



Mitigating Economic Damage in Kenya's Upper Tana River Basin: An Application of Arc-View SWAT

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ABSTRACT

The Upper Tana River Basin is one of Kenya's most important natural resource bases. Its Masinga Reservoir supplies water and hydroelectric power for 65 percent of the nation. Unregulated deforestation and expansion of cultivation practices onto marginal soils has resulted in significant reservoir siltation, reduced ecosystem function, and more erratic downstream flows. An appraisal conducted for this study identified potential areas where reforestation could occur, enabling a doubling of the reforested areas currently in the Upper Tana River catchments. The Soil and Water Assessment Tool (SWAT) model was used to evaluate alternative reforestation scenarios. An economic model was developed to determine the opportunity costs associated with reforestation and the economic incentives, i.e. green payments, which would be required to induce upper catchment users to reforest. The analysis found that reforestation would decrease sediment loading in the Masinga Reservoir by 7 percent. Users in the upper catchment would be paid \$33 for each ton of sediment they retained in their fields, but benefits were found to be insufficient for downstream users to sponsor green payments. Under an alternative price structure that targeted green payments to specific upstream producer groups the downstream benefits would increase, providing adequate incentives to implement green payments. The findings of this research can assist environmental policy implementation by the Kenyan government that will foster improved environmental results.

Key Words: reforestation, Kenya, Tana River, SWAT, erosion, runoff, green payments.

INTRODUCTION

Over the last 100 years Kenya's forests have dwindled significantly: only 1.7 percent of Kenya's forests remain standing (UNEP, 2001). The rapid deforestation has been fueled by the increased demand for forest products (i.e. charcoal) and cultivated land and enabled by weak land tenure policies that failed to prevent the logging of indigenous species (Lambrechts et al., 2003; Tiffen et al., 1994). Deforestation provides benefits to those doing the cutting but also creates environmental damage that affects broader segments of society. Forests supply both ecologic and hydrologic services to its users: biodiversity, wildlife habitats, carbon sequestration, and water catchments. In particular, forests are critical components of catchments. Forests serve to maintain the hydrologic conditions required to generate hydroelectric power, irrigate crops, and supply water for industrial and household use.

Kenya has five major water catchment catchments that are located near Mount Kenya, Mount Elgon, the Aberdare Range, the Mau Complex, and the Cherangani Hills. These catchments are described as the five "water towers" that provide the majority of the Kenya's water (Gathaara, 1999). The Tana River and its tributaries form the major water flow outlet from two of the five "water towers", Mount Kenya and the Aberdare Range. The Tana River is the largest river in Kenya and its catchment area occupies approximately 17% of the country (Pacini et al., 1998).

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The Upper Tana River Basin and the Masinga Reservoir are extremely important components of the Tana River System. The Masinga Dam has been identified as the most effective regulator of the Tana River system because of its great size and its strategic location in the upper reaches of the system (Pacini et al., 1998). The Masinga Dam serves as a storage reservoir, controlling hydrology through a series of downstream hydro-electric reservoirs. Electricity is generated by the reservoirs but at a lower capacity than the electricity generated by other reservoirs in Kenya. The Masinga reservoir has a high trap efficiency that ranges between 75 and 98 percent, which results in an average loss of 23 million m³ of water per year (Schneider, 2000). Based on these estimates, the complete siltation of the Masinga reservoir will occur within 65 years unless some type of intervention is undertaken (Watermeyer et al., 1976). This would drastically reduce the Masinga dam's life span, which was estimated to reach upwards of 500 years prior to its construction.

A critical need is to reverse these trends by identifying strategies that can reduce the higher than expected levels of sedimentation and runoff into the Masinga reservoir. Contemporary catchment planning seeks innovative ways to alter production practices and producer behavior to mitigate environmental damage (Kerr 2002). An emerging trend is the use of green payments. These are cash transfers made to producers in the upper reaches of the catchment in exchange for providing environmental services: shifts in land use and agricultural practices that reduce sedimentation and runoff to the lower catchment areas.

This paper assesses the effectiveness of alternative land use interventions in the Upper Tana River catchment. A hydrologic model of the Tana River basin catchment was constructed to predict impacts of land use on the Masinga Reservoir. The focus of the land use interventions is on reforestation of the upper reaches of the catchment. This provides improved catchment hydrology and water quality by reducing sediment and runoff into the lower portions of the Tana River basin. An economic model was developed and integrated with the hydrologic model. The economic model was used to analyze the economic benefits and associated costs with establishing a green payment program in the Tana River basin.

STUDY AREA

The study area is the Upper Tana River basin, a catchment area northeast of Nairobi that encompasses the cities of Embu and Nyeri. This catchment area is the headwaters of the Tana River, which runs approximately 1,000 km to the eastern coast of Kenya and empties into the Indian Ocean (Figure 1). The entire Tana River catchment area covers approximately 100,000 km². The study includes about 10,000 km² of this area. The Tana River is an important source of water and hydroelectric power to the surrounding region. Most of the highland forests of the Tana system occur in the upper Tana catchment above the Masinga Dam (Schneider and Brown 1998). Below the dam the Tana River flows through semi-arid rangeland vegetation and is bordered by lush riverine forests dominated by *Acacia* spp. which have declined over 27% since 1989 (Maingi and Marsh 2001).

The elevation of the study area ranges from a high of 4,700 m on Mt. Kenya to a low of 730 m near the Masinga Dam. Soils, rainfall, and land use follow this general elevation gradient. The soils in the area consist of Andosols (M2) in the upper elevations, Nitosols (R1, R2, and R3) in the mid-elevations, and both Ferallsols (Um19) and Vertisols (L11, Up4) in the lower elevations of the catchment. Mt. Kenya and the Aberdare Ranges receive more than 1,800 mm of rainfall per year. Forests and tea crops are

predominately found in this area. The mid-elevations, between 1,200 and 1,800 m, receive between 1,000 and 1,800 mm of rainfall. This area supports most of the intensive agriculture. Crops include coffee, maize, bananas, napier grass, and beans. The lower elevations, below 1,000 m, receive less than 700 mm/yr rainfall. This area consists mainly of rangelands which are used for livestock grazing (Otieno and Maingi, 2000).

At all elevations there is a distinct seasonal variation in river flow. There are two wet periods throughout the year, with each lasting three months. Most of the rain falls from March through May in the first wet period; the second wet period from September through November has less rainfall. Between the two wet periods rainfall is very light placing a high demand for supplemental water. Irrigation, urban consumption, and hydroelectric power all place demands on the Tana River basin to supply water during the dry periods. The Masinga Dam was constructed to address this need for a consistent water supply to the area. This dam is situated at the outlet of the study area catchment. It regulates the flow of water to a chain of downstream reservoirs (Kamburu, Gitaru, Kindaruma and Kiambere) and serves as a water supply to the surrounding area (Watermeyer et al., 1976).

CATCHMENT MODEL

The Soil and Water Assessment Tool (SWAT) model was used to simulate the environmental implications of reforestation in the higher elevations of the Upper Tana River Basin. SWAT is a basin-scale, distributed parameter model which operates on a daily time-step (Neitsch et al., 2001a). The primary use of the SWAT model is to predict the impact of management practices on water, sediment, and agricultural chemical yields in large river basins over long periods of time. SWAT is physically based: this requires less up-front calibration and enables SWAT to analyze catchments where extensive stream gauge data is not available. In addition, the model uses readily available inputs, is continuous in time and capable of simulating water quantity and quality over long periods, and includes an extensive phenological crop growth model.

The SWAT model has been applied in a number of studies in the U.S. involving the assessment of water supply and non-point source pollution. Arnold et al. (1999) reported the results of SWAT applications for hydrologic simulation of every river basin in the U.S. Several other studies (Rosenthal et al., 1995; Bingner, 1996; Bingner et al., 1996; Srinivasan et al., 1998; King et al., 1999) provide empirical support for SWAT's capability in simulating streamflow and sediment movement in large basins. SWAT was previously used in Kenya to assess the hydrology in the Sondu River catchment as part of technology impact assessment studies (Jayakrishnan et al., 2000).

The SWAT model has been integrated with a Geographic Information System (GIS) interface. This SWAT-GIS interface allows the model to preserve the spatial nature of topographic, soils, and landuse databases, thereby preserving the distributed nature of model parameters and improving the model's effectiveness. The ArcView interface for SWAT (Di Luzio et al., 2002) was used for preprocessing and hydrologic simulations in this study.

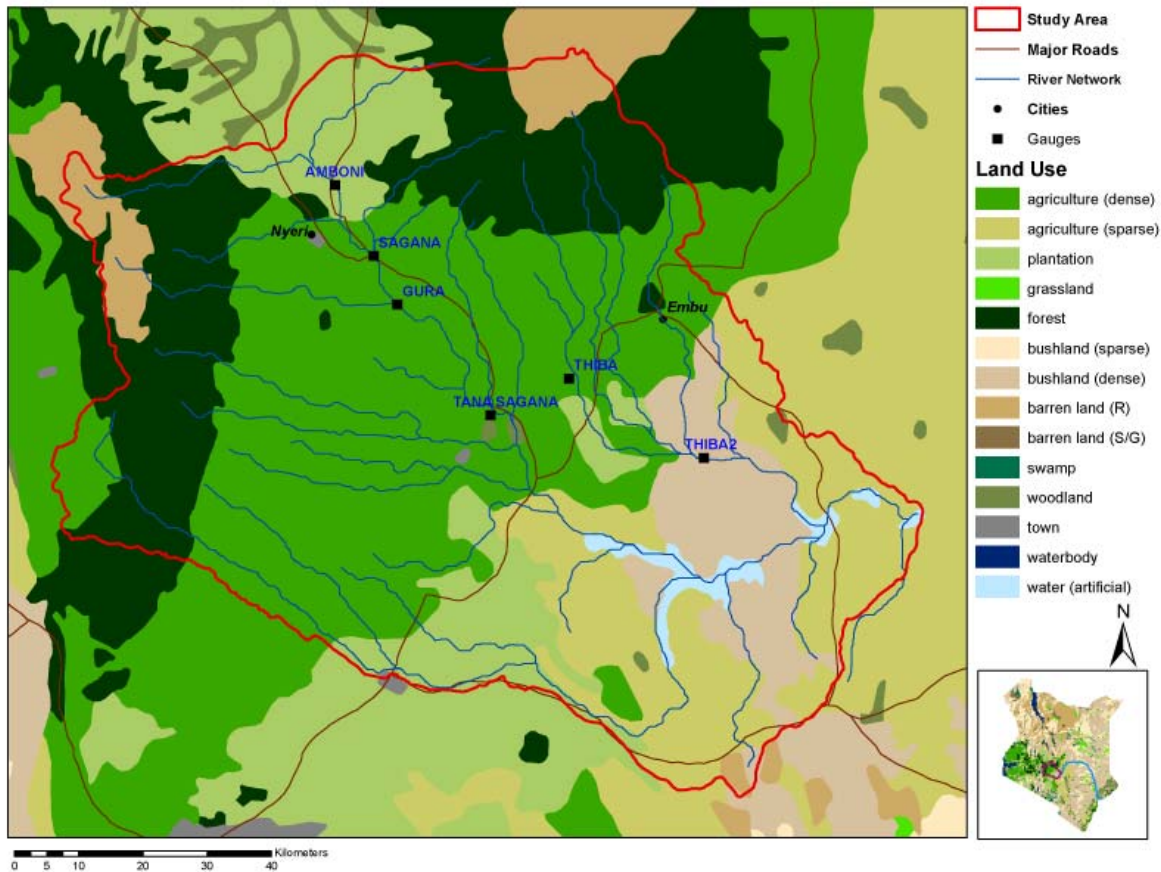


Figure 1. Location of the study area and general land use classes (JICA 1987) in Kenya's Tana River catchment.

Catchment Characterization

The Upper Tana River basin catchment was characterized using the ArcView-SWAT interface's preprocessing toolkit. The toolkit includes ArcView routines that intersect geo-referenced data layers on land use, climate, geography, soils, and farm management practices. Data used in this study was obtained from a wide variety of sources, including government agencies, non-governmental organizations (NGOs), and other world organizations, and required extensive reorganization to be useful for hydrologic and economic models.

Climate data was obtained from three sources. First, historical precipitation and air temperature data were collected from two World Meteorological Organization (WMO) stations within the study area. These were the Nyeri and Embu stations, which had data available for the period from 1978 to 1997. Additional rainfall data was obtained for the northern portions of the study area from the Natural Resources Management Trust, Nanyuki, Kenya. This historical data was collected from towns, farms, and plantations in the Laikipia region of Kenya. Finally, in the southern portion of the study area, rainfall data was obtained from the Collaborative Historical African Rainfall Model (CHARM) dataset (Funk et al., 2003). This dataset provided spatially and temporally explicit daily rainfall amounts on an 11 km x 11km

resolution and was derived from combined daily rainfall reanalysis fields, monthly interpolated rainfall, and an orographic precipitation model (Funk et al., 2003).

CHARM represents "smoothed" 10-day accumulated historical rainfall data. For the purposes of this study, however, it was "event corrected" using the WMO data. This enables the rainfall data to behave in a more hydrologically correct manner. Event correction entailed disaggregating the 10-day rainfall to daily events the proportional pattern of corresponding precipitation events measured at the nearest WMO station. For example, if the 10 day rainfall for a grid cell in CHARM was 25 mm during the first dekad in January and the nearest WMO weather station reported rainfall of 5mm on January 2, 10 mm on January 5, and 5 mm on January 7, then the event correction factor would be determined by dividing the daily rainfall from the WMO station by the 10 day sum for that period. The event correction factor for each day is then multiplied by the 10-day CHARM value to establish the event correction rainfall value. In the example above, the event corrected rainfall for January 2 would be 6.25 mm ($[5 \text{ mm} / 20 \text{ mm}] \times 25 \text{ mm}$). Data for the period from 1978 to 1997 was extracted from the Laikipia and CHARM datasets to match the WMO data period.

The main source of land use/land cover data for this study was obtained from the Kenya Department of Resource Surveys and Remote Sensing (DRSRS) survey of medium and high potential agricultural areas (Njuguna 2001). This survey resulted in a 2,400 x 4,800 m irregular grid of land use/land cover designations represented by centroid points. A total of 97 unique land use/land cover types were established in the survey. The data was converted to grid form and dominant land use types were assigned to each grid cell for the model simulations. Dominant land use was defined as land that accounted for greater than 90% of the total land use for a given grid cell. Up to three additional land uses were defined for a single grid cell, resulting in approximately 1,100 unique land use combinations. For regions in the study area omitted from the DRSRS survey, mainly forestlands in the northern portions and low potential agricultural areas (rangelands) in the southern portions of the study area, a coarser scale land use map was used (JICA, 1987). The two datasets were again merged to create a seamless land use/land cover map for use in model simulations.

Soil units for the study area were defined by the Kenya 1:1 million scale. Soil and Terrain (KENSOTER) database developed by the Kenya Soil Survey (KSS) and the International Soils Reference and Information Centre (ISRIC). KENSOTER soil units may represent a single soil series or an association of several soils. For this analysis the dominant soil type was identified for each soil unit polygon within the KENSOTER database to be used in model applications. Soil parameter estimators in the EPIC crop model (Sharpley and Williams 1990) and the Soil Water Characteristics calculator were used to estimate missing soil parameters such as saturated hydraulic conductivity and water holding capacity (Saxton et al., 1986).

Geography in the Upper Tana River basin was characterized using a 100 meter Digital Elevation Model (DEM). This 100 meter DEM was obtained by resampling the Shuttle Radar Topography Mission (SRTM) DEM data. The DEM was used to develop the reforestation scenarios at various elevations within the study area.

SWAT Model Setup

The study area was represented by 60 subbasins (Figure 2) delineated using the catchment delineation tool in the ArcView-SWAT model interface and consisted of a 9,752.82 km² area. The time period from

1978 to 1995 was used for model simulation. However, the first three years of the simulation were used as a “warm-up” period in which the model’s initial conditions were established. These years were therefore not included in the final result comparisons. The results reported in this study for various simulations consist of data for the time period from 1981 to 1995. In addition, no model calibration was attempted except for adjustments in the baseflow recession constant. To derive this constraint a baseflow filter program (Arnold et al., 1995; Arnold and Allen, 1999) was used to separate the baseflow and runoff portions of total streamflow. In addition, the baseflow alpha factor (baseflow days) was calculated for the four gauging stations along the main channel of the catchment, the Sagana River. The recession constant is an index of groundwater flow response to changes in recharge and varies between 0-0.3 for slow response and 0.9-1.0 for rapid response (Neitsch et al., 2001b).

Scenarios

This study consisted of a two-phase approach. In phase one, the model was developed to represent existing conditions. Detailed information concerning runoff and sediment transport was collected from this run. In phase two, the model was configured to reflect management scenarios, namely zonal reforestation in the upper reaches of the catchment, in order to determine the change in runoff and sediment transport caused by management practices.

Four scenario analyses were conducted. Current land cover maps show forest land located above the 2,000 m elevation contour; therefore, a graded reforestation scenario was implemented at the 2,000, 1,950, 1,900, and 1,850 m intervals. In each of these cases the entire area above a given elevation contour was filled with forest land cover. No additional changes were made to land cover or other baseline conditions. Each successive land use grid was then used in a new SWAT simulation for the time period from 1981 to 1995.

ECONOMIC MODEL

The capacity of the catchment to deliver environmental services and supply its resources depends on the economic (i.e. anthropogenic) activity of its user base (Kerr, 2002). In particular deforestation and other land use changes can significantly alter the catchment’s landscape and its hydrologic properties. A key aspect of catchment management is the recognition that the economic activity of one user group can affect users in other parts of the catchment (Ciriacy-Wantrup, 1959). Thus geography and location play a critical role in how the resources and environmental services are supplied to user groups. Typically it’s the upstream users that impact the downstream users, and most often in a negative manner. This reduces the catchment’s capacity to provide its services to downstream users. Conflict often ensues between the upper and lower portions of the catchment (Echevarría, 2002).

An economic model of the Upper Tana River basin was constructed to predict the economic benefits generated by reforestation (Farrington et al., 1999). Because reforestation requires upper catchment producers to change their land use, economic incentives are required to redirect decision making towards more environmentally prudent production practices (Johnson et al., 2002). The purpose of the economic analysis is to estimate the economic gains that can be achieved from resolving the conflict between the upstream and downstream users in the Tana River basin (Coase, 1960). The analysis focuses on the role of green payments in providing economic incentives for upstream users to adopt more environmentally friendly practices that reduce downstream damage. Primarily this involves reforestation, and requires that producers shift away from standing crop production.

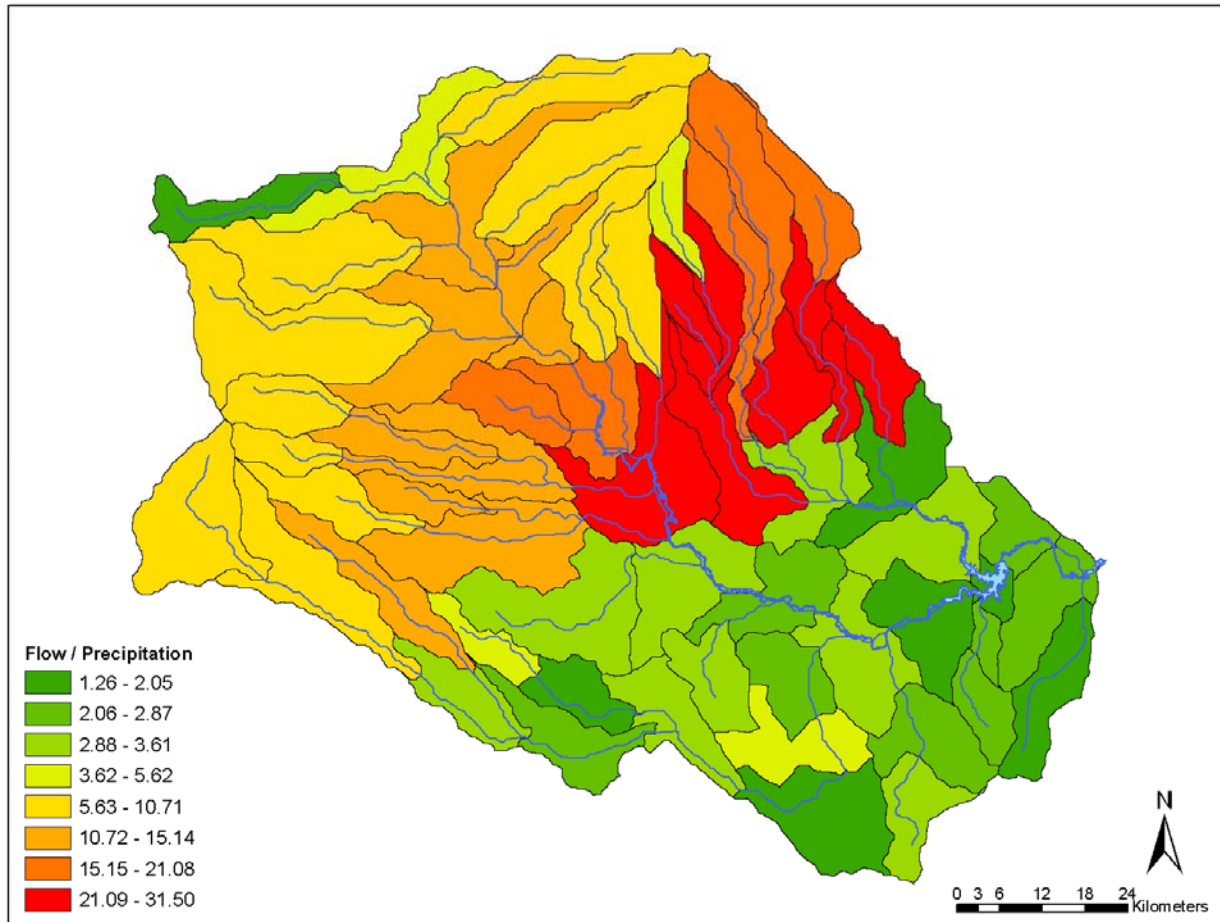


Figure 2. Subbasin Delineation of the Tana River Basin and the Average annual percentage of predicted runoff from rainfall.

In free markets upper catchment users are not held accountable for the damage they inflict on downstream users (Coase, 1960). This can lead to an inefficient allocation of resources and environmental services within the catchment's economy as illustrated in Figure 3 (Hardin, 1968). The inefficiencies are called negative externalities, which occur since producers in the upstream catchment do not have to pay for the damage they inflict downstream. The net effect of a negative externality is that from society's perspective firms will produce too much output because they do not include the damage they create in their decision making (Pigou, 1920). Firms produce up to the point where their marginal cost of production equals market demand, which occurs at price P_1 and quantity Q_1 . The total damage that the upstream users create is measured by the area D, which is called a dead weight loss, since no groups in society capture this quantity of wealth. The goal of watershed management is to find ways to reallocate production in the upstream areas so that part or all of the dead weight loss, D, can be regained by the watershed economy (Baumol and Oates, 1988).

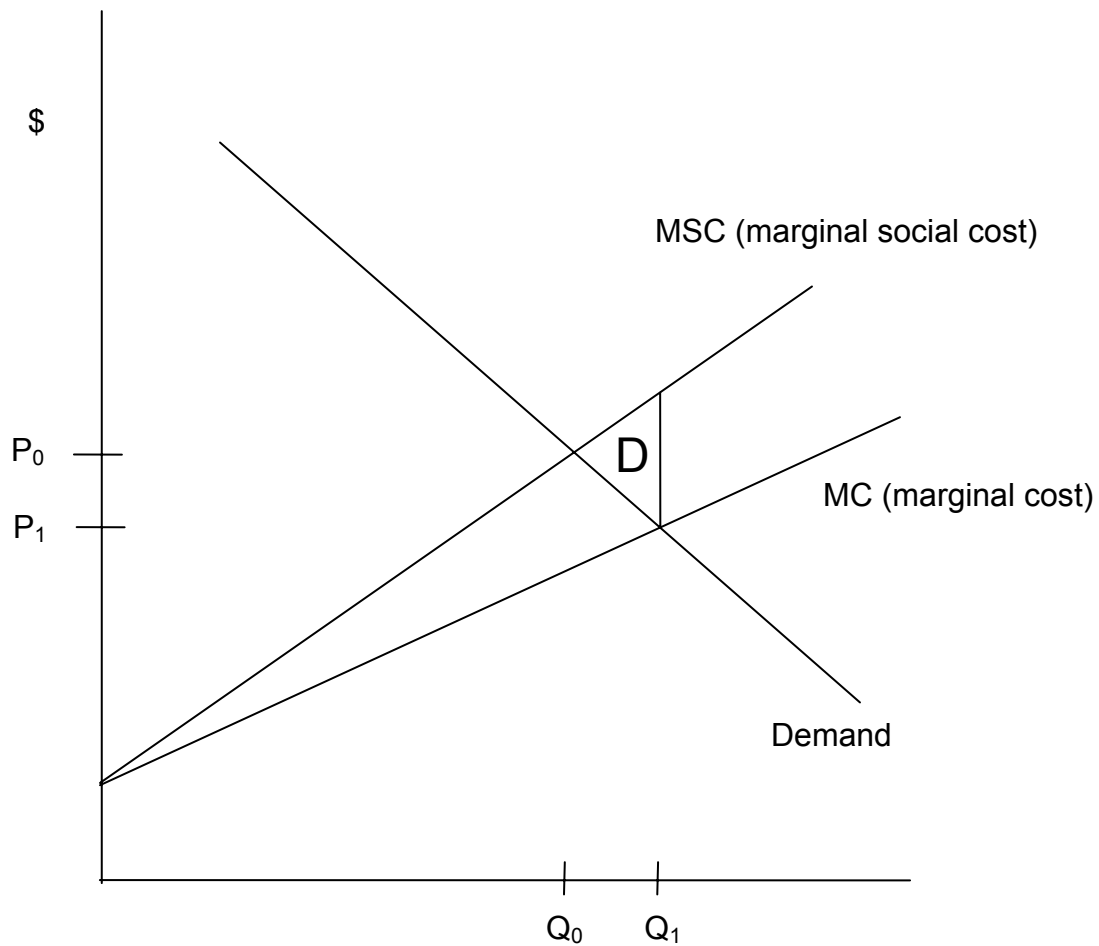


Figure 3. Negative externality imposed by upper catchment users on lower catchment users.

GREEN PAYMENTS

Contemporary catchment planning employs innovative approaches to resolve negative externalities (Johnson et al., 2002; Plantinga and Wu, 2003). The focus is placed more on using the market to get rid of its own “failures” rather than relying on more traditional approaches such as Pigouvian taxes (Pigou, 1920). Market-based price structures, called green payments, are implemented within the catchment to eliminate part, or all, of the efficiency loss (Pagiola, 2002). Pricing mechanisms are used to induce upstream users to internalize the damage they create for other users, as captured by the social cost curve in Figure 4 (Tam, 2002). Instead of taxing upstream users and making them pay directly for the damage, property rights are assigned such that downstream users make payments to upstream users. These payments are called green payments because they are made to upper catchment users in exchange for providing environmental services to the downstream catchment users (Landell-Mills, 2002). The demand for environmental services is determined by the benefits that can be generated from mitigating upstream damage (Rodriguez and Southgate, 2003). In this study the upstream damage is mitigated by reforestation, which reduces runoff and sediment loading to the lower reaches of the catchment¹ (Figure 4). Downstream users identify producers in the upper catchment that are willing to

¹ The economic benefits from reduced sediment loadings include: reduced dredging costs in dams, cleaner drinking water and lower water treatment costs, increased hydroelectric power generation, and reduced flooding incidence.

accept green payments in exchange for providing environmental services (Subak, 2000). Provided that the benefits from the environmental services exceed the green payment costs then it will make economic sense for downstream users to sponsor a green payment program.

Upstream producers that supply environmental services will lose their farm income since they agree to shift their land out of agricultural uses (Pagiola and Platais, 2002). The upward sloping curve in Figure 4 represents the aggregate economic loss that is incurred by upstream users. Upstream producers will only supply environmental services provided that the green payment adequately compensates them for their losses. The green payment is given by the equilibrium point where the demand for mitigating the externality is balanced by the cost of supply the environmental service (Klauer, 2000). As illustrated in Figure 4, demand and supply are balanced at the price P_E , which is the price that the green payment program would need to pay producers in the upper catchment for each unit of sediment reduced. Because producers are paid the price P_1 their cost of supplying the environmental service is always compensated by the green payment. Likewise although downstream users are paying the price P_1 to the upstream users causing the damage, the downstream users still gain; the downstream benefits are always greater than the price P_E that they pay to reduce the sediment (Figure 4). Green payments maximize the economic gains to society and the catchment is able to regain all of the deadweight loss, D.

Targeted Green Payments

An alternative pricing mechanism is to charge the upstream user groups with targeted green payments (Limburg et al., 20002). If only a single price is established for green payments, such as P_E , then the upstream users would receive windfall benefits for participating in the program. The total windfall benefit would be the area B (Figure 4). Targeted green payments pay upstream users only for the actually economic loss that they incur (Hannon, 2001). Hence targeted green payments would give each producer a unique price that reflects their own loss incurred from the supplying environmental services. The price would be the corresponding point on the upward sloping supply curve (Figure 4). By doing this the benefits are shifted to the downstream users, the group that is sponsoring the payments.

The practical significance of targeted green payments is that the total cost of a green payment program would be reduced (Chomitz, 1998). The cost of the green payment program under an average (uniform) price would be $P_E S_E$. This type of green payment program would provide benefits given by the area A illustrated in Figure 4. So under uniform prices benefits are given by:

$$\text{Benefits}_{\text{Uniform Price}} = A \quad (1)$$

Under targeted pricing, however, the program cost is reduced by the area B (Figure 4), which is the amount regained by downstream users from targeted green payment prices. The resulting program cost is $P_1 S_E - B$, which widens the conditions under which green payments would be economically lucrative for the downstream users of the Masinga Dam. Hence under targeted prices the benefits would be given by the sum of the areas A and B illustrated in Figure 4. Targeted payments require a lower cost hurdle for the benefits to satisfy, as given by:

The demand for sediment reduction falls as the quantity of sediment is reduced, with the largest willingness-to-pay occurring over the initial range of sediment reduction as illustrated in Figure 4.

$$\text{Benefits}_{\text{TargetedPrices}} = A + B \quad (2)$$

Establishing targeted payments requires apportioning the economic damage to the sub-regional scale. In this study the water runoff and sedimentation from each subbasin was found to be channeled independent of the other subbasins. Through successive replacement the contribution of each subbasin was identified. This enable the analysis to apportion economic damage back to each of the subbasins included in the Tana River basin's catchment.

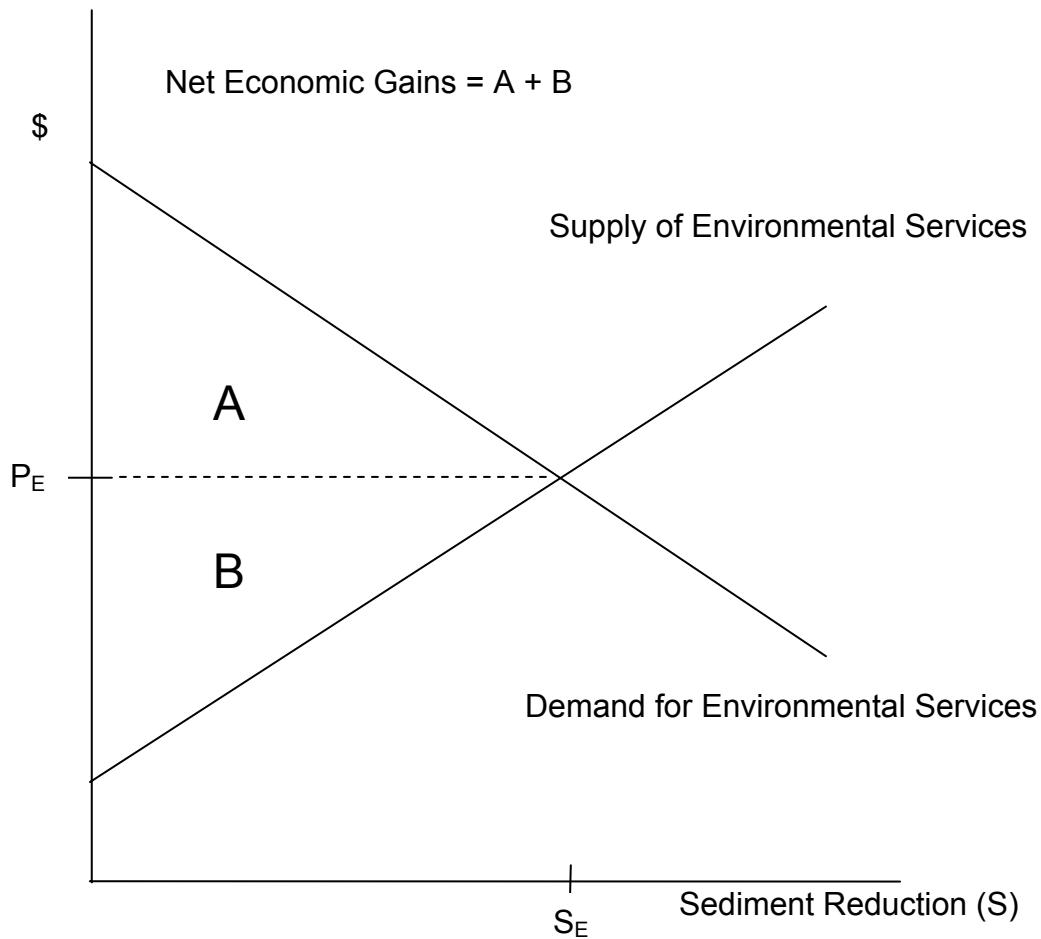


Figure 4. Net economic gains to society from upstream sediment reduction.

ECONOMIC MODEL OF THE CATCHMENT

An economic model of the Tana River basin catchment was developed in this study to determine the economic benefits from reforestation. Math programming was used to maximize the net benefits to the catchment through the change in social welfare (Babcock et al., 1997). This is the area labeled A+B in Figure 4, which is the difference the lower catchment benefits and the opportunity costs incurred by the upper catchment from adopting green payments. The economic model is spatially explicit: reforestation

decisions (green payments) are made at the subbasin level to better target and connect downstream damage to the upstream users that caused it (Horan et al., 1999).

The economic model's objective function maximizes the benefits (social welfare) across the catchment, for both the upstream and downstream users (Avila-Foucat et al., 2004). The objective function is given by:

$$\text{Max } SW = \int_0^{Q_1} (WTP^{-1}(S) - WTA^{-1}(S))dS \quad (3)$$

where SW is the social welfare, $WTP^{-1}(S)$ is the inverse downstream demand for reducing sediment runoff given in terms of maximum willingness-to-pay, S, and $WTA(S)$ is the upstream supply of environmental services from enrolling in the green payment program given in terms of minimum willingness-to-accept. The objective function social welfare is maximized by integrating the area between the inverse downstream demand and the upstream opportunity cost.

The demand for reducing sediment runoff, $S(WTP)$, is derived from the economic losses incurred by downstream users (Antle and Stoorvogel, 2006). Equivalent variation (EV) is used to determine their willingness to pay (WTP) for reducing damage from upstream users under a green payment scheme (Varian, 2002). This is a technique that expresses downstream users' maximum WTP to reduce sediment runoff by equating their utility with and without the green payments. Using indirect utility, which defines utility in terms of income, the maximum WTP for green payments, δ_E , is obtained by solving the following equation:

$$U_0(\Pi(S_1 + \Delta S) - \delta_E \Delta S) = U_1(\Pi(S_1)) \quad (4)$$

where U_0 and U_1 are the indirect utility levels with and without green payments, S_1 is the sediment runoff corresponding to free market conditions, ΔS is the change in sediment runoff from the adoption of upstream BMP, Π are the user groups profit, and δ_E is the maximum WTP for sponsoring green payments.

The supply of environmental services from upstream users is determined in an analogous manner to Equation 4 (Pattanayak and Kramer, 2001). Equivalent variation expresses upstream users' minimum willingness to accept (WTA) green payments from downstream users by equating their utility with and without the adoption of the program's BMP (Varian, 2002). Using indirect utility, which defines utility in terms of income, the minimum WTA for green payments, λ_E , is obtained by solving the following equation:

$$V_0(\Pi(Q_0) + \lambda_E \Delta S) = V_1(\Pi(Q_1)) \quad (5)$$

where V_0 and V_1 are the indirect utility levels with and without green payments for upstream users, Q_0 is the quantity produced under green payments, Q_1 is the quantity produced under free market conditions, ΔS is the change in sediment runoff from the adoption of upstream BMP, Π is the user groups profit, and λ_E is the minimum WTA green payments.

Farm programming models are used to develop profit functions for representative agricultural users in the upstream portion of the Tana River basin (Hazell and Norton, 1986). These are separable forms of the

more general household models that include consumption and leisure (DeJanvry, 1990). Green payments are included in the profit function as an added source of revenue. Embedded within the farm models are crop production functions (Antle and Capalbo, 2001). The functions specify how crop productivity varies across alternative management practices. Included within the farm programming models is an accounting equation that tracks the sediment runoff for each of the farm management alternatives. The farm model's profit equation is given by:

$$\text{Max. } \Pi = \sum_i \sum_j (P_{jk} Y_{jk} X_{jk} + P_E S_{ij} - X_{ij} C_{jk}) \quad (6)$$

where Π is profit, X_{ij} is the area planted in crop i using the j^{th} management alternative, P_i is the crop price, Y_{ij} is the yield of crop i using the j^{th} management alternative, and C_{ij} is the cost of producing crop i using the j^{th} alternative.

RESULTS

SWAT Baseline Model Results

SWAT model predictions were compared to observed stream flow to calibrate baseline conditions. Calibration was conducted using statistical analysis, linear regression (coefficient of determination, r^2 , and slope with zero intercept), and estimation efficiency (Nash and Sutcliffe, 1970). Table 1 is a summary of the comparison between the observed and predicted stream flow results for the six stream gauges included in this analysis. Due to the uncertainty in the sources of rainfall inputs and the lack of spatial correlation between these rainfall inputs, comparisons were made with the middle 95% of the data. The observed and predicted streamflow data were sorted and the top and bottom 2.5% of the data were removed. This process removed both predicted and observed outliers from statistical analysis. In other cases data points were removed based on missing or incomplete observed streamflow data.

The SWAT model slightly under predicted flow for all but the uppermost gauging station, Amboni, in which case flow was slightly over predicted. In addition, SWAT generally over predicted flow for large events. However, it should be noted that the predicted flow generally tracked the observed flow patterns throughout the study period. A lack of representative, high quality input data for the study area prevented further calibration; therefore, the model was run on a relative basis (i.e., scenario model results were compared to baseline model results in terms of a percent change in model variables). Despite some inconsistencies between model predictions and observed data, the inconsistencies were within the expected range of accuracy from a model predicting stream flow over a catchment area. Moreover, the calibration was considered adequate since the model results were used as a baseline for the relative, and not absolute, comparisons between stream flow and sediment transport under the alternative forest restoration scenarios. There was no significant change in flow or in the variance of flow across the reforestation scenarios and hence variance was omitted from further evaluation.

Precipitation data was the driving factor used to produce the model results tracked in this analysis, including runoff and sediment loads (Figure 2). This was highlighted by the complimentary patterns of these parameters across the catchment. Rainfall estimates, based on observed raingauge station data assigned to each subbasin, ranged from 22,056,514 m³ to 403,787,196 m³. In general it was found that rainfall increased in going from the lower to higher elevations.

SWAT model simulated runoff generally matched these rainfall patterns, ranging from 307,322 m³ to 107,016,347 m³ in a northwest to southeast direction. The ratio of rainfall to runoff, or the proportion of rainfall that became runoff, was higher in the upper reaches of the catchment, as was expected based on rainfall patterns and land cover types. However, the northeastern portions of the catchment were noticeably higher than other areas (Figure 5). Simulated sediment loads ranged from 11 to 388,294 tons with the highest levels again identified for the upper and middle reaches of the catchment.

For the purposes of this study the catchment was divided into three main branches that combine to create the Masinga Dam inflow. These include the main branch, or Tana River, in the central reaches, the Thiba River in the northeastern reaches, and the Thika River in the southwestern reaches of the catchment (Figure 5). Simulated percent rainfall, runoff, and sediment contributions to the reservoir were calculated for these three branches. The greatest contributions were from the Tana subbasins, followed by the Thiba and Thika subbasins. The Tana River subbasins account for 93% of the rainfall in the catchment, 52% of the catchment runoff, and 50% of the sediment load to the reservoir. The Thiba subbasins account for only 4% of the catchment rainfall, but contribute 40% of the catchment runoff, and 44% of the sediment load to the reservoir. This is an interesting simulation model result since the Thiba generates a disproportionate amount of sediment. The disproportionate contributions from the Thiba subsystem are due to the larger number of small holder agriculture sites with longer periods of exposed soil as well as the relatively large area of rangelands in the Thiba subsystem (Figure 1). The Thika subbasins play only a minor role in the catchment with 3% of the rainfall, 8% of the catchment runoff, and only 6% of the sediment load (Figure 5). In addition, the total cumulative reservoir inflow and sediment load was calculated at 70.94 million m³ and 46.39 million tons, respectively, for the 14 year study period (1981-1995).

Table 1. Summary of statistical comparison between observed and predicted stream flows.

	Stream Guage Location											
	<u>Amboni</u>		<u>Sagana</u>		<u>Gura</u>		<u>Tana Sagana</u>		<u>Thiba</u>		<u>Thiba 2</u>	
	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.
<i>n</i>	169	171	157	171	168	171	155	159	165	171	127	147
Monthly Mean (m ³ s ⁻¹)	1.6	1.79	7.30	5.41	12.01	9.70	34.52	22.20	11.07	5.63	19.86	17.15
St. Dev.	1.33	1.93	6.09	5.20	8.94	10.25	30.10	23.42	8.87	6.11	14.26	16.51
<i>COE</i>	-0.64		0.251		0.320		0.370		-0.335		0.332	
y-intercept	0.992		0.629		0.829		0.616		0.414		0.812	
<i>R</i> ²	0.223		0.380		0.547		0.527		0.052		0.527	

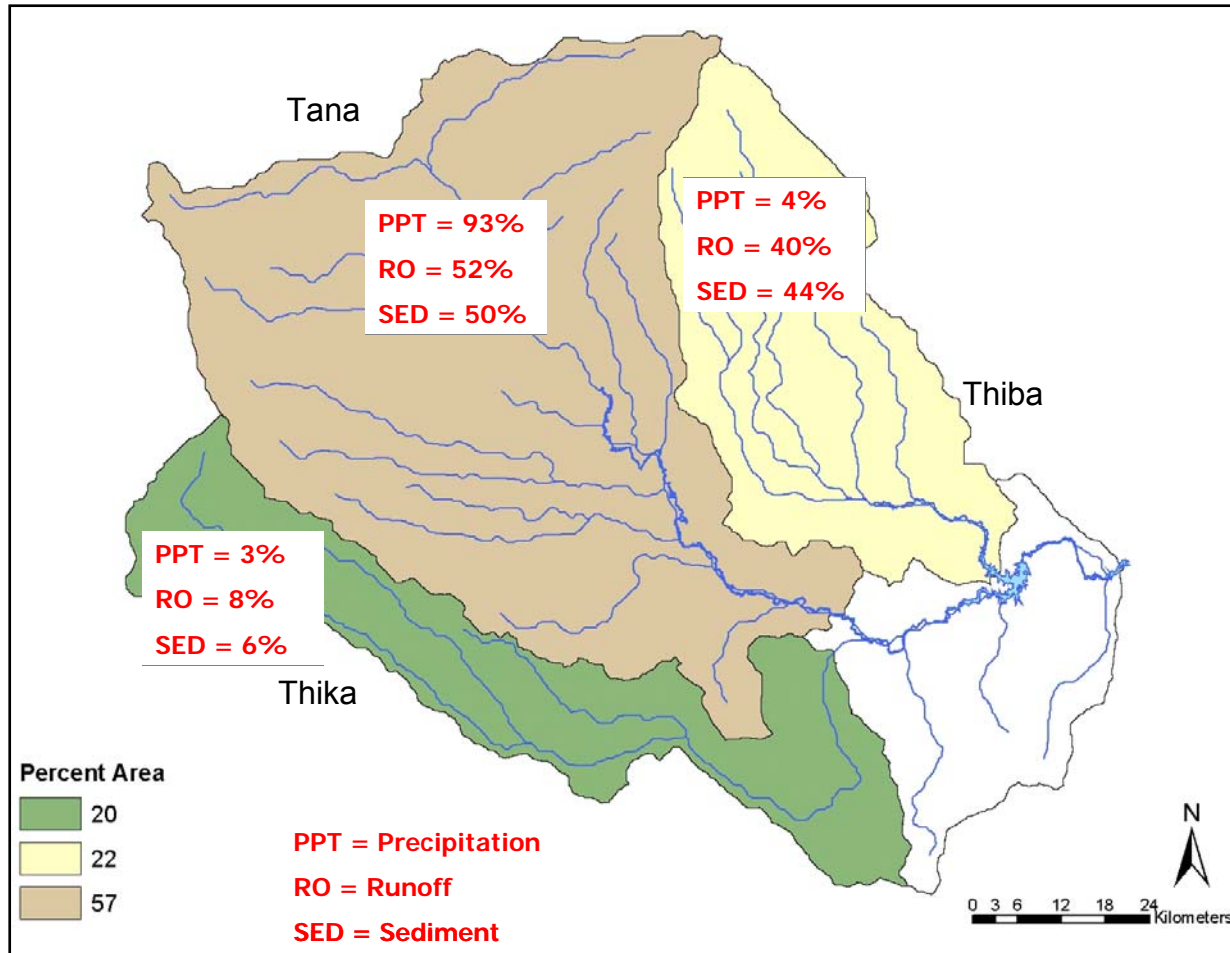


Figure 5. Percent rainfall, runoff, and sediment contributions to the Masinga Reservoir.

SWAT Scenario Results

Four reforestation scenarios were simulated by SWAT, with scenarios representing the elevation above which reforestation occurred. For the 2,000m interval simulation, forest cover over the catchment was 2,932 km², and increased over each successive simulation of 1950m, 1900m, and 1850m to include 3,077 km², 3,253 km² and 3,453 km² of forest cover (Table 2). Grazing lands and tea were the main land use types displaced by forest restoration activities in each of the scenarios (Table 2). Maize also had significant areas displaced by reforestation, with 64.8 km² of maize being replaced in 2000m interval scenario.

In general, sediment yield decreases with each successive scenario simulation going down slope from the 2,000m scenario as forest cover is increased. Sediment yields to the reservoir ranged in value from an annual average of 3.43 million tons under Baseline conditions to 3.18 million tons of sediment under the 1850m scenario (Figure 6). With forest cover in place down to the 1,850 m contour, sediment in the Masinga Dam would have been reduced upwards of 7%, or 0.25 million tons per year, over the course of the study period. There is, however, a 0.6% increase in sediment yield in going from the 2,000m to 1,950m scenario. This was due to the relatively high displacement of tea plantations that are prevalent at

the 1,950m elevation. Established tea plantations would provide a denser canopy cover than forests, thereby reducing sediment loss compared to reforested areas.

Table 2. Land use, total land area at baseline conditions (km²), and the change in land use types for the forest restoration scenarios evaluated in the Tana River study area.

Land Use	Baseline ^a (km ²)	Scenario			
		2000 m (km ²)	1950 m (km ²)	1900 m (km ²)	1850 m (km ²)
Forest	2,216	+2,932	+3,077	+3,253	+3,453
Grazing land	703	-457.7	-70.9	-92.4	-82.2
Tea	220	-114.7	-35.8	-32.6	-37.5
Maize	134	-64.8	-16.8	-21.3	-31.4
Woodlot	97	-48.0	-10.0	-11.4	-27.7
Bush	49	-24.0	-4.8	-9.9	-9.8
Coffee	26	-7.6	-3.9	-7.1	-7.4
Other ^b	725	-7.6	-2.3	-1.9	-4.4

^a Areas reported under the Baseline scenario include all land use areas above the 1850 m elevation in the study area.

^b Other consists of the following land uses: banana, hedges, maize-banana, and roads.

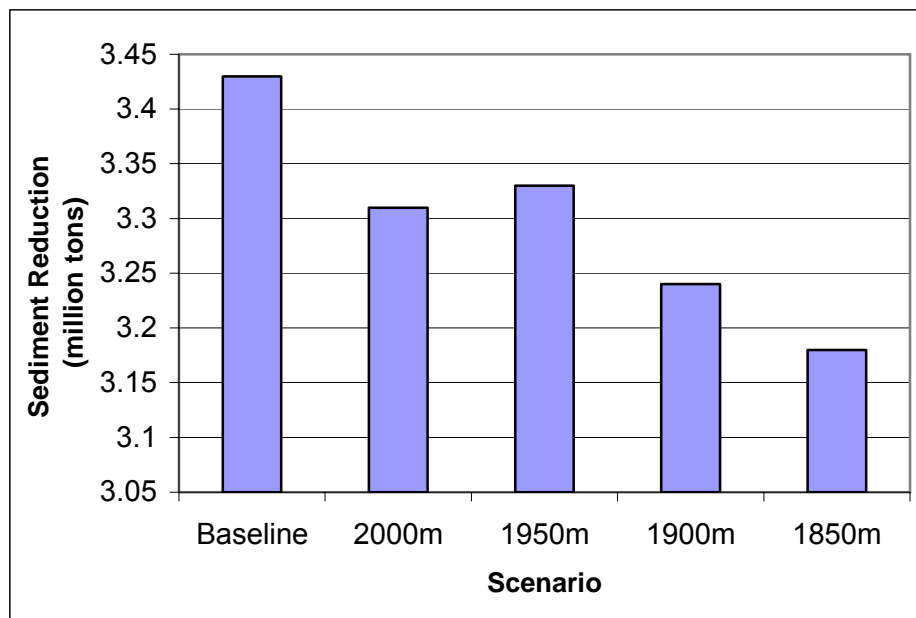


Figure 6. Average annual sediment yield to the Masinga Dam from the Upper Tana River Basin catchment area under Baseline and reforestation scenarios. Scenarios represent elevation zones of reforestation activities going down slope from 2000m to 1850m.

SWAT Scenario Conclusions

The SWAT simulations generated some implications for reforestation activities in the catchment. The Thiba River subsystem should be considered for initial implementation based on its relatively large contribution of sediment to the reservoir. This area receives only a small portion of the rainfall in the catchment (4.25%), but contributes nearly half of the sediment to the reservoir (43.81%). It is here that efforts to reforest denuded rangelands and to provide improved land cover over the large number of smallholder farms would provide the largest sediment reductions. The SWAT simulation results also suggest that tea production should not be targeted for reforestation. This would be the only land use that would provide equal, if not superior, protection as reforestation. Maintaining tea as a land cover would help achieve the full benefits of the restoration activities with minimal impacts to the established agricultural areas in the catchment.

The benefits of the reforestation efforts would also be more significant during high flow events. The SWAT simulation results reflect average conditions, but in years of high runoff the sediment reductions would be much larger than illustrated in Figure 6. The restoration efforts also improved the flow qualities in the catchment by decreasing flow variability. It should be noted, however, that the current forest cover used in the Baseline scenario likely overestimates the actual forested area in the catchment based on undocumented observations of local forest and wildlife managers. If as expected this is true then the change in stream flow and sediment yield, and thereby the benefits of forest restoration, would be greater than what was achieved with the model simulations presented in this study.

Upstream Supply of Environmental Services

The supply of environmental services from upstream producers in the catchment is illustrated by an upward sloping curve (Figure 7). This supply curve has three distinct regions that reflect the different types of producers that are in the catchment. The initial region of the supply curve is highly price elastic, meaning that large quantities of sediment can be reduced at a very low cost. Over 150,000 tons per year of sediment could be reduced at a cost of less than \$1/ton. These low costs of sediment reduction are from marginal land uses such as woodland, grassland, and grazing areas; these tend to be denuded areas with minimal economic value. A second region along the supply curve was found in which the supply costs increased linearly at a modest rate of about \$1 for every 10,000 tons of sediment reduced, and ends at 240,000 tons where the cost would be \$7.48/ton. Beyond this point the supply curve increases nearly exponentially without any noticeable reduction in sediment loading. These high costs correspond to producers of high valued crops, such as tea and coffee, which also provide good protection from soil erosion and runoff problems.

The upstream costs of supplying environmental services were mapped using GIS to illustrate its spatial distribution throughout the Tana River catchment area (Figure 8). Fourteen of the forty-two sub-basins analyzed were found to have supply costs of 2 \$/ton or less, which correspond to the initial portion of the supply curve (Figure 7). These sub-basins were found to be located in the upper reaches of the catchment area and contain large tracts of deforested lands that have been left in disrepair. Their economic value is limited to marginal farming resulting in very low opportunity costs associated with reforestation. Because these are high slope, erosive prone areas they have the potential to provide significant environmental services to downstream users through reduced sediment loading once reforested. As result of low economic value and a high potential to reduce sedimentation their supply costs are the lowest in the catchment area.

Five of the forty-two subbasins were found to have opportunity costs that ranged between 2 \$/ton and 10 \$/ton (Figure 8). These subbasins correspond to the linear region of the supply curve and are located primarily in the mid-elevation portions of the catchment (Figure 7). The land use in these subbasins is a mixture of marginal lands that support grazing and rangelands as well higher quality lands where crop production occurs. This is mainly areas of standing crop production, primarily maize, which generates modest income yet generates considerable sedimentation downstream. Hence reforestation provides significant benefits with only modest losses in income. The remaining nine sub-basins, illustrated using two shades of red in Figure 8, were found to be the high cost sub-basins that correspond to the exponential portion of the supply curve (Figure 7). In these sub-basins, converting back to forested areas provides only negligible sediment reductions and requires the conversion of tea and coffee plantations to less profitable uses as land cover. As a result the cost of foresting these subbasins result in very high costs that reach \$100/ton and beyond (Figure 8).

Green Payments

The demand for environmental services (reduced sediment) from the downstream user groups is drawn in Figure 7 as a downward sloping curve. The initial portion of the demand curve indicates that downstream users of the reservoir would pay as much as \$95/ton to reduce sediment loadings. Demand for environmental services would taper off as more sediment is reduced at the rate of about \$0.27 for each thousand tons of sediment reduced by producers in the upper catchment. The demand curve is elastic, with an average price elasticity over the initial 250,000 tons of sediment reduction of -1.98. This indicates that downstreams users of the Masinga Reservoir have only a modest demand for environmental services. As the price for environmental services is increased the demand for environmental services decreases quickly (Figure 7).

The Green Payment price is found where supply and demand intersect. As drawn in Figure 7, this occurs at a price of \$33 for each ton of sediment reduced. In the standard Green Payment scheme each upstream producer would be paid the same price, \$33/ton, for reducing sediment to the Masinga Reservoir. Under this type of uniform pricing the economic gains to the catchment area would increase by \$13.3 million each year (Table 3).

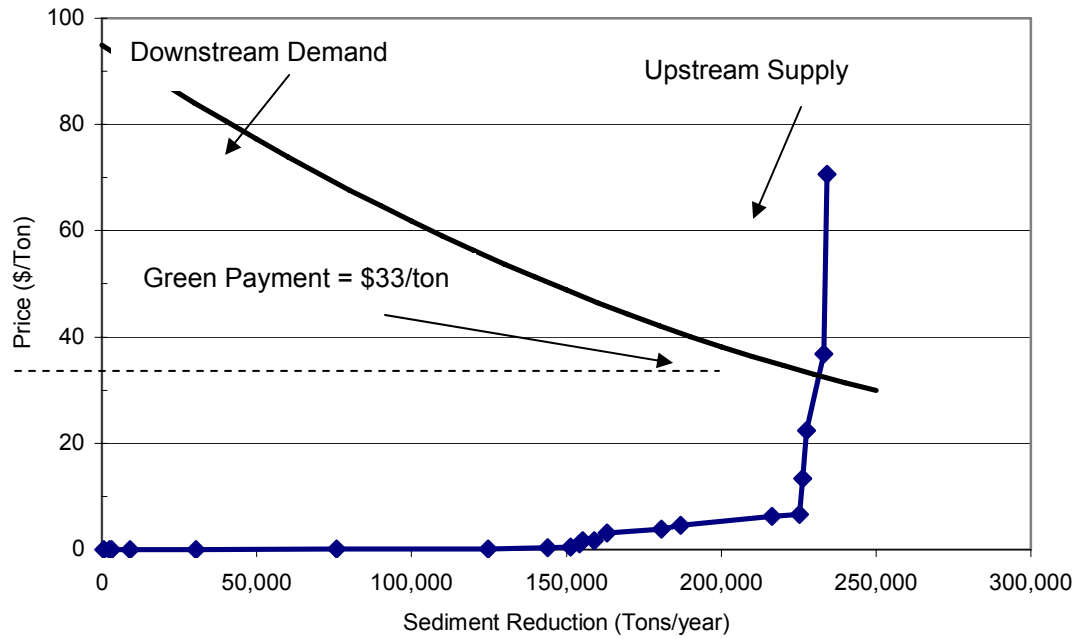


Figure 7. Supply and demand curves for environmental services in the Tana River basin.

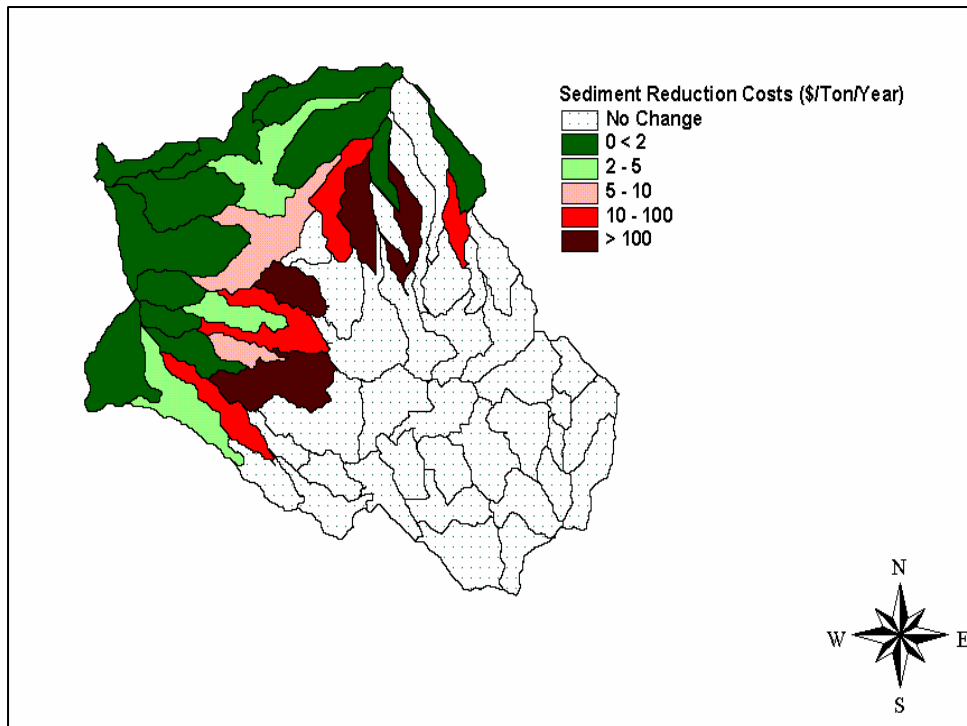


Figure 8. GIS mapping illustrating the sediment reduction costs incurred by upstream producers.

Using Equation 1, the economic gains were found to be divided almost equally among the upstream and downstream users, with the upstream users capturing a slight majority of the benefits. Upstream users would capture \$7.1 million in economic surplus, nearly 54 percent of the total increase in social welfare (Table 3). The remaining \$6.2 million in surplus would be captured by the downstream users. With a price of \$33/ton to reduce sediment the downstream users of the Masinga Reservoir would have to pay on average \$7.59 million each year to the upstream producers. Since the benefits generated by reducing sediment would be \$13.79 million per year, the downstream users of the Masinga Dam would end up with a net economic gain of \$6.20 million per year (Table 3).

An alternative approach is to use targeted green payments. This alternative pays producers different prices for reducing sediment and would never exceed the uniform price of \$33/ton since producers would be paid according to their individual supply costs (Figure 7). The targeted green payments were found to provide a much better outcome for the downstream users of the Masinga Dam as their benefits would increase and their costs would decrease (Table 3). Using targeted green payments it was found that the net gains received by the downstream users of the Masinga Dam would more than double from \$6.2 million to \$13.3 million per year, even though the net gains to society would remain at \$13.3 million per year (Table 3).

This large increase in net economic gains is achieved through reducing green payment program costs from \$7.59 to \$0.49 million each year (Table 3). The spatially explicit modeling found that because upstream producers earn very distinct profits depending on the crops they produce, the cost that they would incur in reducing sediment flow downstream would vary significantly. For instance, areas that are currently deforested and used only for marginal production activities would require minimal green payments of about \$1 per ton of sediment reduced, whereas tea plantations would require green payments upwards of \$100 per ton. With targeted payments it would be possible to pay the marginal producers only \$1/ton; by comparison a uniform pricing structure, in which all producers receive the same green payment, all producers, including the marginal producer, would receive \$33 for each ton of sediment reduced. Hence by paying each producer their individual supply cost targeted green payments would decrease costs by from \$7.1 to \$0.49 million per year.

Under targeted green payments the distribution of benefits would shift entirely to the downstream users: targeted green payments would enable the downstream users to recapture all \$13.3 million of the economic gains. Upstream producers would lose their share of the economic benefits, which would be \$7.1 million under the uniform pricing of \$33/ton. With targeted prices upstream producers would only be compensated for their economic losses and would not receive any increased income profit from the Green Payment program. Moreover the Benefit-Cost Ratio of the targeted Green Payment program would be large, 29.3, which compares favorably with the Benefit-Cost ratio under the uniform green payment price, 1.81.

CONCLUSIONS

The findings of this research suggest that reforestation and adoption of improved agricultural practices would enhance water quality, decrease flow variability, and extend the life of the Masinga Dam. The implementation of reforestation would reduce sediment in the Masinga Dam by about seven percent per year. This is equivalent to abating one-quarter of a million tons of sediment per year from entering the Masinga Dam. With increased operational potential, the Masinga Dam would be better able to supply

services to its users. Irrigation schemes, urban consumers, and hydroelectric power supply would all benefit from reforestation activities in the upper catchment areas. Additional benefits of reforestation would include improved water routing and channeling following large rainfall events and hence a reduced likelihood of flooding.

The actual forest cover in the Upper Tana River basin is difficult to measure. This study has been conservative and perhaps has underestimated the amount of forested area in the Upper Tana River basin. Moreover, the conservative nature of the SWAT simulations conducted in this study underestimate reforestation's ability to supply environmental services throughout the catchment. Hence the benefits of reforestation are understated to some extent and the actual benefits could be much larger than has been presented in this paper.

The Thiba River subsystem would provide the largest benefits from reforestation to the Masinga reservoir and based on this it should receive the highest priority. The Thiba River subsystem is also noteworthy since it receives only a small portion of the rainfall in the catchment, about four percent, but contributes nearly half of the sediment to the Masinga reservoir. This is explained by the large number of small holder agriculture sites within the Thiba river subsystem that leave large tracts of soil exposed to water erosion throughout the calendar year and generate only marginal income from farming. This study found that reforesting this land would provide economic gains to catchment area.

Both the SWAT simulations and its supporting economic analysis found that tea is an acceptable crop for upstream farmers to produce and that tea should not be targeted for reforestation. Tea plantations were not found to make any significant contribution to the downstream sedimentation problems in the Masinga Dam. The SWAT simulations actually found in some areas of the catchment that tea performed better than the forest land cover in reducing sedimentation. The economic analysis estimated that the costs of reducing sediment by displacing tea plantations with forest would cost upwards of \$100 per ton, which would exceed demand by at least \$5/ton.

Targeting green payments appears particularly useful in the Tana River basin. Paying upstream users a uniform price to reduce downstream sedimentation was found to be less economical since the total costs of green payments would be \$7.59 million per year. Alternatively, targeting green payment prices to individual producer groups upstream would decrease costs by \$7.1 million per year, creating an additional \$7.13 million in net economic gains for the downstream users of the Masinga Dam. Shifting more of the benefits to the downstream user groups is important since they are primary group to initiate and sponsor the green payments. Increasing the economic returns to green payments makes it more likely that the downstream user groups would be able to organize and act collectively to establish a green payment program.

The reforestation scenario developed in this study would require planting approximately 30 million trees over an area nearly 124,000 ha in size. The success of reforestation will require a collaborative effort on the part of various stakeholders: forest managers, natural resource specialists, local governments, user groups of the Masinga Dam, and upstream small holder producers. Together they would need to develop a meaningful plan to implement reforestation. This is expected to include an education outreach effort to inform the public about the issues facing the entire catchment and in particular the role of Green Payments. These steps are vital to solving such complex ecosystem problems.

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