

Targeting of intervention areas to reduce reservoir sedimentation in the Tana catchment (Kenya) using SWAT

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Abstract A measurement campaign was carried out in the Upper Tana basin (Kenya) to quantify soil erosion and reservoir sedimentation rates, including a bathymetric reservoir survey and sediment load sampling during one year. Then, distributed soil erosion modelling was performed to study sediment budgets throughout the basin and to evaluate the potential of upstream erosion control through vegetated contour strips and check dams. Finally, the areas where these measures would be most effective were identified and local stakeholder associations to implement them were prioritized. The influence of the scale of implementation was evaluated by using the model to consider three adoption scenarios. This study illustrates the relevance of distributed erosion models to target erosion control measures when sufficient information on the eroding areas is available from field surveys. Bathymetric surveys were fundamental to validate the long-term model response, while point measurements were valuable to verify the spatial variability of model predictions.

Key words soil erosion; sediment yield; sedimentation rate; distributed model; SWAT; Kenya; erosion control; soil conservation; watershed management

Détermination des zones d'intervention pour la réduction de la sédimentation des réservoirs du bassin du Tana (Kenya) en utilisant SWAT

Résumé Une campagne de mesures a été réalisée dans le bassin du Haut Tana (Kenya) afin de quantifier l'érosion des sols et les taux de sédimentation dans le réservoir, comprenant une étude bathymétrique du réservoir et l'échantillonnage des sédiments déposés pendant un an. Une modélisation distribuée de l'érosion des sols a ensuite été réalisée pour étudier le bilan des sédiments dans le bassin et évaluer le potentiel de contrôle de l'érosion en amont, par des bandes de végétation suivant les courbes de niveau et des barrages de retenue. Nous avons enfin identifié les zones où ces mesures seraient les plus efficaces, de même que les associations d'intervenants locaux susceptibles de les mettre en œuvre. L'influence de la mise en œuvre a été évaluée en utilisant le modèle selon trois scénarios. Cette étude illustre la pertinence des modèles d'érosion distribués pour concevoir des mesures de lutte contre l'érosion lorsque suffisamment d'informations sur les zones érodées, provenant d'enquêtes sur le terrain, sont disponibles. Les levés bathymétriques ont été fondamentaux pour valider la réponse du modèle à long terme, tandis que les mesures ponctuelles ont été utiles pour vérifier la variabilité spatiale des prévisions du modèle.

Mots clefs érosion des sols; production de sédiments; vitesse de sédimentation; modèle distribué; SWAT, Kenya; lutte contre l'érosion; conservation des sols; gestion des bassins versants

INTRODUCTION

In many countries, sustainable use of reservoirs is seriously threatened by their declining storage

capacity due to the trapping of sediments. This process reduces and eventually eliminates the storage capacity required for hydropower generation,

flood control and water supply (Einsele and Hinderer 1997, Syvitski *et al.* 2005, Verstraeten *et al.* 2006, Vanmaercke *et al.* 2011), yet the dependence on water storage in reservoirs has increased over the years in many basins due to population growth, socio-economic and hydrological changes and increased irrigated agriculture (e.g. Wisser *et al.* 2010).

In Africa, often harsh environmental conditions and poor land management causes substantial erosion rates and losses in reservoir capacity, as has been observed in, or estimated for, several countries (Walling 1984, Shahin 1993, Haregeweyn *et al.* 2006, Boardman and Foster 2011). Agriculture in many of these areas strongly depends on irrigation water from reservoirs, and several countries, including Kenya, strongly rely on hydropower for their energy supply. Therefore, land managers and policy makers look for effective and efficient solutions to reduce reservoir sedimentation.

Former studies in the Upper Tana basin (Kenya) of erosion (Ongwenyi *et al.* 1993, Brown *et al.* 1996) and reservoir sedimentation (Wooldridge 1984) indicated that the reservoirs could have lost between 10% and 30% of capacity in 30 years, and that the services that rely on these water storages may be threatened in the near future. In addition, some studies point out that this particular part of Kenya may suffer serious consequences due to climate change and that rainfall variability will be greater in the future (Herrero *et al.* 2010). As these changes may further affect water storage capacity and requirements for irrigation and drinking water, a study was required by the government of Kenya to assess erosion and reservoir sedimentation of the Upper Tana basin under present and possible future land-use and management conditions. Reduction of reservoir sedimentation requires reduction of upstream erosion through the promotion of soil conservation practices and implementation of hydrological control works like check dams and reforestation (e.g. Trimble 1981). However, erosion control measures are often poorly conceived and implemented (Gebremedhin 2004, Oñate and Peco 2005, Liniger and Critchley 2007, Boix-Fayos *et al.* 2008), and fail to achieve the desired reductions in sediment yield. One of the reasons for the low success rates is the fact that farmers, being those that have to actually execute and maintain the adopted measure, get hardly any short-term benefits from the adopted measures, and often conservation measures are not well-adapted to local socio-economic and cultural conditions (Gebremedhin 2004, Oñate and Peco 2005). Given the often precarious economic situation

of African land users, the long-term benefit of preserving soil fertility and reservoir storage capacity, and thus saving money for fertilizers and water provision, is generally not convincing enough (e.g. Ervin and Ervin 1982, Shiferaw and Holden 1998). Support to farmers to implement certain practices should therefore be well targeted so as to dedicate the resources exactly to the areas where most profit can be expected. Moreover, decisions over *which* measures to implement *where* are far more effective when taken in a well-designed participatory process with the involvement of all relevant stakeholders (Reed 2008, Schwilch *et al.* 2009).

For a higher success rate in the implementation of erosion control measures, information is required on where to optimally intervene to best dedicate efforts and resources. For this purpose, monitoring of soil erosion status and field surveys are crucial components to targeting interventions. To make assessments of large catchments and test the impacts of various conservation strategies, distributed erosion modelling is needed to obtain a complete picture of the sediment budgets. Calibration and validation of erosion models requires experimental field data and spatially distributed databases of soil, topography and climate parameters with sufficiently high quality and resolution (de Vente *et al.* 2009). Most evaluations of the impacts of conservation measures (e.g. Bewket and Sterk 2003, Van Noordwijk *et al.* 2004, Hengsdijk *et al.* 2005) have focused on plot-scale effects on vegetation, runoff, soil and nutrient loss. Much less is known about the regional impact on the sediment budgets. Several studies have assessed actual sediment budgets at the catchment scale, stressing the importance of distributed approaches (e.g. Lenhart *et al.* 2005, Haregeweyn *et al.* 2013), but only a few studies on the regional impact of soil conservation measures have been made (Bellin *et al.* 2009, Lesschen *et al.* 2009, White and Arnold 2009, Nyssen *et al.* 2010, Tuppad *et al.* 2010).

Most spatially-distributed hydrological and erosion models require a large number of detailed spatially-distributed data on climate, soil, topography, land-use and land-cover variables. The absence or low quality of available data often impedes the successful application of such models at the catchment scale (Merritt *et al.* 2003, de Vente and Poesen 2005), although the use of satellite imagery and remote sensing techniques has been reported to be successful in some cases (de Jong 1994, de Jong *et al.* 1999, de Vente *et al.* 2009). For large catchments, relatively simple regression models or semi-quantitative

expert-based models often give better results for prediction of sediment yield than more complex physically-based models (Van Rompaey and Govers 2002, Jetten *et al.* 2003, de Vente *et al.* 2008). However, many of those models do not give predictions of spatial patterns of soil erosion, or strongly depend on calibration procedures, making them less suited for application in scenario studies (Cerdà *et al.* 2013).

Process-based models provide a good alternative to explore the impacts of changes in land use and management in scenario studies. While application of many of these models is limited by their high data requirements, SWAT (Soil and Water Assessment Tool) is a process-based model that was successfully applied for large catchments, and also in data-poor regions of the world (e.g. Immerzeel and Droogers 2008, Schuol *et al.* 2008, Betrie *et al.* 2011). After calibration, the model can be applied at different spatial resolutions and levels of detail, and provides semi-spatially distributed output of sources and sinks of sediment. This gives the model strong potential for use in scenario studies of changing land-use and management conditions (e.g. Tripathi *et al.* 2003, Mishra *et al.* 2007, Parajuli *et al.* 2008, Rostamian *et al.* 2008, Hunink *et al.* 2013).

The main objective of this paper is to demonstrate how distributed erosion modelling, together with field surveys, can be an effective tool for evaluating the impacts of land-use and management scenarios on soil and water resources, and selecting priority areas for implementation of soil conservation measures. The paper presents an assessment of the spatial patterns of soil erosion by water and the potential of erosion control measures to reduce sedimentation of the reservoirs in the Upper Tana basin (Kenya) based on a wide range of data sets and field measurements, together with the application of the SWAT model.

METHODS

Study area

The Upper Tana basin (9500 km²) (Fig. 1) is a relatively humid basin with average annual rainfall amounts of about 2000 mm at higher altitudes, drier conditions (about 500 mm year⁻¹) at lower elevations, and annual potential evapotranspiration rates of around 1000 mm (Jaetzold *et al.* 2006). There are two wet seasons and two dry seasons as a result of the monsoon. Approximately half of the annual rainfall in the basin falls from mid-March to June,

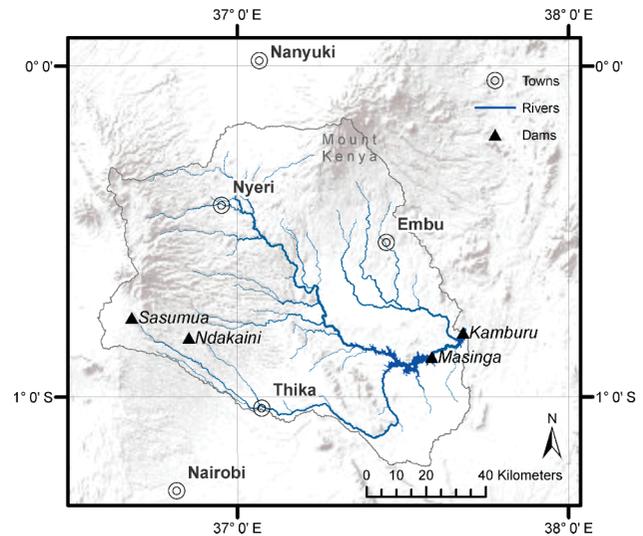


Fig. 1 Location of the Upper Tana catchment.

known as the long rains. The so-called short rains are between October and December when the area receives approximately a third of its annual rainfall. The Upper Tana can be divided into two main geological structures: volcanic rocks of the Cenozoic Era are found in the higher mountain areas, while in the lower areas the bedrock consists mainly of metamorphic rocks of the Mozambique belt (Veldkamp *et al.* 2011). The soils in the mountain areas are dominated by volcanic ash soils, while at lower elevations soils are derived from metamorphic rocks, mainly gneiss, banded gneiss and schists, resulting in fertile clay soils as well as poorer leached clay soils (Dijkshoorn *et al.* 2010). The lower slopes of the mountains are mainly cultivated and forested, and are highly dissected with steep-sided V-shaped valleys. The higher mountain areas are characterized by moorland, with U-shaped and shallower valleys created by glaciations (Veldkamp *et al.* 2011).

During recent decades, the population in the higher mountain areas has increased, and formerly non-cultivated areas have been converted to agricultural lands. Rainfed subsistence agriculture now constitutes over 60% of the land use. The main rainfed crops are maize, coffee and tea, principally cultivated in the higher and wetter areas of the basin where crop rotation is common (Muriuki and Macharia 2011). At lower altitudes, irrigated crops (flowers, fruit and vegetables) are also produced for the international market (Jaetzold *et al.* 2006).

Five major reservoirs were built between the years 1968 and 1987 for hydropower, storage for irrigation and drinking water supply, and flow regulation.

Two additional smaller upstream reservoirs are used for water supply to Nairobi city. The reservoirs guarantee about half of the national energy production (Droogers *et al.* 2011). Recent severe droughts in 2005, 2006 and 2009, resulting in low water volumes, made it necessary to ration water and electricity throughout the country.

Field data

A total of 14 monitoring points for river discharge and suspended sediment were selected across the catchment (Fig. 2), among which preference was given to gauging stations that were used previously used by the local water authority. Other selection criteria were the accessibility (roads, bridges) and the presence of a steady flow regime. Measurements of flow and suspended sediment sampling were carried out between March 2010 and February 2011. Measurements of discharge and sediment sampling took place on a bimonthly basis resulting in a total of 24 measurements for each point.

To derive the long-term sedimentation rate since construction of the reservoirs, bathymetric surveys were conducted on four reservoirs in the Upper Tana basin, the Masinga, Kamburu, Ndakaini (Thika) and Sasumua dam reservoirs. The surveys were conducted using state-of-the-art differential GPS positioning

and a conventional single beam echo sounder to measure water depth and measurement location. Measurements were performed under very favourable conditions with three out of four reservoirs near their full-supply level during the survey, which means that only limited extrapolation of the obtained profiles was necessary using available aerial imagery.

To further estimate the sediment budgets of the reservoirs, the sediment bulk density was estimated from sediment texture, reservoir operation and reservoir age using the empirical formula proposed by Miller (1953). The trap efficiency of the reservoirs was calculated with the analytical method described by Julien (1995).

Data on daily discharge measured from 1980 until the present at various stations throughout the basin were available for the study and provided by the national water authority. A quality assessment of these data was done based on visual inspection of the time series and a selection was made from the gauges available, giving a total of 10 stations. The selected gauges are located both at upstream and at downstream points in the river network (Fig. 2).

Modelling approach

The Soil and Water Assessment Tool (SWAT) (Arnold *et al.* 1998) was used for prediction of discharge,

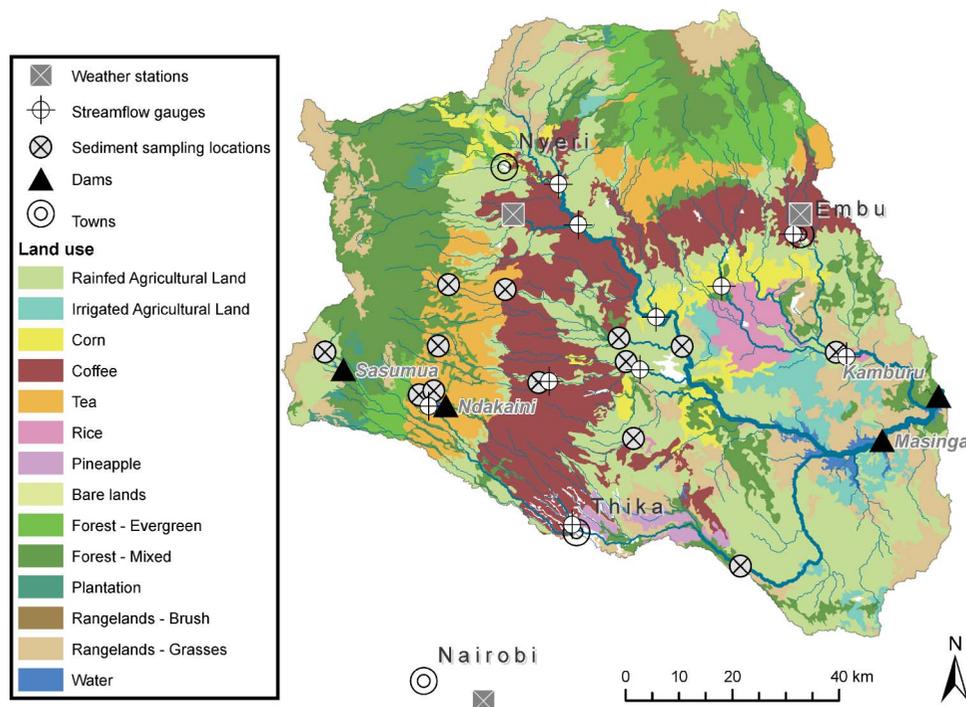


Fig. 2 Land use in the catchment and the different measurement locations.

soil erosion and sediment yield. The SWAT model allows the simulation of erosion processes based on soil type, topography, land-use and climate data, with a relatively high level of spatial detail necessary for decision support. For spatial discretization of the catchment, SWAT uses the concept of hydrological response units (HRU) (Neitsch *et al.* 2002): portions of a sub-basin that possess unique land-use, management and soil attributes.

Surface runoff volume was calculated in SWAT for each HRU using the SCS (Soil Conservation Service) curve number procedure (USDA-SCS 1972), aggregated for each delineated sub-basin and routed through the stream network using a variation of the kinematic wave model. Runoff peak rate is calculated with the rational method slightly modified for the HRU concept (Neitsch *et al.* 2002).

The Universal Soil Loss Equation (USLE) is the method most commonly used to estimate long-term erosion rates from field or farm sites that are subject to different management practices. Wischmeier and Smith (1965) developed the method based on data from many experimental plots in the USA, but the method has been applied and argued about, globally (e.g. Wischmeier 1976, Sonneveld and Nearing 2003).

The SWAT model estimates erosion and sediment yield with the Modified Universal Soil Loss Equation (MUSLE) (Williams 1975). While the USLE uses rainfall as an indicator of erosive energy, MUSLE uses the amount of runoff to simulate erosion and sediment yield. This modification is reported to increase the prediction accuracy of the model, the need for a delivery ratio is eliminated, and single storm estimates of sediment yields can be calculated (Wang *et al.* 2009). The MUSLE equation as used in SWAT is as follows:

$$Q_s = 11.8(Q_r \cdot q_{\text{peak}} \cdot A_{\text{HRU}})^{0.56} \cdot K \cdot C \cdot P \cdot LS \cdot \text{CFRG} \quad (1)$$

where Q_s is the sediment yield (t/d); Q_r is the surface runoff volume (mm/ha); q_{peak} is the peak runoff rate (m^3/s); A_{HRU} is the area of the HRU (km^2); K is the USLE soil erodibility factor; C is the USLE cover and management factor; P is the USLE support practice factor; LS is the USLE topographic factor; and CFRG is the coarse fragment factor. The crop management factor of the USLE equation is recalculated every day that runoff occurs and is a function of above-ground biomass, residue on the soil surface, and the minimum

C factor for the plant. The other factors of the erosion equation are evaluated as described by Wischmeier and Smith (1978).

The sediment yields of each HRU are routed to the channel of the corresponding sub-basin. The transport of sediment in the channel is controlled by the simultaneous operation of two processes, deposition and degradation. SWAT uses Williams (1980) simplified version of Bagnold's (1977) definition of stream power to develop a method for determining channel degradation as a function of channel slope and velocity. The maximum amount of sediment that can be transported from a channel segment is simulated as a function of the peak flow rate and is computed as follows:

$$S_{\text{max}} = c_{\text{sp}} \left(\frac{q_s}{A_{\text{ch}}} \right)^{\text{sp}} \quad (2)$$

where S_{max} is the maximum concentration of sediment that can be transported or the channel carrying capacity ($10^3 \text{ kg}/\text{m}^3$); c_{sp} is an empirical coefficient which needs to be calibrated; q_s is the peak flow rate (m^3/s); A_{ch} is the cross-sectional area of flow in the channel; and sp is an exponent defined by the user.

Spatial model input

Daily climate data from the period 1980–2010 were gathered from three stations (Fig. 2). The origin of these data was the Global Summary of the Day (GSOD) database archived by the US National Climatic Data Center (NCDC) (<http://www.ncdc.noaa.gov/>). The variables used were precipitation and those needed for the calculation of potential evapotranspiration by the Penman-Monteith method, i.e. temperature, solar radiation, wind speed and air humidity.

The importance of orographic rainfall in the higher parts of the basin where no data were available required the use of a second data source to account for the high spatial variability of rainfall. Many satellite rainfall products are available today, all of them with different characteristics, spatial and temporal resolutions, and coverage (e.g. PERSIANN, TRMM, CMORPH, TAMSAT). A good-quality product focused on the African continent is prepared operationally at the Climate Prediction Center (CPC) for the US Agency for International Development (USAID). They provide daily estimates of precipitation that are used for the Famine Early Warning System (FEWS) network. The latest product

(RFE2) is available from October 2000 on a 0.1-degree spatial resolution. This data set was found to outperform other satellite products in this part of Africa (Asadullah *et al.* 2008) when compared with ground measurements.

For this particular study, the CPC data set does not provide a time series long enough to cover the entire simulation period (1980–2010). Therefore, a GIS procedure was carried out to generate daily gridded rainfall maps for the entire period, by combining the daily time series of the three point locations with monthly gridded averages of the 10-year data set from RFE2. Funk and Verdin (2010) used a similar method to derive improved gridded climatologies with satellite rainfall averages as a basis. This methodology benefits from the ability of satellite rainfall estimates to capture spatial gradients in rainfall and the relative accuracy of rainfall gauges (Hunink *et al.* 2011).

Spatial information on land use was obtained from the FAO Africover data set at 1:100 000 resolution (<http://www.africover.org>) (Fig. 2). Digital elevation data at 1 arc second resolution were obtained from the public domain database of the Shuttle Radar Data Topography Mission (SRTM). Soil data were used from the Harmonized Upper Tana SOTER database (Dijkshoorn *et al.* 2010), including data on soil depth, texture of each soil layer and available water capacity. The saturated hydraulic conductivity was estimated using pedo-transfer functions as described by Jabro (1992):

$$\log(K_{\text{sat}}) = 9.56 - 0.81 \cdot \log(\% \text{silt}) - 1.09(\% \text{clay}) - 4.64(\text{Bd}) \quad (3)$$

where K_{sat} is the saturated soil hydraulic conductivity (cm/h) and Bd is the soil bulk density (g/cm³).

The SWAT interface overlays the digital elevation model, the land use and the soil GIS layers, and creates the HRUs from the unique combinations. For computational efficiency, HRUs that covered less than 10% of each sub-basin were merged with others, resulting in a total of 2226 HRUs, distributed over 376 sub-basins.

Model calibration

The calibration and validation of erosion models is a difficult task due to the dynamic and nonlinear responses that characterize basin-scale sediment transport. The following issues have to be dealt with when setting up such a model:

- (a) scarce data on extreme events;
- (b) biased field observations by non-experts;
- (c) scarce data on historical land-use changes or interventions that may have caused significant changes in erosion and deposition (e.g. McIntyre 1993);
- (d) different scale levels (temporal and spatial) of available data;
- (e) model representation of all relevant erosion processes; and
- (f) field measurement of all forms of sediment transport including bedload and mass movements.

These issues require a multi-step calibration approach in which field data on discharge and sediment transport from various points in time and space are taken into account.

The first step is to calibrate the model for river discharge as this dominates the erosion and sediment transport to the reservoirs. This was done based on monthly 30-year time series (1980–2009) calculated from daily measurements at the 10 selected streamflow gauges throughout the basin. A sensitivity analysis was carried out by systematically running the model for a range of parameter values to evaluate which of the possible calibration parameters are most responsive for the ratio of fast runoff/baseflow. Based on this, two parameters (one determining the travel time between the soil profile and aquifer, and the second the baseflow recession constant) were adjusted for the whole basin (see Table 1). Another parameter (SLSOIL) was adjusted using a basin-wide multiplier to improve the ratio of lateral interflow to baseflow. By increasing this parameter, the travel time for lateral flow through the soil layers increases and relatively more water is available for percolation to the aquifers. The final calibrated value is different for each sub-basin. The root mean square error (RMSE) was used to optimize the model, defined as:

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (Q_{\text{obs},i} - Q_{\text{sim},i})^2} \quad (4)$$

where $Q_{\text{obs},i}$ is the observed monthly discharge in month i ; $Q_{\text{sim},i}$ is predicted river discharge in month i ; and n is the total number of values within the period of analysis.

Three performance indicators commonly used for the evaluation of watershed models (Moriassi *et al.* 2007) were used for the validation: the Nash and Sutcliffe (1970) efficiency (NSE) criterion; the

Table 1 SWAT parameters used for calibration, the range used for calibration and the value used for the analysis.

SWAT parameter	Unit	Description	Range used for calibration	Calibrated value
ALPHA_BF	d ⁻¹	Baseflow recession constant	0.01–0.1	0.015
GW_DELAY	d	Groundwater delay time	15–60	50
SLSOIL	m	Slope length for lateral subsurface flow	10–2000	90–1200*
<i>c_{sp}</i>	–	User defined coefficient determining channel carrying capacity	0.0001–0.01	0.003
<i>sp</i>	–	Exponent parameter for calculating sediment re-entrained in channel sediment routing	1.0–2.0	1.5

Note: *Different for each HRU, calibrated with a multiplier.

RMSE-observations standard deviation ratio (RSR), which is calculated as the ratio of the RMSE and standard deviation of measured streamflow (Singh *et al.* 2004); and the percent bias (PBIAS), which measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta *et al.* 1999). The NSE ranges between $-\infty$ and 1.0, with $NSE = 1.0$ being the optimal value. The RSR varies from the optimal value of 0, which indicates zero RMSE, or residual variation and therefore perfect model simulation, to a large positive value. Generally, values <0.70 are considered acceptable (Moriassi *et al.* 2007). For PBIAS, values of 10–20% can be considered acceptable, depending on the desired level of accuracy.

Calibration of the sediment module requires calibration of the two empirical parameters related to the Bagnold stream power equation (equation (2)): C_{sp} and sp need to be calibrated for the basin as a whole. The calibration of both coefficients was based on the comparison of the mean annual reservoir sediment inflow that was simulated by the model and the mean annual sediment inflow calculated from the bathymetric surveys (Table 2). This comparison was done for the period from the year in which each reservoir became operational to the month in which the survey was made. Calibration was done using one of the major downstream reservoirs (Masinga) and validation was done with the downstream Kamburu reservoir

Table 2 Simulated sediment inflow into the reservoirs *versus* sediment inflow derived from the bathymetric surveys (observed).

Reservoir	Simulated sediment inflow (Mt year ⁻¹)	Observed sediment inflow (Mt year ⁻¹)	Simulated as % of observed (%)
Sasumua	0.0	0.0	N/A
Ndakaini	0.0	0.0	N/A
Masinga	6.6	8.0	83
Kamburu	0.9	1.1	80

Scenario analysis

The erosion control measures to be studied were discussed with the local authorities in two meetings (May and July 2010) attended by staff from the water authority and a few representatives of farmers. It was agreed to assess the potential of implementing vegetated contour strips on hillslopes and check dams in permanent gullies in order to reduce the erosion and sediment yields in the basin. Vegetated contour strips are narrow buffer strips about 1 metre wide that have grass or other permanent vegetation to help trap runoff, sediment and nutrients and reduce slope length, sheet and rill erosion in a contoured field. For this scenario, it was assumed that the steep gully areas were protected with check dams in order to reduce flow velocities and gully erosion. The parameter changes that were applied in the model to simulate this scenario are summarized in Table 3 together with the references they were based on.

RESULTS

Model calibration and validation

Model calibration was performed with the 30-year time series of daily discharges from the 10 selected locations. Afterwards, the model was validated with data on the monthly water inflow into the largest downstream reservoir (Masinga). This data set was derived from the recorded water stages of the reservoir and the measured reservoir water outflow (Fig. 3(a)) and was available for 1982–2006. The values obtained for the three performance indicators are: $NSE = 0.75$, $RSR = 0.50$, $PBIAS = -9\%$. The NSE was slightly higher (0.76) for high flows (>75 th percentile). This indicates relatively good validation results with a slight systematic overestimation of discharge.

The long-term mean annual reservoir sediment inflow rates that were calculated from the bathymetric

Table 3 Parameter changes for the scenario combining permanent vegetative contour strips and check dams.

SWAT Parameter	Description	Land use	Parameter change (%)	Source
CN2	Runoff curve number	Coffee	-16	USDA-SCS (1986)
		Maize	-10	
		Tea	-16	
P _{USLE}	Support practice factor for soil loss	Coffee	-30	Wischmeier and Smith (1978)
		Maize	-10	
		Tea	-30	
HRU_SLP	Mean slope of HRU	Coffee, Maize, Tea	-5	Nyssen <i>et al.</i> (2010)

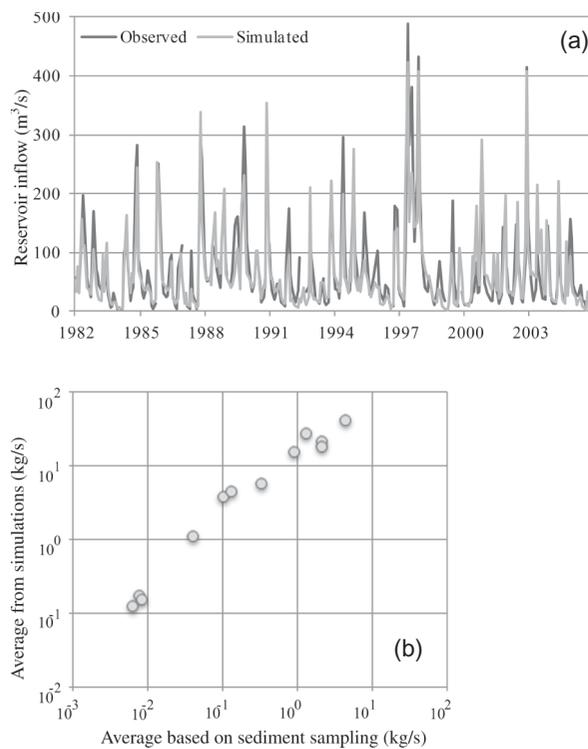


Fig. 3 (a) Observed and simulated water inflow into the Masinga Reservoir. (b) Scatterplot showing the mean annual sediment discharge based on the periodic one-year sampling *vs* the mean annual simulated sediment discharges over the 30-year simulation period.

surveys were used for the calibration and validation of the two empirical parameters that define the basin-wide channel sediment transport capacity (equation (2)). The model was run systematically changing these parameters within a fixed range (see Table 1). For the calibration, it was assumed that around 20% of the total sediment yield can be attributed to roads, trails and settlements, which are potential sediment sources that are not included in the SWAT model. This assumption was based on the analysis by Dunne (1979) in several Kenyan catchments including the Upper Tana catchment, in which

he found that roads contributed 15–35% of the total sediment yield. Other studies in regions with similar climate and geographical conditions have found similar values (e.g. Ziegler and Giambelluca 1997, Jungerius *et al.* 2002, Rijdsdijk 2005). Due to the size of the Masinga Reservoir and its high trap efficiency, the sediment inflow into the downstream Kamburu Reservoir is almost fully independent of the Masinga Reservoir and its upstream drainage area. Therefore, the Kamburu Reservoir could be used for validation of the calibration parameters. Table 2 shows the simulated and observed sediment yield data for the reservoirs. The simulated sediment yield is about 80% of the measured values, for both the Masinga and the Kamburu reservoirs, which means that the calibration and validation results are similar. For the other smaller upstream reservoirs that are used only for urban water supply (Sasumua and Ndakaini), no significant sediment yield was observed based on the bathymetric surveys, and it was not predicted by the model.

In order to evaluate the spatial prediction accuracy of the model, the sediment loads measured bimonthly during one year were averaged and compared with the average simulated loads in the same channel segment over the 30-year period. A coefficient of determination (R^2) of 0.95 between predicted and observed mean sediment fluxes (kg/s) indicates good agreement (Fig. 3(b)). This result suggests that the model accounts correctly for the spatial variability that exists throughout the catchment in terms of erosion and sediment yield. The absolute values of both data sets differ considerably, as argued in the Discussion section below.

Spatial analysis of the baseline scenario

The baseline scenario represents current land-use and land management conditions and was based on the previously described data sets and calibration efforts.

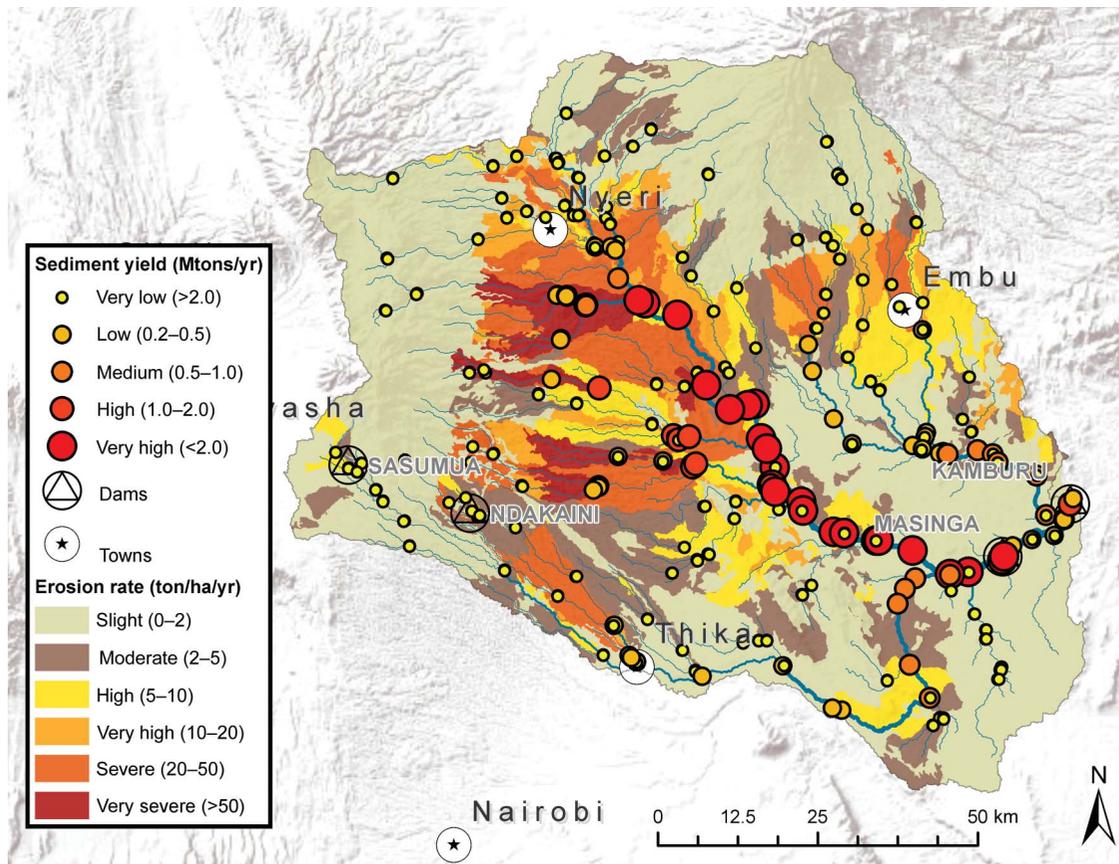


Fig. 4 Mean annual sediment yield at the river confluences and erosion rates of the baseline scenario based on the 30-year simulation period (1981–2010).

The baseline sediment budget is calculated from the 30-year model output (1981–2010). A map was produced (Fig. 4) representing the erosion rate throughout the basin for each HRU. Included in this map is the mean annual sediment yield that was predicted at each river confluence included in the model (377 in total), represented with dots of different size.

The erosion rates were classified according to the following scheme (adapted from Singh *et al.* 1992):

- slight (0–2 t ha⁻¹ year⁻¹)
- moderate (2–5 t ha⁻¹ year⁻¹)
- high (5–10 t ha⁻¹ year⁻¹)
- very high (10–20 t ha⁻¹ year⁻¹)
- severe (20–50 t ha⁻¹ year⁻¹) and
- very severe (>50 t ha⁻¹ year⁻¹)

As can be seen, large spatial differences exist in terms of the erosion rates. Natural areas in the higher mountain areas hardly contribute any sediment (3% of total basin sediment yield) while cultivated and grazed areas contribute the rest. The main sediment producing areas are located on steep slopes. Clearly,

the main erosive areas are those where coffee is produced, with an average erosion rate of 50 t ha⁻¹ year⁻¹, but also the areas where maize is cultivated together with other subsistence crops show high erosion rates, on average 10 t ha⁻¹ year⁻¹. Tea, in spite of being characterized by a dense canopy cover, is cultivated only on the steeper slopes and shows similar erosion rates to the subsistence crops. Similar trends and values were found in an earlier study on erosion in this region by Archer (1996).

Scenario analysis and targeting

The potential of the proposed conservation strategy, consisting of a joint implementation of vegetated contour strips and check dams to reduce erosion and reservoir sedimentation, was assessed by incorporating the corresponding parameter changes into the model (Table 3). The output was compared with the baseline scenario to assess the effectiveness of these measures on reducing sediment export to reservoirs. Figure 5 shows the mean annual erosion reductions that were simulated in each HRU for the studied

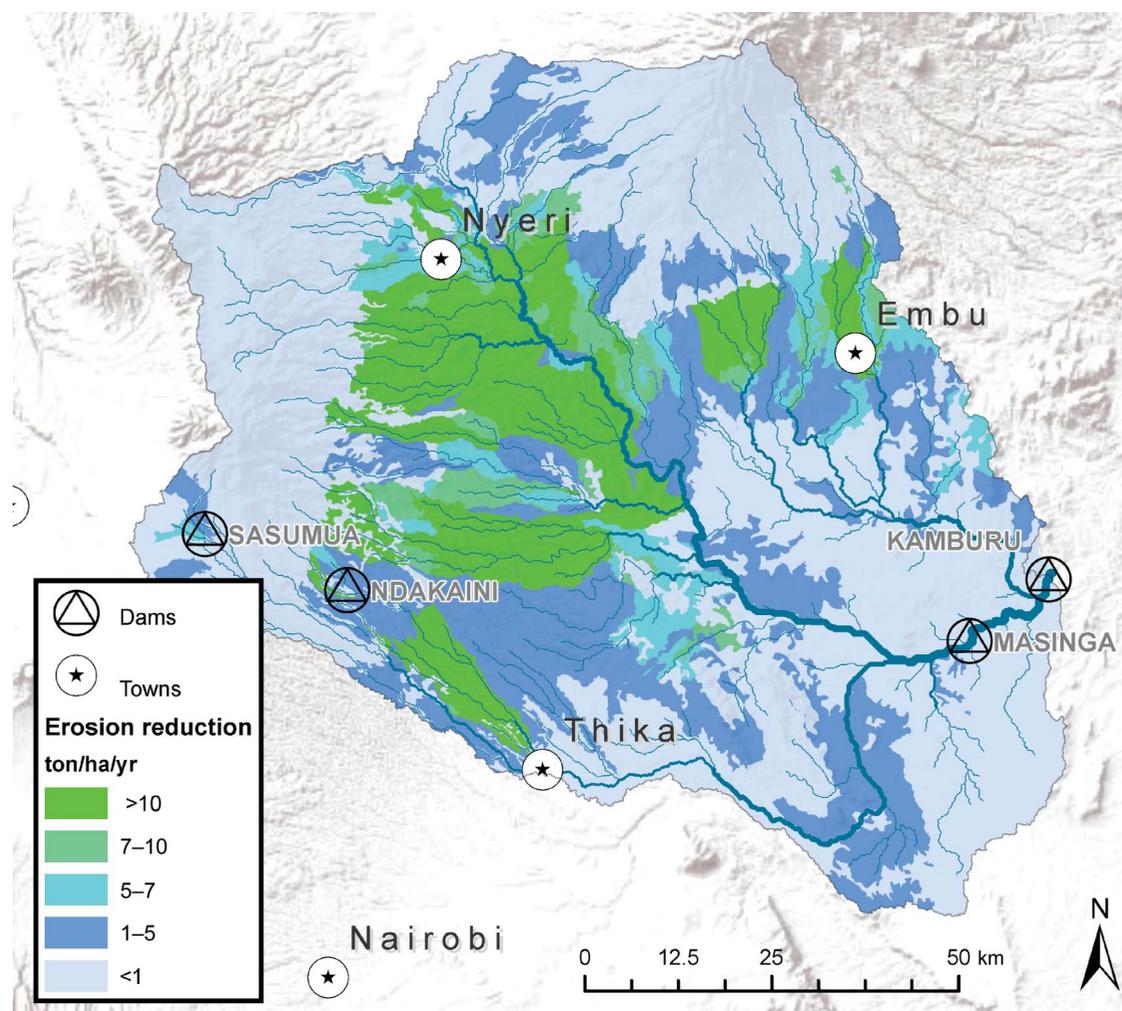


Fig. 5 Potential reduction in erosion rate if the studied measures were applied throughout the entire catchment.

scenario. The simulations show that if these measures were implemented in all the areas where coffee, maize and tea are cultivated, the total sediment inflow into the two main downstream reservoirs could potentially be reduced by 47%. The main reductions in erosion were predicted for those cultivated areas with the steepest slopes combined with the highest rainfall amounts, such as the eastern slopes of Mount Kenya and Aberdares.

The spatial output on the potential to reduce erosion with the studied measures was used to identify areas in which most benefit can be expected from implementation of conservation measures. The following step in the analysis was to study different adoption scenarios. These adoption scenarios were based on the existence of local farmers' associations, the Water Resources User Associations (WRUA). In this particular basin, the WRUA is the only type of farmers' organization. Nowadays, 25 WRUAs are operational in the Upper Tana basin and they cover

around 50% of the total cultivated area. In the rest of the basin, no such association has been defined yet and the mainly smallholders operating there work more or less autonomously. Supported by the national water act, these WRUAs have an overall coordinating role in the development of sub-catchment water management plans that include catchment protection, soil and water conservation. Several of the WRUAs have coordinated (financial, dissemination, monitoring) the implementation of previous projects involving catchment protection measures. For this reason, the regional authority appointed the currently existing associations to implement and coordinate future interventions to reduce erosion and reservoir sedimentation.

The WRUAs can be prioritized based on the potential that exists within their management area to reduce erosion and sediment yield. This targeting procedure was required by the local authority in order to address the funds and efforts precisely to the areas

where the highest benefits can be expected. To this aim, the potential reductions of all the HRUs belonging to the territory of each WRUA were averaged. Based on this aggregation, an assessment was made of the potential effect of implementing conservation measures in each WRUA; all WRUAs were classified and given a priority level according to their potential impact on reducing erosion. These priority levels were assigned according to the following scheme, similar to the legend classification in Fig. 5:

- Priority I: reductions in erosion rate of more than $10 \text{ t ha}^{-1} \text{ year}^{-1}$
- Priority II: reductions in erosion rate of $7\text{--}10 \text{ t ha}^{-1} \text{ year}^{-1}$
- Priority III: reductions in erosion rate of $5\text{--}7 \text{ t ha}^{-1} \text{ year}^{-1}$

Consequently, to obtain insight to the relation between the level of implementation and its impact on the reduction in reservoir sedimentation, three adoption scenarios were simulated. These adoption scenarios were based on the priority levels assigned, as shown in Table 4. The model predicts that sediment inflow to the reservoirs can be reduced in total by around 7% when the measures are implemented only in WRUAs with Priority I (Table 5), which cover around 8% of the total cultivated area. If the WRUAs with the assigned priority level II are added to the analysis (implementation area covers 20% of cultivated area) a total sediment yield reduction of 13% is predicted. Further reductions can be achieved when Priority III

Table 4 The adoption levels, the corresponding priority levels, the implementation area compared to the total cultivated area, and the number of WRUAs involved.

Adoption level	Priority level	% of cultivated area	Number of WRUAs
1	I	8	5
2	I and II	20	11
3	I, II and III	35	15

Table 5 The erosion rate reduction for the key crops and the sediment reduction for the entire basin and the downstream reservoirs for each of the adoption levels studied (% in parentheses is change relative to baseline).

	Erosion rate ($\text{t ha}^{-1} \text{ year}^{-1}$)			Sediment yields (Mt year^{-1})		
	Coffee	Maize	Tea	Basin	Masinga	Kamburu
Baseline	27	18	14	10.1	6.3	0.93
Adoption level 1	25 (−8%)	17 (−5%)	13 (−5%)	9.5 (−6%)	5.8 (−8%)	0.89 (−5%)
Adoption level 2	23 (−17%)	16 (−7%)	13 (−6%)	9.1 (−10%)	5.6 (−11%)	0.71 (−24%)
Adoption level 3	22 (−19%)	16 (−10%)	12 (−12%)	8.8 (−13%)	5.3 (−16%)	0.68 (−27%)

areas are included, reducing sediment input into the Masinga Reservoir by about 16%, while sediment inflow to the Kamburu Reservoir can potentially be reduced by 27% (total reduction 17%).

DISCUSSION

The principal objective of this research was to identify priority intervention areas where erosion control measures are likely to generate the highest reductions in downstream sediment inflow into reservoirs. This requires an appropriate distributed approach and suitable data to calibrate and validate the model. The baseline scenario of this study was the 30-year period used for calibration. It is obvious that land use in this catchment has changed considerably during this period. However, no reliable data could be obtained to quantify and locate changes. These non-stationary conditions are likely to affect the outcome of the calibration and validation of the model. For this reason, a multi-site and a multi-variable (discharge and erosion) validation approach was used, instead of the split-sample test, which is another common way of validating watershed models (Refsgaard 1997). The erosion model was calibrated and validated based on three data sources, each with different spatial and temporal resolution: (a) streamflow data from daily measurements over 30 years at 10 points throughout the catchment; (b) long-term sediment inflows into the main reservoirs derived from the bathymetric surveys; and (c) bi-monthly sampling of sediment concentration at 12 points during one year. Given the fair agreement between observed and simulated streamflow, and between the observed and simulated sediment yields, the model was assumed to be fit for further scenario analysis. Also, the fact that uncertainty related to the predicted relative changes of scenario outcomes can be assumed to be considerably smaller than the prediction uncertainty of absolute model outcomes was taken into consideration (Arabi *et al.* 2007, Droogers *et al.* 2008).

The data on discharge and erosion gathered and measured for this study form a unique data set for a reservoir sedimentation modelling study in a large African catchment. However, not enough data have become available to establish reliable relationships between discharge and sediment, due to the extremely nonlinear nature of the sediment discharge–stream discharge relationship. Dunne (1979) showed that for Kenyan basins the highest 10% of flows carry an average of 80% of the mean annual yield and the highest 1% carries an average of 41% of the yield. This implies that it is much more essential to predict accurately the relationship for high discharges than for low ones. During this one-year measurement campaign, no peak flood events were captured so no information was obtained on sediment loads during the periods when the sediment yield is most significant. Calibration of the model based on the fixed-interval sampling scheme was not useful for this reason, as the measurements did not include enough information to build reliable sediment rating curves to compare measurements with simulated peak sediment discharges. Similar to the proposals of Dickinson (1981) and Walling *et al.* (1992), for this catchment it is recommended to design a sampling scheme with a higher frequency, even with within-day intervals. Nevertheless, the sediment load measurements obtained during one single year could be used to validate the spatial variability in sediment yields predicted by the model, by comparing the mean annual simulated loads with the measured ones.

The principal uncertainties in the estimation of the sediment yields in this study are related to the importance of roads, trails and settlements, being potential sediment sources that are not included in the SWAT model, but have been estimated by other studies as mentioned above. Based on the ranges found in the literature for similar basins, a realistic value of 20% was taken for this study. Another sediment source that was neglected in this assessment is bed load. Few studies of bed load transport have been undertaken for African rivers, but some suggest that it may account for approximately 10% of the total load (e.g. Walling 1984).

CONCLUSION

To adequately and effectively target and implement erosion control measures to reduce reservoir sedimentation, distributed erosion modelling can be used to support the decision making. However, the

availability of sufficient data to calibrate and validate streamflow and sediment dynamics is crucial for successful application of such models. The study conducted in the Upper Tana basin, Kenya, included bathymetric surveys of the main reservoirs and point measurements of suspended sediment loads, while a large data set of historic streamflow measurements was also available. Calibration and validation results for SWAT showed that these multiple sources of data provided relatively good results allowing its use for scenario analysis.

Evaluation of the impacts of scenarios with implementation of erosion control measures is essential as successful implementation in Africa has often been poor. It is a cost-effective way to provide decision makers and other stakeholders with comprehensive information on the effectiveness of certain measures before implementation, potentially leading to higher success rates and social acceptance. The applied methodology allows the identification of priority sites based on the predicted effectiveness of the measures. Successful implementation also requires institutional support to coordinate the correct implementation and maintenance of measures. Therefore, as an additional selection criteria the existence of local institutional arrangements in the form of WRUAs was used. Based on these two criteria, quantitative insight was provided in priority areas of implementation and as to how the scale of implementation influences the reduction of sediment yield.

With the methodology applied it was shown that erosion rates are highest in the coffee zones and areas where maize and other cereals are cultivated on steep slopes. Based on the scenario analysis, erosion control priority levels were given to the areas that correspond to the currently existing WRUAs in the basin. The analysis showed that if WRUAs could be successfully involved in the implementation and maintenance of the erosion control measures, the sediment yield to reservoirs could be reduced significantly by up to around 25%, depending on the level of adoption. Consequently, the reservoir life expectancy would increase by the same amount.

The presented methodology and results indicate that distributed erosion and sediment yield modelling with SWAT, supported by sufficient data on discharge and sediment yields of different points in time and space, can provide quantitative insight to the effectiveness of erosion control measures and its downstream impact on reservoir sedimentation and other off-site effects. The distributed approach also allows taking into account of certain factors that may

be crucial for the successful implementation, and areas can be prioritized based on simulated adoption scenarios.

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