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

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 m³/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 m³/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 km².

![Figure 1: Tana basin, location](image)

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  
\[ \Delta W \] = 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.

![Diagram of land-phase processes simulated within SWAT](image)

**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.
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).
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](image)

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 km² 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](image)

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>
<thead>
<tr>
<th>Zone</th>
<th>Name</th>
<th>Record Period</th>
<th>Altitude (m)</th>
<th>Annual Rainfall (mm yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Embu Forest</td>
<td>1950 - 1994</td>
<td>1936</td>
<td>1450</td>
</tr>
<tr>
<td>IIa</td>
<td>Embu</td>
<td>1908 - 1994</td>
<td>1493</td>
<td>1257</td>
</tr>
<tr>
<td>IIb</td>
<td>Meru</td>
<td>1914 - 1994</td>
<td>1554</td>
<td>1191</td>
</tr>
<tr>
<td>III</td>
<td>Mwea</td>
<td>1980 - 1994</td>
<td>1463</td>
<td>948</td>
</tr>
<tr>
<td>IV</td>
<td>Thika</td>
<td>1980 - 1994</td>
<td>1159</td>
<td>858</td>
</tr>
<tr>
<td>V</td>
<td>Makindu</td>
<td>1904 - 1991</td>
<td>1000</td>
<td>611</td>
</tr>
<tr>
<td>VI</td>
<td>Galole</td>
<td>1904 - 1991</td>
<td>100</td>
<td>470</td>
</tr>
<tr>
<td>VII</td>
<td>Garissa</td>
<td>1931 - 1996</td>
<td>147</td>
<td>282</td>
</tr>
</tbody>
</table>

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](image)

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>1167</td>
</tr>
<tr>
<td>1991</td>
<td>612</td>
</tr>
<tr>
<td>1992</td>
<td>785</td>
</tr>
<tr>
<td>1993</td>
<td>942</td>
</tr>
<tr>
<td>1994</td>
<td>917</td>
</tr>
<tr>
<td>1995</td>
<td>984</td>
</tr>
<tr>
<td>1996</td>
<td>521</td>
</tr>
<tr>
<td>1997</td>
<td>1479</td>
</tr>
<tr>
<td>1998</td>
<td>860</td>
</tr>
<tr>
<td>1999</td>
<td>670</td>
</tr>
<tr>
<td>2000</td>
<td>578</td>
</tr>
<tr>
<td>2001</td>
<td>744</td>
</tr>
<tr>
<td>2002</td>
<td>1091</td>
</tr>
</tbody>
</table>
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 (IICA 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.
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)

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

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).
WOFOST requires soil water content at saturation, field capacity and permanent wilting point. 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

<table>
<thead>
<tr>
<th>Soil group</th>
<th>Rooting depth, cm</th>
<th>Water content (a) (%) at</th>
<th>Available water capacity (b) %</th>
<th>Total available water (c) mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Saturation</td>
<td>Field capacity</td>
<td>Wilting point</td>
<td></td>
</tr>
<tr>
<td>Acrisols</td>
<td>110</td>
<td>56</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>Andosols</td>
<td>80</td>
<td>60</td>
<td>40</td>
<td>24</td>
</tr>
<tr>
<td>Arenosols</td>
<td>90</td>
<td>53</td>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td>Chernozems</td>
<td>75</td>
<td>55</td>
<td>37</td>
<td>21</td>
</tr>
<tr>
<td>Calcisols</td>
<td>40</td>
<td>41</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>Cambisols</td>
<td>53</td>
<td>48</td>
<td>28</td>
<td>14</td>
</tr>
<tr>
<td>Fluvisols</td>
<td>93</td>
<td>44</td>
<td>17</td>
<td>4</td>
</tr>
<tr>
<td>Ferralsols</td>
<td>90</td>
<td>53</td>
<td>26</td>
<td>17</td>
</tr>
<tr>
<td>Gleysols</td>
<td>45</td>
<td>56</td>
<td>37</td>
<td>21</td>
</tr>
<tr>
<td>Leptosols</td>
<td>10</td>
<td>53</td>
<td>21</td>
<td>12</td>
</tr>
<tr>
<td>Luvisols</td>
<td>80</td>
<td>47</td>
<td>25</td>
<td>13</td>
</tr>
<tr>
<td>Lixisols</td>
<td>88</td>
<td>47</td>
<td>16</td>
<td>11</td>
</tr>
<tr>
<td>Nitisols</td>
<td>105</td>
<td>53</td>
<td>31</td>
<td>22</td>
</tr>
<tr>
<td>Phaeozems</td>
<td>80</td>
<td>56</td>
<td>38</td>
<td>26</td>
</tr>
<tr>
<td>Planosols</td>
<td>25</td>
<td>50</td>
<td>35</td>
<td>22</td>
</tr>
<tr>
<td>Regosols</td>
<td>35</td>
<td>48</td>
<td>19</td>
<td>9</td>
</tr>
<tr>
<td>Solonetz</td>
<td>25</td>
<td>45</td>
<td>28</td>
<td>13</td>
</tr>
<tr>
<td>Vertisols</td>
<td>80</td>
<td>50</td>
<td>46</td>
<td>22</td>
</tr>
</tbody>
</table>

(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 5 An important characteristic not provided 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:

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

- \( K_{\text{sat}} \): saturated hydraulic conductivity (cm/h), \( st \): silt content (%), \( cl \): clay content (%)
- \( BD \): bulk density (kg/dm³)

SWAT requires values in mm/h:

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

**Table 5: Soil parameters required for the SWAT model**

<table>
<thead>
<tr>
<th>Code</th>
<th>Definition</th>
<th>minimum</th>
<th>maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNAM</td>
<td>Soil name</td>
<td>character</td>
<td></td>
</tr>
<tr>
<td>HYDGRP</td>
<td>Soil hydrologic group</td>
<td>character</td>
<td></td>
</tr>
<tr>
<td>SOL_ZMX</td>
<td>Maximum rooting depth of soil profile (mm)</td>
<td>0</td>
<td>3500</td>
</tr>
<tr>
<td>ANION_EXCL</td>
<td>Fraction of porosity (void space) from which anions are excluded</td>
<td>0.01</td>
<td>1.00</td>
</tr>
<tr>
<td>SOL_CRK</td>
<td>[OPTIONAL] Crack volume potential of soil (% of soil volume)</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>TEXTURE</td>
<td>[OPTIONAL] Texture of soil layer</td>
<td>character</td>
<td></td>
</tr>
<tr>
<td>SOL_Z</td>
<td>Depth from soil surface to bottom of layer (mm)</td>
<td>0</td>
<td>3500</td>
</tr>
<tr>
<td>SOL_BD</td>
<td>Moist bulk density (g/cm³)</td>
<td>1.10</td>
<td>2.50</td>
</tr>
<tr>
<td>SOL_AWC</td>
<td>Available water capacity of the soil layer (mm water/mm soil)</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>SOL_K</td>
<td>Saturated hydraulic conductivity (mm/hr)</td>
<td>0</td>
<td>2000</td>
</tr>
<tr>
<td>SOL_CBN</td>
<td>Organic carbon content (% mass)</td>
<td>0.05</td>
<td>10.00</td>
</tr>
<tr>
<td>CLAY</td>
<td>Clay content (% mass)</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>SILT</td>
<td>Silt content (% mass)</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>SAND</td>
<td>Sand content (% mass)</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>ROCK</td>
<td>Rock fragment content (% mass)</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>SOL_ALB</td>
<td>Moist soil albedo</td>
<td>0.00</td>
<td>0.25</td>
</tr>
<tr>
<td>USLE_K</td>
<td>USLE equation soil erodibility (K) factor (tonne/m²/hr)</td>
<td>0.00</td>
<td>0.65</td>
</tr>
<tr>
<td>NLAYERS</td>
<td>Number of layers in the soil</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>NUMLAYER</td>
<td>The layer being displayed</td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>
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

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

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Name</th>
<th>Soil loss reduction (t/ha) (a)</th>
<th>Soil loss reduction (%)</th>
<th>Runoff reduction (% of rainfall) (a)</th>
<th>Run-off reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSA33</td>
<td>Agronomic &amp; vegetative rehabilitation</td>
<td>0</td>
<td>50</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>RSA52</td>
<td>Controlling of soil erosion</td>
<td>0.3</td>
<td>60</td>
<td>30</td>
<td>75</td>
</tr>
<tr>
<td>THA01</td>
<td>Vegetative erosion control</td>
<td>15</td>
<td>75</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>THA25</td>
<td>Small bench terrace</td>
<td>40</td>
<td>80</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>45</strong></td>
<td><strong>76</strong></td>
<td><strong>29</strong></td>
<td><strong>62</strong></td>
</tr>
</tbody>
</table>

(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 Rhee (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

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

- 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.
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):

\[ Y = 11.8 \times (V \times qp)^{0.56} \times K \times C \times P \times LS \]

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

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

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](image-url)
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 the water balance for a reservoir as:

\[ V = V_{\text{stored}} + V_{\text{flowin}} - V_{\text{flowout}} + V_{\text{pcp}} - V_{\text{evap}} - V_{\text{seep}} \]

where:
- \( V \) the volume of water in the impoundment at the end of the day (m³)
- \( V_{\text{stored}} \) the volume of water stored in the water body at the beginning of the day (m³)
- \( V_{\text{flowin}} \) the volume of water entering the water body during the day (m³)
- \( V_{\text{flowout}} \) the volume of water flowing out of the water body during the day (m³)
- \( V_{\text{pcp}} \) the volume of precipitation falling on the water body during the day (m³)
- \( V_{\text{evap}} \) the volume of water removed from the water body by evaporation during the day (m³)
- \( V_{\text{seep}} \) the volume of water lost from the water body by seepage (m³).

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 (m³)
- principal spillway surface area (ha)
- principal spillway volume (m³)

The following initial conditions are required:
- volume (m³)
- 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.
Table 8: Characteristics of the reservoirs in Tana (KenGen 2005)

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Masinga</th>
<th>Kamburu</th>
<th>Kindaruma</th>
<th>Gitaru</th>
<th>Kiambere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of dam m</td>
<td></td>
<td>69.5</td>
<td>56.0</td>
<td>24.3</td>
<td>30.0</td>
<td>112.0</td>
</tr>
<tr>
<td>Capacity m$^3$ x1000</td>
<td></td>
<td>1.560E+06</td>
<td>1.500E+05</td>
<td>1.600E+04</td>
<td>2.000E+04</td>
<td>5.850E+05</td>
</tr>
<tr>
<td>Area m$^2$ x1000</td>
<td></td>
<td>120,000</td>
<td>15,000</td>
<td>250</td>
<td>310</td>
<td>25,000</td>
</tr>
<tr>
<td>Emergency spillway surface area ha</td>
<td></td>
<td>1.440E+04</td>
<td>1.800E+03</td>
<td>3.000E+01</td>
<td>3.720E+01</td>
<td>3.000E+03</td>
</tr>
<tr>
<td>Emergency spillway volume m$^3$</td>
<td></td>
<td>1.872E+09</td>
<td>1.800E+08</td>
<td>1.920E+07</td>
<td>2.400E+07</td>
<td>7.020E+08</td>
</tr>
<tr>
<td>Principal spillway surface area ha</td>
<td></td>
<td>1.200E+04</td>
<td>1.500E+03</td>
<td>2.500E+01</td>
<td>3.100E+01</td>
<td>2.500E+03</td>
</tr>
<tr>
<td>Principal spillway volume m$^3$</td>
<td></td>
<td>1.560E+09</td>
<td>1.500E+08</td>
<td>1.600E+07</td>
<td>2.000E+07</td>
<td>5.850E+08</td>
</tr>
</tbody>
</table>

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).

![Inflow and Outflow of Masinga Reservoir](image)

**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.
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

<table>
<thead>
<tr>
<th></th>
<th>Masinga</th>
<th>Kamburu</th>
<th>Kindaruma</th>
<th>Gitaru</th>
<th>Kiambere</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991/92</td>
<td>185</td>
<td>402</td>
<td>206</td>
<td>811</td>
<td>872</td>
</tr>
<tr>
<td>1992/93</td>
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<td>757</td>
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</table>

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

<table>
<thead>
<tr>
<th>Code</th>
<th>River</th>
<th>Location</th>
<th>Period</th>
<th>Source</th>
<th>SWAT basin</th>
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Table 11: Overview of stream flow data availability

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</tr>
</tbody>
</table>

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 gives the 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.
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.
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:

\[ \Delta W = P + R + T + E + D \]

where:
- \( P \) = precipitation,
- \( R \) = runoff,
- \( T \) = transpiration,
- \( E \) = evaporation from the soil surface,
- \( D \) = deep percolation

\( \Delta W \) = 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

<table>
<thead>
<tr>
<th>Zone - station</th>
<th>Elevation (m)</th>
<th>Record Period</th>
<th>Mean Rainfall, mm</th>
<th>Maximum Rainfall, mm</th>
<th>Minimum Rainfall, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>IIa Embu</td>
<td>1493</td>
<td>1914 - 1994</td>
<td>1257</td>
<td>2950</td>
<td>649</td>
</tr>
<tr>
<td>IIb Meru</td>
<td>1554</td>
<td>1980 - 1994</td>
<td>1191</td>
<td>1298</td>
<td>642</td>
</tr>
<tr>
<td>III Mwea</td>
<td>1159</td>
<td>1960 - 1994</td>
<td>948</td>
<td>1287</td>
<td>552</td>
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<tr>
<td>IV Thika</td>
<td>1463</td>
<td>1980 - 1994</td>
<td>858</td>
<td>1254</td>
<td>184</td>
</tr>
<tr>
<td>V Makindo</td>
<td>1000</td>
<td>1904 - 1991</td>
<td>611</td>
<td>808</td>
<td>70</td>
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<tr>
<td>VII Garissa</td>
<td>147</td>
<td>1931 - 1996</td>
<td>282</td>
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<td></td>
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<tr>
<td>VI Galole</td>
<td>100</td>
<td></td>
<td>470</td>
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</table>
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

<table>
<thead>
<tr>
<th>Climatic zone</th>
<th>Growing period</th>
<th>TSUM1 (b)</th>
<th>TSUM2 (b)</th>
<th>Start month of GP</th>
<th>End month of GP</th>
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<td>6</td>
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<tr>
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<td>GP1</td>
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<td>746</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>III</td>
<td>GP1</td>
<td>694</td>
<td>781</td>
<td>3</td>
<td>6</td>
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<td>V</td>
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<td>851</td>
<td>957</td>
<td>3</td>
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<td>GP2</td>
<td>889</td>
<td>1001</td>
<td>10</td>
<td>12</td>
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</tbody>
</table>

(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 oversimplification. 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

<table>
<thead>
<tr>
<th>Dominant soil and phase</th>
<th>Rooting depth (cm)</th>
<th>Water content at saturation (%)(^{(a)})</th>
<th>Water at field capacity (%)</th>
<th>Water at wilting point (%)</th>
<th>Available water(^{(b)}) (%)</th>
<th>Total available water(^{(c)}) (mm)</th>
</tr>
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<tbody>
<tr>
<td>Acrisol haplic</td>
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<tr>
<td>Luvisol ferric</td>
<td>75</td>
<td>53</td>
<td>35</td>
<td>19</td>
<td>16</td>
<td>120</td>
</tr>
<tr>
<td>Luvisol haplic</td>
<td>65</td>
<td>46</td>
<td>22</td>
<td>9</td>
<td>13</td>
<td>84</td>
</tr>
<tr>
<td>Luvisol eutric</td>
<td>100</td>
<td>45</td>
<td>18</td>
<td>10</td>
<td>8</td>
<td>80</td>
</tr>
<tr>
<td>Lixisol ferric</td>
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<td>48</td>
<td>12</td>
<td>8</td>
<td>4</td>
<td>40</td>
</tr>
<tr>
<td>Lixisol haplic</td>
<td>75</td>
<td>46</td>
<td>20</td>
<td>14</td>
<td>6</td>
<td>45</td>
</tr>
<tr>
<td>Nitisol haplic</td>
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<td>52</td>
<td>32</td>
<td>22</td>
<td>10</td>
<td>95</td>
</tr>
<tr>
<td>Nitisol rhodic</td>
<td>100</td>
<td>53</td>
<td>28</td>
<td>20</td>
<td>8</td>
<td>80</td>
</tr>
<tr>
<td>Nitisol humic</td>
<td>123</td>
<td>56</td>
<td>34</td>
<td>23</td>
<td>10</td>
<td>119</td>
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<tr>
<td>Phaeozem haplic</td>
<td>75</td>
<td>55</td>
<td>38</td>
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<td>60</td>
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<td>Phaeozem luvic</td>
<td>85</td>
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</tr>
<tr>
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<td>25</td>
<td>50</td>
<td>35</td>
<td>22</td>
<td>13</td>
<td>33</td>
</tr>
<tr>
<td>Regosol calcic (rudic)</td>
<td>40</td>
<td>55</td>
<td>25</td>
<td>11</td>
<td>14</td>
<td>56</td>
</tr>
<tr>
<td>Regosol dystric (lithic)</td>
<td>30</td>
<td>46</td>
<td>23</td>
<td>12</td>
<td>11</td>
<td>28</td>
</tr>
<tr>
<td>Regosol eutric (lithic)</td>
<td>40</td>
<td>42</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>Solonetz gleic</td>
<td>25</td>
<td>41</td>
<td>20</td>
<td>6</td>
<td>14</td>
<td>35</td>
</tr>
<tr>
<td>Solonetz haplic</td>
<td>30</td>
<td>48</td>
<td>35</td>
<td>19</td>
<td>16</td>
<td>48</td>
</tr>
<tr>
<td>Vertisol eutric</td>
<td>80</td>
<td>50</td>
<td>46</td>
<td>22</td>
<td>24</td>
<td>191</td>
</tr>
</tbody>
</table>

\(^{(a)}\) 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)

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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Climatic zone</th>
<th>Evaporation</th>
<th>Transpiration</th>
<th>Percolation</th>
<th>Runoff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff from 10% to 20%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>0</td>
<td>4</td>
<td>132</td>
<td>-143</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>-1</td>
<td>12</td>
<td>41</td>
<td>-70</td>
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</tr>
<tr>
<td>III</td>
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<td>7</td>
<td>23</td>
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</tr>
<tr>
<td>IV</td>
<td>3</td>
<td>4</td>
<td>51</td>
<td>-59</td>
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</tr>
<tr>
<td>V</td>
<td>7</td>
<td>5</td>
<td>4</td>
<td>-26</td>
<td></td>
</tr>
<tr>
<td>Runoff from 20% to 40%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>1</td>
<td>19</td>
<td>247</td>
<td>-299</td>
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</tr>
<tr>
<td>II</td>
<td>8</td>
<td>65</td>
<td>45</td>
<td>-140</td>
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</tr>
<tr>
<td>III</td>
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<td>-95</td>
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</tr>
<tr>
<td>IV</td>
<td>13</td>
<td>8</td>
<td>123</td>
<td>-151</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>20</td>
<td>8</td>
<td>0</td>
<td>-50</td>
<td></td>
</tr>
</tbody>
</table>
Table 17: Changes on the water balance by runoff reduction for a wet year, mm

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Climatic Zone</th>
<th>Evaporation</th>
<th>Transpiration</th>
<th>Percolation</th>
<th>Runoff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff from 10% to 20%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>0</td>
<td>9</td>
<td>126</td>
<td>-139</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>0</td>
<td>7</td>
<td>130</td>
<td>-140</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>-3</td>
<td>23</td>
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<td>-98</td>
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</tr>
<tr>
<td>IV</td>
<td>-4</td>
<td>32</td>
<td>62</td>
<td>-97</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>0</td>
<td>12</td>
<td>44</td>
<td>-60</td>
<td></td>
</tr>
<tr>
<td>Runoff from 20% to 40%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>-1</td>
<td>29</td>
<td>235</td>
<td>-289</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>-4</td>
<td>26</td>
<td>250</td>
<td>-297</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>-16</td>
<td>81</td>
<td>90</td>
<td>-197</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>-26</td>
<td>89</td>
<td>127</td>
<td>-204</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>1</td>
<td>31</td>
<td>84</td>
<td>-122</td>
<td></td>
</tr>
</tbody>
</table>
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)
6.2 Inflow to Masinga reservoir

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 km² on Mt Kenya and 4728 km² 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 m³/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
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 m³, 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 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:

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

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):

\[ sed = 11.8 \times (Q_{surf} \times q_{peak} \times \text{area}_{hru})^{0.56} \times C_{USLE} \times P_{USLE} \times K_{USLE} \times L_{USLE} \times C_{FRG} \]

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 (m³/s)
- \( \text{area}_{hru} \) is the area of the HRU (ha)
- \( K_{USLE} \) is the USLE soil erodibility factor (0.013 tonne/m²/hr/m³/tonne/cm)
- \( C_{USLE} \) is the USLE cover and management factor
- \( P_{USLE} \) is the USLE support practice factor
- \( L_{USLE} \) is the USLE topographic factor
- \( C_{FRG} \) 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>
<thead>
<tr>
<th>Slope gradient (%)</th>
<th>( P_{USLE} ) values</th>
<th>Maximum Length, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 2</td>
<td>0.60</td>
<td>122</td>
</tr>
<tr>
<td>3 to 5</td>
<td>0.50</td>
<td>91</td>
</tr>
<tr>
<td>6 to 8</td>
<td>0.50</td>
<td>61</td>
</tr>
<tr>
<td>9 to 12</td>
<td>0.60</td>
<td>37</td>
</tr>
<tr>
<td>13 to 16</td>
<td>0.70</td>
<td>24</td>
</tr>
<tr>
<td>17 to 20</td>
<td>0.80</td>
<td>18</td>
</tr>
<tr>
<td>21 to 25</td>
<td>0.90</td>
<td>15</td>
</tr>
</tbody>
</table>
Table 19: $P_{USLE}$ factor values, maximum strip width and slope-length limits for contour ridging (strip cropping)
(Wischmeier and Smith 1978)

<table>
<thead>
<tr>
<th>Slope gradient (%)</th>
<th>$P_{USLE}$ values</th>
<th>Strip width (m)</th>
<th>Maximum length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 2</td>
<td>0.30 0.45 0.60</td>
<td>40</td>
<td>244</td>
</tr>
<tr>
<td>3 to 5</td>
<td>0.25 0.38 0.50</td>
<td>30</td>
<td>183</td>
</tr>
<tr>
<td>6 to 8</td>
<td>0.25 0.38 0.50</td>
<td>30</td>
<td>122</td>
</tr>
<tr>
<td>9 to 12</td>
<td>0.30 0.45 0.60</td>
<td>24</td>
<td>73</td>
</tr>
<tr>
<td>13 to 16</td>
<td>0.35 0.52 0.70</td>
<td>24</td>
<td>49</td>
</tr>
<tr>
<td>17 to 20</td>
<td>0.40 0.60 0.80</td>
<td>18</td>
<td>37</td>
</tr>
<tr>
<td>21 to 25</td>
<td>0.45 0.68 0.90</td>
<td>15</td>
<td>30</td>
</tr>
</tbody>
</table>

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)

<table>
<thead>
<tr>
<th>Land Use</th>
<th>Treatment or practice</th>
<th>Hydrologic condition</th>
<th>Hydrologic Soil Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Fallow</td>
<td>Bare soil</td>
<td>- - -</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>Crop residue cover*</td>
<td>Poor</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td>74</td>
</tr>
<tr>
<td>Row crops</td>
<td>Straight row</td>
<td>Poor</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>Straight row w/ residue</td>
<td>Poor</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Contoured</td>
<td>Poor</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>Contoured w/ residue</td>
<td>Poor</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Contoured &amp; terraced</td>
<td>Poor</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td>62</td>
</tr>
<tr>
<td>Small grains</td>
<td>Straight row</td>
<td>Poor</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>Straight row w/ residue</td>
<td>Poor</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Contoured</td>
<td>Poor</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>Contoured w/ residue</td>
<td>Poor</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Contoured &amp; terraced</td>
<td>Poor</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>Contoured &amp; terraced w/ residue</td>
<td>Poor</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td>58</td>
</tr>
<tr>
<td>Close-seeded or broadcast legumes or rotation</td>
<td>Straight row</td>
<td>Poor</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>Contoured</td>
<td>Poor</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Contoured &amp; terraced</td>
<td>Poor</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td>51</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Cover Type</th>
<th>Hydrologic condition</th>
<th>Hydrologic Soil Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pasture, grassland, or range—continuous forage for grazing*</td>
<td>Poor</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>Fair</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>Good</td>
<td>39</td>
</tr>
<tr>
<td>Meadow—continuous grass, protected from grazing and generally mowed for hay</td>
<td>- - -</td>
<td>30</td>
</tr>
<tr>
<td>Brush—brush-weed-grass mixture with brush the major element*</td>
<td>Poor</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Fair</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Good</td>
<td>30</td>
</tr>
<tr>
<td>Woods—grass combination (orchard or tree farm)</td>
<td>Poor</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>Fair</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>Good</td>
<td>32</td>
</tr>
<tr>
<td>Woods*</td>
<td>Poor</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>Fair</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Good</td>
<td>30</td>
</tr>
<tr>
<td>Farmsteads—buildings, lanes, driveways, and surrounding lots.</td>
<td>- - -</td>
<td>59</td>
</tr>
</tbody>
</table>
It is evident that a proper determination of the SCS curve number CN2 is essential. Less sustainable land use and land management, reflected 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\textsubscript{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\textsubscript{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

<table>
<thead>
<tr>
<th>Indicators</th>
<th>1996</th>
<th>1997</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflow Masinga (Mm³)</td>
<td>3 242</td>
<td>7 152</td>
</tr>
<tr>
<td>Sediment Input Masinga (tonne)</td>
<td>953 300</td>
<td>5 281 000</td>
</tr>
<tr>
<td>Outflow Garissa (Mm³)</td>
<td>4 358</td>
<td>21 482</td>
</tr>
<tr>
<td>Crop Transpiration (mm)</td>
<td>396</td>
<td>510</td>
</tr>
<tr>
<td>Evaporation (mm)</td>
<td>205</td>
<td>224</td>
</tr>
<tr>
<td>Groundwater recharge (mm)</td>
<td>169</td>
<td>745</td>
</tr>
<tr>
<td>Groundwater recharge (m³/ha)</td>
<td>1 695</td>
<td>7 445</td>
</tr>
<tr>
<td>Sediment loss (tonne/ha)</td>
<td>1</td>
<td>14</td>
</tr>
</tbody>
</table>

#### Basin Balance

| Area (km²)                          | 32 741       | 32 741       |
| Precipitation (Mm³)                 | 19 126       | 57 023       |
| Transpiration (Mm³)                 | 10 950       | 16 141       |
| Evaporation (Mm³)                   | 6 289        | 7 375        |
| Outflow (Mm³)                       | 4 358        | 21 482       |
| Groundwater change (Mm³)            | -2 471       | 12 024       |

#### Maize

| Area (km²)                          | 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 (km²)                          | 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 (km²)                          | 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**

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Contour strips</th>
<th>Mulch</th>
<th>Tied ridges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflow Masinga (Mm³/yr)</td>
<td>3270</td>
<td>7074</td>
<td>3396</td>
</tr>
<tr>
<td>Sediment input Masinga (tonne)</td>
<td>646200</td>
<td>4093000</td>
<td>343400</td>
</tr>
<tr>
<td>Sediment output Masinga (tonne)</td>
<td>187800</td>
<td>262100</td>
<td>179600</td>
</tr>
<tr>
<td>Transpiration (mm)</td>
<td>396</td>
<td>510</td>
<td>400</td>
</tr>
<tr>
<td>Evaporation (mm)</td>
<td>205</td>
<td>225</td>
<td>195</td>
</tr>
<tr>
<td>Groundwater recharge (mm)</td>
<td>178</td>
<td>789</td>
<td>190</td>
</tr>
<tr>
<td>Groundwater recharge (m³/ha)</td>
<td>1776</td>
<td>7885</td>
<td>1904</td>
</tr>
<tr>
<td>Sediment loss (tonne/ha)</td>
<td>1</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td><strong>Basin Balance</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area (km²)</td>
<td>32741</td>
<td>32741</td>
<td>32741</td>
</tr>
<tr>
<td>Rainfall (Mm³)</td>
<td>19126</td>
<td>57023</td>
<td>19126</td>
</tr>
<tr>
<td>Transpiration (Mm³)</td>
<td>10957</td>
<td>16143</td>
<td>11068</td>
</tr>
<tr>
<td>Evaporation (Mm³)</td>
<td>6302</td>
<td>7406</td>
<td>6006</td>
</tr>
<tr>
<td>Outflow (Mm³)</td>
<td>4384</td>
<td>21202</td>
<td>4506</td>
</tr>
<tr>
<td>Groundwater change (Mm³)</td>
<td>-2517</td>
<td>12272</td>
<td>-2455</td>
</tr>
<tr>
<td><strong>Maize</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transpiration (mm)</td>
<td>234</td>
<td>361</td>
<td>249</td>
</tr>
<tr>
<td>Evaporation (mm)</td>
<td>314</td>
<td>358</td>
<td>270</td>
</tr>
<tr>
<td>Groundwater recharge (mm)</td>
<td>168</td>
<td>802</td>
<td>200</td>
</tr>
<tr>
<td>Runoff (mm)</td>
<td>26</td>
<td>469</td>
<td>20</td>
</tr>
<tr>
<td>Soil loss (tonne/ha)</td>
<td>1</td>
<td>17</td>
<td>1</td>
</tr>
<tr>
<td><strong>Tea</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transpiration (mm)</td>
<td>475</td>
<td>524</td>
<td>479</td>
</tr>
<tr>
<td>Evaporation (mm)</td>
<td>215</td>
<td>140</td>
<td>193</td>
</tr>
<tr>
<td>Groundwater recharge (mm)</td>
<td>419</td>
<td>1195</td>
<td>443</td>
</tr>
<tr>
<td>Runoff (mm)</td>
<td>26</td>
<td>382</td>
<td>19</td>
</tr>
<tr>
<td>Soil loss (tonne/ha)</td>
<td>0</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td><strong>Coffee</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transpiration (mm)</td>
<td>482</td>
<td>521</td>
<td>487</td>
</tr>
<tr>
<td>Evaporation (mm)</td>
<td>197</td>
<td>136</td>
<td>176</td>
</tr>
<tr>
<td>Groundwater recharge (mm)</td>
<td>393</td>
<td>1268</td>
<td>412</td>
</tr>
<tr>
<td>Runoff (mm)</td>
<td>17</td>
<td>254</td>
<td>12</td>
</tr>
<tr>
<td>Soil loss (tonne/ha)</td>
<td>1</td>
<td>30</td>
<td>1</td>
</tr>
</tbody>
</table>

a) 1996 is dry and 1997 is a wet year
Table 24: Change under green water management compared with baseline

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Contour Strips</th>
<th>Mulch</th>
<th>Tied ridges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflow, Masinga (Mm³)</td>
<td>28</td>
<td>-79</td>
<td>155</td>
</tr>
<tr>
<td>Sediment input, Masinga (tonne)</td>
<td>-307 100</td>
<td>-1 188 000</td>
<td>-609 900</td>
</tr>
<tr>
<td>Transpiration (mm)</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Evaporation (mm)</td>
<td>0</td>
<td>1</td>
<td>-10</td>
</tr>
<tr>
<td>Groundwater recharge (mm)</td>
<td>8</td>
<td>44</td>
<td>21</td>
</tr>
<tr>
<td>Groundwater recharge (m³/ha)</td>
<td>81</td>
<td>440</td>
<td>209</td>
</tr>
<tr>
<td>Soil loss (tonne/ha)</td>
<td>-1</td>
<td>-5</td>
<td>-1</td>
</tr>
</tbody>
</table>

**Basin Balance**

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Transpiration (Mm³)</td>
<td>7</td>
<td>2</td>
<td>118</td>
<td>91</td>
<td>9</td>
</tr>
<tr>
<td>Evaporation (Mm³)</td>
<td>13</td>
<td>31</td>
<td>-283</td>
<td>-333</td>
<td>32</td>
</tr>
<tr>
<td>Outflow (Mm³)</td>
<td>-25</td>
<td>281</td>
<td>-148</td>
<td>397</td>
<td>-60</td>
</tr>
<tr>
<td>Groundwater change (Mm³)</td>
<td>45</td>
<td>-248</td>
<td>-17</td>
<td>-640</td>
<td>101</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Contour Strips</th>
<th>Mulch</th>
<th>Tied ridges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflow, Masinga</td>
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<td>-1</td>
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<td>-64</td>
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<td>Sediment output, Masinga</td>
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<td>-1</td>
<td>-7</td>
</tr>
<tr>
<td>Transpiration</td>
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</tr>
<tr>
<td>Groundwater recharge</td>
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<td>6</td>
<td>12</td>
</tr>
<tr>
<td>Soil loss</td>
<td>-47</td>
<td>-33</td>
<td>-71</td>
</tr>
<tr>
<td><strong>Baseline Balance</strong></td>
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<tr>
<td>Transpiration</td>
<td>0</td>
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<td>1</td>
</tr>
<tr>
<td>Evaporation</td>
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<tr>
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<tr>
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<tr>
<td><strong>Maize</strong></td>
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<tr>
<td>Transpiration</td>
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<td>0</td>
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</tr>
<tr>
<td>Evaporation</td>
<td>1</td>
<td>1</td>
<td>-13</td>
</tr>
<tr>
<td>Groundwater recharge</td>
<td>26</td>
<td>31</td>
<td>49</td>
</tr>
<tr>
<td>Runoff</td>
<td>-55</td>
<td>-29</td>
<td>-66</td>
</tr>
<tr>
<td>Soil loss</td>
<td>-71</td>
<td>-50</td>
<td>-75</td>
</tr>
<tr>
<td><strong>Tea</strong></td>
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<tr>
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<td>1</td>
</tr>
<tr>
<td>Evaporation</td>
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<td>0</td>
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<tr>
<td>Groundwater recharge</td>
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<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Runoff</td>
<td>-44</td>
<td>-22</td>
<td>-59</td>
</tr>
<tr>
<td>Soil loss</td>
<td>-64</td>
<td>-44</td>
<td>-72</td>
</tr>
<tr>
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<td>9</td>
</tr>
<tr>
<td>Soil loss</td>
<td>-65</td>
<td>-48</td>
<td>-72</td>
</tr>
</tbody>
</table>

<sup>a</sup> 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.
soil and water management scenarios

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

<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>Transpiration</td>
<td>233</td>
<td>475</td>
<td>481</td>
<td>361</td>
<td>524</td>
<td>521</td>
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<td>Evaporation</td>
<td>312</td>
<td>214</td>
<td>197</td>
<td>354</td>
<td>140</td>
<td>135</td>
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<tr>
<td>Groundwater</td>
<td>134</td>
<td>396</td>
<td>377</td>
<td>614</td>
<td>1092</td>
<td>1176</td>
</tr>
<tr>
<td>Runoff</td>
<td>59</td>
<td>47</td>
<td>31</td>
<td>663</td>
<td>487</td>
<td>347</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Transpiration</td>
<td>16</td>
<td>4</td>
<td>6</td>
<td>11</td>
<td>3</td>
<td>4</td>
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<tr>
<td>Evaporation</td>
<td>-42</td>
<td>-22</td>
<td>-20</td>
<td>-50</td>
<td>-14</td>
<td>-13</td>
</tr>
<tr>
<td>Groundwater</td>
<td>65</td>
<td>47</td>
<td>34</td>
<td>285</td>
<td>159</td>
<td>137</td>
</tr>
</tbody>
</table>
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 m³ per ha per year;
- Increase groundwater recharge by 4-57 per cent or 16-160 mm/160-1600 m³ 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 m²
- 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 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.
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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](image)

**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](image)

**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 km²) 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 particularly 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 build 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: m² 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.

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**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/).

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**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

<table>
<thead>
<tr>
<th>Model</th>
<th>A b)</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWAT</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>ACRU</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>WEAP</td>
<td>+</td>
<td>0</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>MIKEASIN</td>
<td>0</td>
<td>0</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>MIKESHE</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SWAP</td>
<td>++</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>WATERGAP</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>HSPF</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
</tbody>
</table>

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

References


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

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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**

<table>
<thead>
<tr>
<th>Land cover</th>
<th>Area (km²)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bush (dense)</td>
<td>9 320</td>
<td>29</td>
</tr>
<tr>
<td>Agriculture (sparse)</td>
<td>9 221</td>
<td>28</td>
</tr>
<tr>
<td>Agriculture (dense)</td>
<td>5 473</td>
<td>17</td>
</tr>
<tr>
<td>Bush (sparse)</td>
<td>2 883</td>
<td>9</td>
</tr>
<tr>
<td>Forest</td>
<td>2 500</td>
<td>8</td>
</tr>
<tr>
<td>Plantation</td>
<td>1 257</td>
<td>4</td>
</tr>
<tr>
<td>Woodland</td>
<td>723</td>
<td>2</td>
</tr>
<tr>
<td>Barren (R)</td>
<td>639</td>
<td>2</td>
</tr>
<tr>
<td>Grassland</td>
<td>492</td>
<td>2</td>
</tr>
<tr>
<td>Water (artificial)</td>
<td>146</td>
<td>0</td>
</tr>
<tr>
<td>Swamp</td>
<td>21</td>
<td>0</td>
</tr>
<tr>
<td>Town</td>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>32 689</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

![Figure 86: Upper Tana, land cover (JICA 1987)]
Table 28: Upper Tana household data (census and WRMA 2006)

<table>
<thead>
<tr>
<th>District/Province</th>
<th>Rain-fed</th>
<th>ratio</th>
<th>Persons District</th>
<th>Urban Upper</th>
<th>Rural Upper</th>
<th>Hh/Upper Tana Area</th>
<th>Area (ha)</th>
<th>Upper Tana (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CENTRAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kiambu pp.</td>
<td>+</td>
<td>0.20</td>
<td>744010</td>
<td>148802</td>
<td>189706</td>
<td>37941</td>
<td>132400</td>
<td>26480</td>
</tr>
<tr>
<td>Kirinyaga</td>
<td>+</td>
<td>1.00</td>
<td>457105</td>
<td>57000</td>
<td>400105</td>
<td>114439</td>
<td>147800</td>
<td>147800</td>
</tr>
<tr>
<td>Muranga</td>
<td>+</td>
<td>1.00</td>
<td>348304</td>
<td>69000</td>
<td>279304</td>
<td>84900</td>
<td>84900</td>
<td>93000</td>
</tr>
<tr>
<td>Nyandarua pp.</td>
<td>+</td>
<td>0.10</td>
<td>479902</td>
<td>4000</td>
<td>43990</td>
<td>104401</td>
<td>10440</td>
<td>330400</td>
</tr>
<tr>
<td>Nyeri pp.</td>
<td>+</td>
<td>0.80</td>
<td>661156</td>
<td>250000</td>
<td>278925</td>
<td>168786</td>
<td>135029</td>
<td>335800</td>
</tr>
<tr>
<td>Thika pp.</td>
<td>+</td>
<td>0.42</td>
<td>645713</td>
<td>107000</td>
<td>164199</td>
<td>171569</td>
<td>72059</td>
<td>196000</td>
</tr>
<tr>
<td>Maragua</td>
<td>+</td>
<td>1.00</td>
<td>387969</td>
<td>95000</td>
<td>292969</td>
<td>90744</td>
<td>90744</td>
<td>86800</td>
</tr>
<tr>
<td>EASTERN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Embu</td>
<td>+</td>
<td>1.00</td>
<td>278196</td>
<td>110000</td>
<td>168196</td>
<td>63893</td>
<td>63893</td>
<td>72900</td>
</tr>
<tr>
<td>Kitui pp.</td>
<td>+/-</td>
<td>0.15</td>
<td>515422</td>
<td>1500</td>
<td>75813</td>
<td>97196</td>
<td>14579</td>
<td>2040200</td>
</tr>
<tr>
<td>Machakos pp.</td>
<td>+/-</td>
<td>0.15</td>
<td>906644</td>
<td>135997</td>
<td>186297</td>
<td>27945</td>
<td>628100</td>
<td>94215</td>
</tr>
<tr>
<td>Mbeere</td>
<td>+/-</td>
<td>1.00</td>
<td>170953</td>
<td>3200</td>
<td>167753</td>
<td>37036</td>
<td>37036</td>
<td>209300</td>
</tr>
<tr>
<td>Meru Central</td>
<td>+</td>
<td>1.00</td>
<td>498880</td>
<td>139500</td>
<td>359380</td>
<td>120265</td>
<td>120265</td>
<td>298200</td>
</tr>
<tr>
<td>Mwingi pp.</td>
<td>+/-</td>
<td>0.50</td>
<td>303828</td>
<td>151914</td>
<td>58863</td>
<td>29432</td>
<td>100300</td>
<td>501500</td>
</tr>
<tr>
<td>Meru North pp.</td>
<td>+</td>
<td>0.80</td>
<td>604050</td>
<td>175000</td>
<td>465740</td>
<td>119664</td>
<td>95731</td>
<td>394200</td>
</tr>
<tr>
<td>Tharaka</td>
<td>+/-</td>
<td>1.00</td>
<td>100992</td>
<td>7000</td>
<td>100992</td>
<td>20239</td>
<td>20239</td>
<td>157000</td>
</tr>
<tr>
<td>Meru South</td>
<td>+</td>
<td>1.00</td>
<td>205451</td>
<td>7000</td>
<td>198451</td>
<td>46984</td>
<td>46984</td>
<td>109300</td>
</tr>
<tr>
<td>NORTHEASTERN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Garissa pp.</td>
<td>-</td>
<td>0.20</td>
<td>392510</td>
<td>69000</td>
<td>9502</td>
<td>48141</td>
<td>9628</td>
<td>4495200</td>
</tr>
<tr>
<td>Isiolo pp.</td>
<td>-</td>
<td>0.20</td>
<td>100861</td>
<td>4000</td>
<td>16172</td>
<td>22583</td>
<td>4517</td>
<td>2569800</td>
</tr>
<tr>
<td>TOTAL rural Upper Tana</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4214885</td>
</tr>
<tr>
<td>TOTAL rural rain-fed districts Upper Tana</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>859200</td>
<td>3204803</td>
</tr>
</tbody>
</table>

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


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 cmolc /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 cmolc 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:

\[ \text{Vol. } \% = (1 - \text{Db}/2.65) \times 100 \]

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:

\[ \text{Db } = 1.1674 + 0.0049\% \text{ sand} - 0.0085\% \text{OC} \] \( \text{n=123; } r^2=0.64; \text{ CI=95%} \)

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

- Topsoils of low-activity clays (FAO soil groups² AC, FR, NT, LX)
  \[ \text{FC1 } = 37.379 - 0.3839\% \text{ sand} \] \( n=18; \text{ } r^2=0.78 \)

- Subsoils of low-activity clays (AC, FR, NT, LX)
  \[ \text{FC2 } = 38.522 - 0.4207\% \text{ sand} \] \( n=35; \text{ } r^2=0.77 \)

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

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)

\[ FC4 = 43.215 - 0.3440\% \text{sand} \quad (n=36; \quad r^2=0.47) \]

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

Andosols: \[ FC5 = 45.439 - 0.2103\% \text{clay} \quad (n=14; \quad r^2=0.33) \]

Vertisols: \[ FC6 = 40.692 + 0.0604\% \text{clay} \quad (n=3; \quad r^2=0.25) \]

**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:

\[ \text{Wilting point} = 26.975 - 0.302\% \text{sand} \quad (n = 68; \quad r^2 = 0.77; \quad \text{CI} = 95\%) \]

### A4.2 Harmonized KENSOTER database

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

**Table 29: SWAT soil parameters**

<table>
<thead>
<tr>
<th>SNAME</th>
<th>PRID_SNAME</th>
</tr>
</thead>
<tbody>
<tr>
<td>HYDGRP</td>
<td>Estimated from clay% , drainage and soil group</td>
</tr>
<tr>
<td>Layer</td>
<td>Soil layer per 20 cm up to actual soil depth (&lt;100 cm) or 100 cm. Soil depth &gt;100 cm from profile descriptions (layer 6 and 7) inserted</td>
</tr>
<tr>
<td>Botdep</td>
<td>Lower depth from description, cm</td>
</tr>
<tr>
<td>SOL-ZMX</td>
<td>Maximum rooting depth, from profile description</td>
</tr>
<tr>
<td>ANION_EXCL, AND</td>
<td>Not done (estimated)</td>
</tr>
<tr>
<td>SOL_C,CK AND SOL_K</td>
<td></td>
</tr>
<tr>
<td>SOL_CBN</td>
<td>Total soil organic carbon, g/kg</td>
</tr>
<tr>
<td>SGRADE, SSIZE, STYPE</td>
<td>Structure description according to SOTER manual (van Engelen and Wen 1995)</td>
</tr>
<tr>
<td>CFRAG</td>
<td>Fragments &gt;2 mm</td>
</tr>
<tr>
<td>SDTO</td>
<td>Sand %</td>
</tr>
<tr>
<td>STPCL</td>
<td>Silt %</td>
</tr>
<tr>
<td>CLPCL</td>
<td>Clay %</td>
</tr>
<tr>
<td>PSCL</td>
<td>Texture class, USDA</td>
</tr>
<tr>
<td>BULK</td>
<td>Bulk density, g/cm³</td>
</tr>
<tr>
<td>TAWC</td>
<td>Available water content (30-1500 kPa)</td>
</tr>
<tr>
<td>ELCO</td>
<td>Electrical conductivity dS/m</td>
</tr>
</tbody>
</table>

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:

<table>
<thead>
<tr>
<th>SOTER depth class</th>
<th>Depth range, cm</th>
<th>Average depth, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>&lt; 30</td>
<td>15</td>
</tr>
<tr>
<td>S</td>
<td>30-50</td>
<td>40</td>
</tr>
<tr>
<td>M</td>
<td>50-100</td>
<td>75</td>
</tr>
<tr>
<td>D</td>
<td>100-150</td>
<td>125</td>
</tr>
<tr>
<td>X</td>
<td>&gt;150</td>
<td>150</td>
</tr>
</tbody>
</table>
A4.3 Runoff and soil erosion data

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

Table 30: Seasonal runoff, mm, 1993-97

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>20.9</td>
<td>4.9</td>
<td>18.5</td>
<td>40.9</td>
<td>22.6</td>
<td>10.6</td>
<td>107.7</td>
</tr>
<tr>
<td>Napier</td>
<td>15.5</td>
<td>5.3</td>
<td>17.7</td>
<td>23.7</td>
<td>7.7</td>
<td>4.1</td>
<td>49.4</td>
</tr>
<tr>
<td>Calliandra</td>
<td>10.9</td>
<td>3.7</td>
<td>9.2</td>
<td>27.9</td>
<td>16.5</td>
<td>5.0</td>
<td>48.2</td>
</tr>
<tr>
<td>Combination</td>
<td>13.3</td>
<td>3.6</td>
<td>13.6</td>
<td>22.5</td>
<td>7.3</td>
<td>4.3</td>
<td>40.4</td>
</tr>
<tr>
<td>Mean</td>
<td>15.2</td>
<td>4.4</td>
<td>14.7</td>
<td>28.7</td>
<td>13.5</td>
<td>6.0</td>
<td>61.4</td>
</tr>
</tbody>
</table>

LR: long rains, SR: short rains

Table 31: Seasonal soil loss, tonne/ha

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.1</td>
<td>3.1</td>
<td>6.6</td>
<td>18.0</td>
<td>11.7</td>
<td>8.1</td>
<td>51.3</td>
</tr>
<tr>
<td>Napier</td>
<td>0.0</td>
<td>4.3</td>
<td>5.2</td>
<td>9.3</td>
<td>3.3</td>
<td>2.1</td>
<td>9.9</td>
</tr>
<tr>
<td>Calliandra</td>
<td>0.1</td>
<td>1.8</td>
<td>4.4</td>
<td>12.3</td>
<td>8.1</td>
<td>4.2</td>
<td>13.4</td>
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<tr>
<td>Combination</td>
<td>0.1</td>
<td>2.4</td>
<td>5.3</td>
<td>11.9</td>
<td>3.2</td>
<td>2.2</td>
<td>9.9</td>
</tr>
<tr>
<td>Mean</td>
<td>0.1</td>
<td>2.9</td>
<td>5.4</td>
<td>12.78</td>
<td>6.6</td>
<td>4.4</td>
<td>29.8</td>
</tr>
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</table>

Data from Kianjuka catchment:

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

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

* = No data; soils strongly weathered
Table 33: Kianjuki catchment, soil particle-size distribution

<table>
<thead>
<tr>
<th>Slope</th>
<th>Treatment</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Sand (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 per cent</td>
<td>Control</td>
<td>69</td>
<td>18</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Hedge</td>
<td>64</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>40 per cent</td>
<td>Control</td>
<td>53</td>
<td>29</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Hedge</td>
<td>55</td>
<td>28</td>
<td>17</td>
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</table>

References


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)

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

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

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td>H513</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>H511</td>
<td>34</td>
<td>39</td>
<td>18</td>
<td>18</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>H512</td>
<td>14</td>
<td>13</td>
<td>10</td>
<td>7</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>C5222</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Pan 5195</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>CG 4141</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>PHB 3253</td>
<td>1</td>
<td>2</td>
<td>25</td>
<td>33</td>
<td>34</td>
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<tr>
<td>H614</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>H611</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H626</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H625</td>
<td>6</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>KCB</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
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<tr>
<td>DLC1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Own seed</td>
<td>41</td>
<td>41</td>
<td>44</td>
<td>39</td>
<td>43</td>
<td>45</td>
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</tbody>
</table>

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)

<table>
<thead>
<tr>
<th>Variety</th>
<th>Days from emergence to silking</th>
<th>Days from emergence to maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short maturity</td>
<td></td>
<td></td>
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<tr>
<td>KCB</td>
<td>54</td>
<td>99</td>
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<tr>
<td>Medium maturity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H511</td>
<td>68</td>
<td>134</td>
</tr>
<tr>
<td>H513</td>
<td>71</td>
<td>136</td>
</tr>
<tr>
<td>Late maturity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H614</td>
<td>81</td>
<td>157</td>
</tr>
<tr>
<td>H628</td>
<td>84</td>
<td>158</td>
</tr>
</tbody>
</table>

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

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

<table>
<thead>
<tr>
<th>Maize variety</th>
<th>With 20:20:0 fertilizer 200 kg/ha</th>
<th>Without fertilizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>KCB</td>
<td>991</td>
<td>707</td>
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<td>DLC – 1</td>
<td>1315</td>
<td>1104</td>
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<tr>
<td>Local</td>
<td>1333</td>
<td>1241</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LR</td>
<td>SR</td>
<td>LR</td>
<td>SR</td>
<td>LR</td>
<td>SR</td>
</tr>
<tr>
<td>Control</td>
<td>3.99</td>
<td>0.83</td>
<td>6.70</td>
<td>4.87</td>
<td>4.05</td>
<td>8.05</td>
</tr>
<tr>
<td>Napier</td>
<td>4.17</td>
<td>0.77</td>
<td>6.71</td>
<td>3.50</td>
<td>3.43</td>
<td>5.50</td>
</tr>
<tr>
<td>Calliandra</td>
<td>4.33</td>
<td>1.12</td>
<td>7.76</td>
<td>5.07</td>
<td>4.40</td>
<td>8.22</td>
</tr>
<tr>
<td>Combination</td>
<td>3.98</td>
<td>0.82</td>
<td>7.23</td>
<td>4.12</td>
<td>4.01</td>
<td>6.64</td>
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<tr>
<td>Mean</td>
<td>4.12</td>
<td>0.88</td>
<td>7.10</td>
<td>4.39</td>
<td>3.97</td>
<td>7.14</td>
</tr>
</tbody>
</table>

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)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mean yield (t ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize alone</td>
<td>2.60</td>
</tr>
<tr>
<td>Maize in Kudzu fallow</td>
<td>3.48</td>
</tr>
<tr>
<td>Maize in Desmodium fallow</td>
<td>4.20</td>
</tr>
<tr>
<td>Maize in Calliandra fallow</td>
<td>3.38</td>
</tr>
<tr>
<td>Maize in Sesbania fallow</td>
<td>5.20</td>
</tr>
</tbody>
</table>

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, Verkuilj 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>
<thead>
<tr>
<th>AfriCover</th>
<th>SWAT class</th>
<th>IRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed woody (broadleaved deciduous) with sparse trees</td>
<td>FRSD</td>
<td></td>
</tr>
<tr>
<td>Closed woody with sparse trees</td>
<td>FRST</td>
<td></td>
</tr>
<tr>
<td>Open woody with herbaceous ground cover</td>
<td>RNGE</td>
<td></td>
</tr>
<tr>
<td>Open woody with closed to open herbaceous ground cover on temporarily flooded land - fresh water</td>
<td>WETL</td>
<td></td>
</tr>
<tr>
<td>River</td>
<td>WATR</td>
<td></td>
</tr>
<tr>
<td>Artificial lakes or reservoirs</td>
<td>WATR</td>
<td></td>
</tr>
<tr>
<td>Natural lakes</td>
<td>WATR</td>
<td></td>
</tr>
<tr>
<td>Fish pond</td>
<td>WATR</td>
<td></td>
</tr>
<tr>
<td>Irrigated orchard, large to medium fields - citrus</td>
<td>ORCD</td>
<td>irrigated</td>
</tr>
<tr>
<td>Rice - large to medium fields</td>
<td>RICE</td>
<td>irrigated</td>
</tr>
<tr>
<td>Trees plantation - large fields, rain-fed, permanent</td>
<td>PLAN</td>
<td></td>
</tr>
<tr>
<td>Rain-fed tree crop (1 add. herbaceous crop) - clustered medium fields</td>
<td>AGRR</td>
<td></td>
</tr>
<tr>
<td>River banks</td>
<td>BARE</td>
<td></td>
</tr>
<tr>
<td>Lake shore</td>
<td>BARE</td>
<td></td>
</tr>
<tr>
<td>Cereals, rice - Small Fields</td>
<td>RICE</td>
<td>irrigated</td>
</tr>
<tr>
<td>Rain-fed tree crop (1 add. herbaceous crop), small fields</td>
<td>AGRR</td>
<td></td>
</tr>
<tr>
<td>Rain-fed tree crop, small fields</td>
<td>AGRR</td>
<td></td>
</tr>
<tr>
<td>Rain-fed tree crop (1 add. shrubs crop), clustered small fields</td>
<td>AGRR</td>
<td></td>
</tr>
<tr>
<td>Rain-fed tree crop (1 add. herbaceous crop), clustered small fields</td>
<td>AGRR</td>
<td></td>
</tr>
<tr>
<td>Rain-fed tree crop, clustered small fields</td>
<td>AGRR</td>
<td></td>
</tr>
<tr>
<td>Rain-fed tree crop, isolated small fields</td>
<td>AGRR</td>
<td></td>
</tr>
<tr>
<td>Sand beaches</td>
<td>BARE</td>
<td></td>
</tr>
<tr>
<td>Needle-leaved evergreen forest plantation</td>
<td>FRSE</td>
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</tr>
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<td>Forest Plantation, broad-leaved evergreen, rain-fed, permanent</td>
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<tr>
<td>Closed herbaceous on temporarily flooded land - fresh water</td>
<td>WETL</td>
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</tr>
<tr>
<td>Sparse herbaceous</td>
<td>AGRL</td>
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</tr>
<tr>
<td>Closed to very open herbaceous</td>
<td>AGRL</td>
<td></td>
</tr>
<tr>
<td>Closed to open herbaceous on permanently flooded land</td>
<td>WETL</td>
<td></td>
</tr>
<tr>
<td>Closed to very open herbaceous with sparse trees and shrubs</td>
<td>AGRL</td>
<td></td>
</tr>
<tr>
<td>Closed to very open herbaceous with sparse shrubs</td>
<td>AGRL</td>
<td></td>
</tr>
<tr>
<td>Closed to very open herbaceous with sparse shrubs on temporarily flooded land - fresh water</td>
<td>WETL</td>
<td></td>
</tr>
<tr>
<td>Quarry</td>
<td>BARE</td>
<td></td>
</tr>
<tr>
<td>Snow</td>
<td>WATR</td>
<td></td>
</tr>
<tr>
<td>Rain-fed shrub crop, large fields - pineapple</td>
<td>PINE</td>
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<td>Rain-fed shrub crop, large fields - coffee</td>
<td>COFF</td>
<td></td>
</tr>
<tr>
<td>Rain-fed shrub crop, large fields - tea</td>
<td>TEA</td>
<td></td>
</tr>
<tr>
<td>Rain-fed shrub crop, large fields</td>
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</tr>
<tr>
<td>Rain-fed shrub crop, small fields - coffee</td>
<td>COFF</td>
<td></td>
</tr>
<tr>
<td>Rain-fed shrub crop, small fields - tea</td>
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<td>IRR</td>
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<td>-----</td>
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<tr>
<td>Rain-fed shrub crop, small fields - orchard</td>
<td>AGRL</td>
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</tr>
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<td>Rain-fed shrub crop, clustered small fields - coffee</td>
<td>COFF</td>
<td></td>
</tr>
<tr>
<td>Rain-fed shrub crop, clustered small fields - tea</td>
<td>TEA</td>
<td></td>
</tr>
<tr>
<td>Rain-fed shrub crop, clustered small fields</td>
<td>AGRL</td>
<td></td>
</tr>
<tr>
<td>Rain-fed shrub crop, isolated small fields - tea</td>
<td>TEA</td>
<td></td>
</tr>
<tr>
<td>Rain-fed shrub crop, isolated small fields</td>
<td>AGRL</td>
<td></td>
</tr>
<tr>
<td>Closed multilayered trees (broadleaved evergreen)</td>
<td>FRSE</td>
<td></td>
</tr>
<tr>
<td>Closed trees with shrubs</td>
<td>FRST</td>
<td></td>
</tr>
<tr>
<td>Closed trees - bamboo</td>
<td>FRST</td>
<td></td>
</tr>
<tr>
<td>Open trees (broadleaved deciduous) with closed to open herbaceous and sparse shrubs</td>
<td>FRST</td>
<td></td>
</tr>
<tr>
<td>Very open trees (broadleaved deciduous) with closed to open herbaceous and sparse shrubs</td>
<td>FRST</td>
<td></td>
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<td>Open trees (broadleaved deciduous) with closed to open shrubs</td>
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<td>Closed trees (broadleaved evergreen) on permanently flooded land - brackish water</td>
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<td>Open trees with closed to open herbaceous on temporarily flooded land - fresh water</td>
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<td>Bare rock</td>
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<tr>
<td>Large-medium fields, rain-fed</td>
<td>AGRL</td>
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<tr>
<td>Large fields - wheat, rain-fed</td>
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<tr>
<td>Herbaceous - medium fields - maize, rain-fed</td>
<td>CORN</td>
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<tr>
<td>Herbaceous - medium fields - wheat, rain-fed</td>
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<td>Large-medium fields - maize, rain-fed</td>
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<td>Large-medium fields - sisal, rain-fed</td>
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<td>Herbaceous - large to medium fields, surface-irrigated, permanent</td>
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<td>Irrigated herbaceous crop, large fields</td>
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<td>Lessons learned from payments for environmental services</td>
<td>Grieg-Gran M and others 2006</td>
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<td>Green and blue water resources and assessment of improved soil and water management scenarios using an integrated modelling framework.</td>
<td>Kauffman JH and others 2007</td>
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<td>Quantifying water usage and demand in the Tana River basin: an analysis using the Water and Evaluation and Planning Tool (WEAP)</td>
<td>Hoff H and others 2007</td>
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<td>Farmers' adoption of soil and water conservation: the potential role of payments for watershed services</td>
<td>Porras I and others 2007</td>
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<td>GWC 6</td>
<td>Political, institutional and financial framework for Green Water Credits in Kenya</td>
<td>Meijerink G and others 2007</td>
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<td>GWC 7</td>
<td>The spark has jumped the gap. Green Water Credits proof of concept</td>
<td>Dent DL and JH Kauffman 2007</td>
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