3 Water Resource Implications of Upgrading Rainfed Agriculture – Focus on Green and Blue Water Trade-offs

L. Karlberg,[1]* J. Rockström[1] and M. Falkenmark[2]
[1]*Stockholm Environment Institute (SEI), Stockholm, Sweden;*
[2]*Stockholm International Water Institute (SIWI), Drottninggatan 33, SE-111 51 Stockholm, Sweden;*
*email: *louise.karlberg@sei.se*

Introduction

Every increase in water use in agriculture will affect water availability for other water-dependent uses, both direct human use (water supply) and ecosystem use (terrestrial and aquatic ecosystems). In overcommitted watersheds, upgrading rainfed agriculture through investments in water-harvesting systems may result in severe water trade-offs with downstream users and ecosystems (Calder, 1999). Even so, the downstream impacts on stream flow from small-scale water storage systems have been shown to be very limited in some cases, even as a result of large-scale implementation (Evenari *et al*., 1971; Schreider *et al*., 2002; Sreedevi *et al*., 2006). Investing in water management in rainfed agriculture can lead to positive environmental impacts on other ecosystems, as a result of reduced land degradation and relative improvement of water availability (i.e. enabling more food to be produced with *relatively* less water) and water quality downstream.

Rainfall is partitioned in two categories of freshwater resource: a *green water* resource, i.e. the soil moisture generated from infiltrated rainfall that is available for root water uptake by plants, and which constitutes the main water resource in rainfed agriculture; and a *blue water* resource, i.e. the stored run-off in dams, lakes and aquifers, which is the main water source for irrigated agriculture (Fig. 3.1) (Falkenmark, 1995). These green and blue water resources generate flows in the hydrological cycle. Green water flows are the vapour flows that go back to the atmosphere (evaporation, interception and transpiration) and amount to 65% of global precipitation (Rockström *et al*., 1999; Rockström

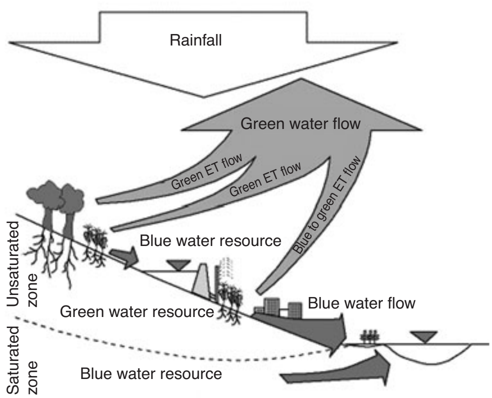

Fig. 3.1. Green and blue water resources and flows in rainfed and irrigated agriculture (ET = evapotranspiration).

© CAB International 2009. *Rainfed Agriculture: Unlocking the Potential* (eds S.P. Wani *et al*.)

and Gordon, 2001; Falkenmark and Rockström, 2004). Blue water flows, on the other hand, are the liquid flows of water recharging groundwater and flowing in rivers to lakes, wetlands and ultimately the ocean, and amount to 35% of global precipitation. It has been estimated that the total green water flow from croplands globally is around 6800 km^3/year (Rockström *et al.*, 1999), which corresponds to around 6% of global precipitation. Of this, 5000 km^3/year originates from rainfed agriculture, and the remainder from irrigated agriculture (Rockström *et al.*, 1999).

In a holistic view on water, as depicted in Fig. 3.1, water is regarded as the bloodstream of the biosphere. The water continuum starts off as rainwater and flows through the terrestrial ecosystems as surface water, groundwater and soil water, until it leaves the surface as a consumptive flow (green water flow) or discharges into the sea. During its journey through the landscape it can be used and reused as long as it is not consumed. It is collected for drinking purposes, stored in water-harvesting devices and used for supplementary irrigation in rainfed agriculture, dammed to produce hydropower, and withdrawn for irrigation purposes. Irrigation drain water can be used again to irrigate more salt-tolerant crops further downstream. Water fills up lakes used for tourism, fisheries and navigation. It is used by households and industries, after which it is purified and again re-enters the ecosystems. The most beneficial use of water depends on the local conditions, the quantity and quality of the water and the location within the basin. In developed countries, a larger share of the water resource is allocated towards industry compared with developing countries. Thus, in the future we can expect the demand of water from industry to gradually increase in those countries classified as developing countries today.

In closed and closing basins, more water is used than is renewably available in a river basin during at least part of the year. This situation puts constraints on water management within the basin, as described by Molden *et al.* (2001) and Molle (2003). However, improvements in water productivity, land-use change and decreased evaporative losses of blue water from rainwater captured close to the source convey larger opportunities to upgrade rainfed agriculture than hitherto believed. This chapter aims to give an overview of the implications of upgrading rainfed agriculture on green and blue water resources and flows. Special attention is given to trade-offs between upstream implementation of water management techniques for rainfed agriculture and the impacts on the downstream water users and ecosystems. The potential for minimizing trade-offs is discussed, and finally some implications on policy making are addressed.

Options for Upgrading Rainfed Agriculture

Improved crop yields and water productivity can be accomplished in many ways (Critchley and Siegert, 1991), as summarized in Table 3.1. One option is to maximize plant water availability in the root zone, which involves practices to capture surface run-off for *ex-situ* water harvesting and supplemental irrigation, redirect local run-off to the plant roots and maximize rainfall infiltration through *in-situ* water management, and by managing soil evaporation. Second, management can be targeted at maximizing the plant water-uptake capacity, which involves practices of crop and soil management to increase root water uptake. To achieve these aims, there is a wide spectrum of integrated land and water management options. Some of them focus on increasing water productivity, such as mulch practices, drip irrigation techniques, and crop management to enhance canopy cover, while most of them primarily aim at improving crop production by capturing more water.

Implications on Green and Blue Water Resources

The fundamental principle behind green and blue water resources in agriculture is that plants take up water from the root zone in the uppermost part of the soil profile, i.e. the green water resource, which subsequently leaves the plant as transpiration, i.e. a *productive* green water flow (as opposed to *non-productive* green flows as evaporation and interception). In rainfed agriculture the green water resource mainly originates from naturally infiltrated rainwater,

Table 3.1. Rainwater management strategies and corresponding management options to improve crop yields and water productivity.

Rainwater management strategy	Purpose	Management options
Increase plant water availability *Ex-situ* (external) water-harvesting systems	Dry spell mitigation, protective irrigation, spring protection, groundwater recharge, enable off-season irrigation, multiple water use	Surface micro-dams, subsurface tanks, farm ponds, percolation dams/tanks, diversion and recharging structures
In-situ water-harvesting systems	Concentrate run-off to cropped area and/or other use	Bunds, ridges, broad-beds and furrows, micro-basins, run-off strips
	Maximize rainfall infiltration	Terracing, contour cultivation, conservation agriculture, dead furrows, staggered trenches
Evaporation management	Reduce non-productive evaporation	Dry planting (early), mulching, conservation agriculture, intercropping, windbreaks, agroforestry, early plant vigour, vegetative bunds, optimum crop geometry
Increase plant water uptake capacity Integrated soil and crop management	Increase proportion of water balance flowing as productive transpiration	Improved crop varieties, soil fertility, optimum crop rotation, pest control, organic matter

but it can be augmented through irrigation by allowing the application of blue water resource to infiltrate the land. At this stage it is perhaps pertinent to point out that irrigated versus rainfed agriculture is a distinction made in the realm of agronomy and water resource management, which does not have any basis in hydrology. The difference in hydrological terms between irrigated and rainfed agriculture, as defined in this Comprehensive Assessment, is that in rainfed agriculture the main part of the green water resource originates from naturally infiltrated rainfall, whereas in irrigated agriculture yields depend to a large extent on external inputs of blue water to augment the green water resource (i.e. blue to green water redirections). In reality, irrigated agriculture depends to a significant degree on infiltrated rainfall as a supplementary water resource, and many of the key strategies to improve rainfed agriculture involve supplementary addition of blue water resources.

Table 3.2 outlines the major water management strategies and the implications of those on blue and green water resources. By improving water productivity through water management that aims at minimizing non-productive green water losses, more green water will be available for crop production. This results in higher yields for the same amount of green water use. Irrigation expansion, on the other hand, means that blue water is captured and is allowed to infiltrate in the field, thereby augmenting the green water resource in a process that can be described as blue to green water redirection. The green water resource is also augmented when strategies to improve the local use of rainfall are implemented through *in-situ* rainwater harvesting. This takes place at the partitioning point when rainwater either infiltrates the soil to form green water or generates run-off to form blue water. In effect, the process results in an increase in the green water resource and a corresponding decrease in the blue water resource. Yields can also be improved by converting non-agricultural land to agriculture. Green water that previously sustained the former ecosystem is then used for crop production instead. The impact on the blue water resource depends on differences in water demand and infiltration capacity between the two systems. Non-conventional water sources like saline water and drainage water from industries can also be used sustainably in agriculture if combined with proper management (Karlberg, 2005). In this case, precipitation is supplemented by an additional water source, resulting in an augmentation of both blue and green water.

Table 3.2. Implications of water management strategies on blue and green water resources.

Water management strategy	Implications on blue and green water resources
Improving water productivity (demand management) e.g. evaporation management, integrated soil, crop and water management, deficit irrigation	Reduce green water losses
Expanding irrigation (supply augmentation) e.g. *ex-situ* rainwater harvesting and supplemental irrigation	Adding blue water to the field, blue to green redirection
Improving local use of rainfall (supply augmentation) e.g. *in-situ* rainwater harvesting such as conservation agriculture	Reduce blue water losses, increase green water resources
Agricultural area expansion (supply augmentation)	Convert green water use in natural ecosystems to green water use in agriculture. Possible effects on blue water generation
Use of non-conventional water sources (supply augmentation) e.g. desalinization of seawater, use of marginal-quality water, reuse of drainage water from cities and industries	Adding more water to the hydrological cycle, generating more blue and green water

Sometimes, water management strategies target only demand management. For example, when mulch is applied to the field the non-productive green water flow is reduced, and thus more green water is available for productive green water flow. The net result is a higher yield for the same amount of green water used, i.e. an improved water productivity. However, improved water productivity is often also a secondary result of enhanced crop growth due to either improved supply or demand management. Larger plants have canopies that shadow a larger area of the soil surface. This shadowing effect is important since it leads to lower soil evaporation, which in turn results in more green water for productive green water flow and concurrent improvements in water productivity. Thus, there are important feedback links between supply and demand management.

Impacts of Water Management Strategies on Downstream Water Users and Ecosystems

From the previous section it is clear that many of the strategies to upgrade rainfed agriculture will impact on both the hydrological flows within the watershed and also directly on the non-agricultural terrestrial ecosystem through agricultural area expansion. Many of these impacts will require trade-offs between water for food production and water for other purposes.

Water productivity improvements entail a vapour shift between non-productive and productive green water use (Fig. 3.2a). Such a shift does not affect the blue water resource and as such does not have any specific negative or positive implications for downstream ecosystems or water users.

By expanding irrigation through *ex-situ* water harvesting, less blue water is available downstream (Fig. 3.2b). Therefore, less water is left to sustain downstream terrestrial and aquatic ecosystems and to satisfy downstream industrial, domestic and agricultural water use. Irrigation expansion is thus likely to result in trade-offs with other ecosystems and water users. The magnitude of this trade-off depends on the amount of water captured upstream and the volumes of water lost to evaporation during the conveyance from upstream to downstream, as well as the need for water downstream.

When *in-situ* soil water harvesting is implemented, less blue water is generated from precipitation due to higher infiltration of rainwater (Fig. 3.2c). Thus, the effect on downstream water users and ecosystems is similar to that originating from expanding irrigation, i.e. trade-offs can be expected. However, it is mainly the surface run-off component of the total blue water flow that is lower, while subsurface run-off is likely to be affected to a lesser degree.

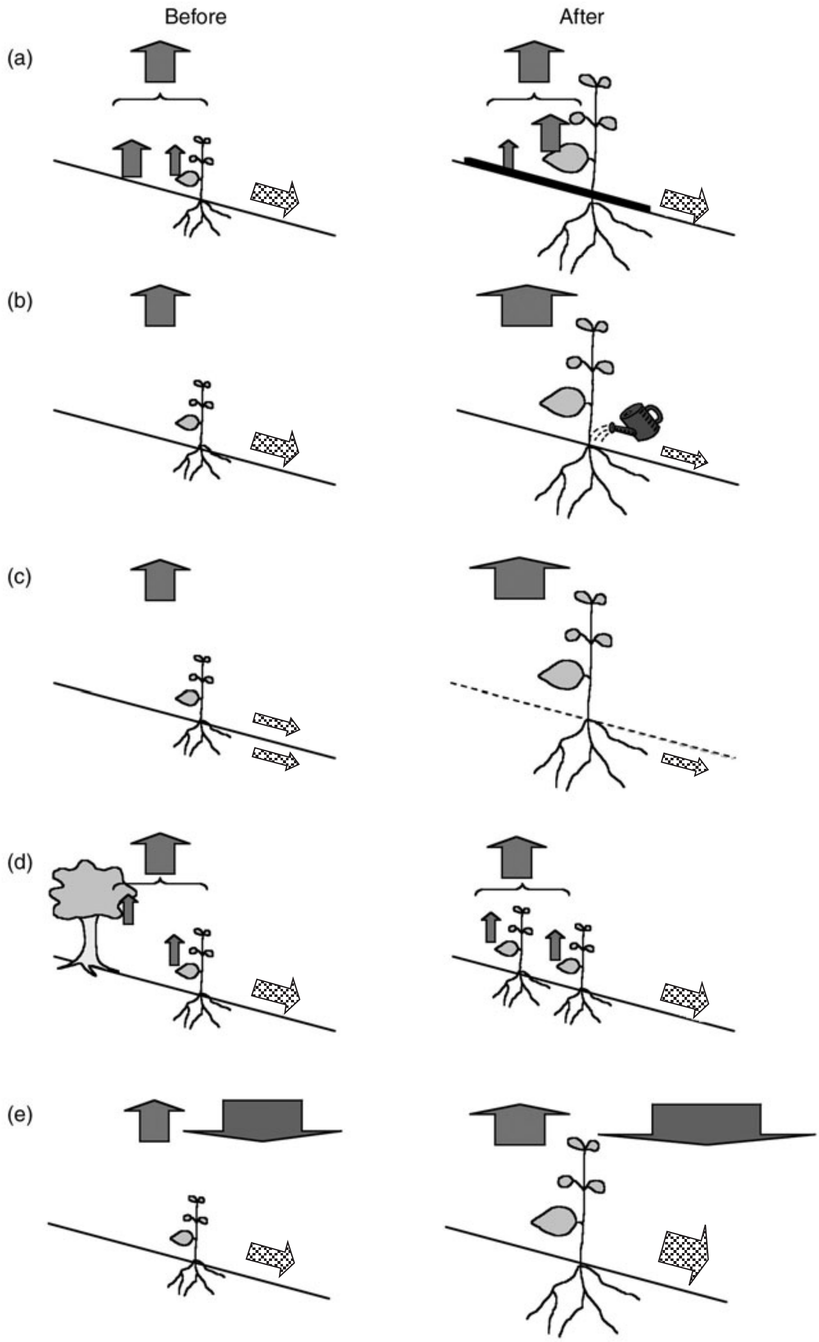

Fig. 3.2. Impacts on green (shaded arrows) and blue (hatched arrows) water flows of different water management strategies before (left) and after (right) implementation, (a) improving water productivity, (b) *ex-situ* water harvesting, (c) *in-situ* water harvesting, (d) agricultural area expansion, (e) use of non-conventional water sources.

Expanding the agricultural area has a direct effect on adjacent ecosystems as it inevitably encroaches on other ecosystems. Trade-offs with other land uses, such as forestry, biofuel production and pasture, are therefore to be expected, as well as impacts on biodiversity. Agricultural area expansion probably also affects blue water flows (Fig. 3.2d); however, whether this means a reduction or an increase will depend on the change in soil infiltrability and vegetation type.

Many of the non-conventional water resources that have been suggested for agricultural water use are of marginal quality, and if not managed properly can cause salinization, build-up of heavy metals and health concerns from pathogens. Although the use of non-conventional water resources might not necessarily have any negative impacts on other ecosystems or water users in terms of water amounts (Fig. 3.2e), water quality factors might, in fact, be very problematic.

Opportunities for Minimizing Trade-offs

There are several opportunities to minimize the trade-offs between water consumption for food and water consumption for other purposes. Even if it might not be possible to completely eliminate all trade-offs, they could be decreased substantially.

In rainfed agriculture, yields are currently very low in many regions (see Chapter 6, this volume). Yield improvements in low-productivity regions result in relatively large improvements in water productivity, compared with high-productivity regions (Fig. 3.3). Therefore, investments in *in-situ* or *ex-situ* water harvesting in rainfed agriculture that are able to increase yields from 1 t/ha to 2 t/ha would result in a concurrent improvement of water productivity from approximately 3500 m^3/t to less than 2000 m^3/t. The same gains in water productivity would not be possible at higher productivity levels common to large-scale irrigated agriculture.

Another benefit of investments in *ex-situ* water harvesting is that the collected water can be used for an off-season, fully irrigated cash crop. If this period coincides with the winter season, radiation and air temperature are likely to be low, and thus the atmospheric demand for water. The consequence of this is higher water productivity.

When blue water is formed and travels through the landscape to the sea, some of this water is being evaporated along the way. Moreover, a large part of the blue water is generated during storms and is lost from the basin in

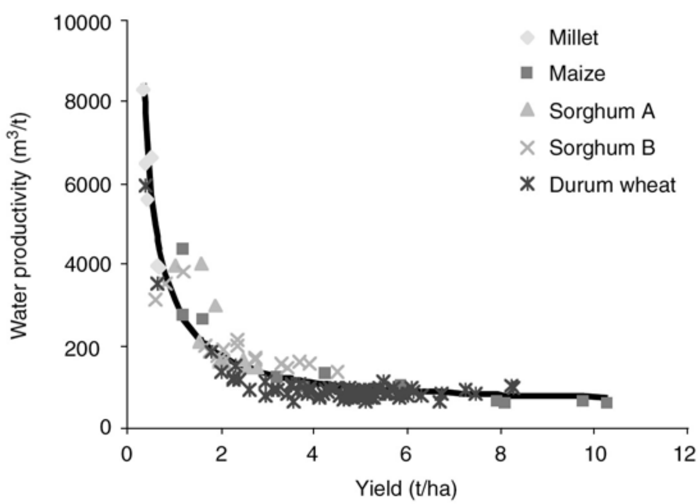

Fig. 3.3. Dynamic relationship between green water productivity and yield for cereal crops in different climatic conditions and management. Data from: Rockström *et al.* (1998) (millet), Stewart (1988) (maize), Dancette (1983) (sorghum A), Pandey *et al.* (2000) (sorghum B) and Zhang and Oweis (1999) (durum wheat). Regression line after Rockström (2003).

large pulses of water without any beneficiary use, also causing problems with erosion (Bewket and Sterk, 2005). Improvements in the local use of rainwater (*in-situ* water harvesting) mean that water is being used close to the source of rainfall, i.e. within the farmer's field. In this way, evaporation losses from the blue water resources become smaller, less water is lost as storm run-off and erosion problems are restricted. Thus, in general, upstream capture of blue water for agriculture is more advantageous compared with downstream. Since rainfed agriculture is often located upstream, investments in upgrading water management in rainfed agriculture might convey less trade-offs with other water users and ecosystems, compared with investments in irrigated agriculture, which is often located downstream. Moreover, *in-situ* water harvesting primarily reduces surface run-off, while subsurface run-off is reduced to a lesser degree. The latter blue water resource should be preferred, since it causes less erosion and evaporation losses are smaller. Therefore, *in-situ* water harvesting has an advantage compared with other irrigation management techniques.

The hydrological impact of agricultural area expansion at the watershed scale depends on land use prior to conversion into agriculture. Historic land-cover change has reduced the green water flows to the atmosphere, owing to conversions from natural ecosystems to agriculture (Gerten *et al*., 2005). Similarly, a modelling exercise over land use in a semi-arid catchment in South Africa indicated a reduction in blue water flows from increased forestry (Jewitt *et al*., 2004). Therefore, by replacing forest plantations with agricultural land, a positive effect on downstream blue water availability can be expected. Expanding agriculture into degraded lands with low infiltration capacity is likely to result in more groundwater formation (blue water) as well as reduced floods and erosion during heavy storms.

Assessments of Implications of Water Management Strategies for Upgrading Rainfed Agriculture Require a Holistic Approach

From the above analysis of impacts of different water management strategies in rainfed agriculture, it is clear that the interactions between different management strategies are complex and that the impacts depend on many factors, such as the location of the agricultural fields in relation to other ecosystems and water users in the watershed, climatic factors and present agricultural productivity. This calls for a holistic approach to evaluate trade-offs between all water users and ecosystems from different water-impacting water management strategies (Falkenmark, 2000). The starting point for such an approach has to be the rainfall over the river basin. However, with globalization, the issue of spatial scales becomes increasingly important as food and other water-consuming goods are produced and consumed in different river basins. In addition, with changing climate, addressing the implications of various temporal scales is highly relevant. The latter is also of importance for comparisons between annual and perennial crops. Fortunately, tools that handle temporal changes at different spatial scales are available today and could be applied in catchments to form a platform for informed decision making on water management, although at present this is very rarely done.

It is well established that *in-situ* and *ex-situ* water-harvesting techniques are useful for improving yields in small-scale rainfed agriculture where water is the key limiting production factor to growth; however, the question that remains to be answered is what effect large-scale adoption of these techniques would have on green and blue water resources in the watershed. For example, what would the return to investments in upgrading rainfed agriculture be in terms of water productivity, yields and money, compared with similar investments in large-scale irrigation? There is a need for more research that targets these issues at the watershed level, which can translate into decision-support tools for water planners and policy makers.

Looking beyond the realm of rainfed agriculture, it is clear that most ecosystems today are in one way or another affected by human activity, and that the choice of land use inevitably affects the hydrological cycle (Falkenmark, 2000). Forests, for instance, consume on average 720 mm/year (green water flow) compared with 510 mm/year for grasslands (Rockström and Gordon, 2001). These figures give an indication of the implications a change in land use might have on the hydrological flows in the catchment.

Examples of deforestation and reforestation from Australia, South Africa and Hungary illustrate how conversions of land use result in downstream blue water depletion as well as waterlogging and salinization.

Especially in catchments where the key limiting factor to biomass growth is water, an integrated analysis of the impact of different land use options on poverty alleviation, livelihoods, economic return of water (i.e. amount of money gained per drop of water consumed) and ecosystem resilience is needed to make informed decisions on optimum land management strategies. To argue that the water management strategy that causes 'minimum disturbance of natural ecosystems' should always be implemented ignores the fact that humans are not separate from the ecosystems but in fact form an integral part of them. In order to satisfy societal needs, humans have to manipulate various landscape elements. Therefore, the challenge is to find the 'best possible manipulation' of the ecosystems and not the 'least possible manipulation' (Falkenmark, 2003).

Policy Implications

The agricultural sector is heavily reliant not only on the green water resource but also on blue water to varying degrees. In order to achieve efficient water management on the national level, the legislation governing water resources management must account for both green and blue water use, especially in regions where water poses a constraint on economic development and the trade-offs between water users and ecosystems are substantial. This is gradually being realized throughout the world. In South Africa, the National Water Act from 1998 stipulates that a reserve of water, incorporating water for basic human needs and environmental flows, is given the highest priority in terms of water allocations. Moreover, the importance of green water flows is partly acknowledged in the legislation. The law regulates the trade-off between upstream activities such as forestry that have an impact on stream flow through increased use of green water and downstream water users.

Changes in land and water use upstream impact on water availability downstream. With increasing demand for water, particularly in basins and catchments subject to water scarcity, there is an increasing realization of the need to develop policy options that address water trade-offs between upstream and downstream water demands. An innovative, incentive-based policy initiative has been taken by IFAD (the International Fund for Agricultural Development), where a 'Green Water Credit' (GWC) system is piloted in the Tana river basin in Kenya. The objective is to create an incentive-based system for improved green water management in upper catchments (i.e. reduce non-productive vapour flows in land management upstream in order to increase blue water availability downstream). Water credits are given to upstream land and water users by downstream water-using sectors (e.g. industry and irrigated agriculture) as payment for increased blue water availability. Such a mechanism requires the ability to carry out catchment assessments of current water use and partitioning and estimates of increased release of water when adopting different water-saving technologies (e.g. conservation tillage, water-harvesting practices, mulching and drip irrigation).

At the regional level, there is a need for efficient tools to assess green and blue water flows to be able to compare different water management strategies and to study the impact of changing the land use in an area. Such decision-support tools must be user-friendly and flexible to suit the local conditions. Moreover, they must be able to operate in areas where data availability is limited.

There are economic pay-offs for downstream societies of investments upstream in improved water and land management. Examples are emerging in different parts of the world where downstream communities compensate upstream communities for economic gains of environmental services downstream received because of wise water management investments upstream (FAO, 2004). However, most documented experiences have so far largely been of deforestation and/or afforestation in the upstream watershed (Perrot-Maître and Davis, 2001; Landell-Mills and Porras, 2002).

Training of extension officers in the realm of water management working at the local level is crucial for adoption of new techniques to upgrade rainfed agriculture. Through the extension officers, the farmers get access to new knowledge and strategies for improving current yield levels.

Conclusions

In most cases, water management strategies to upgrade rainfed agriculture will result in trade-offs with downstream water users and ecosystems. However, depending on the choice of management strategy, these trade-offs can be minimized. An increase in yield in areas where the productivity is presently very low results in a relatively large improvement in water productivity, compared with yield improvements in areas with higher yields. Improvements in water productivity causes a vapour shift, which means that the productive flows of green water increase while the non-productive flows decrease to the same extent, and hence blue water flows are not affected at all. Therefore, investments in rainfed agriculture, such as *in-situ* or *ex-situ* water harvesting, where yields are low at present might cause comparatively large improvements in water productivity. Moreover, the augmentation of the green water resource in *in-situ* water harvesting comes from blue water that has been captured close to the source. This leads to lower evaporative losses of blue water compared with when the blue water is used for irrigation further downstream and also limits erosion. An integrated approach is needed to assess the impact of different investment strategies in rainfed agriculture in terms of poverty alleviation, livelihoods, economical returns and ecosystem resilience. The conclusion is that there seems to be ample room for improving yields in rainfed agriculture, while at the same time limiting trade-offs with downstream water users and ecosystems.

References

Bewket, W. and Sterk, G. (2005) Dynamics in land cover and its effects on stream flow in the Chemoga watershed, Blue Nile, Ethiopia. *Hydrological Processes* 19, 445–458.

Calder, I.R. (1999) *Blue Revolution: Land Use and Integrated Water Resources Management*. Earthscan, London, UK.

Critchley, W. and Siegert, K. (1991) *Water Harvesting: a Manual for the Design and Construction of Water Harvesting Schemes for Plant Production*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Dancette, C. (1983) Estimation des besoins en eau des principales cultures pluviales en zone Soudano-Sahélienne. *L'Agronomie Tropicale* 38(4), 281–294.

Evenari, M., Shanan, L. and Tadmor, N.H. (1971) *The Negev: the Challenge of a Desert*. Harvard University Press, Cambridge, Massachusetts, USA.

Falkenmark, M. (1995) Land–water linkages: a synopsis. In: *Land and Water Integration and River Basin Management*. FAO Land and Water Bulletin No. 1. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, pp. 15–16.

Falkenmark, M. (2000) Competing freshwater and ecological services in the river basin perspective – an expanded conceptual framework. *Water International* 25(2), 172–177.

Falkenmark, M. (2003) Freshwater as shared between society and ecosystems: from divided approaches to integrated challenges. *Philosophical Transactions of the Royal Society of London Series B – Biological Sciences* 358, 2037–2049.

Falkenmark, M. and Rockström, J. (2004) *Balancing Water for Humans and Nature: the New Approach in Ecohydrology*. Earthscan, London, UK.

FAO (2004) Payment schemes for environmental services in watersheds. Regional Forum, 9–12 June 2003 in Arequipa, Peru. Land and Water Discussion Paper No. 3. FAO, Rome, Italy.

Gerten, D., Hoff, H., Bondeau, A., Lucht, W., Smith, P. and Zaehle, S. (2005) Contemporary 'green' water flows: simulations with a dynamic global vegetation and water balance model. *Physics and Chemistry of the Earth* 30, 334–338.

Jewitt, G.P.W., Garrat, J.A., Calder, I.R. and Fuller, L. (2004) Water resources planning and modelling tools for the assessment of land use change in the Luvuvhu Catchment, South Africa. *Physics and Chemistry of the Earth* 29, 1233–1241.

Karlberg, L. (2005) Irrigation with saline water using low-cost drip-irrigation systems in sub-Saharan Africa. PhD thesis, KTH Architecture and the Built Environment, Stockholm, Sweden.

Landell-Mills, N. and Porras, T.I. (2002) *Silver Bullet or Fools' Gold? A Global Review of Markets for Forest Environmental Services and their Impact on the Poor*. Instruments for Sustainable Private Sector Forestry Series, International Institute for Environment and Development, London, UK (http://www.iied.org/pubs/pdf/full/9066IIED.pdf).

Molden, D.J., Sakthivadivel, R. and Keller, J. (2001) *Hydronomic Zones for Developing Basin Water Conservation Strategies*. Research Report 56, International Water Management Institute (IWMI), Colombo, Sri Lanka.

Molle, F. (2003) *Development Trajectories of River Basins – a Conceptual Framework*. Research Report 72. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Pandey, R.K., Maranville, J.W. and Admou, A. (2000) Deficit irrigation and nitrogen effects on maize in a Sahelian environment: I. Grain yield and yield components. *Agricultural Water Management* 46(1), 1–13.

Perrot-Maître, D. and Davis, P. (2001) *Case Studies of Markets for Innovative Financial Mechanisms for Water Services from Forests*. Forest Trends, Washington, DC, USA (http://www.forest-trends.org).

Rockström, J. (2003) Water for food and nature in the tropics: vapour shift in rainfed agriculture. *Philosophical Transactions of the Royal Society of London Series B – Biological Sciences* 358(1440), 1997–2009.

Rockström, J. and Gordon, L. (2001) Assessment of green water flows to sustain major biomes of the world: implications for future ecohydrological landscape management. *Physics and Chemistry of the Earth* 26(11–12), 843–851.

Rockström, J., Jansson, P.-E. and Barron, J. (1998) Estimates of on-farm rainfall partitioning in pearl millet field with run-on and run-off flow based on field measurements and modelling. *Journal of Hydrology* 210, 68–92.

Rockström, J., Gordon, L., Folke, C., Falkenmark, M. and Engwall, M. (1999) Linkages among water vapour flows, food production and terrestrial ecosystem services. *Conservation Ecology* 3(2), 5, 1–28 (http://www.consecol.org/vol3/iss2/art5).

Schreider, S.Y., Jakeman, A.J., Letcher, R.A., Nathan, R.J., Neal, B.P. and Beavis, S.G. (2002) Detecting changes in streamflow response to changes in non-climatic catchment conditions: farm dam development in the Murray-Darling basin, Australia. *Journal of Hydrology* 262(1–4), 84–98.

Sreedevi, T.K., Wani, S.P., Sudi, R., Mahesh, S., Patel, J.T., Singh, S.N. and Tushar, S. (2006) *On-site and Off-site Impact of Watershed Development: a Case Study of Rajasamadhiyala, Gujarat, India*. Global Theme on Agroecosystems, Report No. 20. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, 502 324, Andhra Pradesh, India.

Stewart, J.I. (1988) *Response Farming in Rainfed Agriculture*. The WHARF Foundation Press, Davis, California, USA.

Zhang, H. and Oweis, T. (1999) Water–yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. *Agricultural Water Management* 38, 195–211.