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# A watershed approach to upgrade rainfed agriculture in water scarce regions through Water System Innovations: an integrated research initiative on water for food and rural livelihoods in balance with ecosystem functions

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**Abstract**

The challenge of producing food for a rapidly increasing population in semi-arid agro-ecosystems in Southern Africa is daunting. More food necessarily means more consumptive use of so-called green water flow (vapour flow sustaining crop growth). Every increase in food production upstream in a watershed will impact on water user and using systems downstream. Intensifying agriculture has in the past often been carried out with negative side effects in terms of land and water degradation. Water legislation is increasingly incorporating the requirement to safeguard a water reserve to sustain instream ecology.

To address the challenges of increasing food production, improving rural livelihoods, while safeguarding critical ecological functions, a research programme has recently been launched on "Smallholder System Innovations in Integrated Watershed Management" (SSI). The programme takes an integrated approach to agricultural water management, analysing the interactions between the adoption and participatory adaptation of water system innovations (such as water harvesting, drip irrigation, conservation farming, etc.), increased water use in agriculture and water flows to sustain ecological functions that deliver critical ecosystem services to humans. The research is carried out in the Pangani Basin in Tanzania and the Thukela Basin in South Africa. A nested scale approach is adopted, which will enable the analysis of scale interactions between water management at the farm level, and cascading hydrological impacts at watershed and basin scale.

This paper describes the integrated research approach of the SSI programme, and indicates areas of potential to upgrade rainfed agriculture in water scarcity-prone agro-ecosystems while securing water for downstream use.


*Keywords:* Rainfed agriculture; Water productivity; Watershed; Catchment hydrology; Semi-arid

## 1. Introduction

The dominant water resources management challenge over the coming generations is how to secure water to cover food demands of a rapidly expanding world

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population. This applies especially to developing countries where 95% of the world's population growth occurs, and most particularly to sub-Saharan Africa, hosting the largest proportion of water scarcity-prone areas as well as the highest levels of malnutrition (Rockström et al., 2003). The preconditions to sustainable livelihood improvements are dynamic. The world is continuously experiencing social–ecological changes (van der Leeuw, 2000; McIntosh et al., 2000) that can alter the capacity of ecosystems to generate goods (including food) and services on which society depends (Daily, 1997).

Furthermore, it is becoming increasingly clear that diverting more water for agriculture may have serious implications for other water users and water using activities and systems. As shown by Conway (1997) no less than a new Green–green revolution in required, which not only (at least) doubles food production particularly among resource poor rural societies hosted in ecologically vulnerable and degraded landscapes, but also achieves large production increases in agriculture without compromising essential ecological functions. Compared to the previous Green Revolution, which in the 1950s and 60s lifted large parts of Asia and Latin America from imminent risks of large scale food deficits, the challenges at present are even more daunting. Not only will food production have to increase as fast or faster than the first Green Revolution, now the production increase has to occur among poor farming communities often depending on unreliable crop water supply (generally rainfall in semi-arid and dry sub-humid savanna agro-ecosystems) (Falkenmark and Rockström, 2004).

As shown by Rockström (2003) present food production requires some 7000 $km^3$/yr of consumptive freshwater (i.e., green water as evapotranspiration) (of which 1800 $km^3$/yr originates from blue water use—i.e., runoff water—in irrigation and the remaining 5200 $km^3$/yr from direct green water use in rainfed agriculture). Two hot-spot regions of the world emerge, in terms of water needs for food and livelihoods, namely sub-Saharan Africa (SSA) and Asia. For sub-Saharan Africa indications suggest a tripling of agricultural water demand by 2025, and an almost five-fold increase by 2050 (Falkenmark and Rockström, 2004).

Growth of food production in sub-Saharan Africa has during the last decades primarily been achieved through expansion of agricultural land and increase in water use. Land degradation and desiccation have in many areas resulted in diminishing crop yields, with average yields oscillating in the range of 1 ton of grain per hectare. Conventionally, the focus of attention is on blue water (river, lake or groundwater flow used for irrigation, industry and domestic uses) with limited attention given to direct use of productive green water (transpiration flow) in rainfed agriculture (which constitutes >95% of the agricultural land use in sub-Saharan Africa).

A specific area in need of fundamental research is the inter-linkage at watershed and river basin scales of how to use and balance water resources between food and environmental security. This gap has recently received international attention in the Global Dialogue on Water for Food and Environmental Security (http://www.iwmi.org/dialogue). Recently (July 2003) WOTRO, the Dutch funding organisation for research in tropical regions residing under NWO (the Netherlands organisation for scientific research), the Development Agencies of Sweden (Sida) and the Netherlands (DGIS), the International Water Management Institute (IWMI) and Unesco-IHE Institute for Water Education, supported the launch of an integrated and applied research programme on how to balance water for food and nature (Smallholder system innovations in integrated watershed management (SSI)). Particular focus is given to research on opportunities to upgrade smallholder rainfed agriculture through water system innovations while securing water to sustain critical ecological functions in vulnerable semi-arid tropical and sub-tropical river basins.

This paper outlines the rationale for a new approach to integrated water resource management from the local field scale to the watershed and basin scale, which incorporates the balancing of green and blue water flows in agriculture with freshwater to sustain ecosystems and downstream human use of water and describes the scope of the SSI programme, in Tanzania and South Africa.

## 2. Agrarian crisis

After the failures in the 1960s and 1970s, to offer developing countries "technological short-cuts" through top-down development approaches, a new era of participatory approaches emerged in the 1980s, which today form the mainstream of agricultural development methodology. These approaches, as applied in the field, depend strongly on indigenous knowledge as a vehicle to livelihood improvements among rural poor (Chambers, 1994). Indigenous knowledge plays a central role in managing local human and natural resources, and is a key for present livelihood security and to enable improvements in the future. However, it is becoming increasingly clear that smallholder farming systems in SSA are in a transient evolutionary stage, today characterised in large by an agrarian crisis.

Only a century ago (and in some parts even today), land productivity was sustained through shifting cultivation practices dependent on highly extensive farming practices. The population driven abandonment of a strategy for soil fertility recycling and soil and water productivity maintenance (long fallows) has not been compensated for by the introduction of a new management strategy, particularly to sustain soil fertility and soil structure (a key for soil water availability and water holding capacity). Fertiliser use in sub-Saharan Africa is on average below 10 kg/ha (FAO, 2002) and studies in Eastern and Southern Africa show that the farming systems suffer from extensive nutrient mining. The farming systems have dropped down to a new, lower agro-ecological climax, adapted to the "new" situation of extremely low soil fertility and low organic matter contents, resulting in a "one-ton-agriculture". As shown, e.g., by Rockström and Falkenmark (2000) there seems to be no hydrological limitations, even in semi-arid regions, to attain a maximum climax 5–10 times higher than the yields experienced at present (0.5–1 ton/ha yields). The adoption of plough tillage practices which have a highly detrimental effects on soil structure and fertility in tropical soils has further speeded up the process towards extremely low on-farm yields. The result is a dramatic loss of ecological resilience, related both to quick biophysical cycles, manifested as low levels of soil moisture available to plants, and slow cycles related to soil biology, soil crusting and plant cover.

Over the last 50–70 years many efforts have been made by farmers, extension workers, researchers and donor agencies to address this agrarian crisis. All ingredients of the industrial farming systems (fertilisers, mechanization, and pesticides) have been promoted. This has been done together with "old" indigenous elements in "new" disguise, such as improved manure management, stalled livestock in zero grazing systems, composting, green manures, and short fallows.

Today, as opposed to twenty years ago, there is a firm understanding that technology transfer of temperate zone successes alone will not work. Instead, tailor-made, site-specific adaptations, building on indigenous knowledge are required. But the magnitude of the agrarian crisis is so large that development and refinement of indigenous knowledge alone will not be enough. Instead, innovations—often alien innovations that go through a participatory process of local adaptation—are required in all fields of land-use management such as the handling of crop choice, of water, soil, livestock, and forests. Small-holder system innovations in agricultural water management are important cornerstones in sustainable agricultural development—not in isolation—but as an integral part of a participatory development process, following, e.g, the approaches to innovations in land management experienced by the Regional Land Management Unit (RELMA) of Sida in East Africa (RELMA, 2002), and the recent developments of the national catchment approach in Kenya (Lundgren, 1993).

## 3. A widened ecohydrological freshwater approach in IWRM

Irrigated agriculture will have to play an important role in contributing to the staggering increase in food production required to keep pace with population growth and eradicate malnourishment in SSA. Similarly, virtual water, through increase food trade, will certainly continue to fill a part of the increased demand for food (and the green water hidden behind each kg of food). However, both irrigation development and realistic options for substantial increase in dependence on food imports have serious limitations, suggesting that indigenous small-holder farming systems will continue to contribute the bulk of food (Parr et al., 1990) over the next two generations. Rainfed agriculture is today practised on 97% of the agricultural land in SSA. Despite optimistic outlooks on the development of irrigated agriculture (FAO, 2002), past trends indicate that it is precarious to rely too strongly on irrigation as the panacea for food security in SSA. Irrigation expansion has been much slower than expected over the last 20 years, and irrigation schemes have suffered from problems related to degradation of irrigated crop land, mismanagement of irrigation schemes, difficulties in maintaining and rehabilitating schemes, and problems of upstream/downstream sharing of water resources. However, water resource policy and management continues to focus largely on blue water (runoff) supply for irrigation, domestic use in households, municipalities and for livestock, and water for industry. Among these direct blue water using sectors, irrigation dominates by far—withdrawing some 70% of the managed blue water resource.

There is a growing realisation that the conventional 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. The SSI programme aims at applying an integrated approach to freshwater management that acknowledges the vital role played by both green and blue water flows in sustaining direct and indirect ecological functions and services benefiting human beings. Fig. 1 shows a conceptual framework for such an integrated approach to water management.

The water flow domain is divided into green (vapour) flows and blue (runoff) flows. The use domain is distinguished between direct uses and indirect uses. Conventionally our freshwater management focus has been on the direct blue water use sustaining irrigation, industry and domestic water uses. Green water sustains ecosystem services that directly benefit humans in rainfed food production, forests for timber, biomass for fuel wood and fibres, pastures for grazing, and other biomass growth directly used by humans (such as wild fruit).

| Water Flow Domain / Use Domain | Green | Blue |
|---|---|---|
| Direct | **ECONOMIC BIOMASS GROWTH**<br>Rainfed food, timber, fibres, fuel wood, fruit, pastures<br>Direct human consumption | **ECONOMIC USE IN SOCIETY**<br>Irrigation, Industry, Domestic/Municipal<br>Direct human consumption |
| Indirect | **ECOSYSTEM BIOMASS GROWTH**<br>Plants and trees in wetlands, grasslands, forests and other biotopes.<br>Biodiversity, resilience. | **ECOSYSTEM FUNCTIONS**<br>Aquatic freshwater habitats.<br>Biodiversity, resilience. |

Fig. 1. An integrated approach to freshwater management indicating the four freshwater use domains. Each cell includes ecological and human systems supported, and functions sustained (direct human consumption, biodiversity, resilience).

Indirect blue use includes water flows that sustain ecological functions in aquatic ecosystems, such as fish habitats in rivers, wetlands, and lakes. Indirect green water use includes vapour flow that sustains grasslands, natural forests, plant growth in wetlands, meadows etc., that constitute habitats for wildlife, and the vast biodiversity of flora and fauna.

## 4. The SSI programme

The SSI programme is an applied and development oriented research programme, which aims at contributing to improved livelihoods of rural poor and sustainable natural resources management in semi-arid agro-ecosystems. At the same time, SSI is a research programme that has taken on the scientific challenge of advancing the knowledge on how to balance water for food and nature with particular focus on upgrading smallholder rainfed agriculture in water scarce landscapes.

The objectives of the programme are to:

(1) Advance the knowledge for improved eco-hydrological landscape management at watershed and basin scale with particular focus on system interactions between water for food requirements in upgraded smallholder rainfed farming systems and water to sustain ecological functions and other societal needs.
(2) Analyse the hydrological, environmental and socio-economic consequences of upscaling water system innovations in small-holder, predominantly rainfed agriculture at watershed scale,
(3) Develop methodologies and decision support tools for improved rainwater management and equitable sharing of water between upstream and downstream users and uses in nature and society.

The programme is inter- and multi-disciplinary, and aims at addressing multiple scale interactions, from the farmer's field to the basin scale. It consists of six research projects, which form an integrated entity, with mutual inter-dependence and synergies (Fig. 2).

SSI will include the following research components:

- Adaptive and participatory identification, development and assessment of system innovations in rainfed farming systems (Projects 1, 2).
- Spatial analysis of potential and criteria for upscaling of system innovations at watershed scale (Projects 2, 5).
- Research on vulnerability and resilience of ecological functions to water dynamics in managed tropical agro-ecosystems (Project 2, 3).

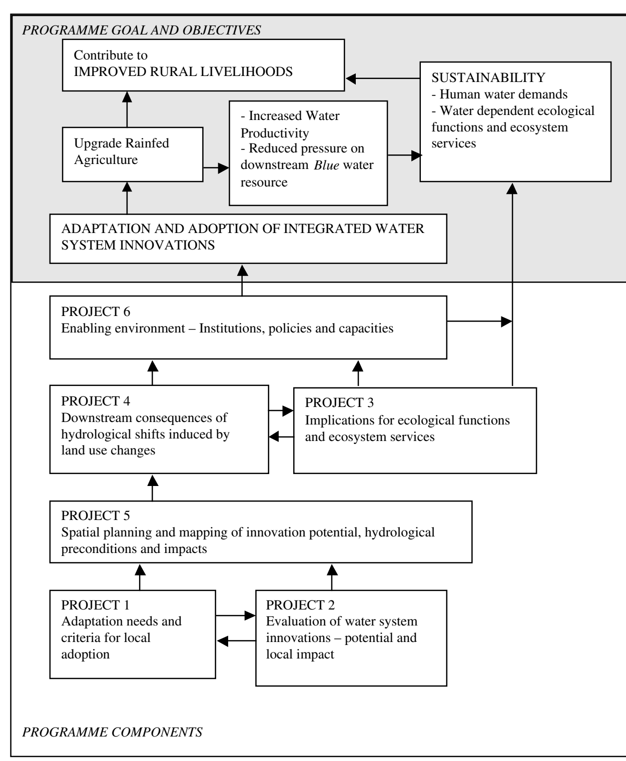


Fig. 2. Research components of the SSI programme.

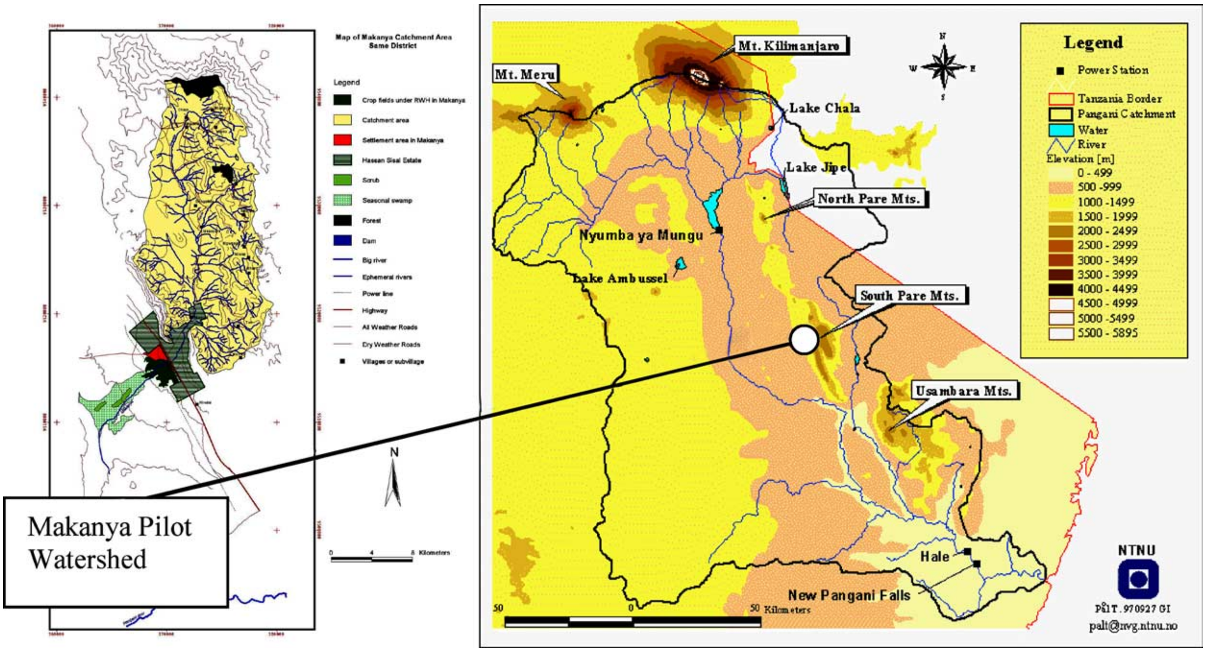


Fig. 3. Map of the Pangani Basin, Tanzania, showing the location and drainage network of the Makanya pilot watershed. (The map on the right, is from earlier studies by the Department of Geography, Faculty of Social Sciences, Norwegian University of Technology and Science, Trondheim. http://www.sv.ntnu.no/geo/Forskning/Pangani/).

- Research on hydrological, environmental and socio-economic impacts of upscaling (Projects 4, 5).
- Research on institutional and policy requirements to balance water for food and environmental security at watershed and basin scale (Projects 4, 6).

The research is carried out in two river basins in Southern Africa; the Pangani basin in Tanzania, and the Thukela basin in South Africa. The Pangani river, the third largest river basin in Tanzania covering some 56,000 $km^2$, has its head waters in Kilimanjaro and Meru mountains, passes through large tracts of low-lying semi-arid savannas hosting rural communities, before discharging in the Indian Ocean. Field research is focused in the Makanya watershed (approximately 200 $km^2$) located in the South Pare Mountains in the mid/upper reaches of the Pangani basin (Fig. 3).

The Thukela basin covers approximately 29,000 $km^2$, and flows from Drakensberg mountains in KwaZulu-Natal, Eastwards and joins the Indian Ocean in Durban. Thukela is a highly diverse basin, with valuable aquatic and terrestrial ecosystems, mixed with subsistence and commercial farming activities. The research is focused on the Emmaus watershed located in the western upstream parts of the Thukela basin (Fig. 4).

## 5. Scale interactions and hydrological modelling

A nested catchment approach will be applied to test the scaling influence of shifts in hydrological determinants caused by land use change. The hydrological research will integrate findings at the field, sub-watershed and river basin scales.

The basic modelling approach is on understanding major driving forces and processes in a complex reality. Methodologically, the research builds on the downward approach (Klemes, 1983) where focus is set on building model complexity from the simplest representation of the dominating hydrological determinants to the more complex. A scientific challenge in this respect is to represent rainfall-runoff relations at a relevant scale for smallholder system innovation development (generally the hillslope scale depending on sheet, rill and gully storm flow) at the catchment scale.

Distributed hydrological modelling is carried out using the ACRU model developed at University of KwaZulu-Natal (Schulze, 2000), and the MIKE-SHE model developed at DHI (the Danish Hydrological Institute) in Denmark (http://www.dhisoftware.com/mikeshe/). The distributed hydrological modelling will provide scientific data on reserved water allocation to humans and the environment and quantify the possibilities of equitable sharing of water with agriculture, industry, inter-catchment transfers, conservation and mining, accounting for impacts of land use and population dynamics. The objective needs to be met, and the information made available, at a range of scales, both spatial and temporal, from that of the local rural community through that of small watershed to operational sub-watersheds (called Quaternary Catchments) of 100–400 $km^2$, to the entire basin of nearly 30,000 $km^2$

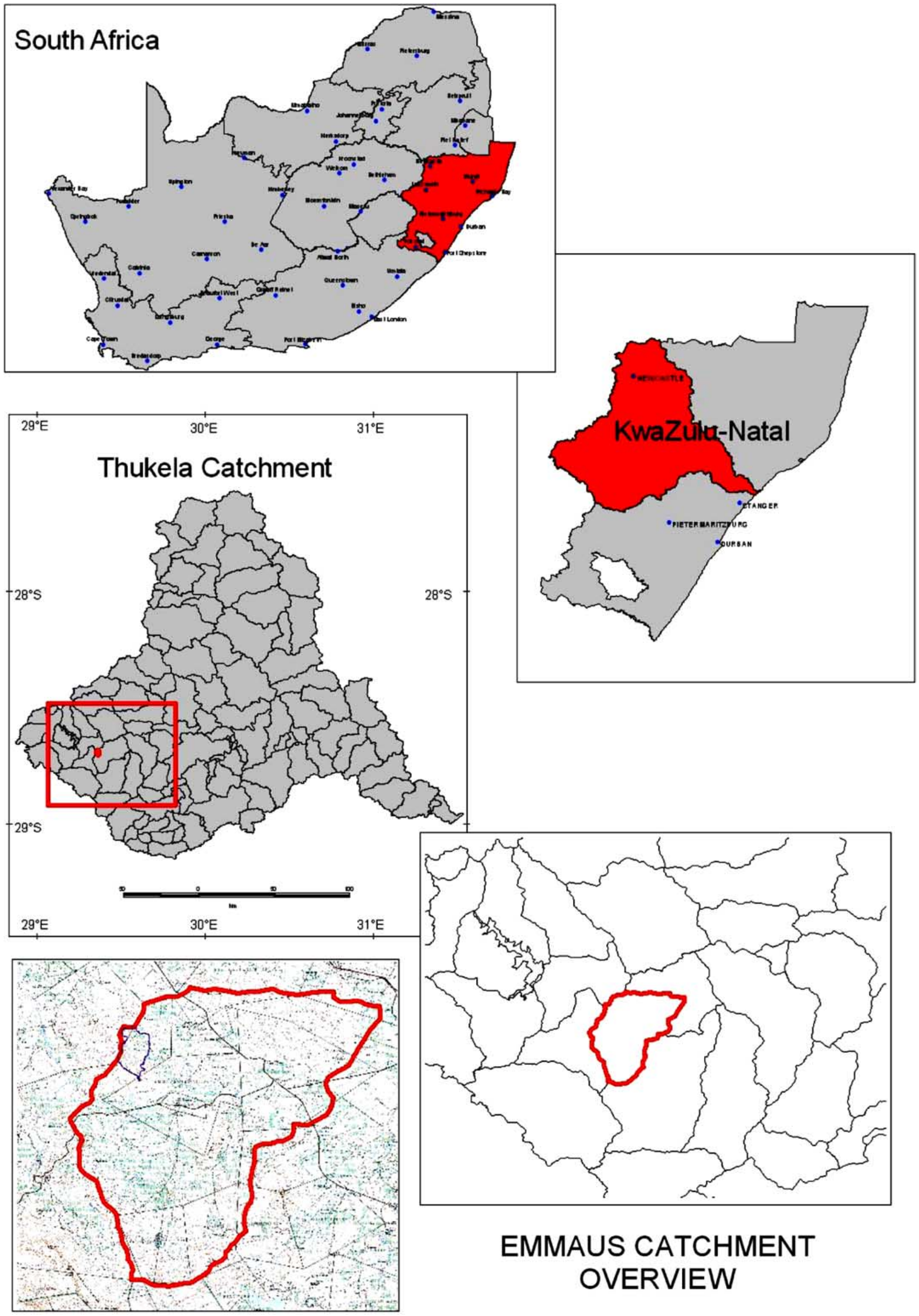


Fig. 4. The Thukela Basin, South Africa, showing the location of the SSI focal watershed, the Emmaus watershed.

such that the interactions and implications between responses at the different scales can be evaluated according to biophysical and socio-economic criteria.

A generic research challenge in this research programme is how to map water management zones in the landscape that captures water flows and includes water dependent natural systems and human land use, and water impacting activities. The recently developed concept of hydronomic zones, will be adopted and streamlined with the presently used method of delineating small homogenous hydrological response units in the landscape (Molden et al., 2001). The hydronomic zones concept identifies spatial units in a catchment based on its downstream hydrological determinant. Focus is on the interactions between the upstream hydronomic "water source zone", which, at the larger scale is the source of blue water flow downstream, and its interactions with the downstream hydronomic zones involved in different direct uses, such as "final use" zone (e.g., irrigation), "regulated zones" (e.g., dams), and zones with specific hydrological characteristics, such as "stagnation" zones and "environmentally sensitive zones".

All water flows in the hydrological cycle, are studied with a specific effort of *direct* estimates of green water flows, i.e., non productive evaporation and productive transpiration flow, rather than the conventional hydrological approach of *indirect* estimates of vapour flows (as the residual from Rainfall—Runoff observations). This is achieved using heat-pulse techniques (http://www.dynamax.com) at the plant scale and Scintillometer methodology at the system scale of a farm-household or land use type (http://www.scintec.com). The reason for this is the critical role of green water flow in sustaining biomass growth, thereby being the consumptive water flow that will have the strongest effects on upstream–downstream availability in scenarios of changes in, e.g., food production. The objective is to link field methodologies with remote sensing research to quantify evaporation and transpiration flows at different scales, as a means of improving validation of the modelling research (Bastiaanssen, 1998).

## 6. Water system innovations in rainfed agriculture

System innovations, including water harvesting, drip irrigation, precision agriculture and conservation farming technologies (green and blue water interactions), that aim at improving water productivity (increasing water use efficiencies) while conserving resources, have been developed and tested often with success in several tropical savannas of the world (Agarwal and Narain, 1997; Sivannapan, 1997; Ngigi, 2003). However, they are generally applied at the field scale with limited biophysical and socio-economic linkages and assessment at the larger watershed or river basin scale. For example, it is popular today to promote water harvesting as a panacea for upgrading rainfed agriculture in water scarce tropical areas, but the question of the hydrological and environmental impacts at watershed and river basin scale if successfully upscaled have not been addressed. Furthermore, it is increasingly understood that soil quality, in terms of both soil structure and soil fertility, often is a more limiting factor to crop growth than water, even in semi-arid tropical agro-ecosystems. This requires special attention to integrated soil and water management, with special focus on soil fertility, without which maximum benefits from water innovations cannot be achieved.

Improved soil and water management at the field scale can improve agricultural productivity, resulting in increased consumptive green water flow from that scale. Such intensification of agricultural land management will often be followed by more intensive use of capital resources, such as labour, but also additional inputs such as fertilisers, hybrid seed and pesticides. At the larger watershed scale, such intensification at the farm scale, is generally seen as having negative environmental impacts (Acreman, 2000). For smallholder farming systems in water scarcity-prone environments, this link between intensification and negative environmental impacts is questionable for several reasons. Firstly, low productivity is often linked to high levels of land degradation and expansion of agriculture to marginal lands. Secondly, the present use of external inputs is extremely low—e.g., fertiliser use averages some 10 kg/ha/yr compared to an average export of nitrogen from crop land of 70 kg nitrogen per hectare each year (Stoorvogel and Smaling, 1990).

As suggested by recent research on irrigation system efficiency, it is important to assess water productivity (WP) at the system and watershed scale. As shown by Seckler et al. (2003) low conventional efficiency of water use (basically the ratio of water consumed to water supply) tells little of system efficiency as excess drainage of water can be reused downstream. The only true depletion of water at any given terrestrial scale is consumptive green water (if we omit deterioration of water quality to a point beyond use). Runoff flows can always serve ecological functions further downstream. In terms of water for food, it is therefore critical to investigate the green water productivity of water use in agriculture. Conventionally, this is done by assessing evapotranspiraton (ET), and estimating WP as the ratio of ET flow to biomass produced (economic yield, total biomass etc.). Molden and Sakthivadivel (1999) developed a framework of water accounting that assesses water productivity at different scales, taking into consideration the actual depleted fraction of water at each scale.

Research at nested scales is important in studying options to improve water productivity and to assess downstream implications of changes in land use upstream. As shown, e.g., by Evenari et al. (1971), from research on water harvesting systems in the Arid Negev desert, collection of local runoff in many cascading small water harvesting storage systems increased water productivity compared to one storage system at the downstream end of a watershed. The reason was the large transmission losses of water through evaporation, during its journey from upstream to downstream. The most effective spatial location for productive water, based on the hydronomic zones methodology and recent water productivity approaches will be studied at watershed level in the SSI research.

## 7. Sustaining ecological functions

Water plays a fundamental role in sustaining ecological functions and biodiversity. In semi-arid and dry sub-humid tropical ecosystems the dynamics of the hydrological regime will influence the generation of ecosystem services and point out the importance of ecosystem resilience to hydro-climatic shocks (like droughts and floods). Resilience is important in order to sustain the generation of ecosystem goods and services when faced with dynamics and change. Resilience is defined as the capacity of a socio-ecological system to remain within a certain "state" or stability domain by absorbing disturbance and maintaining the capacity for adaptation and re-organisation (Gunderson and Holling, 2002). Shifts to another stability domain may cause irreversible loss of essential ecological goods and services (Scheffer et al., 2001). Therefore, in studying interactions between ecological functions and economic biomass production in tropical farming systems, addressing quantity and quality of water flow is not enough. The dynamics of the hydrological system are much more important than the quantity of water per se. Hence, understanding is required on the role of spatial and temporal dynamics of water flows under various land management modes. There is very little empirical research from savanna watersheds on the interactions between changes in land use to stabilise and increase yields and altered hydrological dynamics affecting ecosystem functioning of the larger landscape. This important research highlights the possible trade-offs between food security and environmental security and is addressed in the SSI research.

## 8. Resilience biodiversity and slow variables

Disturbances and extreme conditions at different temporal and spatial scales are an inherent part of ecosystem dynamics and development (Holling, 1986). Disturbances open up patches of opportunity for renewal and reorganisation of ecosystems, for development and evolution. Biological diversity can be of particular importance in times of reorganisation and change. The dynamic interactions within a network of species and between its environment make reorganisation after disturbance possible. However, it has been suggested that diversity at the level of species is of limited importance when it comes to functional ecosystems (Naeem and Wright, 2003). Instead the role of functional diversity and response diversity has been emphasised. Tilman (2001) defined functional diversity as the "components of biodiversity that influence how an ecosystem operates or functions" and it considers the functions different species perform in an ecosystem. Response diversity deals with how species within a functional group respond differently to disturbances. This is particularly important in determining how a system will perform in the face of disturbance and change (Elmqvist et al., 2003). Hence, ecological resilience is a key property of life-support ecosystems and diversity helps build resilience. Resilience sustains the flow of ecosystem services through the dynamic capacity to absorb change and provides the components for reorganisation, opportunity and novelty. Within SSI a special focus will be on the interplay of functional diversity and the hydrological regime in agro-ecosystems.

Slow processes in ecosystems are particularly important to secure long-term ecological resilience (Gunderson and Holling, 2002). In agro-ecosystems, these include the build up of organic matter contents, soil structure, rooting depth, and micro-climatic conditions. Particular focus is required in monitoring the slow variables, which form the basis of ecological resilience. SSI-studies will in relation to slow variables focus on how stabilised and increased yields affect the dynamics of the slower variables in the agricultural soils.

## 9. Resilience of social–ecological systems

Building capacity to shape and respond to various changes in a way that keep complex social–ecological systems on sustainable trajectories is thus essential for a long-term societal development. In many regions people find ways to adapt, learn and shape change in ways that build the resilience of those social–ecological systems (Berkes et al., 2003). Development and application of proper methodologies and procedures for learning about and responding to ecosystem feedback have been shown to be of importance. Such methodologies should be flexible and consider extremes, both in socio-economic conditions, and in natural variability of components of the hydrological cycle.

Being 'adaptive', i.e., being able to cope with uncertainty, complexity, and change is a key property when managing complex social–ecological systems. "Adaptive management" (Holling, 1978) has been widely advocated as a new management paradigm. It is built on a recognition that ecosystems are complex, "adaptive" and "self organising" systems, and that in order to utilise such systems sustainable, society must have the capacity to adapt to change or surprise in them. Scientific experimental knowledge is one key component of this capacity, but the importance of complementing this knowledge with local and traditional experiential knowledge has been emphasised (Olsson et al., 2004). Social capacity building further includes social mechanisms to avoid ecological surprises (King and Louw, 1998), social and institutional learning of ecosystem management (Gunderson et al., 1995), and participation of resource users, decision-makers and other interest groups.

## 10. Unlocking the potential of sustainable agriculture—the policy challenge

Integrated watershed management, which broadens the freshwater outlook to address both direct and indirect green and blue water functions in a landscape, requires shifts in policy and institutional arrangements. Even though the South African Water Act includes consumptive use of, e.g., alien vegetation as a freshwater factor in policy making, the challenge still remains of how to make rainfall the basic freshwater resource, which as soon as it hits land, is considered part of the legal framework for water resource management. Water resource planning at scales from the individual farm to the basin scale, which incorporates direct and indirect social and ecosystem services generated by blue and green water flows (Savenije and van der Zaag, 2000), is required and constitutes a research and development gap.

Institutional arrangements that address trade-offs between water dependent ecosystem services in upper and lower parts of catchments are—theoretically—being addressed through the recent introduction, e.g., of Catchment Councils in Zimbabwe, and the Catchment Management Agencies in South Africa. Focus has so far been attributed to developing methodologies to quantify environmental water flows or instream water requirements in aquatic freshwater systems (e.g, King and Louw, 1998). The role of green water flows in sustaining terrestrial ecosystem services, and in determining the amount of blue water released to sustain ecological functions, has not been properly addressed. SSI research studies the institutional and policy issues related water for food and environmental security, by including the role of green water flows in generating ecosystem services, and in its role as determinant of blue water generation.

## 11. Conclusions

This paper has outlined some of the challenges facing smallholder farmers in water scarcity-prone savanna agro-ecosystems in sub-Saharan Africa. It argues that there are large opportunities to improve rural livelihoods through the adaptive adoption of smallholder system innovations in integrated land and water management. Changes in land use upstream will affect water flows downstream, which in turn may lead to unacceptable trade-offs between water for food generation in upper catchments and blue water requirements for nature and humans in downstream areas.

The SSI research programme takes an integrated approach to agricultural water management, and focus on four major aspects of IWRM in the context of smallholder livelihoods; (1) local management options through smallholder system innovations to improve agricultural productivity while increasing water productivity and ecosystem conservation, (2) study the water trade-offs at field, watershed and basin scale between water for food in upper watersheds and water for ecological functions in downstream areas, (3) study the dynamics of resilience building in social and ecological systems, and analyse how land management will affect the dynamics of resilience in the long-term, and (4) the institutional and policy needs to embark on a watershed management approach which incorporates direct and indirect blue and green water functions.

It is increasingly acknowledged that IWRM forms an integral part of endeavours to attain sustainable development. The Millennium Development Goals (MDGs) on poverty reduction, food security and environmental security, are key indicators of sustainability. This paper outlines a conceptual framework, which indicates that upgrading rainfed agriculture in upper watersheds, through sustainable water management and water productivity improvements, constitutes a necessary development investment to attain the MDGs and thus long-term sustainability.

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