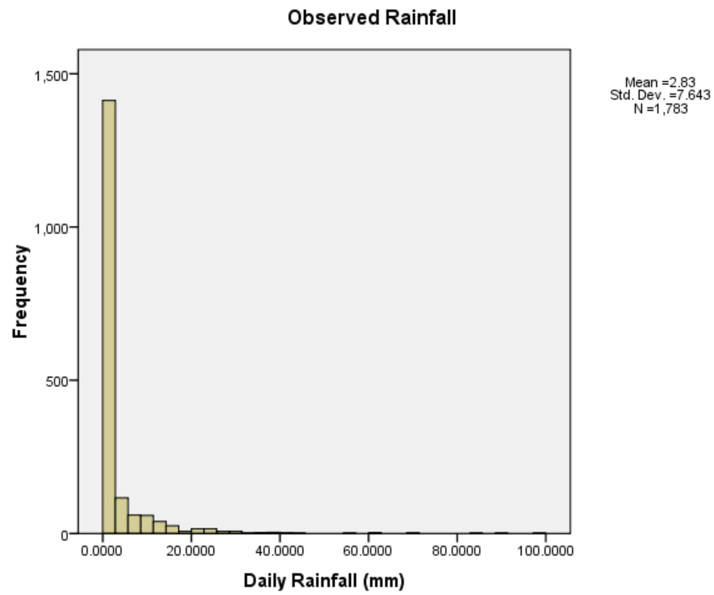
```
- Terrain Processing>Stream Definition
- Terrain Processing>Stream Segmentation
- Terrain Processing>Catchment Grid Delineation
- Terrain Processing>Catchment Polygon Processing
- Terrain Processing>Drainage Line Processing
- Terrain Processing>Adjoint Catchment Processing
- Point Delineation button
- Convert graphic to feature
```

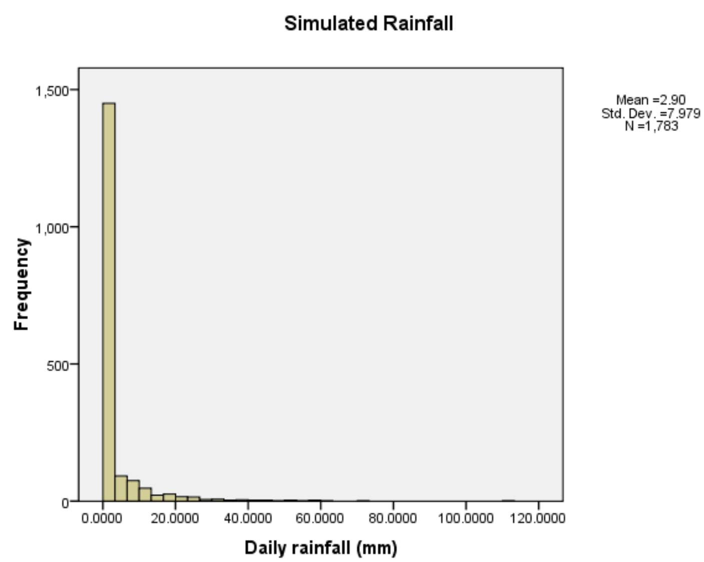
(2) *Rainfall validation*

Basic descriptive statistics and daily rainfall percentiles:

		Obs	Sim
N	Valid	1783	1783
	Missing	0	0
Mean		2.829277	2.903010
Median		.000000	.000000
Mode		.0000	.0000
Std. Deviation		7.6432165	7.9793118
Variance		58.419	63.669
Skewness		5.640	4.952
Std. Error of Skewness		.058	.058
Kurtosis		45.649	35.871
Std. Error of Kurtosis		.116	.116
Percentiles	5	.000000	.000000
	10	.000000	.000000
	15	.000000	.000000
	20	.000000	.000000
	25	.000000	.000000
	30	.000000	.000000
	35	.000000	.000000
	40	.000000	.000000
	45	.000000	.000000
	50	.000000	.000000
	55	.100000	.000000
	60	.200000	.000000
	65	.400000	.000000
	70	.840000	.280000
	75	1.700000	1.287000
	80	3.230001	3.044000
	85	5.240000	5.447000
	90	9.500000	9.486000
	95	14.800000	17.680000
	100	97.200004	111.020000

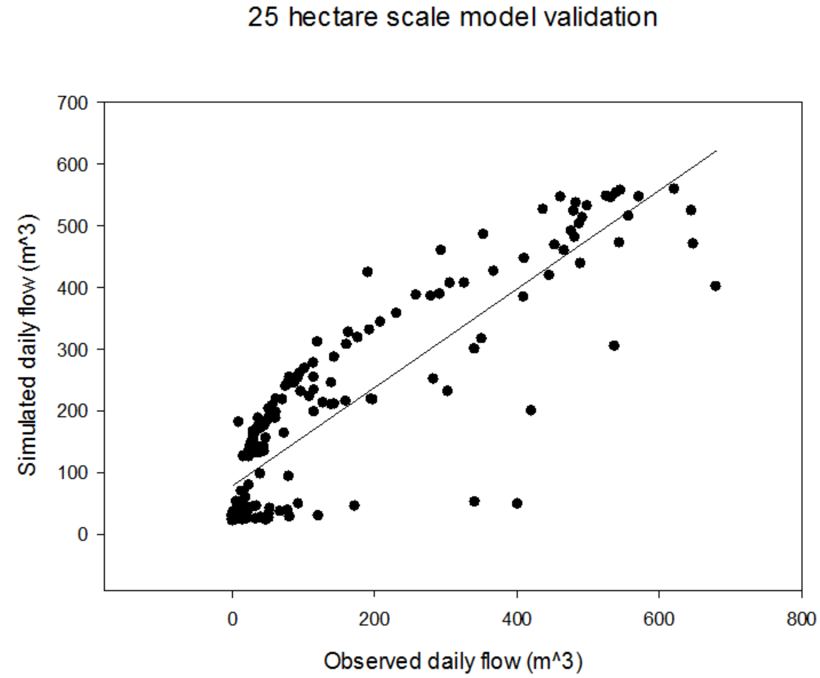
Frequency plots:





(3) *Streamflow validation*

Streamflow validation statistics:



Nash-Sutcliffe model efficiency coefficient: E = 0.676574

Equation: f = y0+a*x

	Coefficient	Std. Error	t	P
y0	78.9394	7.1195	11.0878	<0.0001
a	0.7982	0.0319	24.9944	<0.0001

Model Summary

Model	R	R Square	Adj. R Square	Std. Error of the Estimate
1	.874[a]	.763	.762	79.4306955

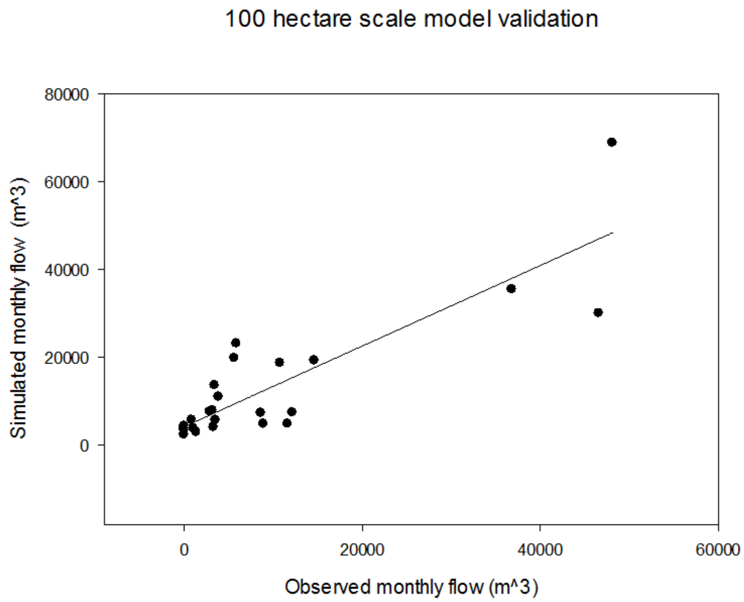
a. Predictors: (Constant), Qobs

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3941490.999	1	3941490.999	624.718	.000[a]
	Residual	1223991.665	194	6309.235		
	Total	5165482.664	195			

a. Predictors: (Constant), Qobs

b. Dependent Variable: Qsim



Nash-Sutcliffe model efficiency coefficient: E=0.627418

Equation: f = y0+a*x

	Coefficient	Std. Error	t	P
y0	4274.8147	1960.6440	2.1803	0.0402
a	0.9183	0.1170	7.8508	<0.0001

Model Summary

Model	R	R Square	Adj. R Square	Std. Error of the Estimate
1	.858[a]	.737	.725	7.8285447E3

a. Predictors: (Constant), Qo

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3.777E9	1	3.777E9	61.634	.000[a]
	Residual	1.348E9	22	6.129E7		
	Total	5.126E9	23			

a. Predictors: (Constant), Qo

b. Dependent Variable: Qs