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Quantitative simulation tools to analyze up- and downstream interactions of soil and water conservation measures: Supporting policy making in the Green Water Credits program of Kenya

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A B S T R A C T

Upstream soil and water conservation measures in catchments can have positive impact both upstream in terms of less erosion and higher crop yields, but also downstream by less sediment flow into reservoirs and increased groundwater recharge. Green Water Credits (GWC) schemes are being developed to encourage upstream farmers to invest in soil and water conservation practices which will positively effect upstream and downstream water availability. Quantitative information on water and sediment fluxes is crucial as a basis for such financial schemes. A pilot design project in the large and strategically important Upper-Tana Basin in Kenya has the objective to develop a methodological framework for this purpose. The essence of the methodology is the integration and use of a collection of public domain tools and datasets: the so-called Green water and Blue water Assessment Toolkit (GBAT). This toolkit was applied in order to study different options to implement GWC in agricultural rainfed land for the pilot study. Impact of vegetative contour strips, mulching, and tied ridges were determined for: (i) three upstream key indicators: soil loss, crop transpiration and soil evaporation, and (ii) two downstream indicators: sediment inflow in reservoirs and groundwater recharge. All effects were compared with a baseline scenario of average conditions. Thus, not only actual land management was considered but also potential benefits of changed land use practices. Results of the simulations indicate that especially applying contour strips or tied ridges significantly reduces soil losses and increases groundwater recharge in the catchment. The model was used to build spatial expressions of the proposed management practices in order to assess their effectiveness. The developed procedure allows exploring the effects of soil conservation measures in a catchment to support the implementation of GWC.

1. Introduction

Increasing pressure on land and water resources often leads to tension among inhabitants in many basins in the world, because activities in one area of the basin can have major and often negative impacts in other areas. This interrelationship is particularly relevant for soil and water conservation (SWC) practices that may result in clear benefits upstream, while impacts downstream might be positive or negative. For example, upstream terracing reduces surface runoff and thereby enhances infiltration, soil moisture storage, and groundwater recharge. This, in turn, results in less erosion, less sediment in surface waters, and a more consistent streamflow with the result that water in rivers and reservoirs can be managed better. A lower surface runoff and at the same time increased crop transpiration may, however, lead to less water downstream. The use of mulching in agricultural land may reduce soil evaporation and weed growth. Fewer weeds will limit unbeneficial transpiration, which in turn may contribute to more groundwater and streamflow.

Besides from such downstream effects caused by upstream activities, there may also be socio-economic interactions. For example, downstream economic activities often affect price levels and the availability of resources such as land, causing people to use upstream land for agriculture. Such tendencies are likely to increase in future by rapid population growth and climate change.

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Population growth and economic development put huge demands on higher water and food availability and this demand can only be met through improved water-, soil conservation-, and agricultural policies, which consider the interactions between conservation practices, resource use, socio-economic factors, and incentive schemes.

Many efforts have already been made to enhance cooperation within basins, linking upstream and downstream activities related to water use (Rogers, 1993; Bergsma, 2000; Kosoy et al., 2007; Blackman and Woodward, 2010). To facilitate this cooperation, the Green Water Credits concept is being developed, linking the interests of upstream farmers and downstream water users. The term *Green Water* refers to water in the unsaturated zone of the soil which is available for crop growth and lost to the atmosphere through evapotranspiration whereas *Blue Water* refers to free water in streams and aquifers (Falkenmark and Rockström, 2004). GWC promotes the use of specified conservation practices to generate both on-site, upstream, as well as off-farm downstream benefits. Farmers may be unable to sustainably implement SWC because they lack capital investment capacity and because of an unfavourable cost:benefit ratio in the short term. This unfortunately happens in many basins of the world. Even though SWC measures are usually well defined for particular locations, implementation does not occur. Thus, both up- and downstream benefits remain elusive. The Green Water Credits (GWC) concept provides financial support to farmers to implement SWC measures in terms of initial investments and maintenance practices (Batjes, 2012). A requirement is that such measures are not only benefiting the farmers themselves but also provide ecosystem services to (downstream) society at large, where water is used for instance for hydropower, urban consumption, and irrigation. Payments for these services by downstream private and public water users allow the establishment of a GWC Investment Fund to be used to support implementation of upstream SWC practices by upstream farmers.

Policy-makers have been actively involved from the start of the GWC program in Kenya. However, the commitment and engagement of both upstream and downstream stakeholders is crucial for a successful implementation. Quantitative data are necessary to convince them that different actors in the basin have shared problems as well as interests and that all actors will benefit from a joint GWC approach to increase agricultural production, reduce erosion, silting of reservoirs, improve water management in rivers and reservoirs, and to increase availability of groundwater. This study focuses therefore on methods to provide the quantitative soil and water conservation data needed to present a convincing case to participants in the GWC scheme.

Off-farm benefits of SWC measures have been studied before (e.g. Bewket and Sterk, 2003; Hengsdijk et al., 2005; Panagopoulos et al., 2011). Most of the studies focus on crop-related effects, runoff and soil and nutrient loss, while paying less attention to the regional impact on the water resources. On a basin-scale, the hydrological impacts of land-use change (e.g. Choi and Deal, 2008; Qi and Altinakar, 2011) and its complex relationship with the provision of environmental services in spatially separated areas (e.g. Aylward, 2005; Immerzeel et al., 2008; Van Noordwijk et al., 2004) has been studied before but without a GWC focus. GWC requires an integral and comprehensive assessment of the basin-scale impacts of changes in land management in which a clear distinction is made between upstream (land users) and downstream (water users) effects.

In summary, the objective of this paper is to develop and present a methodology that allows quantifying the effects of implementing land management practices on specific processes relevant to upstream and downstream water users in a basin. More specifically, the modelling procedure analyzes the impacts of these practices on streamflow, *green* versus *blue water* and erosion and sediment flows, and allows an assessment of their effectiveness in space and under different climatic conditions. Outcomes can be used to demonstrate to stakeholders in the basin the feasibility and potential benefits of improved soil and water management.

2. Methodology and study area

2.1. Modelling approach

To assess the effects of land management practices on processes of interest, in space and under different climatic conditions, the Soil and Water Assessment Tool (SWAT) was selected. SWAT is a distributed hydrological model providing spatial coverage of the entire hydrological cycle including atmosphere, plants, unsaturated zone, groundwater and surface water. The model is comprehensively described in literature (Arnold et al., 1998; Srinivasan et al., 1998).

SWAT has the advantage that it is a physically based model that can characterize the main basin-scale processes of erosion, surface runoff, baseflow and evapotranspiration while providing sufficient detail to allow characterization of processes defining land use and management (e.g. Parajuli et al., 2008; Rostamian et al., 2008; Ullrich and Volk, 2009). For spatial discretization of the basin SWAT uses the concept of Hydrological Response Units (HRUs) (Neitsch et al., 2002): portions of a subbasin that possess unique land use/management/soil attributes. For large basins, it is recommendable to reduce the computational burden by filtering unique combinations that cover a small fraction of the subbasin.

Surface runoff volume was calculated in SWAT for each HRU using the SCS (Soil Conservation Service) curve number procedure method (USDA-SCS, 1972), aggregated for each delineated subbasin and routed through the stream network. SWAT estimates erosion and sediment yield using a modified version of the Universal Soil Loss Equation (USLE) method, which is used to estimate long-term erosion rates from field or farm sites that are subject to different management practices. Wischmeier and Smith (1965) developed the method based on data from many experimental plots in the United States, but the method has been applied and argued, globally (e.g. Wischmeier, 1976; Sonneveld and Nearing, 2003). The Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) uses the amount of runoff to simulate the daily erosion rates and sediment yield.

SWAT simulates crop growth on the basis of daily temperature sum and water availability. For each day of simulation, potential plant growth, i.e. plant growth under ideal growing conditions (adequate water and nutrient supply) is calculated and corrected to actual growth by applying stress functions related to temperature, water, and nutrient stress. SWAT also simulates irrigated crops by applying irrigation water from a defined source (reservoirs, river or groundwater) as a function of the level of crop water stress in each simulation time step.

2.2. Basin selection and data

The Upper Tana basin (17,500 km^2) in Kenya (Fig. 1) was selected to demonstrate the feasibility of the GWC concept, as the catchment faces severe challenges to meet increasing water demands due to poverty and population growth (Githui et al., 2009). Rainfed agriculture in the Upper Tana catchment has increased rapidly over the last decades and constitutes over 60% of the land use. Around 5% of the basin is irrigated and the remainder corresponds to natural and urban areas. The main crops are maize, coffee, and tea, but flowers, fruit and vegetables are also produced for the international market. Water downstream is used for hydropower,

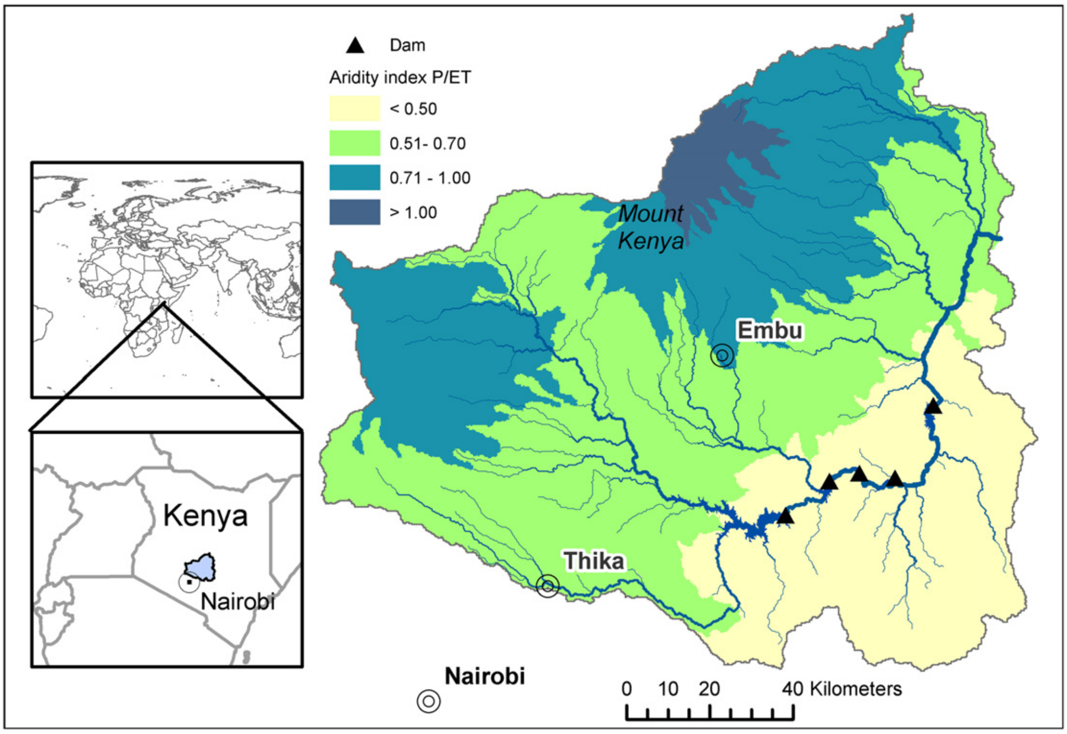

Fig. 1. Location of the Upper Tana basin, main reservoirs, drainage network and climatic zones according to the P/ET aridity index.

irrigation, and domestic use in the capital Nairobi, calling attention to upstream soil and water management procedures that can enhance availability of clean water. In 2008, the Upper Tana catchment was selected to develop a GWC Pilot involving potential interventions for an estimated 100,000 to 150,000 small holder farmers in the upstream rainfed areas. The targeted downstream water users are the hydropower companies, domestic water suppliers and irrigators. Implementation over a period of 7 years will follow the design phase starting in 2012.

The Upper Tana basin is of strategic importance for the water and energy supply of the country. The Tana River is relatively large compared to other rivers in the country and drains Mount Kenya and the Aberdares Range catchment areas. Rainfall is mainly a function of elevation, with average annual rainfall amounts around 2000 mm at higher altitudes, while drier conditions prevail at lower elevations, with annual rainfall amounts of around 500 mm, and high potential evapotranspiration rates. Fig. 1 shows the climatic zones that were identified according to the aridity index, defined as the ratio between rainfall and potential evapotranspiration (UNEP, 1992). Potential evapotranspiration was determined using the Penman–Monteith method (Allen et al., 1989). Downstream in the drier part of the basin, five major reservoirs have been built for hydropower, storage, and flow regulation. The irrigated areas can be found around these reservoirs. Two additional smaller upstream reservoirs are used for water supply to Nairobi city. Siltation of the reservoirs and thus loss of storage capacity is considered one of the main threats being faced. Population growth in recent years caused a steady increase in water and electricity demand, both upstream and downstream. Recent severe droughts made it necessary to ration water and electricity. There is circumstantial evidence of permanent rivers becoming seasonal and of continuously lowering water levels in boreholes.

Data on monthly climate statistics were collected and analyzed from local databases provided by the local water authority and from existing studies and documents. However, data availability from these sources was not sufficient; hence most of the required climate and other data for the schematization of the model were obtained from global public domain datasets. Climate data for three weather stations in the basin were obtained from the Global Summary of the Day (GSOD) database archived by the National Climatic Data Centre (NCDC), USA. However, given the high spatial variability of rainfall, it was decided to use satellite-derived rainfall data as model input for daily precipitation. One-day estimates of precipitation for the African continent are prepared operationally at the Climate Prediction Centre (CPC) for the United States Agency for International Development (USAID) as part of the Famine Early Warning System (FEWS) Network. The RFE2 product is available from October 2000 on a 0.1° resolution. The satellite estimates showed a good correlation with the observed data (R^2 between 0.60 and 0.78 on a monthly time-scale). Bias was removed by matching the total yearly accumulated rainfall amounts between both time series.

Spatial information on land use was obtained from the FAO Africover dataset (www.africover.org, last accessed 9th of March 2012). Fig. 2 shows a map, in which the land use categories of Africover were converted into those used in SWAT. This land cover map has been produced from automatic and visual interpretation of digitally enhanced LANDSAT TM satellite images acquired mainly in the year 1999. The land cover classes have been developed applying the standard FAO Land Cover Classification System (LCCS) and the effective scale is about 1: 250,000.

Soil data was used from the World SOil and TERrain Digital Database (SOTER) (Oldeman and Van Engelen, 1993). This database aims to provide information for a wide range of applications, as biophysical assessments and soil degradation. The Harmonized Upper Tana SOTER dataset (Dijkshoorn et al., 2010) is part of this database and provides data on a scale of 1:250,000. This SOTER dataset contains most of the soil water information necessary for the SWAT model, as soil profile information, available water

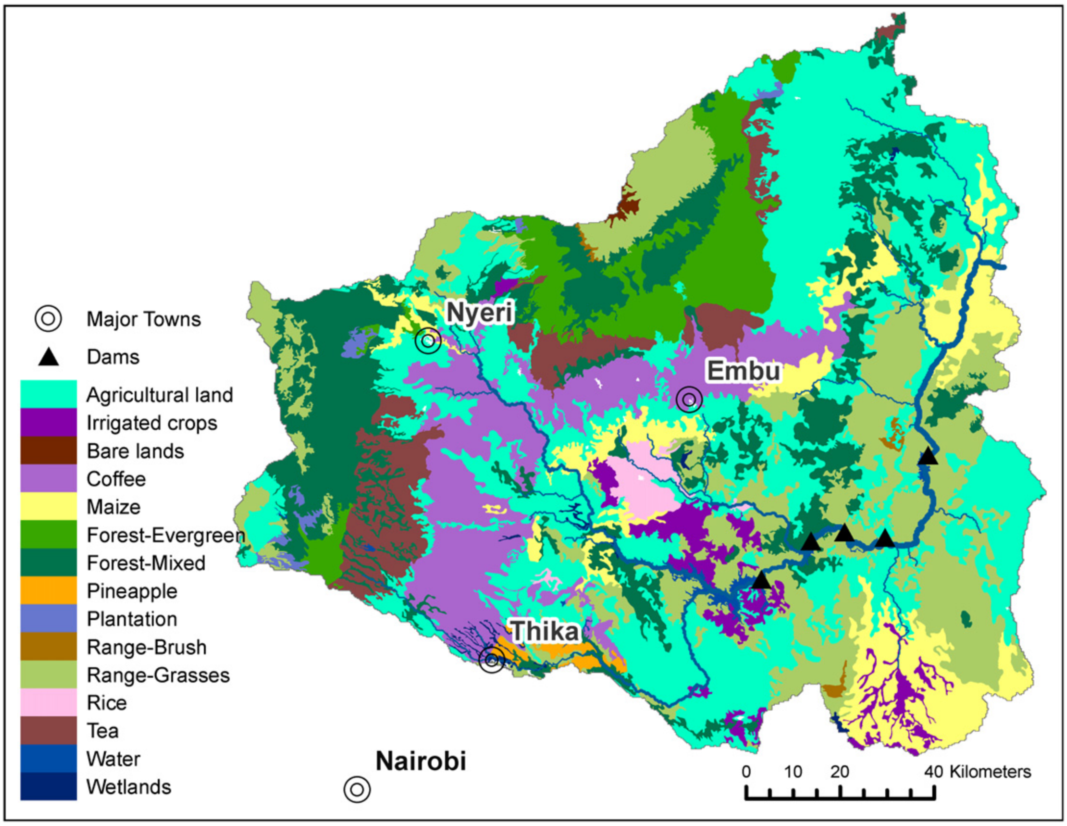

Fig. 2. Land use map as used in the SWAT model.

capacity, and bulk density (Bouma et al., 2011). One key lacking parameter was the saturated hydraulic conductivity, which was estimated by the so-called pedotransfer functions described by Jabro (1992). Model parameters related to soil loss were adjusted based on various studies previously done in this region on erosion and sediment dynamics (Dunne, 1979; Dickinson, 1981; Wooldridge, 1983; Walling et al., 1992; Brown et al., 1996). A total of 2226 HRUs were defined based on the combination of soil and land use layers after filtering those that covered a fraction of less than 10% of each subbasin (564 in total).

2.3. Tool validation

Combining the various public domain datasets (GSOD, FEWS, FAO Africover, SOTER and further on explained WOCAT) with the physical based SWAT model presents a unique research tool for referred to as GBAT (Green water and Blue water Assessment Toolkit). These established and validated databases combined with a model that has been successfully used by a large user community are the basis of the tool. Baseline results have been thoroughly discussed with local experts and farmers who indicated that results are realistic and acceptable to them and very relevant to support policy making. The procedure involves a process-based “best practices” approach to address a necessary and urgent societal problem.

The GWC assessment of the effectiveness of different scenarios is based on a comparison of relative differences rather than absolute values. Generally, the uncertainties related to the predicted relative changes of scenario outcomes are considerably smaller than the prediction uncertainty of absolute model outcomes (Arabi et al., 2007; Droogers et al., 2008). There are no straightforward computational procedures which can account for the uncertainties related to the effectiveness of management scenarios. Most studies and procedures published so far focus on uncertainty analysis of absolute values of predictions at a point. We propose that the “best practices” approach, as presented, is acceptable for this policy-supporting exploratory exercise, but refinement of the uncertainties involved in the GBAT procedures during a detailed design stage is advised. Also, a first order validation was still considered necessary to demonstrate the applicability to policy makers.

Monthly discharge data from 2000 to 2006 was used to validate this specific GBAT application for the Upper Tana study area, using observed and simulated flows at two key downstream locations in the basin: (i) total inflow into the Masinga reservoir derived from water levels and measured outflow, and (ii) flows measured at a station downstream of the Thiba catchment draining into the Kamburu reservoir. Observed and simulated monthly discharge values compared well as can be seen in Fig. 3. The Nash and Sutcliffe (1970) Efficiency (NSE) criterion is the most commonly used performance indicator to evaluate watershed models, which gave values of 0.76 for the Masinga and 0.80 for the Kamburu reservoir. Values close to one for this coefficient indicate a good correspondence between both series. NSE values between 0.75 and 1.00 are considered optimal for validating models on monthly observations (Moriasi et al., 2007). Further details regarding calibration and validation of the tool can be found elsewhere (Hunink et al., 2011).

2.4. Scenario definition

The most extensive database on Soil and Water Conservation (SWC) practices is maintained by the World Overview of Conservation Approaches and Technologies (WOCAT) initiative (Liniger and Critchley, 2007). It aims to promote the integration of successful soil and water conservation approaches and techniques into land use systems world-wide. Based on discussions with stakeholders and policy makers, three practices were selected that

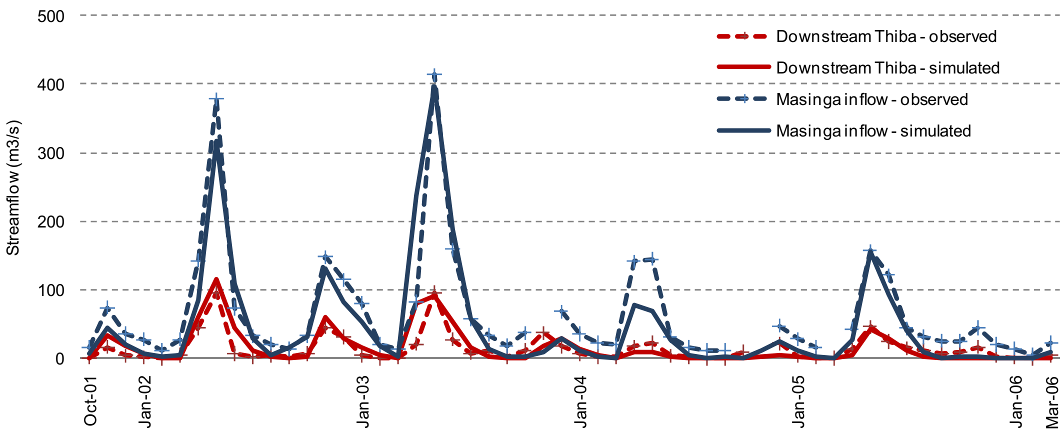

Fig. 3. Simulated and observed inflow at downstream points of two major catchments of the basin.

could be realistically implemented in the upstream rainfed areas of the Tana basin and of which the WOCAT database provides experimental data in catchments with similar physiographic conditions. The three management practices selected were:

i Permanent vegetative contour strips, consisting of grass or other permanent vegetation in a contoured field to help trap sediment and nutrients. Because the buffer strips are established following the contours, runoff flows slower and evenly across the grass strip, reducing sheet and rill erosion. Permanent vegetative contour strips are in fact an inexpensive substitute for terraces.

ii. Mulching, requiring residues produced within the cropping area and/or residues collected from elsewhere. These residues are applied in the field by spreading them on top of the soil. They protect to a certain extent the soil from erosion and reduce compaction from the impact of heavy rains.

iii. Tied soil ridges, which consists of establishing ridges of varying width and height, while at regular intervals, crossties are built between the ridges. The ties are about two-thirds the height of the ridges, so that if overflowing occurs, it will be along the furrow and not down the slope.

To assess how a specified SWC practice would affect the *green water*, *blue water* and sediment flows in the basin, a scenario was defined for each of the three practices and compared to the baseline scenario, representing actual conditions. To parameterize the scenarios, relevant parameters from the SWAT model for each of the three practices were identified. These SWAT parameters were:

- Runoff curve number (CN2). USDA-SCS (1986) and Arabi et al. (2008) provide reference values for different land uses and practices
- Support practice factor for soil loss (P_{USLE}). Wischmeier and Smith (1978) and Ullrich and Volk (2009) provide reference values for different land uses and practices
- Soil evaporation compensation coefficient (ESCO). The sensitivity analysis of Kannan et al. (2007) was used for the parameterization of the scenarios.

These parameters have been altered to reflect the scenario changes and were subsequently run to assess the impact of the measures on upstream as well as downstream water flows, erosion, sedimentation, evapotranspiration and crop yields. To obtain insight in the variability of the impact of each management practice, the analysis was focused on the driest year (2005) with 523 mm of rainfall, the wettest year (2006) having 1078 mm of rainfall, and the annual average based on the entire simulated period (2000–2009).

Scenarios were run for the entire basin and for subsections that turned out to be particularly relevant. Thus, data are relevant for large scale policy decisions as well as for localised decision making on small farm scale. It is clear that the eventually actual implementation will never take place throughout the entire area, but by doing so the most relevant areas will emerge from the analysis.

3. Results and discussion

3.1. Basin-scale upstream and downstream impacts

In order to compare the relative impact of the three defined land management scenarios, a set of basin-scale indicators was introduced (i) soil loss or erosion, (ii) crop transpiration, (iii) soil evaporation, (iv) reservoir sediment inflow and (v) groundwater recharge (Table 1). To calculate these indicators, results of the simulations of all HRUs were averaged to obtain a basin-scale representative value. These five were selected in order to give insight both in the effects upstream, as well as downstream. Erosion and crop transpiration are typically of interest to the upstream farmers practicing rainfed agriculture, while sediment inflow into reservoirs and groundwater recharge may benefit downstream main water users. If reduction in soil evaporation will

Table 1
Five indicators expressing the basin-scale impact of the three scenarios for a dry and a wet year.

Indicator	Unit		Baseline		Contour strips		Mulching		Tied ridges	
		Average	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Soil loss	ton/ha/y	6.6	2.1	10.0	1.1	6.1	1.8	8.7	1.4	7.9
Crop transpiration	mm/y	381	382	360	383	360	387	363	383	361
Soil evaporation	mm/y	143	145	146	145	146	137	138	145	146
Reservoir[a] sediment inflow	Mton/y	2.0	0.9	4.1	0.6	2.6	0.8	3.8	0.8	3.7
Groundwater recharge	mm/y	147	57	229	69	260	59	232	73	267

[a] Reservoir = Masinga dam.

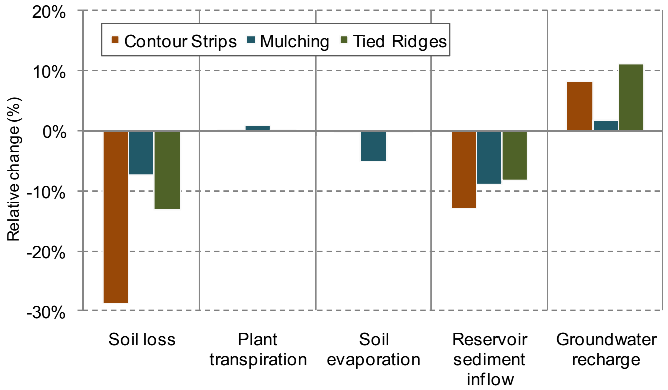

Fig. 4. Relative changes of the five key indicators for the three scenarios compared to the baseline situation, based on yearly averages. Some changes are (near to) zero.

be achieved, both upstream and downstream stakeholders may benefit, as the additional water available may potentially increase crop transpiration (and yield) or recharge groundwater (thus rivers and reservoirs).

The model results confirm that changes in erosion on the agricultural fields match with changes in reservoir sediment inflow. Fig. 4 shows the average changes to four of the key indicators, based on the annual means of the 10-year simulation period. Reductions in reservoir sediment inflow are all comparable (around −10%), while basin-scale reductions of soil loss are much more divergent among the three scenarios (between −7% and −29%). The main reason for this difference is that hydrological processes related to the different scenarios vary. The spatially distributed model routes the sediment to the basin outlet taking into account the spatial distribution of the erosion-prone surfaces and the corresponding changes in land management. Therefore, the location where the changes take place affect the processes in the channels controlling its sediment transport capacity (deposition and entrainment), something SWAT accounts for by using methods described in Arnold et al. (1995).

Surface runoff in farm land is decreased by the SWC measures analyzed in the scenarios and infiltration into the soil is enhanced. Part of this soil water percolates to the groundwater, which is a process enhanced by two of the scenarios by around 10%. The increase in infiltration and soil water availability led to minor changes in plant transpiration compared to the baseline scenario. Generally, the areas where the scenarios were assessed receive relatively high amounts of rainfall, so the effects were most clear for a dry year. The small short-term benefit of these practices for farmers may explain their unwillingness to change their practices, and highlights the importance of an integrated approach like GWC. Soil evaporation is diminished on average by about 5% when mulching is applied, which is water gained for other purposes. The other scenarios showed no significant impact on soil evaporation or transpiration, meaning that reduced surface runoff in those cases was a groundwater gain.

3.2. Spatial differences

The impacts of the scenarios were modelled on HRU level, and used to generate a map based on the HRU distribution. Fig. 5 shows the maps of two indicators: (i) the change in erosion and (ii) groundwater recharge for the contour strips scenario (expressed as % difference compared to the baseline scenario). The highest soil loss reductions are observed in the upstream cultivated areas where steep slopes are common. At these sites particularly, the scenario analysis indicates that application of vegetative contour strips may considerably reduce erosion and increase groundwater recharge. These areas are also wetter: they receive about twice as much rainfall as the lower areas of the study basin. This explains why the indicators are relatively sensitive to changes in the runoff dynamics of these areas. Enhanced groundwater recharge reduces peak flows and contributes to sustainable streamflow throughout the year, which makes it easier for downstream water users to regulate their reservoir capacities. How exactly the reservoir management can be optimized by the altered flows was not part of this assessment but should be studied separately.

Another advantage of the HRU approach is that the effectiveness of specific practices can be expressed spatially. Fig. 6 shows two

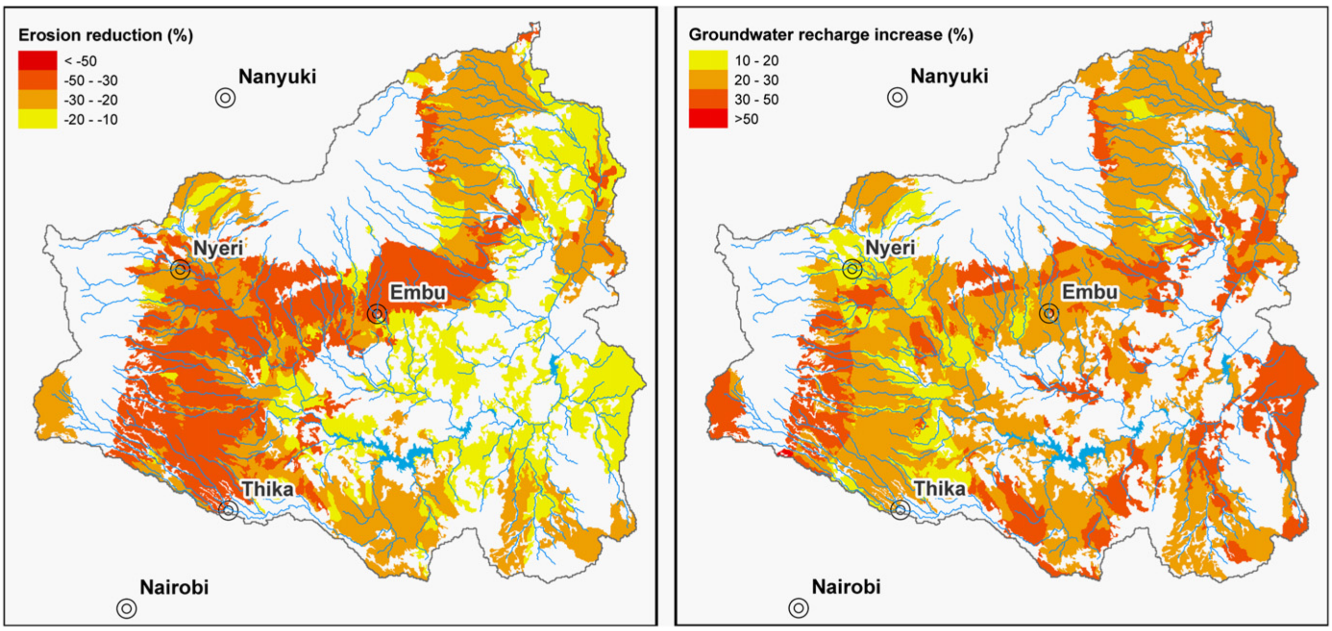

Fig. 5. Spatial distribution of relative erosion reduction (left) and the increase in groundwater recharge (right) for the vegetative contour strips scenario, based on yearly averages.

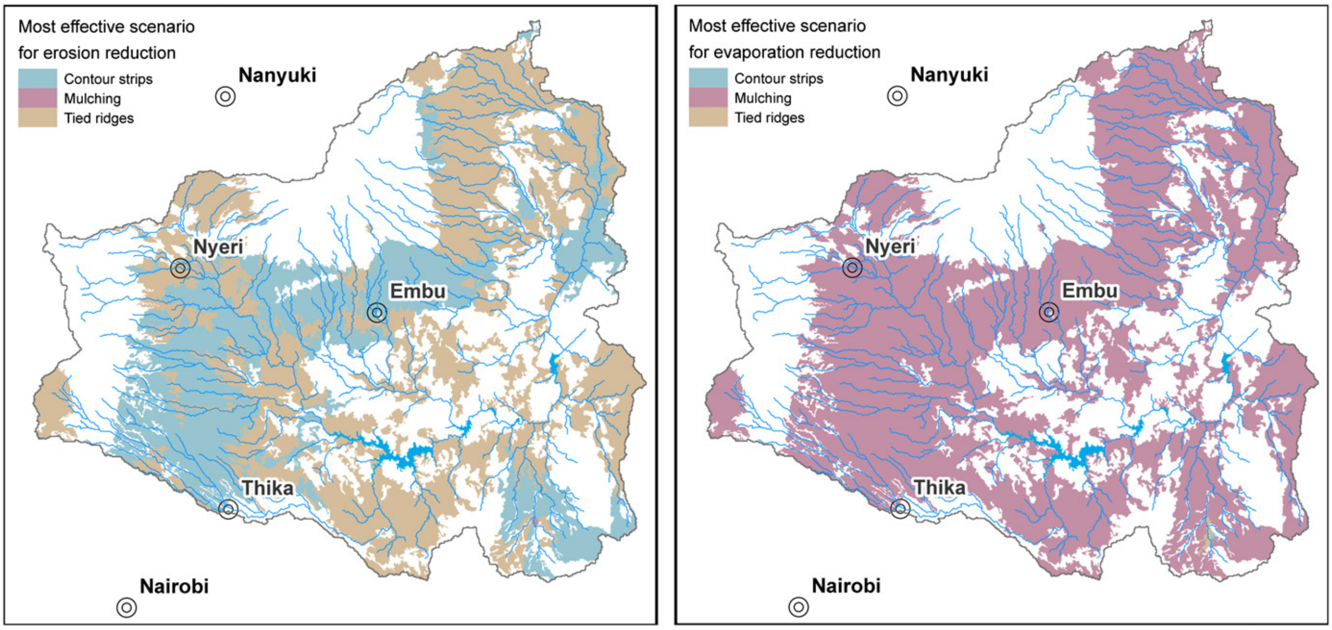

Fig. 6. Map showing which practice is most effective in reducing erosion (left) and soil evaporation (right).

maps indicating spatially which practice is most effective in reducing the erosion rate and which practice reduces soil evaporation most. Vegetative contour strips are most effective in the steep slope areas where mainly coffee is cultivated. Tied ridges were only incorporated in the maize areas where they are more effective than the other two scenarios. This can be attributed mainly to the significant runoff reductions that can be obtained by this practice.

4. Conclusions

A methodology, to be named GBAT (Green water and Blue water Assessment Toolkit) using the simulation model SWAT and data from various databases, was developed to quantify the upstream and downstream effects of soil and water conservation practices on soil loss, crop transpiration, soil evaporation, sediment and water inflow in reservoirs, and groundwater recharge. SWAT, a spatially distributed hydrological model, also allowed expression of spatial heterogeneity of the effects of the various practices, allowing identification of areas where soil and water management measures could be most effective.

By analyzing dry, wet and average conditions a range of effects could be determined as a function of variable weather conditions. The SWAT model simulated streamflow in the catchment well compared to observed data and it was therefore assumed suitable for the scenario analysis to support in an explorative way policy making in the context of Green Water Credits. We compared relative differences among alternative land management scenarios against a baseline scenario. Comparative assessments of the effects of vegetative contour strips, mulching, and tied ridges were made for up- and downstream land and water users by using five indicators related to soil loss and the water balance. Although the effectiveness of these practices differs spatially depending on land use, soil and slope, the results of the simulations indicated that the most effective practice to a) reduce reservoir sediment inflow is the implementation of contour strips, b) to increase *green water* available for plant growth is mulching and c) to increase groundwater recharge is tied ridges.

The GBAT methodology can be used to quantitatively illustrate potential benefits for both upstream agriculturalists and downstream water users when specific soil and water conservation measures are introduced. This is an effective way to convince farmers and citizens to apply the much needed improved land and water management at a large scale. The distributed approach, as used by SWAT, allows for a spatial analysis as to where, under which conditions, and to what extent a certain practice contributes to the basin-scale impact. This facilitates improved land-use management advice at local scale, and enables the identification of key areas for further GWC studies. If, for example, the impact on overall basin hydrology by a given site is high, more attention can be given to the specific requirements of that particular site when involving local farmers. Also for a socio-economic and cost-benefit analysis these data are necessary to compare various optional scenarios which are of crucial importance for an operational GWC system.

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