Green Water Credits

Green and blue water resources and assessment of soil and water management scenarios using an integrated modelling framework

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Green Water Credits Report 3

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Green Water Credits is a mechanism to pay rural people for specified land and soil management activities that determine all fresh water resources at source. These activities are presently unrecognized and un-rewarded. This proof-of-concept program is supported by the International Fund for Agricultural Development (IFAD) and the Swiss Agency for Development and Cooperation (SDC)

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MAIN POINTS

Green Water Credits tackle fresh water management at source - where the rain falls and land use and management determine its fate. There is a trade off between runoff that flows directly to streams and infiltration that may contribute to *green* water resources available to crops, groundwater recharge and stream base flow. Green water management will cut runoff and, so, mitigate floods, soil and bank erosion, and siltation of reservoirs; it will increase *green water* resources, groundwater recharge and stream base flow. All these flows have been quantitatively estimated to demonstrate the links between land use and management in the source areas and downstream water supply and water quality.

Data from the Upper Tana basin, Kenya, are used in hydrological and crop models to establish the spatial and temporal patterns of water resources and to investigate various green water management scenarios in terms of downstream delivery of water and sediment:

- Various hydrological and crop models were evaluated and the following chosen:
  - Soil and Water Assessment Tool (SWAT) to define the extent of the *water towers*, the sources of sediment entering the streams, stream flow, sediment delivery and groundwater recharge;
  - Water Evaluation and Planning Tool (WEAP) for water allocation, infrastructure, and economic evaluation;
  - World Food Studies (WOFOST) model to quantify crop growth and water balance at the field scale.

- Relief and drainage are derived from a 90m-horizontal resolution digital elevation model. The catchment has steep gradients from elevations above 3000m on Mt Kenya and the Aberdares to about 200m in the Middle Tana.

- Climatic data have been collated from first-category meteorological stations and the Climate Research Unit dataset for the period 1900–2003. For the proof of concept, the dry years 1987/1996 and wet years 1988/1997 are used as exemplars. Relief and climate, closely related with high rainfall and a soil water surplus at high elevations, and low rainfall and a soil water deficit at low elevations.

- AfriCover 2005 land use data (effective scale 1:100 000), soil data from the updated KENSOTER (effective scale 1:250 000), and river discharge data collated by the University of Nairobi are used to assess soil and water conservation status and erosion risk for major land uses: coffee, maize, sorghum-sunflower-cotton, and tea.

- Field data from the World Overview of Conservation Approaches and Technologies database (from within and beyond Kenya) are used in scenario analysis to evaluate three low-cost green water management practices: grassed contour strips, tied ridges, and mulch.

Depending on management, crop, rainfall and local soil and terrain, green water management will:

- **Abate sediment input** to the Masinga reservoir by 22-72 per cent (0.3-2.5 million tonne/year)
- **Increase groundwater recharge from cropland** by 4-57 per cent (16-160 mm per year), a potential annual gain of accessible water of 160-1600 m^3/ha
- **Cut damaging runoff** by 22-66 per cent
- **Reduce unproductive evaporation of water from the soil surface** by up to 15 per cent (50 mm/year), a water gain of 500 m^3/ha/year.

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Acronyms and abbreviations

AEZ	agro-ecological zone
CRU	Climatic Research Unit, University of East Anglia
DEM	digital elevation model
ESCO	soil evaporation compensation factor
FAO	Food and Agricultural Organization of the United Nations
GRDD	Global Runoff Discharge Data
HRU	hydrological response unit
JICA	Japan International Co-operation Agency
KARI	Kenya Agricultural Research Institute
KenGen	Kenya Electricity Generating Company
KENSOTER	Kenya Soil and Terrain database
MDGs	Millennium Development Goals
MUSLE	Modified Universal Soil Loss Equation
MW	megawatt
SOTER	Soil and Terrain digital database
SRTM	Shuttle Radar Topography Mission, NASA/US Geological Survey
SWAT	Soil and Water Assessment Tool
UoN	University of Nairobi
USLE	Universal Soil Loss Equation
WEAP	Water Evaluation and Planning Tool
WOCAT	World Overview of Conservation Approaches and Technologies
WOFOST	World Food Studies crop growth model
WRMA	Water Resources Management Authority

1 Introduction

Water is a basis of life and human wellbeing - directly as drinking water for people and livestock, for crop production, and industry; and indirectly as environmental flows maintain supporting ecosystems. Almost 1 000 million people live in absolute poverty, of whom 70 per cent rural people (United Nations 2000), the vast majority depending on smallholder rain-fed farming. Many of these suffer water scarcity now; scarcity will only increase with climate change; and there is urgent need for adaptive strategies to increase food and water security and alleviate poverty.

Water resource management and water policy has focused almost exclusively on management of accessible flows in rivers, lakes and groundwater – known as *blue water*. The management of the resource at source, where rain falls on the soil, has been ignored. *Green water* is water held in the soil and accessible to plants; attention is focused on water availability for agriculture, especially rain-fed farming. Soils are also responsible for the delivery of water to streams and groundwater.

Green Water Credits is a mechanism for transfer of payments from water users to land users in return for water management services – specified management activities that determine the supply of water downstream. These activities are presently unrecognized and unrewarded. Payment will enable better management - which means less damaging runoff, more beneficial infiltration, more groundwater recharge and more stream base flow. At the same time, Green Water Credits may diversify rural incomes, enabling communities to adapt to economic, social and environmental change through asset-building in the shape of stable soils, more reliable local water supply, improved crops and infrastructure. This proof-of-concept aims to demonstrate the viability and feasibility of Green Water Credits.

The Upper Tana Basin, in Kenya, was chosen following a comparative analysis of candidates (Droogers and others 2006). It has good rainfall and many farmers, so there is a big potential for improved downstream water supply; there are big water users who are in the position to pay for water management services - hydro-electric power, Nairobi city water supply, and irrigators; water scarcity is already an issue; current land use and management causes high runoff, soil erosion and evaporation - leading to less river base flow and high silt loads that are filling of reservoirs and damaging hydro-power turbines.

This report assesses the effects of green water management - soil management practices that increase infiltration of rainfall into the soil, in turn arresting damaging runoff and, also, cutting unproductive evaporation from the soil surface. Assessments are made at both the field scale and the basin scale. The results are used in scenario analysis of water allocation (Hoff and Noel 2007) and in social, economic and policy studies (Porras and others 2007), (Meijerink and others 2007).

2 Tana River basin

2.1 Overview

The Tana River basin extends from the crests of Mt. Kenya, the Aberdares Range and the Nyambene Hills to the Indian Ocean (Figure 1). Mt Kenya and the Aberdares are the water towers, each providing almost half of the water flow (WRMA 2006). This report focuses on the catchment upstream of Garissa, sometimes referred to as Upper and Middle Tana River but in this report referred to as the Upper Tana, encompassing 32 688 km^2.

Figure 1: Tana basin, location

Figure 2 shows the Upper Tana, which has been greatly changed over the last 50 years by five dams (Figure 3), which have regulated the river and provide hydro-power and have extended irrigation- at the expense of wetlands, and farmers downstream who previously practiced flood irrigation.

Potential buyers of water management services include:

- Hydro-power generators – Kenya Electricity Generating Company (KenGen)
- Municipal water utilities – Nairobi Water Company
- Irrigators – large and smallholder operators
- Re-insurers, seeking to reduce their risks from floods and landslides
- Agencies responsible for environmental services, and the tourism sector.

Issues include:

- River regulation and maintaining reservoir levels;
- Reducing the silt load delivered to reservoirs;
- Groundwater recharge;
- Water quality.

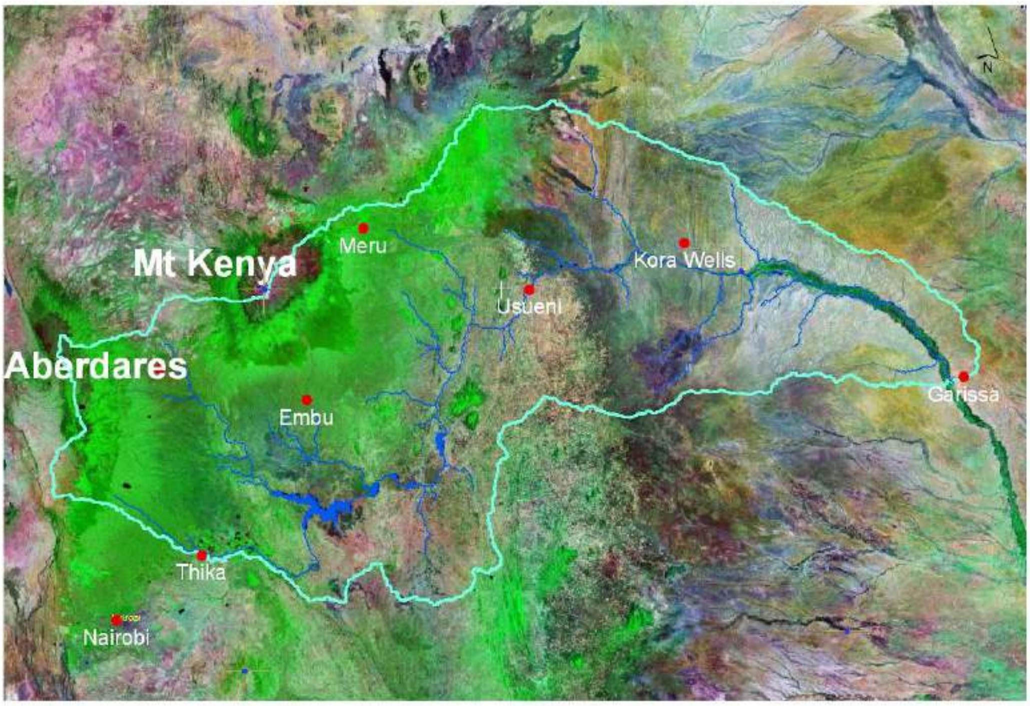


Figure 2: Upper Tana, Landsat image
True-colour image: well-vegetated, high-rainfall areas of Mt Kenya and the Aberdares Range appear green; catchment boundary overlaid in light blue, streams and reservoirs in blue

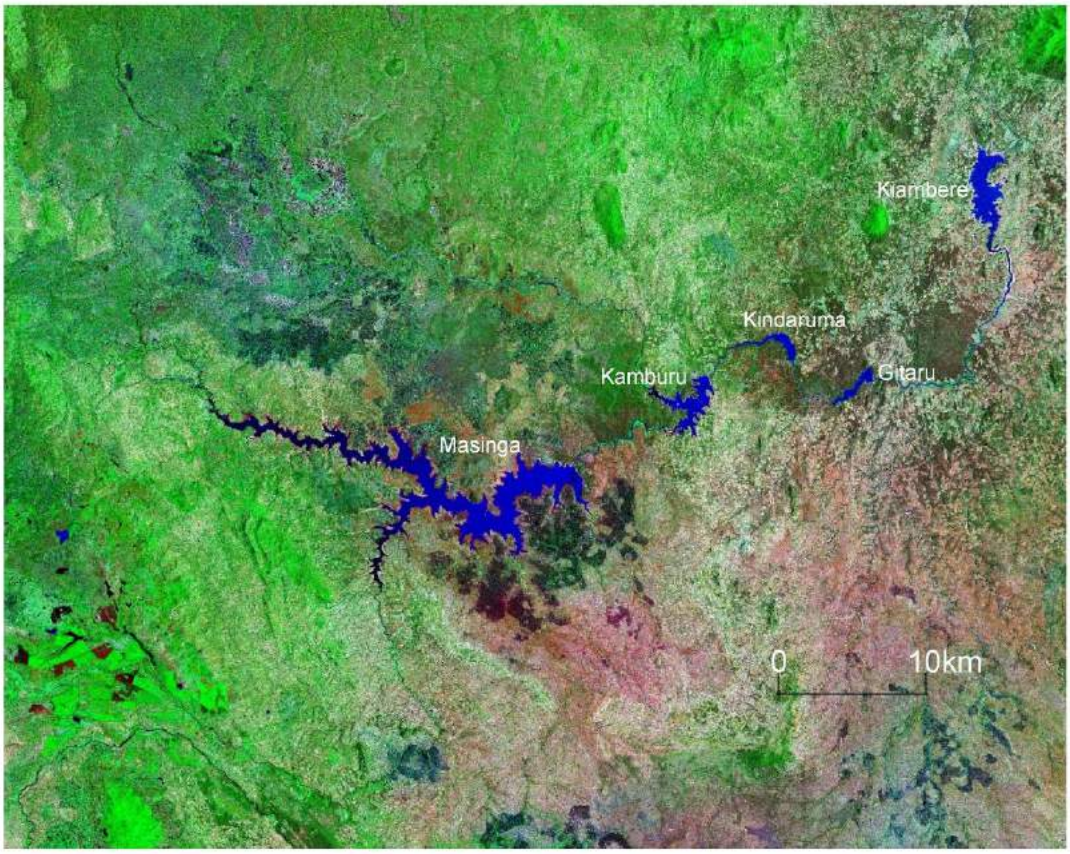


Figure 3: Catchment of Upper Tana reservoirs, Landsat image

The potential providers of water management services are mainly the farmers in the upper catchment, especially those in the immediate catchments of the reservoirs. The services may include measures to:

i. Minimize runoff, soil erosion and stream bank erosion;
ii. Maximize infiltration of rain water, leading to more groundwater recharge and an extended period of river base flow;
iii. Reduce unproductive evaporation from the soil surface, benefiting *green* water use by crops, stream flow and groundwater.

Two ministries, the Ministry of Agriculture and the Ministry of Water & Irrigation and their specialist agencies, are mandated to ensure effective and equitable use of land and water resources. The Ministry of Agriculture considers *green water management* a core concept, which it promotes through soil and water conservation approaches and techniques. The Ministry of Water and Irrigation espouses *integrated water management* which includes green water management and rational development of the resulting *blue water* flows. Both activities have been identified as necessary to the attainment of Millennium Development Goals 1 and 7 – to alleviate poverty and protect environmental services.

3 Biophysical Modelling

3.1 Methods and techniques

Models are used to simulate water flows under different scenarios. Annex 1 reviews available models for analysis of water relationships at the field and basin level. Based on this assessment, the Soil and Water Assessment Tool (SWAT) was chosen to evaluate the impact of crop-land-soil management on downstream water and sediment flows, and the World Food Studies (WOFOST) model was chosen for field-level analysis of the effects of crop and soil management. The field-level calculations are input to the basin model.

3.2 Field-level assessment

WOFOST (Boogaard and others 1998) calculates daily potential water-limited and nutrient-limited production and water balance according to weather, crop, soil, and management (including practices to enhance infiltration). The water balance is calculated from a daily account of in- and out-going water flows between the soil, crop and atmosphere: rainfall, transpiration, evaporation from the soil surface, runoff, water storage in the soil, and deep percolation (Figure 4 and Box 1). Rainfall either infiltrates or runs off. Water-limited yield of rain-fed crops is constrained by rainfall, runoff, and run-on. Infiltrated water that exceeds the storage capacity recharges groundwater; groundwater flow is included in the SWAT basin hydrology model (Section 3.3).

Six yield and water balance determining factors are assessed at field level: climate, soil available water content, rootable soil depth, crop, crop management, and green water management practices that determine runoff, infiltration and evaporation.

Data input and output

Climate: WOFOST requires 6 climatic parameters: radiation, temperature, relative humidity, run of wind, rainfall and number of rain days. In the case of monthly rainfall data, a rainfall generator facility mimics daily rainfall. Management scenarios were explored for each of the seven climatic zones in the Upper Tana, which were characterized by representative meteorological stations.

Crop: WOFOST uses well-tested crop files for widely cultivated crops. For this study, maize was used, being the staple crop in the Upper Tana.

Soil: WOFOST calculates a water balance with a minimum of soil data, as available in the KENSOTER database. Soil water storage capacity is controlled by soil thickness: soil water holding capacity - requiring soil water content at saturation

(-0.1 kPa), field capacity (taken as -20 kPa), and permanent wilting point (-1500 kPa); and rootable depth. Free drainage is assumed and the saturated hydraulic conductivity/percolation rate set at 10 cm/day.

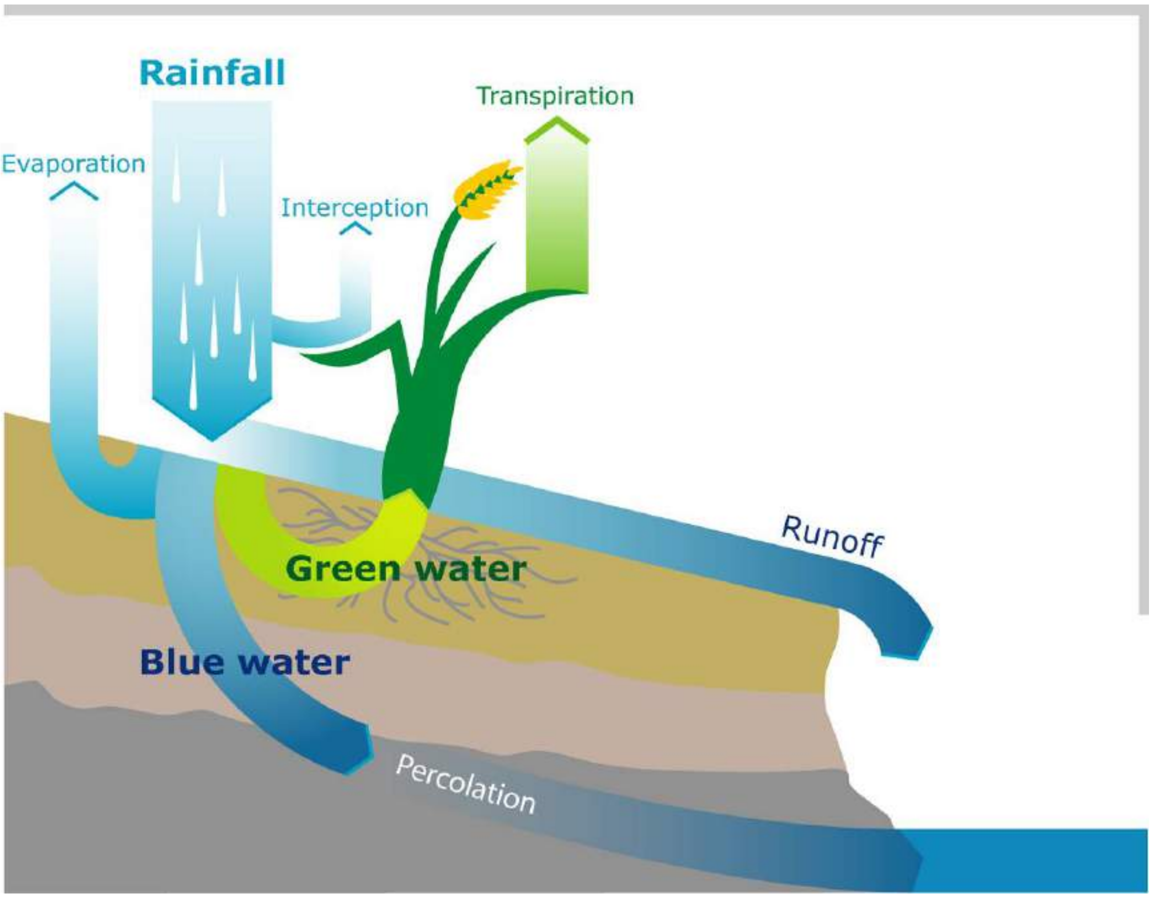


Figure 4: Partitioning of rain water

Box 1: Water balance

$$P = R + T + E + D + \Delta W$$
$$I = P - R$$

P = precipitation
R = runoff
T = transpiration
E = evaporation from the soil surface
D = deep percolation
ΔW = difference in water stored in the soil at the beginning and at the end of the growing period
I = water infiltrating into the soil

WOFOST generates point-based tabular data. Maps were created automatically using the Continuous Growth Monitoring system (van Ittersum and others 2003).

3.3 Basin-level assessment

SWAT divides a basin into smaller, discrete calculation units: sub-catchments or hydrological response units (HRUs) for which the physical properties are defined and hydrological processes can be treated as homogeneous. The water balance for each HRU is computed in daily time steps. The total basin behaviour is a net result of many HRUs.

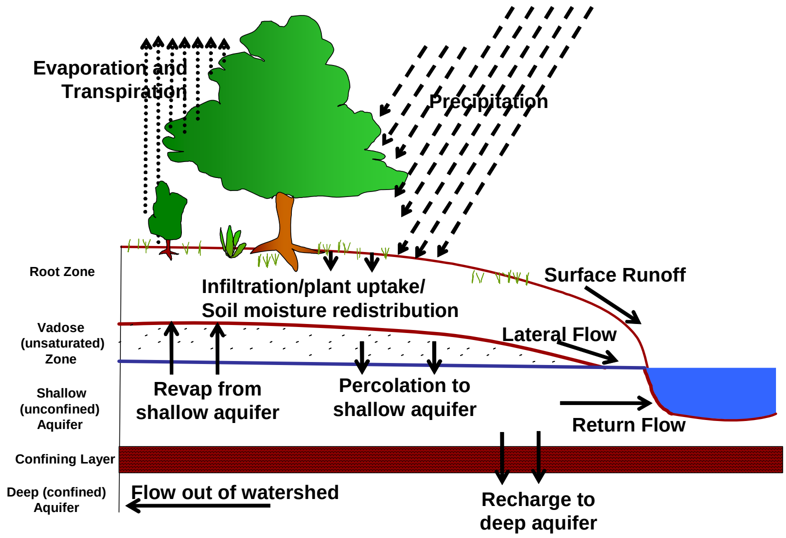


Figure 5: Main land-phase processes simulated within SWAT

SWAT simulates groundwater processes (Figure 5): water recharges of groundwater by infiltration/percolation and by seepage from surface water bodies; it leaves groundwater storage by discharge into rivers and lakes, by upward flux into the soil, and by abstraction – e.g. for irrigation. The model distinguishes recharge and discharge zones. Unconfined aquifers are recharged through deep percolation; recharge of confined aquifers occurs only at the upstream end of the aquifer, where it is exposed at the surface. Irrigation and linking canals may be connected to the groundwater system and either draw upon or recharge the groundwater.

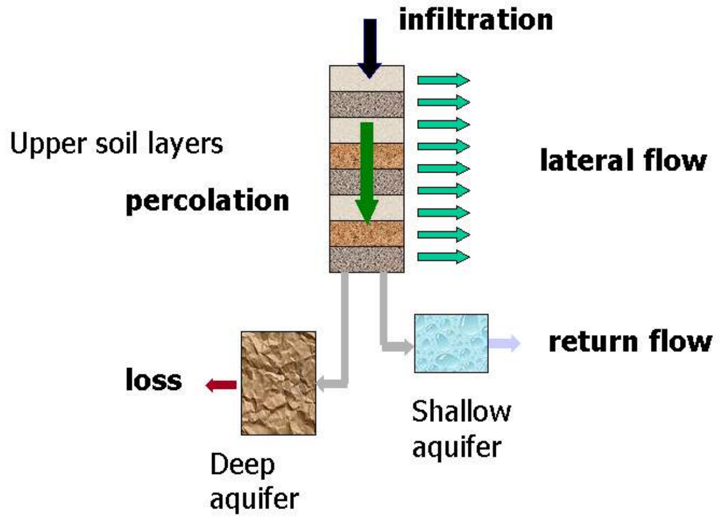


Figure 6: Sub-surface water fluxes simulated in SWAT

After water infiltrates into the soil, it may move as lateral flow from the soil layer, which mimics a 2-D flow domain in the unsaturated zone, or as return flow seeping from the shallow aquifer into streams. Surplus soil water recharges the deep aquifer. The total return flow thus consists of surface runoff, lateral outflow from the root zone and aquifer drainage to streams (Figure 6).

The plant growth component of SWAT is based on the EPIC plant growth model (Williams 1995). Growth depends on accumulated heat units; potential biomass production on intercepted energy, estimated as a function of solar radiation and leaf-area index - also simulated according to heat units. The daily potential increase in biomass is estimated as the product of this intercepted energy and a crop function converting energy to biomass. Yield is calculated based on plant-specific harvest indices. Plant growth is constrained by temperature, water, nitrogen or phosphorus stress (Figure 7).

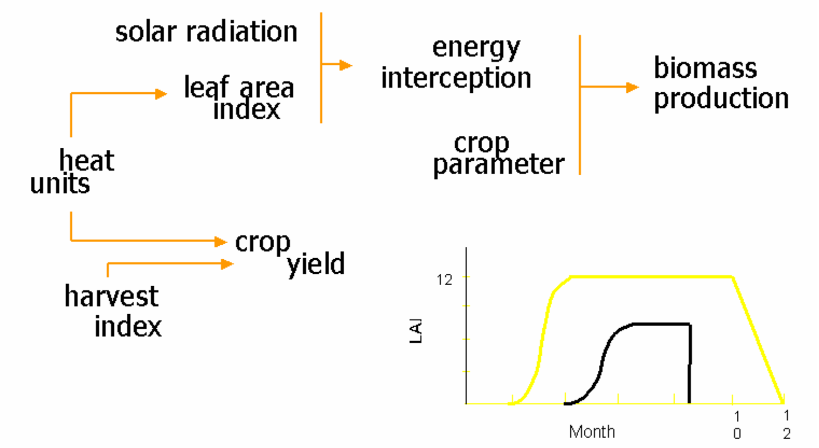


Figure 7: Parameterization of crop production

4 Baseline information

4.1 Landform and river network

4.1.1 Relief

Digital elevation data at 90m resolution from the Shuttle Radar Data Topography Mission (SRTM) 2000, obtained from the CGIAR Consortium for Spatial Information (USGS 2003), were used to generate elevation and slope gradient maps following SOTER procedures (van Engelen and Huting 2004)(Figure 8).

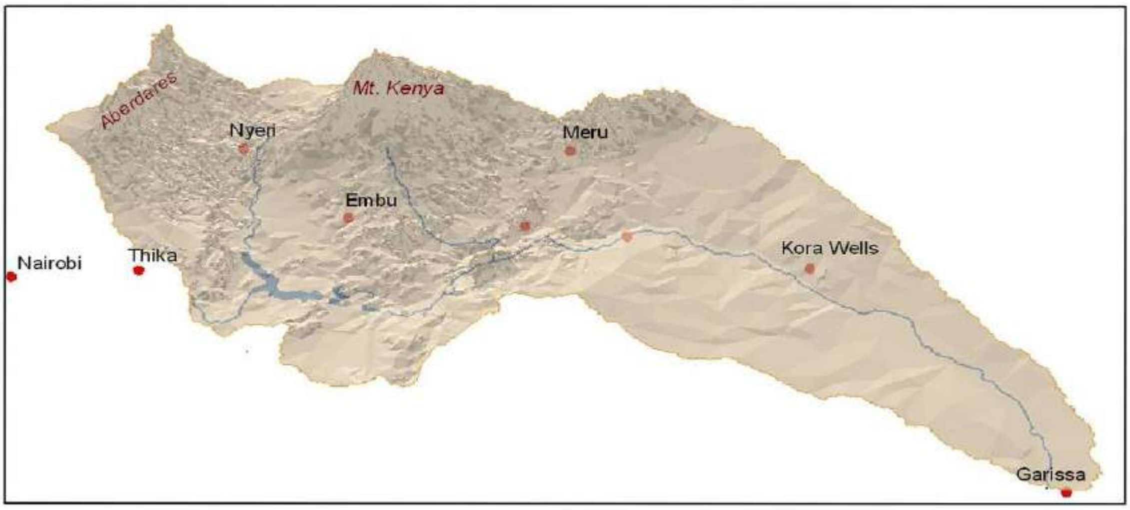


Figure 8: Upper Tana, relief

There is a steep gradient from the eastern slopes of the Aberdares Range and the southern slopes of Mt Kenya, at elevations above 3000m, to Garissa on the Tana River at about 200m (Figure 9). The slope gradient map (Figure 10) shows a parallel structure of steeply incised valleys of the mid- and foot slopes of the highlands. Use of these steep lands for agriculture has led to severe soil erosion, contributing to the big sediment load of the Upper Tana and its tributaries.

4.1.2 Digital Elevation Model for SWAT

For the proof of concept, the 90m-resolution DEM data were re-sampled to a spatial resolution of 250m (Figure 11) to delineate the catchment boundary and stream network (Figure 12) and create sub-basins of appropriate size for treatment in SWAT (Figure 13); details are given in Annex 2. A threshold area of 25 000 ha was selected. As outlet point, Garissa was chosen, giving a total catchment area of 32 741 km^2 and a total of 82 sub-basins, subsequently divided into smaller Hydrological Response Units (HRUs) upon overlay of land use and soil maps.

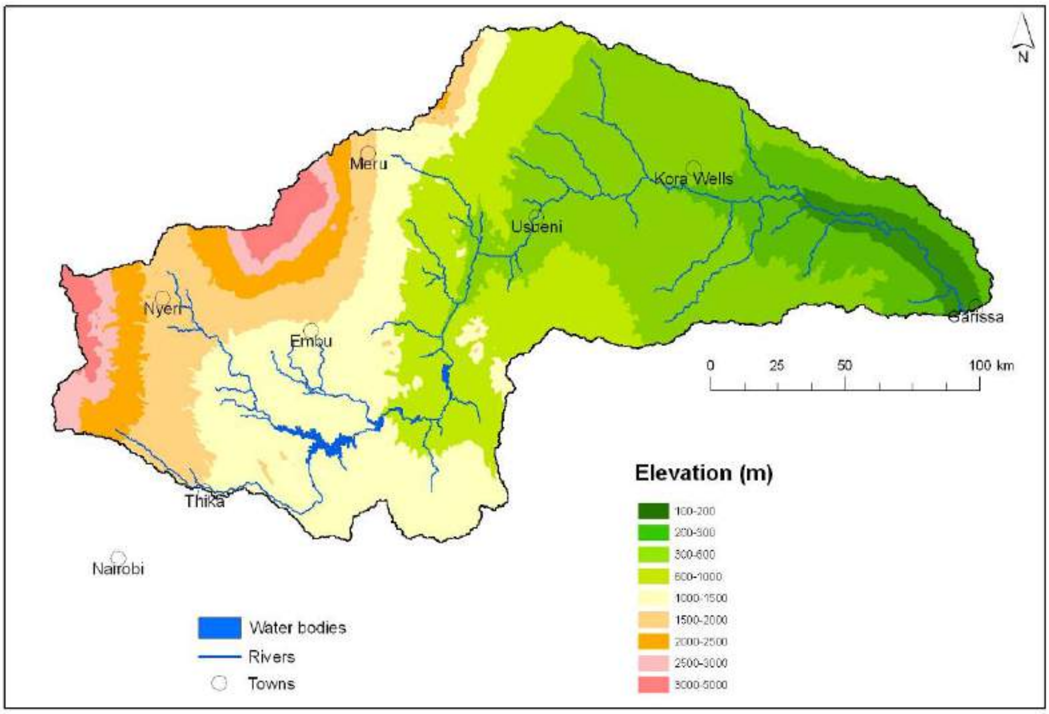


Figure 9: Upper Tana, elevation

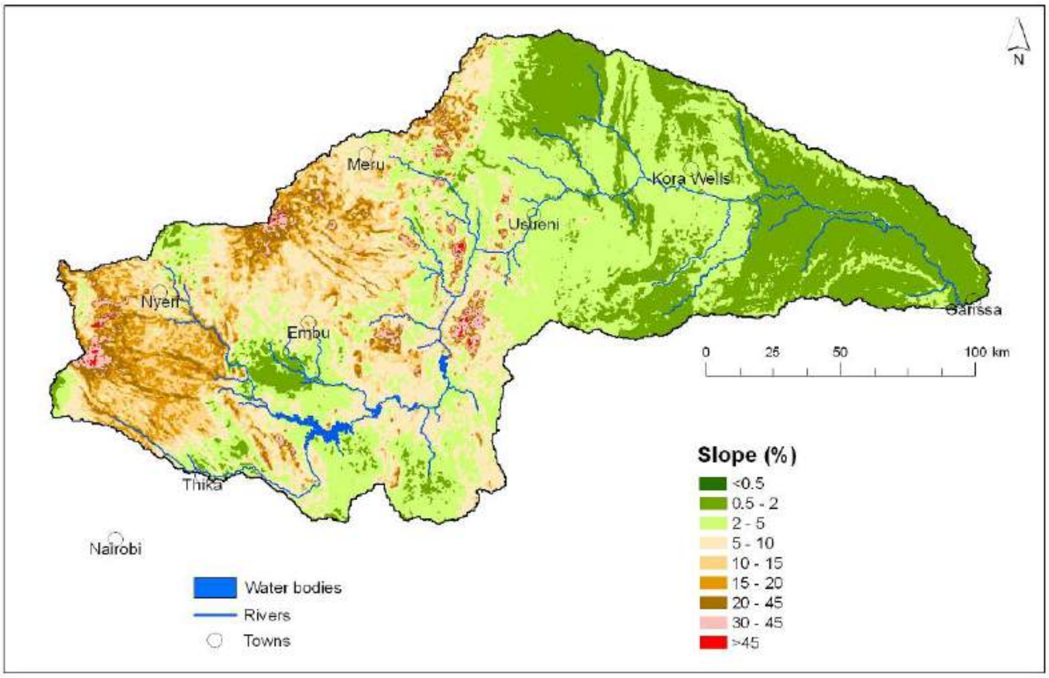


Figure 10: Upper Tana, slope gradient

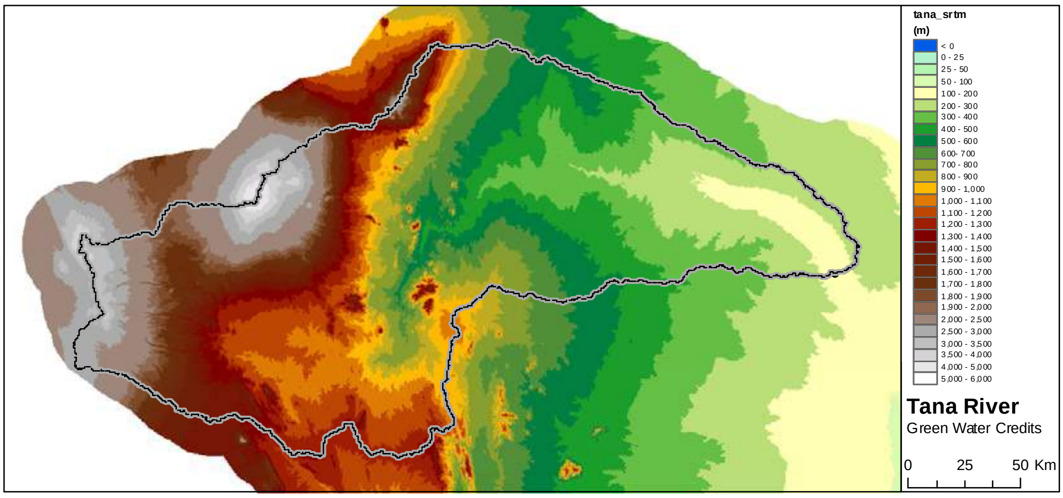


Figure 11: SRTM Digital Elevation Model at 90 m resolution

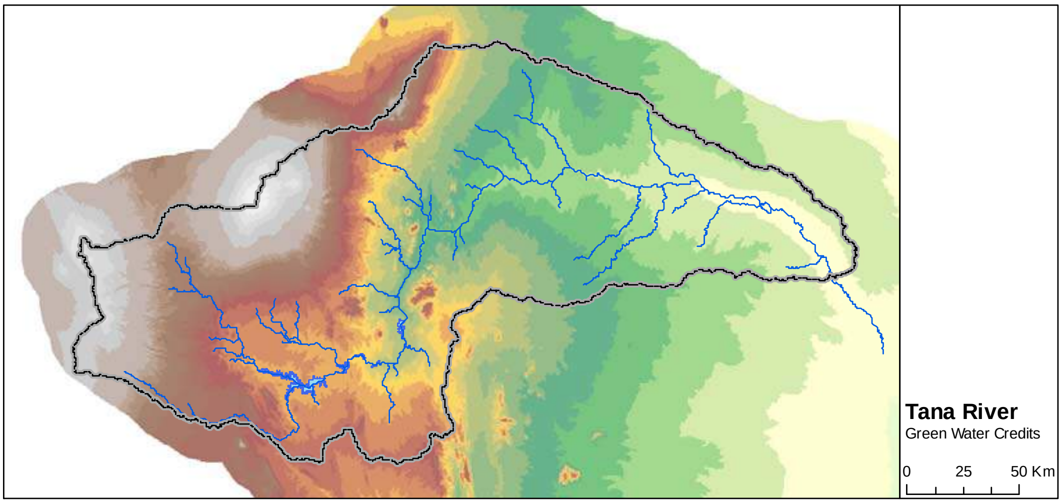


Figure 12: Stream flow network as derived from DEM

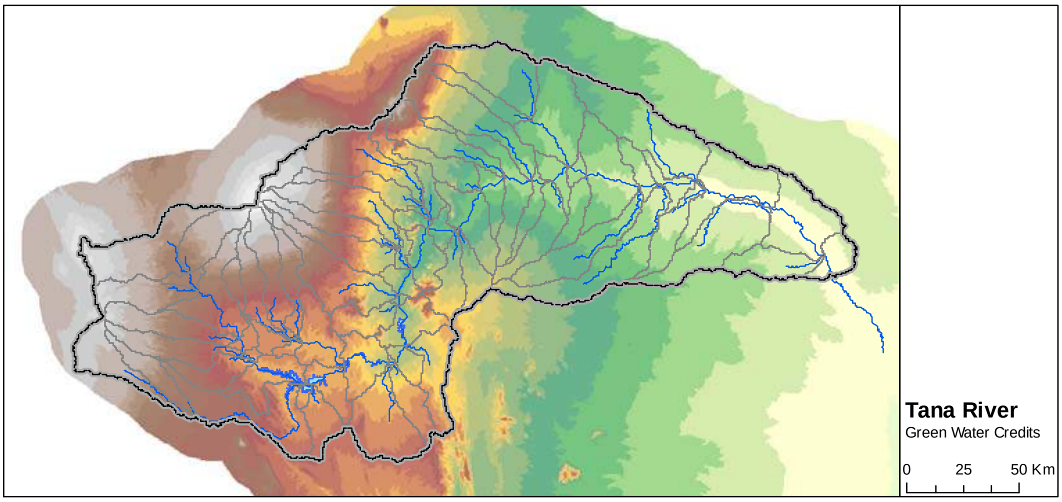


Figure 13: Sub-basins as derived from DEM

4.2 Climate

4.2.1 Agro-climatic zones

Agro-climatic zones (AEZs), delineated according to rainfall and evaporative demand (Jaetzold and Schmidt 1983), are shown in Figure 14. The Upper Tana encompasses seven climatic zones ranging from humid to arid, with a close correlation of elevation and climatic zones.

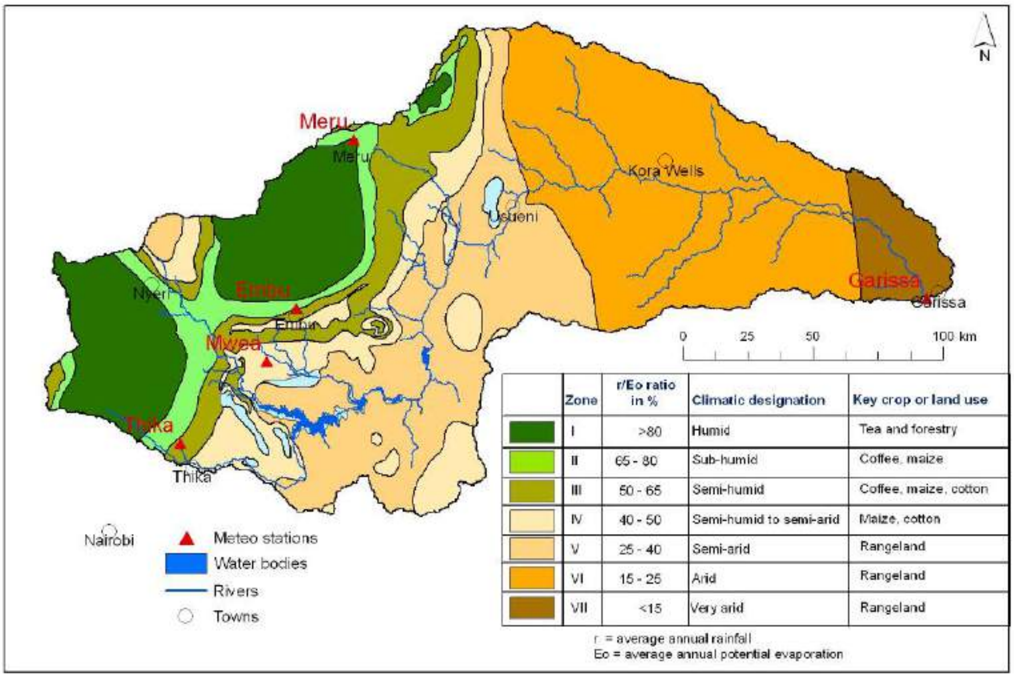


Figure 14: Agro-ecological zones of the Upper Tana basin

A representative meteorological station having at least 10 years of continuous records was selected for each climatic zone (Table 1). Data for rainfall, radiation, temperature, relative humidity and wind speed, from (FAO 2000b) and (Jaetzold and Schmidt 1983) were used for WOFOST water balance calculations.

Table 1: Agro-climatic zones and representative meteorological stations

Zone	*Name*	*Record Period*	*Altitude (m)*	*Annual Rainfall (mm yr^{-1})*
I	Embu Forest	1950 - 1994	1936	1450
IIa	Embu	1908 - 1994	1493	1257
IIb	Meru	1914 - 1994	1554	1191
III	Mwea	1980 - 1994	1463	948
IV	Thika	1980 - 1994	1159	858
V	Makindu	1904 - 1991	1000	611
VI	Galole		100	470
VII	Garissa	1931 - 1996	147	282

Long-term mean monthly rainfall and evapotranspiration for the selected stations are shown in Figure 15. Rainfall is bi-modal with *long rains* from March to May and *short rains* from October to December. Only in Zone I does rainfall exceed evapotranspiration in nearly all months; in zones V to VII there is a rainfall deficit throughout the year.

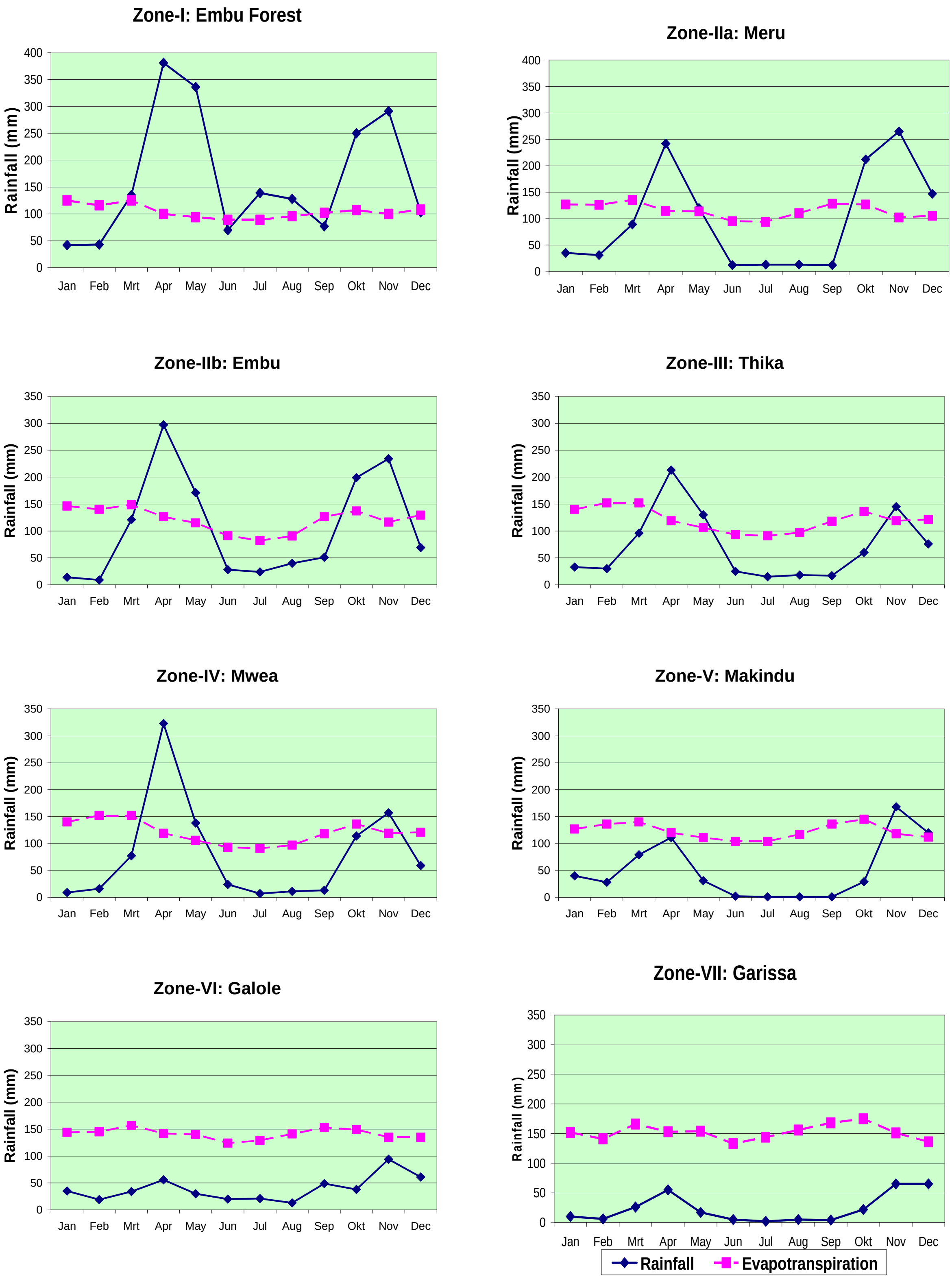


Figure 15: AEZ mean monthly rainfall and evapotranspiration

4.2.2 Meteorological data for SWAT

Data from the Climate Research Unit of the University of East Anglia are used: the CRU TS 2.0 dataset comprises 1200 monthly grids for the period 1901-2000 at 0.5° × 0.5° resolution, comprising: cloud cover, diurnal temperature range, precipitation, temperature and vapour pressure (Mitchell and others 2004). For the Upper Tana, 28 points were used (Figure 16).

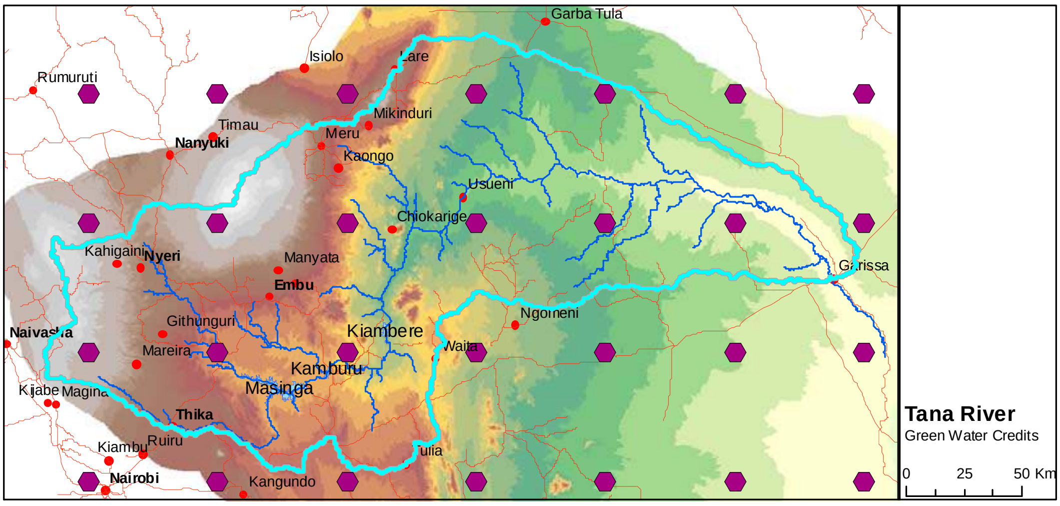


Figure 16: Upper Tana, meteorological data points

CRU-derived annual and monthly average precipitation for Masinga Dam are plotted in Figure 17 and summarized in Table 2; these average monthly rainfall data are similar to the station-measured records from Thika and Mwea. For the proof of concept, analysis was performed for a dry (1996) and a wet (1997) year as examples of historic extremes.

Table 2: Annual precipitation for Masinga – CRU data

Year	*Precipitation (mm)*
1990	1167
1991	612
1992	785
1993	942
1994	917
1995	984
1996	521
1997	1479
1998	860
1999	670
2000	578
2001	744
2002	1091

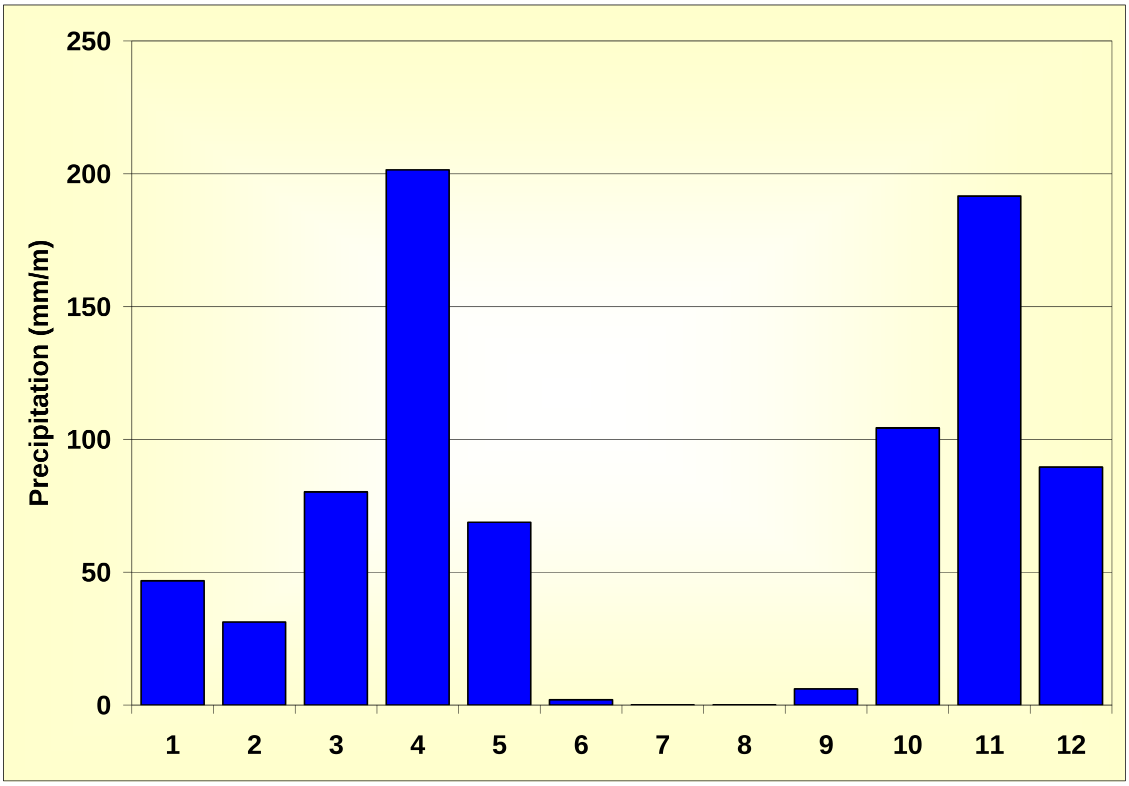


Figure 17: Masinga, mean monthly rainfall (1901-2002), CRU data

4.3 Land use and population

4.3.1 Land cover

The available data are less than ideal: an overview is given by the Land Cover Institute (LCI 2006); there is a moderate-resolution land cover map published by the International Livestock Research Institute (JICA 1987) (Annex 3). The best source is the AfriCover dataset (FAO 2000a) which designates land use/land cover for points on an approximately 2400 x 4800 m irregular grid. AfriCover recognizes 50 land cover classes in the Upper Tana; these have been generalized into 18 classes, in 4 main groups (Figure 18, Table 3, and Annex 6).

Rain-fed cropping occupies much of the highlands, covering 1 million ha (32 per cent) of the Upper Tana; rangeland occupies most of the drylands. Tea and coffee are important crops in the humid to sub-humid areas (climatic zones I, II and III), see also (Macharia 2004) and very relevant for assessment of erosion and sedimentation under different management scenarios. Under well-managed tea, erosion hazard is restricted to the early establishment stage; erosion is much reduced after closure of the canopy. In contrast, the coffee zone is erosion-prone because common agronomic practices enhance runoff, and poor coffee prices mean that management effort has been much reduced in recent years.

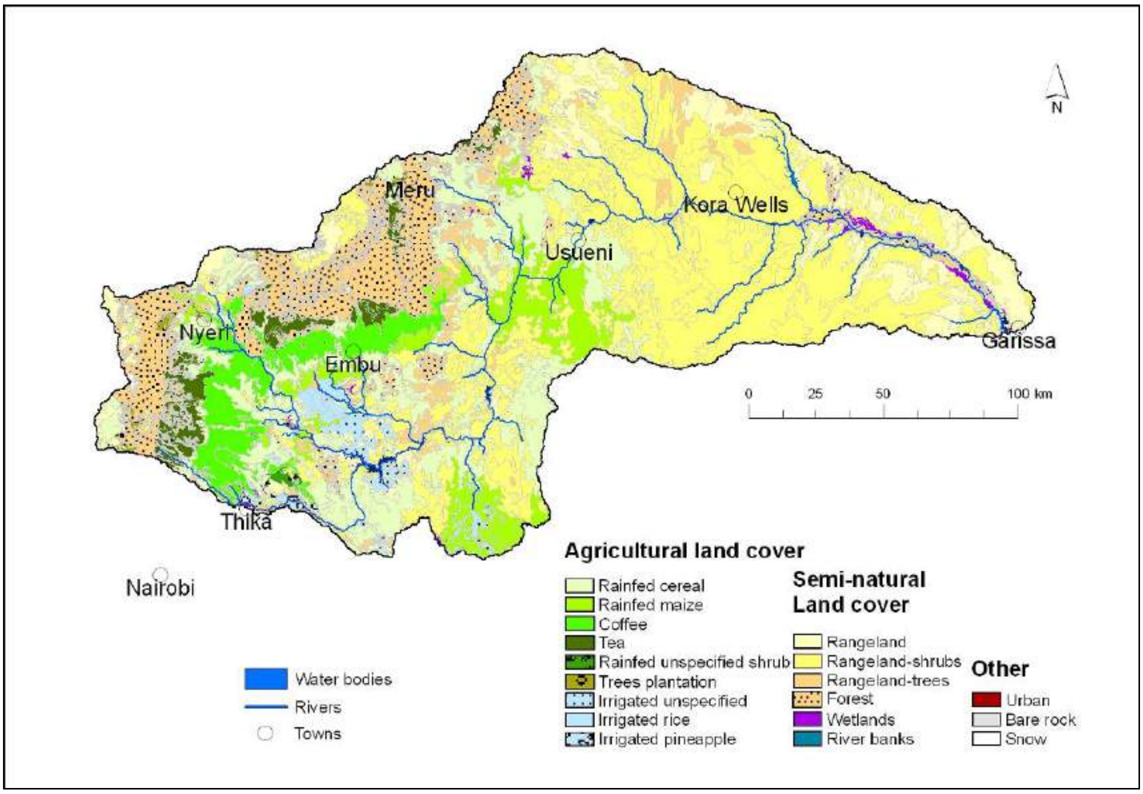


Figure 18: Upper Tana, land cover

Maize is the staple cereal, appearing in the category *rain-fed maize* but, also, under the *rain fed cereal* category. It is usually grown in combination with other crops such as bananas, pulses and vegetables. AfriCover does not distinguish cotton cultivation although this is important in zones IV and V. Due to the poor ground cover, cotton cultivation results in serious erosion. Also, the main soil types in these zones are less resilient than those in zones I to III.

Irrigated agriculture includes large public and commercial schemes; also myriad smallholder enterprises that are underestimated on the map.

Table 3: Land cover according to AfriCover
(FAO 2000a)

Land cover class	*Area (ha)*	*Area (%)*
Rain- fed		
Coffee	174 684	5.3
Cereal	547 561	16.7
Maize	221 901	6.8
Tea	84 152	2.6
Plantation	12 122	0.4
Unspecified shrub	6 871	0.2
Irrigated crops		
Pineapple	7 812	0.2
Rice	23 335	0.7
Unspecified	40 260	1.2
Semi- natural land cover		
Bare rock	2 109	0.1
Forest	456 182	13.9
Rangeland	311 807	9.5
Rangeland-shrubs	1 232 960	37.5
Rangeland-trees	114 696	3.5
River banks	4 825	0.1
Snow	9	0.0
Wetlands	19 101	0.6
Other		
Urban	1 819	0.1
Water	22 422	0.7
Total area	**3 284 630**	**100.0**
Total rain fed cropland	**1 047 291**	**31.9**

For SWAT the AfriCover classes for the Upper Tana have been converted to 17 units (Figure 19, Annex 6).

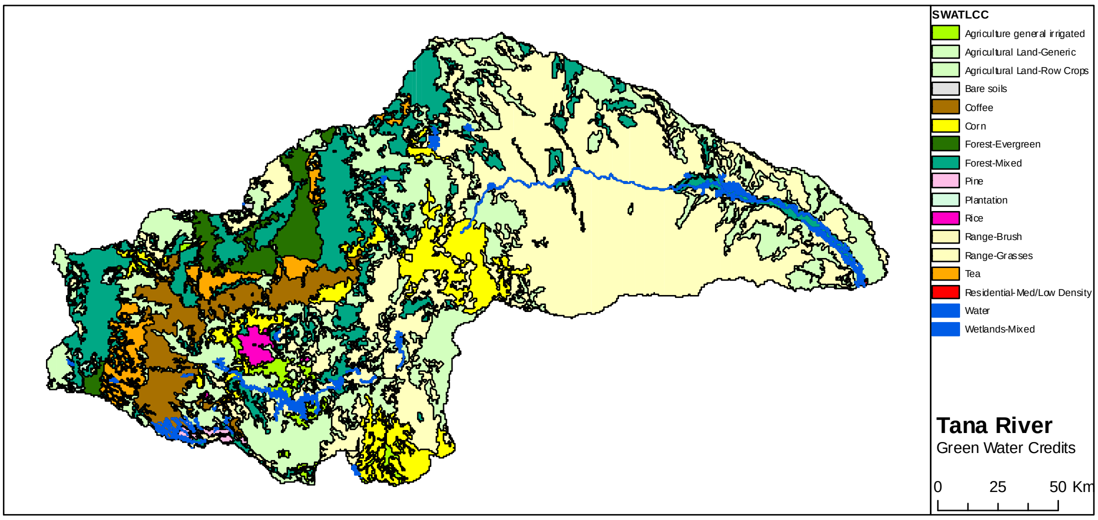


Figure 19: AfriCover land use converted to SWAT units

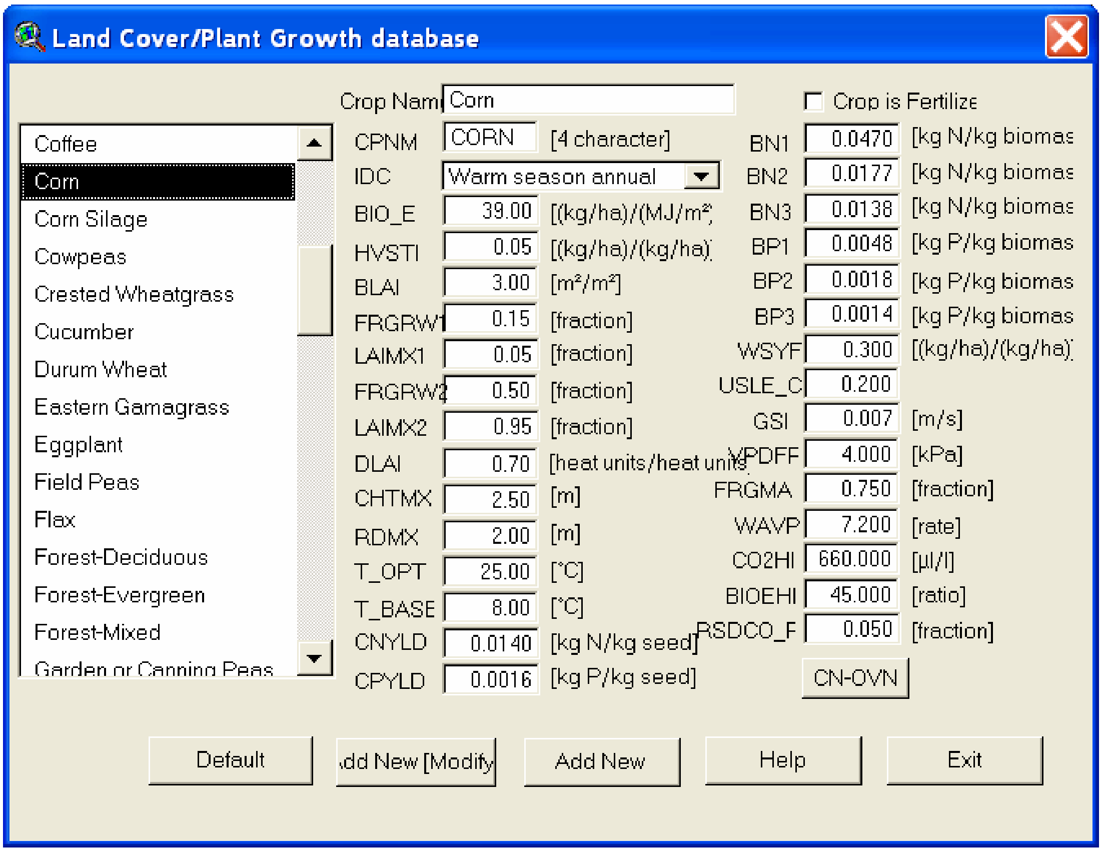


Figure 20: Required crop characteristics for the SWAT analysis, using maize as an example

4.3.2 Crop characteristics for SWAT

Crop-specific characteristics are needed by SWAT to simulate actual crop growth and the actual evapotranspiration. Figure 20 lists the crop parameters used. Besides these generic crop characteristics, management information of the crop is needed, including e.g. planting date, fertilizer application, and irrigation if applicable.

4.3.3 Population

At the 1999 Census, the population of the Tana basin stood at 5 million. We estimate that there are some 950 000 rural households in the Upper Tana, taking account of the classification of districts with dominantly rain-fed farming and the division of urban and rural population (Annex 3).

4.4 Soils

4.4.1 Soil information for SWAT and WOFOST

Digital soil data are available in the Kenya Soil and Terrain database (KENSOTER) at scale 1:1 million, a primary dataset holding field-observed and laboratory-measured soil characteristics, and the harmonized KENSOTER, a secondary dataset which includes calculated median values for standard depths. KENSOTER was used for WOFOST calculations as this model requires moisture retention data of defined matric potentials; the harmonized KENSOTER dataset is used for SWAT as it contains the required standardized data.

4.4.2 KENSOTER

KENSOTER (KSS 1996) holds data on landform, parent material and main soil types in standard digital format (van Engelen and Wen 1995). It was updated in 2004 (Batjes and Gicheru 2004) and expanded for Green Water Credits with additional profile data, especially measured water retention data for the Upper Tana. The latest version contains data for 340 soil profiles, of which 68 are in the Upper Tana; this dataset will be referred to it as KENSOTER-version 2 (KSS and ISRIC 2007).

The soil pattern in the Upper Tana (Figure 21) is broadly related to relief and climate. The higher slopes of Mt Kenya and the Aberdares carry Andosols derived from volcanic ash; the middle foot slopes carry deep, well-structured red clays (Nitisols) derived from intermediate-basic volcanic parent materials. The lower slopes are dominated by thick, strongly weathered, strongly leached red clays (Ferralsols) along with less-strongly weathered Cambisols and Luvisols. At lower elevations, below about 1000 m, Cambisols and, also, sodic Solonetz are extensive (KSS 1996; Sombroek and others 1982).

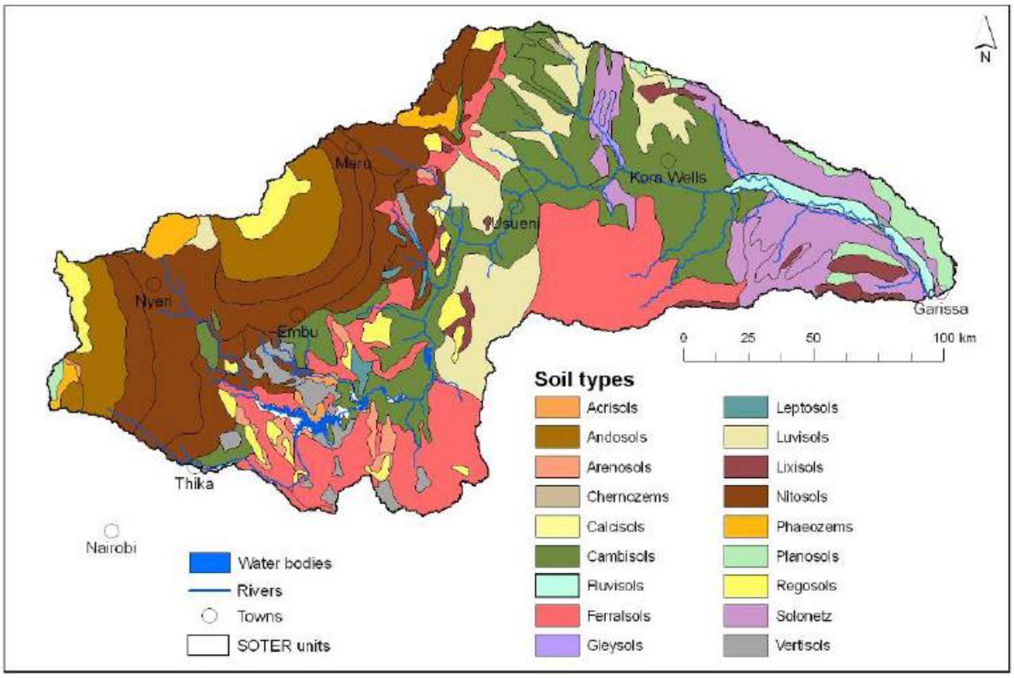


Figure 21: Upper Tana, dominant soil types, KENSOTER-version 2

WOFOST requires soil water content at saturation, field capacity and permanent wilting point[1]. Some profiles in KENSOTER-version 2 lack these data so to complete the missing data, linear regression functions for field capacity and wilting point were developed for high- activity and low-activity clay soil subsets; Andosols and Vertisols were treated separately. Various soil attributes were tested to find the best correlation; regression functions based on total silt + clay, and organic carbon, gave the best results but data for organic carbon is not available for subsoils, so functions were based only on total silt + clay (Annex 4). Rootable depth was derived from the KENSOTER-version 2 using attributes that limit the rooting of maize - high bulk density, very low nutrient status, and sodicity (Annex 4).

Rootable depth and available water capacity (water held between field capacity and permanent wilting point) are key soil properties determining the water balance.
Table 4, Figure 22 and Figure 23 summarise these characteristics for the soils of the Upper Tana; there is a factor 5 to 10 difference between the lowest and highest values of available water capacity.

[1] In Kenya, most measured field capacities have been determined at -20 kPa and permanent wilting point at -1500 kPa

Table 4: Mean soil water characteristics of soils of the Upper Tana catchment

Soil group	*Rooting depth, cm*	*Water content (a) (%) at*			*Available water capacity(b) %*	*Total available water(c) mm*
		Saturation	*Field capacity*	*Wilting point*		
Acrisols	110	56	24	16	9	98
Andosols	80	60	40	24	16	128
Arenosols	90	53	16	3	12	96
Chernozems	75	55	37	21	16	120
Calcisols	40	41	16	10	6	24
Cambisols	53	48	28	14	14	74
Fluvisols	93	44	17	4	13	120
Ferralsols	90	53	26	17	9	82
Gleysols	45	56	37	21	16	72
Leptosols	10	53	21	12	9	9
Luvisols	80	47	25	13	12	95
Lixisols	88	47	16	11	5	43
Nitisols	105	53	31	22	9	95
Phaeozems	80	56	38	26	12	96
Planosols	25	50	35	22	13	32
Regosols	35	48	19	9	10	35
Solonetz	25	45	28	13	15	38
Vertisols	80	50	46	22	24	192

(a) Volume percentages; (b) Available water capacity (mm/dm); (c) Total available water capacity over the effective rooting depth (rounded figures)

4.4.3 Harmonized KENSOTER

Harmonized KENSOTER is a secondary dataset with gaps in the measured data filled using taxo-transfer rules (Batjes and others 2007) and attribute values derived by statistical analyses of the much larger WISE dataset. It includes available water capacity of the soil for five 20 cm depth intervals up to 100 cm; rootable soil depth is directly extracted from the harmonized KENSOTER database.

4.4.4 Soil hydrological data

Soil hydrological parameters needed for SWAT are listed in Table 5. Table 5An important characteristic not provided in is saturated hydraulic conductivity; this has been derived from pedo-transfer functions applied successfully at field and basin scales (Droogers and others 2001).

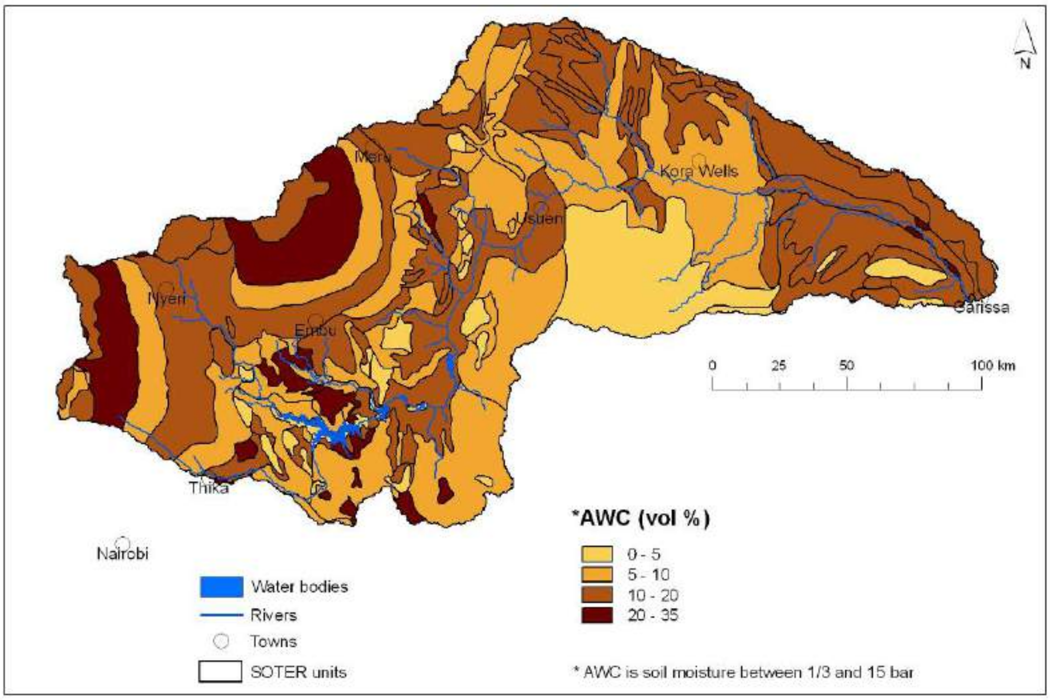


Figure 22: Upper Tana, available water capacity of dominant soils

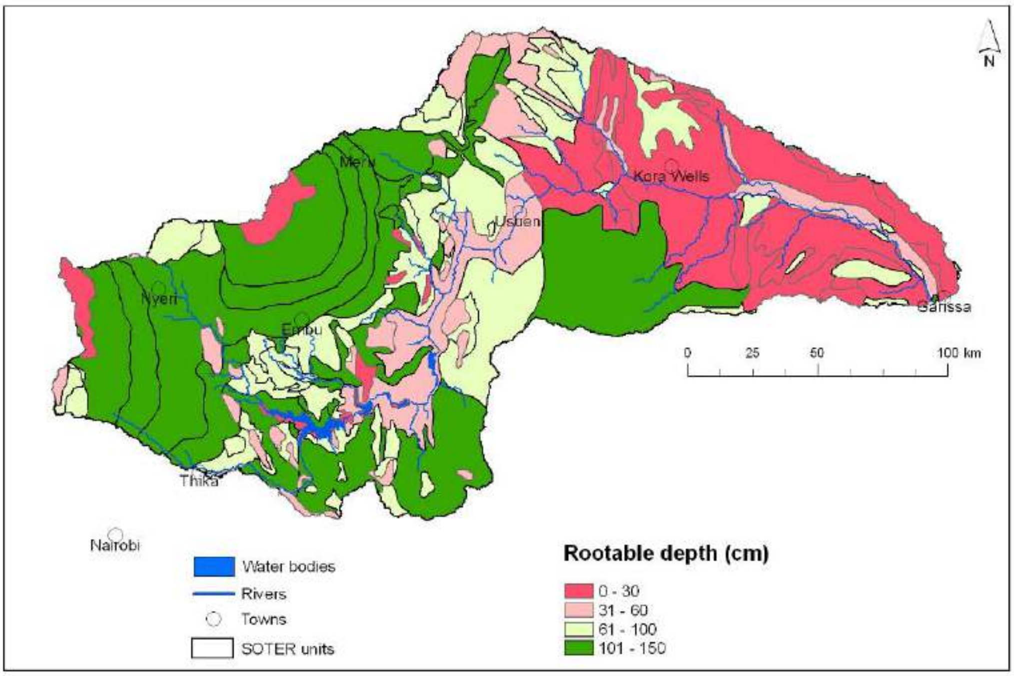


Figure 23: Upper Tana, rootable depth of dominant soils

The Jabro equation (Jabro 1992) generates hydraulic conductivity values close to the measured ones:

$$K_{sat} = \exp(9.56 - 0.81\log(st) - 1.09(cl) - 4.64(BD))$$

K_{sat} saturated hydraulic conductivity (cm/h), st silt content (%), cl clay content (%)
BD bulk density (kg/dm^3)

SWAT requires values in mm/h:

$$K_{sat} = \exp(11.86 - 0.81\log(st) - 1.09\log(cl) - 4.64(BD))$$

Table 5: Soil parameters required for the SWAT model

Code	*Definition*	*minimum*	*maximum*
SNAM	Soil name		character
HYDGRP	Soil hydrologic group		character
SOL_ZMX	Maximum rooting depth of soil profile (mm)	0	3500
ANION_EXCL	Fraction of porosity (void space) from which anions are excluded	0.01	1.00
SOL_CRK	[OPTIONAL] Crack volume potential of soil (% of soil volume)	0.00	1.00
TEXTURE	[OPTIONAL] Texture of soil layer		character
SOL_Z	Depth from soil surface to bottom of layer (mm)	0	3500
SOL_BD	Moist bulk density (g/cm^3)	1.10	2.50
SOL_AWC	Available water capacity of the soil layer (mm water/mm soil)	0.00	1.00
SOL_K	Saturated hydraulic conductivity (mm/hr)	0	2000
SOL_CBN	Organic carbon content (% mass)	0.05	10.00
CLAY	Clay content (% mass)	0	100
SILT	Silt content (% mass)	0	100
SAND	Sand content (% mass)	0	100
ROCK	Rock fragment content (% mass)	0	100
SOL_ALB	Moist soil albedo	0.00	0.25
USLE_K	USLE equation soil erodibility (K) factor (tonne/ m^2/hr)	0.00	0.65
NLAYERS	Number of layers in the soil	1	10
NUMLAYER	The layer being displayed	1	10

4.5 Soil and crop management

4.5.1 Green water management

Soil and crop management determine water infiltration, runoff and erosion, and evaporation in farmland. Runoff and evaporation constitute significant losses of water on-farm and, also, determine supplies downstream. Practices that enhance infiltration and reduce runoff and unproductive evaporation are called *green water management;* this includes mulching, minimum tillage, vegetation strips along the contour, tied ridging, and terracing.

Both farmers and government agencies have a wealth of knowledge of green water management but there is much room for improvement in practice. Comparison of air photos of the Upper Tana taken in 1960 and 1996 shows that bush has decreased in favour of coffee and that the area of well-maintained terraces has decreased substantially (Ekbom and others 2001) - the result is extensive soil erosion and siltation. Various figures for soil loss are quoted, for instance a loss of soil from cultivated fields increasing from 1.7 tonne/ha/year for the period 1956-1970 to 2.6 tonne/ha/year for 1970-1977 (Mwago and Okoth 1990), even up to 150 tonne/ha/year^{-}, equivalent to an annual loss of 1 cm of soil. These figures corroborate with data from runoff plots on well-structured red clays in Kisii district, which show runoff of 27 per cent of the annual rainfall, coupled to a loss of 120 tonne/ha/year for bare soils. In plots with good ground cover, both runoff and erosion decrease to very low levels (Tong'i and Mochoge 2000). But all these data are all from small plots and should not be extrapolated across whole catchments.

A field visit in August 2007 by Kenya Soil Survey and ISRIC staff observed correlation between green water management and farming profitability: practice was generally good under tea; moderate to poor under coffee fields - due to the low coffee prices in recent years; and practically nil under maize. These observations tally with the sediment load of the rivers, which is low in the tea zone but increases to very heavy in the coffee zone, in particular in the lower elevation marginal coffee zone, threatening the life of the reservoirs.

4.5.2 Runoff and erosion reduction

Green water management aims to hold runoff, enabling water to infiltrate and increase storage of water in the soil and groundwater. A review by (Ringersma and others 2003) includes field studies in several countries confirming that runoff represents an important water loss from cropland. Estimates of runoff, as a percentage of the total annual rainfall, range from 40-50 per cent for the Sahel (FAO 2005) to 70-80 per cent in semi-arid conditions in Kenya (Biamah 2005; Gitonga 2005). Wanyonyi cites a reduction of 80 per cent in siltation following the introduction of green water management in the catchment of the Tungabhada reservoir in India (Wanyonyi 2002). In addition to measures on farmland, afforestation of land above 1850 m may result in a 7 per cent decrease in sediment loading in the Masinga reservoir (Jacobs and others 2003).

Runoff measurements are available only from a few research sites; field evaporation data are even scarcer. In the absence of measurements, runoff scenarios are introduced to analyze water balance effects at field level and at basin level. Based on the runoff-reduction estimates in the WOCAT database (WOCAT 2007a, b), calculations are made for runoff scenarios of up to 40 per cent reduction. Table 6 presents 36 cases of relevant runoff and erosion reduction technologies, twelve cases are from Kenya, mostly in the Upper Tana (see Figure 24).

Table 6: Case studies of green water management

Case ID	*Name*	*Soil loss reduction (t/ha)* [(a)]	*Soil loss reduction (%)*	*Runoff reduction (% of rainfall)*[(a)]	*Run-off reduction (%)*
CHN21	Orchard inter-cropped with Bahia grass	21	88	35	50
CHN40	Zero tillage	22	88	25	83
CHN41	Subsoiling	45	90	25	83
CHN42	Auto-flowing slurry dam	59	74	8	19
CHN43	Pits	10	77	8	80
CHN45	Terrace	122	68	6	60
CHN47	Check dam	70	39	18	38
CHN49	*Caragana Korshinskii* planting	95	56	8	80
ETH01	Trash lines	90	90	45	64
ETH11	Multiple cropping			40	80
KEN05	*Fanya Juu* terrace	9	82	30	60
KEN10	Road runoff management - Nyeri	10	40	30	60
KEN11	Road runoff system - Mwingi	10	83	70	88
KEN15	Double dug beds - Busia experience			10	67
KEN16	*Grevillea* tree planting	2	30	5	13
KEN22	Water harvesting and enlarged structures	7	90	38	84
KEN23	Riverbed reclamation & silt trapping	7	58	40	67
KEN24	Gully reclamation	609	100	50	83
KEN25	Pasture management	2	67	12	60
KEN26	Water table management	1	67	4	50
KEN27	Gully blocking by stone checks	5	91	40	80
KEN30	Conservation tillage through ripping	0		30	60
NEP11	Landslip and stream bank stabilization	190	95	45	56
PHI03	Natural vegetative strips	38	95	37	82
PHI07	Multi-storey cropping	10	100	30	43
PHI08	Residue incorporation (maize)	10	50	20	33
PHI09	Planted vegetative strips	40	80	30	43
PHI10	Stone bunds and small basins	8	80	30	75
RSA01	Old motor tyre contours	6	75	40	80
RSA09	Combating invasive plants & bush	0		60	67
RSA11	Runoff control on cultivated land	21	84	40	67
RSA32	Rangeland rehabilitation	3	75	40	44

Case ID	*Name*	*Soil loss reduction (t/ha)* [(a)]	*Soil loss reduction (%)*	*Runoff reduction (% of rainfall)*[(a)]	*Run-off reduction (%)*
RSA33	Agronomic & vegetative rehabilitation	0		50	71
RSA52	Controlling of soil erosion	0.3	60	30	75
THA01	Vegetative erosion control	15	75	10	50
THA25	Small bench terrace	40	80	5	25
Average		**45**	**76**	**29**	**62**

(a) Soil loss and runoff reduction are expressed as the difference of with and without the practice under consideration

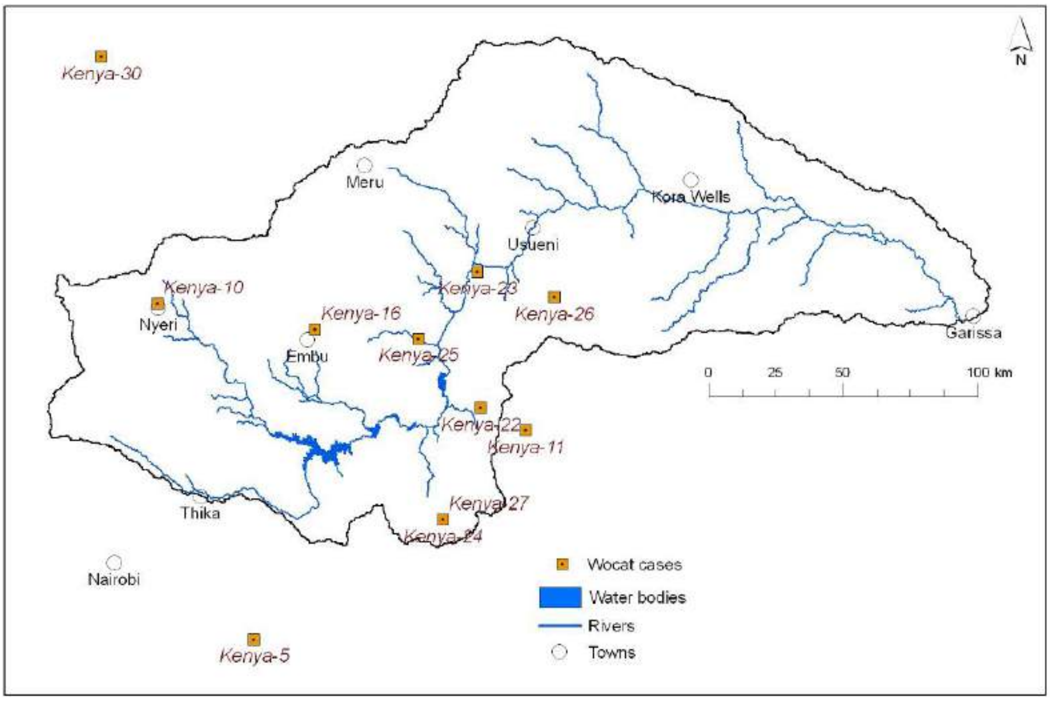


Figure 24: Location of WOCAT case studies around the Upper Tana

In the WOCAT case studies, the average runoff reduction is 63 per cent and, for soil loss reduction, 76 per cent, consistent with the field studies reviewed by Ringersma (2003). Runoff may be reduced by 70 per cent with mulching, by 60 per cent with appropriate tillage, and by about 65 per cent with water harvesting. Comparable figures on the beneficial effects of mulch on infiltration, runoff and erosion reduction were given in an early review (Jacks and others 1955). Based on these field studies, we adopt a conservative figure 50 per cent reduction of runoff and 75 per cent reduction of soil erosion for our green water management scenarios.

4.5.3 Evaporation reduction

Unproductive evaporation of water from the soil surface depends on evaporative demand (depending on soil and air temperature, relative humidity and wind speed), surface roughness, soil wetness, salt content and transmissivity. Fine-textured soils have a higher and more prolonged evaporation rate than coarse soils. But surface cover is the key factor; the surface may be shielded from sun and wind by plants or mulch. As much as 60-70 per cent of rainfall is evaporated in South Africa (Falkenmark and Rockström 2004); 40 per cent of total rainfall and 80 per cent of infiltrated rainfall under natural vegetation in the Southern Sahel of West Africa, with evaporation of 2.5 mm per day for a bare soil to 1.5 mm for a soil with a full vegetation cover (Hoogmoed 1999); and 45-80 per cent in Kenya (Gitonga 2005). Evaporation reduction measures include tillage, mulch or other ground cover:

Tillage: Tillage loosens the soil, preventing capillary rise of water (Jalota and Prihar 1998). This is a short- term effect, so requires regular labour, and it keeps the soil bare which means runoff during heavy rain.

Mulch: Mulch reduces evaporation and, at the same time, enhances infiltration, prevents erosion, and it may enrich the soil with organic matter. Organic mulches include crop residues and cut weeds, and composted wastes. Composted municipal wastes could be used (Agassi and others 1998). In Kenya, several field studies have emphasized the importance of mulch in enhancing infiltration, soil water availability and reduction of evaporation (Gicheru 2002) (Njihia 1979); early field trials in Kenya demonstrated large increases in soil moisture and yields when mulch was applied before the rains (Pereira and Jones 1954). Potential negative effects are that: under high evaporative demand and frequent light showers, mulch may intercepts most of the rain; plant residues are in strong demand for other purposes, such as fuel and animal feed; and mulch may encourage plant diseases and pests.

There are few data on the effects of mulch on evaporation over a complete growing season, and most studies lump the combined effects on evapotranspiration, soil water storage, and infiltration; field measurements are quoted by Jalota and Prihar (1998) and Stroosnijder and van Rheenen (2001). The evaporation-reduction parameters are, in rank order: residue thickness > surface cover > residue application rates > potential evaporation > residue specific density > relative humidity. We use the average evaporation reduction of 40 per cent for mulch applied during the first part of the growing period (during the rains when crop cover is low) in comparison to a bare tilled soil; and an evaporation reduction of 20 per cent for mulch before the rains.

Plastic: Plastic covering between crop rows is very effective in reducing evaporation. Attention is needed: to prevent litter, or pollution in the case of ploughing in; adverse effects on below-ground biodiversity; and a significant research and development effort to develop good practice under local conditions.

4.5.4 Green water management scenarios

For the proof-of-concept, a three feasible green water management practices are evaluated, following discussion with local experts (Table 7).

Table 7: Evaluation of green water management packages

Climate zone + dominant crop	*Recommended GW management package*	*Expected effects on runoff, evaporation and erosion*
I Tea	o Grassed contour strips o Mulch and weeding in young and pruned tea	o 50% runoff reduction o 75% erosion reduction o 40% evaporation reduction
II+III Coffee	o Grassed contour strips o Mulch and weeding	o 50% runoff reduction o 75% erosion reduction o 40% evaporation reduction
II, III and IV Maize III + IV Cotton	o Grassed contour strips o Tied ridges o Mulch and weeding	o 50% runoff reduction o 75% erosion reduction o 40% evaporation reduction

- Grassed contour strips, whether native grasses or planted Napier and Vetiver, is a cheap and effective measure for reducing runoff and soil erosion; it is already used in the Upper Tana. In Zone III and IV trash lines of maize stover, bushes, banana leaves etc., and stone lines may be considered. Grassed contour strips on the upper and lower tea border may need to be combined with physical measures such as *Fanya juu* terraces where slopes are very steep.
- To minimize the loss of cropped area and, thus, loss of income, forage grasses or other economically useful plants may be used.
- In between the vegetative strips, it is assumed that land preparations such as planting and ridging will be done parallel to the contour.
- Mulch and weeding greatly reduce evaporation and transpiration by weeds. For zones I and II, pruning from tea and shade trees are available and, probably, not much needed for other uses; for zones III and IV competition is an issue.
- Mulch is hardly applied under maize; tied ridges are an alternative to arrest runoff. Tied ridges not commonly used, but farmers who are currently using ridges can easily adopt them.
- Weeding is necessary but should be combined with measures to arrest runoff, otherwise it can easily enhance erosion; ground cover should be the prime consideration. Cover crops - legumes, sweet potatoes, pumpkins etc. may be considered to fill areas not covered by the main crop but this depends on labour, water and nutrient availability.
- Conservation measures beyond farmers' fields such as river bank protection and diversions to re-route road runoff should be part of integrated soil and water management.

4.6 Estimation of erosion

4.6.1 Erosion risk

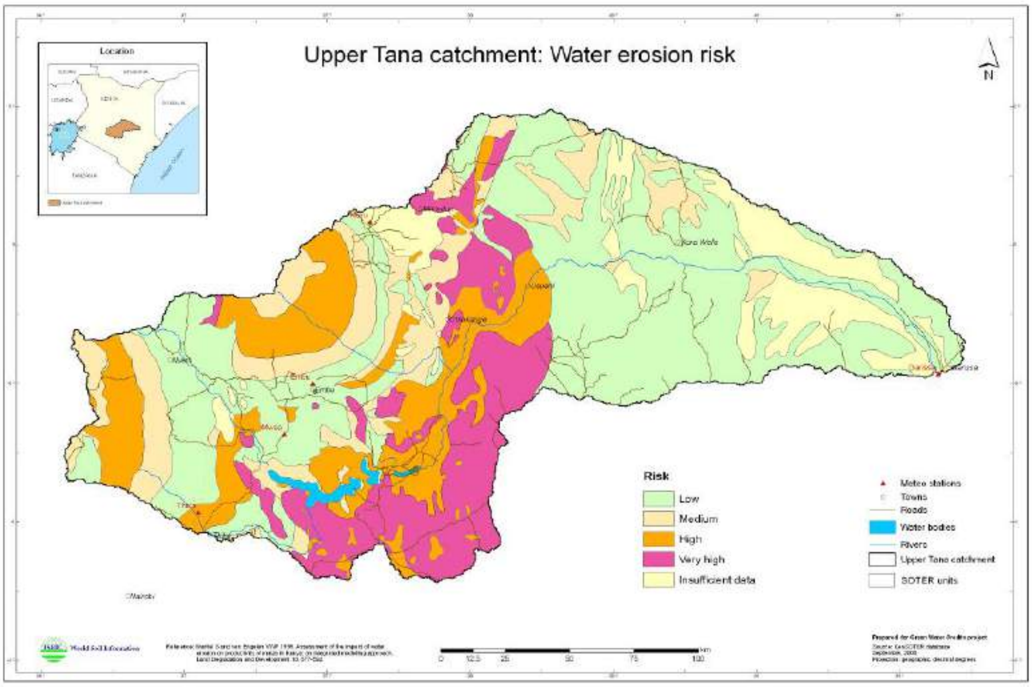


Figure 25: Upper Tana, risk of soil erosion by water
(Mantel and van Engelen 1999)

Figure 25 and Figure 26 show early assessments of erosion risk. Both maps show considerable differences across the Upper Tana, and from each other. Figure 25 (Mantel and van Engelen 1999) is based on the Universal Soil Loss Equation (Wischmeier and Smith 1978), using data for the dominant soil type, land use, dominant slope gradient and estimated slope length for each mapping unit in the KENSOTER database, but assuming a uniform land use of unimproved cultivation of maize – which is not the actual situation over the whole Upper Tana. Figure 26, by the Kenya Soil Survey (Mwago and Okoth 1990), is based on climate, soil and slope gradient but takes no account of land use and management. Neither assessment is taken any further in this study; instead, erosion under different management scenarios is calculated using the SWAT model.

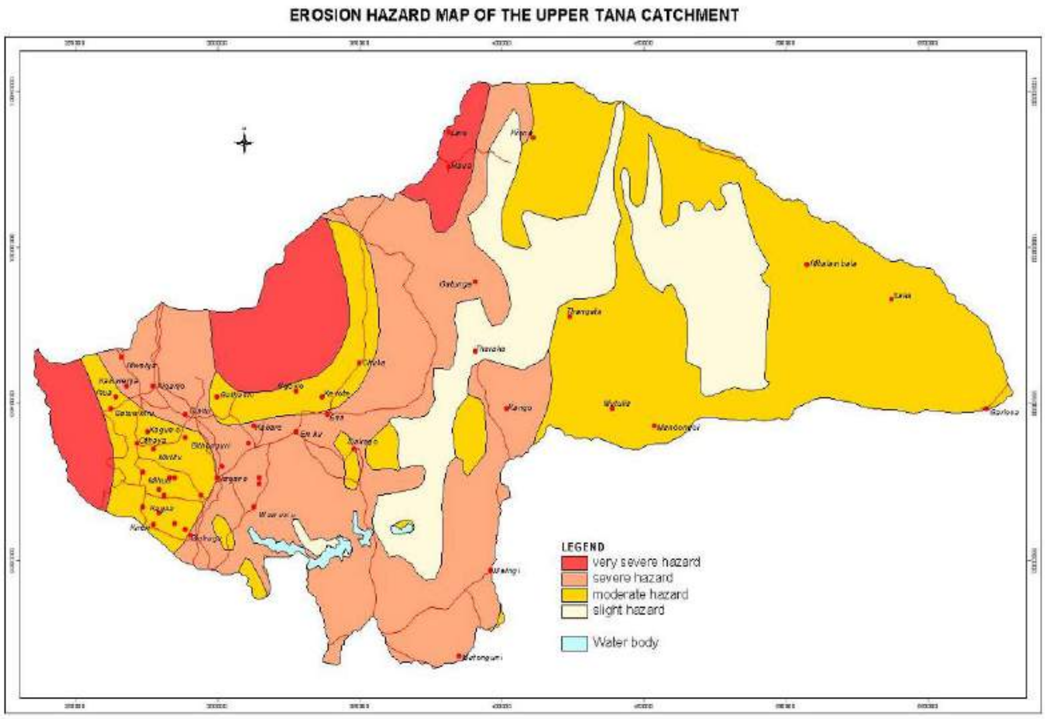


Figure 26: Upper Tana, erosion hazard
(Mwago and Okoth 1990)

4.6.2 Erosion – SWAT model

SWAT calculates sediment yield for each sub-basin with the Modified Universal Soil Loss Equation (Williams and Berndt 1977):

$$Y = 11.8 * (V * qp)^{0.56} * K * C * P * LS$$

Where: 11.8 and 0.56 are constants

- Y — the sediment yield from the sub basin in tonne,
- V — the surface runoff for the sub basin in m^3,
- qp — the peak flow rate for the sub basin in m^3/s
- K — the soil erodibility factor,
- C — the crop management factor,
- P — the erosion control practice factor, and
- LS — the slope length and steepness factor

The hydrology model estimates runoff volume and peak runoff rate. The crop management factor is evaluated as a function of above-ground biomass, crop residue on the surface, and the minimum C factor for the crop. Other factors of the erosion equation are evaluated as described in the original Universal Soil Loss Equation. The three most relevant factors in terms of green water management scenarios are the K, P and C factors, each of which ranges from 0, indicating no erosion, to 1, indicating high erosion.

K is the soil erodibility factor: the soil loss rate per erosion index unit for a specified soil as measured on a unit plot. Direct measurement of the erodibility factor is time-consuming and the USLE_K factor was derived using the transfer functions derived by Williams (1995).

P is the water erosion support practice factor: the ratio of soil loss with a specific support practice to the corresponding loss with up-and-down slope cultivation. Support practices include contour tillage, strip cropping on the contour, and terracing with stabilized waterways for the disposal of runoff.

4.7 Basin hydrology

4.7.1 Hydrological response units

The SWAT basin model is built up by aggregating *hydrological response units* (HRUs), each with a unique combination of land use, management and soil attributes. It is assumed that there is no interaction between HRUs in any one sub-basin. Loadings (runoff with sediment, nutrients, etc. transported by the runoff) from each HRU are calculated separately and then summed to arrive at the total loadings from the sub-basin. If the interaction of one land use area with another is important, rather than defining those land use areas as HRUs they should be defined as sub-basins – at which level spatial relationships can be specified. In practice the HRUs are defined by overlaying: (i) sub basins, (ii) land cover, and (iii) soils. A total of 874 HRUs has been used in the analysis (Figure 27).

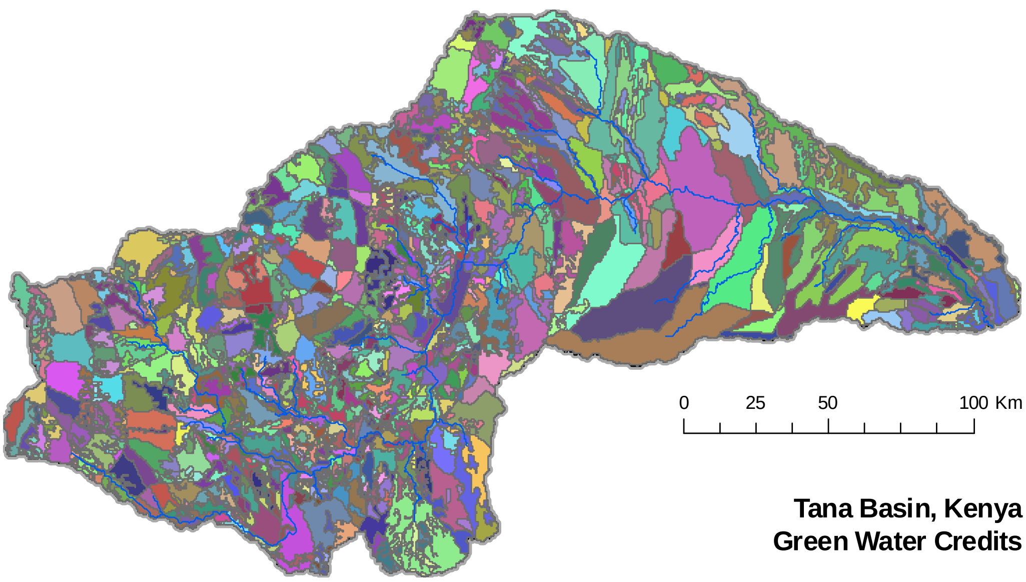


Figure 27: Upper Tana, hydrological response units

4.7.2 Reservoir characteristics

In SWAT, a reservoir is considered as an impoundment on the main channel network of a basin (Figure 28); natural and man-made structures are not distinguished. SWAT tracks of the water balance for a reservoir as:

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep}$$

where:
V the volume of water in the impoundment at the end of the day (m^3)
V_{stored} the volume of water stored in the water body at the beginning of the day(m^3)
V_{flowin} the volume of water entering the water body during the day (m^3)
$V_{flowout}$ the volume of water flowing out of the water body during the day (m^3)

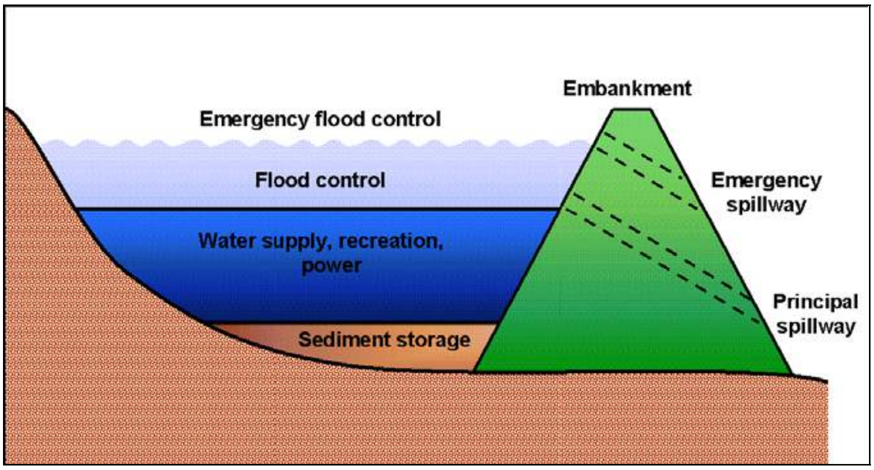


Figure 28: Terminology of reservoir characteristics in SWAT

V_{pcp} the volume of precipitation falling on the water body during the day (m^3)
V_{evap} the volume of water removed from the water body by evaporation during the day (m^3)
V_{seep} the volume of water lost from the water body by seepage (m^3).

Outflow may be specified by measured daily outflow, measured monthly outflow, average annual release rate (for uncontrolled reservoir), or by controlled outflow with target release. The last option is used here as the actual practice for the Upper Tana. For this option, the following reservoir characteristics and operational rules are required:
- emergency spillway surface area (ha)
- emergency spillway volume (m^3)
- principal spillway surface area (ha)
- principal spillway volume (m^3)

The following initial conditions are required:
- volume (m^3)
- sediment concentration (mg/l)
- normal sediment concentration (mg/l)

SWAT only works for one reservoir per sub-basin. Therefore, sub-basin boundaries have been altered to ensure that individual reservoirs are properly represented

(Figure 29): Masinga, in sub-basin 78; Kamburu, in sub-basin 79; Gitaru, in sub-basin 80; Kindaruma, in sub-basin 81; Kiambere, in sub-basin 82.

Key features of these reservoirs are summarised in Table 8 and their annual outflow is depicted in Figure 30. Outflow from the Masinga reservoir is somewhat lower than from the other reservoirs; this indicates that tributaries between Masinga and Kamburu are contributing significantly to the flow of the main stream.

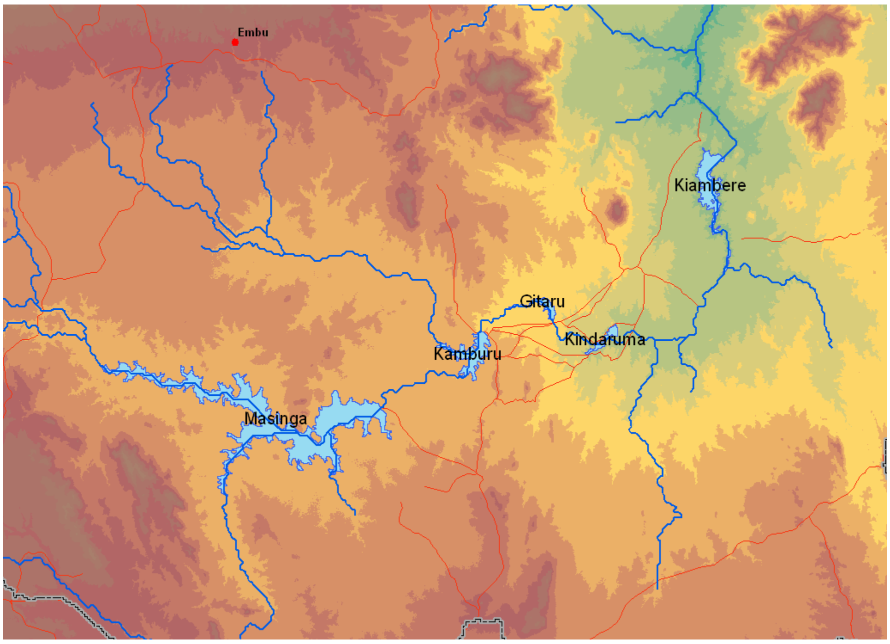


Figure 29: Upper Tana, location of reservoirs

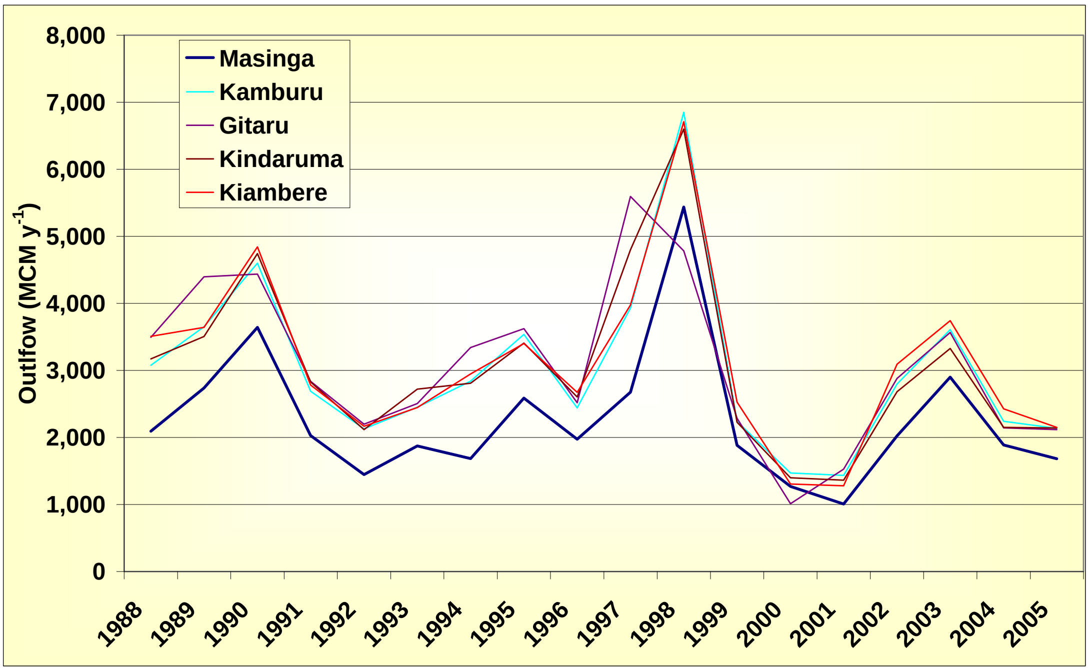


Figure 30: Annual outflow of the five reservoirs along Upper Tana

Table 8: Characteristics of the reservoirs in Tana
(KenGen 2005)

Item	*Unit*	*Masinga*	*Kamburu*	*Kindaruma*	*Gitaru*	*Kiambere*
Year of completion		1980	1974	1968	1978	1987
Height of dam	m	69.5	56.0	24.3	30.0	112.0
Capacity	x1000 m^3	1.560E+06	1.500E+05	1.600E+04	2.000E+04	5.850E+05
Area	x1000 m^2	120,000	15,000	250	310	25,000
Emergency spillway surface area	ha	1.440E+04	1.800E+03	3.000E+01	3.720E+01	3.000E+03
Emergency spillway volume	m^3	1.872E+09	1.800E+08	1.920E+07	2.400E+07	7.020E+08
Principal spillway surface area	ha	1.200E+04	1.500E+03	2.500E+01	3.100E+01	2.500E+03
Principal spillway volume	m^3	1.560E+09	1.500E+08	1.600E+07	2.000E+07	5.850E+08

Figure 31 shows the monthly inflow and outflow of Masinga reservoir, demonstrating the buffering of stream flows: during wet season inflows are higher than outflows and during dry seasons the opposite, except during periods when the buffer capacity is exceeded (1989, 1990, 1998 and 2003).

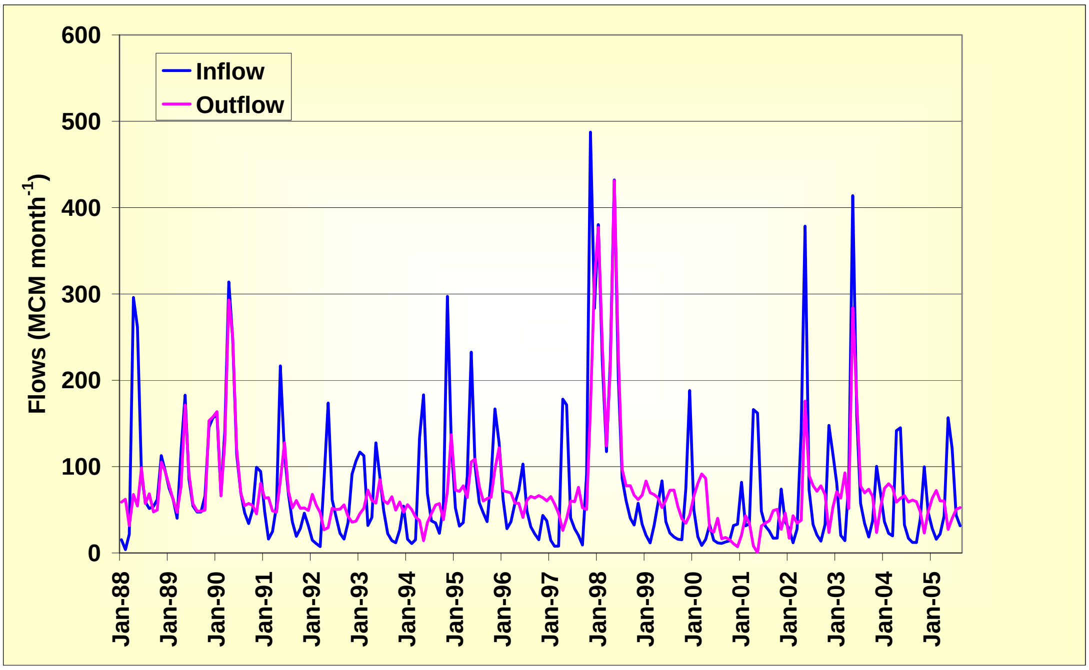


Figure 31: Monthly inflows and outflows of Masinga reservoir

The five reservoirs operate as a cascade so that water lost over the spillway at Masinga may be captured and/or used by the other reservoirs. However, Figure 32 indicates that spills by Masinga are often not captured, hence the need for increasing reservoir storage. Green Water Credits addresses this issue in two ways: by arresting further loss of reservoir storage by siltation, and by improving river regulation by enhancing the very much greater natural reservoir in the soil.

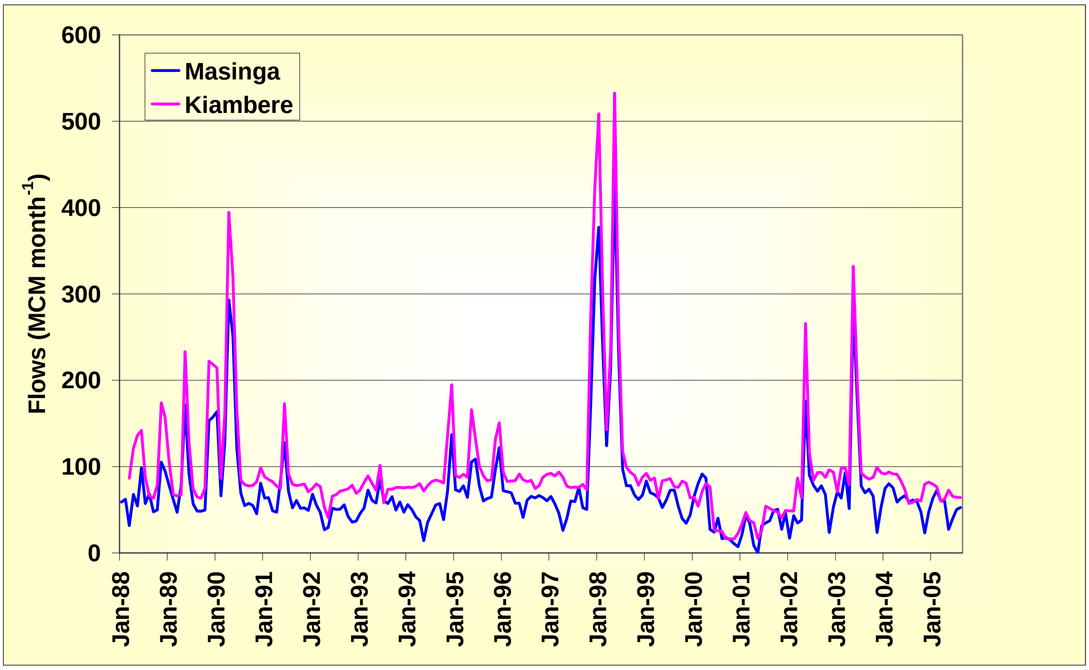


Figure 32: Monthly outflows from Masinga and Kiambere

4.7.3 Hydropower

Electricity generation from the five reservoirs is summarised in Table 9. The total power generated has been quite stable, except for the three-year period of low rainfall 2000-2001. Installed capacity is of 677.3 MW and the power generated makes up some 70 per cent of national electricity output.

Table 9: Generated electricity for the major hydro-power plants, GW/hr

	Masinga	*Kamburu*	*Kindaruma*	*Gitaru*	*Kiambere*
1991/92	185	402	206	811	872
1992/93	177	417	213	844	887
1993/94	180	421	217	856	892
1994/95	200	485	213	704	996
1995/96	225	491	239	701	1031
1996/97	215	446	230	926	1028
1997/98	204	480	198	818	1023
1998/99	223	410	240	789	1037
1999/00	142	247	157	734	813
2000/01	28	181	81	364	293
2001/02	127	330	162	665	703
2002/03	206	470	224	945	999
2003/04	230	470	221	938	1010
2004/05	169	381	170	757	814

Data provided over the financial year, ended at June 30th , e.g. 1991/1992 relates to July 1st 1991 to June 30th 1992. Source: (KenGen 2005; Oludhe 2003)

4.7.4 Discharge observations

Stream-gauge data have been assembled by the University of Nairobi (UoN), and some additional data are taken from the Global Runoff Discharge Data (GRDD): Table 10; Figure 33 shows the locations. The most complete series of observed stream flow data is from 1962-1977 (Table 11).

Table 10: Stream flow data

Code	*River*	*Location*	*Period*	*Source*	*SWAT basin*
4BE10	Sagana		1980-1994	UoN	64
4CB04	Thika		1945-1997	UoN	75
4CC05	Thika		1966-1980	UoN	72
4DD01	Thiba		1948-2006	UoN	69
4DD02	Thiba		1966-1993	UoN	57
4EA07	Mutonga		1966-1990	UoN	41
4ED03	Tana	Kamburu	1951-1972	UoN	79
4F13	Tana	Grand Falls	1962-1995	UoN	33
4F19	Kazita		1966-1994	UoN	29
4G01	Tana	Garissa	1941-1993	UoN	77
GAR	Tana	Garissa	1934-1975	GRDD	77
GRF	Tana	Grand Falls	1962-1977	GRDD	33

Table 11: Overview of stream flow data availability

		1935	1940	1945	1950	1955	1960	1965	1970	1975	1980	1985	1990	1995	2000	2005
1980-1994	4BE10															
1945-1997	4CB04															
1966-1980	4CC05															
1948-2006	4DD01															
1966-1993	4DD02															
1966-1990	4EA07															
1951-1972	4ED03															
1962-1995	4F13															
1966-1994	4F19															
1941-1993	4G01															
1934-1975	GAR															
1962-1977	GRF															

The data are variable, with many missing records, unknown units and locations, and conflicting names so an interpolation program was written with the following rules:

i. If one day is missing, the average of the previous and following day is used;
ii. If two consecutive days are missing, the average of the two closest days is used;
iii. If more than two consecutive days are missing, the long-term average is used.

Procedures were included to reformat the data into a regular shape: each record consists of year, month, day, flow. Also, daily data are converted to monthly.

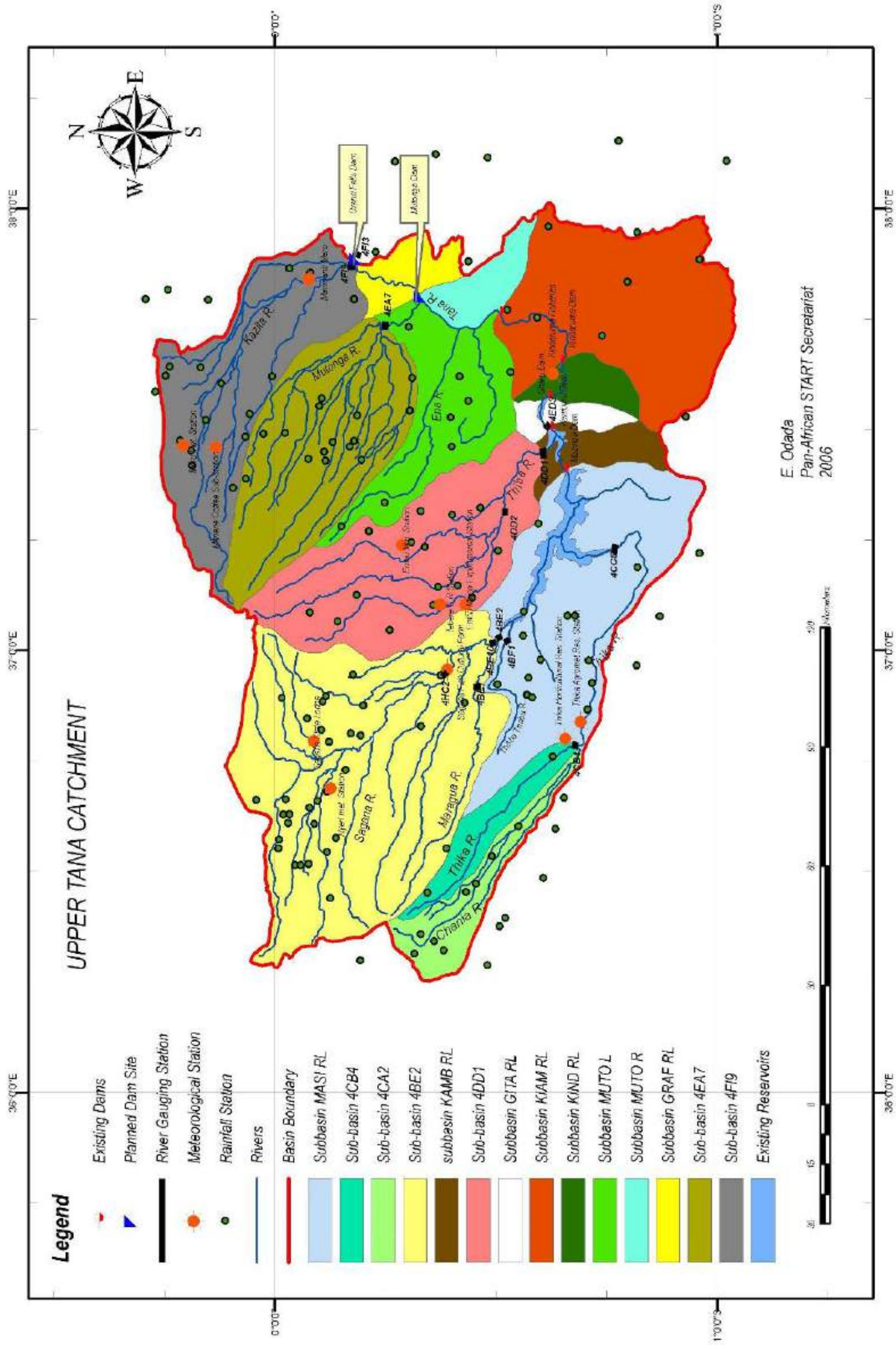


Figure 33: Location of gauging stations related to sub-basins

Figure 34 gives examples of the interpolation for a case with large continuous missing data (top) and a case with smaller data gaps (bottom). For the latter, values are interpolated close to the missing data. For large continuous data gaps, missing values are replaced by long-term monthly averages.

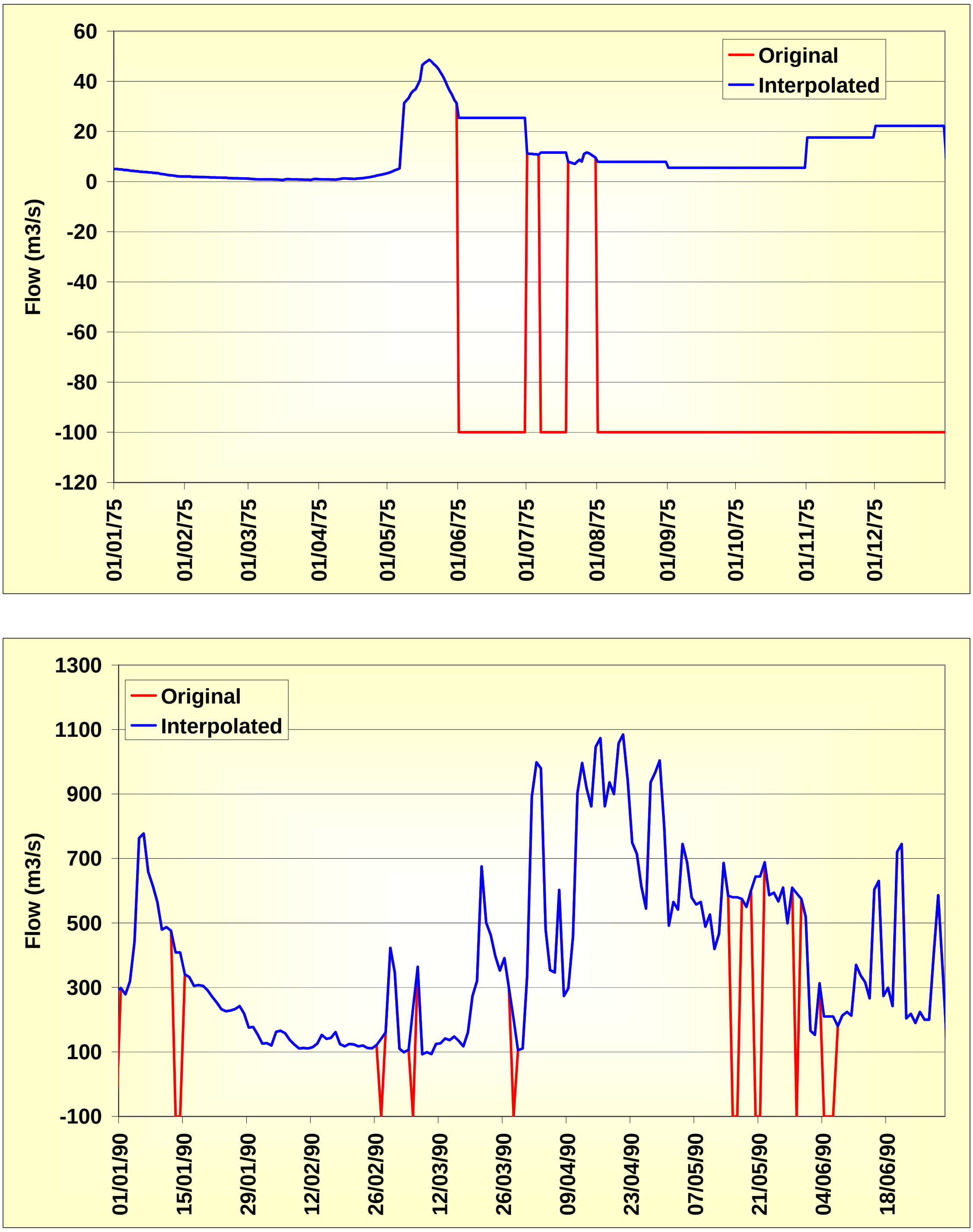
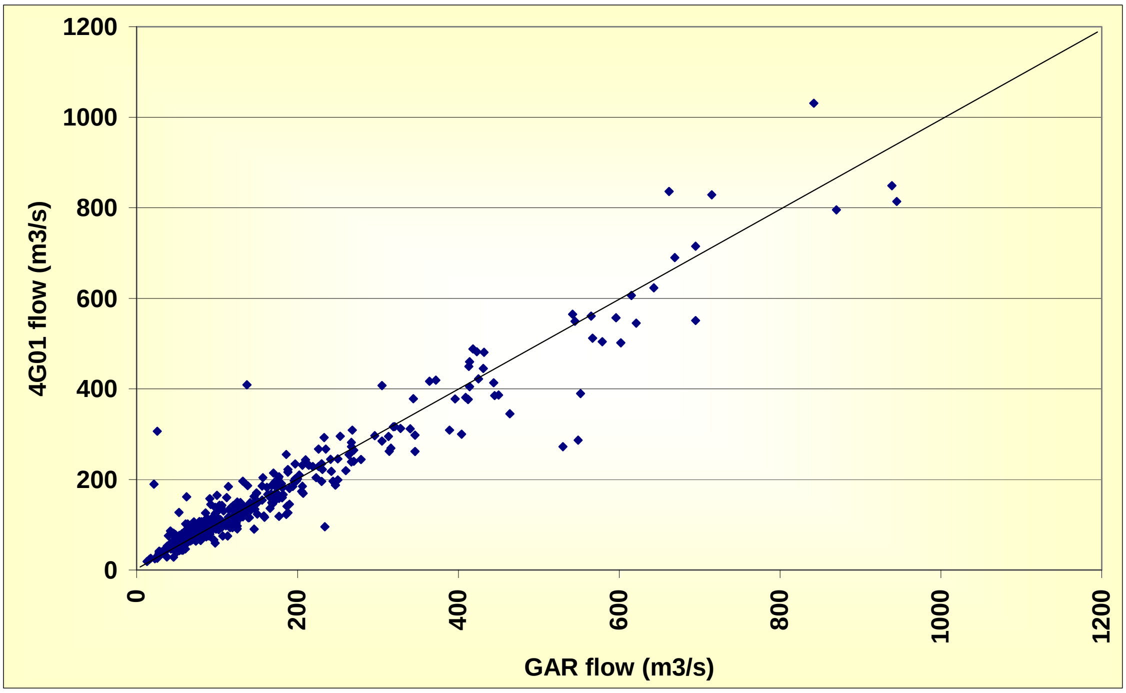


Figure 34: Examples of the interpolation of flow data

Data quality also depends on the source. For example, data for Garissa were obtained from the University of Nairobi (UoN) and, also, GRDD. UoN provided daily records from 1941 to 1993, while GRDD supplied monthly data from 1934 to 1975. Figure 35 shows marked difference between these two data sources for the overlapping period of 1941 to 1975. Nonetheless, patterns are quite comparable in terms of peak and low flows are comparable for the two datasets.



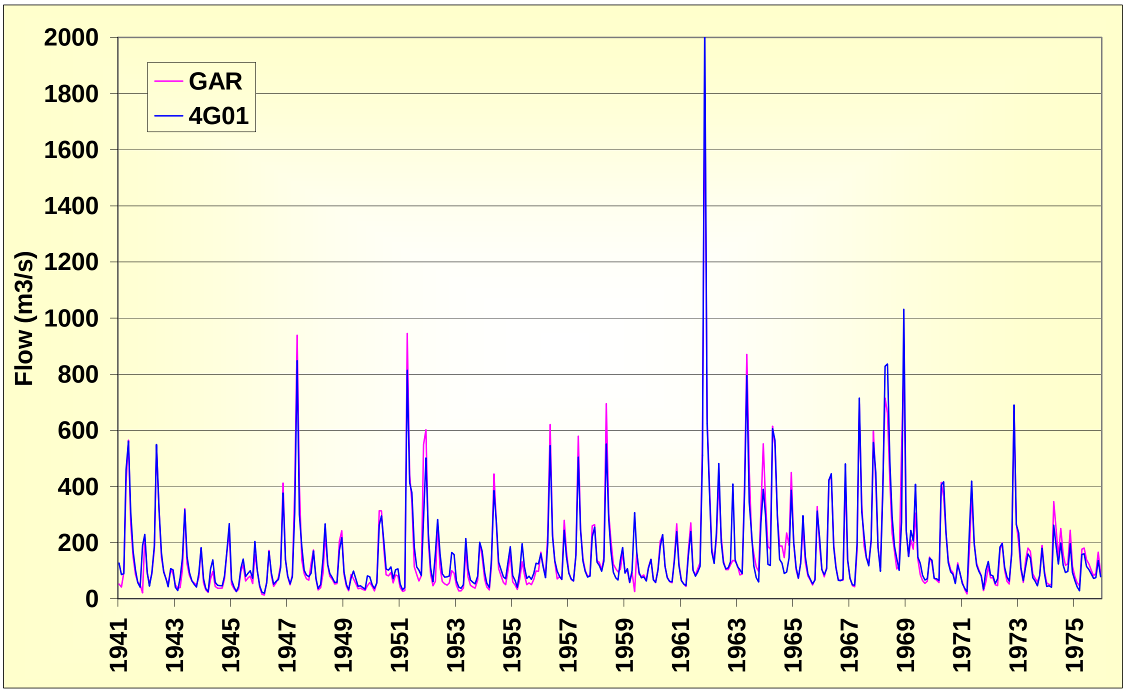


Figure 35: Comparison between data for Garissa from the Global Runoff Discharge Data (GAR) and from University of Nairobi (4G01)

Besides data from gauging stations, reservoir data on inflow and outflow were obtained from UoN and KenGen. For Masinga inflow and outflow data were available, while for the other reservoirs (Kamburu, Gitaru, Kindaruma, and Kiambere) only inflow and levels were obtained. Figure 36 shows the damping effect of the reservoir on stream flow and, also, that the capacity of Masinga is not sufficient to store all peak flows.

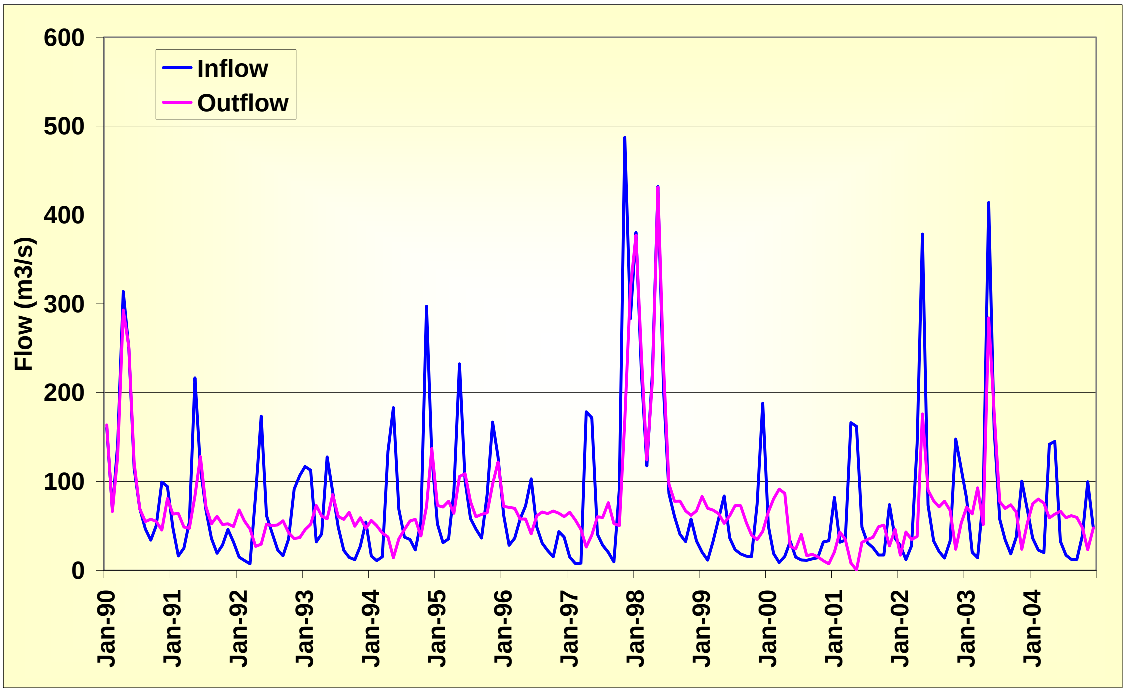


Figure 36: Inflow and outflow from Masinga reservoir

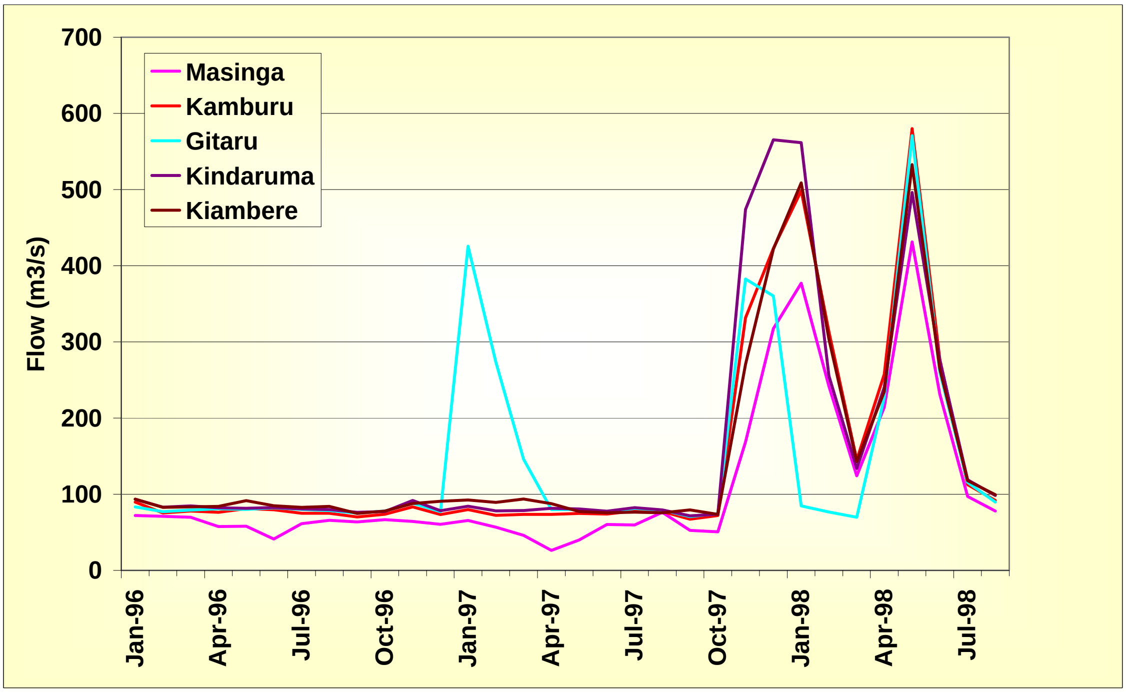


Figure 37: Outflow from main Tana reservoirs

5 Field-scale green water management scenarios

5.1 WOFOST

The effects of the proposed green water management practices on *green* and *blue* water flows at farmers' field level were calculated with WOFOST, following the water balance equation:

$$\mathbf{P} = \mathbf{R} + \mathbf{T} + \mathbf{E} + \mathbf{D} + \mathbf{\Delta W}$$

where:

P = precipitation,
R = runoff,
T = transpiration,
E = evaporation from the soil surface,
D = deep percolation
ΔW = difference in water stored in the soil at the beginning and at the end of the growing period.

WOFOST uses daily time steps to calculate the water balance for the proposed runoff-reduction and evaporation-reduction scenarios for specific local conditions of climate, soil and land use. For the proof of concept, maize is selected as the crop and runoff-reduction of 0, 10, 20, 30 and 40 per cent and evaporation reduction of 0 and 40 per cent are simulated. Results are aggregated over the two growing seasons per year.

5.2 Data input

5.2.1 Climate

Data for radiation, temperature, relative humidity, run of wind, rainfall and number of rain days for 7 met-stations representing the main climatic zones in the Upper Tana were used (Table 12).

Table 12: Selected meteorological stations in the Upper Tana

Zone - station	*Elevation (m)*	*Record Period*	*Mean Rainfall, mm*	*Maximum Rainfall, mm*	*Minimum Rainfall, mm*
I Embu Forest	1935		1992		
IIa Embu	1493	1908 - 1994	1257	1934	562
IIb Meru	1554	1914 - 1994	1191	2950	649
III Mwea	1159	1980 - 1994	948	1298	642
IV Thika	1463	1980 - 1994	858	1287	552
V Makindo	1000	1904 - 1991	611	1254	184
VII Garissa	147	1931 - 1996	282	808	70
VI Galole	100		470		

5.2.2 Crops

WOFOST is operational for a wide range of crops. Maize was chosen for the proof-of-concept, being the staple cereal in the Upper Tana. For each climatic zone the maize variety crop parameters TSUM1 and TSUM2 were chosen to represent the temperature regime of that zone (Table 13); the Upper Tana has two rainy seasons, giving two growing periods.

Table 13: Crop parameters TSUM1 and TSUM 2 and length of growing period

Climatic zone	*Growing period*	*TSUM1[(b)]*	*TSUM2[(b)]*	*Start month of GP*	*End month of GP*
I	GP1[(a)]	703	791	2	6
IIa	GP1	623	700	3	6
IIb	GP1	664	746	3	6
III	GP1	694	781	3	6
IV	GP1	831	935	3	6
V	GP1	851	957	3	6
VI	GP1	1108	1247	3	6
VII	GP1	928	1043	3	5
I	GP2	515	579	9	12
IIa	GP2	450	506	10	12
IIb	GP2	479	539	10	12
III	GP2	511	575	10	12
IV	GP2	613	690	10	12
V	GP2	632	712	10	12
VI	GP2	1072	1206	9	12
VII	GP2	889	1001	10	12

(a) GP1 = first growing period, GP2 = second growing period

(b) TSUM1 is the temperature sum from germination to anthesis; TSUM2 the temperature sum from anthesis to maturity

5.2.3 Soil

WOFOST calculates a soil-crop-atmosphere water balance using a minimum soil dataset, as available in KENSOTER-version 2 (Table 14).

5.3 Runoff reduction

The water balance for the various green water management scenarios are presented for the average over the period 1980 – 1989 and, also, for a *dry year* and a *wet year*. The results are carried forward to the basin-scale SWAT modeling.

For simplicity, maize results are presented for the whole of climate zones I to V (Zones VI and VII are too dry for rain-fed maize) although this is an over-simplification. The WOFOST calculations are made to assess at field level the effects of soil and crop management on the water balance and yield.

Table 14: Soil water characteristics of main soil types in the Upper Tana

Dominant soil and phase	*Rooting depth (cm)*	*Water content at saturation (%)[a]*	*Water at field capacity (%)*	*Water at wilting point (%)*	*Available water[b] (%)*	*Total available water[c] (mm)*
Acrisol haplic	113	56	24	16	9	98
Andosol mollic	75	69	41	30	11	82
Andosol umbric	125	50	38	17	21	262
Arenosol ferralic	100	53	16	3	13	130
Chernozem calcic	75	55	37	21	16	120
Calcisol petric	40	41	16	10	6	24
Cambisol calcaric	25	36	24	14	10	25
Cambisol eutric	88	49	26	12	14	121
Cambisol gleyic	50	47	27	13	14	70
Cambisol humic	40	52	34	18	16	64
Cambisol chromic	75	52	27	13	14	105
Cambisol chromic (lithic)	45	52	22	9	13	58
Cambisol chromic (rudic)	50	51	36	21	15	75
Fluvisol calcaric	60	47	17	4	13	78
Fluvisol eutric	125	41	17	4	13	162
Ferralsol rhodic	135	54	26	16	10	127
Ferralsol rhodic (lithic)	45	52	25	17	8	36
Gleysol eutric	45	56	37	21	16	72
Leptosol eutric	15	48	10	5	5	8
Leptosol lithic	5	57	31	18	13	6
Luvisol ferric	75	53	35	19	16	120
Luvisol haplic	65	46	22	9	13	84
Luvisol chromic	100	43	18	10	8	80
Lixisol ferric	100	48	12	8	4	40
Lixisol haplic	75	46	20	14	6	45
Nitisol haplic	90	52	32	22	10	95
Nitisol rhodic	100	53	28	20	8	80
Nitisol humic	123	56	34	23	10	119
Phaeozem haplic	75	55	38	30	8	60
Phaeozem luvic	85	57	38	22	16	136
Planosol eutric	25	50	35	22	13	33
Regosol calcaric (rudic)	40	55	25	11	14	56
Regosol dystric (lithic)	30	46	23	12	11	28
Regosol eutric (lithic)	40	42	8	4	4	16
Solonetz gleyic	25	41	20	6	14	35
Solonetz haplic	30	48	35	19	16	48
Vertisol eutric	80	50	46	22	24	191

(a) Volume %; (b) Available water or plant extractable water; (c) Available water within rootable depth

The effects of green water management on runoff, transpiration, deep-percolation (groundwater recharge) and evaporation from the soil surface are depicted in Figure 38 as a percentage of the annual rainfall (note that in the *Runoff 0 scenario*, there will be some runoff, because the infiltration rate is set at 100 mm/day - so runoff may occur in high-intensity showers of greater intensity).

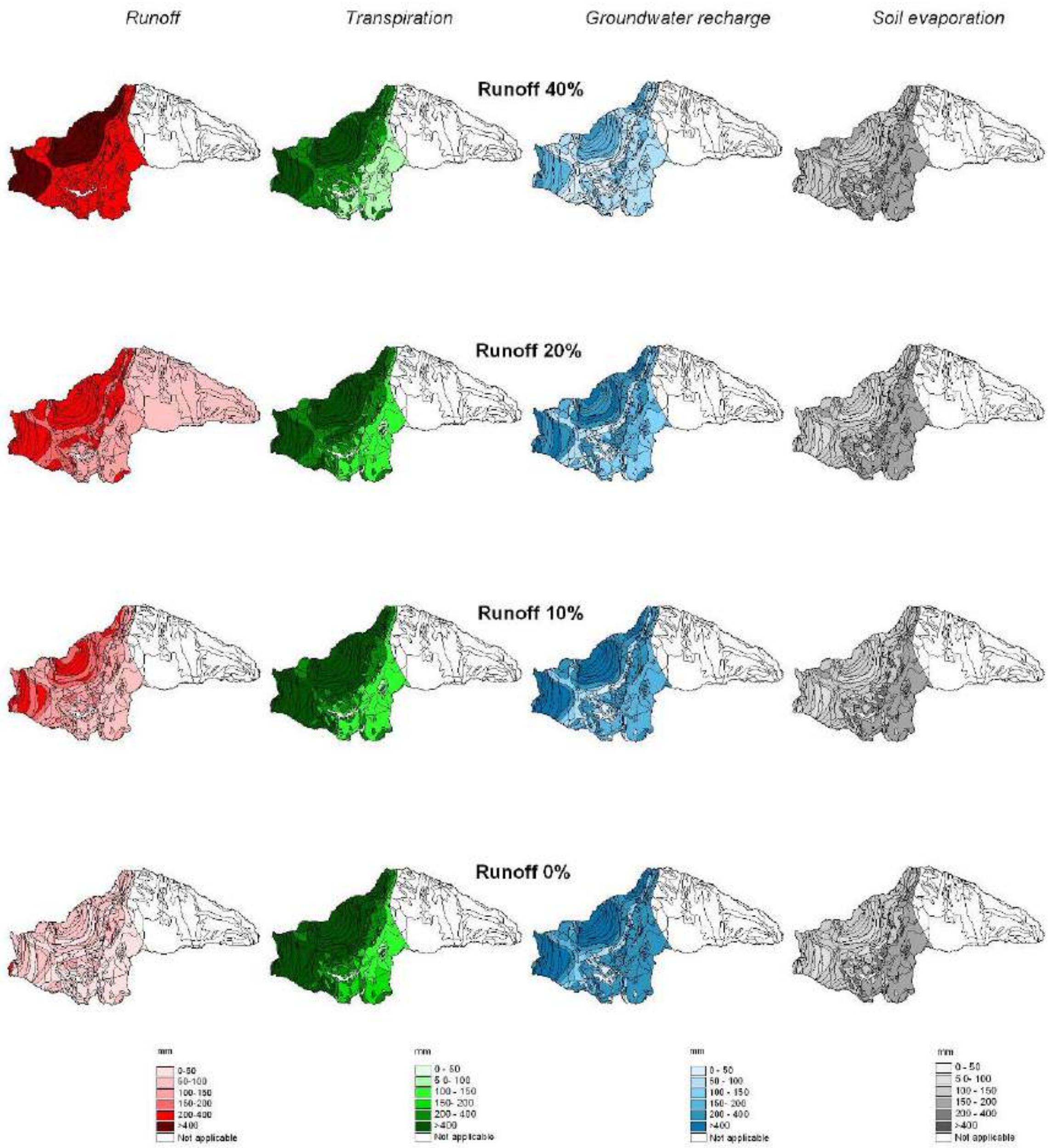


Figure 38: Water balance effects under scenarios of 0, 10, 20 and 40% runoff reduction , averaged for 1980-1989

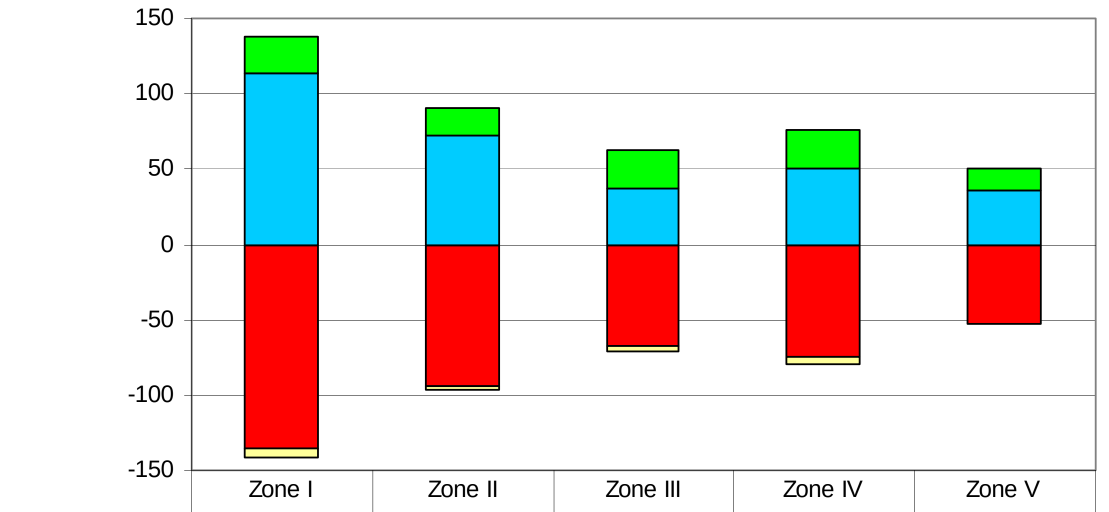
High elevation moist temperate (climatic zones I, II, III and IV): In all scenarios, runoff and groundwater recharge are strongly correlated - the less the runoff, the greater the groundwater recharge. Only in case of high runoff (greater than 20-40 per cent) is transpiration and, thus, crop yield reduced. In this situation, improved soil management will lead to a greater infiltration, increasing both groundwater recharge and *green water* available for crops.

Low elevation dry hot areas (climatic zones V, VI and VII): Although rainfall is lower than in the highlands, green water management will still lead to greater infiltration and groundwater recharge - although less than in the high rainfall zone; most benefit will be felt in greater *green water* resources.

Table 15 and Figure 39 summarise changes to the water balance. Effects depend on the climatic zone. Runoff reduction results in an increase of both deep-percolation and transpiration. The increase in transpiration (*green water flow*) is beneficial for increase in crop yield; however it will reduce total *blue water* flow – though not groundwater recharge and river base flow.

Table 15: Mean changes on the water balance for two runoff-reduction scenarios, 1980-1989, (mm)

Scenario	*Climatic zone*	*Evaporation*	*Transpiration*	*Percolation*	*Runoff*
Runoff from 20% to 10%					
	I	-7	24	114	-135
	II	-1	12	69	-90
	III	-3	25	37	-68
	IV	-5	26	50	-75
	V	0	15	36	-53
Runoff from 40% to 20%					
	I	-12	57	210	-279
	II	-4	46	120	-185
	III	-11	75	51	-140
	IV	-8	60	96	-159
	V	0	35	61	-106



	Zone I	Zone II	Zone III	Zone IV	Zone V
Transpiration	24	18	25	26	15
Evaporation	-7	-3	-3	-5	0
Groundwater	114	72	37	50	36
Runoff	-135	-94	-68	-75	-53

Figure 39: Mean annual changes on the water balance for runoff reduction, 1980-1989, (mm)

Reduction in *blue water flow* resulting from greater transpiration may be compensated by a reduction of unproductive evaporation from the soil surface. Figure 40 shows the effects of evaporation reduction during the growing period (if evaporation-reduction is also applied during the months outside the growing period, then potential evaporation and evaporation reduction will be at least double). It is clear that any reduction in blue water flows from increased transpiration may be more than compensated by evaporation reduction. The combined effects of runoff-reduction and evaporation-reduction measures at basin level are calculated in Section 7.2.

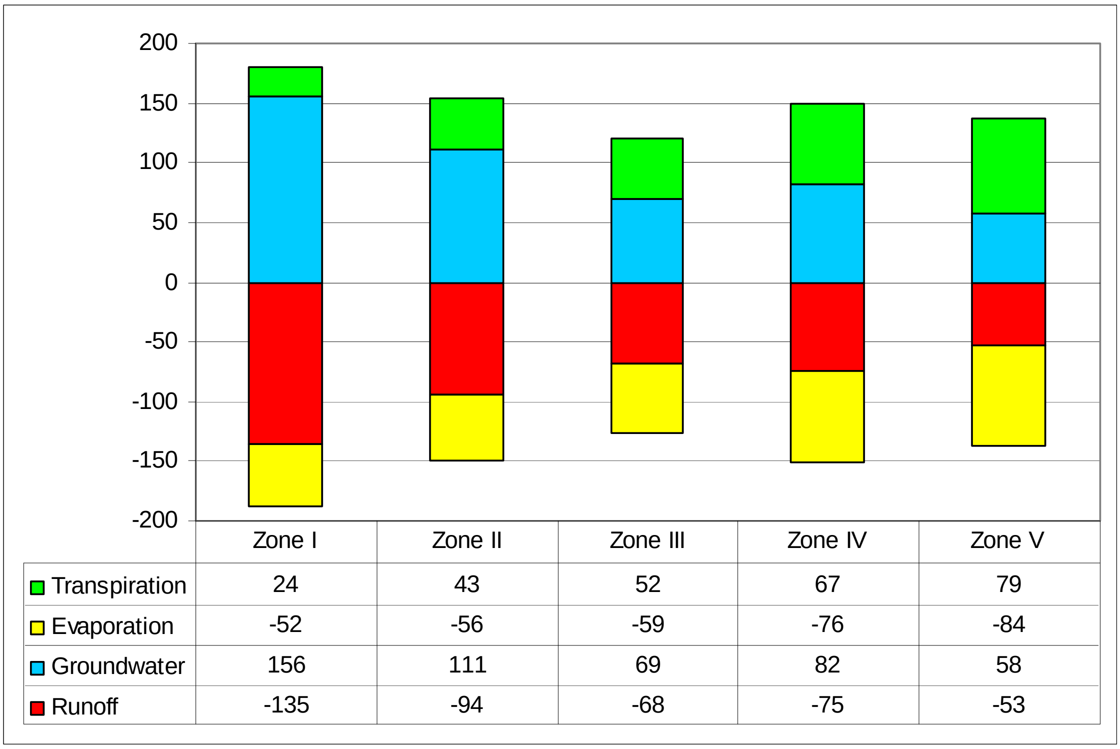


Figure 40: Mean annual water balances for the combination of 40% evaporation-reduction and a 20 to 10% runoff-reduction scenarios, 1980-1989

The runoff-reduction scenarios for a dry year (1987) and for a wet year (1988) are presented in Table 16 and Table 17.

Table 16: Changes on the water balance by runoff reduction for a dry year (mm)

Scenario	*Climatic zone*	*Evaporation*	*Transpiration*	*Percolation*	*Runoff*
Runoff from 10% to 20%					
	I	0	4	132	-143
	II	-1	12	41	-70
	III	7	7	23	-47
	IV	3	4	51	-59
	V	7	5	4	-26
Runoff from 20% to 40%					
	I	1	19	247	-299
	II	8	65	45	-140
	III	5	28	44	-95
	IV	13	8	123	-151
	V	20	8	0	-50

Table 17: Changes on the water balance by runoff reduction for a wet year, mm

Scenario	*Climatic Zone*	*Evaporation*	*Transpiration*	*Percolation*	*Runoff*
Runoff from 10% to 20%					
	I	0	9	126	-139
	II	0	7	130	-140
	III	-3	23	74	-98
	IV	-4	32	62	-97
	V	0	12	44	-60
Runoff from 20% to 40%					
	I	-1	29	235	-289
	II	-4	26	250	-297
	III	-16	81	90	-197
	IV	-26	89	127	-204
	V	1	31	84	-122

6 Basin-scale soil and water management scenarios

A SWAT model for Upper Tana has been built using the data and assumptions presented in the foregoing Sections. The objective is to demonstrate the technical feasibility and viability of Green Water Credits by evaluating green water management scenarios in terms of potential downstream water benefits. This does not require a full calibration and verification of the model, although this will be needed for operational design of the mechanism for the Tana Basin. SWAT has been run for three successive years: 1995 was used to generate initial conditions, 1996 and 1997 represent a dry year and a wet year, respectively. If required, the model may be run for any other period for which meteorological data are available, including for climate-change scenarios generated by general circulation models.

6.1 Observed and simulated flows

A few gauging stations have records for 1995-1997: 4CB04, Thika river, receiving water from the Aberdares; 4DD01, Thiba river, contributing to flows into Kamburu reservoir; GRF, Tana river at Grand Falls; MAS, total inflow to Masinga reservoir (sub-basin 78); KIA, total inflow in Kiambere reservoir (sub-basin 82). Comparison of observed and simulated results (Figure 41 to Figure 45) indicates that low flows (Thika), intermediate flows (Thiba) and high flows are all well simulated. All simulated flows in May 1997 are higher than the observed flows; probably, high rainfall was measured at one station that is used to represent large parts of the basin (the more precise satellite-measured Tropical Rainfall Measuring Mission data will be used for operational planning). No model calibration has been undertaken for the present study; calibrating some of the unknown parameters would be expected to improve the performance of the model.

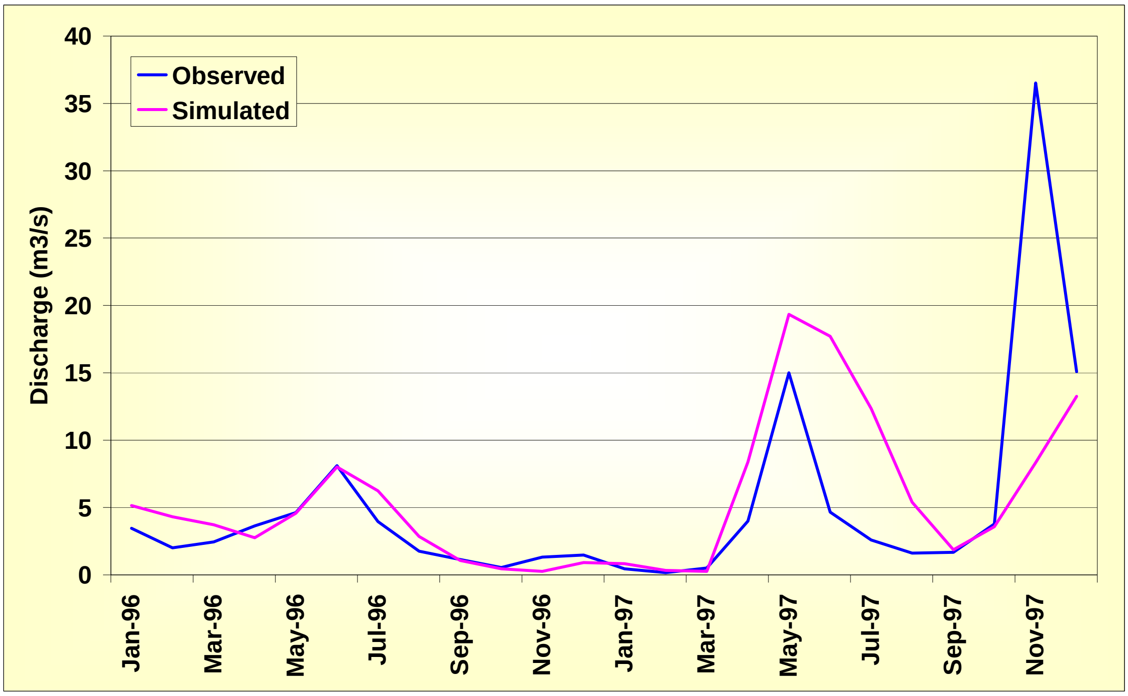


Figure 41: Observed and simulated flows of Thika river (4CB04)

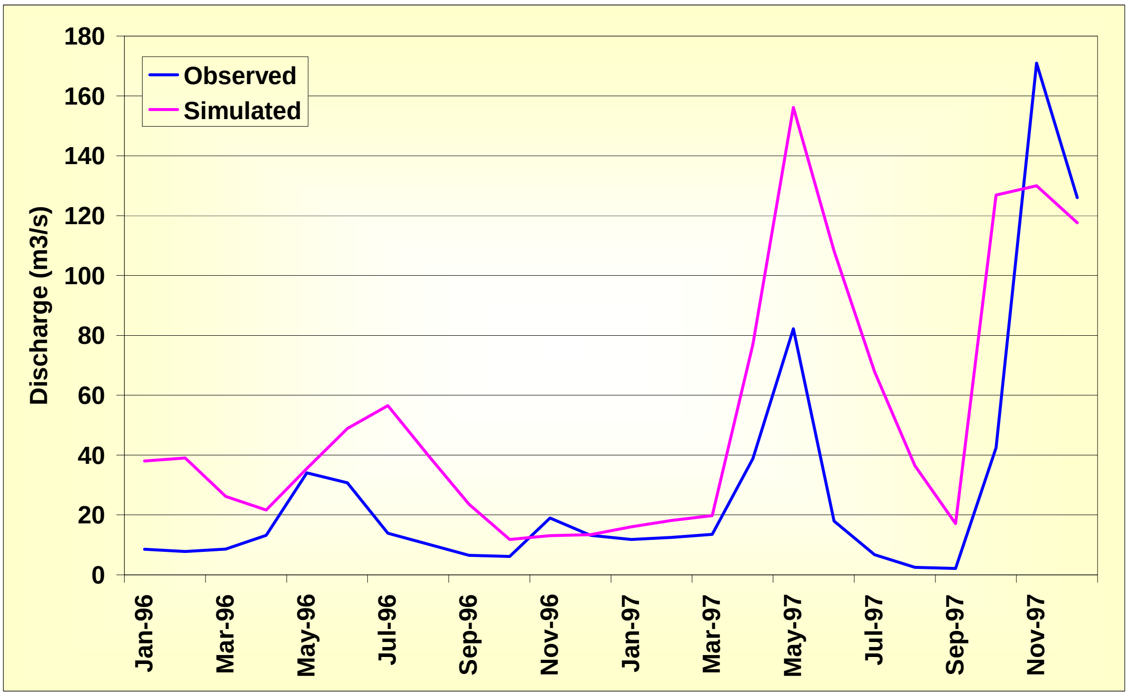


Figure 42: Observed and simulated flows of Thiba river (4DD01)

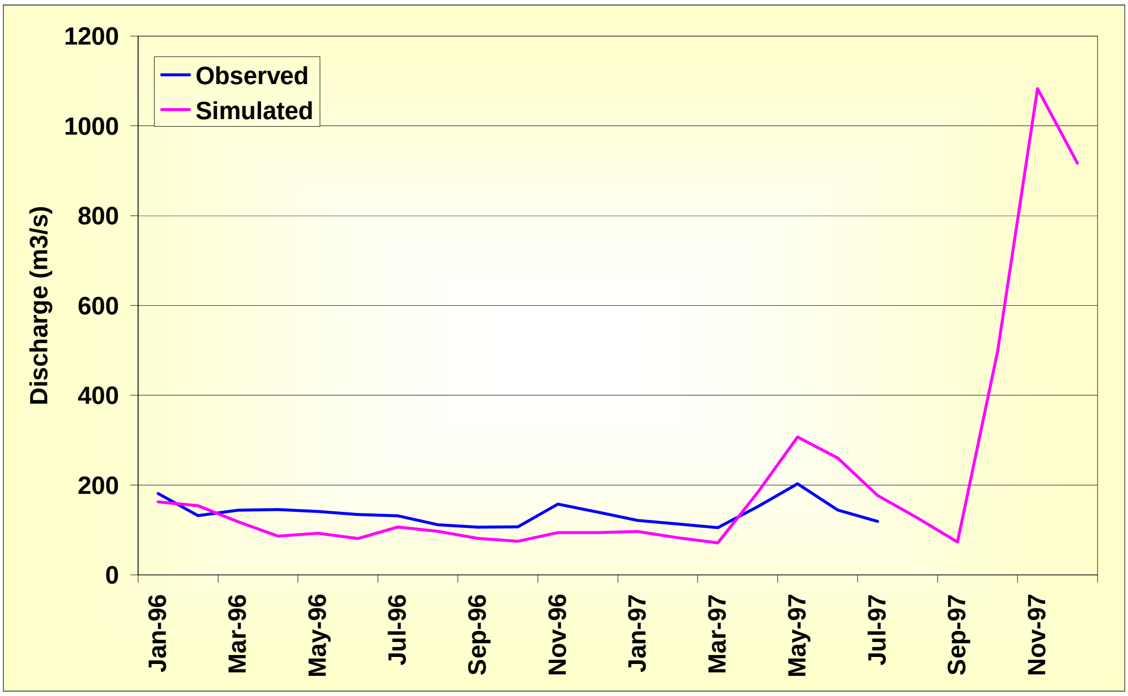


Figure 43: Observed and simulated flows of Tana River at Grand Falls (GRF)

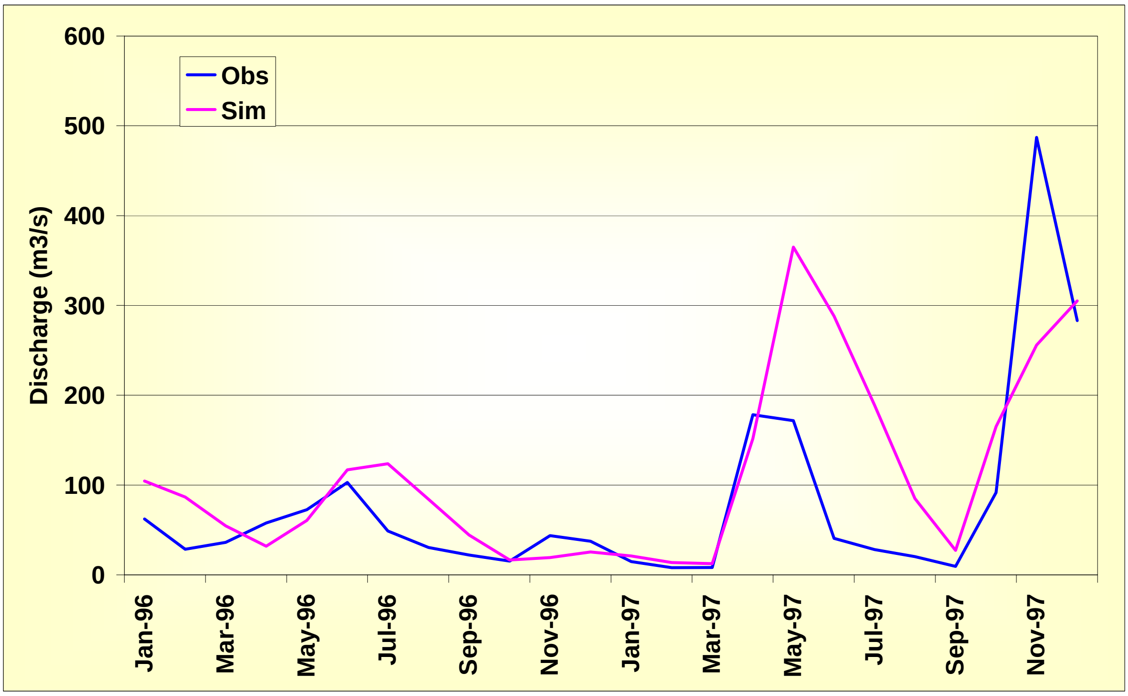


Figure 44: Observed and simulated inflows in Masinga reservoir (MasIn)

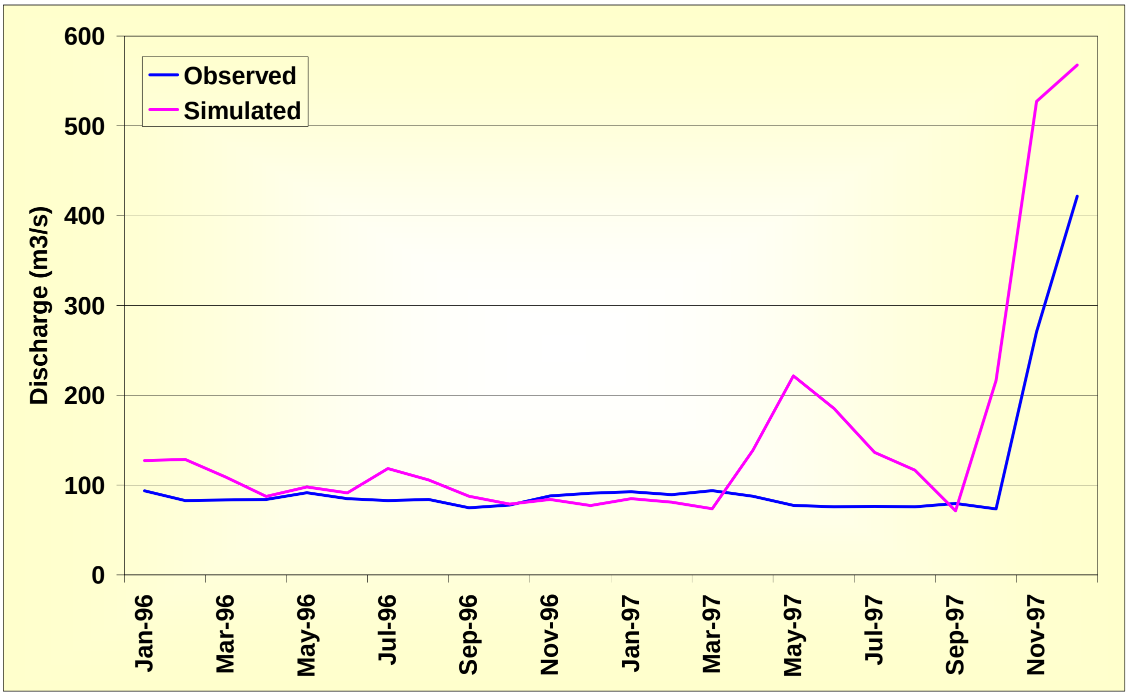


Figure 45: Observed and simulated inflows in Kiambere reservoir (KiaIn)

6.2 Inflow to Masinga reservoir

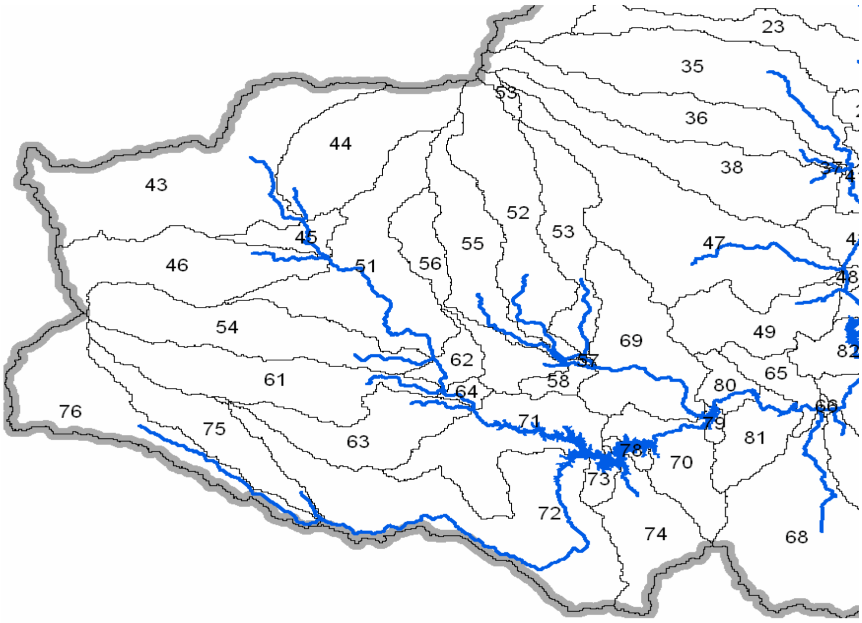


Figure 46: Tributaries to Masinga Reservoir as represented in SWAT

The Sagana, rising on Mount Kenya, is a bigger contributor to Masinga Reservoir (Figure 46) than the Thika, rising in the Aberdares: the two-year simulated mean flows are 18 m^3/s for the Thika river and 89 m^3/s for the Sagana (Figure 47). Stream-gauge data (stations 4be10 and 4cc05) show the same pattern; long-term mean flows are 16 m^3/s for Thika and 54 m^3/s for Sagana. But several tributaries to the Sagana are sourced in the Aberdares; the Masinga catchment comprises 1388 km^2 on Mt Kenya and 4728 km^2 on the Aberdares and Figure 48 shows that the contribution of Aberdares to the Masinga inflow is greater than that from Mt Kenya (80 compared with 26 m^3/s).

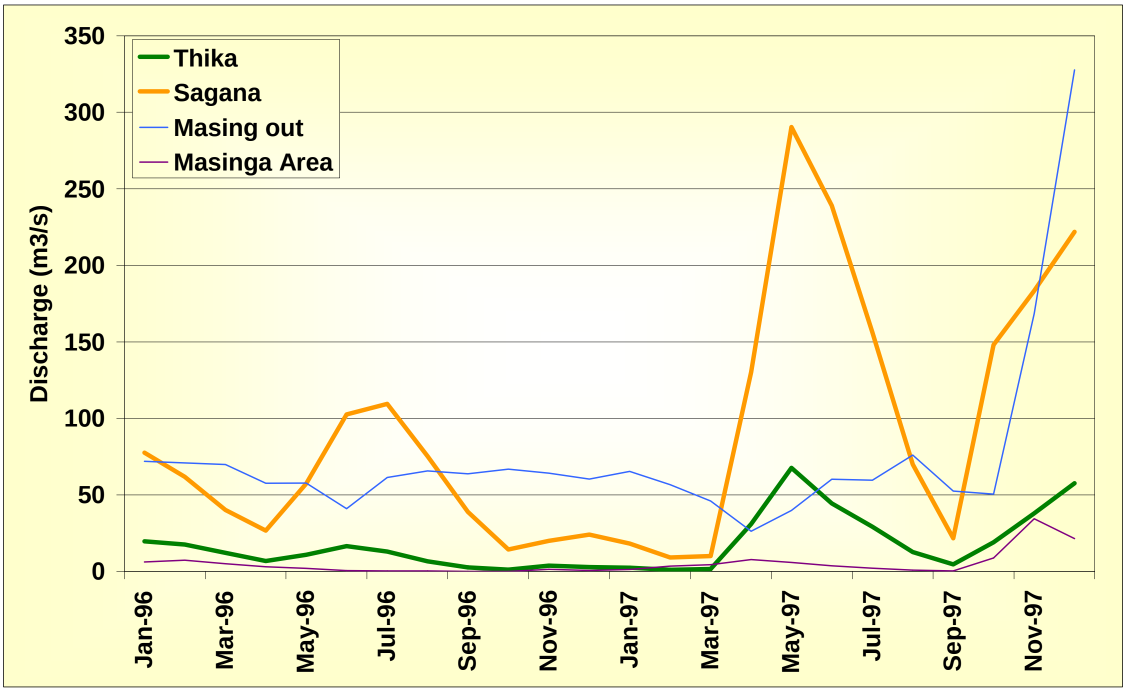


Figure 47: Simulated contribution of Thika and Sagana rivers to Masinga

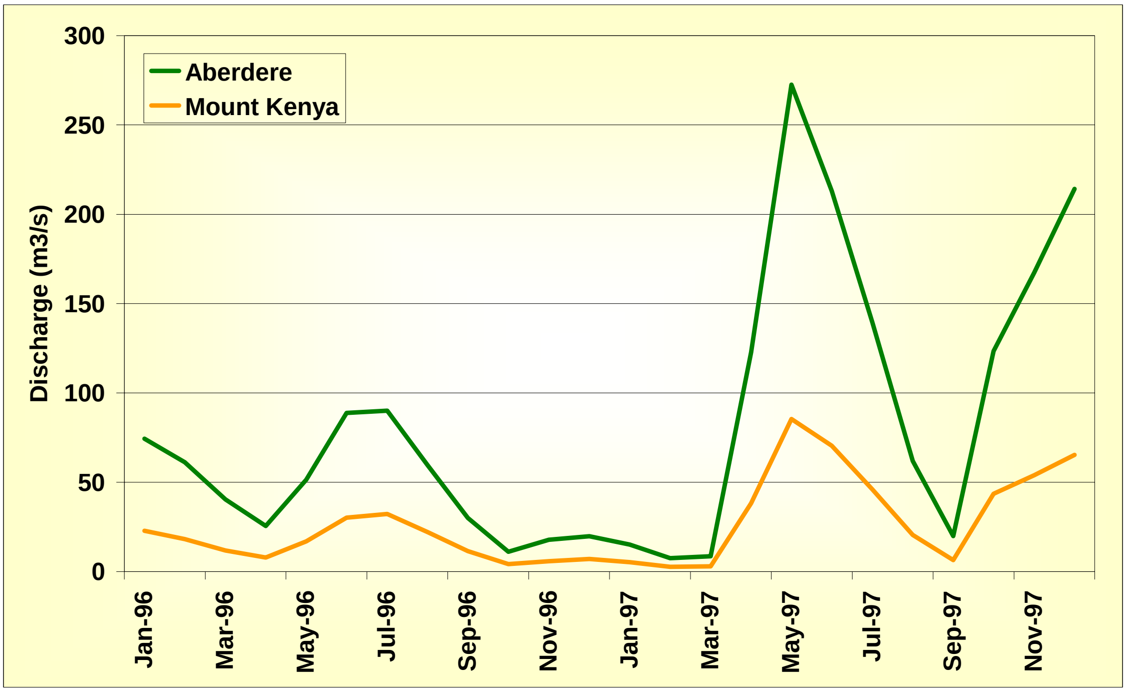


Figure 48: Simulated contribution of the Aberdares and Mt Kenya to Masinga

6.3 WOFOST input to SWAT

In SWAT, 72 out of the 874 HRUs are characterised as under maize cultivation, about 6 per cent of the study area. Figure 49 and Figure 50 show the monthly water balances for one area with maize, as simulated by SWAT.

6.4 Spatial patterns

To identify the areas where green water management will bring the greatest downstream water benefits, SWAT is used to map, for a representative dry year (1996) and a wet year (1997):

- Evapotranspiration: consumptive use of water by vegetation and evaporation from the soil surface (Figure 51);
- Transpiration: water use by vegetation (crops and semi-natural vegetation) to produce biomass; i.e. *green water* (Figure 52);
- Unproductive evaporation from the soil surface (Figure 53);
- T- percentage: percentage of consumptive use used in transpiration (Figure 54);
- *Blue Water*, entering the streams by runoff and seepage (Figure 55);
- Groundwater recharge: water recharging deep groundwater - water entering the shallow groundwater which will contribute to seepage to streams is included in *blue water* (Figure 56);
- Soil erosion: total soil loss (Figure 57).

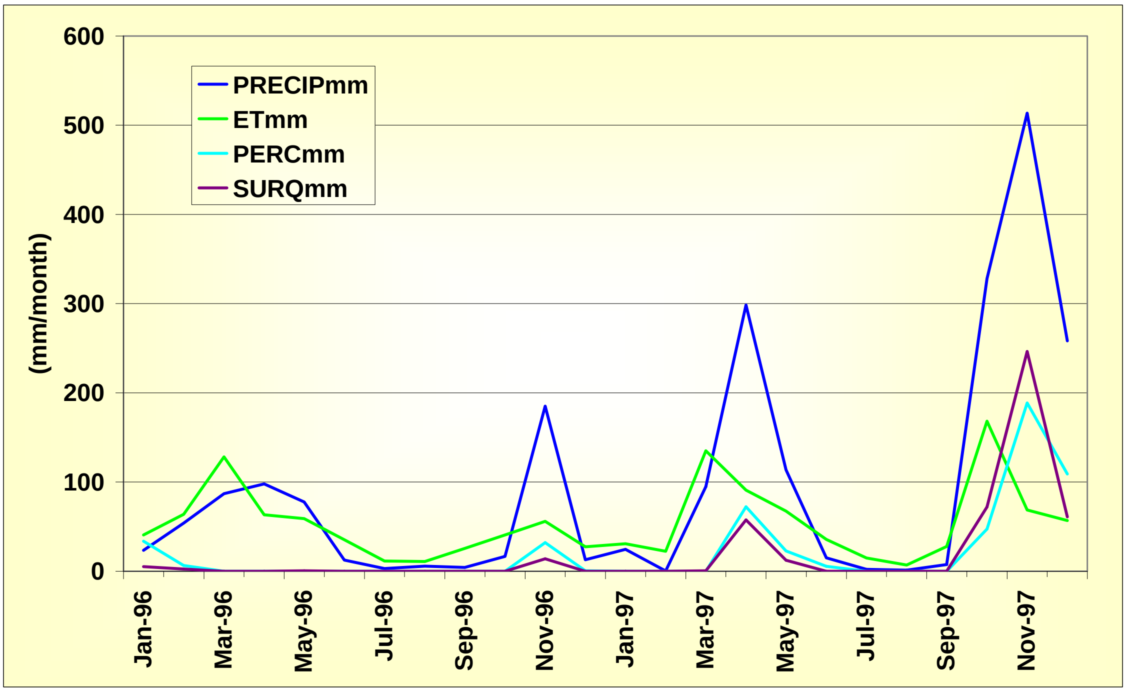


Figure 49: Monthly water balance under maize (HRU 686, sub-basin 68)

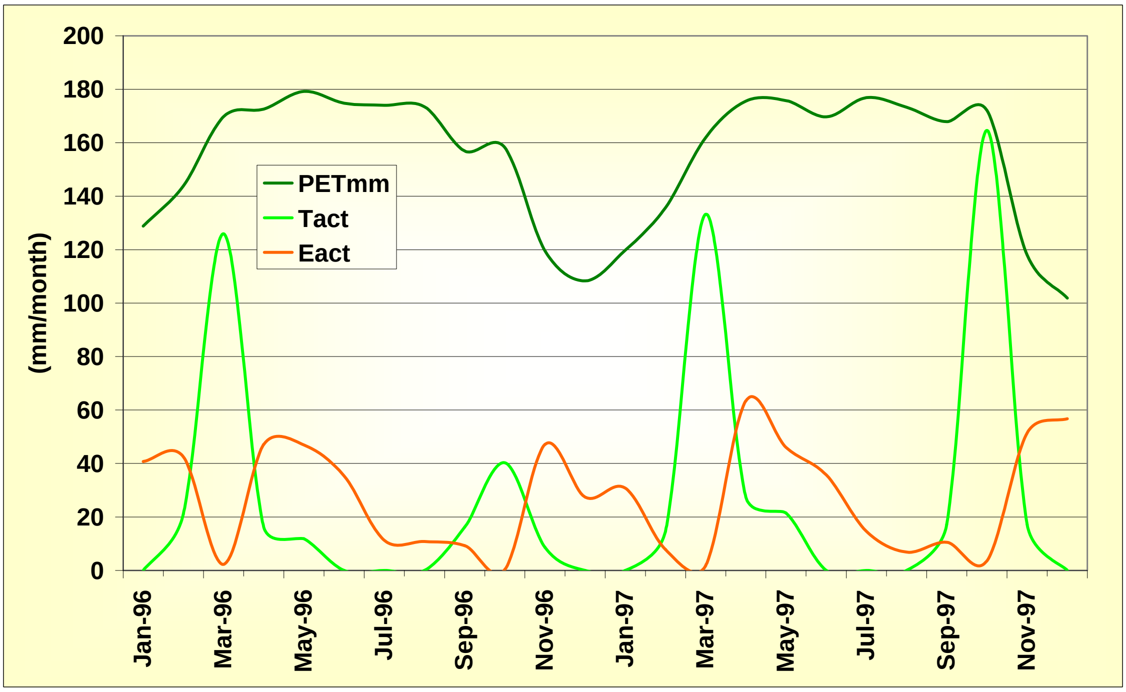
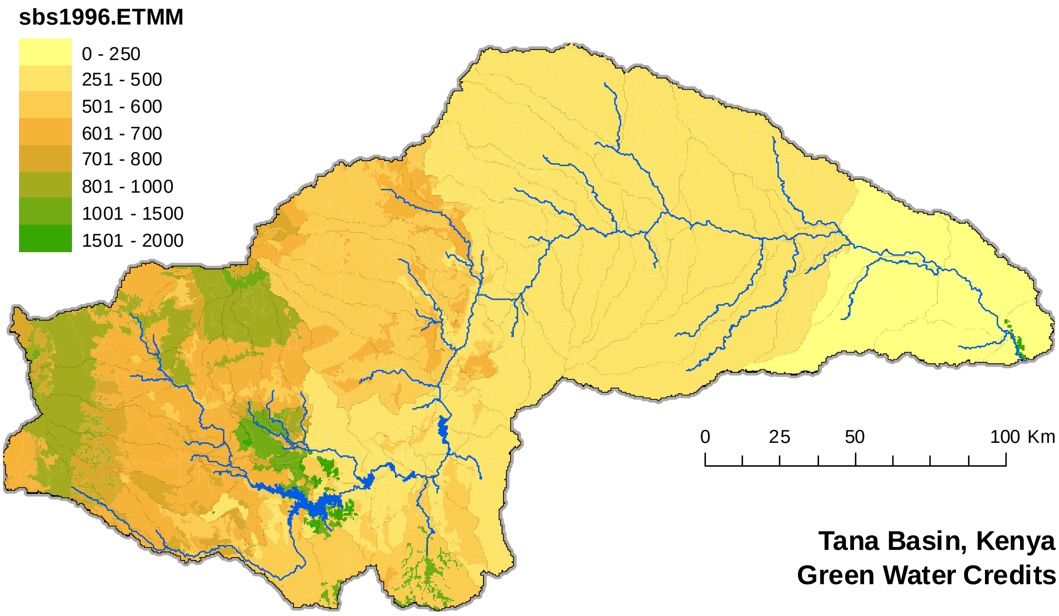


Figure 50: Potential and actual evapotranspiration under maize (HRU 686, sub-basin 68)



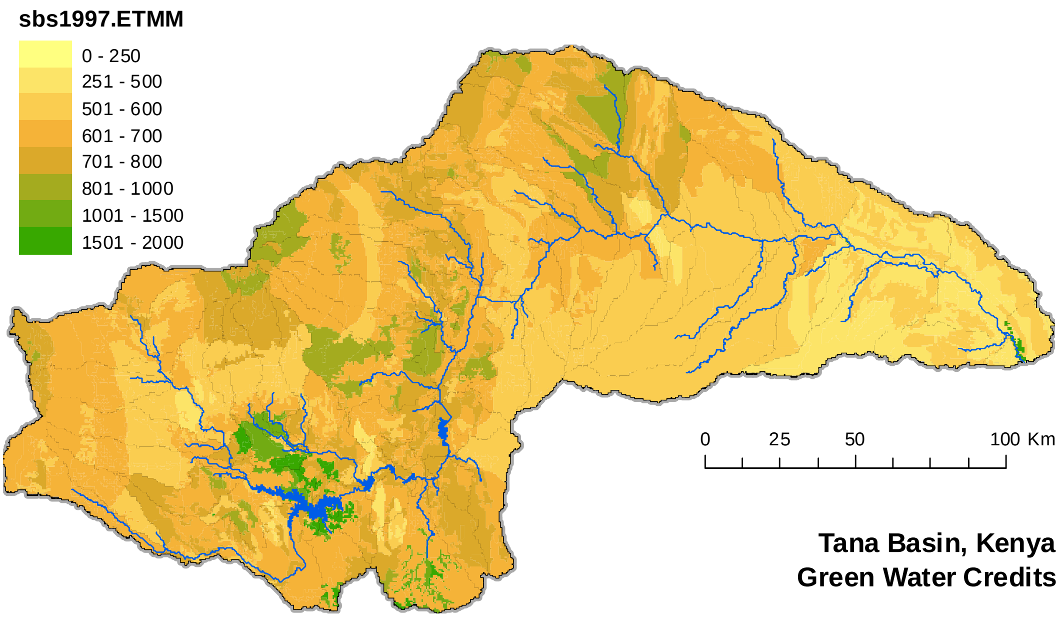
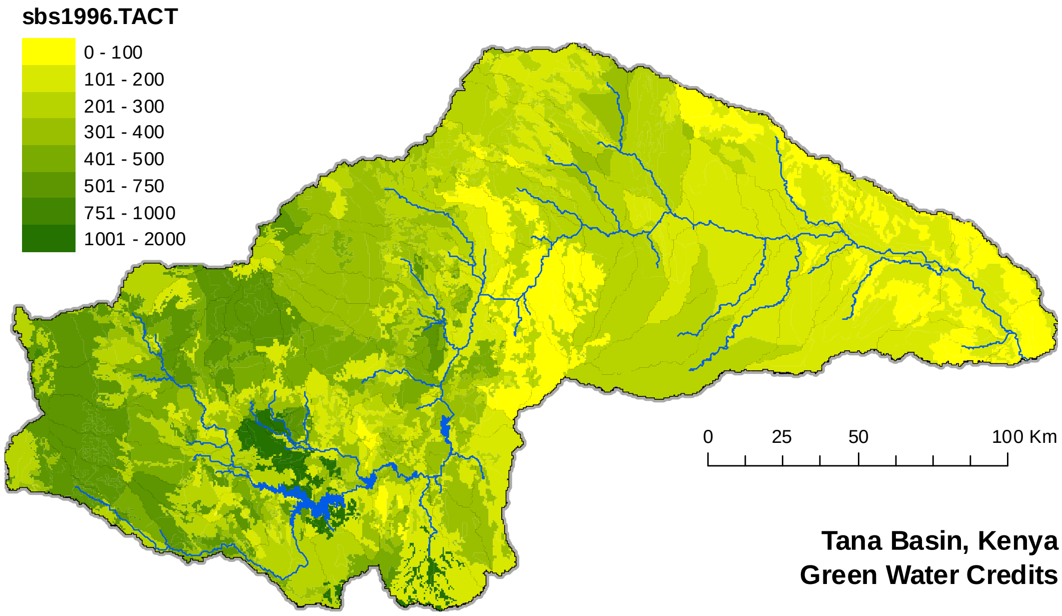


Figure 51: Actual evapotranspiration for a dry year (1996, top) and a wet year (1997, bottom), mm/yr



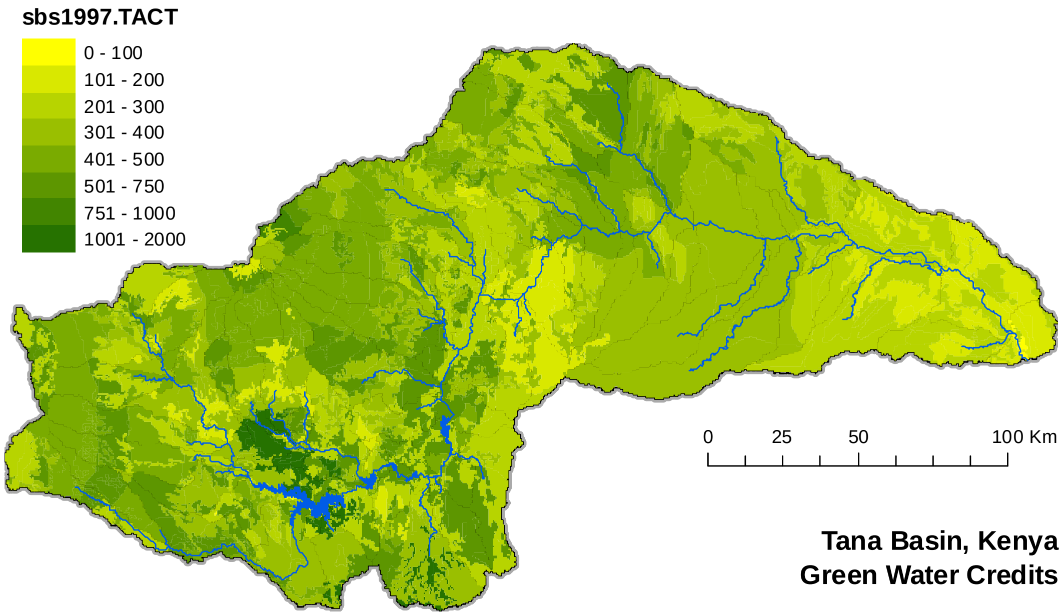


Figure 52: Transpiration *(green water)* for a dry year (1996, top) and a wet year (1997, bottom), mm/yr

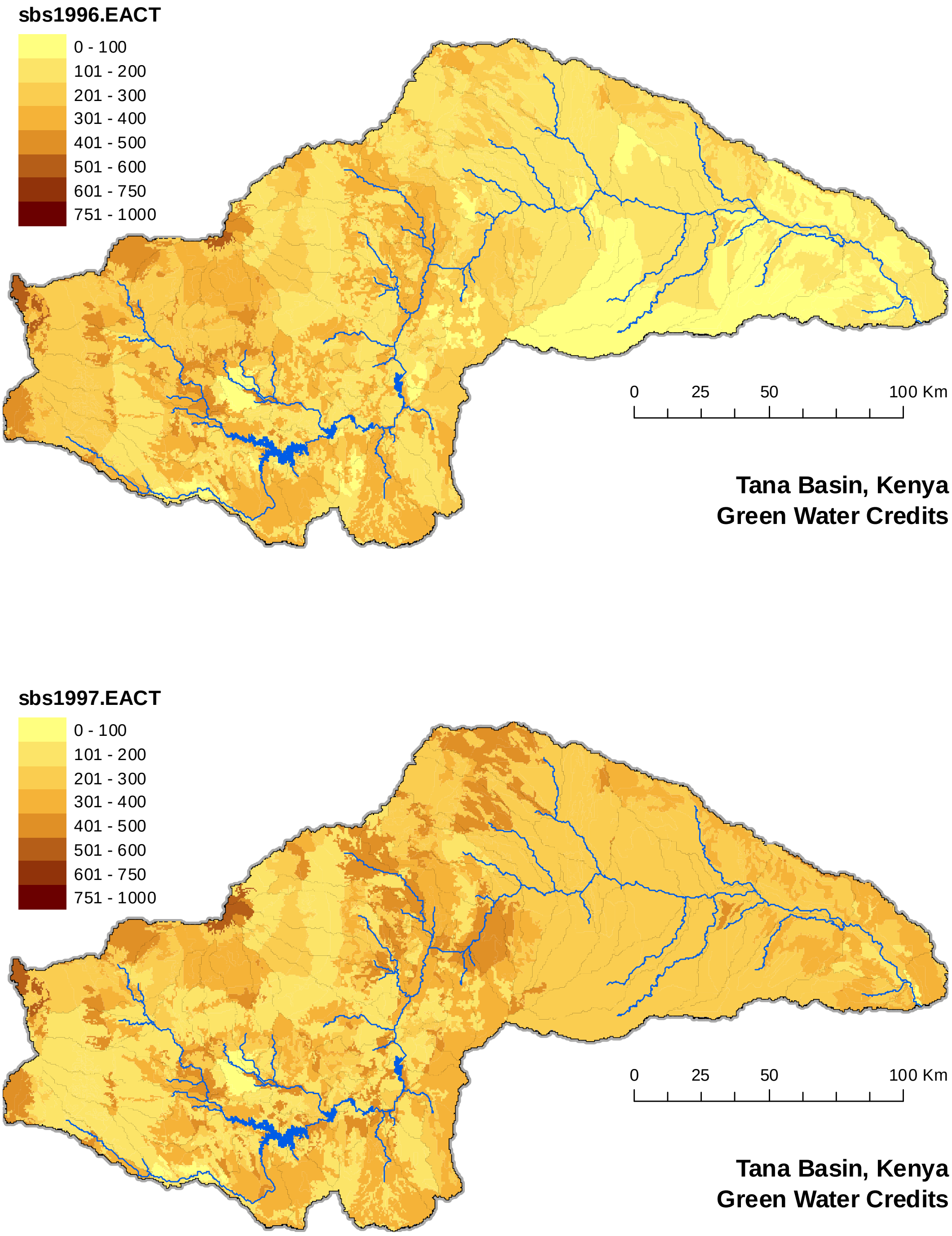
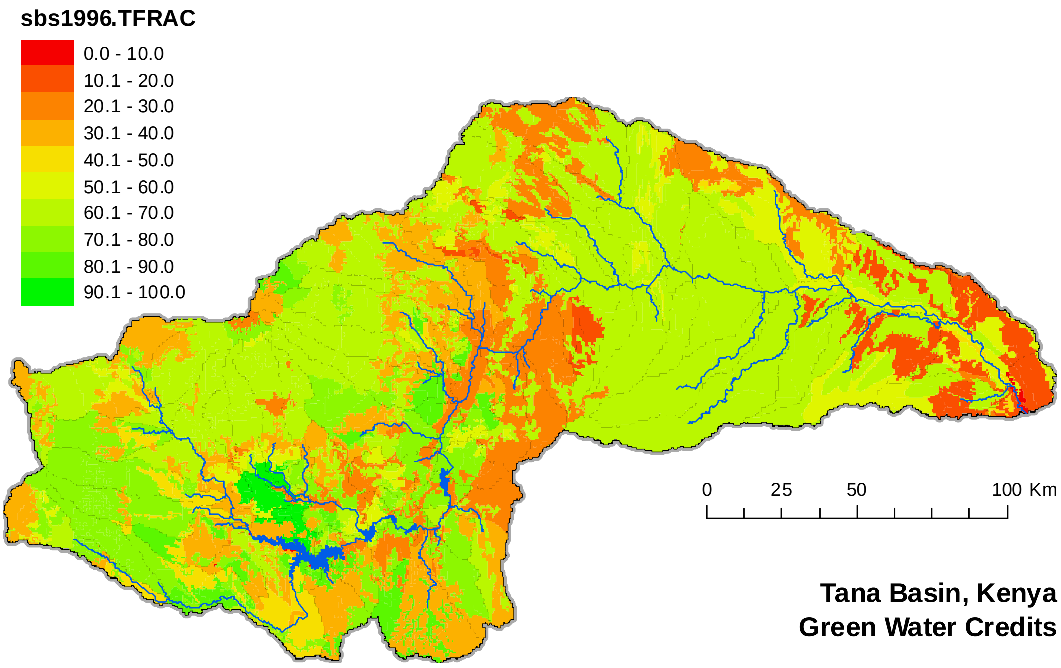


Figure 53: Evaporation from the soil surface for a dry year (1996, top) and a wet year (1997, bottom), mm/yr



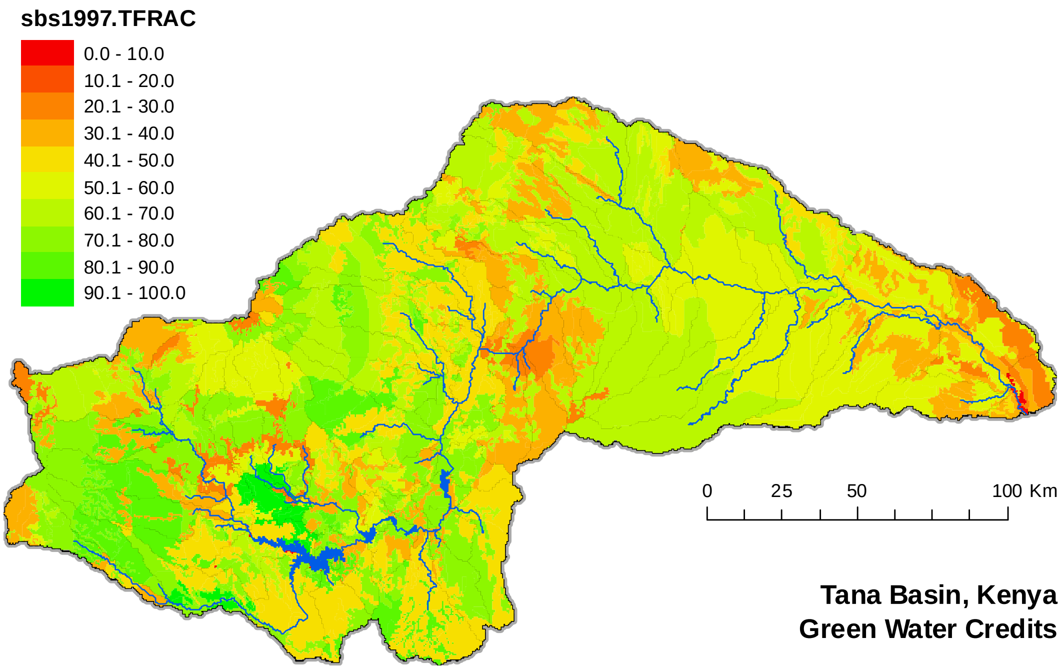
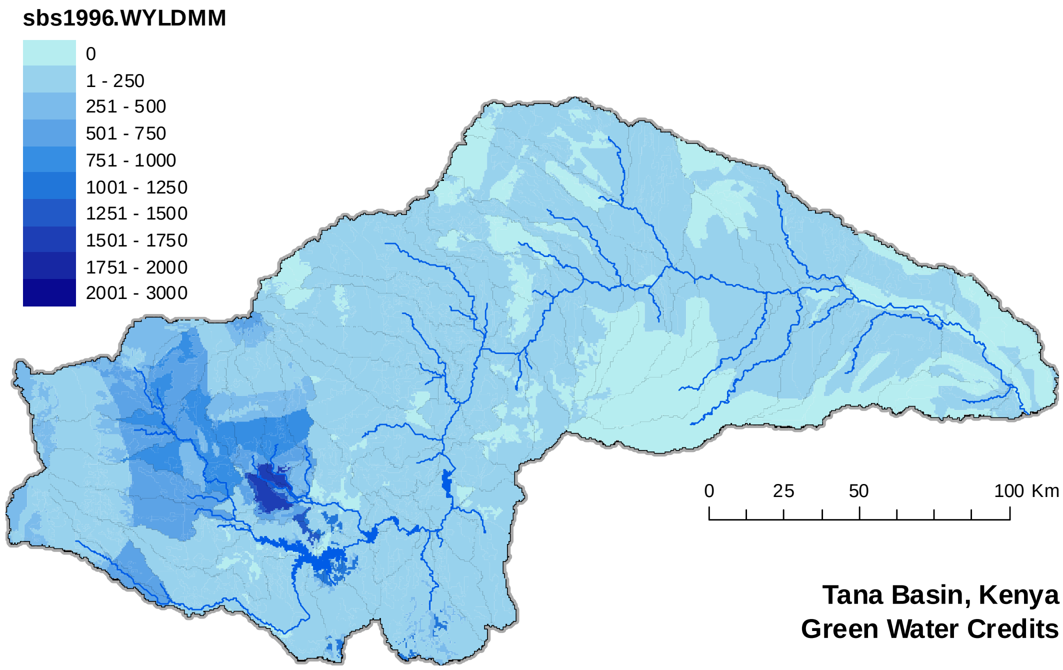


Figure 54: Percentage of total consumptive water use appearing as green water for a dry year (1996, top) and a wet year (1997, bottom)



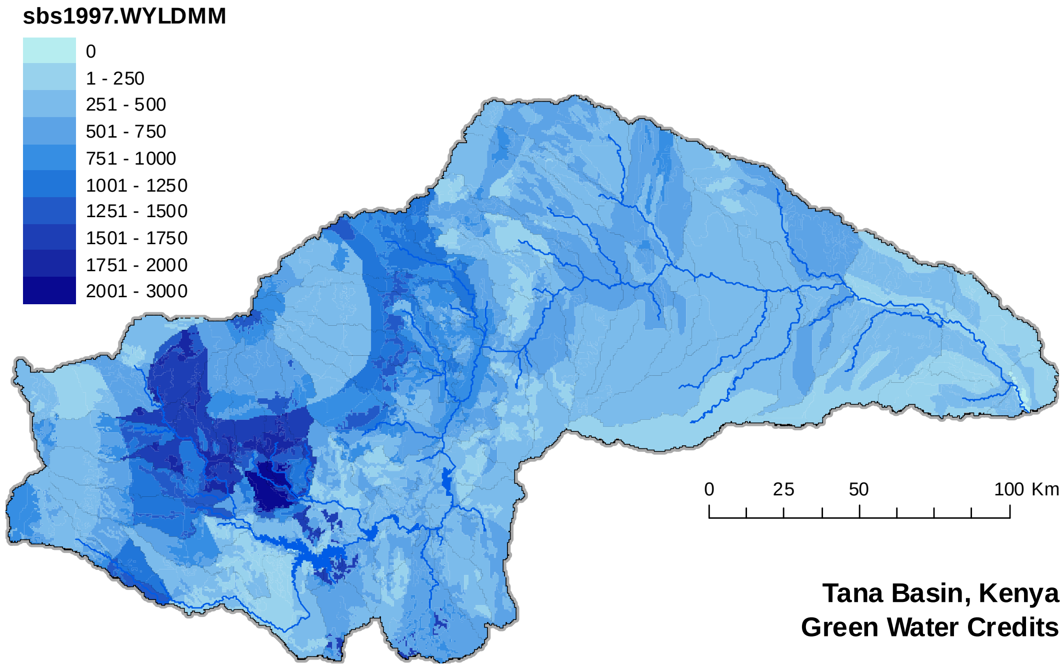
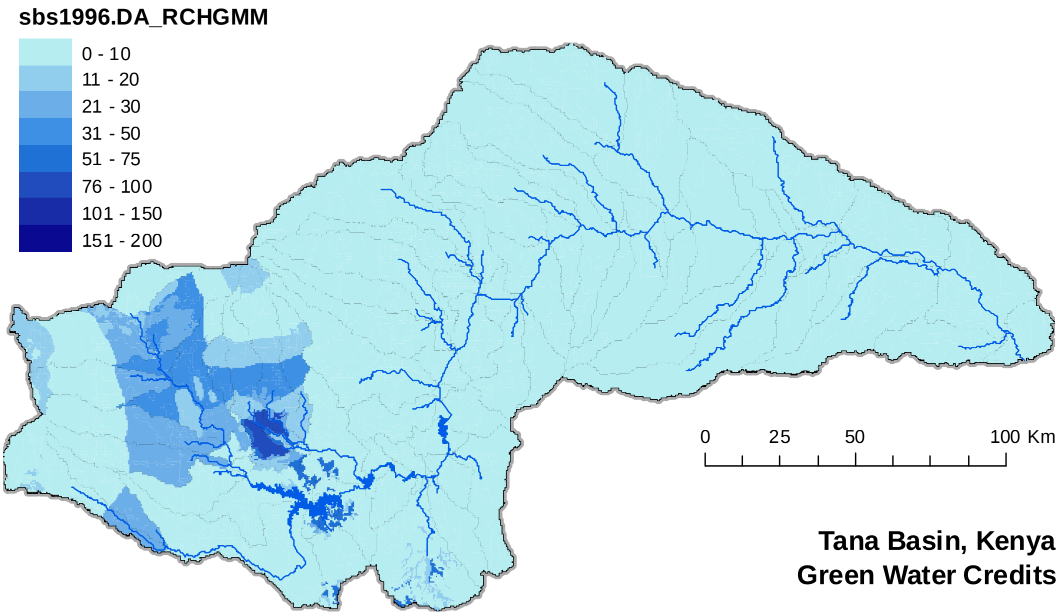


Figure 55: ***Blue water*** **(entering the streams by runoff and seepage) for a dry year (1996, top) and a wet year (1997, bottom), mm/yr**



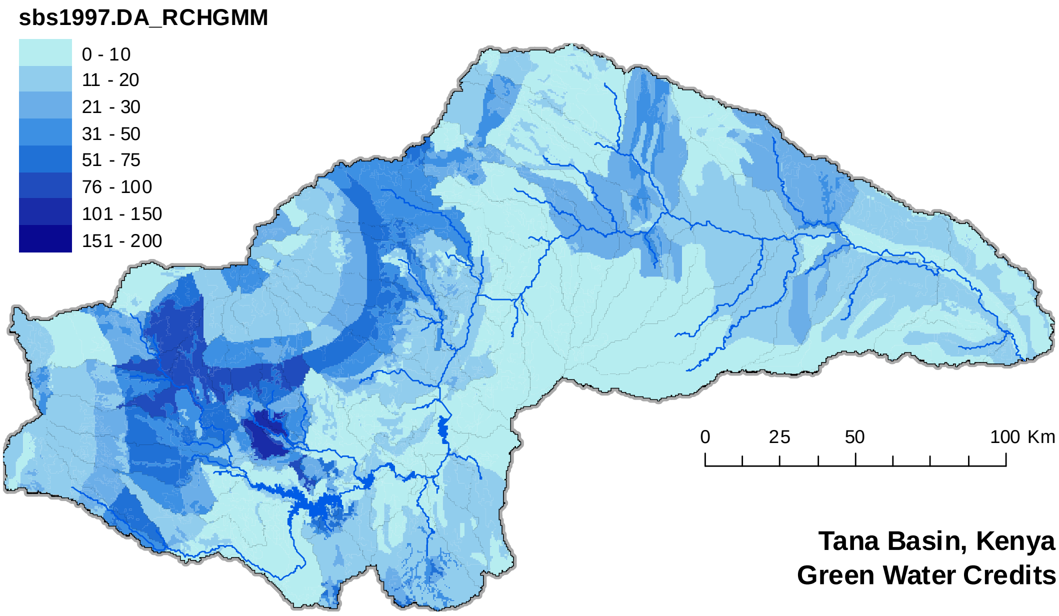
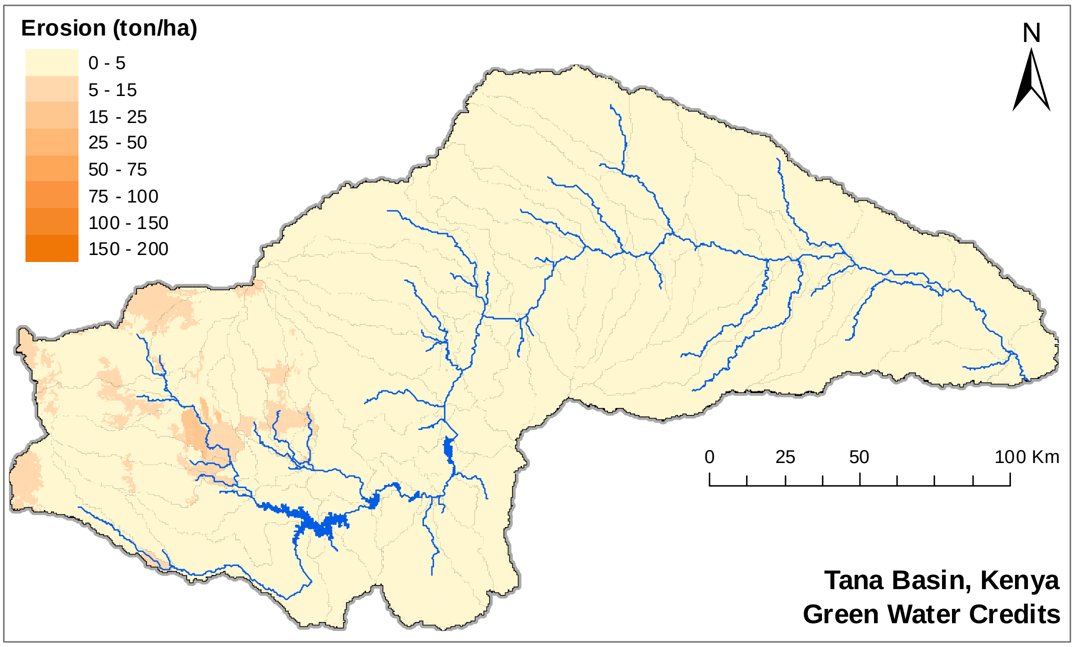


Figure 56: Groundwater recharge for a dry year (1996, top) and a wet year (1997, bottom), mm/yr



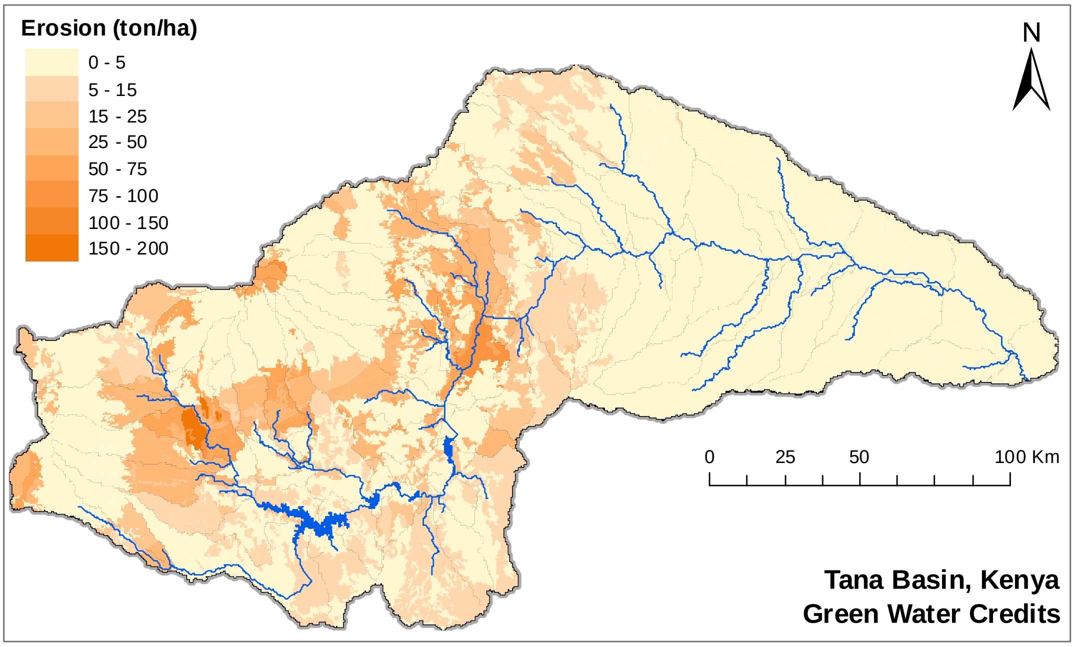


Figure 57: Erosion for a dry year (1996, top) and a wet year (1997, bottom), tonne/ha/yr

6.5 Aggregation by land use type

To establish which land use types are most relevant for Green Water Credits, data are aggregated for each land use:

- Evapotranspiration (Figure 58);
- T-percentage (Figure 59);
- *Blue* Water (Figure 60);
- Erosion (Figure 61).

Land classes: AGRI/AGRL = rain-fed crops, COFF = coffee, CORN = maize, FRSE/FRST = Forest, PINE = pineapple, PLAN =forest plantation, RICE = irrigated rice, RNGE = rangeland, TEA = tea, WATR = open water, WETL = wetlands

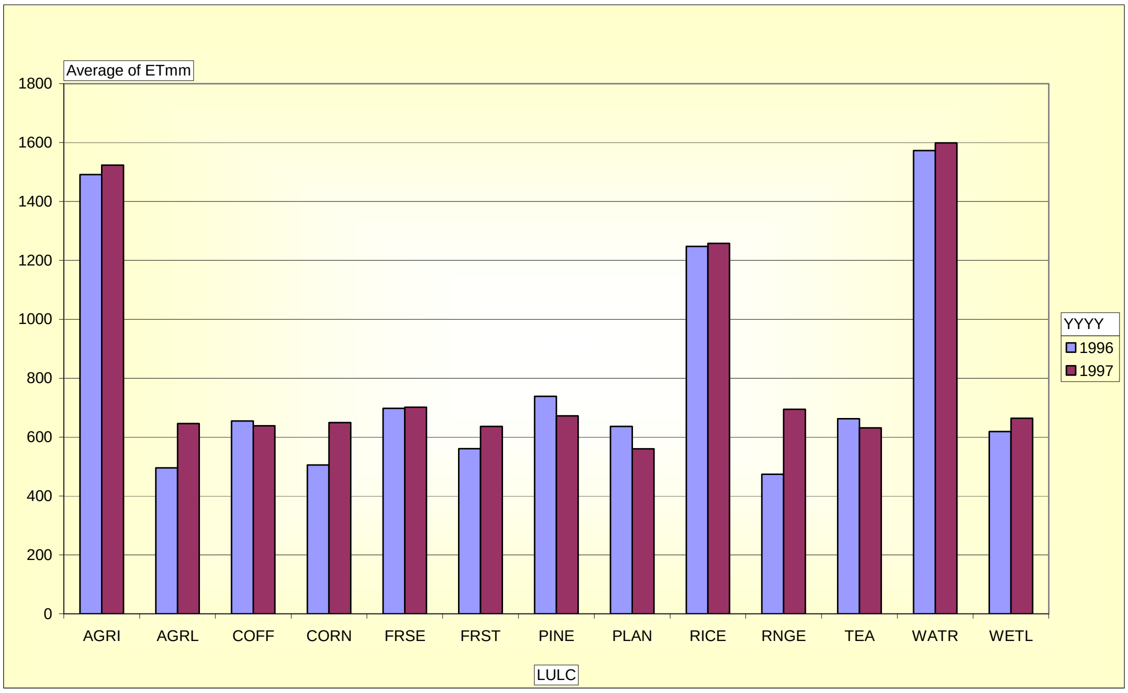


Figure 58: Mean actual evapotranspiration for the land classes defined for a dry year (1996) and a wet year (1997)

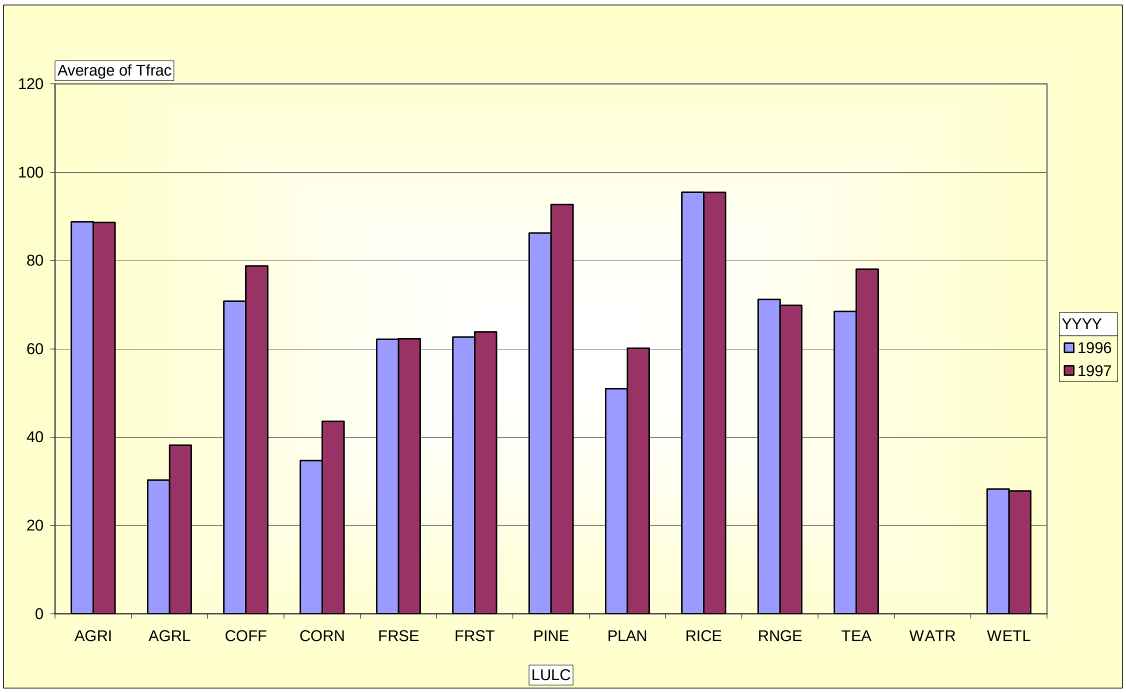


Figure 59: T-percentage (% of total evapotranspiration used as green water) for a dry year (1996) and a wet year (1997)

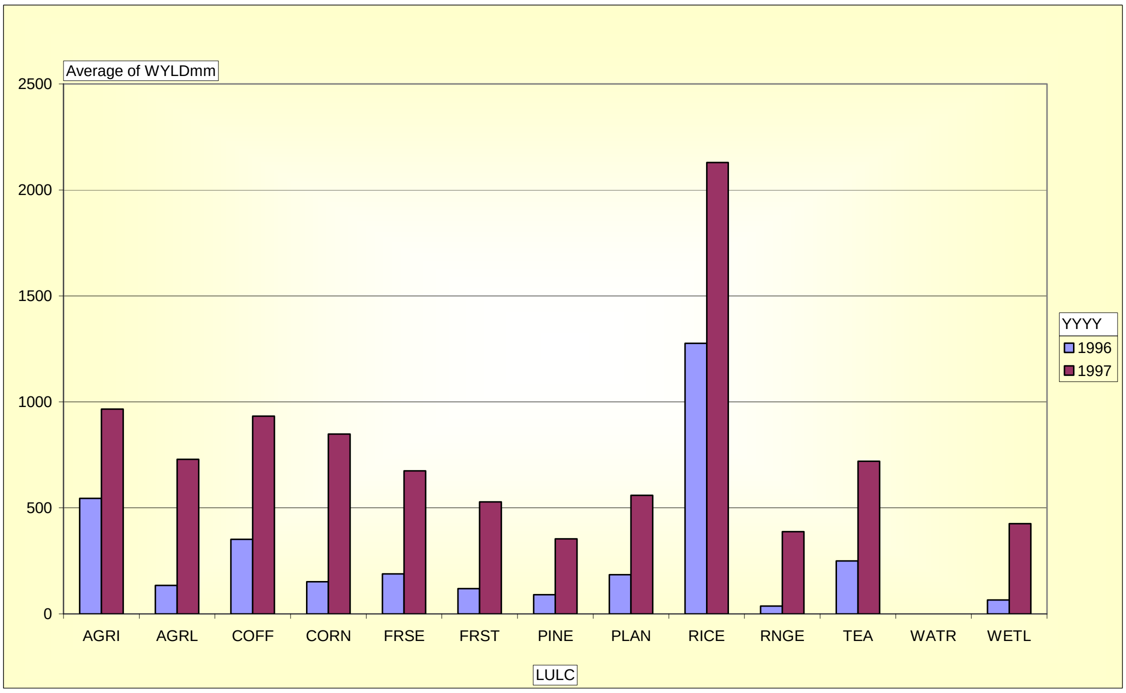


Figure 60: *Blue water* for a dry year (1996) and a wet year (1997), mm/yr

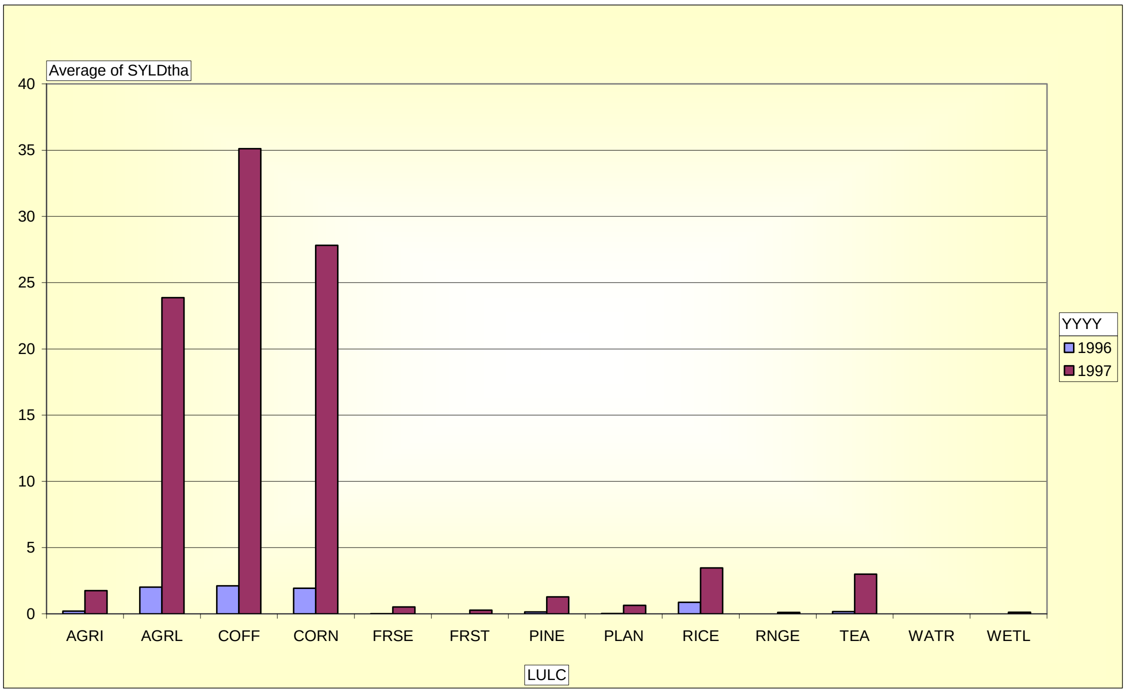


Figure 61: Erosion in a dry year (1996, top) and a wet year (1997, bottom), tonne/ha/yr

Land use change, of itself, can make a big difference to water supply downstream. As an example, though the most extreme one, substitution of rain-fed maize for the irrigated rice in the Mwea scheme, would mean for the dry year of 1996 and the wet year of 1997, a difference in evapotranspiration of 700mm. For the total scheme of 12 000 ha and assuming an irrigation efficiency of 20 per cent, this would amount to some 420 million m^3, twice the consumption of Nairobi!

6.6 Reservoirs and flows

Two important issues in Green Water Credits are: 1) the trade-off between *green water* and *blue water* flows; and 2) soil erosion, which translates to siltation of reservoirs. For the Masinga Reservoir, SWAT simulations are presented for:

- Comparison between observed and simulated flows (Figure 62);
- Reservoir dynamics (Figure 63);
- Sediment transport (Figure 64).

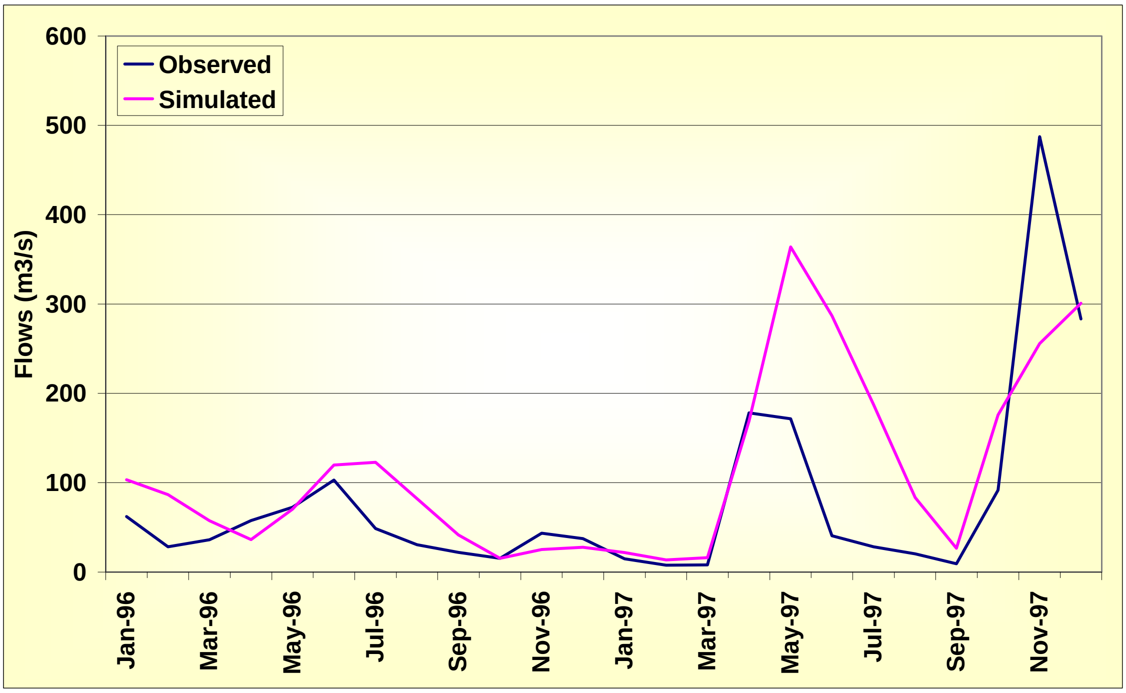


Figure 62: Comparison between observed and simulated inflow into Masinga reservoir

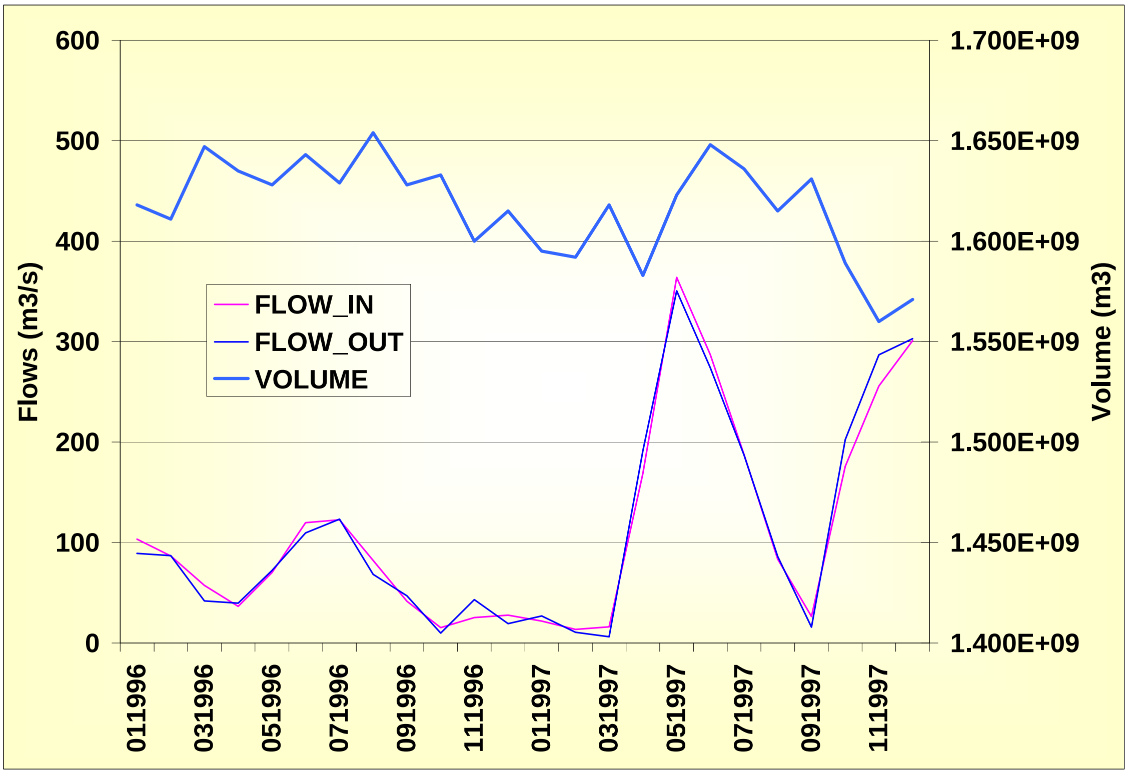


Figure 63: Masinga reservoir volumes, inflows and outflows

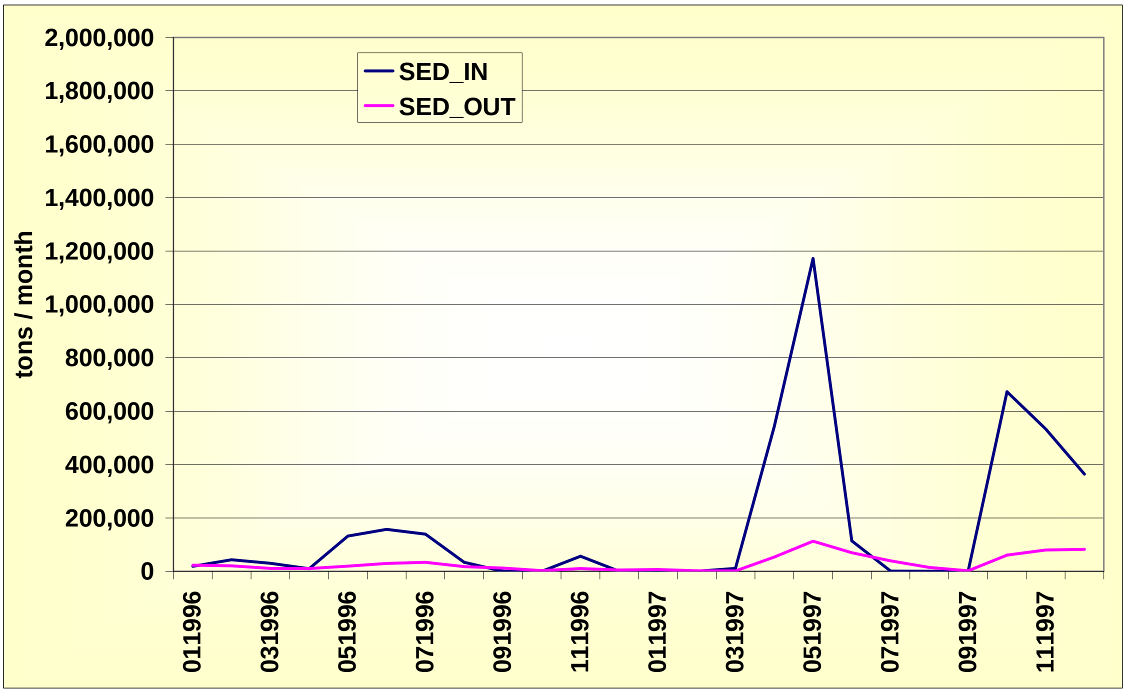


Figure 64: Masinga reservoir sediment inflows and outflows

6.7 Current hydrology

Noting that a rigorous calibration and validation has not been carried out for the SWAT model of the Upper Tana, it is apparent that the model simulates processes related to *green* water, *blue* water, soil erosion, and siltation of reservoirs at high spatial and temporal resolutions. The model can accommodate data of different quality and detail; the better the data, the more reliable the results. The model of the Upper Tana, as it stands, is based on some coarse data but comparison between measured and simulated flows shows reasonable agreement. The following indications are clear:

1. The fraction of rainwater that is not used beneficially as *green water* or delivered as *blue water*, but is lost as unproductive evaporation, varies greatly. Improvement of this fraction by green water management will be a an absolute gain of useful water resources;
2. Increase in water productivity, the quantity or value of crop produced per unit of water, is another potential gain e.g. by change from subsistence to marketable crops, or to higher yielding varieties – both of which require proper marketing mechanisms, skilful application of fertilizer and pest control, and supportive policy;
3. Arrest of soil erosion is an immediate benefit in terms of maintaining farm production, regulation of river flows by the soil reservoir, and combating siltation of man-made reservoirs.

7 Green Water Credits Options

7.1 Green water management in SWAT

Three scenarios for improved rain-fed cropping systems are evaluated: runoff reduction, erosion reduction, and evaporation reduction, by means of 1) permanent grassed contour strips, 2) mulching, and 3) tied ridges. Reduction percentages (Table 6) derived from WOCAT and other Kenyan sources represent typical or average values; actual values will vary from one situation to another. Rather than assert that a certain measure will reduce erosion by a certain percentage, SWAT goes back to the actual processes and assesses the impact of a certain measure based on data from the local area. The average figures have been used as a check on the SWAT results.

A sensitivity analysis was performed to assess the impact of the chosen practices on the water balance as simulated by SWAT:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

Where:
SW_t is the final soil water content (mm)
SW_0 is the initial soil water content (mm)
t is the time (days)
R_{day} is the amount of rainfall on day i (mm)
Q_{surf} is the amount of runoff on day i (mm)
E_a is the amount of evapotranspiration on day i (mm)
w_{seep} is the amount of percolation and bypass flow leaving the soil on day i (mm)
Q_{gw} is the amount of return flow on day i (mm).

If we consider long time periods the change in soil water content is close to zero. The soil water balance, rewritten to Input = Output, reads:

$$\text{PRECIP} + \text{IRR} + \text{REVAP} = \text{ET} + \text{PERC} + \text{SURQ}$$

PRECIP is precipitation, IRR is irrigation, REVAP is capillary rise from shallow groundwater, ET is evapotranspiration, PERC is percolation to shallow groundwater, and SURQ is surface runoff. All in mm per time step. PERC (percolation) will be GW_RCH (groundwater recharge) over longer time frames. WYLD (water yield) is total water contributing to stream flow = SURQ + LATQ + GWQ – TLOSS (surface runoff + lateral runoff + groundwater runoff – seepage losses).

7.1.1 ESCO

ESCO is a soil evaporation compensation coefficient to modify the depth of soil used to meet the evaporative demand - accounting for capillary action, crusting and cracks. ESCO must be between 0.01 and 1.0, the default value is 0.95. As ESCO is reduced, more evaporative demand will be met from the deeper subsoil (Figure 65); changing the default value from 0.95 to 0.80 increases evaporation by 10 per cent; changing the default value to 0.99 reduces evaporation by 10 per cent (Figure 66).

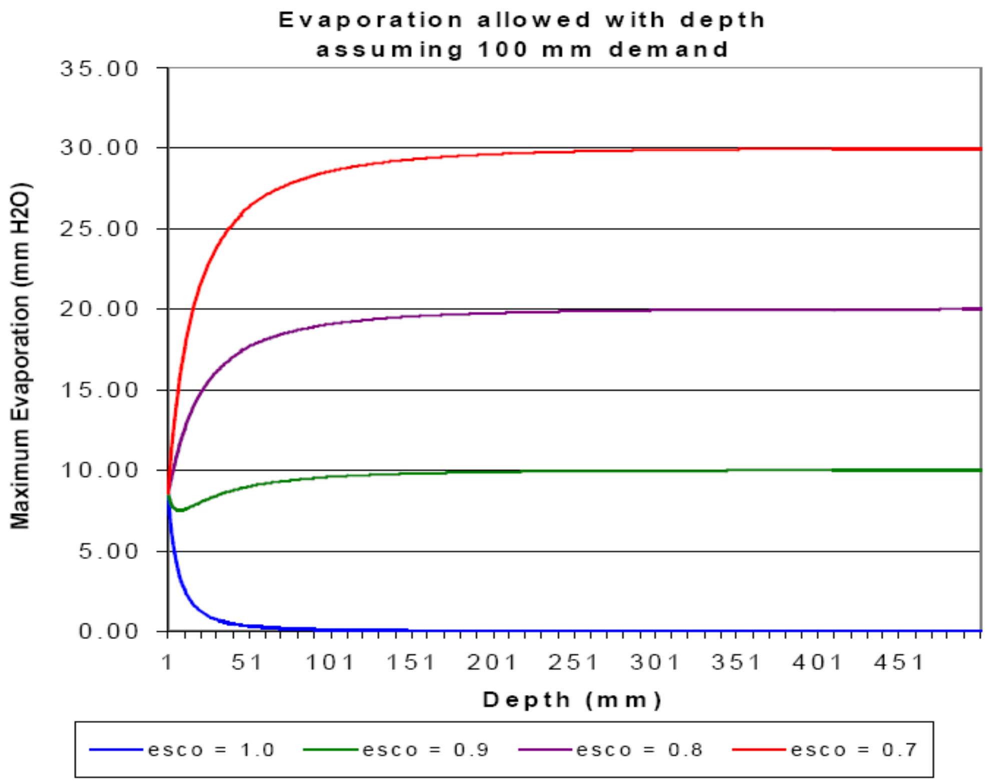


Figure 65: Effect of ESCO on thickness of soil from which evaporation is drawn

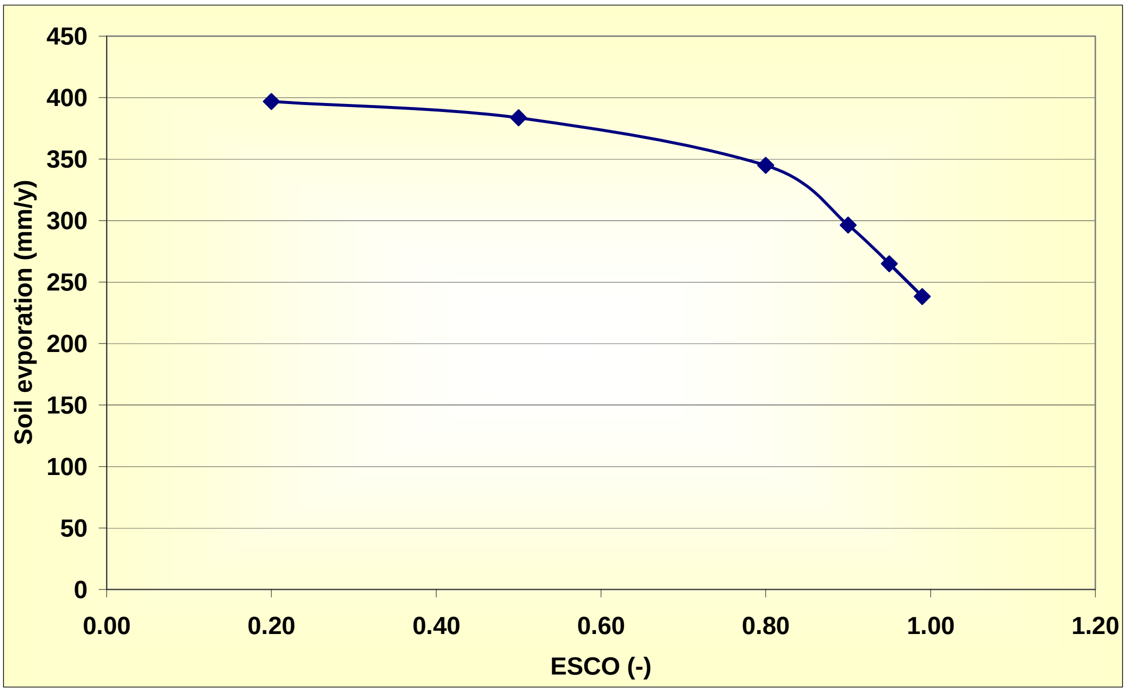


Figure 66: Sensitivity analysis of ESCO for one HRU (501 = tea) for 1996

7.1.2 Soil erosion

Erosion and sediment yield are estimated for each HRU using the Modified Universal Soil Loss Equation (Williams 1995; Williams and Berndt 1977):

$$sed = 11.8 * (Q_{surf} * q_{peak} * area_{hru})^{0.56} * K_{USLE} * C_{USLE} * P_{USLE} * LS_{USLE} * CFRG$$

Where:
sed is the sediment yield on a given day (tonne)
Q_{surf} is the surface runoff volume (mm/ha)
q_{peak} is the peak runoff rate (m^3/s)
$area_{hru}$ is the area of the HRU (ha)
K_{USLE} is the USLE soil erodibility factor (0.013 tonne/m^2/hr/m^3/tonne/cm)
C_{USLE} is the USLE cover and management factor
P_{USLE} is the USLE support practice factor
LS_{USLE} is the USLE topographic factor
CFRG is the coarse fragment factor.

While the USLE uses rainfall as an indicator of erosive energy, the Modified version uses the amount of runoff to simulate erosion and sediment yield.

The crop management factor is a function of above-ground biomass, residue on the soil surface, and the minimum C factor for the plant; it is recalculated for every day that runoff occurs.

The support practice factor, P_{USLE}, is defined as the ratio of soil loss for a specific support practice to the corresponding loss with up-and-down slope cultivation. Support practices include contour ridging and strip cropping on the contour. Stabilized waterways for the disposal of excess rainfall are a necessary part of each of these practices. Contour ridging and planting provides almost complete protection against erosion from rainfall of low to moderate intensity, but little or no protection against storms that breaks through the ridges; it is most effective on slopes of 3 to 8 per cent. Values for P_{USLE} and slope-length limits for contour support practices are given in Table 18. Strip cropping involves sodded strips alternating with equal-width strips of row crop or small grain (Table 19).

Table 18: P_{USLE} factor values and slope-length limits for contour cultivation *(Wischmeier and Smith 1978)*

Slope gradient (%)	*P_{USLE} values*	*Maximum Length, m*
1 to 2	0.60	122
3 to 5	0.50	91
6 to 8	0.50	61
9 to 12	0.60	37
13 to 16	0.70	24
17 to 20	0.80	18
21 to 25	0.90	15

Table 19: P_{USLE} factor values, maximum strip width and slope-length limits for contour ridging (strip cropping)
(Wischmeier and Smith 1978)

Slope gradient (%)	*P_{USLE} values*			*Strip width (m)*	*Maximum length (m)*
	A	B	C		
1 to 2	0.30	0.45	0.60	40	244
3 to 5	0.25	0.38	0.50	30	183
6 to 8	0.25	0.38	0.50	30	122
9 to 12	0.30	0.45	0.60	24	73
13 to 16	0.35	0.52	0.70	24	49
17 to 20	0.40	0.60	0.80	18	37
21 to 25	0.45	0.68	0.90	15	30

P values:

A: For 4-year rotation of row crop, small grain with meadow seeding, and 2 years of meadow. A second row crop can replace the small grain if meadow is established in it.

B: For 4-year rotation of 2 years row crop, winter grain with meadow seeding, and 1-year meadow.

C: For alternate strips of row crops and winter grain.

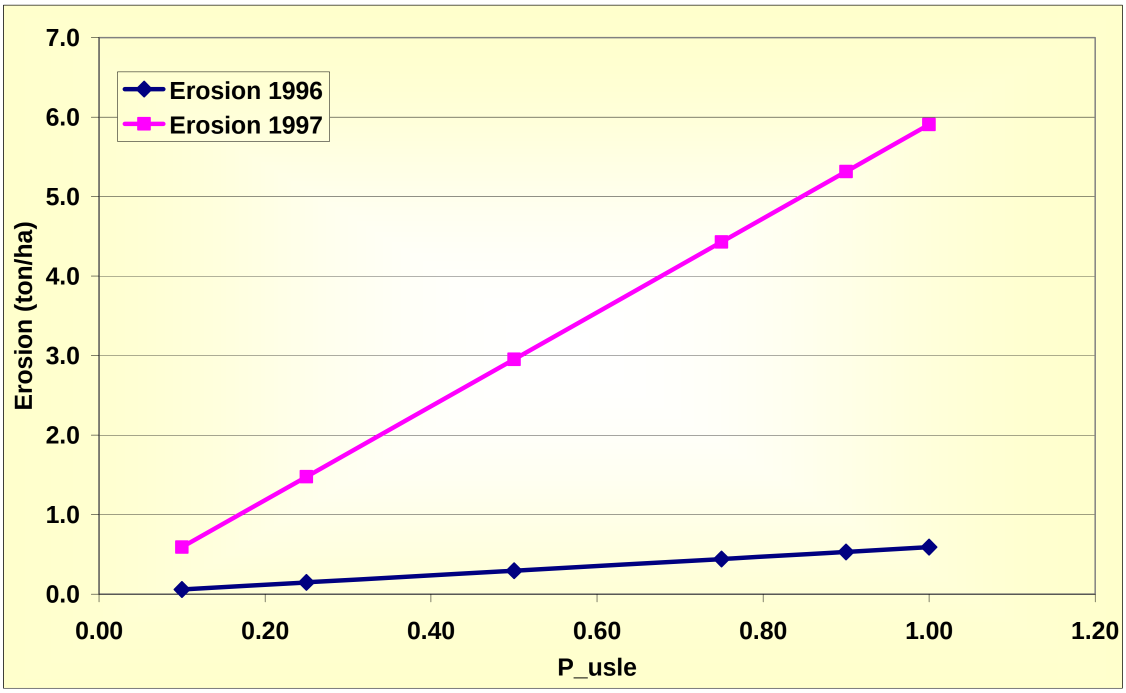


Figure 67: Sensitivity analysis of P_{USLE}, for one HRU (501 = tea)

7.1.3 SCS runoff curve number

Runoff occurs when the rate of water application to the ground surface exceeds the rate of infiltration. SWAT uses the SCS runoff equation (USDA-SCS 1972) developed to provide a consistent basis for estimating the amounts of runoff under varying land use and soil types (Rallison and Miller 1981). The SCS curve number is a function of soil permeability, land use, and antecedent soil water conditions.

Typical curve numbers for moisture conditions (appropriate for a 5 per cent slope) and various land covers and soil types are listed in Table 20 and Table 21.

Table 20: Runoff curve numbers for cultivated agricultural lands
(USDA-SCS 1986)

Cover			Hydrologic Soil Group			
Land Use	**Treatment or practice**	**Hydrologic condition**	**A**	**B**	**C**	**D**
Fallow	Bare soil	- - - -	77	86	91	94
	Crop residue cover*	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row	Poor	72	81	88	91
		Good	67	78	85	89
	Straight row w/ residue	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured	Poor	70	79	84	88
		Good	65	75	82	86
	Contoured w/ residue	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced	Poor	66	74	80	82
		Good	62	71	78	81
Small grains	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
	Straight row w/ residue	Poor	64	75	83	86
		Good	60	72	80	84
	Contoured	Poor	63	74	82	85
		Good	61	73	81	84
	Contoured w/ residue	Poor	62	73	81	84
		Good	60	72	80	83
	Contoured & terraced	Poor	61	72	79	82
		Good	59	70	78	81
	Contoured & terraced w/ residue	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation	Straight row	Poor	66	77	85	89
		Good	58	72	81	85
	Contoured	Poor	64	75	83	85
		Good	55	69	78	83
	Contoured & terraced	Poor	63	73	80	83
		Good	51	67	76	80

Table 21: Runoff curve numbers for other agricultural lands
(USDA-SCS 1986)

Cover		Hydrologic Soil Group			
Cover Type	**Hydrologic condition**	**A**	**B**	**C**	**D**
Pasture, grassland, or range—continuous forage for grazing[1]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, protected from grazing and generally mowed for hay	- - - -	30	58	71	78
Brush—brush-weed-grass mixture with brush the major element[2]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30	48	65	73
Woods—grass combination (orchard or tree farm)	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods[3]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	- - - -	59	74	82	86

It is evident that a proper determination of the SCS curve number CN2 is essential. Less sustainable land use and land management, refelected by higher CN2 values, will increase runoff and soil erosion substantially (Figure 68 and Figure 69).

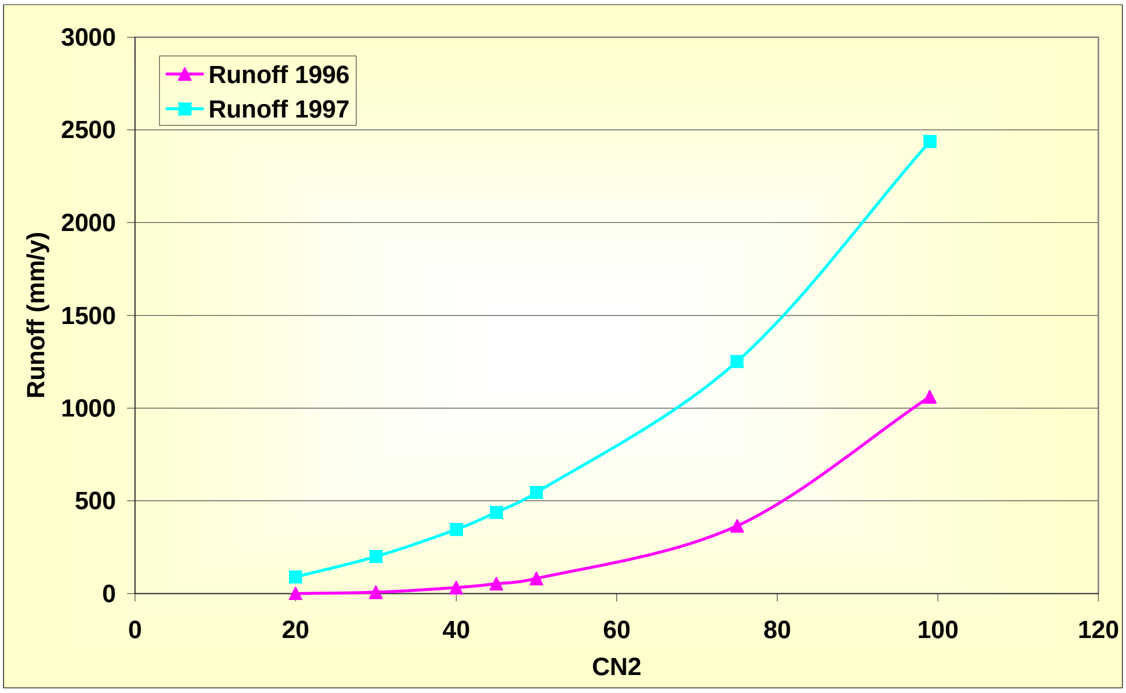


Figure 68: Sensitivity analysis of the curve number CN2 runoff coefficient for HRU 501 (tea) on runoff

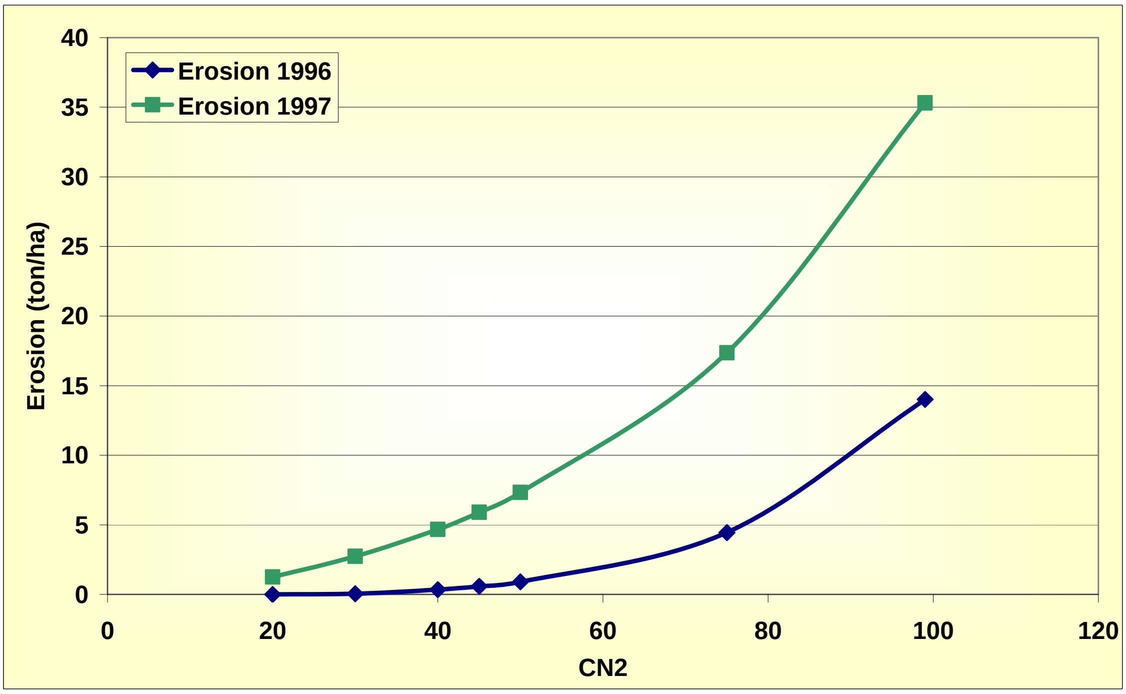


Figure 69: Sensitivity analysis of the curve number CN2 runoff coefficient for HRU 501 (tea) on erosion

7.2 Analysis of green water management practices

7.2.1 Grassed contour strips

Grassed contour strips affect three processes modeled by SWAT:

1. *Reduction in runoff and increase in percolation:* implemented by changing the Curve Number CN2 - lower numbers mean less runoff and more percolation. The following values are used in the *business as usual* and *grassed contour strips* scenarios: maize 67 → 55 per cent; coffee 45 → 35 per cent; tea 45 → 35 per cent; cropland unspecified 67 → 62 per cent
2. *Reduction in erosion:* implemented by reducing P_{USLE}. The following values are used for the *business as usual* (1.00) and *grassed contour strips* scenarios: maize 0.70; coffee 0.70; tea 0.70; cropland, unspecified 0.90.

7.2.2 Mulch

Mulch, combined with weeding, affects several processes:

1. *Reduction in evaporation from the soil surface and increased infiltration and percolation:* implemented by adjusting the ESCO coefficient. In the absence of references to the value of ESCO and the field situation, expert judgment was used to relate ESCO to water conservation measures: maize 0.99; coffee 0.99; tea 0.99; cropland, unspecified 0.97
2. *Reduction in erosion:* implemented by reducing P_{USLE}. The following values are used for the *business as usual* (1.00) and *mulch* scenarios: maize 0.80; coffee 0.80; tea 0.80; cropland, unspecified 0.90.

7.2.3 Tied ridges

Tied ridges contain runoff and so enhance infiltration. Effects may be calculated by changing the CN2 factor of the Curve Number calculations; lower numbers are associated with less runoff and more percolation. The following values are used for business *as usual* and *tied ridges*: maize 67 → 40 per cent; cropland, unspecified 67 → 40 per cent.

7.3 Scenario Analysis

Results of this analysis will be presented basin-wide, per crop, and spatially. With respect to the comparison between baseline and green water management scenarios: *Baseline* describes the actual situation, as modeled, in 1996 and 1997; *Scenarios* refer to the years 1996 and 1997 if green water management had been implemented. Any inaccuracies in data and assumptions are present in both analyses, so the *difference* between calculated results for the baseline and other scenarios is likely to be more accurate than the baseline as such.

A set of indicators has been introduced to showing the impact of each proposed measure. Table 22 summarises these indicators with their baseline values as calculated by SWAT.

Table 22: Indicators and baseline values

	1996	*1997*
Indicators		
Inflow Masinga (Mm^3)[1]	3 242	7 152
Sediment Input Masinga (tonne)	953 300	5 281 000
Outflow Garissa (Mm^3)	4 358	21 482
Crop Transpiration (mm)	396	510
Evaporation (mm)	205	224
Groundwater recharge (mm)[2]	169	745
Groundwater recharge (m^3/ha)	1 695	7 445
Sediment loss (tonne/ha)	1	14
Basin Balance		
Area (km^2)	32 741	32 741
Precipitation (Mm^3)	19 126	57 023
Transpiration (Mm^3)	10 950	16 141
Evaporation (Mm^3)	6 289	7 375
Outflow (Mm^3)	4 358	21 482
Groundwater change (Mm^3)[3]	-2 471	12 024
Maize		
Area (km^2)	2 203	2 203
Transpiration (mm)	233	361
Evaporation (mm)	312	354
Groundwater recharge (mm)	134	614
Runoff (mm)	59	663
Soil loss (tonne/ha)	3	34
Tea		
Area (km^2)	838	838
Transpiration (mm)	475	524
Evaporation (mm)	214	140
Groundwater recharge (mm)	396	1092
Runoff (mm)	47	487
Soil loss (tonne/ha)	0	7
Coffee		
Area (km^2)	1 739	1 739
Transpiration (mm)	481	521
Evaporation (mm)	197	135
Groundwater recharge (mm)	377	1 176
Runoff (mm)	31	347
Soil Loss (tonne/ha)	4	58

[1] Million cubic meters
[2] Groundwater *recharge* is total amount of water percolating to the deep groundwater; groundwater *change* is percolation minus extraction minus base flow

In a dry year, about half of the rainfall is used beneficially to support crop growth but, at the same time, one third is lost as unproductive evaporation from the soil surface. In a wet year, crops transpire 60 per cent more water. In a wet year, 38 per cent of rainfall flows to the Lower Tana; in a dry year 23 per cent.

Transpiration is higher for perennial crops than for maize, and unproductive evaporation from the soil surface is significant. Runoff cause serious erosion, especially in wet years under maize and coffee. As a result, sediment inputs to the Masinga reservoir are enormous; in a wet year as much as 5 million tonnes.

Table 23, Table 24, and Table 25 summarise the changes under green water management.

Table 23: Indicators for green water management scenarios

	Contour strips		*Mulch*		*Tied ridges*	
	1996[a)]	*1997*	*1996*	*1997*	*1996*	*1997*
Indicators						
Inflow Masinga (Mm^3/yr)	3 270	7 074	3 396	7 048	3 330	6 928
Sediment input Masinga (tonne)	646 200	4 093 000	343 400	3 143 000	266 400	2 766 000
Sediment output Masinga (tonne)	187 800	262 100	179 600	255 400	176 300	251 600
Transpiration (mm)	396	510	400	513	397	510
Evaporation (mm)	205	225	195	213	206	227
Groundwater recharge (mm)	178	789	190	844	189	866
Groundwater recharge (m^3/ha)	1 776	7 885	1 904	8 437	1 885	8 660
Sediment loss (tonne/ha)	1	9	0	8	0	7
Basin Balance						
Area (km^2)	32 741	32 741	32 741	32 741	32 741	32 741
Rainfall (Mm^3)	19 126	57 023	19 126	57 023	19 126	57 023
Transpiration (Mm^3)	10 957	16 143	11 068	16 232	10 960	16 144
Evaporation (Mm^3)	6 302	7 406	6 006	7 042	6 321	7 448
Outflow (Mm^3)	4 384	21 202	4 506	21 085	4 418	20 640
Groundwater change (Mm^3)	-2 517	12 272	-2 455	12 664	-2 573	12 790
Maize						
Transpiration (mm)	234	361	249	372	234	361
Evaporation (mm)	314	358	270	304	315	360
Groundwater recharge (mm)	168	802	200	898	190	960
Runoff (mm)	26	469	20	416	7	307
Soil loss (tonne/ha)	1	17	1	17	0	16
Tea						
Transpiration (mm)	475	524	479	527	475	524
Evaporation (mm)	215	140	193	126	215	140
Groundwater recharge (mm)	419	1195	443	1251	427	1240
Runoff (mm)	26	382	19	338	19	336
Soil loss (tonne/ha)	0	4	0	4	0	5
Coffee						
Transpiration (mm)	482	521	487	524	482	521
Evaporation (mm)	197	136	176	122	197	136
Groundwater recharge (mm)	393	1268	412	1314	398	1304
Runoff (mm)	17	254	12	218	12	217
Soil loss (tonne/ha)	1	30	1	30	1	37

[a)] 1996 is dry and 1997 is a wet year

Table 24: Change under green water management compared with baseline

	Contour Strips		*Mulch*		*Tied ridges*	
	1996[a)]	*1997*	*1996*	*1997*	*1996*	*1997*
Indicators						
Inflow, Masinga (Mm^3)	28	-79	155	-104	88	-224
Sediment input, Masinga (tonne)	- 307 100	- 1 188 000	- 609 900	-2 138 000	- 686 900	- 2 515 000
Transpiration (mm)	0	0	4	3	0	0
Evaporation (mm)	0	1	- 10	- 11	1	2
Groundwater recharge (mm)	8	44	21	99	19	122
Groundwater recharge (m^3/ha)	81	440	209	992	190	1 215
Soil loss (tonne/ha)	- 1	- 5	- 1	- 6	- 1	- 7
Basin Balance						
Transpiration (Mm^3)	7	2	118	91	9	3
Evaporation (Mm^3)	13	31	- 283	- 333	32	73
Outflow (Mm^3)	-25	281	-148	397	-60	842
Groundwater change (Mm^3)	45	-248	-17	-640	101	-766
Maize						
Transpiration (mm)	1	0	16	11	1	0
Evaporation (mm)	2	4	-42	-50	3	6
Groundwater recharge (mm)	34	188	65	285	55	347
Runoff (mm)	-32	-195	-39	-247	-51	-357
Soil loss (tonne/ha)	-2	-17	-2	-17	-2	-18
Tea						
Transpiration (mm)	0	0	4	3	0	0
Evaporation (mm)	0	0	-22	-14	0	0
Groundwater recharge (mm)	23	103	47	159	31	149
Runoff (mm)	-21	-105	-28	-150	-29	-151
Soil loss (tonne/ha)	0	-3	0	-3	0	-2
Coffee						
Transpiration (mm)	0	0	6	4	0	0
Evaporation (mm)	0	0	-20	-13	0	0
Groundwater recharge (mm)	16	91	34	137	21	128
Runoff (mm)	-15	-93	-19	-129	-20	-130
Soil loss (tonne/ha)	-3	-28	-3	-28	-3	-21

[a)] 1996 is dry and 1997 is a wet year

Table 25: Per cent change under green water management compared with baseline

	Contour Strips		*Mulch*		*Tied ridges*	
	1996[a)]	*1997*	*1996*	*1997*	*1996*	*1997*
Indicators						
Inflow, Masinga	1	-1	5	-1	3	-3
Sediment input, Masinga	-32	-22	-64	-40	-72	-48
Sediment output, Masinga	-3	-1	-7	-3	-9	-5
Transpiration	0	0	1	1	0	0
Groundwater recharge	5	6	12	13	11	16
Soil loss	-47	-33	-71	-46	-82	-49
Basin Balance						
Transpiration	0	0	1	1	0	0
Evaporation	0	0	-5	-5	1	1
Outflow	1	-1	3	-2	1	-4
Groundwater change	2	2	-1	5	4	6
Maize						
Transpiration	0	0	7	3	0	0
Evaporation	1	1	-13	-14	1	2
Groundwater recharge	26	31	49	46	41	57
Runoff	-55	-29	-66	-37	-87	-54
Soil loss	-71	-50	-75	-50	-90	-53
Tea						
Transpiration	0	0	1	1	0	0
Evaporation	0	0	-10	-10	0	0
Groundwater recharge	6	9	12	15	8	14
Runoff	-44	-22	-59	-31	-60	-31
Soil loss	-64	-44	-72	-44	-65	-30
Coffee						
Transpiration	0	0	1	1	0	0
Evaporation	0	0	-10	-10	0	0
Groundwater recharge	4	8	9	12	5	11
Runoff	-47	-27	-62	-37	-62	-37
Soil loss	-65	-48	-72	-49	-65	-36

[a)] *1996 is dry and 1997 is wet*

Some key indicators are plotted in Figure 70 and Figure 71. Figure 72 shows crop water balances; Figure 73 illustrates the beneficial effects of mulch on the water balance, particularly by arresting unproductive evaporation from the soil surface. All three green water management scenarios have a very positive impact by reducing runoff and erosion, and increasing groundwater recharge.

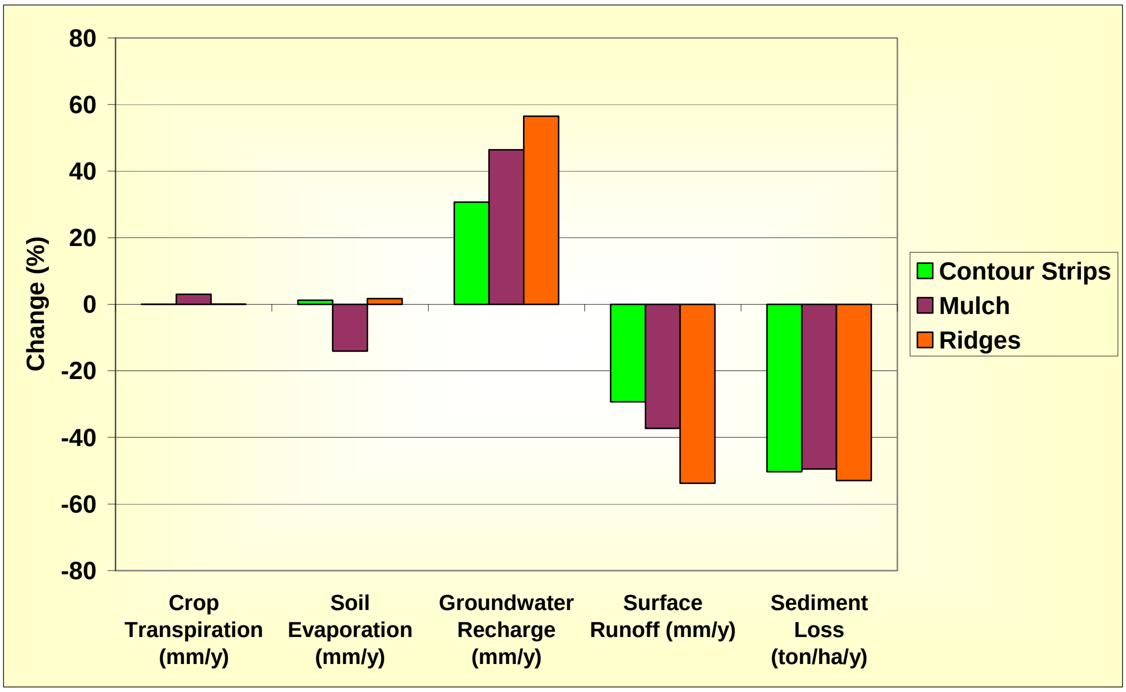
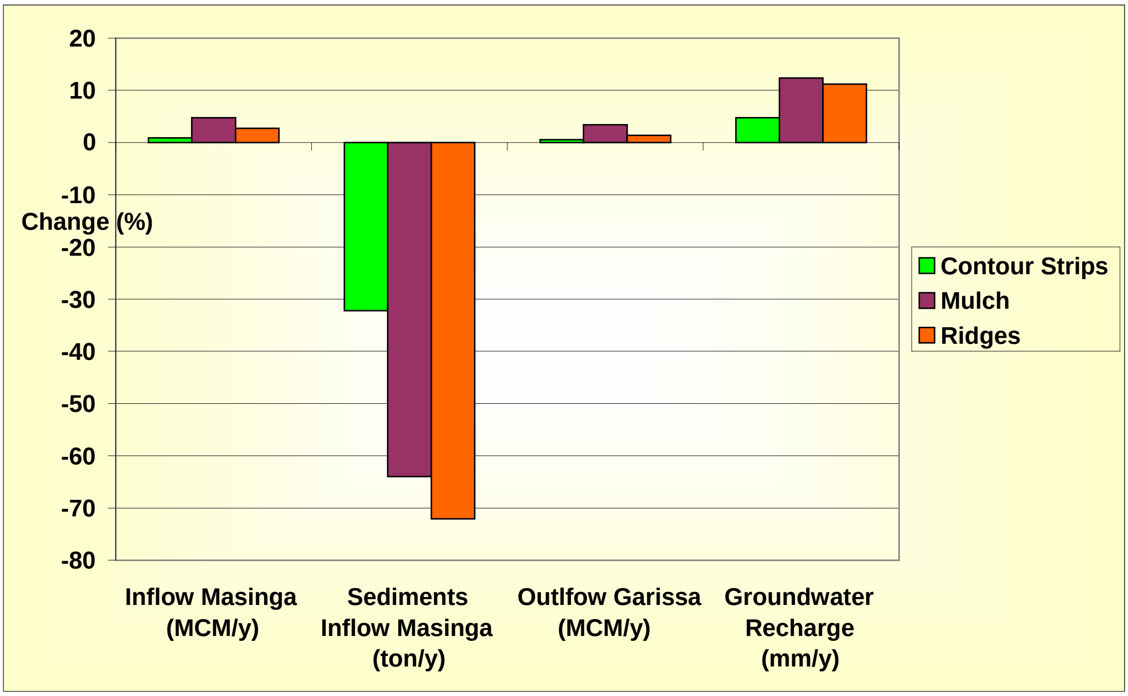


Figure 70: Main indicators comparing the three different scenarios to the baseline for maize for a wet year (1997)



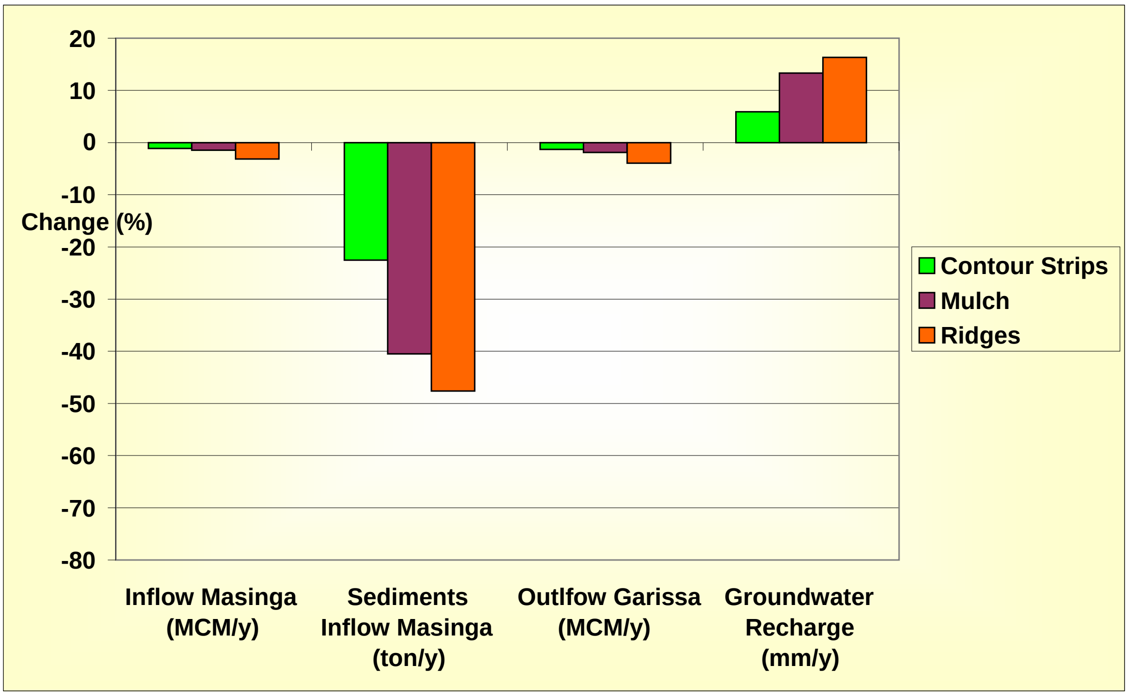
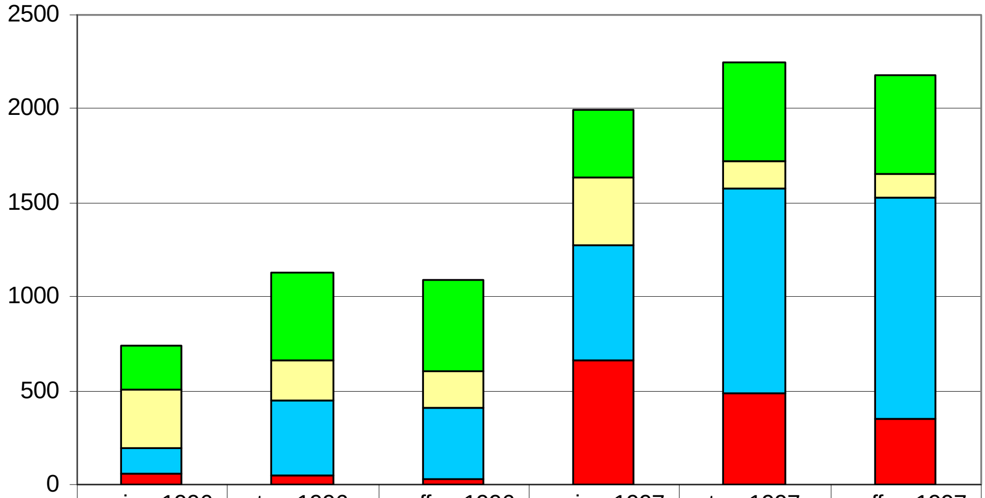
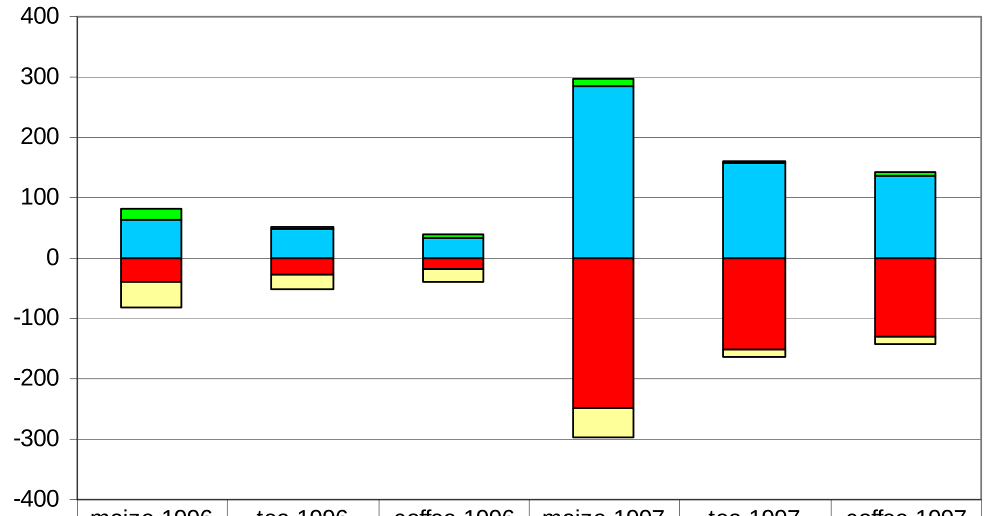


Figure 71: Percentage change of main indicators under green water management compared with the baseline for a dry year (1996), above, and a wet year (1997), below



	maize 1996	tea 1996	coffee 1996	maize 1997	tea 1997	coffee 1997
Transpiration	233	475	481	361	524	521
Evaporation	312	214	197	354	140	135
Groundwater	134	396	377	614	1092	1176
Runoff	59	47	31	663	487	347

Figure 72: Baseline water balances for a dry year (1996) and a wet year (1997)



	maize 1996	tea 1996	coffee 1996	maize 1997	tea 1997	coffee 1997
Transpiration	16	4	6	11	3	4
Evaporation	-42	-22	-20	-50	-14	-13
Groundwater	65	47	34	285	159	137
Runoff	-39	-28	-19	-247	-150	-129

Figure 73: Changes in water balances with mulch compared to the baseline

As well as basin-wide indicators, there are important spatial differences in the effectiveness of green water management across the basin. As examples: Figure 74 shows where grassed contour strips will have the greatest effect in reducing soil erosion from cropland - differences in effectiveness of this practice are due to the interplay of slopes, soils, crops, distance to river, and rainfall intensity; Figure 75 shows the effect of mulching in reducing unproductive evaporation from the soil surface; Figure 76 depicts the effect if tied ridges on arresting runoff and increasing infiltration and percolation.

Note that the results shown at the basin level assume that green water management is applied to all cropland. The issue of variable patterns of adoption is taken up in Section 7.5.

In summary, green water management can:

- By cutting runoff by 22-66 per cent, reduce sediment input to the Masinga reservoir by between 22 and 72 per cent, or 307 000 to 2 515 000 tonnes per year, the range depending mainly on the rainfall;
- Increase crop transpiration and, thus, crop production by 7 per cent;
- Cut unproductive evaporation from the soil surface by as much as 14 per cent, or 50 mm/500 m^3 per ha per year;
- Increase groundwater recharge by 4-57 per cent or 16-160 mm/160-1600 m^3 per ha per year.

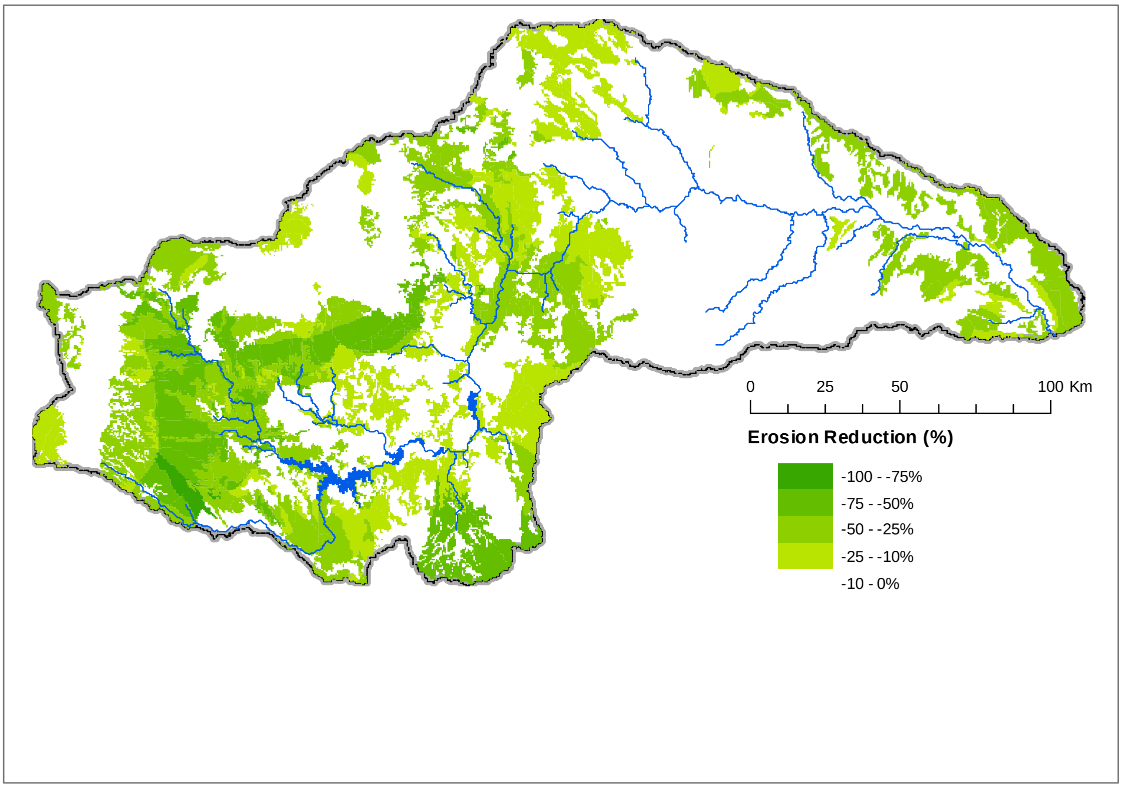
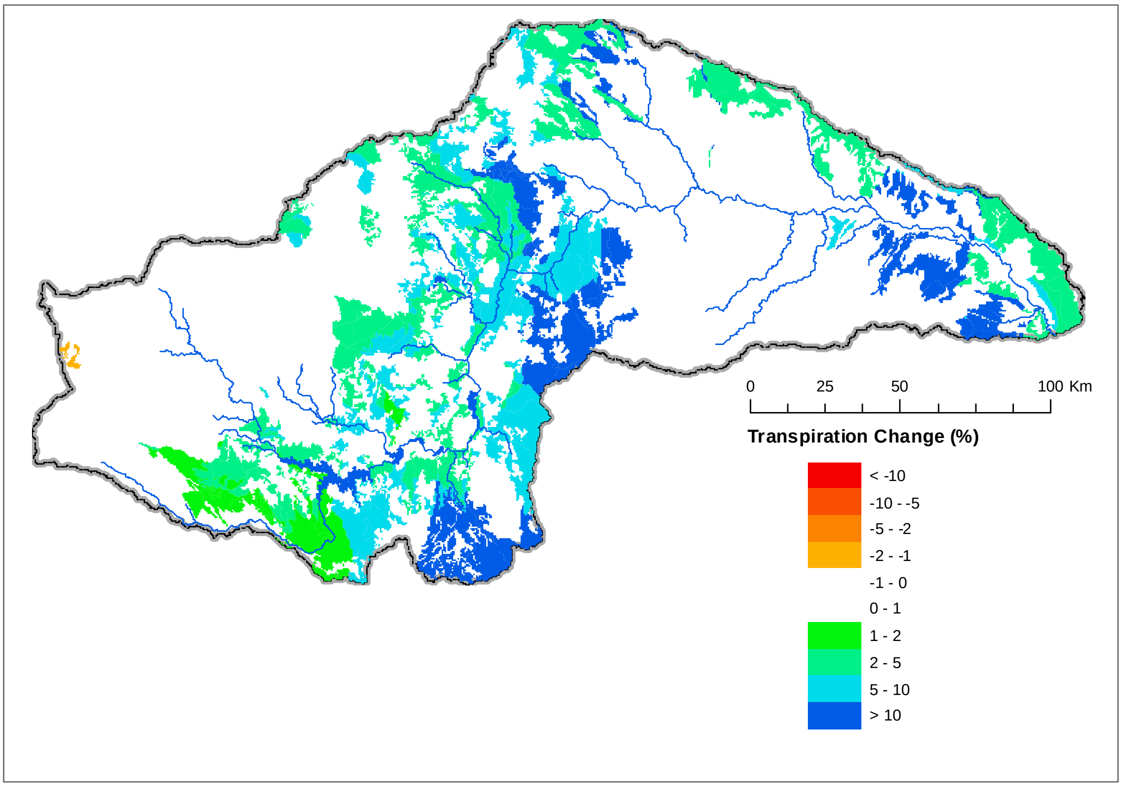


Figure 74: Reduction in erosion by grassed contour strips compared to baseline for a wet year (1997)



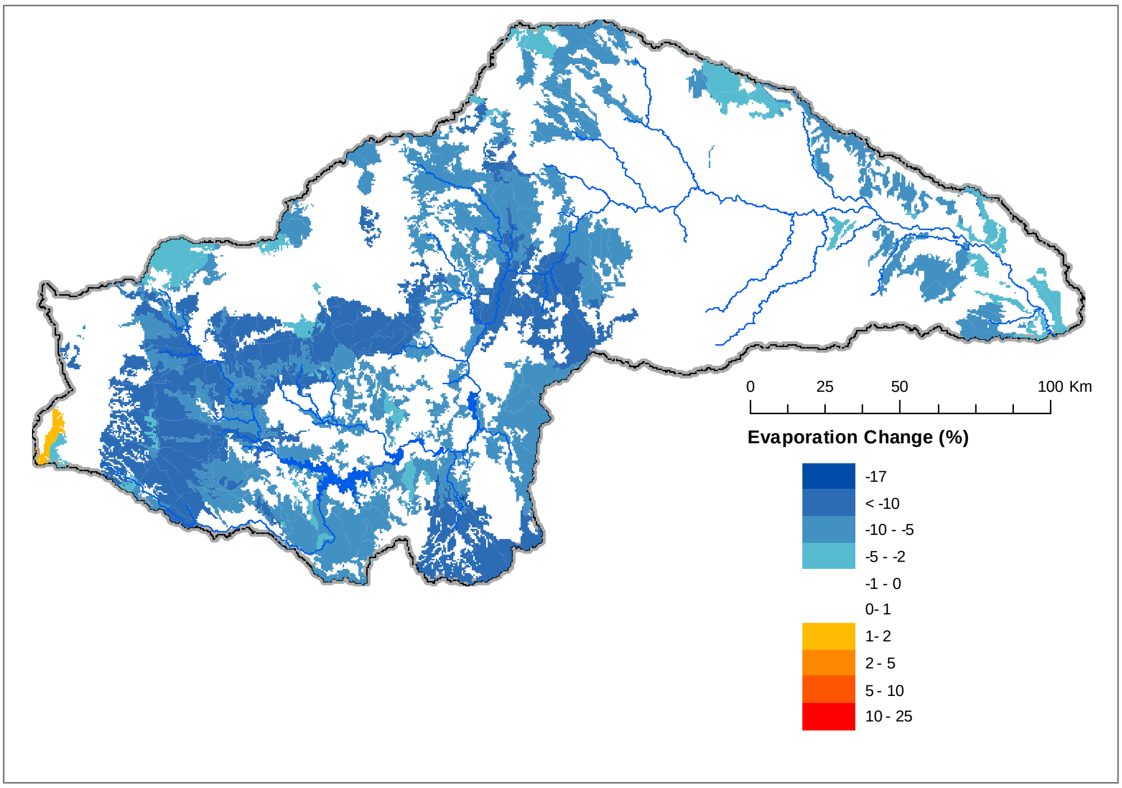
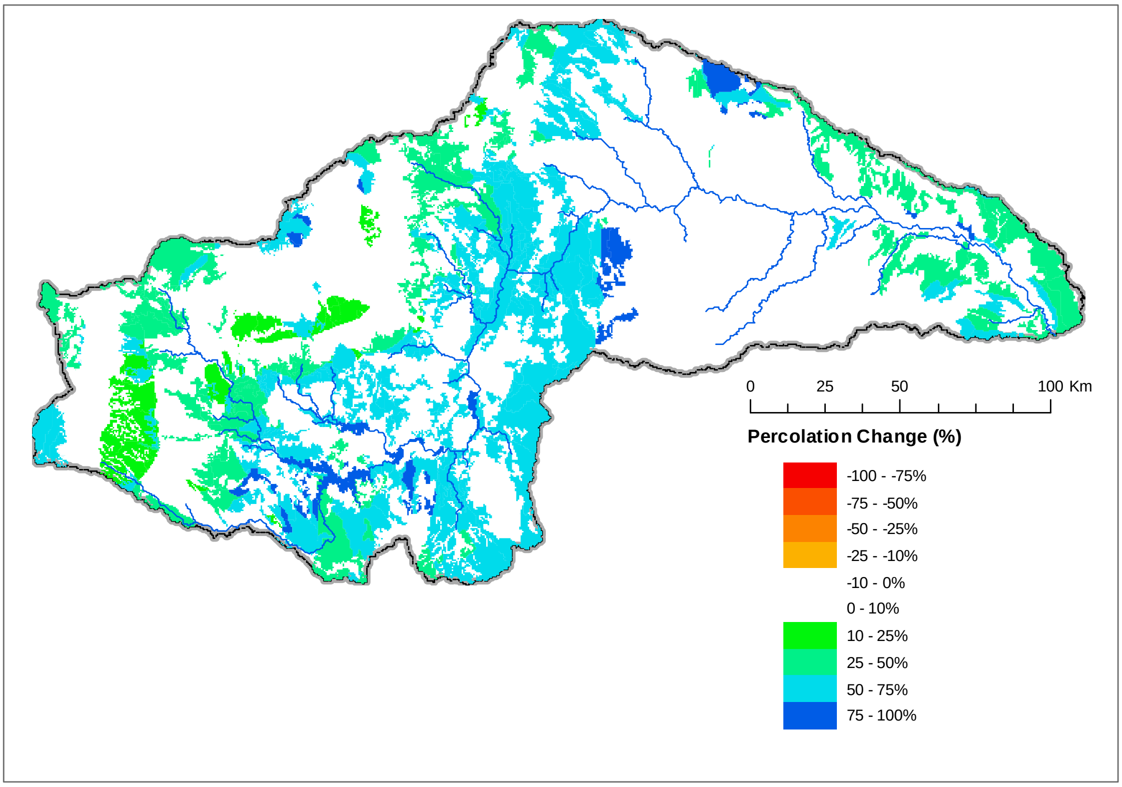


Figure 75: Change transpiration (above) and evaporation from the soil surface (below) under mulch compared with the baseline in a dry year (1996)



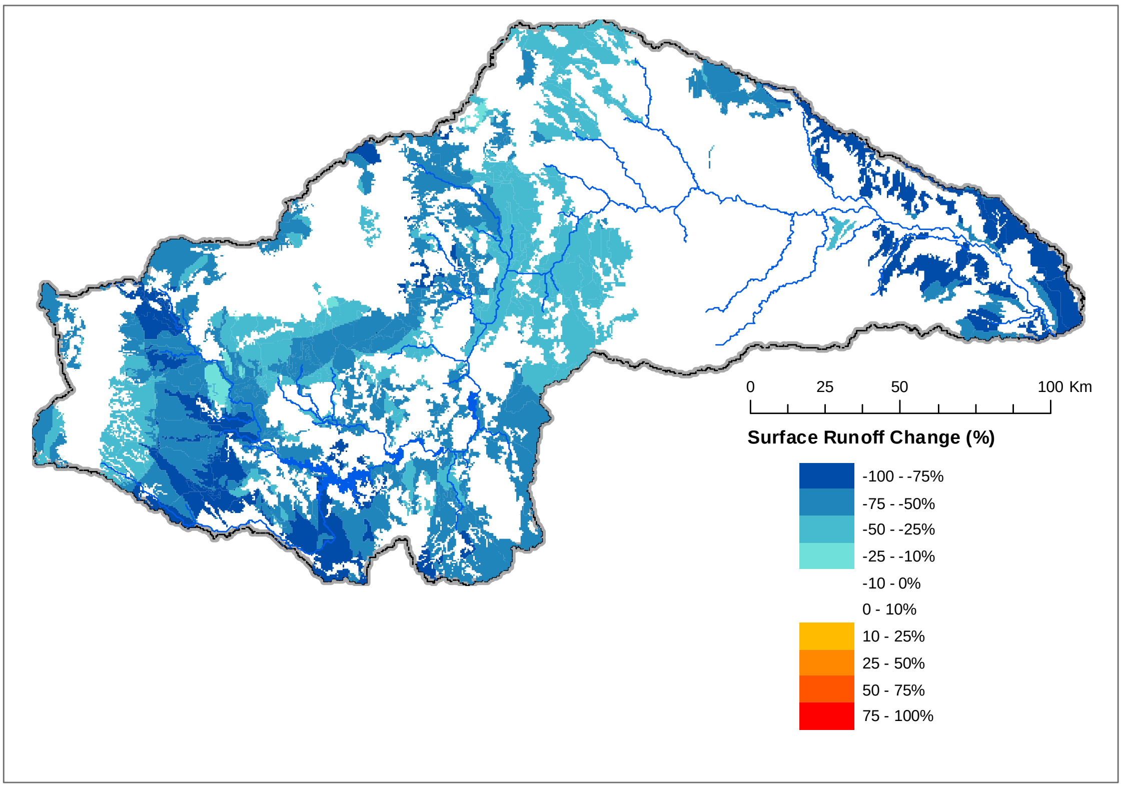


Figure 76: Change in percolation (above) and runoff (below) with tied ridges compared with the baseline in a wet year (1997)

7.4 Patterns of adoption of green water management

The impact of green water management on *green* and *blue water* flows is a linear function; the more farms adopting improved management, the greater the water gains. But the impact on soil erosion, sediment transport and siltation of reservoirs is not linear; it depends on where best practice is adopted, especially in relation to the stream channels that carry the sediment. A simple model in Microsoft Excel illustrates the impact of partial uptake of green water management on sediment transport, assuming:

- Fields of 25 m^2
- Area of 50 ha (500 x 1000 m = 20 x 40 fields) with a river in the middle;
- Without intervention, erosion of 30 tonne/ha/yr (~2 mm) and 75 per cent of sediment eroded from upslope is transported across each field;
- Green water management cuts erosion to 5 tonne/ha/yr;
- All fields are similar (in practice, fields close to streams will have gentler slopes, less-erodible soils, and better vegetation cover).

Without conservation measures (Figure 77), sediment yield is 1500 tonnes/yr. Figure 78 shows 20 per cent adoption of green water management at random locations; sediment transfer to the river is 812 tonnes/yr.
Figure 79 shows 20 per cent uptake with field bordering the river; sediment transfer to the river is 405 tonnes/yr.

Figure 80 shows the non-linear relationship between the proportion of fields where conservation measures are implemented and the sediment load in the river. Even a partial uptake of Green Water Credits will make a significant impact on sediment loads in the streams and, therefore, on reservoir siltation.

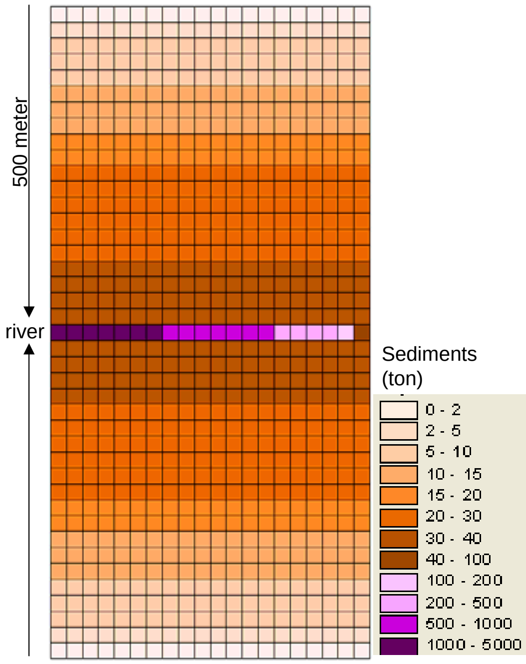


Figure 77: Projected erosion without green water management

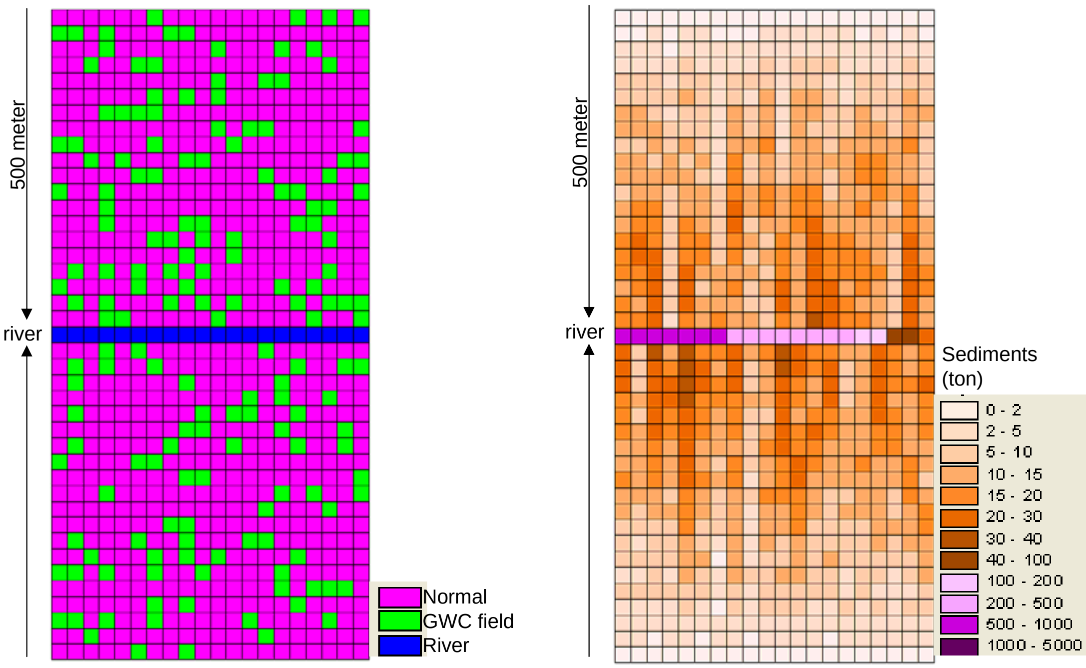


Figure 78: Projected erosion with random 20% uptake of green water management

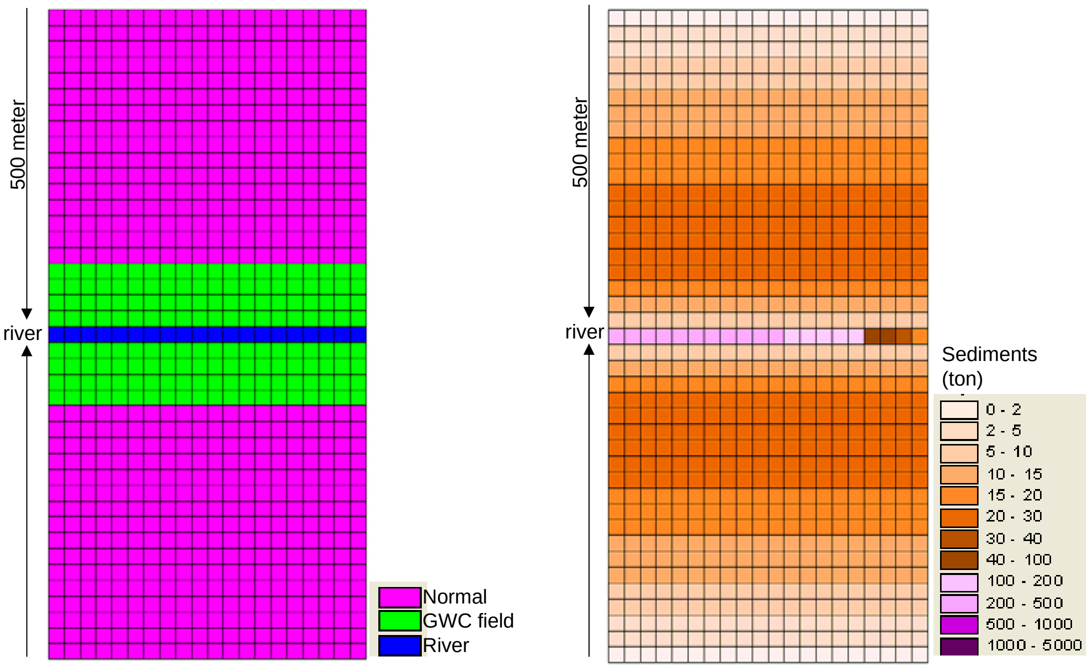


Figure 79: Projected erosion with 20% implementation, all next to the river

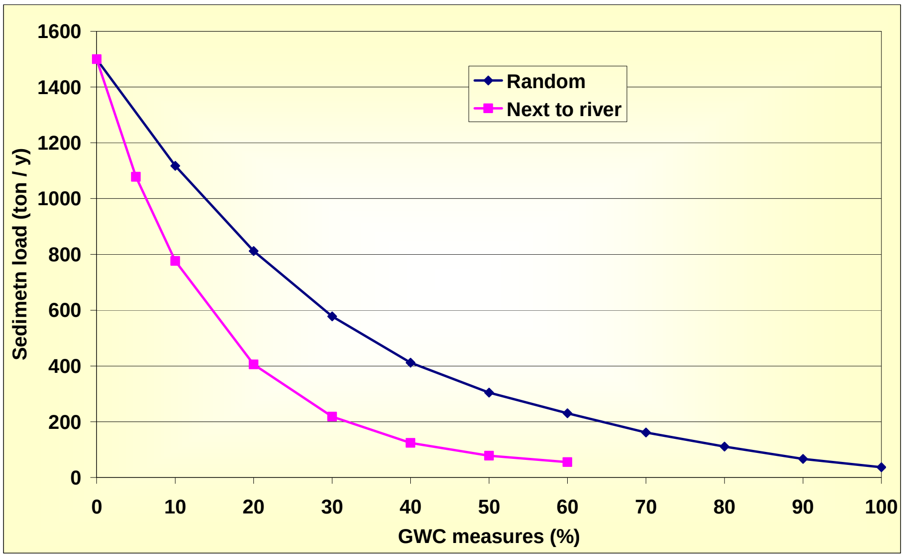


Figure 80: Relation between proportion of fields under green water management and the sediment load of the river

In summary, the key areas for intervention are identified and the proportion of these areas in which intervention is needed can be estimated according to the required impacts on water and sediment discharge.

8 References

Agassi M, Hadas A, Benyamini Y, Levy GJ, Kautsky L, Avrahamov L and Zhevelev H 1998. Mulching effects of composted MSW on water percolation and compost degradation rate. *Compost Science & Utilization* 6, 34-41

Alcamo J, Döll P, Henrichs T, Kaspar F, Lehner B, Rösch T and Siebert S 2003. Development and Testing of the WaterGAP 2 Global Model of Water Use and Availability. *Hydrological Science*, 48, 317-337

BASINS 2006. BASINS: Better Assessment Science Integrating Point and Non-point Sources (http://www.epa.gov/waterscience/basins/index.html)

Batjes NH and Gicheru PT 2004. *Soil data derived from SOTER for studies of carbon stocks and change in Kenya (ver. 1.0). GEFSOC Project.* Report 2004/01, ISRIC - World Soil Information, Wageningen

Batjes NH, Al-Adamat R, Bhattacharyya T, Bernoux M, Cerri CEP, Gicheru. P., Kamoni P, Milne E, Pal DK and Rawajfih Z 2007. Preparation of consistent soil data sets for SOC modelling purposes: secondary SOTER data sets for four case study areas. *Agriculture, Ecosystems and Environment* 112, 26-34

Biamah EK 2005. Coping with drought: options for soil and water management in semi-arid Kenya. Ph.D. thesis, Wageningen University and Research Centre, Wageningen

Boogaard HL, Van Diepen CA, Rötter RP, Cabrera JMCA and Van Laar HH 1998. WOFOST 7.1: Users' guide for the WOFOST 7.1 crop growth simulation model and WOFOST Control Centre 1.5 (www.alterra.wur.nl/UK/prodpubl/modellen/WOFOST/wofost_intro.htm [24 March 2005])

Centre for Water and Climate 2007. Soil Water Atmosphere Plant (SWAP), Wageningen University and Research Centre (http://www.swap.alterra.nl/)

Cosgrove WJ and Rijsberman FR 2000. *World water vision: making water everybody's business*. Earthscan, London

Crawford NH and Linsley RK 1966. *Digital simulation in hydrology: Stanford Watershed Model IV*, Stanford Univ. Dept Civil Eng

DHI 2007a. MIKE-BASIN (http://www.mikebasin.com)

DHI 2007b. MIKE-SHE (http://www.dhigroup.com/Software/WaterResources/MIKESHE.aspx)

Droogers P, Torabi M, Akbari M and Pazira E 2001. Field scale modeling to explore salinity in irrigated agriculture. *Irrigation and Drainage* 50, 77-90

Droogers P, Kauffman JH, Dijkshoorn JA, Immerzeel W and Huting JRM 2006. *Green Water Credits: Basin identification*. GWC Report 1, ISRIC - World Soil Information, Wageningen

Ekbom A, Knutsson P and Ovuka M 2001. Is sustainable development based on agriculture attainable in Kenya? A multidisciplinary case study of Murang'a district. *Land Degradation and Development* 12, 435-447

EPA 2006. Environmental Protection Agency, Information Sources (http://www.epa.gov/epahome/ models.htm)

Falkenmark M and Rockström J 2004. *Balancing water for humans and nature*. Earthscan, London

FAO 1988. *FAO/Unesco Soil Map of the World, Revised Legend, with corrections*. World Resources Report 60. FAO, Rome

FAO 2000a. *East Africa Module Land Cover mapping based on satellite remote sensing*, Food and Agriculture Organisation of the United States, Rome

FAO 2000b. *World-wide agroclimatic database, version 2.01*, FAO, Rome

FAO 2005. Synthesis report of the e-conference "Drought Resistant Soils: optimization of soil moisture for sustainable plant production" (ftp://ftp.fao.org/agl/emailconf/soilmoisture/docs/proceedings_synthesis.doc)

Feddes RA, Kowalik PJ and Zaradny H (editors) 1978. Simulation of field water use and crop yield. Simulation Monographs. Pudoc, Wageningen

Gicheru TG 2002. The effect of different soil management practices on crust formation, soil moisture conservation and crop growth in Machang'a area, M'Beere district, Kenya, University of Nairobi, Nairobi, 157 pp

Gitonga JNL 2005. Monitoring and modeling crop growth, water use and production under dry-land environment North-West of Mount Kenya. Ph.D. thesis, University of Bern, Bern

Grassland Soil and Water Research Laboratory 2007. Soil and Water Assessment Tool, USDA Agricultural Research Service (http://www.brc.tamus.edu/swat)

Hoff H and Noel S 2007. *Quantifying water usage and demand in the Tana River basin: an analysis using the Water and Evaluation and Planning Tool (WEAP)*. GWC Report 4, ISRIC - World Soil Information, Wageningen

Hoogmoed W 1999. Tillage for soil and water conservation in the semi-arid tropics, *Environment Sciences. Ph.D. thesis*. Tropical Resource Management papers. Wageningen University and Research Centre, Wageningen, pp 184

Jabro JD 1992. Estimation of saturated hydraulic conductivity of soils from particle distribution and bulkdensity data. *Trans. ASEA* 35(2), 557-560

Jacks GV, Brind WD and Smith R 1955. *Mulching*. Bureau of Soil Technical Communication, 49. England: Commonwealth Agricultural Bureaux, Farnham Royal, Bucks

Jacobs J, Angerer J, Vitale J, Srinivasan R, Kaitho R and Stuth J 2003. *Exploring the potential impact of reforestation on the hydrology of the Upper Tana River catchment and the Masinga dam, Kenya (draft report)*, Texas A&M University

Jaetzold R and Schmidt H 1983. *Farm management handbook of Kenya*, Volume II - Natural conditions and farm management information. Ministry of Agriculture, Nairobi

Jalota SK and Prihar SS (editors) 1998. Reducing soil water evaporation with tillage and straw mulching. Iowa State University Press, Ames, 142 p

JICA 1987. Land Use derived from Landsat images for Kenya, International Livestock Research Institute (http://www.ilri.org/gis/search.asp?id=288)

KARI 1996. *Annual Report*, Regional Research Centre, Kenya Agricultural Research Institute, Embu

KARI 1998. *Annual Report*, Regional Research Centre, Kenya Agricultural Research Institute, Embu

KARI 2000. *Annual Report*, Regional Research Centre, Kenya Agricultural Research Institute, Embu

KenGen 2005. Annual Report Kenya Electricity Generating Company (http://www.kengen.co.ke/IPO/annual_report.pdf)

KSS 1996. The Soil and Terrain Database for Kenya at scale 1:1,000,000 (ver. 1.0), Kenya Soil Survey, National Agricultural Laboratory, Kenya Agricultural Research Institute

KSS and ISRIC 2007. Kenya Soil and Terrain database at scale 1:1,000,000 - version 2. Kenya Soil Survey and ISRIC - World Soil Information (http://www.isric.org/UK/About+ISRIC/Projects/Track+Record/SOTER+Kenya.htm)

LCI 2006. Land Cover Institute (LCI) of the U.S Geological Survey (USGS), at the EROS Centre ((http://landcover.usgs.gov/index.php))

Macharia P 2004. Kenya Country Overview, FAO Gateway to Land and Water Information (http://www.fao.org/ag/agL/swlwpnr/reports/y_sf/z_ke/ke.htm)

Mantel S and van Engelen VWP 1999. Assessment of the impact of water erosion on productivity of maize in Kenya: an integrated modelling approach. *Land Degradation and Development* 10, 577-592

Meijerink G, Muchena F, Njue E, Noel S, Onduru D and Porras I 2007. *Political, institutional and financial framework for Green Water Credits in Kenya*. GWC Report 6, ISRIC - World Soil Information, Wageningen

Mitchell TD, Carter TR, Jones PD, Hulme M and New M 2004. A comprehensive set of high resolution grids of monthly climate for Europe and the globe: the observed records (1901 - 2000) and 16 scenarios (2001-20016), Climate Research Unit, School of Environmental Sciences, University of East Anglia, UK

MRC 2000. *Water Utilisation Project Component*, Mekong River Commission

Mwago MG and Okoth PF 1990. Erosion hazard in Kenya, *1st Symposium on disaster management in Kenya*, Eldoret

Njihia CM 1979. The effect of tied ridges, stover mulch and farmyard manure on rainfall abstraction in a medium potential area Katumani, Kenya. In: Lal R (editor), *Soil Tillage and Crop Production*. IITA, Ibadan, Nigeria

NWCC 2006. Water Management Models. (http://www.wcc.nrcs.usda.gov/nrcsirrig/irrig-mgt-models.html)

Oludhe C 2003. *Capacity Building and the Development of Tools for Enhanced Utilization of Climate Information and Prediction Products for the Planning and Management of Hydropower Resources in Kenya*, Department of Meteorology, University of Nairobi, Nairobi, Kenya

Ouma JO, Muriithi FM, Mwangi W, Verkuijl H, Gethi M and De Groote H 2002. *Adoption of maize seed and fertilizer in Embu District, Kenya*

Pereira HC and Jones PA 1954. A tillage study in Kenya. The effects of tillage practices on the structure of the soil. *Emp. J. Exp. Agric.* 23, 323-331

Porras I, Grieg-Gran M and Meijerink G 2007. *Farmers' adoption of soil and water conservation: potential role of payments for watershed services*. GWC Report 5, ISRIC - World Soil Information, Wageningen

Rallison RE and Miller N 1981. Past, Present and Future SCS Runoff Procedure. *International Symposium on Rainfall-Runoff Modeling*. Mississippi State University, Littleton pp 355-364

Reed S, Koren V, Smith M and others 2004. Overall distributed model inter-comparison project results. *J. Hydrology* 298, 27-60

REM 2006. Register of Ecological Models (http://www.wiz.uni-kassel.de/ecobas.htm)

Ringersma J, Batjes NH and Dent D 2003. *Green Water: definitions and data for assessment*. Report 2003/2, ISRIC - World Soil Information, Wageningen

Schulze RE 1975. Catchment evapotranspiration in the Natal Drakensberg. Ph D thesis, University of Natal, Pietermaritzburg, 244 pp

Schulze RE 1995. The ACRU Theory Manual, Hydrology and Agrohydrology (http://www.beeh.unp.ac.za/acru/)

Seckler DR, Barker and Amarasinghe U 1999. Water scarcity in the twenty-first century. *Water Resources Development* 15, 29-42

SEI US Center 2007. Water Evaluation and Planning System, Stockholm Environment Institute US Center (http://www.brc.tamus.edu/swat/)

Singh J, Knapp HV, Arnold JG and Demissie M 2005. Hydrological modeling of the Iroquois river watershed using HSPF and SWAT. *J. American Water Resources Association* 41, 343-360

SMIG 2006a. Surface-water quality and flow modeling interest group (http://smig.usgs.gov/SMIG/SMIG.html)

SMIG 2006b. Archives of models and modeling Tools (http://smig.usgs.gov/SMIG/model_archives.html)

Sombroek WG, Braun HMH and van der Pouw BJA 1982. *Exploratory soil map and agro-climatic zone map of Kenya, 1980, scale 1:1,000,000*. Exploratory Soil Survey Report No E1. Kenya Soil Survey, Ministry of Agriculture, Nairobi

TNRCC 1998. *An evaluation of existing water availability models*. 2, Texas Natural Resource Conservation Commission

Tong'i ERN and Mochoge BO 2000. Effect of soil type and cropping system on sediment and runoff yield in Kisii District. *Proceedings of the 2nd Scientific Conference of the Soil Management and Legume Research Network Projects*. KARI, Nairobi, Mombasa, Kenya

United Nations 1997. *Comprehensive assessment of the freshwater resources of the World (overview document)*. World Meteorological Organization, Geneva

United Nations 2000. Linkages between agriculture, land and water (UN, agenda 21) Addendum. Sustainable agriculture and rural development. Report of the Secratary-General, Economic and Social Council, United Nations (http://www.un.org/documents/ecosoc/cn17/2000/ecn172000-7add3.htm)

US-EPA 1997. Hydrological Simulation Program. (http://www.epa.gov/ceampubl/swater/hspf)

USDA-SCS 1972. National Engineerin Handbook, Hydrology Section, Chap.4-10. US Dept. of Agriculture, Soil Conservation Service, Washington, DC, USA

USDA-SCS 1986. *Urban hydrology for small watersheds*, Us Dept. of Agriculture, Soil Conservation Service, Washington, DC, USA

USGS 2003. Shuttle Radar Topographic Mission Digital Elevation Model, available through CGIAR-Consortium for Spatial Information (CGIAR-CSI) (http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp [accessed: November 2006])

USGS 2006. Water resources applications software (http://water.usgs.gov/software)

van Engelen V and Huting J 2004. The use of DEMs in SOTER: a tool for delineation of landform for soil and terrain databases. . *Innovative techniques in soil survey*. Land Development Department, Chattuchak, Bangkok, Cha-Am, Thailand

van Engelen VWP and Wen TT 1995. *Global and National Soil and Terrain Digital Database (SOTER). Procedures Manual*. ISRIC - World Soil Information, Wageningen

van Ittersum MK, Leffelaar PA, Van Keulen H and others 2003. On approaches and applications of the Wageningen crops models. *Europ. J. Agronomy* 18, 201-234

Vorosmarty CJ, Green P, Salisbury J and others 2000. Global water resources: vulnerability from climate change and population growth. *Science* 289, 284-288

Wanyonyi SW 2002. Sediment management in Masinga reservoir, Kenya, University of Agricultural Sciences (BOKU), Vienna, 173 pp

Williams JR 1995. *Chapter 25. The EPIC Model.*, *Computer Models of Watershed Hydrology*, Water Resources Publications, Highland Ranch, CO

Williams JR and Berndt HD 1977. Sediment yield prediction based on watershed hydrology. *Trans. ASEA* 20(6), 1100-1104

Wischmeier WH and Smith DD 1978. *Predicting rainfall losses: A guide to conservation planning.* USDA Agricultural Handbook, No. 537. US Gov. Print. Office, Washington, DC

WOCAT 2007a. *Where the land is greener - case studies and analysis of soil and water conservation initiatives worldwide. Editors Hanspeter Liniger and William Critchley*. CTA, FAO, UNEP and Centre for Development and Environment, Bern

WOCAT 2007b. World Overview of Conservation Approaches and Technologies, Centre for Development and Environment (http://www.wocat.net/databs.asp)

WRMA 2006. Catchment Management Strategy: Tana Catchment. Annex 2, Zero draft. Water Resources Management Authority, Nairobi

Annex 1: Selection of hydrology models

A1.1 Introduction

Application of model

Water is now scarce across wide areas; some 1.8 billion out of a world population of 5.7 billion people now live under severe water stress. Projections of future demand and supply indicate a significant worsening of the situation: the number of people living under severe water stress will have grown to 2.2 billion by the year 2025 (United Nations 1997; Vorosmarty and others 2000). In respect of water abstracted from streams and groundwater, irrigation is by far the main water user now accounting for 70-80 per cent. By 2025, the production of staple grains will have to increase by some 40 per cent to meet the demands of the growing human population (Cosgrove and Rijsberman 2000; Seckler and others 1999) - which means 40 per cent increase in consumptive use of water at constant water-use efficiency. Irrigation cannot do it alone and faces increasing competition for water resources from burgeoning cities and increasing recognition of vital environmental flows.

The drainage basin is usually the best unit for water resources planning and management but interventions in field have to be local. Models can explore different scenarios and aspects that cannot be influenced directly, such as climate change, and situations where policy makers and water managers can make decisions that will directly affect the outcomes – such as changes in reservoir operations, water allocation and farm practices (Figure 81).

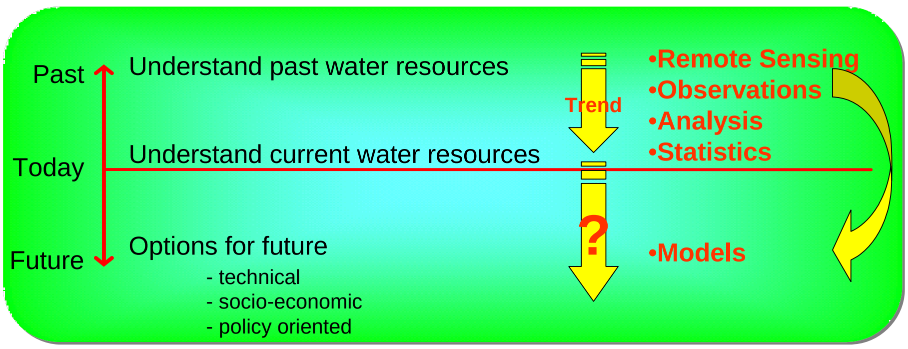


Figure 81: Simulation models in scenario analysis

Concepts

We are using *model* in the sense of a system of postulates, data, and inferences presented as a computer-based, mathematical description of physical processes. Such models are useful to study processes or systems where the actual processes are expensive or difficult to measure, and for creating and comparing alternative scenarios. For the assessment of Green Water Credits, we need to model water resources under present management and compare a variety of possible future management options in terms of water yield and distribution.

An early catchment model, the Stanford Watershed Model (Crawford and Linsley 1966), represented a catchment simply as a set of storage reservoirs linked to each other; values for the parameters describing the interaction between the reservoirs were obtained by matching the simulated with the observed stream flow. At the other end of the spectrum, field-scale models describe unsaturated flow in the soil and water uptake by roots; one of the first was the SWATR model (Feddes and others 1978). Many hydrological and crop-hydrological models are now available; choice of appropriate models for Green Water Credits assessments depends on the spatial scale and physical detail to be considered, the kind of data available for the basin under consideration, expected accuracy, and the expertise required to operate the model. The capabilities of some commonly used models are plotted in Figure 82, in terms of spatial scale and physical detail.

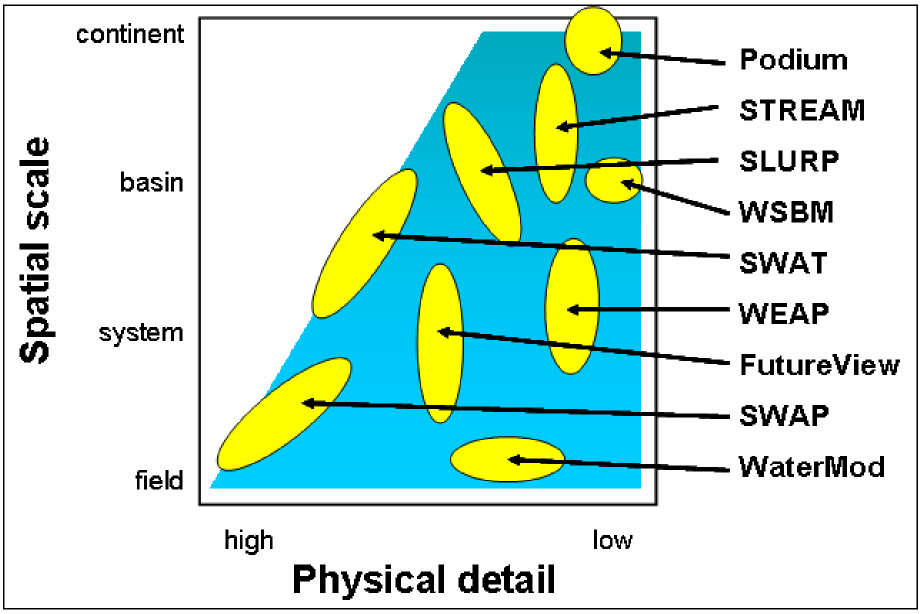


Figure 82: Spatial and physical detail of hydrological models

Overview of models

Several overviews list available models and provide summaries; most of this information is provided by the model developers so tends to be biased towards the capacities of the model. The US Geological Survey (USGS 2006) provides an overview of their own models, about 50, categorized as geochemical, ground water, surface water, water quality, and general. Several are outdated but some commonly used ones are included; all are in the public domain; for most of the models, the source code is provided. The National Water and Climate Center of the US Dept Agriculture provides crop-water models with some water management tools related to field scale irrigation (NWCC 2006).The US Environmental Protection Agency's SWAT model is the *de-facto* standard in basin-scale modelling and has been included in the BASINS package (BASINS 2006); (EPA 2006) provides more linkages and other model overviews. The US Geological Survey Surface water quality and flow Modeling Interest Group (SMIG 2006a) brings together the USGS, USDA, USACE, EPA; together with some other models and, also, provides links to

40 archives (SMIG 2006b). The most up-to-date overview of crop-growth models is the Register of Ecological Models (REM 2006), with 675 models.

Assessments

The overviews listed above do not provide independent judgment of model quality: the method used for spatial aggregation, the ways that the models link climatic, terrain, soil, and land cover data, and how well they predict the hydrology. Model output further depends on how representative, complete and reliable are the basic data; and how representative are any transfer functions that are used to fill gaps in the data. For Green Water Credits assessments, an important criterion is that models should be applicable to any catchment, worldwide, including those for which a wide range of detailed data are not available. Some useful assessments of hydrological models have been undertaken:

> Texas Natural Resource Conservation Commission evaluated 19 river basin (water availability) models for management of water resources according to 26 criteria (TNRCC 1998); most important was the ability of the model to supports water-rights simulation. Five were ranked as suitable (WRAP, MODSIM, STATEMOD, MIKE BASIN, OASIS) and the WRAP model chosen for this specific purpose. Models not selected included WEAP (no appropriation doctrine) and SWAT (not intuitive and user-friendly).
>
> A similar assessment to select appropriate river basin models by the Mekong River Commission (MRC 2000) looked for three different types of model: hydrological (rainfall-runoff), basin water resources, and hydrodynamic. The criteria were: technical capability, user friendliness, and sustainability. Out of 11 hydrological models, SWAT was considered the most suitable; the selected basin simulation model was IQQM; the selected hydrodynamic model was ISIS.
>
> An actual model comparison, testing models using existing data, has been initiated by the Hydrology Laboratory of the United States National Weather Service (NWS) to assess the ability of hydrological models to reproduce hydrographs from detailed radar rainfall data reached no clear conclusions (Reed and others 2004).
>
> (Singh and others 2005) evaluated the basin-scale simulation models HSPF and SWAT, calibrated for a nine-year period and verified using an independent 15-year period by comparing simulated and observed daily, monthly, and annual stream flow. The simulated flows from both models were similar to each other and to observed flows, particularly for the calibration results. SWAT proved slightly better than HSPF for the verification period, in particular providing better simulation of low flows.

A1.2 Summary of selected models

The following models may be useful for Green Water Credits:

- Global scale: WATERGAP
- For land use-water resource interactions at basin scale: ACRU, HSPF, MIKE-SHE, SWAT;
- For water-allocation at basin and sub-basin scale: MIKE-BASIN, WEAP;
- For field-scale soil water and crop simulation: SWAP, WOFOST;

ACRU - Agricultural Catchments Research Unit model

ACRU (Schulze 1995) stems from a distributed catchment evapotranspiration study in the KwaZulu-Natal Drakensberg by the Agricultural Catchments Research Unit of the Dept of Agricultural Engineering of the University of Natal, Pietermaritzburg (Schulze 1975). It has been verified with data from southern Africa and the USA. It has been used to support decision making in southern Africa and, also, in research elsewhere. It estimates soil water status, runoff volume, sediment yield, peak discharge, reservoir water budgets, crop yield, and irrigation water demand and supply in daily time-steps. Menu builder software is provided to assist preparation of input data.

ACRU can operate as a point model or lumped small catchments model. For large catchments or in areas of complex land uses and soils, it can operate as a distributed cell-type model where sub-catchments (ideally not exceeding 30 km^2) are delineated and flows can take place from exterior through interior cells according to a pre-determined scheme, with each sub-catchment able to generate individually requested outputs which may be different from those of other sub-catchments or with different levels of input/information. ACRU is not integrated with GIS-software. In the catchment or basin mode, the basic mapping units (lumped small catchments) are polygons from which the basic data are derived and on which the calculations are based. Results are linked to vector based GIS-files, through polygon attribute files.

The model can be obtained from the School of Bioresources Engineering and Environmental Hydrology, University of Natal, Pietermaritzburg. User documentation on ACRU was updated in 1989 and is available from the internet. (http://www.beeh.unp.ac.za/acru/).

Input: Daily rainfall, daily or monthly evaporation, soils and land use parameters.
Output: Simulated stream flows, sediment and crop yield, reservoir yield analysis.
Evaluation: Well-used in South Africa but the user-community outside South Africa is small.

HSPF- Hydrological Simulation Program

HSPF is public-domain software from the US EPA Center for Exposure Assessment Modeling. It stems from the Stanford Watershed Model; over time, water-quality processes were added as well as improved concepts and computer engineering, preprocessing and post-processing software, algorithm enhancements, and use of the USGS WDM data file system. The current release is Version 11 (US-EPA 1997)**.**

Input: HSPF requires lots of data at high spatial and temporal resolution - precipitation and potential evapotranspiration are required for basin simulation; air temperature, dew point, wind, and solar radiation are required for snowmelt; air temperature, wind, solar radiation, humidity, cloud cover, tillage practices, point sources, and (or) pesticide applications may be required for water-quality simulation; physical measurements and related parameters are required to describe the land area, channels, and reservoirs.
Output: HSPF can generate impressive and overwhelming output as either printed tables at any time step, a flat file, or the WDM file. The post-processing software uses data from the WDM file format. Hundreds of computed time series may be selected for the output files.
Evaluation: HSPF is not particular user-friendly and demands a high-level of computational as well as hydrological skills. It can be obtained free of charge (http://www.epa.gov/ceampubl/swater/hspf).

MIKE-BASIN

MIKE-BASIN (DHI 2007a) is a water allocation model with an Arc-GIS interface. It builds on a network in which branches represent individual stream sections and the nodes represent confluences, diversions, reservoirs, or water users. The ArcGIS interface has been expanded so that the network elements can be edited conveniently. Technically, it is a quasi-steady-state, mass-balance model, however allowing for routed river flows. The water quality solution assumes purely advective transport; decay during transport can be modelled. The groundwater description uses the linear reservoir equation. Areas of application include: water availability analysis - conjunctive surface and groundwater use, optimization: infrastructure planning - irrigation potential, reservoir performance, water supply capacity, wastewater treatment requirements; analysis of multi-sectoral demands and trade-offs; ecosystem studies - water quality, minimum discharge requirements, sustainable yield, effects of global change; regulation - water rights, priorities, water quality compliance.

Evaluation: MIKE-BASIN is a water planning model focused on the water management, water division and the infrastructural planning of water division, rather than on the physical aspects of hydrology. However, the very user-friendly interface and the ability to built quickly models makes MIKE-BASIN suitable for quick, policy-oriented water resources planning at basin or sub-basin scale. The license is costly (http://www.mikebasin.com/)

MIKE-SHE

MIKE-SHE is a dynamic modelling tool that can simulate the entire land phase of the hydrologic cycle - an integrated modeling environment that allows components to be customized and used independently (DHI 2007b). It includes powerful pre-processing and presentation tools.

Input: The input data requirements and model parameters for the fully integrated MIKE SHE model are comprehensive (such as horizontal and vertical soil hydrologic conductivity). Each component of the model applies a range of input data types and parameters. The parameters may be physically measurable or empirical specific to the equations solved in the model.
Output: Includes maps and time-series graphs of all modelled processes.
Evaluation: MIKE-SHE is a complete package for detailed analysis of hydrological processes, so its input requirements are substantial; it also demands high-level knowledge of technical aspects as well as conceptual hydrological and water resources issues. Widely used for consultancy and research. The license is costly (http://www.dhigroup.com/Software/WaterResources/MIKESHE.aspx)

SWAP - Soil Water Atmosphere and Plant model

SWAP (Centre for Water and Climate 2007) simulates the transport of water, solutes and heat in soils at the field scale and during entire growing seasons. Applications include: field-scale water balance, evapotranspiration, plant growth as affected by water and/or salinity stress, improvement of surface water management, and soil-water indicators for natural vegetation.

Input: Soil physical and hydrological properties; crop characteristics (soil cover, leaf-area index, crop height); daily meteorological data; drainage and irrigation-specific data
Output: Flow rate through profile, state variables, crop rate and state variables. Time interval of simulation: 1 day. Basic spatial unit: m^2 to field level.
Evaluation: SWAP is a point model that includes all unsaturated flow processes including crop growth modeling at several levels of detail. There are some semi-2D components in terms of drainage and surface water flow. It has been used extensively, world wide, to evaluate field-scale water and salt management issues.
SWAP is supported by Alterra in Wageningen, and can be downloaded freely from the internet (http://www.swap.alterra.nl/).

SWAT - Soil and Water Assessment Tool

The Soil and Water Assessment Tool – SWAT - (Grassland Soil and Water Research Laboratory 2007) is a basin-scale model to quantify the impact of land management practices in large, complex watersheds. It is a process-based model operating in daily time steps, aggregating effects in many sub-basins, each representing a unique land use and soil type. SWAT2000, the current version, is incorporated into EPA's BASINS 3.0 release. An extension of ArcView GIS has been developed in Avenue – AVSWAT, organized in eight components: Watershed Delineation, Land Use and Soil Definition, Editing of the model Data Bases, Definition of the Weather Stations, Input Parameterization and Editing, Model Run, Read and Map-Chart Results, Calibration tool.

Input: SWAT requires spatial distributed data for the basin, in particular a digital elevation model, land cover and soils. From the DEM, sub-catchments and stream network are generated automatically; these sub-catchments and the land cover and soils are then used to obtain Homogenous Response Units (HRUs). Meteorological data at one or more locations in the basin provides sufficient information to run the model. Reservoirs and operational rules for these may be incorporated. Multiple standardized databases are included to parameterize different land use types, crops, and soils.

Output: The model generates stream flow and land-based results. Stream flow can include water quality. The land-based results include all the components of the hydrological cycle as well as erosion, pollutants, nutrients and crop growth - per sub-catchment and HRU.

Evaluation: SWAT has been calibrated and validated for different conditions worldwide; where land-use interactions are involved, it is the *de-facto* standard for basin-scale modelling. It is in the public domain, available from the internet (http://www.brc.tamus.edu/swat), and is actively supported by the USDA Agricultural Research Service at the Grassland, Soil and Water Research Laboratory in Temple, Texas, as well as by a group of active users.

WATERGAP - Water Global Assessment and Prognosis model

WaterGAP (Alcamo and others 2003) is a global water model developed at the Centre for Environmental Systems Research, University of Kassel, Germany, in cooperation with the National Institute of Public Health and the Environment, the Netherlands. It computes water availability (surface runoff, groundwater recharge and river discharge) and water use at a spatial resolution of 0.5 degree (55 x 55 km at the equator); this is presently the highest feasible resolution for global hydrological models because more-detailed climatic input is not available. WaterGap is based on many global data sets, coupling different disciplines within a single framework; some of its datasets maybe of interest for the Green Water Initiative, e.g. a global map of irrigated areas, drainage direction, lakes and wetlands. The Global Hydrology Model simulates the macro-scale behavior of the terrestrial water cycle to estimate water resources. It calculates a daily vertical water balance for both the land area and the open water bodies at each of the 0.5° cells. The vertical water balance for the land fraction in a cell consists of a canopy water balance and a soil water balance. These are calculated as functions of land cover, soil water capacity, and monthly climate variables (i.e. temperature, radiation, and precipitation). WaterGap includes a hydrological model (http://www.usf.uni-kassel.de/wwap/).

WEAP - Water Evaluation and Planning model

WEAP (SEI US Center 2007) is a tool for water allocation. It includes a semi-physical, irregular grid, lumped–parameter hydrologic simulation model that can account for hydrologic processes within a water distribution system. It works with nodes and arrows as indicators of water flow and distribution. It may be run on any time-step where routing is not a consideration but assumes a monthly time-step; time horizon can be as short as one year up to many. Scenarios are evaluated with regard to water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables. WEAP contains built-in models for: rainfall, runoff and infiltration, evapotranspiration, crop requirements and yields, surface water and groundwater interaction, and in-stream water quality. It has a GIS-based, graphical, *drag and drop* interface, allows user-defined variables and equations, and has a model- building facility, and dynamic links to spreadsheets and other models. Data structures are flexible and expandable.

Input: The major input is related to the demand and supply sites (nodes) that are connected by links: urban areas, agricultural areas, groundwater, reservoirs, catchment nodes, rivers, canals.
Output: Uniquely, WEAP operates in an optimization-of-water-allocation mode, based on priorities set for each demand site. Output includes flows for all connection lines (rivers, canals) and met and un-met demands for all the demand sites, generated in an attractive format.
Evaluation: WEAP is essentially a water planning model for water allocation, infrastructure, and economic evaluation. Excellent support is provided in terms of manuals and training. A single-site license for an accredited academic institution in a rich country costs $1000, a non-consulting license $2500, and it is free of charge to not-for-profit, governmental or academic organizations in developing countries (http://www.weap21.org/).

WOFOST - World Food Studies

Most hydrological flow process-based models require saturated and unsaturated soil hydraulic conductivity data of soils, which are lacking for most developing countries. The field-scale WOFOST crop growth model (Boogaard and others 1998) includes a soil-crop-atmosphere water balance that allows working with a minimum soil dataset. It simulates potential, water-limited and nutrient-limited production. It calculates, on a daily basis, crop growth and water balance for varying climate, crop and soil, and management conditions such as of infiltration enhancing practices and crop germination date. It is best suited for field level calculations but has been used at regional level in the European Crop Growth Monitoring System (van Ittersum and others 2003).

Input: Six factors determining yield and water balance can be assessed: climate, soil available water, rootable depth, crop, crop management, and soil management. The climate file requires: radiation, temperature, relative humidity, run of wind, rainfall, and number of rain days; a rainfall generator mimics daily rainfall based on monthly rainfall data and number of rainy days. WOFOST has well-tested annual crop files for several widely cultivated crops. Soil water storage capacity is controlled by soil thickness, soil water holding capacity and rootable depth.

Evaluation: WOFOST has been calibrated and validated for different conditions, applied worldwide and is easy to use, in particular where soil physical data are scarce. It is in the public domain, can be downloaded from the internet, and is actively supported by Alterra. (http://www2.alterra.wur.nl/UK/prodpubl/modellen/WOFOST/wofost_intro.htm)

A1.3 Conclusions

Criteria used to choose models for application to Green Water Credits assessment are the ability to evaluate upstream water processes (A), upstream erosion processes (B), downstream flow benefits (C), and downstream hydro-power benefits (D); experiences with model (E); external support (F); transferability (G); and cost (H). On this basis, the following models are chosen:

1. SWAT to evaluate the impact of upstream aspects of crop-land-soil management;
2. WEAP to evaluate basin-scale issues with a strong focus on economic benefits of hydropower;
3. WOFOST/SWAP for field-scale analysis on crop-soil-water management.

Table 26: Model suitability for Green Water Credits assessments

Model	*A*[a)]	*B*	*C*	*D*	*E*	*F*	*G*	*H*
SWAT	++[b)]	++	++	+	++	+	+	++
ACRU	++	++	++	o	+	+	o	++
WEAP	+	o	++	++	++	++	++	++
MIKEBASIN	o	o	++	+	+	+	+	o
MIKESHE	++	++	+	+	o	+	o	o
SWAP	++	o	o	o	++	++	++	++
WATERGAP	o	o	+	o	o	+	o	+
HSPF								
WOFOST	+	+	o	o	++	++	++	++

[a)] See text for details
[b)]++ = strong, + = good, o = weak

References

Alcamo J, Döll P, Henrichs T, Kaspar F, Lehner B, Rösch T and Siebert S 2003. Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrological Science*, 48, 317-337
BASINS 2006. BASINS: Better Assessment Science Integrating Point and Non-point Sources. http://www.epa.gov/waterscience/basins/index.html
Boogard HL, Diepen CA van, Rötter RP and others 1998. WOFOST 7.1 users' guide for the WOFOST 7.1 crop growth simulation model and WOFOST Control Centre 1.5. www.alterra.wur.nl/UK/prodpubl/modellen/WOFOST/wofost intro.htm
Centre for Water and Climate 2007. Soil Water Atmosphere Plant (SWAP), Wageningen University and Research Centre http://www.swap.alterra.nl/
Cosgrove WJ and Rijsberman FR 2000. World water vision: making water everybody's business. Earthscan, London
Crawford NH and Linsley RK 1966. Digital simulation in hydrology: Stanford Watershed Model IV, Stanford Univ. Dept Civil Eng
DHI 2007a. MIKE-SHE http://www.dhigroup.com/Software/WaterResources/MIKESHE.aspx
DHI 2007b. MIKE-BASIN http://www.mikebasin.com
EPA 1997. Hydrological simulation program http://www.epa.gov/ceampubl/swater/hspf
EPA 2006. Environmental Protection Agency, Information Sources (http://www.epa.gov/epahome/models.htm)

Feddes RA, Kowalik PJ and Zaradny H (editors) 1978. Simulation of field water use and crop yield. Simulation Monographs. Pudoc, Wageningen

Grassland Soil and Water Research Laboratory 2007. Soil and Water Assessment Tool, USDA Agricultural Research Service http://www.brc.tamus.edu/swat

Ittersum MK van, Leffelaar PA, Keuen H van and others 2003. On approaches and applications of the Wageningen crop models. Europ .J. Agron. 18, 201-234

MRC 2000. Water utilisation project component, Mekong River Commission, Bangkok

Neitsch SL, Arnold JG, Kiniry JR, Williams JR and King KW 2002. Soil and Water Assessment Tool (SWAT). Theoretical Documentation, version 2000, Taxes Water Resources Institute, College Station, Texas ftp://ftp.brc.tamus.edu/pub/swat/doc/swat2000theory.pdf

NWCC 2006. Water management models. http://www.wcc.nrcs.usda.gov/nrcsirrig/irrig-mgt-models.html

REM 2006. Register of ecological models http://www.wiz.uni-kassel.de/ecobas.htm

Reed S, Koren V, Smith M and others 2004. Overall distributed model inter-comparison project results. J. Hydrology 298, 27-60

Seckler DR, Barker and Amarasinghe U 1999. Water scarcity in the twenty-first century. Water Resources Development 15, 29-42

Schulze RE 1975. Catchment evapotranspiration in the Natal Drakensberg. Thesis, University of Natal, Pietermaritzburg

Schulze RE 1995. The ACRU theory manual, hydrology and agrohydrology http://www.beeh.unp.ac.za/acru/

SEI US Center 2007. Water evaluation and planning system. Stockholm Environment Institute, US Center http://www.brc.tamus.edu/swat/

Singh J, Knapp HV, Arnold JG and Demissie M 2005. Hydrological modeling of the Iroquois river watershed using HSPF and SWAT. J. American Water Resources Association 41, 343-360

SMIG 2006a. Surface-water quality and flow modeling interest group http://smig.usgs.gov/SMIG/SMIG.html

SMIG 2006b. *Archives of models and modeling tools* http://smig.usgs.gov/SMIG/ model_archives.html

TNRCC 1998. *An evaluation of existing water availability models*. 2, Texas Natural Resource Conservation Commission

UN 1997. *Comprehensive assessment of the freshwater resources of the World (overview document)*. World Meteorological Organization, Geneva

USGS 2006. *Water resources applications software* http://water.usgs.gov/software

Vorosmarty CJ, Green P, Salisbury J and others 2000. Global water resources: vulnerability from climate change and population growth. *Science* 289, 284-288

Annex 2: Annex Digital Elevation Model delineation

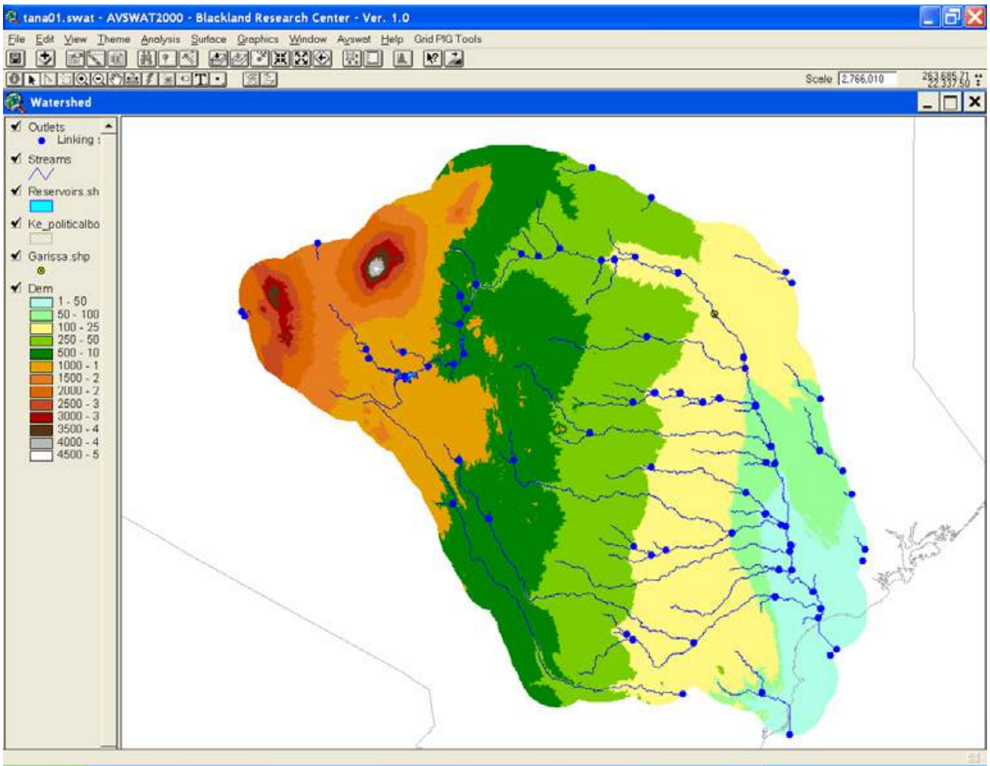


Figure 83: Basin delineation: DEM 250 m, threshold area 50 000 ha

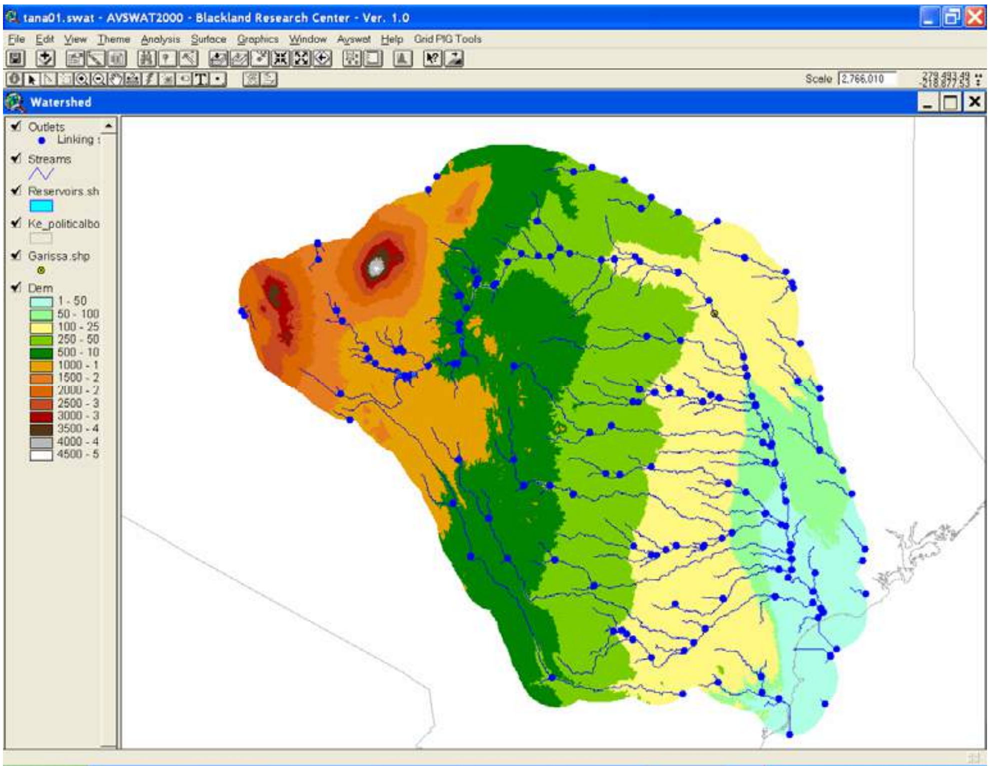


Figure 84: Basin delineation: DEM 250 m, threshold area 25 000 ha

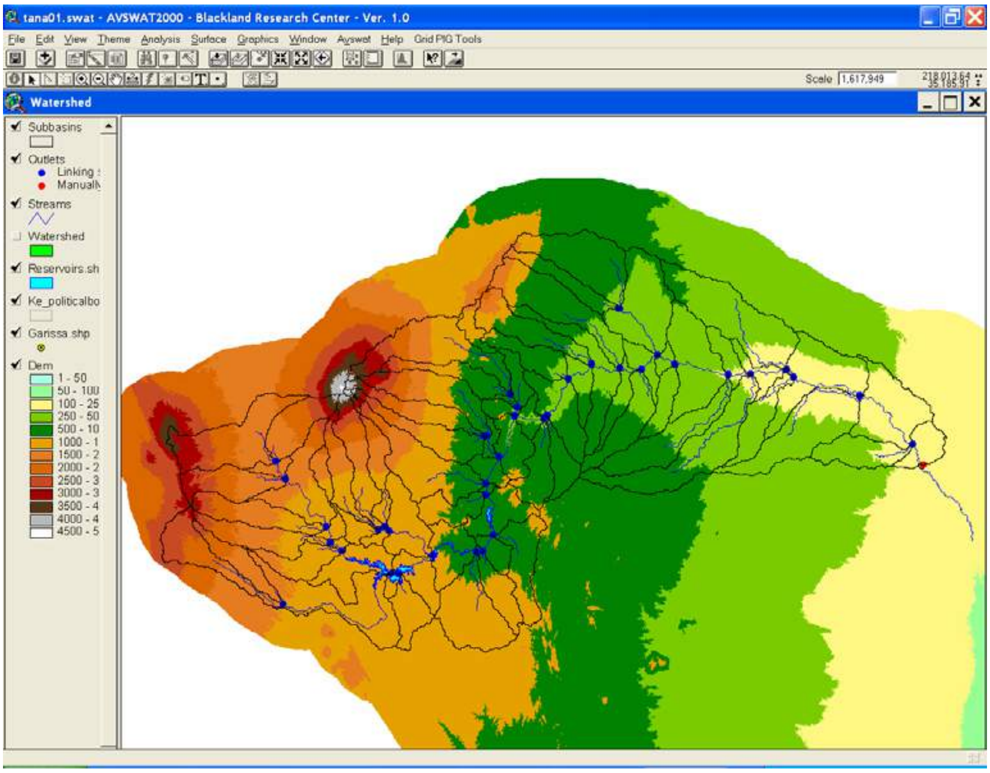


Figure 85: Sub- basins based on DEM 250 m, threshold area 25000 ha, 82 sub-basins are identified

Annex 3: Land cover, cultivated land and population

LCI

An overview of available datasets is given by the Land Cover Institute in the US Geophysical Service (LCI 2006) has identified 19 land cover datasets covering Africa but all of these were created for small-scale work of low spatial detail and with non-specific classes.

JICA/ILRI

A higher resolution land cover map, published by the International Livestock Research Institute, is derived from a study by the Japan International Co-operation Agency to develop National Water Master Plan (JICA 1987). It is derived from Landsat 1980 satellite data and maps 14 land cover classes (Figure 86 and Table 27).

Table 27: JICA land cover areas

Land cover	*Area (km^2)*	*Area (%)*
Bush (dense)	9 320	29
Agriculture (sparse)	9 221	28
Agriculture (dense)	5 473	17
Bush l(sparse)	2 883	9
Forest	2 500	8
Plantation	1 257	4
Woodland	723	2
Barren (R)	639	2
Grassland	492	2
Water (artificial)	146	0
Swamp	21	0
Town	14	0
Total	**32 689**	**100**

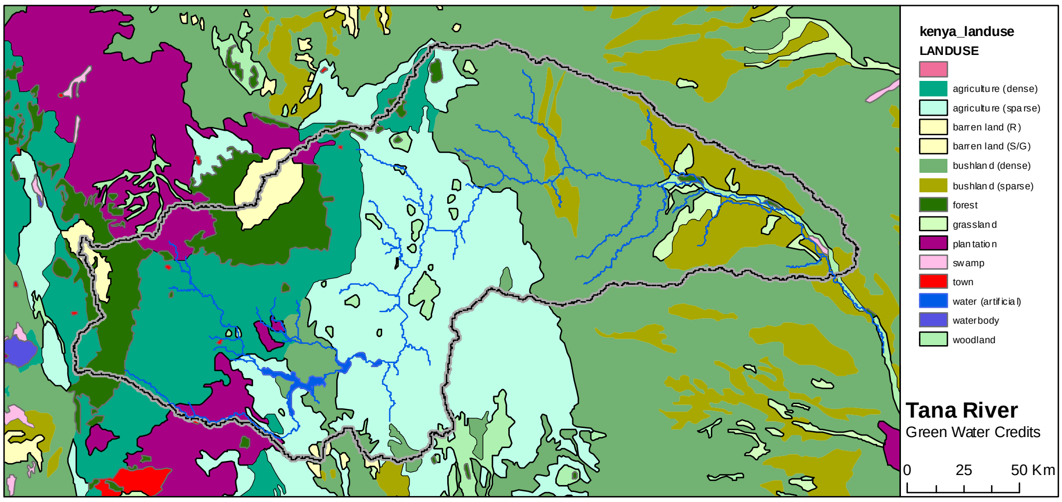


Figure 86: Upper Tana, land cover
(JICA 1987)

Table 28: Upper Tana household data (census and WRMA 2006)

	1	2	3	4	5	6	7	8	9
District/Province	*Rain-fed*	*ratio*	*Persons _District*	*Urban _Upper*	*Rural _Upper*	*Hh/ district*	*Hh/ Upper Tana*	*Area (ha)*	*Upper Tana (ha)*
CENTRAL									
Kiambu pp.	+	0.20	744010		148802	189706	37941	132400	26480
Kirinyaga	+	1.00	457105	57000	400105	114439	114439	147800	147800
Muranga	+	1.00	348304	69000	279304	84900	84900	93000	93000
Nyandarua pp.	+	0.10	479902	4000	43990	104401	10440	330400	33040
Nyeri pp.	+	0.80	661156	250000	278925	168786	135029	335800	268640
Thika pp.	+	0.42	645713	107000	164199	171569	72059	196000	82320
Maragua	+	1.00	387969	95000	292969	90744	90744	86800	86800
EASTERN									
Embu	+	1.00	278196	110000	168196	63893	63893	72900	72900
Kitui pp .	+/-	0.15	515422	1500	75813	97196	14579	2040200	306030
Machakos pp.	+/-	0.15	906644		135997	186297	27945	628100	94215
Mbeere	+/-	1.00	170953	3200	167753	37036	37036	209300	209300
Meru Central	+	1.00	498880	139500	359380	120265	120265	298200	298200
Mwingi pp.	+/-	0.50	303828		151914	58863	29432	1003000	501500
Meru North pp.	+	0.80	604050	17500	465740	119664	95731	394200	315360
Tharaka	+/-	1.00	100992		100992	20239	20239	157000	157000
Meru South	+	1.00	205451	7000	198451	46984	46984	109300	109300
NORTHEASTERN									
Garissa pp	-	0.20	392510	69000	9502	48141	9628	4495200	899040
Isiolo pp	-	0.20	100861	4000	16172	22583	4517	2569800	513960
TOTAL rural Upper Tana				933700	3458205	1745706	1015801		4214885
TOTAL rural rain-fed districts Upper Tana				859200	**3204803**	1332626	957645		

1 = Rain-fed agriculture: dominant (+), medium (+/--), negligible (-)
2 = Ratio of area of the district within/out Upper Tana
3 = Total persons in the district (Census data)
4 = Urban population within the Upper Tana (Census data)
5 = Rural population, calculated ((2*3)-5)
6 = Households per district (census data)
7 = Households in Upper Tana, calculated (6*2)
8 = Total area per district (Census data)
9 = Total area per district within the Upper Tana, calculated (8*2)
TOTAL rain-fed districts = total of rain-fed categories (+) and (+/-)

References

JICA 1987. *Land use derived from Landsat images for Kenya.* International Livestock Research Institute http://www.ilri.org/gis/search.asp?id=288

LCI 2006. *Land Cover Institute of the US Geological Survey* http://landcover.usgs.gov/index.php

WRMA 2006.*Catchment management strategy: Tana Catchment. Zero draft, Annex 2.* Water Resources Management Authority, Nairobi

Annex 4: Soil data

A4.1 KENSOTER-version 2 database

Rootable depth: The rootable depth for maize is derived from KENSOTER v2 (KSS and ISRIC 2007) and set at the upper limit of the horizon that has one or more of the following:

- bulk density greater than 1.65 kg/dm
- gleyic or ferric properties
- very low fertility, exchangeable (Ca+Mg+Na+K) less than 1.5 $cmol_c$ /kg
- sodic properties (ESP>15 per cent)

If none of these criteria apply, then the average depth of the classes is taken as rootable depth.

Soil water retention and available water capacity: There are many gaps in the measured physical data. To fill the gaps, measured data on field capacity, 20 kPa, and permanent wilting point, 1500 kPa (50 profiles with 159 records), were grouped in topsoil and subsoil sub-sets. Based on the soil groupings of the FAO Revised Legend (FAO 1988), linear regression functions were developed for low- and high-activity clay soils (<24 or > 24 $cmol_c\ kg^{-1}$ clay) and a third group of Andosols and Vertisols. Regression functions were calculated for field capacity and permanent wilting point based on clay and total clay+silt content (the inclusion of organic carbon content improved the correlation but, because this attribute is only measured for topsoils, it was not included in the final function). Except for Andosols and Vertisols, total clay+silt content gave better correlation than the clay content. The regression functions are calculated on total sand that equals 100-(clay+silt).

Porosity: Porosity, defined as volumetric water content at saturation, is derived from bulk density by:

Vol. % = (1- Db/2.65)*100

Note: most of the bulk densities (Db) in the KENSOTER database are not measured but based on field judgments. In cases of missing bulk densities, values were derived from the sub-set of samples from the Upper Tana:

Db =1.1674+0.0049% sand - 0.0085%OC (n=123; r^2=0.64; CI=95%)

Field Capacity: Regression functions derived for the calculation of field capacity:

Topsoils of low-activity clays (FAO soil groups[2] AC, FR, NT, LX)
FC1 = 37. 379 – 0.3839%sand (n=18; r^2=0.78)

Subsoils of low-activity clays (AC, FR, NT, LX)
FC2 = 38.522 – 0.4207%sand (n=35; r^2=0.77)

Topsoils of high-activity clays (PH, PL, LV, CM, SN, AR)
FC3 = 45.125 – 0.3787%sand (n=27; r^2=0.78)

[2] For abbreviations see FAO 1988. FAO/Unesco Soil Map of the World, Revised Legend, with corrections. World Resources Report 60. FAO, Rome

Subsoils of high-activity clays (PH, PL, LV, CM, SN, AR)
$FC4 = 43.215 - 0.3440\%sand$ (n=36; r^2=0.47)

Few measured data are available for Andosols and Vertisols, and they are very variable, so no subdivision into topsoil and subsoil sub-sets:

Andosols: $FC5 = 45.439 - 0.2103\%clay$ (n=14; r^2=0.33)

Vertisols: $FC6 = 40.692 + 0.0604\%clay$ (n=3; r2 =0.25)

Wilting Point: Differences in soil water retention at field capacity between topsoil and subsoil are mainly caused by soil structure and organic carbon content; they have much less influence on moisture retention at wilting point so no subdivision into topsoil and subsoil is made:

Wilting point = 26.975 – 0.302%sand (n = 68; r^2 = 0.77; CI = 95%)

A4.2 Harmonized KENSOTER database

The KENSOTER harmonized database contains the soil attributes needed for SWAT:

Table 29: SWAT soil parameters

SNAME	*PRID_SNAME*
HYDGRP	Estimated from clay% , drainage and soil group
Layer	Soil layer per 20 cm up to actual soil depth (<100 cm) or 100 cm. Soil depth >100 cm from profile descriptions (layer 6 and 7) inserted
Botdep	Lower depth from description, cm
SOL-ZMX	Maximum rooting depth, from profile description
ANION_EXCL AND SOL_CRCK AND SOL_K	Not done (estimated)
SOL_CBN	Total soil organic carbon, g/kg
SGRADE, SSIZE, STYPE	Structure description according to SOTER manual (van Engelen and Wen 1995)
CFRAG	Fragments >2 mm
SDTO	Sand %
STPC	Silt %
CLPC	Clay %
PSCL	Texture class, USDA
BULK	Bulk density, g/cm^3
TAWC	Available water content (30-1500 kPa)
ELCO	Electrical conductivity dS/m

The average rootable depth is derived from the SOTER depth classes, except where the depth of the given lower horizon boundary is shallower than the average depth:

SOTER depth class	*Depth range, cm*	*Average depth, cm*
V very shallow	< 30	15
S shallow	30- 50	40
M moderately deep	50-100	75
D deep	100-150	125
X very deep	>150	150

A4.3 Runoff and soil erosion data

Data from long-term trial at Embu (KARI 1998, 2000):

Table 30: Seasonal runoff, mm, 1993-97

Treatment	*1993*		*1994*		*1995*		*1996*		*1997*		*Mean*
	LR	*SR*	*LR*	*SR*	*LR*	*SR*	*LR*	*SR*	*LR*	*SR*	
Control	20.9	4.9	18.5	40.9	22.6	10.6	0.2	10.6	107.7	32.6	27.0
Napier	15.5	5.3	17.7	23.7	7.7	4.1	0.2	1.6	49.4	9.0	13.4
Calliandra	10.9	3.7	9.2	27.9	16.5	5.0	0.1	3.0	48.2	15.3	14.0
Combination	13.3	3.6	13.6	22.5	7.3	4.3	0.2	1.8	40.4	14.4	12.1
Mean	15.2	4.4	14.7	28.7	13.5	6.0	0.1	4.2	61.4	17.8	16.6

LR: long rains, SR: short rains

Table 31: Seasonal soil loss, tonne/ha

Treatment	*1993*		*1994*		*1995*		*1996*		*1997*		*Mean*
	LR	*SR*	*LR*	*SR*	*LR*	*SR*	*LR*	*SR*	*LR*	*SR*	
Control	0.1	3.1	6.6	18.0	11.7	8.1	0.1	10.6	51.3	21.1	13.1
Napier	0.0	4.3	5.2	9.3	3.3	2.1	0.0	1.6	9.9	7.5	4.3
Calliandra	0.1	1.8	4.4	12.3	8.1	4.2	0.0	3.0	38.4	6.4	7.9
Combination	0.1	2.4	5.3	11.9	3.2	3.2	0.0	1.8	19.9	8.3	5.6
Mean	0.1	2.9	5.4	12.78	6.6	4.4	0.0	4.2	29.8	10.8	7.7

Data from Kianjuka catchment:

Table 32: Runoff, soil loss, maize yield and fodder yield

Treatment	*20 per cent slope*			*40 per cent slope*		
	1997 LR	*1997 SR*	*1998 LR*	*1997 LR*	*1997 SR*	*1998 LR*
			Runoff , mm			
Control	92	134	111	64	56	93
Hedge	91	110	92	55	52	80
			Soil loss, tonne/ha			
Control	89	168	216	101	77	276
Hedge	84	119	158	61	71	221
			Maize yield, kg/ha			
Control	586	2366	628	722	2730	966
Hedge	513	2166	628	834	3081	870
			Fodder biomass yield, kg/ha			
Calliandra	*	*	426	*	*	410
Napier	*	*	1507	*	*	1041

* = No data; soils strongly weathered

Table 33: Kianjuki catchment, soil particle-size distribution

Slope	*Treatment*	*Clay (%)*	*Silt (%)*	*Sand (%)*
20 per cent	Control	69	18	13
	Hedge	64	20	16
40 per cent	Control	53	29	18
	Hedge	55	28	17

References

Engelen VWP van and Wen TT 1995. *Global and national soil and terrain digital database (SOTER). Procedures manual.* ISRIC, Wageningen

FAO 1988. *FAO/Unesco Soil Map of the World, Revised Legend, with corrections*. World Resources Report 60. FAO, Rome

KSS and ISRIC 2007. *Kenya soil and terrain database – version 2.* ISRIC – World Soil Information, Wageningen

Annex 5: Maize yield data

Table 34: Recommended maize varieties, year of release, expected yields and maturity period for KARI – Embu Mandate Zone
(Ouma and others 2002)

Land use system	*Altitude, masl*	*Variety*	*Year released*	*Maturity, days*	*Yield potential, tonne/ha*
Tea-Dairy Zone (LH1-UM1)	1500-2100	H627	1996	180-240	3.6
		H626	1989	180-240	3.4
		H625	1981	180-240	2.8
		H614D	1986	165-210	2.7
Coffee-Dairy Zone (UM2-UM3)	1000-1800	H513	1996	120-150	1.8
		C5222	1996	120-150	1.8
		PAN 5195	1996	120-150	1.8
		PHB 3253	1996	120-150	1.8
		CG 4141	1996	105-130	1.4
		H512	1970	120-150	1.8
		H511	1968	120-140	1.5
		EMCO92SR		105-130	1.5
Maize-Sunflower Zone (UM4/LM3/ LM4)	<1800	DH1	1996	90-120	1.2
		DH2	1996	90-120	1.2
		DLC1	1989	90-120	1.1
		KCB	1968	90-120	1.1
		CG4141	1996	110-120	1.2

Table 35: Maize varieties grown Embu District (1996-1998)
(Ouma and others 2002)

	Percentage of farmers					
Year	*LR 1996*	*SR 1996*	*LR 1997*	*SR 1997*	*LR 1998*	*SR 1998*
H513	0	0	0	2	0	4
H511	34	39	18	18	13	15
H512	14	13	10	7	7	5
C5222	0	0	0	0	0	1
Pan 5195	1	2	0	1	0	1
CG 4141	0	0	0	0	0	2
PHB 3253	1	2	25	33	34	34
H614	3	2	2	2	2	0
H611	0	0	0	0	0	0
H626	1	0	0	0	0	0
H625	6	2	3	1	3	0
KCB	1	2	1	0	1	2
DLC1	0	1	0	2	2	2
Own seed	41	41	44	39	43	45

LR – Long rains; SR = Short rains

Notes: Farmers maize yields for the 1999 long rains in Kutus-Sagana (AEZ UM3/LM4/LM3) area with Humic Nitisol soils were 1.2-3.5 tonne/ha, mean of 2.1 tonne/ha; highest yield 6.2 t/ha with NPK fertilizer

Table 36: Maize growth period, Embu
(KARI 2000)

Variety	*Days from emergence to silking*		*Days from emergence to maturity*	
Short maturity				
KCB	54	52*	99	96*
Medium maturity				
H511	68	68*	134	134*
H513	71	71*	136	136*
Late maturity				
H614	81	81*	157	157*
H628	84	84*	158	158*

Notes: Experimental data from KARI Regional Research Centre, Embu, short rains 1999 and long rains 2000; fertilizer applied at 100kg N, 100kg P/ha[1] and regularly irrigated; *1999 long rains season

Table 37: Maize yield, Machang'a (ecological zone LM5), long rains 1996, kg/ha

Maize variety	*With 20:20:0 fertilizer 200 kg/ha*	*Without fertilizer*
KCB	991	707
DLC – 1	1315	1104
Local	1333	1241

For each column, yields were not significantly different at P=0.05 according to Duncan's Multiple Range Test

Table 38: Maize yield from KARI Embu trials

Management	*1993*		*1994*		*1995*		*1996*		*1997*		*Mean*
	LR	*SR*	*LR*	*SR*	*LR*	*SR*	*LR*	*SR*	*LR*	*SR*	
Control	3.99	0.83	6.70	4.87	4.05	8.05	4.67	0.64	2.23	7.51	4.35
Napier	4.17	0.77	6.71	3.50	3.43	5.50	4.40	0.59	2.65	6.51	3.82
Calliandra	4.33	1.12	7.76	5.07	4.40	8.22	5.70	0.55	1.86	8.06	4.71
Combination	3.98	0.82	7.23	4.12	4.01	6.64	4.68	0.81	2.21	6.88	4.14
Mean	4.12	0.88	7.10	4.39	3.97	7.14	4.86	0.64	2.24	7.27	4.26

Notes: Maize variety H511 grown between contour grassed strips and hedgerows, tonne/ha
Mean seasonal rainfall during the experiment was 638 mm (lowest: 252 mm in 1996 Short Rains, highest 1213 mm in 1997 Short Rains)

Table 39: Maize yields with various fallow systems
(KARI 1996)

Treatment	*Mean yield (t ha^{-1})*
Maize alone	2.60
Maize in Kudzu fallow	3.48
Maize in Desmodium fallow	4.20
Maize in Calliandra fallow	3.38
Maize in Sesbania fallow	5.20

References

KARI 1996. *Annual Report*, Regional Research Centre, Kenya Agricultural Research Institute, Embu

KARI 2000. *Annual Report*, Regional Research Centre, Kenya Agricultural Research Institute, Embu

Ouma JO, Muriithi FM, Mwangi W, Verkuijl H, Gethi M and De Groote H 2002. *Adoption of maize seed and fertilizer in Embu District, Kenya*

Annex 6: Conversion for land cover classes

The following table is used to convert the AfriCover land cover data set to SWAT classes. Five groups have been added that were not present in the SWAT standardized data bases: BARE, bare soils; COFF, coffee; TEA, tea; PLAN, forest plantation; AGRI, agriculture general irrigated

Table 40: Conversion of Africover land cover classes to SWAT classes

AfriCover	*SWAT class*	*IRR*
Closed woody (broadleaved deciduous) with sparse trees	FRSD	
Closed woody with sparse trees	FRST	
Open woody with herbaceous ground cover	RNGE	
Open woody with closed to open herbaceous ground cover on temporarily flooded land - fresh water	WETL	
River	WATR	
Artificial lakes or reservoirs	WATR	
Natural lakes	WATR	
Fish pond	WATR	
Irrigated orchard, large to medium fields - citrus	ORCD	irrigated
Rice - large to medium fields	RICE	irrigated
Trees plantation - large fields, rain-fed, permanent	PLAN	
Rain-fed tree crop (1 add. herbaceous crop) - clustered medium fields	AGRR	
River banks	BARE	
Lake shore	BARE	
Cereals, rice - Small Fields	RICE	irrigated
Rain-fed tree crop (1 add. herbaceous crop), small fields	AGRR	
Rain-fed tree crop, small fields	AGRR	
Rain-fed tree crop (1 add. shrubs crop), clustered small fields	AGRR	
Rain-fed tree crop (1 add. herbaceous crop), clustered small fields	AGRR	
Rain-fed tree crop, clustered small fields	AGRR	
Rain-fed tree crop, isolated small fields	AGRR	
Sand beaches	BARE	
Needle-leaved evergreen forest plantation	FRSE	
Forest Plantation, broad-leaved evergreen, rain-fed, permanent	FRSE	
Closed herbaceous on temporarily flooded land - fresh water	WETL	
Sparse herbaceous	AGRL	
Closed to very open herbaceous	AGRL	
Closed to open herbaceous on permanently flooded land	WETL	
Closed to very open herbaceous with sparse trees and shrubs	AGRL	
Closed to very open herbaceous with sparse shrubs	AGRL	
Closed to very open herbaceous with sparse shrubs on temporarily flooded land - fresh water	WETL	
Quarry	BARE	
Snow	WATR	
Rain-fed shrub crop, large fields - pineapple	PINE	
Rain-fed shrub crop, large fields - coffee	COFF	
Rain-fed shrub crop, large fields - tea	TEA	
Rain-fed shrub crop, large fields	AGRL	
Rain-fed shrub crop, small fields - coffee	COFF	
Rain-fed shrub crop, small fields - tea	TEA	

AfriCover	*SWAT class*	*IRR*
Rain-fed shrub crop, small fields - orchard	AGRL	
Rain-fed shrub crop, clustered small fields - coffee	COFF	
Rain-fed shrub crop, clustered small fields - tea	TEA	
Rain- fed shrub crop, clustered small fields	AGRL	
Rain-fed shrub crop, isolated small fields - tea	TEA	
Rain-fed shrub crop, isolated small fields	AGRL	
Closed multilayered trees (broadleaved evergreen)	FRSE	
Closed trees with shrubs	FRST	
Closed trees - bamboo	FRST	
Open trees (broadleaved deciduous) with closed to open herbaceous and sparse shrubs	FRST	
Very open trees (broadleaved deciduous) with closed to open herbaceous and sparse shrubs	FRST	
Open trees (broadleaved deciduous) with closed to open shrubs	FRST	
Very open trees (broadleaved deciduous) with closed to open shrubs	FRST	
Open general trees with shrubs	FRST	
Very open trees with closed to open shrubs	FRST	
Closed trees (broadleaved evergreen) on permanently flooded land - brackish water	FRST	
Open trees with closed to open herbaceous on temporarily flooded land - fresh water	FRST	
Bare rock	BARE	
Large-medium fields, rain-fed	AGRL	
Large fields - wheat, rain-fed	SWHT	
Herbaceous - medium fields - maize, rain-fed	CORN	
Herbaceous - medium fields - wheat, rain-fed	SWHT	
Large-medium fields - maize, rain-fed	CORN	
Large-medium fields - sisal, rain-fed	AGRL	
Large-medium fields - wheat, rain-fed	SWHT	
Herbaceous - large to medium fields, surface-irrigated, permanent	AGRI	irrigated
Herbaceous - medium fields, surface-irrigated, permanent	AGRI	irrigated
Herbaceous - medium fields, sugar cane, surface-irrigated, permanent	SUGC	irrigated
Irrigated herbaceous crop, large to medium fields – sugar cane	SUGC	irrigated
Rain-fed herbaceous - large fields	AGRL	
Rain-fed herbaceous - medium fields	AGRL	
Irrigated herbaceous crop, large fields	AGRI	irrigated
Clustered large-medium fields, rain-fed	AGRL	
Clustered large fields, rain-fed	AGRL	
Rain-fed herbaceous - clustered medium fields, maize	CORN	
Clustered large-medium fields, wheat , rain-fed	SWHT	
Rain-fed herbaceous - clustered medium fields	AGRL	
Rain-fed herbaceous - isolated medium fields, maize	CORN	
Rain-fed herbaceous - isolated medium fields	AGRL	
Herbaceous - small fields - maize, rain-fed	CORN	
Herbaceous - small fields, sugar cane, surface-irrigated permanent	SUGC	irrigated
Continuous rain-fed small fields, cereal	AGRL	
Herbaceous - small fields, surface-irrigated, permanent	AGRI	irrigated
Herbaceous - clustered small fields - maize, rain-fed	CORN	
Rain-fed herbaceous - clustered small fields	AGRL	
Herbaceous - isolated small fields - maize, rain-fed	CORN	
Rain-fed herbaceous - isolated small fields	AGRL	
Closed shrubs	RNGB	
Closed shrubs with sparse trees	RNGB	

AfriCover	*SWAT class*	*IRR*
Open shrubs with closed to open herbaceous	RNGE	
Very open shrubs with closed to open herbaceous	RNGE	
Open shrubs with closed to open herbaceous and sparse trees	RNGE	
Very open shrubs with closed to open herbaceous and sparse trees	RNGE	
Industrial area	UIDU	
Urban area	URML	
Refugee camp	URML	
Rural settlements	URML	
Open shrubs with closed to open herbaceous on temporarily flooded land	WETL	
Sparse shrubs with sparse herbaceous	RNGE	
Airport	UTRN	
Bare soil	BARE	
Sand	BARE	

Green Water Credits reports

GWC 1	*Basin identification*	Droogers P and others 2006
GWC 2	*Lessons learned from payments for environmental services*	Grieg-Gran M and others 2006
GWC 3	*Green and blue water resources and assessment of improved soil and water management scenarios using an integrated modelling framework.*	Kauffman JH and others 2007
GWC 4	*Quantifying water usage and demand in the Tana River basin: an analysis using the Water and Evaluation and Planning Tool (WEAP)*	Hoff H and others 2007
GWC 5	*Farmers' adoption of soil and water conservation: the potential role of payments for watershed services*	Porras I and others 2007
GWC 6	*Political, institutional and financial framework for Green Water Credits in Kenya*	Meijerink G and others 2007
GWC 7	*The spark has jumped the gap. Green Water Credits proof of concept*	Dent DL and JH Kauffman 2007