Green Water Credits for the Upper Tana Basin, Kenya. Phase II – Pilot Operations

Biophysical assessment using SWAT
Addendum

June 2010

Author

J.E. Hunink

P. Droogers

Client

ISRIC

FutureWater

Costerweg 1G

6702 AA Wageningen

The Netherlands

+31 (0)317 460050

info@futurewater.nl

www.futurewater.nl

Summary

This publication is an addendum to the full report that came out in September 2009 called *Biophyiscal Assessment using SWAT for Green Water Credits in the Upper Tana Basin, Kenya*[1]. The addendum was necessary as new information came available during the latest months on land use and soils within the Upper Tana basin. Therefore, it was decided to re-design the model with this information and update the principal outcomes of the assessment, in order to have the most accurate information available for following actions.

[1] Hunink, J.E., W.W. Immerzeel, P. Droogers, 2009. Green Water Credits for the Upper Tana Basin, Kenya. Phase II - Pilot Operations: Biophysical assessment using SWAT. Report FutureWater: 84

Table of contents

1	**Model revision**	**5**
1.1	Introduction	5
1.2	Land use	5
1.3	Soil	6
1.4	Hydrological response units	9
2	**Scenario analysis**	**10**
2.1	Key indicators	10
2.2	Crop-based evaluation	12
2.3	Temporal analysis	13
2.4	Potential target area identification	15
3	**Conclusions**	**18**

Tables

Table 1. Conversion table from FAO drainage classes to soil hydrologic groups (USDA) 7
Table 2. Values of the key indicators for the baseline situation and the 3 scenarios 10
Table 3. Absolute and relative changes (green = increase, red = reduction) of the key indicators for the 3 scenarios compared to the baseline situation 11

Figures

Figure 1. The new land use map (ISRIC, 2009) 6
Figure 2. Dominant FAO90 soil unit for each SOTER unit 7
Figure 3. Bulk density for the first 20 cm of each soil unit 8
Figure 4. Available water capacity of each soil unit 9
Figure 5. Updated HRU distribution within the area 9
Figure 6: Relative changes of three key indicators for the 3 scenarios compared to the baseline situation 12
Figure 7. Absolute changes of the crop water balances for the 'vegetative contour strips' scenario compared to the baseline scenario 12
Figure 8. Absolute changes of the crop water balances for the 'mulching' scenario compared to the baseline scenario 13
Figure 9. Absolute changes of the crop water balances for the 'tied ridges' scenario compared to the baseline scenario 13
Figure 10. Water yield and groundwater discharge for the baseline and contour strips scenarios 14
Figure 11. Precipitation compared to the change in reservoir (Masinga) inflow between baseline and contour strips scenario. 15
Figure 12: Spatial distribution of absolute changes that can be obtained of the four selected parameters for target area identification: erosion reduction (a), groundwater recharge (b), crop transpiration (c) and soil evaporation (d). 16
Figure 13: Spatial distribution of potential target areas. 17

1 Model revision

1.1 Introduction

The additional information that came available recently on land use and soil distribution in the Upper Tana required an update of the model and its results, especially for the identification of the target areas. This update was done in close collaboration with local staff of the Water Resources Management Authority (WRMA) from Kenya in order to incorporate their knowledge and understanding on the input data and contrast it with the outcomes. This collaboration included a 2-week stay of the staff in the Netherlands.

The updated datasets that have been included in the new model are:

1. Land use map based on field work and remote sensing techniques carried out by ISRIC (2009)
2. Soil map and property estimates derived from SOTER and WISE databases (ISRIC) and taxotransfer procedure (2009-2010).

These updated datasets required a new definition of the calculation units of the model SWAT: the hydrological response units (HRUs), as they are unique combination of land use, soil and slope. In the following sections each of these datasets and the HRU definition procedure are described shortly.

1.2 Land use

The land use map used for the updated model is the result of fieldwork and satellite image classification performed by ISRIC staff in 2009. To produce the final land use map of the Tana, the technique Support Vector Machine (SVM) classification was used with Landsat images of 2000 (Figure 1). No multi-temporal analysis was performed.

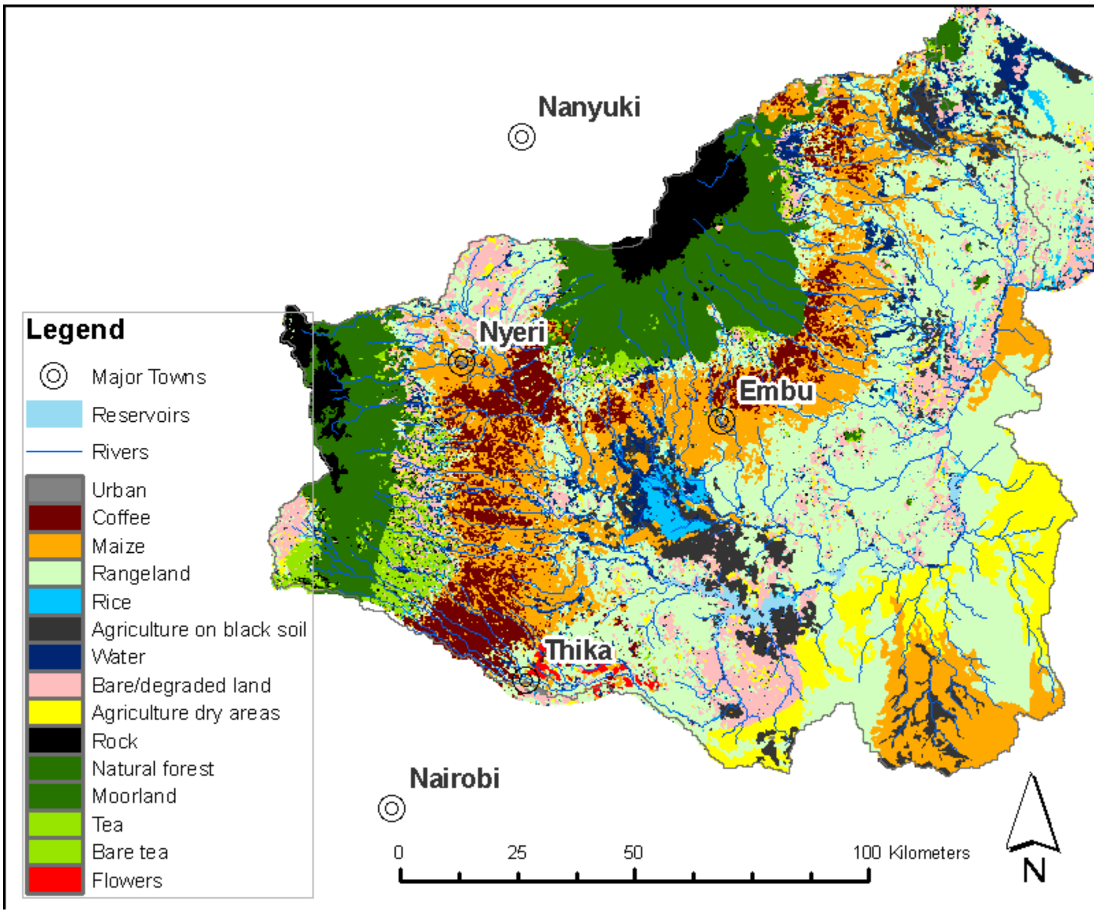


Figure 1. The new land use map (ISRIC, 2009)

For the areas at the south of Tana river which are not part of the Green Water Credits focal areas but form part of the Tana basin, information of the Africover dataset was merged with the updated dataset to guarantee complete land use coverage for the model.

The WRMA-staff had a close look on the land use map and corrected a few polygons which were misclassified. The following changes have been carried out:

1. Changed class “Bare tea” to “Tea”.
2. Replaced class “Flowers” to “Pineapples”.
3. Changed the “Maize” polygons in the southern part of the map and near Chiokariga to Rangelands.
4. Removed “Rice” from other areas apart from the Mwea irrigation scheme.
5. Removed erroneous polygons “Water” and changed to rangeland.
6. Corrected Urban centers and placed correctly.

After having carried out these changes, the resulting land use map was resampled to 250m to use as input for the HRU definition procedure.

1.3 Soil

In the framework of Green Water Credits, a new soil map and derived soil properties were prepared for the Upper Tana, Kenya, for application in exploratory studies. It draws on two databases developed at ISRIC. First, the Soil and Terrain (SOTER) database for the Upper

Tana, Kenya, at scale 1:250 000. Being dependent on historic data with gaps in the measured analytical data, ISRIC used a methodology for filling common gaps in primary SOTER databases to produce secondary (SOTWIS) data sets for general-purpose applications. This taxotransfer rule-based procedure draws heavily on soil analytical data held in the ISRIC-WISE soil profile database.

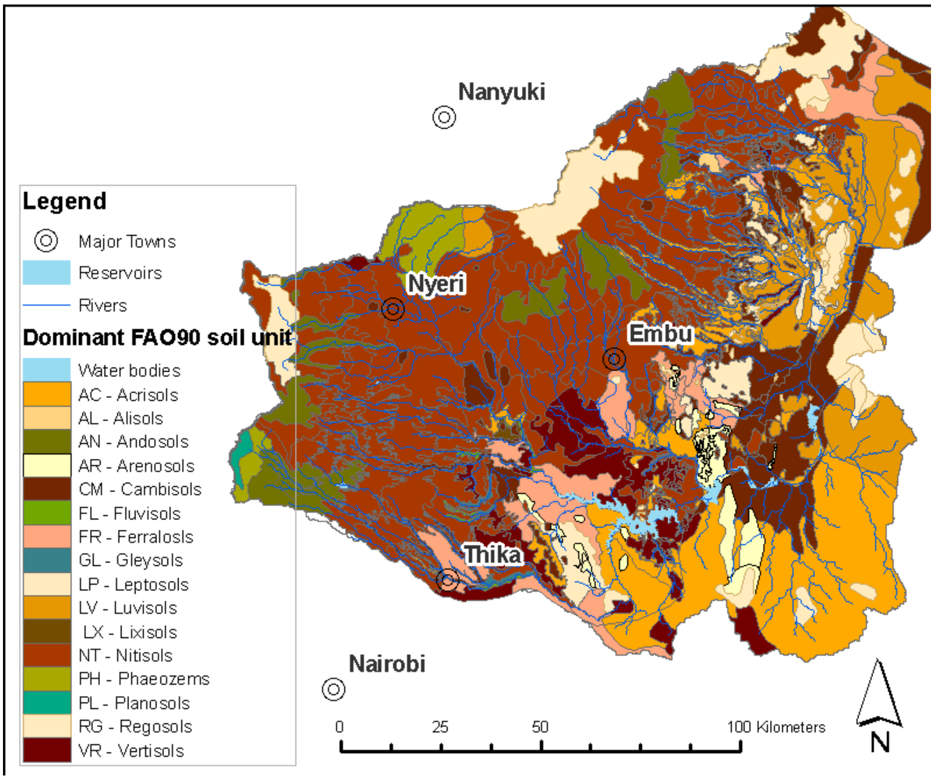


Figure 2. Dominant FAO90 soil unit for each SOTER unit.

The same methodology was used as described in the full report using taxotransfer functions to derive values for all the soil layers on saturated hydraulic conductivity. Besides, for the model SWAT it is necessary to use the soil hydrologic group classification as defined by the USDA Natural Resources Conservation Service for use of the Curve Number method to determine the amount of runoff of a certain area, depending on the soil type and land use. However, the soils in the original SOTER database were classified according to the FAO drainage classification. Table 1 shows the conversion table to transfer the FAO drainage classes in the original dataset to USDA soil hydrologic groups.

Table 1. Conversion table from FAO drainage classes to soil hydrologic groups (USDA)

FAO drainage class	Description	Soil hydrologic group (USDA)
E	Excessively well drained	A
I	Imperfectly drained	C
M	Moderately well drained	B
P	Poorly drained	D
S	Somewhat excessively well drained	A
V	Very poorly drained	D
W	Well drained	A

For each layer of each SOTER soil unit, the following properties were incorporated into the model for each soil layer (maximum of 5 layers, each 20 cm):

a) Moist bulk density
b) Available water capacity
c) Saturated hydraulic conductivity
d) Organic carbon content
e) Clay content
f) Silt content
g) Sand content
h) USLE K factor
i) Soil hydrologic group

Figure 3 and Figure 4 show respectively the bulk density and the available water capacity of the first 20 cm of each soil unit. Both variables determine to a high level the storage dynamics of the soil profiles. As can be seen, the spatial variability is high for both variables, especially between the higher slopes of the Mount Kenya and the Aberdares compared to the lower, dryer regions.

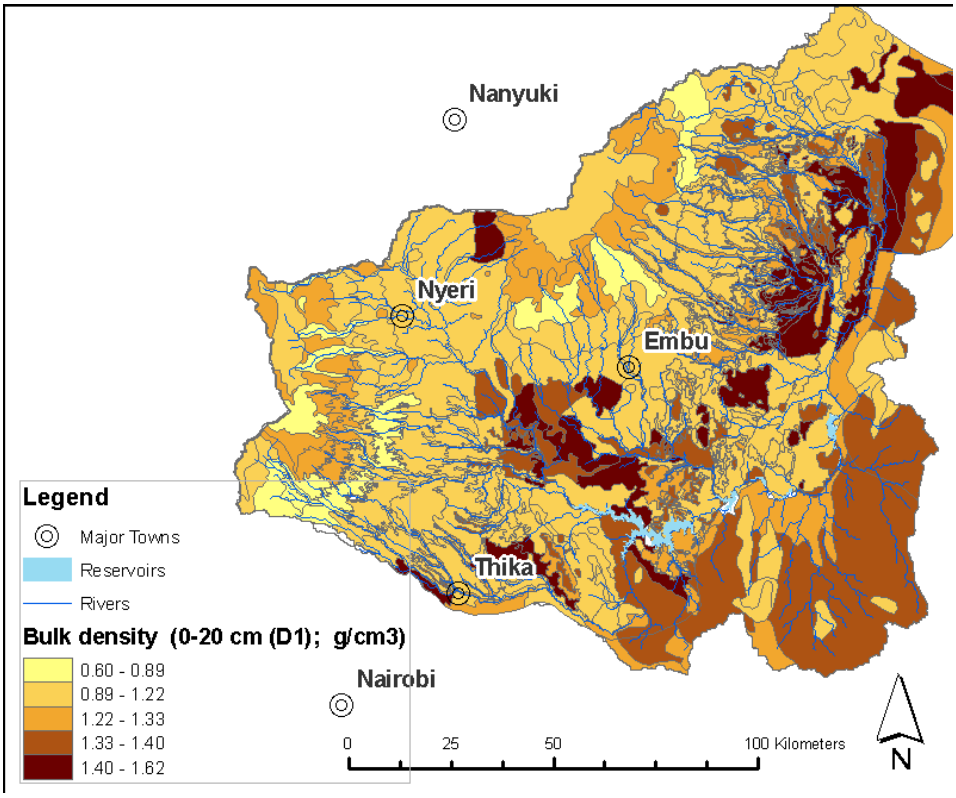


Figure 3. Bulk density for the first 20 cm of each soil unit

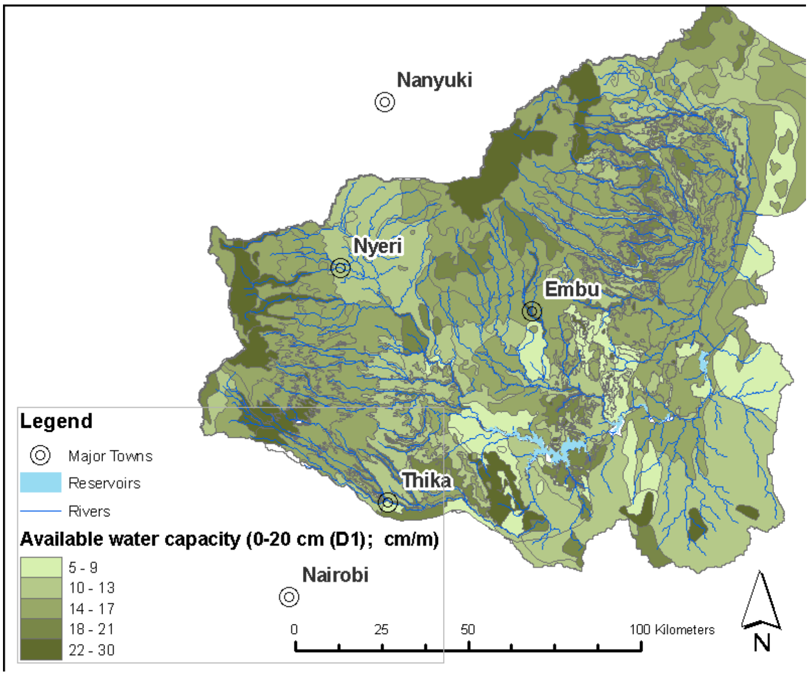


Figure 4. Available water capacity of each soil unit

1.4 Hydrological response units

The new information on land use and soil required the definition of new calculation units used by SWAT. These calculation units are unique combinations of land use, soil and slope, called Hydrological Response Units. Due to computer constraints, it was necessary to reduce the resolution of the soil and land use map to 250 meters. The calculation units that occupied less then 10% of each subbasin were skipped out by the model building procedure. This resulted in a total of 1582 HRUs within 564 subbasins (on average 3 HRUs per subbasin).

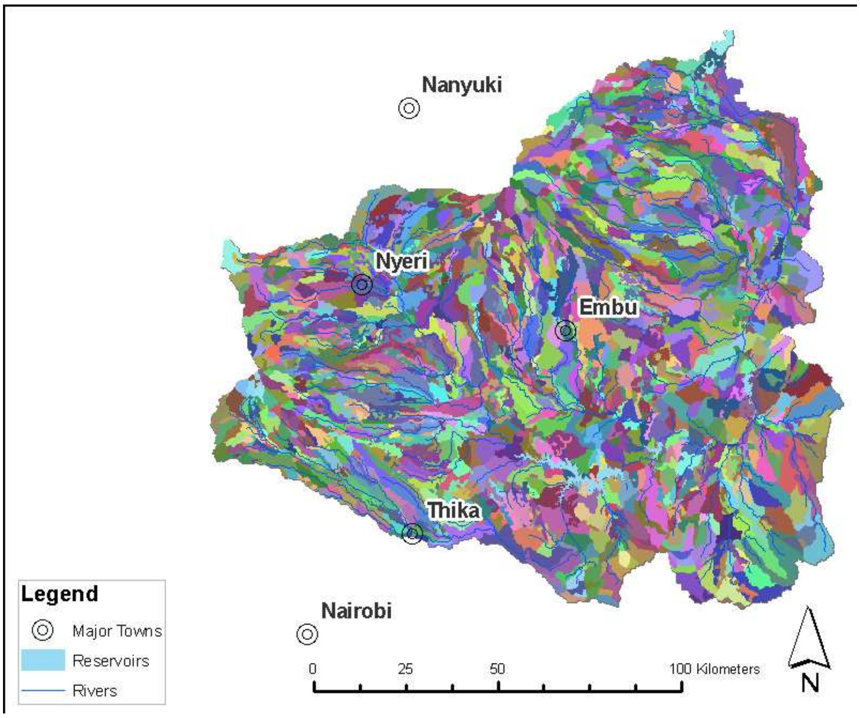


Figure 5. Updated HRU distribution within the area

2 Scenario analysis

The three GWC management practices as discussed in the full report have been implemented in SWAT, using the same parameters changes. Instead of analyzing the outcomes separately of a dry and a wet year, as was done in the full report, it was decided to do the analysis on 10-year averages. The following sections discuss the results of the (1) key indicators, (2) crop-based, (3) temporal analysis and (4) the target area identification.

2.1 Key indicators

In order to compare the three different soil and water management scenarios a set of indicators were introduced as described in the full report. They show the impact of each of the basin wide implemented practices. Table 2 lists the obtained values for these indicators as obtained with the updated model for the baseline situation and the 3 management scenarios. Numbers reflect averages over the entire Upper Tana and over a 10-year period (2000-2009).

The balance component ‘Outflow’ corresponds to the yearly total outflow at the proposed Low Grand Falls dam, the study basin outlet. The ‘Storage Change’ state variable refers to the amount of water that flowed into (negative values) or out of (positive values) the basin storage compartments (aquifers, soil storage and reservoirs).

Table 2. Values of the key indicators for the baseline situation and the 3 scenarios

Key indicators	Baseline	Contour Strips	Mulching	Tied Ridges
Inflow Masinga (MCM/y)	1,599	1,589	1,614	1,593
Sediments Inflow Masinga (10^3ton/y)	2,062	1,793	2,080	1,892
Outflow Low Grand Falls (MCM/y)	4,624	4,603	4,669	4,606
Crop Transpiration (mm/y)	364	364	367	364
Soil Evaporation (mm/y)	117	116	111	116
Groundwater Recharge (mm/y)	69	75	70	77
Sediment loss (ton/ha/y)	5	4	5	4
Basin Balance				
Precipitation (MCM/y)	13,048	13,048	13,048	13,048
Transpiration (MCM/y)	-6,328	-6,341	-6,377	-6,336
Evaporation (MCM/y)	-2,027	-2,026	-1,924	-2,026
Outflow (MCM/y)	-4,624	-4,603	-4,669	-4,606
Storage Change (MCM/y)	-69	-78	-78	-80

On average, inflows in Masinga reservoir are about 1500 MCM per year. The maximum storage capacity of the Masinga reservoir is of the same range, which means that on average the volume held in the reservoir is renewed every year. Sediment inflows into the Masinga reservoir are considerable. On average, yearly sediment inflow is more than 2 million tons of sediments. This corresponds to about 1% of the total dead storage volume of the reservoir.

Besides, the Upper Tana model calculated the total sediment inflow from 2000 until 2009 into this reservoir at about 20 million ton. This value corresponds to more than 10% of the original dead storage volume. It has to be noted that these values are quite conservative compared to others found in literature. This is because no calibration has been carried out on the sediment loads, as no data was available for this study.

The relative impact of the Green Water Credits management practices can be read from Table 2 that shows to which degree the key indicators changed for each of the scenarios compared to the baseline situation.

Table 3. Absolute and relative changes (green = increase, red = reduction) of the key indicators for the 3 scenarios compared to the baseline situation

Key indicators	Contour Strips		Mulching		Tied Ridges	
Inflow Masinga (MCM/y)	-10	-1%	15	1%	-6	0%
Sediments Inflow Masinga (10^3ton/y)	-269	-13%	18	1%	-170	-8%
Outflow Low Grand Falls (MCM/y)	-21	0%	45	1%	-18	0%
Crop Transpiration (mm/y)	1	0%	3	1%	0	0%
Soil Evaporation (mm/y)	0	0%	-6	-5%	0	0%
Groundwater Recharge (mm/y)	6	8%	1	2%	8	11%
Sediment loss (ton/ha/y)	-1	-29%	0	-7%	-1	-13%
Basin Balance						
Precipitation (MCM/y)	0	0%	0	0%	0	0%
Transpiration (MCM/y)	14	0%	49	1%	8	0%
Evaporation (MCM/y)	-1	0%	-103	-5%	-1	0%
Outflow (MCM/y)	-21	0%	45	1%	-18	0%
Storage Change (MCM/y)	-9	12%	-9	-13%	-11	16%

The following conclusions can be drawn from the previous table:

- Implementation of vegetative contour strips or tied ridges at a basin scale leads to a significant reduction of the sediment inflow into the reservoirs.
- Groundwater recharge will increase, stimulating a more continuous water supply through groundwater discharge.

- The mulching scenario causes a considerable reduction in the amount of water evaporated from the soil surface. This additional water available is redistributed to crop transpiration and blue water sources, as shown by the increase of the corresponding key indicators.

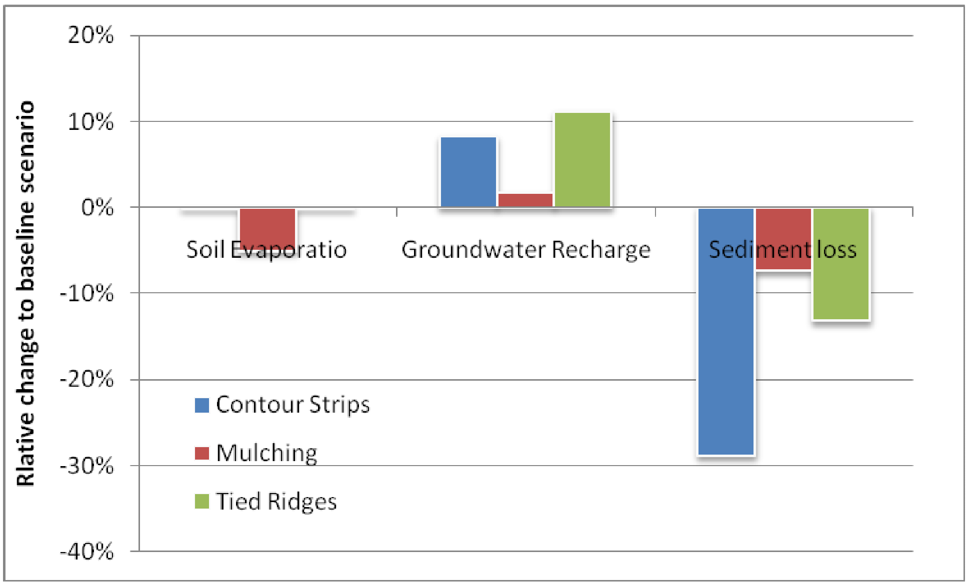
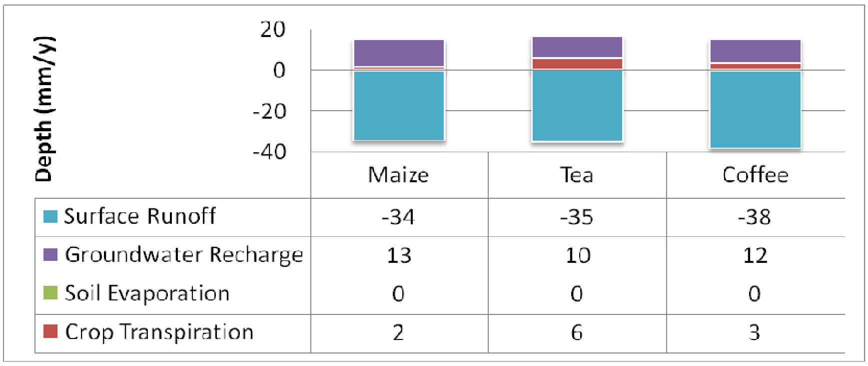


Figure 6: Relative changes of three key indicators for the 3 scenarios compared to the baseline situation

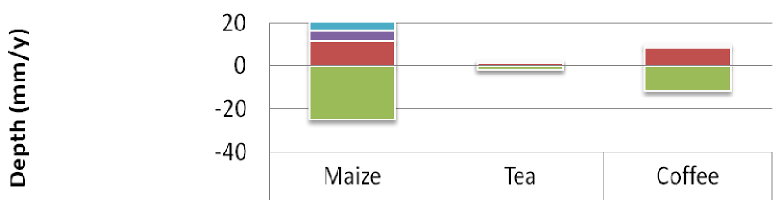
2.2 Crop-based evaluation

The crop water balances were compared with the baseline situation, and the absolute differences between the terms are represented in the following figures for each of the GWC management scenarios. All calculations have been done with yearly averages (2000-2009).



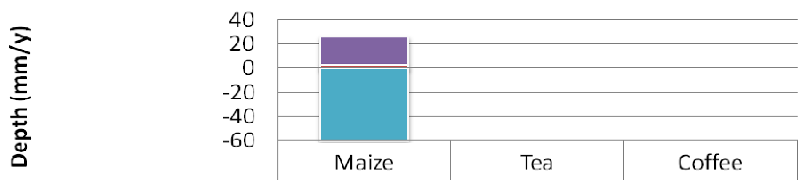
	Maize	Tea	Coffee
Surface Runoff	-34	-35	-38
Groundwater Recharge	13	10	12
Soil Evaporation	0	0	0
Crop Transpiration	2	6	3

Figure 7. Absolute changes of the crop water balances for the 'vegetative contour strips' scenario compared to the baseline scenario



	Maize	Tea	Coffee
Surface Runoff	5	0	1
Groundwater Recharge	4	0	1
Soil Evaporation	-25	-2	-12
Crop Transpiration	12	1	8

Figure 8. Absolute changes of the crop water balances for the 'mulching' scenario compared to the baseline scenario



	Maize	Tea	Coffee
Surface Runoff	-59	0	0
Groundwater Recharge	23	0	0
Soil Evaporation	0	0	0
Crop Transpiration	2	0	0

Figure 9. Absolute changes of the crop water balances for the 'tied ridges' scenario compared to the baseline scenario

A few comments on the previous figures:

- The use of vegetative contour strips causes a reduction in surface runoff (and erosion) and an increase of groundwater recharge. This additional water stored in the aquifer becomes then available for groundwater discharge during following drier periods.

- The implementation of the mulching practice principally leads to changes of the evapotranspiration water balance terms. Productive crop transpiration is increased and soil evaporation is significantly reduced.

- The implementation of 'tied ridges' was only applied to the maize and the generic agricultural land use class. Figure 9 shows a significant reduction in surface runoff and a similar increase in groundwater recharge. The evapotranspiration terms are not affected by this practice.

2.3 Temporal analysis

The potential impact of Green Water Credits options on the flow regime can be observed from having a close look on the temporal dynamics of the water yield from the HRUs and by analyzing the hydrograph at different points within the basin. Figure 10 shows the water yield from an HRU (Coffee) for the baseline scenario and the contour strips scenario. It becomes clear that the water yield for the baseline scenario has higher peak values then the yield for the contour strips, which shows a more attenuated regime. The reason for this is a higher infiltration into the soil storage and percolation to the aquifer due to the use of vegetative contour strips. This results at the same time in higher groundwater discharge a few days after the peak runoff. At that moment, the full water yield is coming from the groundwater discharge. For the contour strips scenario there is more streamflow in the river during days without rainfall compared to the baseline scenario.

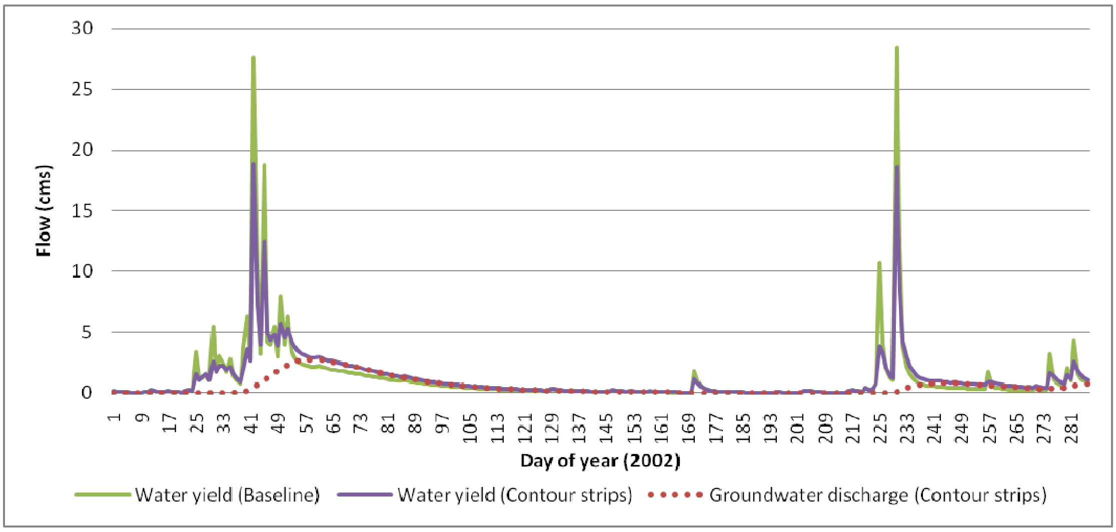


Figure 10. Water yield and groundwater discharge for the baseline and contour strips scenarios

Another way to represent this positive impact of the GWC options is by plotting the absolute change in streamflow entering a reservoir (Masinga) of the contour strips scenario compared to the baseline scenario. Figure 11 shows the monthly precipitation amounts on the left axis and on the right, plotted in red, the difference in streamflow between both scenarios. This graph shows that during a rainy month, less water enters the reservoir, while one or two months after, higher inflow can be expected into the reservoir. The difference in the drier months can reach to up to more than 10 m3/s. This means that about a million additional cubic meters of water a day enters into the reservoirs, which corresponds to three times the water demand of Nairobi city and to about half of the current irrigation demand in the surrounding irrigation districts. This stresses the importance of GWC options for regulating flows and assuring a more continuous flow regime.

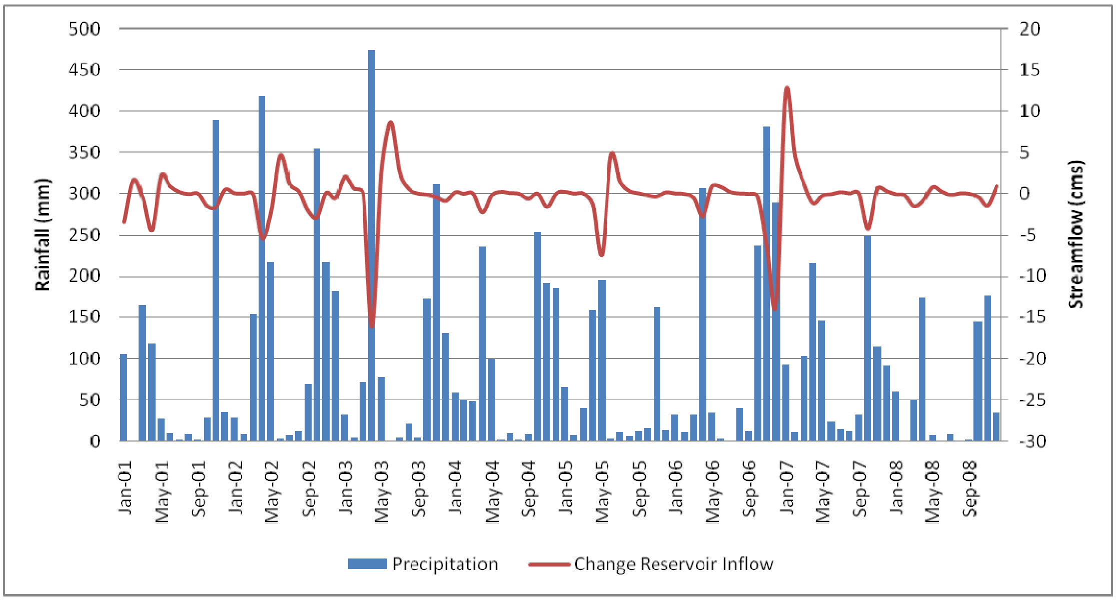


Figure 11. Precipitation compared to the change in reservoir (Masinga) inflow between baseline and contour strips scenario.

2.4 Potential target area identification

The scenario analysis is based on basin wide implementation of management practices on all agricultural lands. One of the objectives of the current design phase of Green Water Credits is to define the potential target areas where the practices are optimally implemented, from a biophysical point of view.

As in the full report, for the selection of target areas the following indicators were chosen to assess the overall impact of GWC options:

1. Reduction in soil erosion
2. Increase in groundwater recharge
3. Increase in crop transpiration
4. Reduction of soil evaporation

The absolute changes in these variables are shown in the following figures:

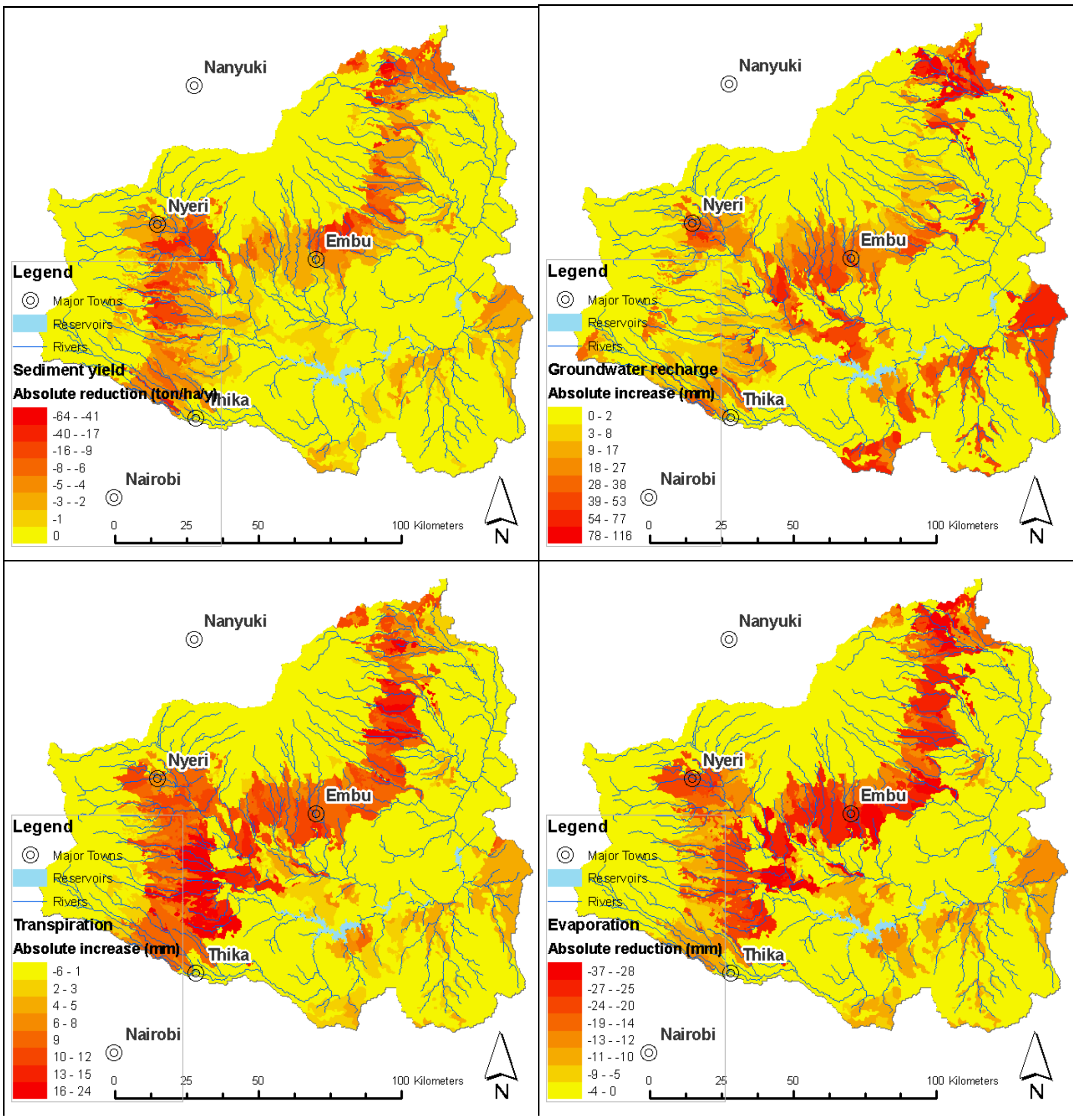


Figure 12: Spatial distribution of absolute changes that can be obtained of the four selected parameters for target area identification: erosion reduction (a), groundwater recharge (b), crop transpiration (c) and soil evaporation (d).

As was explained in the full report, the identification of target areas is a multi-criteria problem and requires an approach that integrates the 4 indicators to one single suitability index. In the full report, this index was based only on information of one single wet year (2006). In this case it was decided to use 10-year averages to calculate the biophysical suitability index (BSI), as defined in the following formula with the weights that correspond to each indicator:

$$BSI = \frac{0.5 \cdot SedYield + 0.25 \cdot GwRch + 0.125 \cdot T + 0.125 \cdot E}{(BSI)_{\max}}$$

As can be observed in the formula, the index is scaled from 0 to 1, by dividing the weighted sum by the maximum value $(BSI)_{max}$. This index was calculated for each of the HRUs, as shown in Figure 13. The highest values for the Suitability Index can be seen at the eastern slopes of Mount Kenya and the slopes of the Aberdares mountain range (particularly the southern part of the Sagana-subcatchment).

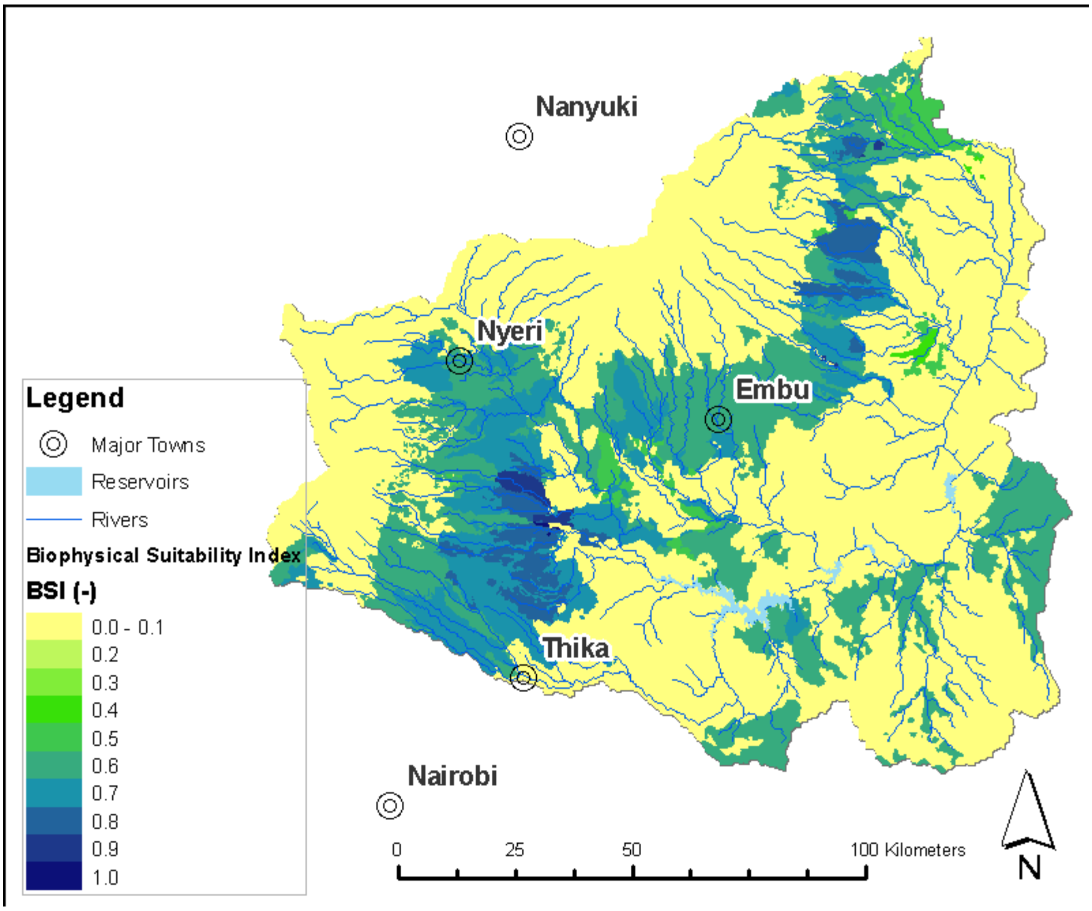


Figure 13: Spatial distribution of potential target areas.

3 Conclusions

The key indicators used to quantify the impact of the Green Water Credit management options show very similar results for the updated model compared to the former one used in the full report. This means that the same conclusions can be drawn on the potential of the management options to meet the Green Water Credit objectives. Most of all, the results confirm that the erosion rates and sediment inflow into the reservoirs form a serious threat to the water holding capacity of the reservoirs. Another considerable benefit for downstream stakeholders is the more continuous streamflow into the reservoirs during months with low rainfall. This is a result of more groundwater discharge upstream and less peak runoff which benefits also the upstream users (erosion, nutrients).

Important changes on the outcomes of the updated model can be observed when looking at the spatial distribution of the potential target areas. These changes are mainly due to the differences in the land use map, compared to the former map used (Africover). Besides, the updated soil properties also changed the outcomes on the impact of the Green Water Credits management options and thus the identification of potential target areas.

The identification of potential target areas for pilot operation was done using the model outcomes on the changes of four key indicators: soil erosion, groundwater recharge, crop transpiration and soil evaporation. For this addendum, it was decided to use 10-year averages instead of a single wet year for the assessment. Results of this biophysical suitability assessment will be the input of the following studies on the socio-economic and institutional issues in the areas. This will lead to the final selection of the pilot operation areas.