Exploring the Potential Impact of Reforestation on the Hydrology of the Upper Tana River Catchment and the Masinga Dam, Kenya

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ABSTRACT

The Upper Tana River Basin is strategically one of the most critical resource areas of Kenya. The Masinga Reservoir, at the outlet of the basin, provides water and hydroelectric power for 65% of the Nation. Unregulated deforestation and expansion of cultivation practices onto marginal soils in this critical river basin has resulted in significant reservoir siltation, reduced ecosystem function and more erratic downstream flows. Using a participatory process, collaborating technical policy analysts working for key government institutions in Kenya identified the need to assess the impact of meeting a national goal for reforestation of 30% of deforested lands with the infusion of new agro-forestry technologies and land tenure laws through the consideration of population expansion to 2015. Using a rapid rural appraisal methodology, it was determined that reforestation below 1,850 m would be difficult to achieve. However, reforestation at elevation increments of 2,000 m, 1,950 m, 1,900 m and 1,850 m would represent a 30 to 55% increase in reforested area in the Upper Tana River catchments. In addition, the results of this analysis show that full implementation of reforestation to 1,850 m would result in a 7% decrease in sediment loading in the Masinga Reservoir. Runoff yields would be similar to baseline conditions but peak annual flows would increase approximately 3% with less inter-annual variability, resulting in greater stability of water levels in the reservoir. However, replacement of tea plantations with forest did not result in hydrologic benefits to the system, thus tea plantations should remain in place. Based on these findings it has been determined that reforestation would allow the government to pursue reduction of lake water levels to stabilize fluctuation in vegetation, thicken the epilimnion with greater nutrient mixing, and greater downstream delivery of more stable water flows and coastal nutrient loading. In addition, priority subbasins were identified for reforestation based on costs of dam sediment management relative to sediment yields which will allow decision makers to sequence reforestation efforts in a more cost effective manner. Sediment reduction costs varied significantly among the subbasins as varied landscapes and land uses were identified under the baseline conditions. In subbasins where reforestation would replace marginal, erosive prone lands, sediment reduction costs were less than $1/Ton; in subbasins with high valued crops (tea and coffee) that contribute little to sedimentation, the costs were well over $100/Ton. Finally, based on evaluations of current activities and the findings of this research, recommendations on government actions have been made. These recommendations include greater enforcement of illegal logging and illicit drug plantations, community based tree nursery and reforestation activities, improved land tenure laws, greater efforts in soil conservation on croplands, patterning reforestation to preserve biodiversity and strategy promotion of tea plantations in key elevational areas.

INTRODUCTION

Although limited in overall extent, forests play an important role in providing ecological services to the people of Kenya, particularly in the mountainous regions in the central part of the country from which the bulk of hydro-electric power and drinking water is derived. Concerns over the negative environmental effects of large scale changes in agriculture, land use and destruction of these forest resources in the last 40 years have been expressed (MENR, 1994). The Tana catchment is the largest river system in the country with forest lands along the Eastern slopes of the Aberdare Range and Mt. Kenya playing an important role in the hydrology of the entire river system.

Recent studies highlighted the extent of deforestation (UNEP, 2001; KIFCON, 1994). Estimates based on remote sensing indicated that Kenya's forest cover stands at a critical 1.7% (UNEP, 2001) of the nation, and further encroachment is expected to have significant negative ecological, social and economic effects. In 1999, the Kenyan government rescinded the protected status of 4% of the remaining forests (Anon, 2002), by de-gazetting 70,000 hectares of public forest land across the country and defining the areas already settled by squatters. Public outcry on the destruction of forests necessitated the Kenya Wildlife Services with the support of UNEP to conduct a systematic aerial survey of the forests of Mt. Kenya (Vanleeuwe, et al., 2003) and the Aberdares (Lambrechts et al., 2003). Reports from these surveys were launched in June 2003. The surveys provided factual information on the extent, type and location of destructive activities in the forests. The excision of forestlands for agriculture (Vanleeuwe, et al., 2003; Lambrechts et al., 2003) and the degradation of forests for commercial reasons were the predominant problems within the forest landscape. The reports clearly illustrated that these forests are under extreme threats emanating from charcoal production, overgrazing, extensive illegal logging of indigenous tree species, abuse of the Shamba-system and additional encroachment from such practices as large-scale marijuana cultivation. Furthermore, effective long-term measures to ensure forest protection are not in place at the moment. Sustainable forest management is faced with various difficulties that must be addressed, both in the short as well as the long-term.

In addition to the survey by the Kenya Wildlife Services, there have been a series of studies on the Tana River system to ascertain the ecological and hydrological impacts of the series of dams built in the upper reaches of the Tana River system near Mt. Kenya (Ongwenyi, 1985; Schneider and Brown, 1998; Mutisya and Mutiso, 1998, Pacini *et al.*, 1998; Maingi and March, 2001; Maingi and Marsh, 2002). Within this region the Masinga Dam is by far the greatest regulator of the Tana River system given its size and strategic location in the upper reaches of the system (Pacini *et al.* 1998). 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 Acacias which have declined over 27% since 1989 (Maingi and Marsh, 2001).

The Masinga Dam serves as a storage reservoir which helps control the flow of water through a series of downstream hydro-electric reservoirs. The Masinga Dam does generate electricity, however at lower capacity than the other reservoirs. The Upper Tana River Basin and the Masinga Reservoir are extremely important resources in the Tana River System given the strategic position of the dam, coupled with the large portion of prime forest habitats within the catchment, and the large source of rainfed runoff and return flow from Mt. Kenya and the Aberdare Range. It is the intent of this paper to explore the hydrologic impacts on the Masinga Reservoir in response to land use interventions in the Upper Tana River catchment with a focus on varying levels of reforestation for improved water quality and quantity.

STUDY AREA

Hydrologic model simulations were conducted in the Upper Tana River basin in Kenya (Figure 1). The basin is north and northeast of Nairobi, and encompasses the cities of Embu and Nyeri. The Tana River begins in this region with major tributaries arising on the slopes of Mt. Kenya and the Aberdare Range. It traverses through the study area and travels approximately 1,000 km to the Indian Ocean on the eastern coast of Kenya (Figure 2). The entire catchment area of the river is approximately 100,000 km^2 and the river is a vital resource for both water and hydroelectric power for the region and Kenya.

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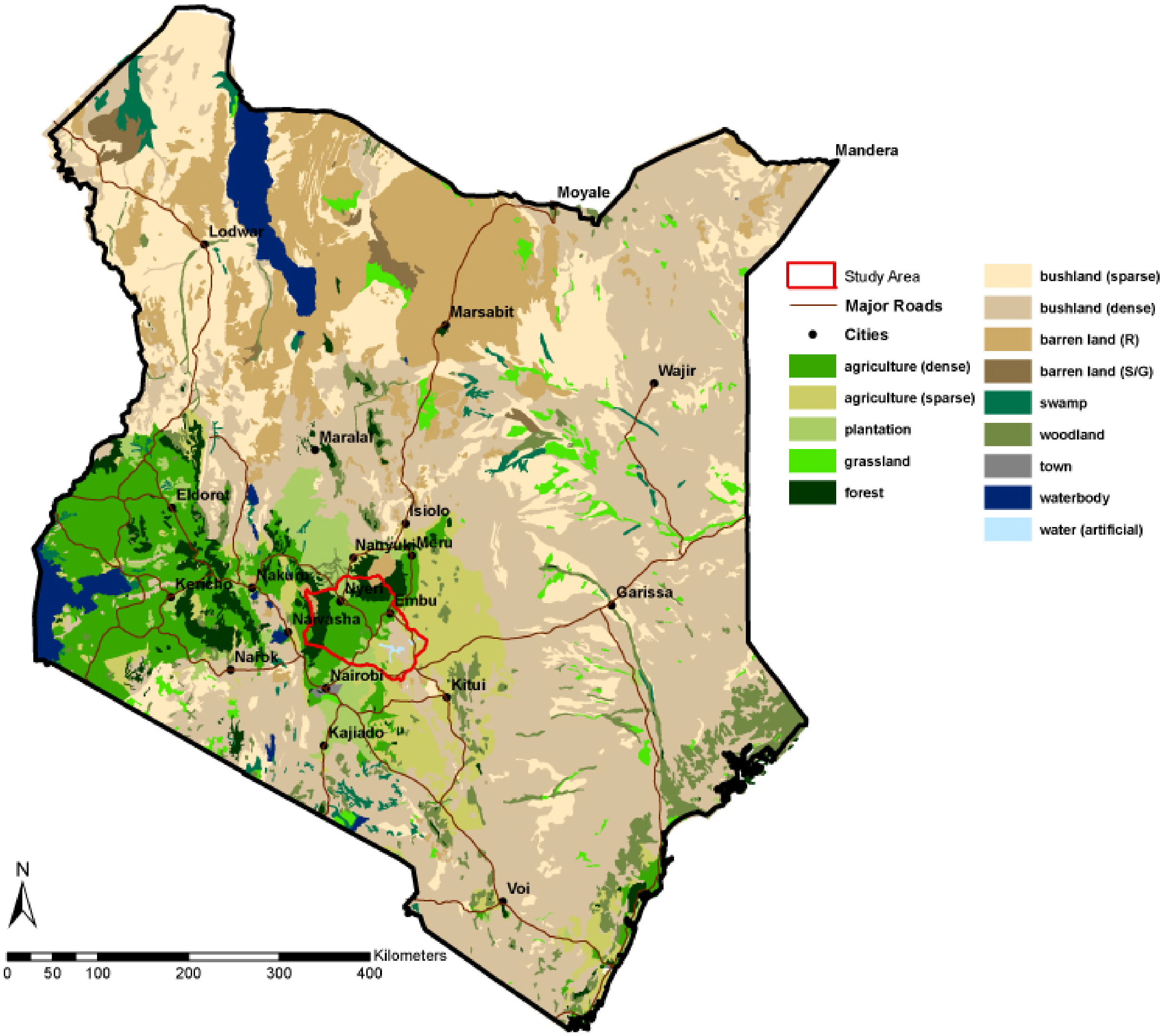

Figure 1. Location of study area.

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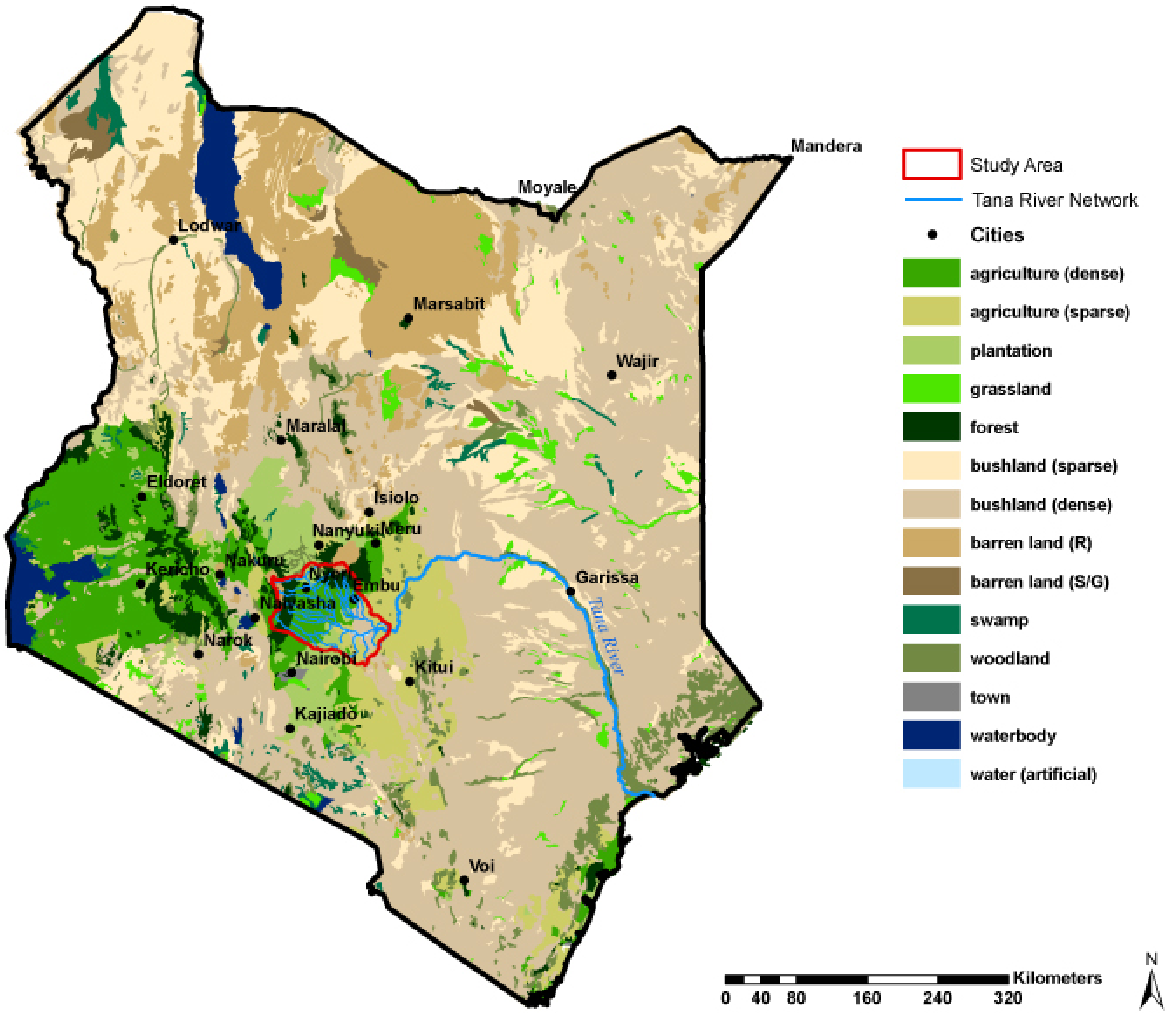

Figure 2. Location of the Tana River system.

The elevation of the study area (Figure 3) ranges from a high of 4,700 m on Mt. Kenya to a low of 730 m near the Kindaruma Dam. Soils vary with elevation in the region (Figure 4) with Andosols (M2) being the predominant soils at the higher elevations, Nitosols (R1, R2 and R3) at the mid elevations, and Ferallsols (Um19) and Vertisols (L11, Up4) are predominant at the lower elevations (Pacini and Harper, 1998). Major land uses within the study area include forests, cropland agriculture, and rangelands (Figure 5). At higher elevations within the study area, forests and tea cropping predominate.

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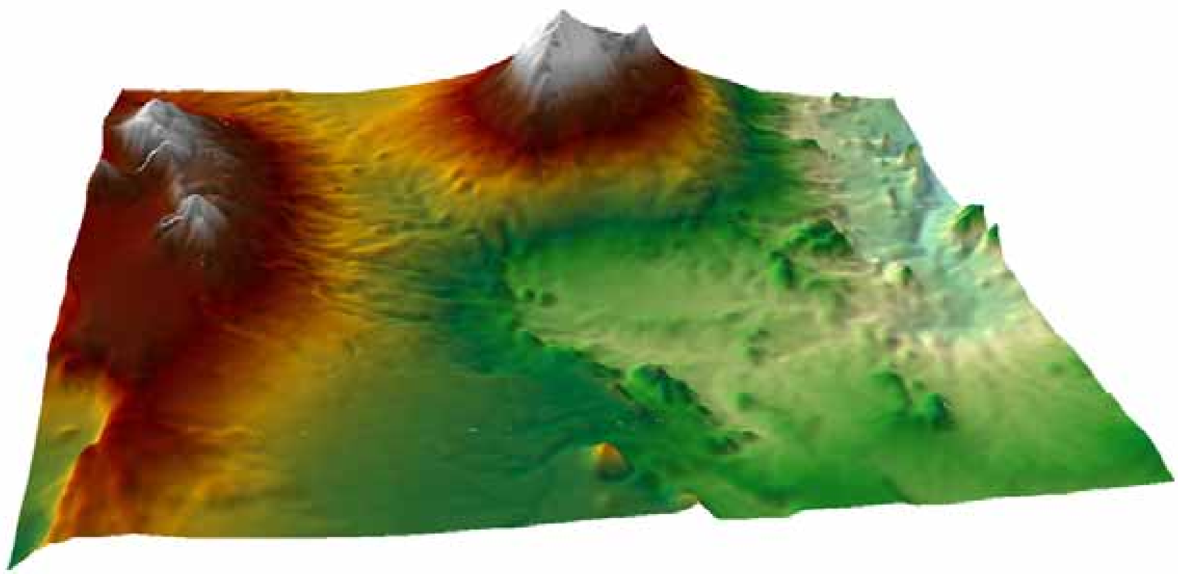

Figure 3. 3-D elevation graphic derived from 100-m DEM for the upper Tana River Basin.

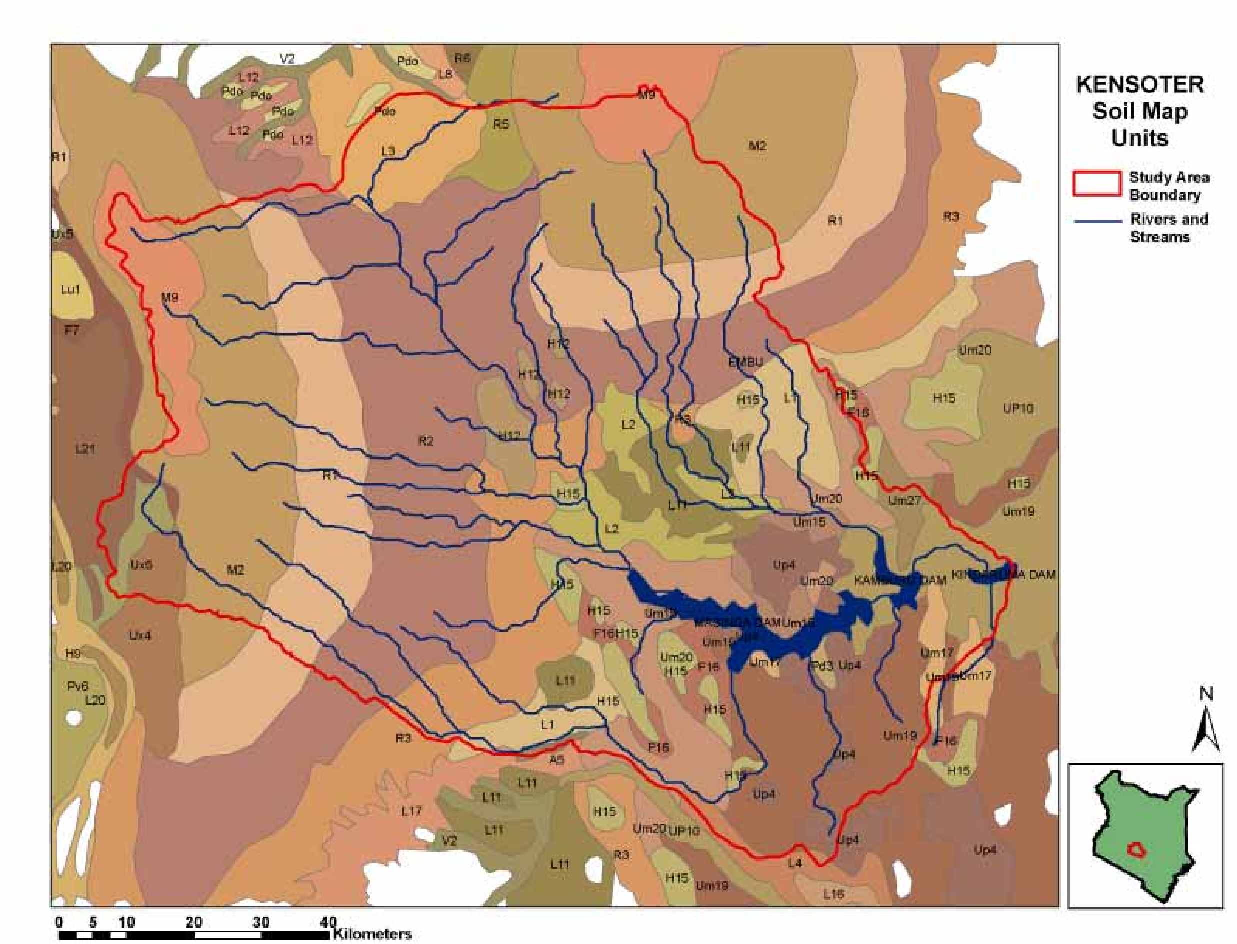

Figure 4. Major soil units within the study area of the upper Tana River basin. Soil map units represent an individual soil or an association of soils. Source: Kenya Soil and Terrain Database

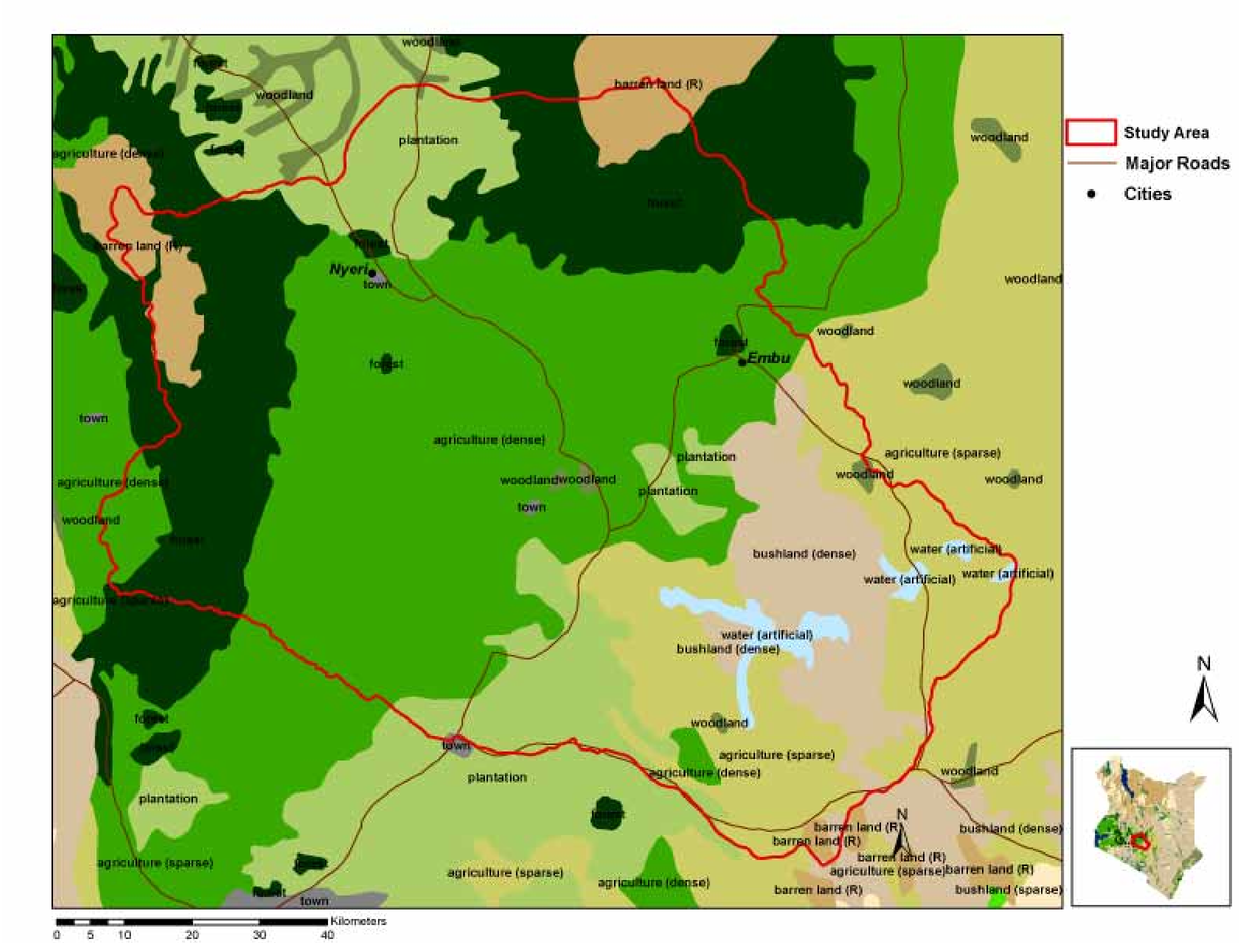

Figure 5. Location of study area and major land uses for the region.

The most intensive agriculture occurs at mid-elevations and a variety of crops are grown including coffee, maize, bananas, napier grass, and beans. At the lower elevations of the basin, the area has less intensive agriculture and livestock grazing is a dominant land use.

Rainfall follows a similar elevation gradient as that of soils. Mt. Kenya and the Aberdare Ranges receive greater than 1,800 mm/yr of rainfall (Otieno and Maingi, 2000). At the mid elevations (1,200 to 1,800 m) where intensive agriculture is predominant, annual rainfall ranges from 1,000 to 1,800 mm/yr. Below 1,000 m, rainfall is less than 700 mm/yr which is too low for intensive agriculture so cropland is sparse and livestock grazing predominates (Otieno and Maingi, 2000).

Hydrologic Characteristics

Even with high rainfall in elevations greater than 1,800 m, there is a marked seasonal variation in river flow. The rainfall pattern has two distinct wet periods each of three months total duration, separated by dry periods. During these dry periods, high demand for water both for irrigation and urban needs as well as sustained electric power generation can not be adequately met. Due to this seasonal fluctuation in river flows, the Masinga Dam was constructed. The dam regulates the flow of water to the downstream reservoirs (Kamburu, Gitaru, Kindaruma and Kiambere) and serves as a water supply for the surrounding areas (Watermeyer *et al.* 1976).

The Masinga dam was first impounded to full supply in June 1981. It is an earth-fill dam with a spillway and power intake, in an open cut, to a surface power station at the foot of the slope. It has a height of 55 m, crest length of 2,100 m and a design capacity of 1,488 mm^3 (Watermeyer et al., 1976). The reservoir has a full operation surface of 125 km^2, and extends approximately 45 km upstream (Otieno and Maingi, 2000). The region above the dam lies within a plateau of gently rolling topography occasionally broken by rounded hills.

The possibility of siltation problems in reservoirs on the Tana River has long been recognized. Indeed, one has only to drive along the main road from Nairobi towards Mt. Kenya in the rainy season and look at the rivers draining the Aberdare foothills to appreciate the amount of silt being transported downstream. Due to rapid population increase in the catchment, there has been severe clearance of natural vegetation both for farming and settlement, which compounds the problem. In addition, in the lower areas and plains lying within the vicinity of Masinga dam, overgrazing and felling of trees for charcoal burning has caused widespread soil erosion.

Although Masinga dam was completed and the reservoir impounded at a time when the problems caused by sedimentation were already well known, no action was taken upstream or at the sides of the reservoir to minimize sedimentation. Indeed, due to the reluctance of the Tana and Athi River Development Authority (TARDA) to address this problem sufficiently, large gullies have developed, measuring 15 to 30 m in depth, on the sides of the reservoir (Roggeri, 1985). This sedimentation is particularly prevalent during the rainy seasons when the Tana overflows it’s banks and temporarily floods the plains. Surface runoff in the ephemeral streams feeding the reservoir from the sides also contributes to sedimentation.

The high production rates of sediment can be linked with the fact that these rivers pass through the intensively cultivated slopes of the Aberdares and Mt. Kenya. Lack of adequate ground cover and steep slopes (often cultivated without carrying out effective soil conservation measures) result in increased surface runoff and soil loss. Thus, soil conservation practices such as channel stabilization, road ditch stabilization terraces and construction of check-dams should be carried out within the catchment. Since Masinga reservoir has a high trap efficiency (between 75 and 98%), with a mean annual loss of capacity of 23 mm^3 (Schneider, 2000), complete siltation of the reservoir would occur within 65 years, as opposed to the original 500 year estimate, without some type of intervention and management (Watermeyer et al., 1976).

This study deals with reforestation as a means of addressing siltation issues in the reservoir. This is a reasonable management choice based on recent changes in the environmental and political climates in Kenya.

Currently, there are numerous statutes that deal with rights of land ownership, control and provisions for conferring and vesting of land interests in Kenya. At present, land falls under one of three tenure categories, government, trust or private. Government land comprises 20% of the total land area in Kenya, whereas trust and private land tenure comprises 78.5 and 1.5%, respectively. After the country’s independence in 1963, all land that was not in private or government ownership became trust land, under the control of the community, and was to be used for the benefit of the residents of the area (MENR, 1994). Land ownership has significant implications for forest reserves. Reserves on government land are managed by the Forest Department, while those on trust lands are managed by local authorities. In 1994, gazetted forest reserves on government land amounted to 1,359,254 ha, while gazetted forest reserves on trust lands totaled 328,136 ha (MENR, 1994). Most of the area of forest reserves (64%) is covered by indigenous forests. Furthermore, a significant 25% of the area in these reserves is covered by non-forest vegetation while 9% is composed of plantation forests. Approximately 65% of indigenous forests are found in gazetted forest reserves, whereas plantation forests represent just over 9.76% of the total cover in Kenya (Wass, 1995).

The main constraint facing the forests and reforestation practices in the study area is a lack of secure ownership over natural resources. The Forest Department, under the Ministry of Environment, Natural Resources and Wildlife, manage the gazetted forests which may be indigenous or plantations. The Kenya Wildlife Services manage those forests which fall under the area controlled by the service. County Councils manage forests in trust land and areas within their jurisdiction, while the local community or private companies manage forest on private lands. The reality on the ground is that forests that are managed by the Forest Department and the County Councils are not performing their functions and are in fact dwindling at a high rate. On the other hand, those forests that fall under Kenya Wildlife Services or are owned by private companies are thriving.

To turn this situation around, a survey of all state forests will be necessary in order to establish boundaries. The survey would establish what resources are available for commercial use or biological diversity conservation. Then areas that can be reforested with plantations could be leased to privately owned paper, timber and tea companies. This would provide resource users an incentive to use and conserve the resources in a sustainable way. The resources obtained from leases could be used for conservation work and provide products such as posts, fuel and charcoal that will continue to be in demand in Kenya. Furthermore, areas that are important for water catchment and biological diversity conservation could be co-managed with a competent agency, such as the community forest associations.

The political and social climate in Kenya is ripe for reforestation. The new government has made a significant attempt at creating an enabling environment for protection of forests and water resources. Some recent positive developments in the environmental sector include the operationalization of the Environmental Management Coordination Act and the establishment of the National Environment Management Authority, which is mandated with the coordination of environmental matters. The Government has also initiated reforms in the land sector, and has produced the Land Sector Strategic Plan (GOK, 2003) addressing some of the community land tenure issues. The plan’s framework shows how local communities and the private sector will be involved in the management and development of forest and water resources.

Overall the government has showed a commitment to addressing environmental and restoration issues and is involving of a wide range of stakeholders in the process. Some such stakeholders include international organizations (UNEP and ICRAF), bilateral government donor communities, the Green Belt Movement and lobby groups such as the Kenya Forest Working Group, local NGOs and the private sector. The main thrust of this movement involves education and promotion of sound forest participatory management practices within the local communities, including reforestation through seedling plantations. For the reforestation scenarios proposed in this study, about 31 million seedlings will be required with a typical forest tree spacing of 2×2 m (Table 1). Currently, the national target is for planting 20 million trees per year (GOK, 2003).

Table 1. Forest acreage and number of seedlings required for the reforestation scenarios

Reforestation scenario	Total forest area (km^2)	Cumulative area displaced (ha)	Number of seedlings required (2×2 m spacing)
Base scenario	2216	---	---
2000 m asl	2933	71700	17,925,000
1950 m asl	3077	86100	21,525,000
1900 m asl	3253	103700	25,925,000
1850 m asl	3453	123700	30,925,000

Data and Processing

Climate data for the study was obtained from multiple sources. Rainfall and temperature data for Embu and Nyeri for the period of 1978 to 1997 was acquired from World Meteorological Organization (WMO) stations (Figure 6). Rainfall for areas in the northern part of the study area (Figure 7) was obtained from the Mpala Research Center which has compiled and digitized rainfall from farms, towns, and plantations in the Laikipia area of Kenya. The rainfall for the period of 1978 to 1997 was extracted to match that of the WMO data. A third data set, the Collaborative Historical African Rainfall Model (CHARM) rainfall data set (Funk *et al.*, 2003) was used to obtain spatially and temporally explicit rainfall amounts for the study area (Figure 7). The CHARM data was derived from combined daily rainfall reanalysis fields, monthly interpolated rainfall, and an orographic precipitation model to allow representation of daily rainfall on an 11 x 11 km grid for the entire African continent for the period from 1961 to 1996 (Funk *et al.*, 2003).

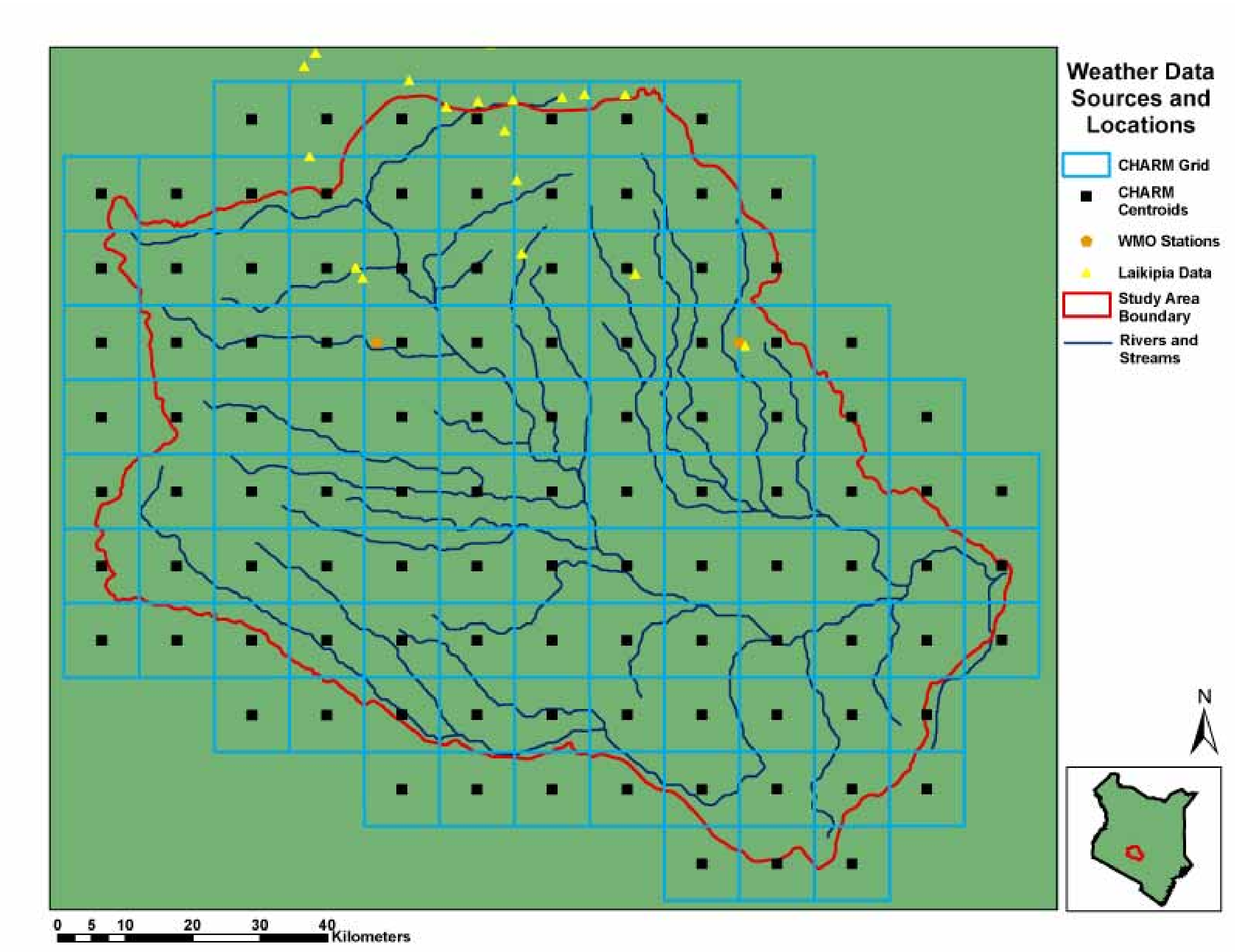

Figure 6. Locations of weather stations and data used for hydrological analysis in the study area.

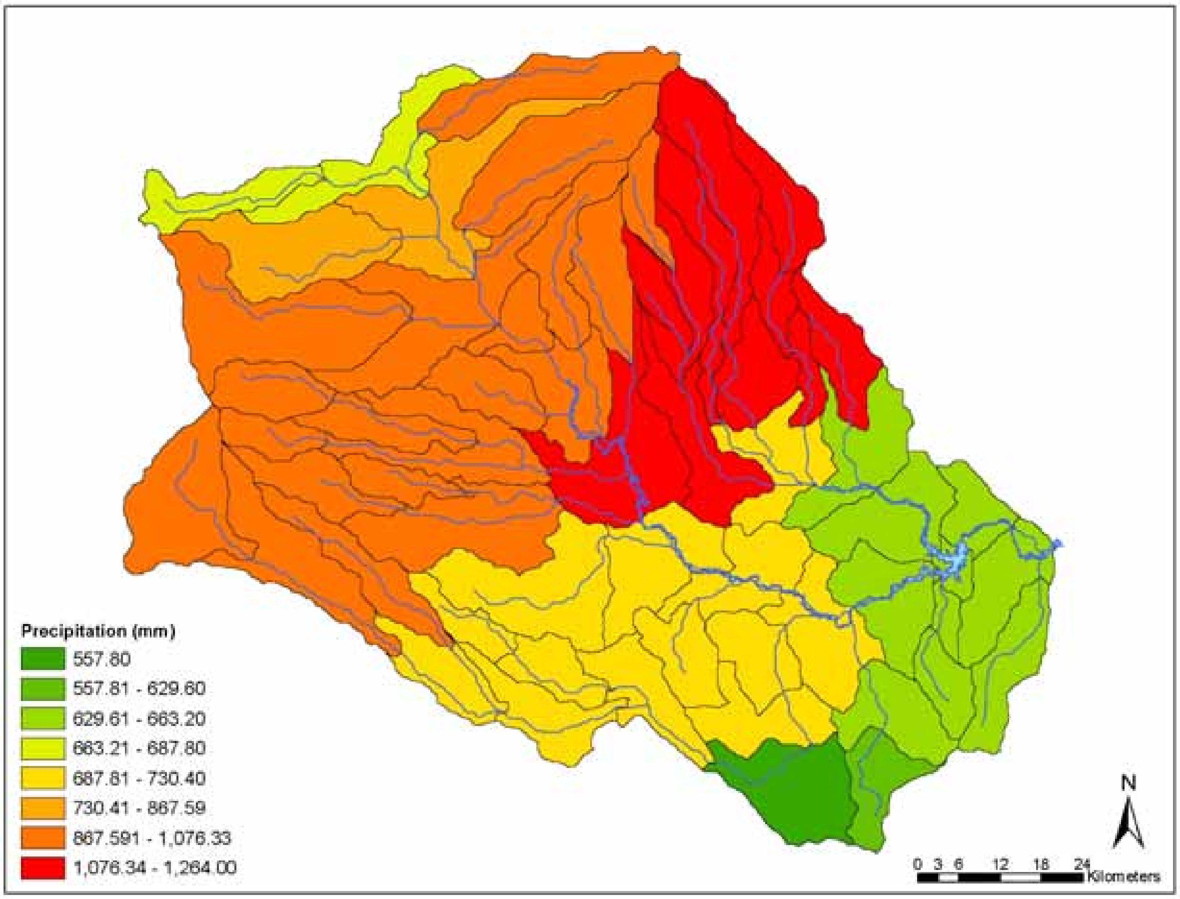

Figure 7. Average annual rainfall for the study area.

The CHARM rainfall data represent a "smoothed" daily rainfall since it is derived from 10-day accumulated historical data. Because the "smoothed" data had a tendency to over or underestimate daily events, the data were "event corrected" using event statistics from the WMO stations, thus allowing the CHARM data to behave in a more hydrologically correct manner.

Climate data used in the SWAT model followed the following order of importance: WMO, Laikipia data, and event corrected CHARM. For the SWAT analysis, the subbasins containing the Amboni and Sagana streamgauge stations used Laikipia rainfall stations (Solio Ranch and Muringato Forest, respectively) for rainfall data. The subbasins containing the Gura, Tana Sagana, and Thiba streamgauge stations used the WMO stations for rainfall data. The Gura station used Nyeri WMO, whereas Tana Sagana and Thiba both used the Embu WMO station. For the final streamgauge, Thiba 2, CHARM rainfall data was used (Figure 8).

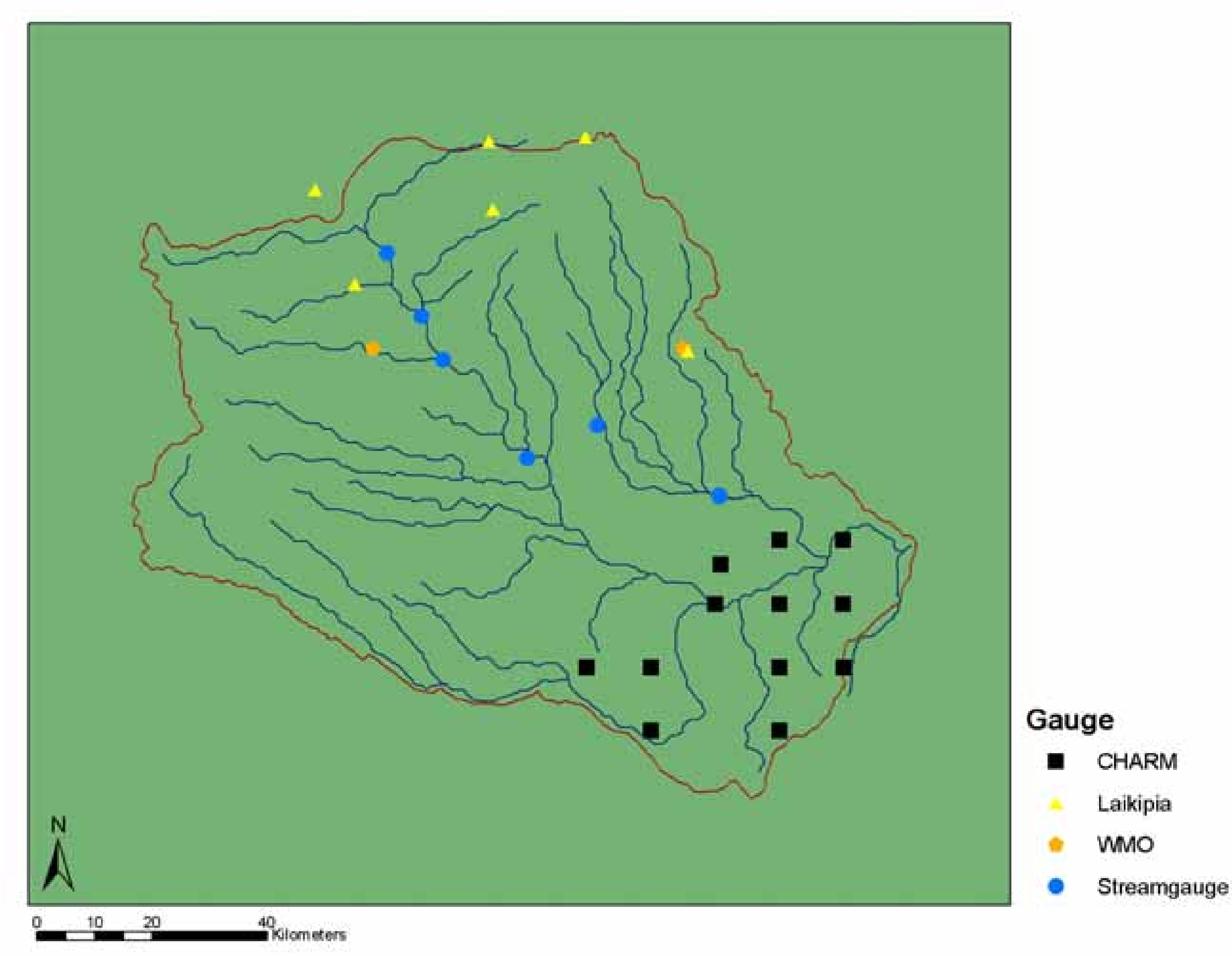

Figure 8. Rain and streamgauge locations for the study area simulations.

Elevation data (Figure 3) was acquired from a resampled version of the USGS 1 km Digital Elevation model. This data has been refined by the USGS using the Shuttle Radar Topography Mission (SRTM) DEM data. The USGS data was resampled back to 100 m using an ArcView Spline routine (Paul Dyke, personal communication). The DEM was used to define slopes, aspects and sub-basin boundaries within the study area.

In order to define soil units within the study area, the Kenya 1:1 million scale Soil and Terrain (KENSOTER) database developed by the Kenya Soil Survey (KSS) along with the International Soils Reference and Information Centre (ISRIC) was used (Figure 4). Soil map units within the KENSOTER spatial database represent a single soil series or an association of several soils. For this analysis, the dominant soil in the soil unit polygon was selected and attribute data for those soils was extracted from the database and used in the model. For soils having no available attribute data, soil parameter estimators from the EPIC crop model and the Soil Water Characteristics calculator (http://www.bsyse.wsu.edu/saxton/soilwater/) were used to fill in missing data.

Land use and land cover in this analysis was derived from the Kenya Department of Resource Surveys and Remote Sensing (DRSRS) survey that was conducted to define land use and land cover for medium and high potential agricultural areas (Njuguna, 2001). The DRSRS survey resulted in land use/land cover designations for points spaced on an approximately 2,400 x 4,800 m irregular grid (Figure 9). At each point, the percentage of each land use/land cover was defined. A total of 97 unique land use/land cover types were established in the DRSRS survey (Table 2). The DRSRS sample points (Figure 10) were converted to a grid format for use in the SWAT hydrologic model. The land uses that comprised greater than 90% of the total land uses at a given point (i.e., the dominant land uses) were used in the SWAT simulations. At most, four land uses were defined for each grid cell. Each land use within each grid cell was given an appropriate weighting factor based on its proportionate contribution to the dominant land uses. For example, if maize, beans, and coffee were the dominant land uses for a grid and maize was 70%, beans 20%, and coffee 10%, then the weighting factors would be 0.7, 0.2, and 0.1 respectively for that grid cell. The DRSRS survey was conducted for only high and moderate potential agricultural areas in Kenya. Because of this, no land use data was available for some of the forested areas in the north western portion of the study area and the low potential areas in the southeastern portion of the study area (Figure 10). For the areas, a coarser scale land use map (JICA, 1987) was used. The areas defined by this method were mostly forests and rangelands.

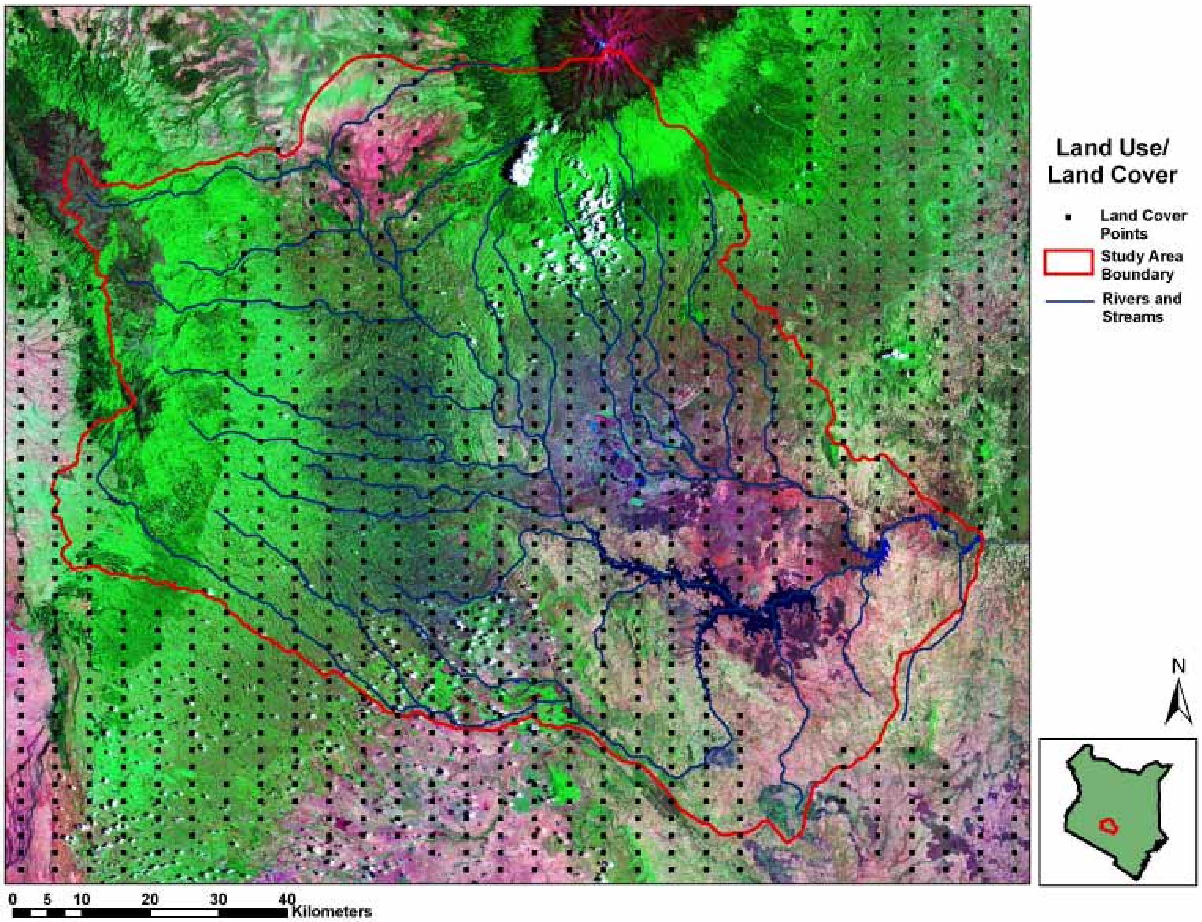

Figure 9. Location of DRSRS land use/land cover points used for defining land uses for they hydrological analysis in the upper Tana River study area. Base image is a LandSat 5 composite from images taken during 1989 to 1991.

Because of the diversity of land uses across the study region and within each grid cell, many combinations of land uses were possible. A summary of the dominant land use combinations indicated that across all grids, approximately 1,100 unique land use combinations were used in this analysis.

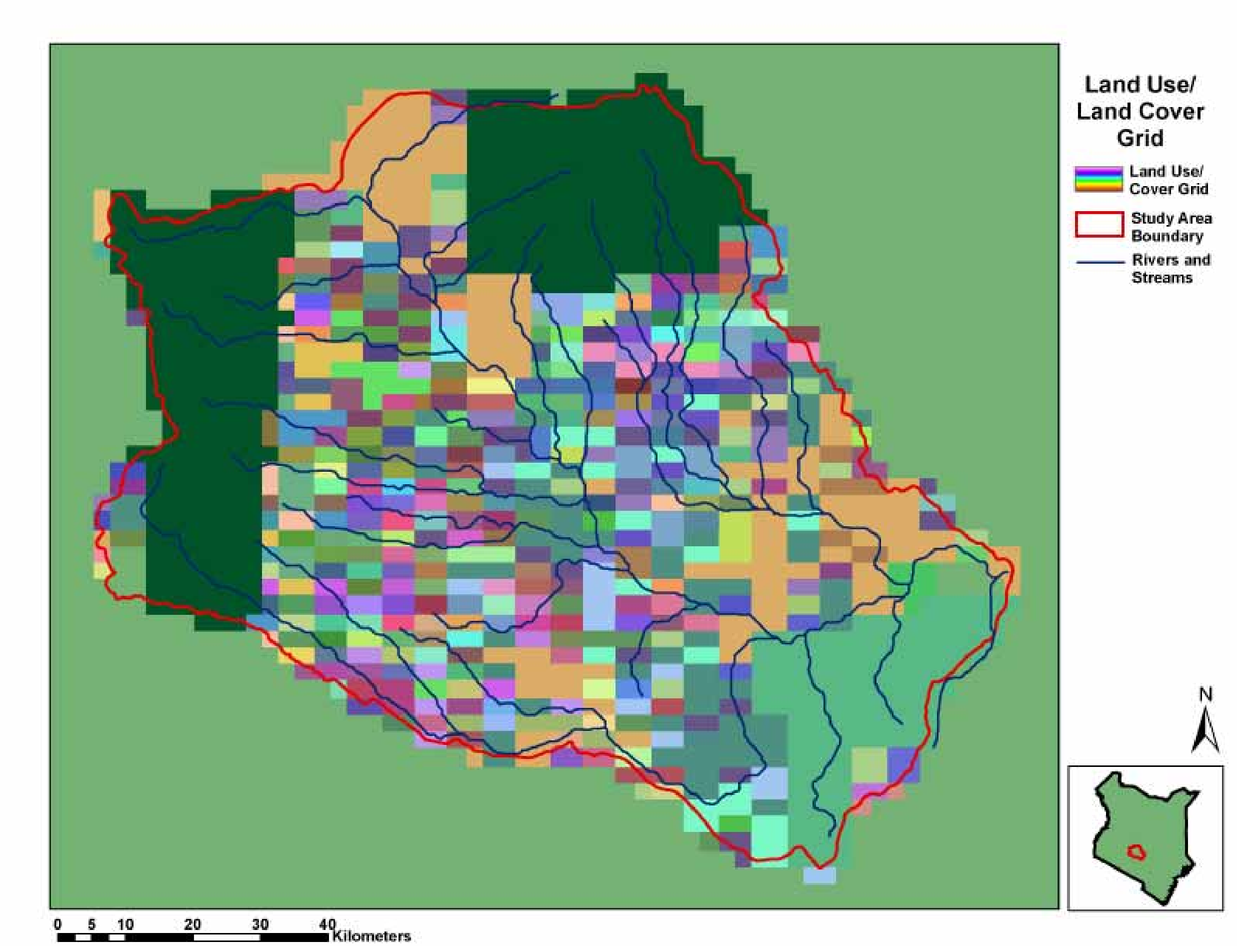

Figure 10. Land use grid used for the base hydrology analysis. Each grid cell (2400 x 4800 meters) represents a combination of up to 4 dominant land uses. Colors represent unique combinations of land uses.

Table 2. Land-use Land-cover types (DRSRS) and the corresponding codes used.

Code	Description	Code	Description	Code	Description	Code	Description
AR	Arrow roots	GR	Grazing	NG	Napier Grass	SN	Saina
AC	Avocados	GN	Ground Nuts	NF	Natural forest	SB	Shrubland
BN	Banana	HD	Hedges	OG	Oranges	SL	Sisal
BP	Banana-P.Peas	HC	Hortculture	OR	Orchard	SG	Sorghum
BO	Banana-Potato	LM	Lemon	OO	Others	ST	Structures
BT	Banana-Tea	MH	Mabati House	PM	P.Peas-Millet	SC	Sugar Cane
BW	Banana-Woodlot	MT	Maiz-Bean-P.Pea	PS	P.Peas-Sorgum	SF	Sun-Flower
BA	Bare	MY	Maiz-Sorg-P.Pea	PC	P.Peas/Coffee	SW	Swamp
BV	BE-VG-PO	MZ	Maize	PT	Path	SP	Sweet Potato
BE	Beans	MB	Maize-Banana	PW	Pawpaw	TE	Tea
BS	Bush	ME	Maize-Beans	PP	Pigeon Peas	EM	Tea-Maize
BG	Bush-Grazing	MA	Maize-Coconut	PA	Pine Apple	TH	Thatched House
CL	Canal	MC	Maize-Coffee	PF	Planted forest	TG	Thatching Grass
CN	Cashew Nut	MG	Maize-Groundnut	PL	Ploughed	TB	Tobacco
CA	Cassava	MM	Maize-Millet	PO	Potato	TM	Tomatoes
CT	Citrus	MO	Maize-Potato	PB	P.Peas-Beans	TR	Track
CC	Coconut	MP	Maize-P.Peas	PK	Pumpkin	VB	Veg.- banana
BX	Coff-Bana-Wlot	MS	Maize-Sorgum	PY	Pyrethrum	VG	Vegetable
CF	Coffee	MV	Maize-Veg..	QR	Quarry	WB	Water Bodies
CB	Coffee-Banana	MN	Mangoes	RL	Railway	WT	Wattle Tree
CW	Coffee-Woodlot	MF	Mangrove Forest	RC	Rice	WH	Wheat
CO	Cotton	MX	Maz-Sorg-Beans	RV	River	WL	Woodlot
FL	Fallow	ML	Millet	RF	Riverine Forest	YM	Yam
FP	Fish-Pond	MR	Miraa	RD	Road		
FR	Forest	MQ	MZ-PO-BE-PP				

Streamflow Data

Stream discharge data used in this study were from the Amboni, Sagana, Gura, Tana-Sagana, Maragua, Yatta Furrow, Thiba 2 and Saba Saba gauging stations located on their respective river tributaries (Table 3). This data was obtained from the Ministry of Water Resources Management and Development headquarters in Nairobi. There were many gaps in the daily data which were associated with seasons when the rivers flooded and gauges were lost. Some of the stations were dropped in the calibration because of incomplete data.

Table 3. Stream gauge data stations in the Upper Tana River Basin,

Gauge ID	River Name	Longitude	Latitude	Year
4AB05	Amboni	36.98889	-0.35	1949-1996
4AC03	Sagana	37.04306	-0.449176	1948-1999
4AD01	Gura	37.07639	-0.517222	1951-1996
4BC02	Tana Sagana	37.20694	-0.672222	1947-2000
4BE01	Maragua	37.15278	-0.75	1945-2000
4CC03	Yatta Furrow	37.36111	-1.094444	1979-1988
4DD02	Thiba	37.50611	-0.731667	1962-1996
4BF02	Saba Saba	37.21944	-0.797222	1967-1999
4DA10	Thiba	37.31667	-0.620833	1966-1993

METHODS

SWAT Hydrologic Model

Most of the prior studies of the Tana Rivers system, and in particular the Upper Tana catchment above the Masinga Dam, have focused on the potential erodabiltiy of soils (Schnieder and Brown, 1998) and the use of the HEC-RAS engineering model (Maingi and Marsh, 2002). In this study, the Soil and Water Assessment Tool (SWAT) model was used to better understand the hydrological processes of reforestation at the higher elevation regions of the Upper Tana basin. The SWAT model is a basin-scale, distributed-parameter model operating on a daily time step. It is the continuation of a long-term effort on hydrologic and nonpoint source pollution modeling by the USDA-Agricultural Research Service (ARS). The objective in model development was to predict the impact of management on water, sediment and agricultural chemical yields in large river basins over long periods. To satisfy this objective, the model (a) is physically based (calibration is not possible on ungauged basins); (b) uses readily available inputs; (c) is computationally efficient to operate on large basins in a reasonable time, and (d) is continuous in time and capable of simulating water quantity and quality for long periods. It also includes a comprehensive phenological crop growth model. The model has been applied in several basin-scale studies involving assessment of water supply and nonpoint source pollution in the United States. Arnold *et al.* (1999) reported the results of SWAT applications for hydrologic simulation in all river basins in the United States. Several other studies (Rosenthal *et al*., 1995; Bingner, 1996; Bingner *et al*., 1996; Srinivasan *et al*., 1998; King *et al*., 1999) indicate the strength of the SWAT model in simulating streamflow and sediment movement in large basins.

SWAT-GIS Interface

Geographic Information Systems (GIS) play an important role in natural resource modeling and are effective tools that aid in hydrologic/water quality modeling studies and analysis of various management scenarios. The SWAT-GIS interface helps to integrate the spatial information on topography, soils, and land use with hydrologic modeling. This allows a large basin to be delineated into hundreds of subbasins or grid cells and thus helps to preserve the spatially distributed nature of model parameters over the basin area and their homogeneous characteristics within a subbasin. The ArcView interface for SWAT (Di Luzio *et al.*, 2002; http://www.brc.tamus.edu/swat/swat2000doc.html) was used for preprocessing and hydrologic simulations in this study.

Model Setup

The Upper Tana River Basin was represented by 60 subbasins with a 9,752.82 km^2 area for the model simulations (Figure 11). Rainfall data for the simulation was obtained from various sources. Actual rainfall was obtained from two WMO and seven Laikipia raingauge stations for the middle and upper subbasins of the watershed. However, no recorded data existed for the lower portions of the watershed and data was therefore obtained from the CHARM Rainfall described in the methods section of this report. Temperature data for the watershed was obtained from the two WMO raingauge stations. This was the only existing temperature data for the study area. Solar radiation, wind speed, and relative humidity were simulated by the SWAT model based on the temperature and rainfall inputs. Finally, streamflow data for the four gauges along the upper reaches of the Sagana River (Amboni, Sagana, Gura, and Tana Sagana) as well as the two gauges in the eastern portion of the watershed (Thiba and Thiba 2) were used as comparison points for the predicted flow from model simulations (Figure 8). The remaining gauges were not used due to large data gaps for the study period.

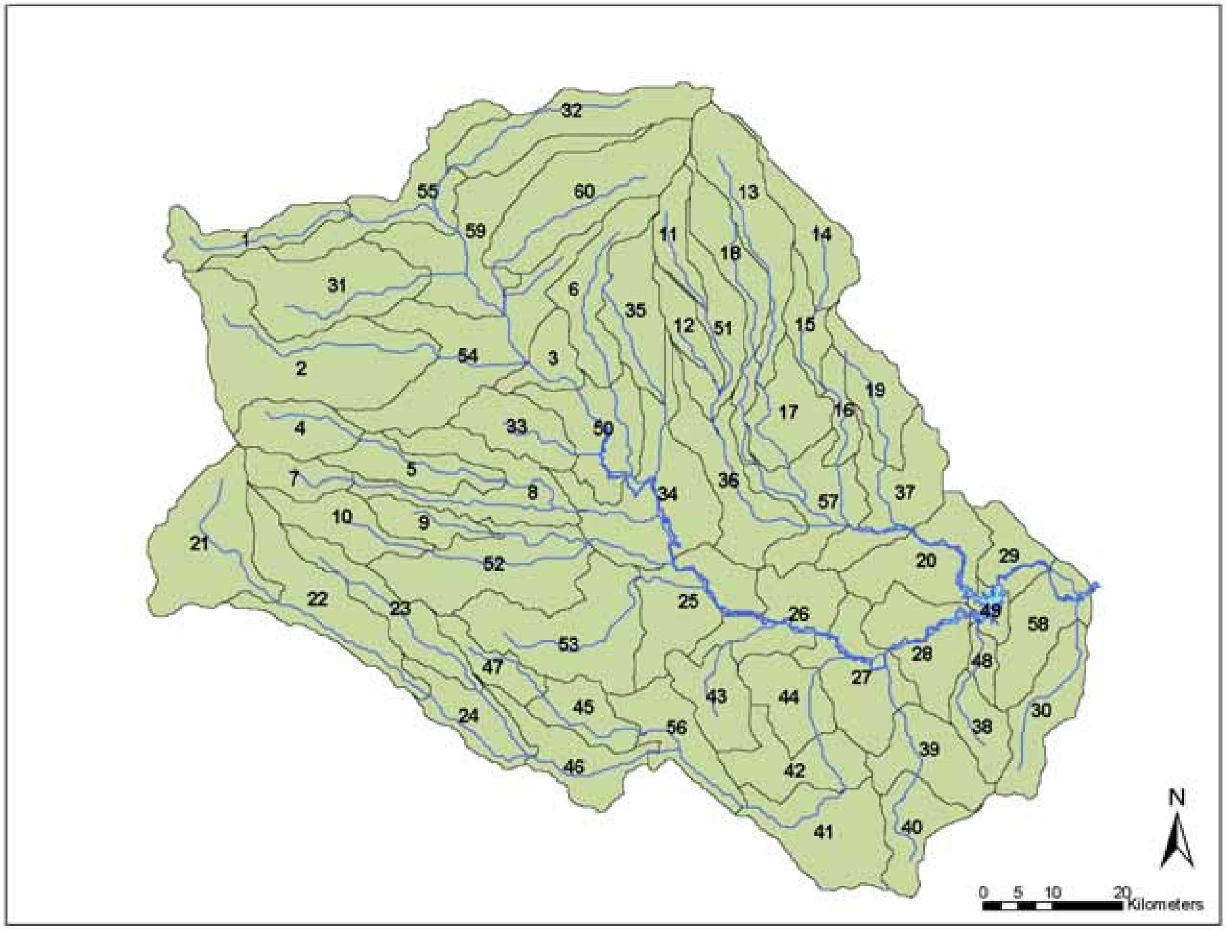

Figure 11. SWAT subbasin delineation for the study area.

The time period from 1978 – 1995 was used for model simulation based on the need to have data overlap between the flow data and the weather input data. The first three years of the simulation were used as a model "warm-up" period during which model conditions stabilized. These years were therefore omitted from final result comparisons. The results reported in this study for various simulations consist of data for the time period from 1981 – 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 and Arnold and Allen, 1999) was used to separate the baseflow and runoff portions of flow from measured streamflow data obtained for the study area. In addition, the baseflow alpha factor, or baseflow days, was calculated for the four streamgauge locations along the main channel of the catchment on the Sagana River. This 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.*, 2001). This recession constant was applied to all model delineated subbasins in the reaches above each gauge in the various simulations. For the last gauge, Tana Sagana, subbasins above and below the gauge were given the same recession constant.

Economic Analysis

Applied welfare analysis is used to model conditions under which net gains to society can be increased through more efficient resource allocations (Figure 12). If the external costs are caused by sedimentation, as in this paper, then efficiency is increased through establishing a new economic equilibrium within the watershed. This is achieved using mechanisms that, in one way or another, incorporate the social costs associated with the use of the watershed's resources into the private decision making calculus. In doing so, the downstream benefits and upper watershed costs of sediment reduction can be better aligned.

Downstream user groups will obtain benefits from reduced sediment loading that can be represented as a demand curve for sediment reduction (Figure 12). These downstream benefits would include reduced dredging costs, better regulated water flow for agricultural and municipal drinking water purposes, fewer disruptions in hydroelectric power generation, and reduced probabilities of flooding. The largest benefits would occur over the initial range of sediment reduction, which would fall as the effects of sedimentation become less severe.

Once incentives are imposed on upper watershed users to account for downstream sedimentation, efficiency requires sediment be reduced in a least cost manner that can be represented using a cost curve (Figure 12). The primary means to reduce sediment involve either (or both) shifts in land use towards alternatives that have increased vegetative protection or the adoption of less erosive agricultural/pastoral practices. The efficient path to sediment reduction typically begins with land use shifts that have low opportunity costs associated with them, such as abandoned, deforested areas and marginal lands that have little pastoral use. Once such alternatives are exhausted, the switch to less erosive farming techniques and crop substitution patterns can typically provide additional sediment reduction at reasonable costs. Sediment reduction costs rise quickly once shifts in land use reach agricultural lands as the associated opportunity costs can be substantial, particularly when cash crops are involved.

Efficiency is maximized at the point where the downstream benefits from sediment reduction equal the associated costs on upstream users, C_E. To the left or right of this point efficiency is reduced due to costs either being above or below the benefits they derive. The net gain to society from this more efficient allocation of watershed resources is given by the area A. This represents the sum of the gains (benefits less costs) accrued along the sediment reduction path. The equilibrium sediment reduction, Q_E, is the quantity of sediment that is maintained in the upper watershed as a result of the more efficient allocation of watershed resources.

Figure 12. Net gains to society from upstream sediment reduction.

Hydro-Economic Model

An empirical hydro-economic model (HEM) was developed to determine the optimal reforestation policy using a sub-basin average approach. This approach accounts for the spatial variability in sediment reduction costs and downstream benefits. The reforestation scenarios used in the SWAT simulation provide the potential for more efficient resource allocations. The HEM considers both the benefits and costs associated within each of the subbasins, given the shifts in land use from one reforestation scenario to the next. Integer programming is used to maximize the net gains to society through optimally selecting which of the subbasins provide positive net economic gains to the watershed's economy.

The HEM maximizes net gains to society (i.e. social welfare) using an objective function that includes the upper watershed opportunity costs from shifts in land use as well as the lower watershed benefits from induced reduction in sediment flow. Subbasins that fail to satisfy economic efficiency, i.e. providing more benefits than sediment reduction costs, are left out of the optimal reforestation strategy. In essence this acts as a filter, leaving intact subbasins that for a given dredging cost have too large an opportunity cost associated with its shifts in land use.

The sub-basin average objective function, for scenario S, is given by:

$$\text{Max} \quad NG_S = \Sigma_i\, d\Delta Q_{si} X_i \; - \Sigma_i \Sigma_j \left[(P_{jk} Y_{jk} A_{jk} - c_{jk})_S - (P_{jk} Y_{jk} A_{jk} - c_{jk})_{Base} \right] X_i \qquad (1)$$

where X_i is the integer decision variable (1=reforest) for the i^{th} subbasin. This equation determines the difference between the upper watershed opportunity costs from shifts in land use and the lower watershed benefits from reduced sedimentation. The opportunity costs are found through summing profits across each of the subbasin HRUs under both the reforestation and baseline scenarios. Benefits within each subbasin are given by the savings in lower watershed dredging costs, d, from reduced sedimentation that is attributed to the sub-basin, ΔQ_{si}. The binary decision variable, X_i, is included in the objective function to select which subbasins to reforest.

The optimal first order economic conditions (FOC) are given by the derivative of the objective function with respect to the sub-basin reforestation decision variable, X_i, being greater than (or equal) to zero. The above notations and definitions are used to write the FOC as:

$$\partial(NG_S)/ \partial X_i = d\Delta Q_{si} - \Delta\Pi_i \geq 0 \quad (2)$$

The subbasin optimal condition requires the downstream sediment reduction benefits induced by the i^{th} subbasin be greater than (or equal) to the change in agricultural profits (i.e. opportunity cost), $\Delta\Pi_i$, from the subbasins shift in land use towards increased forest cover. When this condition (Equation 2) is satisfied, the subbasin will be included in the optimal reforestation strategy (X_i=1). The watershed average optimal condition is similar in concept, requiring that the watershed level benefits be greater than watershed level costs, which in this case can be simplified to read unit dredging costs, d, be greater than watershed level costs, C_E:

$$d - C_E \geq 0 \quad (3)$$

The watershed scale, however, allows only a single decision variable, X_S., where X_S =1 represents a scenario recommended for reforestation based upon the condition of positive net gains.

RESULTS

Baseline Model Values

The precipitation for the model scenarios was plotted by subbasin and ranged from 22,056,514 m^3 to 403,787,196 m^3 (Figure 13). The highest rainfall was found in the upper reaches of the catchment and within a few subbasins in the middle of the catchment. The lowest rainfall totals were found at the lower elevations in the southern portion of the catchment.

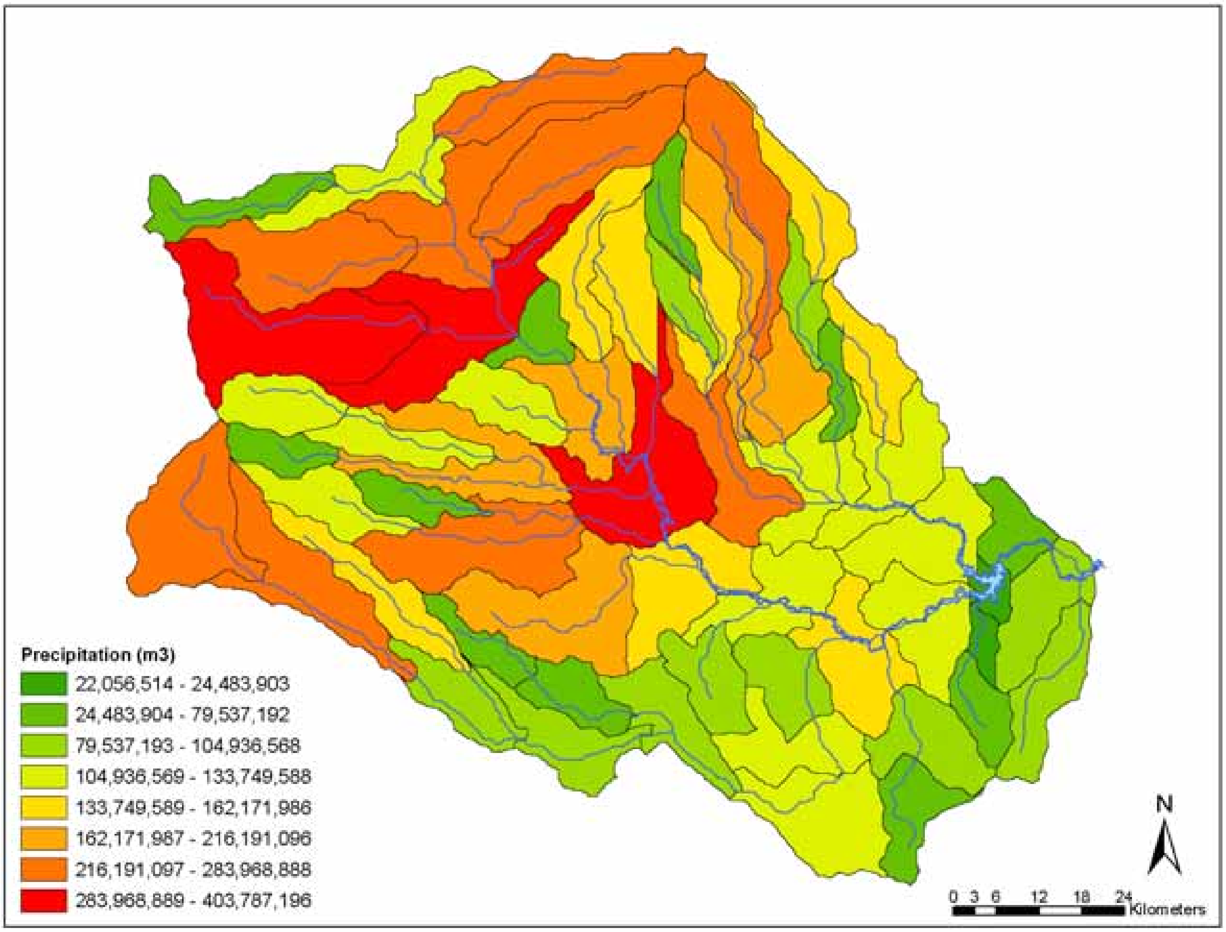

Figure 13. Average annual precipitation for catchment subbasins.

As expected, runoff for the catchment subbasins generally matched the rainfall highs and lows. Runoff ranged from 307,322 m^3 to 107,016,347 m^3 and generally decreased in a northwest to southeast direction (Figure 14).

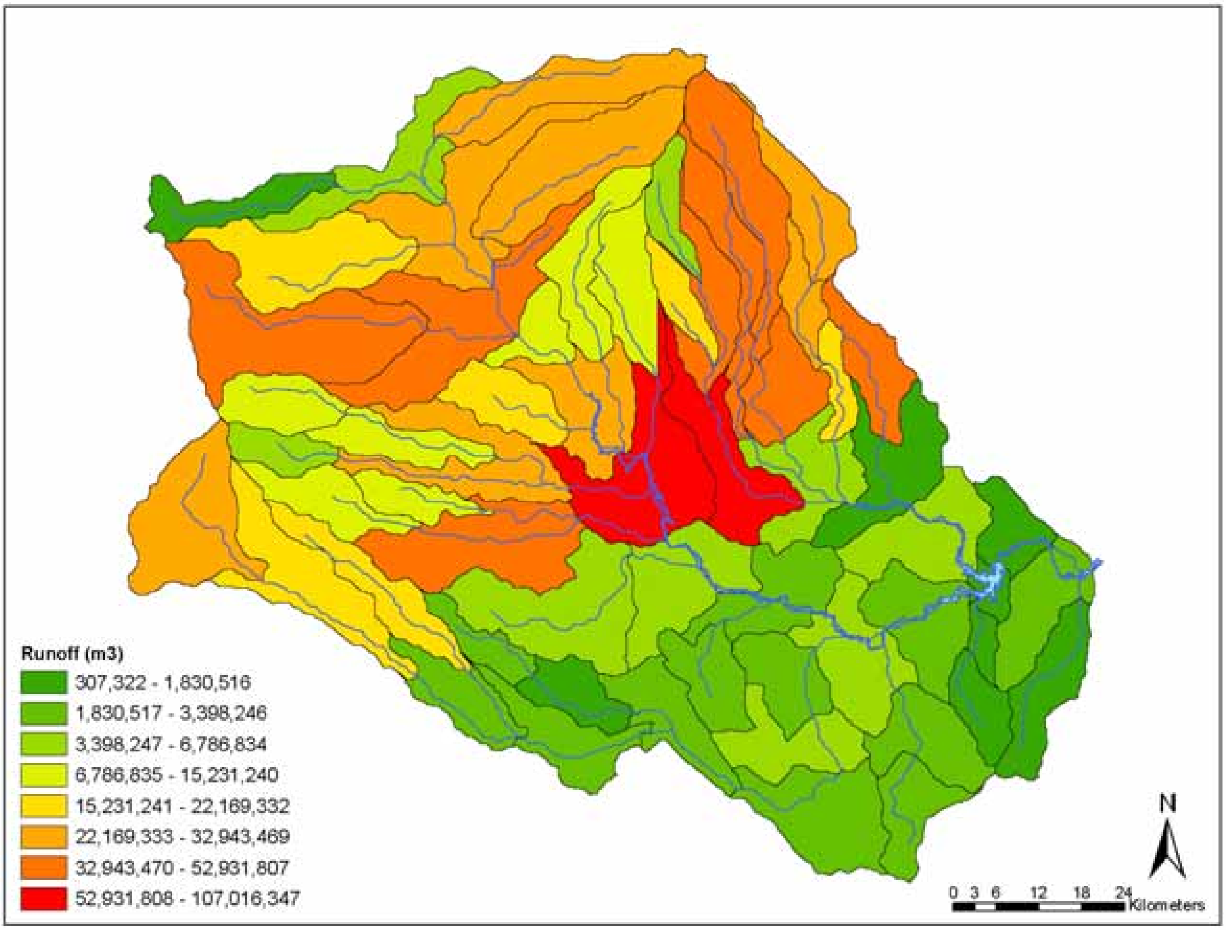

Figure 14. Average annual runoff for catchment subbasins.

Within the sub-basins, the ratio of runoff to rainfall, or the proportion of rainfall that becomes runoff, was highest in the upper and middle areas of the catchment. As was seen with rainfall, runoff decreased in the lower elevations in the southern portion of the catchment (Figure 15). The percentage of rainfall that becomes runoff ranged from over 31% to about 1% in a northwestern to southeastern direction, due mainly to the difference in the amount of rainfall and land cover types over the catchment.

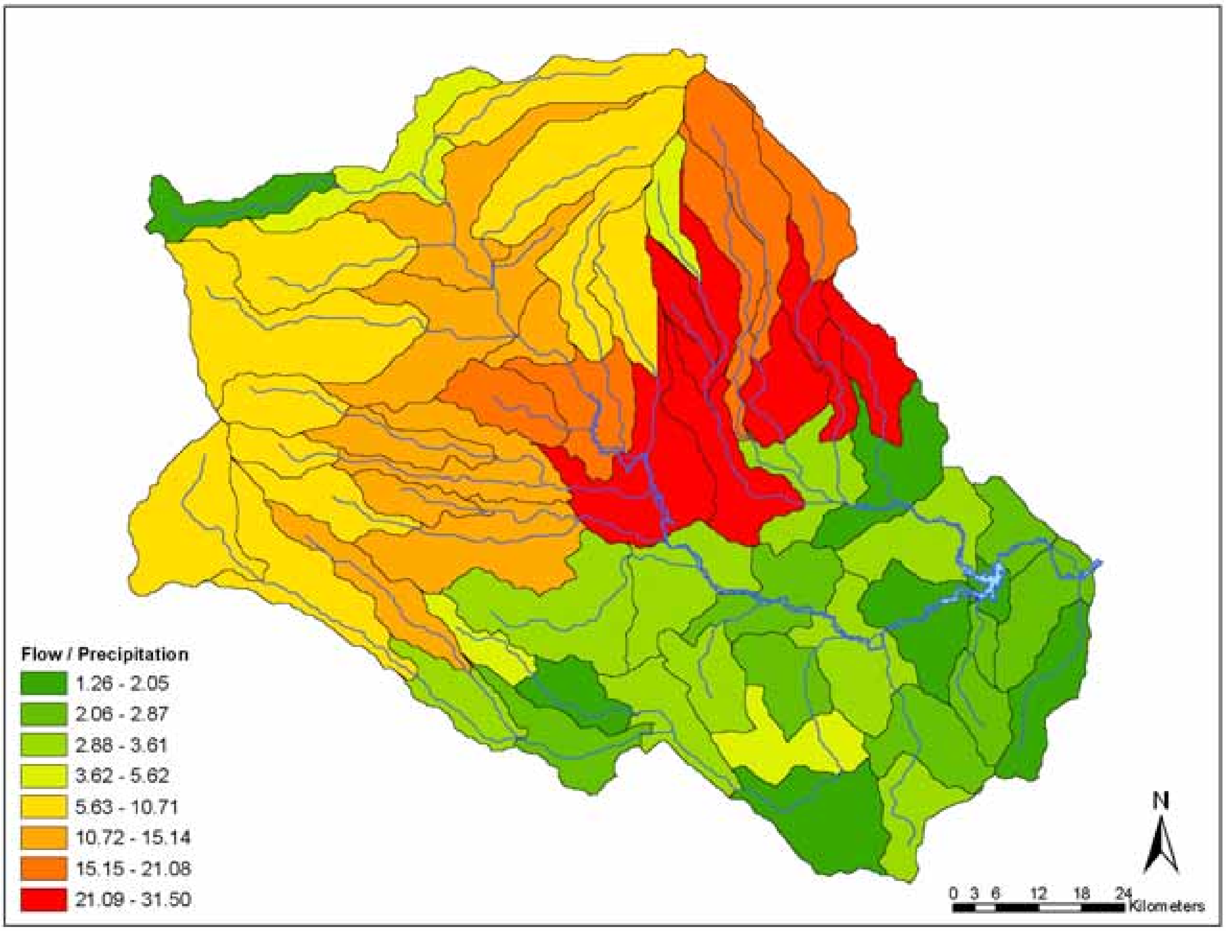

Figure 15. Percentage of runoff from rainfall by subbasin.

The sediment load to the stream network by subbasin ranged from 11 tons to 388,294 tons (Figure 16). This sediment load is highest in the middle portion of the catchment. This is mainly due to the relatively high rainfall in this location as well as the agricultural land use in the area. High population density and intensive cropping in this region leave the soils susceptible to erosion through lack of soil protection and the cropping of marginal lands having steep slopes or high erodibility (Mutisya and Mutiso, 1998).

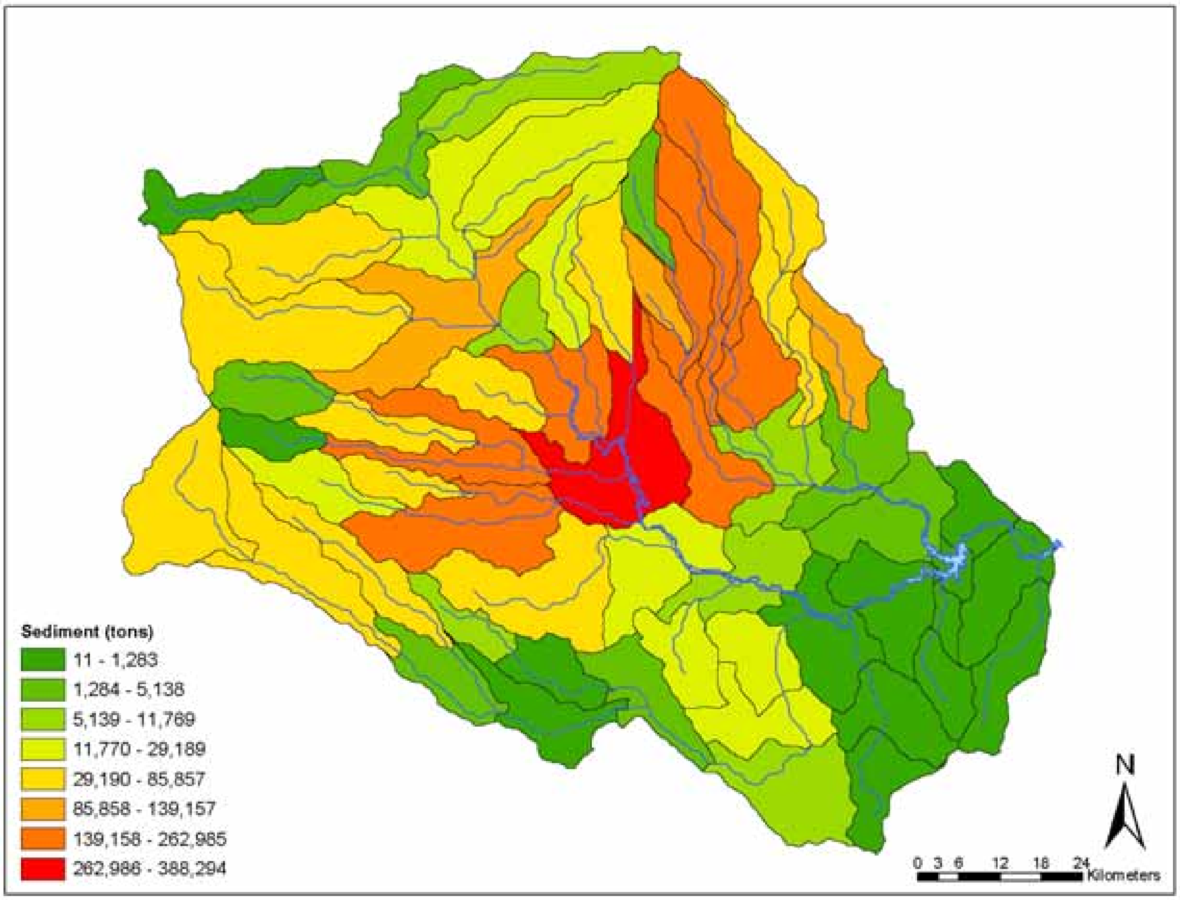

Figure 16. Average annual stream network sediment load by subbasin.

Model predictions were compared to observed data using estimation efficiency (Nash and Sutcliffe, 1970) and linear regression analysis. Estimation efficiency is commonly used in hydrologic model evaluation and is calculated as (Equation 4):

$$COE = 1.0 - \left(\frac{\sum_{i=1}^{n} (O_i - R_i)^2}{\sum_{i=1}^{n} (O_i - O_m)^2} \right) \qquad (4)$$

where *COE* is the coefficient of efficiency, or runoff estimation efficiency, *n* is the number of days of comparison, O_i is the observed streamgauge runoff for a watershed for day *i*, O_m is the mean observed streamgauge runoff for a watershed over all days, and R_i is the predicted (SWAT simulated) runoff for a watershed for day *i*. When $R_i = O_i$, $COE = 1$. This would represent a high correlation between observed and predicted runoff values. Where *COE* is less than one, the predicted runoff value is less representative of actual runoff than the mean value for the dataset. For most watershed studies, a COE value greater than 0.2 is considered a good correspondence between predicted and observed flow.

For linear regression, both the coefficient of determination (r^2) and slope with zero intercept for the linear regression fit between observed (streamgauge) and predicted (SWAT simulated) runoff values were used to determine significance.

Table 4 is a summary of the overall statistical analysis for the six streamgauges in this study including results from basic summary statistics, estimation efficiency, and linear regression. For these comparisons, data was sorted by predicted flow and the upper and lower 2.5% of the data points were removed from comparison. This process removed the outliers from statistical analysis. In some cases additional data points were removed based on missing or incomplete observed flow data. The removal of these points helps to provide a more realistic idea of estimation efficiency in that predicted flow will not be compared to a zero flow in the observed dataset.

The *COE* for the Amboni station was -0.643, which indicates that the predicted value is less representative of actual flow than the mean for the observed flow. Also, the monthly mean observed flow at this station was 1.558 cms, whereas the predicted flow was 1.799 cms (Table 4). This suggests that the model slightly over predicted streamflow at this gauge. This is also visible in the gauge hydrograph (Figure 17). In this instance, the SWAT model seems to over predict during peak events. The y-intercept and r^2 values are 0.992 and 0.223, respectively (Figure 18). The low r^2 provides an indication of the high degree of variability in the observed and predicted flow values. This variability may be due in part to the lack of representative, quality rainfall data for the upper reaches of the watershed. In fact, the Solio Ranch station used for rainfall data in this subbasin is located outside the catchment area; however, this was the raingauge station in closest proximity to the Amboni streamgauge. In addition, this station’s rainfall data was from the Laikipia database which may have had errors and gaps in data reporting and collection.

For the Sagana station, model results were somewhat improved. The *COE* for this station was 0.251, with a y-intercept of 0.629 and r^2 of 0.38 (Figure 19). The model, however, slightly under predicted the flow at this station with an observed mean flow of 7.306 cms and predicted mean flow of 5.414 cms (Table 4). This is evidenced by the hydrograph (Figure 20) in that the model generally under predicted observed values and slightly over predicted flow during peak events. The lack of correspondence between observed and predicted flow could again be attributed to the lack of quality rainfall input data. In addition, this station is missing 14 days of stream flow data, which would further affect the statistical comparisons.

At the Gura station, the statistics were again improved, with a *COE* of 0.32. The model slightly under predicts flow with an observed mean of 12.01 cms and a predicted mean flow of 9.703 cms (Table 4). As seen previous, the hydrograph indicates that the model over predicted during peak events, and under predicted during low flow events; however, as a whole, the predicted flow tracks the observed flow quite well (Figure 21). This gauge had a y-intercept of 0.829 and an r^2 of 0.547 (Figure 22). This station uses the rainfall data from the Nyeri WMO station. The WMO data is the most complete and accurately maintained rainfall dataset used in this study, and Nyeri is very near the Gura streamgauge station. This would help to explain the improved statistics.

The Tana Sagana station had the highest *COE* at 0.370 with a y-intercept of 0.616 and r^2 of 0.527 (Figure 23). The flow was again somewhat under predicted with an observed mean of 34.525 cms and a predicted mean of 22.207 cms (Table 4). However, the hydrograph indicates that the predicted flow from the model generally tracks observed flow (Figure 24). In this subbasin, WMO data was used for rainfall input. Also, 12 days were removed from this comparison based on lack of observed flow data.

Table 4. Summary of statistical analysis of flow data.

	Amboni		**Sagana**		**Gura**		**Tana Sagana**		**Thiba**		**Thiba 2**	
	Observed	**Predicted**	**Observed**	**Predicted**	**Observed**	**Predicted**	**Observed**	**Predicted**	**Observed**	**Predicted**	**Observed**	**Predicted**
n	169	171	157	171	168	171	155	159	165	171	127	147
Monthly Mean (cms)	1.558	1.799	7.306	5.414	12.010	9.703	34.525	22.207	11.074	5.632	19.866	17.155
St. Dev.	1.330	1.931	6.097	5.206	8.945	10.258	30.107	23.427	8.870	6.111	14.264	16.515
COE	-0.643		0.251		0.320		0.370		-0.335		0.332	
y-intercept	0.992		0.629		0.829		0.616		0.414		0.812	
r^2	0.223		0.380		0.547		0.527		0.052		0.527	

Figure 17. Hydrograph for observed vs. predicted flow at the Amboni streamgauge station.

Figure 18. Amboni observed vs. predicted flow comparison.

Figure 19. Sagana observed vs. predicted flow comparison.

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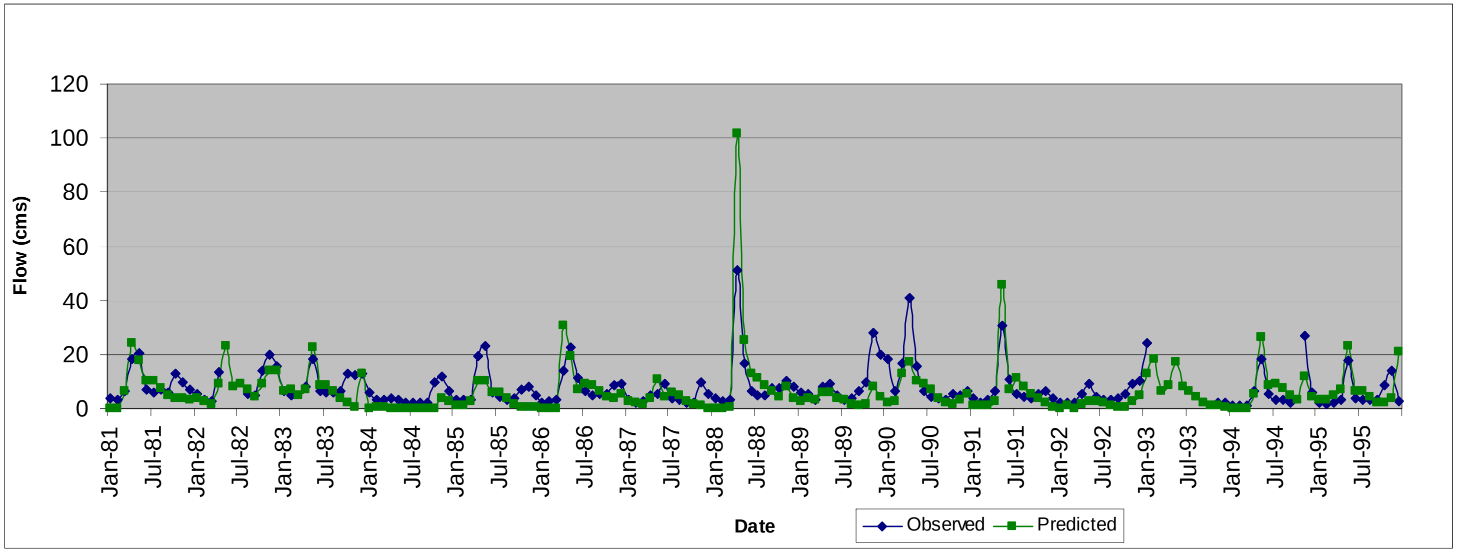

Figure 20. Hydrograph for observed vs. predicted flow at the Sagana streamgauge station.

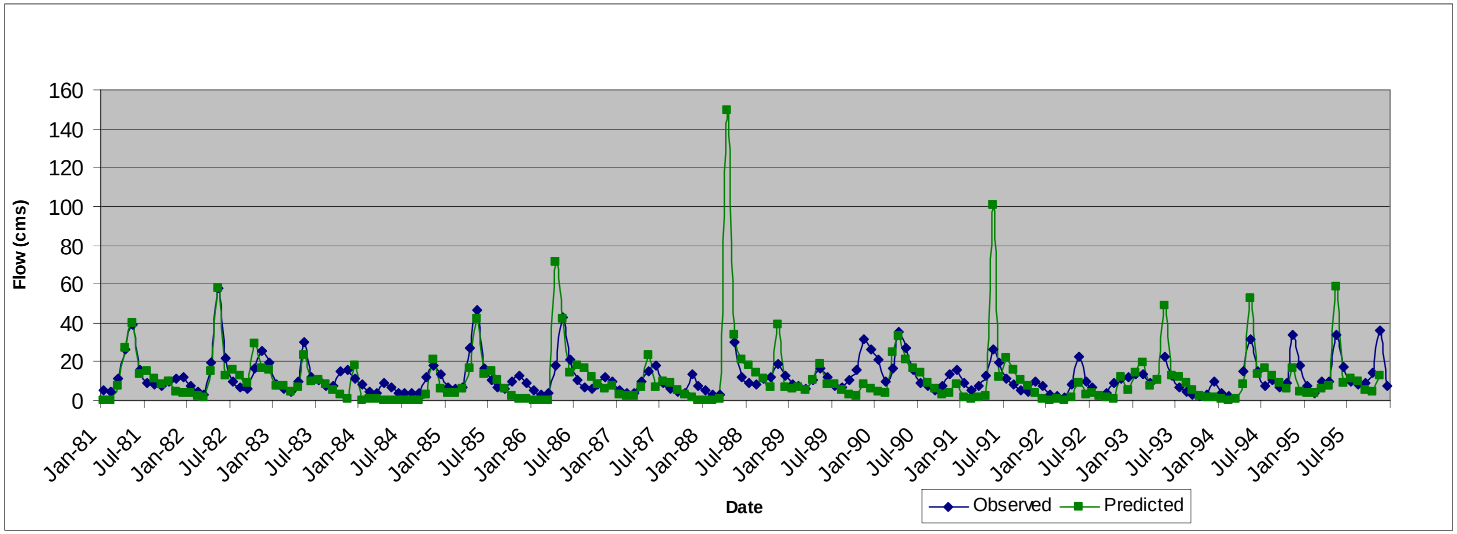

Figure 21. Hydrograph for observed vs. predicted flow at the Gura streamgauge station.

Figure 22. Gura observed vs. predicted flow comparison.

Figure 23. Tana Sagana observed vs. predicted flow comparison.

The Thiba station had a very low *COE* at -0.335. With a few exceptions, as exhibited in the hydrograph (Figure 25), the SWAT simulation generally under predicted flow. The mean observed flow was 11.074 cms, whereas the mean predicted flow was 5.632 cms (Table 4). The y-intercept for this gauge was 0.414 and the r^2 was 0.052 (Figure 26). The general lack of correspondence could be attributed to missing flow data and the lack of rainfall data that was appropriate for this gauging station. The Thiba 2 station has a relatively high *COE* at 0.332 and a y-intercept of 0.812 with an r^2 of 0.527 (Figure 27). Again, the SWAT model slightly under predicted the flow from runoff with an observed mean flow of 19.866 cms and a predicted mean flow of 17.155 cms (Table 4). There were a number of missing data points for this streamgauge, and an additional 24 days were removed from analysis due to these missing data points. In addition, this is the only gauge in which the CHARM data was used as the rainfall data source for the subbasin. The hydrograph supports this in that the predicted flow tracks the observed flow quite well (Figure 28).

Hydrographs were created for each of the gauge stations showing observed vs. predicted flow for two years, 1984 and 1988. These years were selected because they represent extreme periods of rainfall amounts. An extreme drought was recorded for 1984, whereas heavy flooding was recorded for 1988. These hydrographs suggest that for both wet and dry years the SWAT model tracks runoff well (Figures 29-40). However, as discussed previously, the SWAT model has a tendency to over predict flow from large runoff events.

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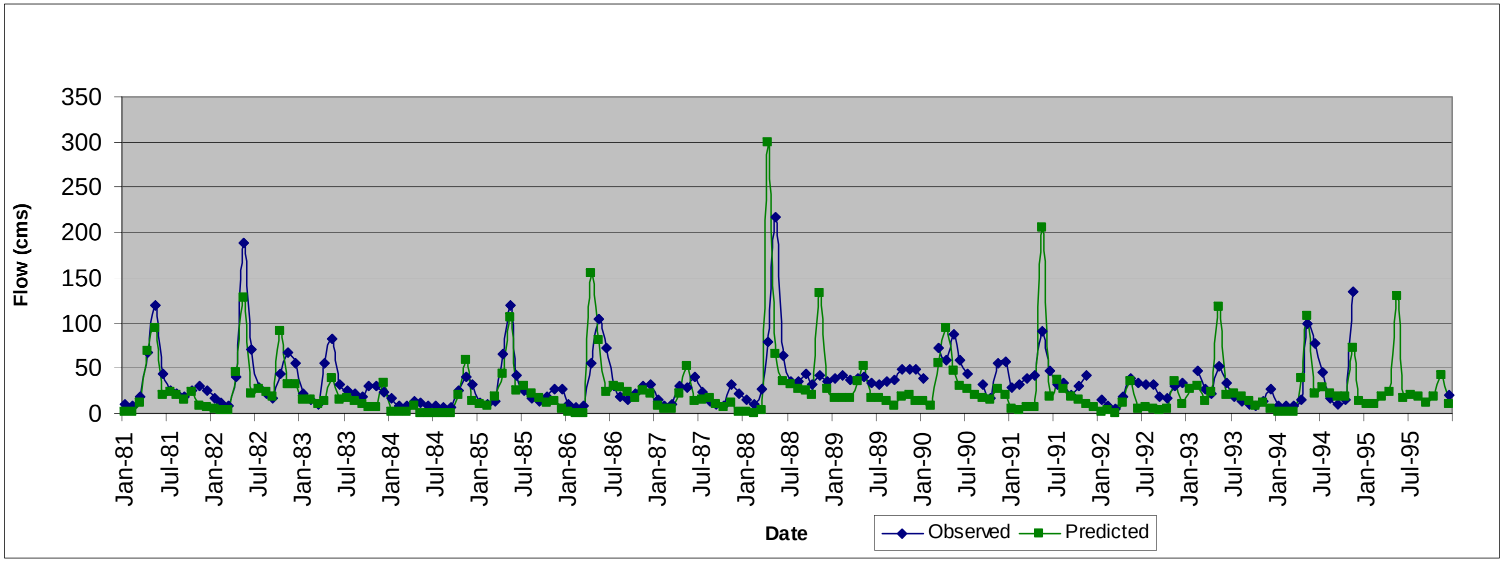

Figure 24. Hydrograph for observed vs. predicted flow at the Tana Sagana streamgauge station.

Figure 25. Hydrograph for observed vs. predicted flow at the Thiba streamgauge station.

Figure 26. Thiba observed vs. predicted flow comparison.

Figure 27. Thiba 2 observed vs. predicted flow comparison.

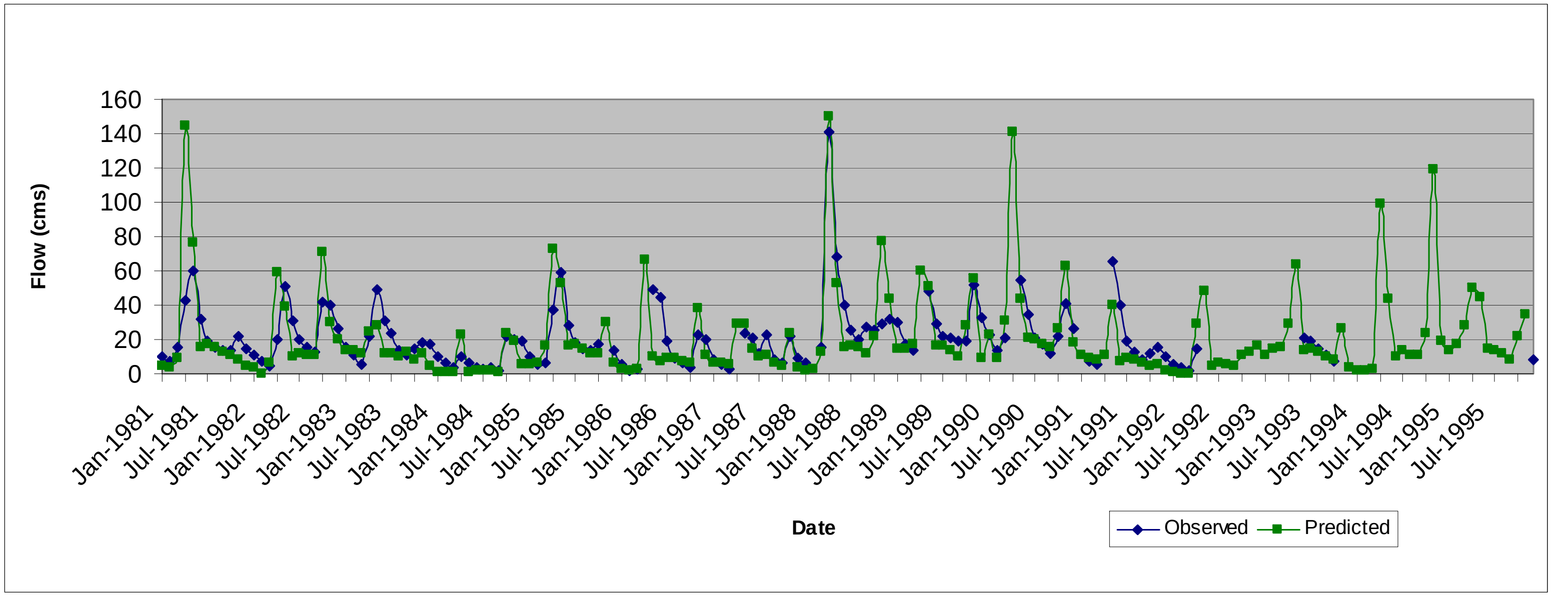

Figure 28. Hydrograph for observed vs. predicted flow at the Thiba 2 streamgauge station.

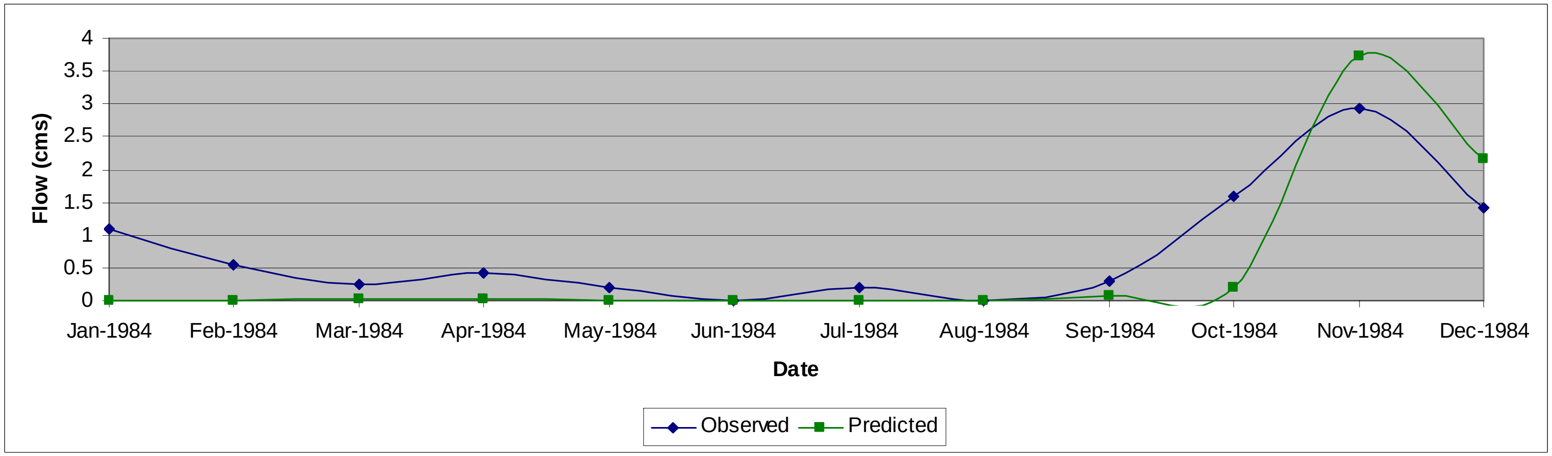

Figure 29. Hydrograph of 1984 drought at Amboni streamgauge.

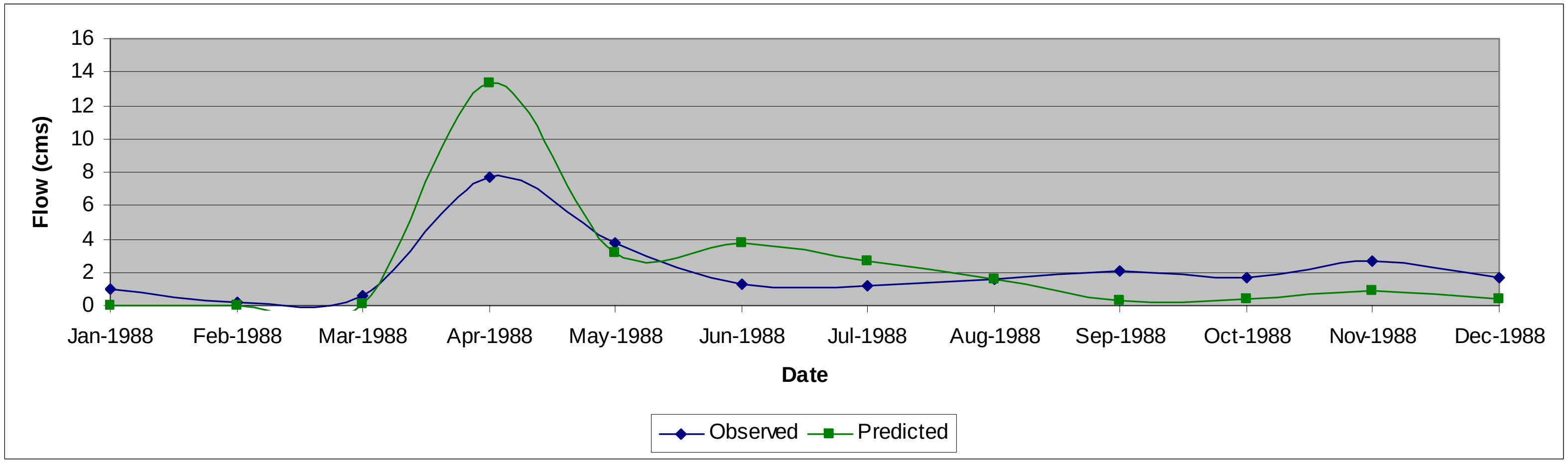

Figure 30. Hydrograph of 1988 (high rainfall year) at Amboni streamgauge.

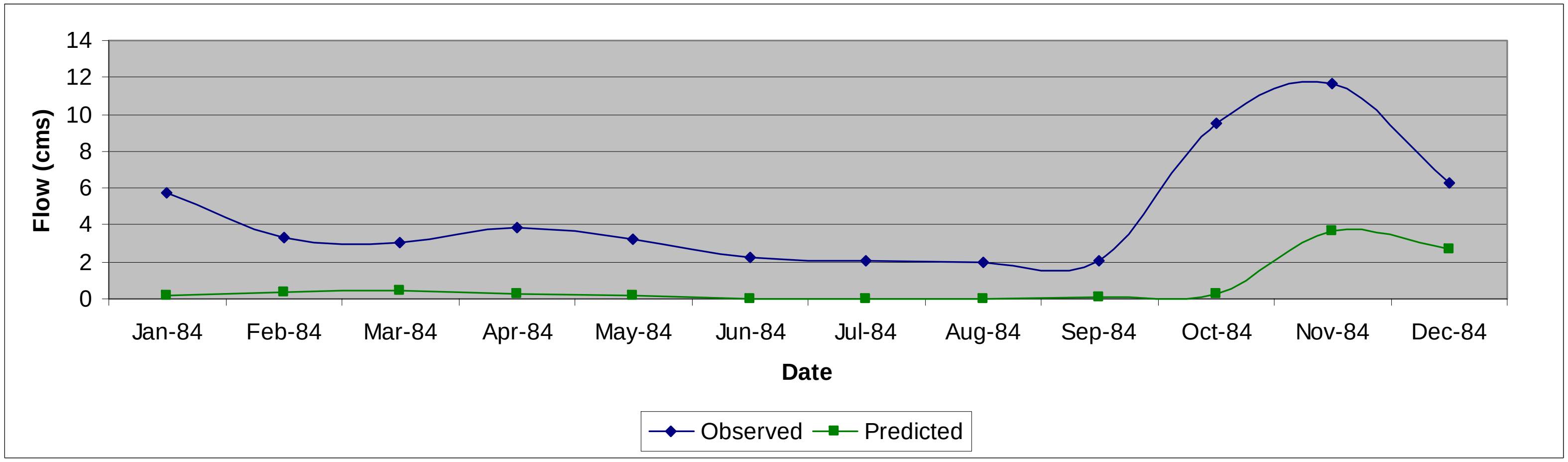

Figure 31. Hydrograph of 1984 drought at Sagana streamgauge.

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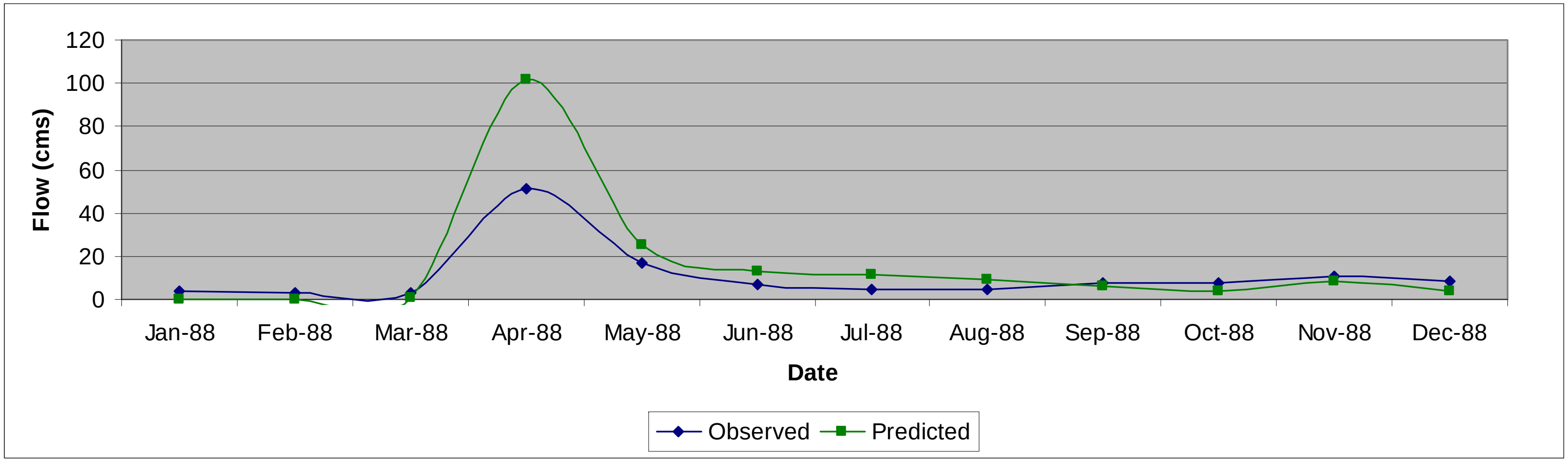

Figure 32. Hydrograph of 1988 (high rainfall year) at Sagana streamgauge.

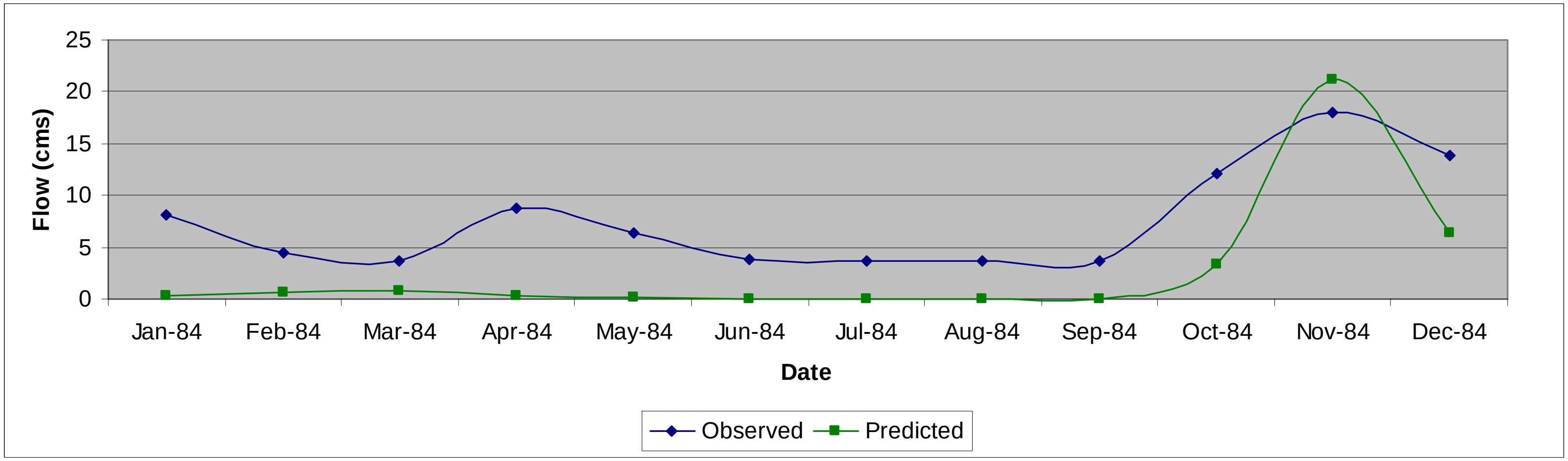

Figure 33. Hydrograph of 1984 drought at Gura streamgauge.

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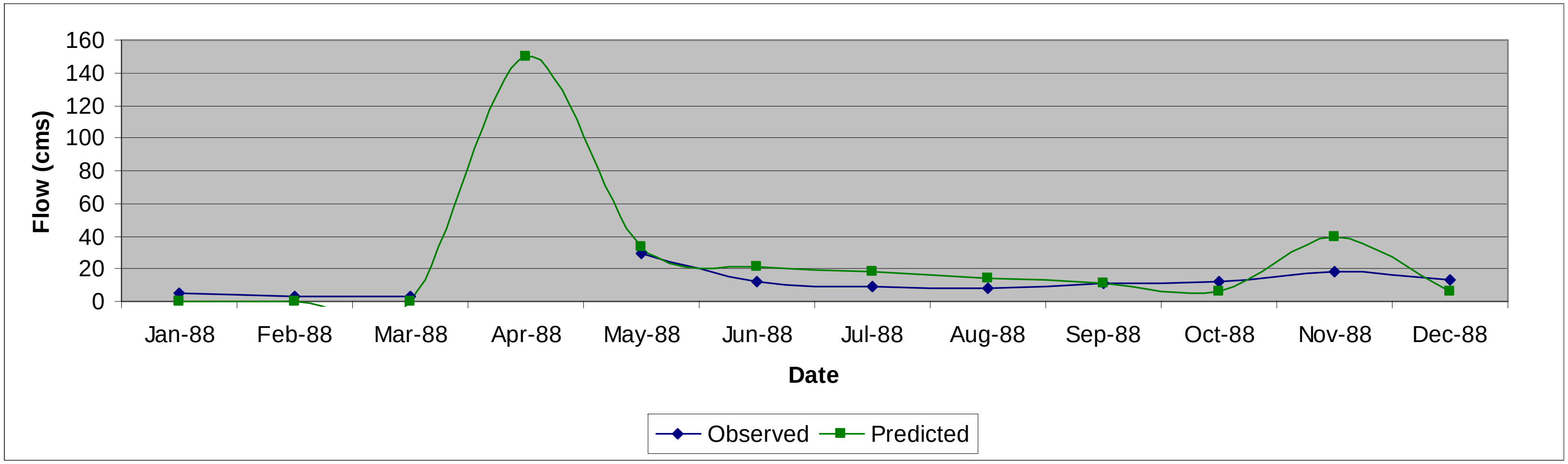

Figure 34. Hydrograph of 1988 (high rainfall year) at Gura streamgauge.

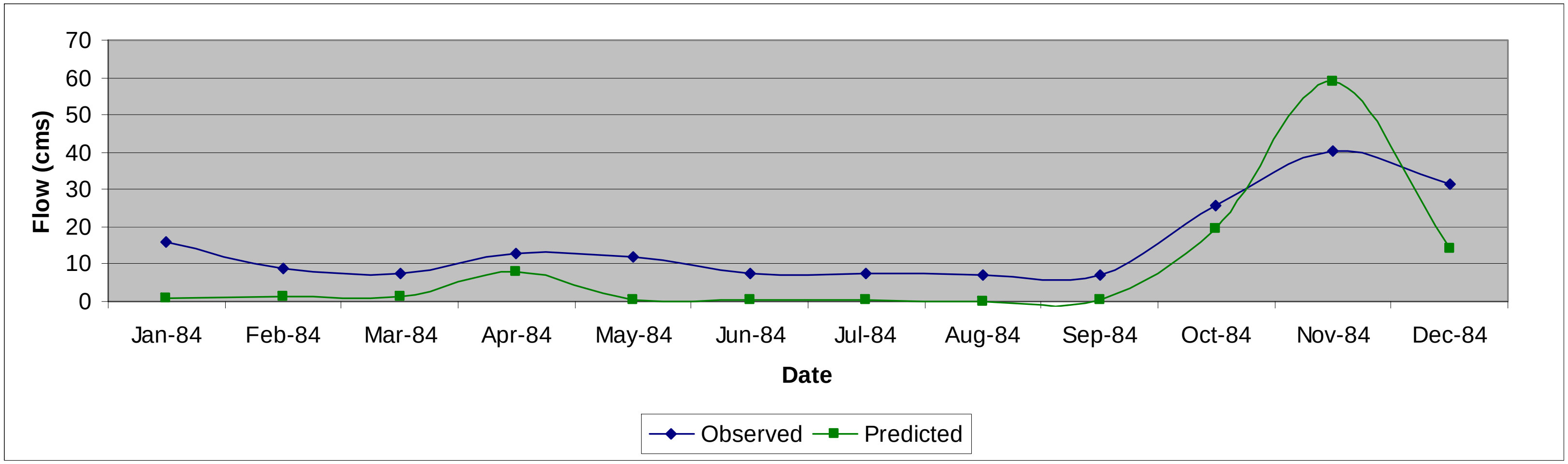

Figure 35. Hydrograph of 1984 drought at Tana Sagana streamgauge.

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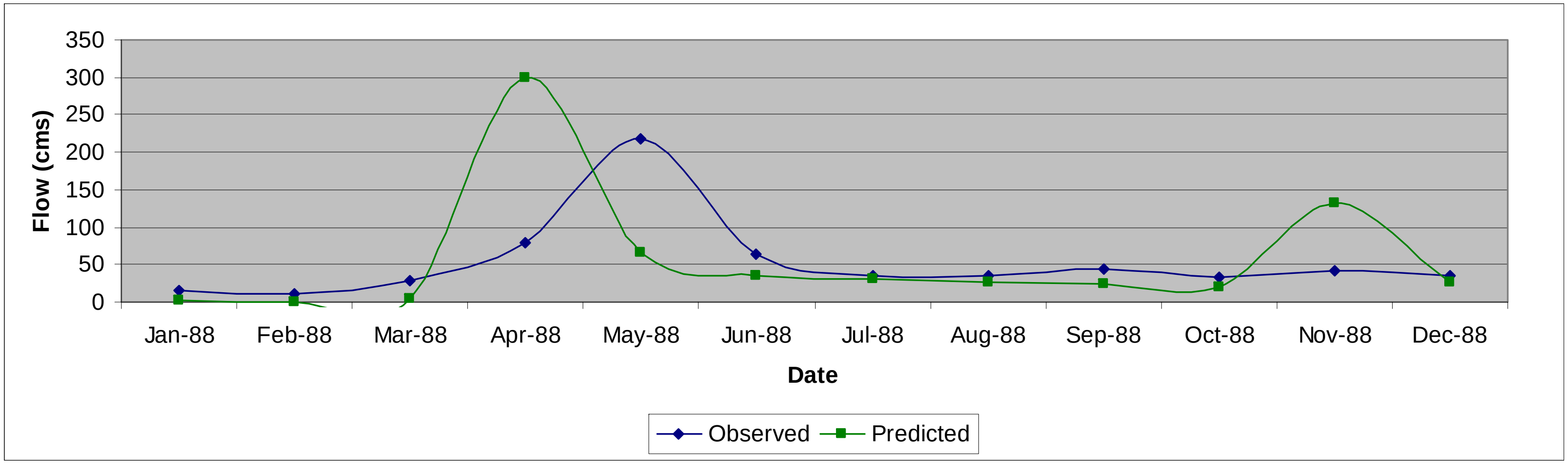

Figure 36. Hydrograph of 1988 (high rainfall year) at Tana Sagana streamgauge.

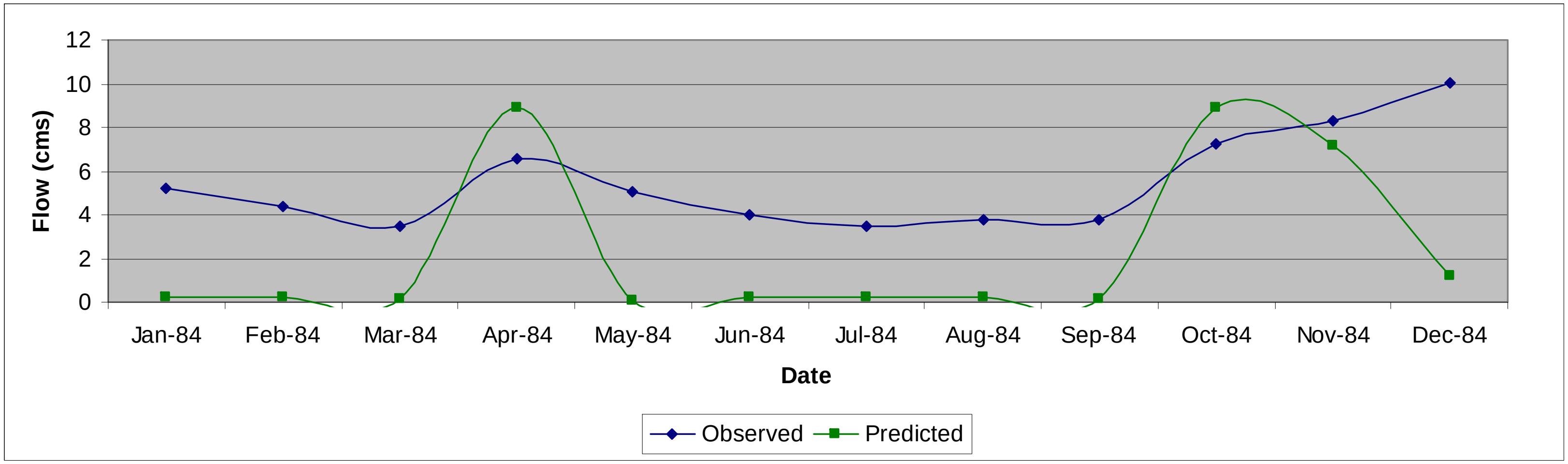

Figure 37. Hydrograph of 1984 drought at Thiba stream gauge.

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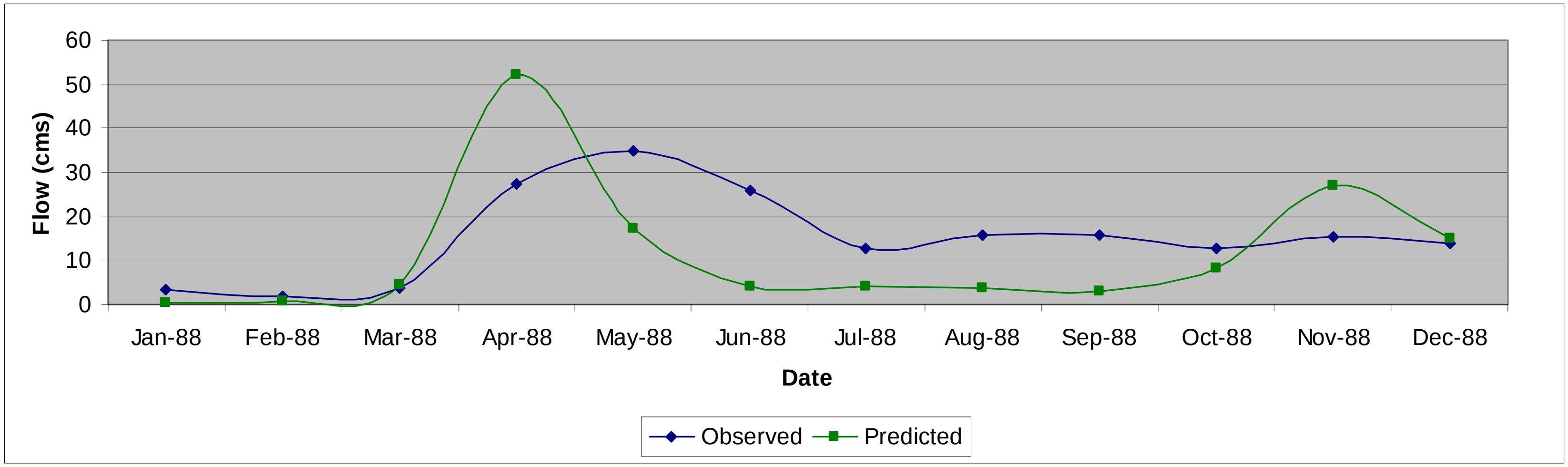

Figure 38. Hydrograph of 1988 (high rainfall year) at Thiba stream gauge.

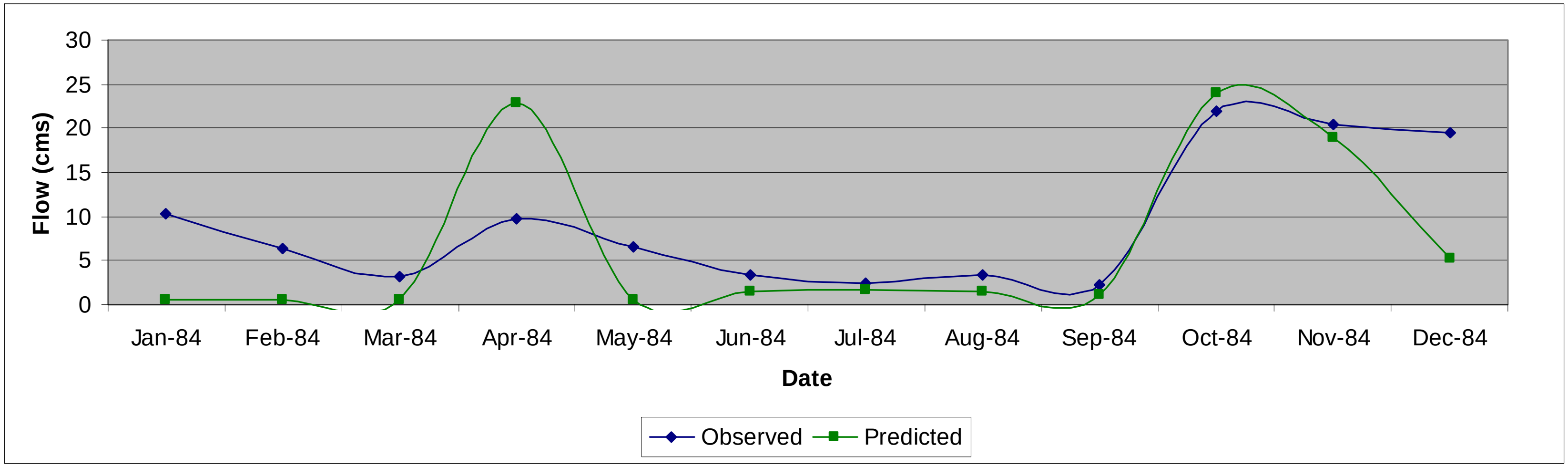

Figure 39. Hydrograph of 1984 drought at Thiba 2 streamgauge.

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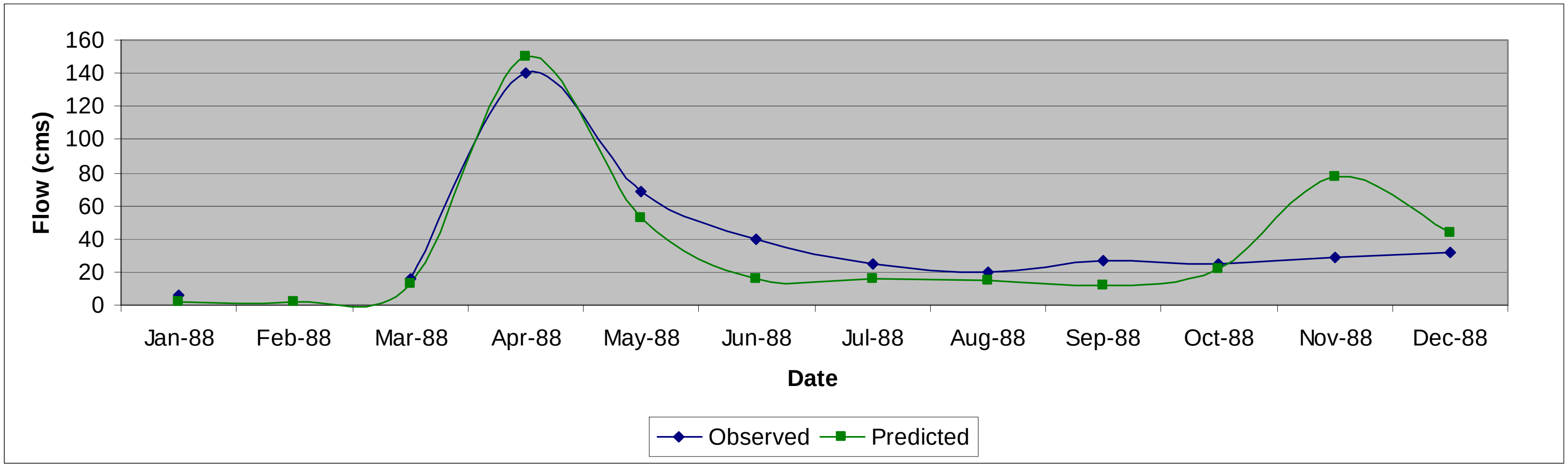

Figure 40. Hydrograph of 1988 floods at Thiba 2 streamgauge.

Three main branches of the Upper Tana River Basin stream network combine to create the Masinga Reservoir inflow. These include the main channel, or Tana River, in the central portion of the watershed, the Thiba River along the eastern portion of the watershed boundary, and the Thika River on the western boundary of the watershed. The flow and sediment out of these stream segments were added to obtain the inputs to the reservoir.

The overall percent rainfall for these three areas, as well as the runoff, and sediment contribution to the reservoir was calculated. In all cases, the contribution of rainfall, runoff, and sediment was greatest from the Tana River subbasins, followed by the Thiba River subbasins, then the Thika River subbasins. Rainfall from the Tana River subbasins accounts for 92.91% of the rainfall in the catchment. The Thiba River subbasins add 4.25% and the Thika River subbasins account for the remaining 2.84% (Figure 41).

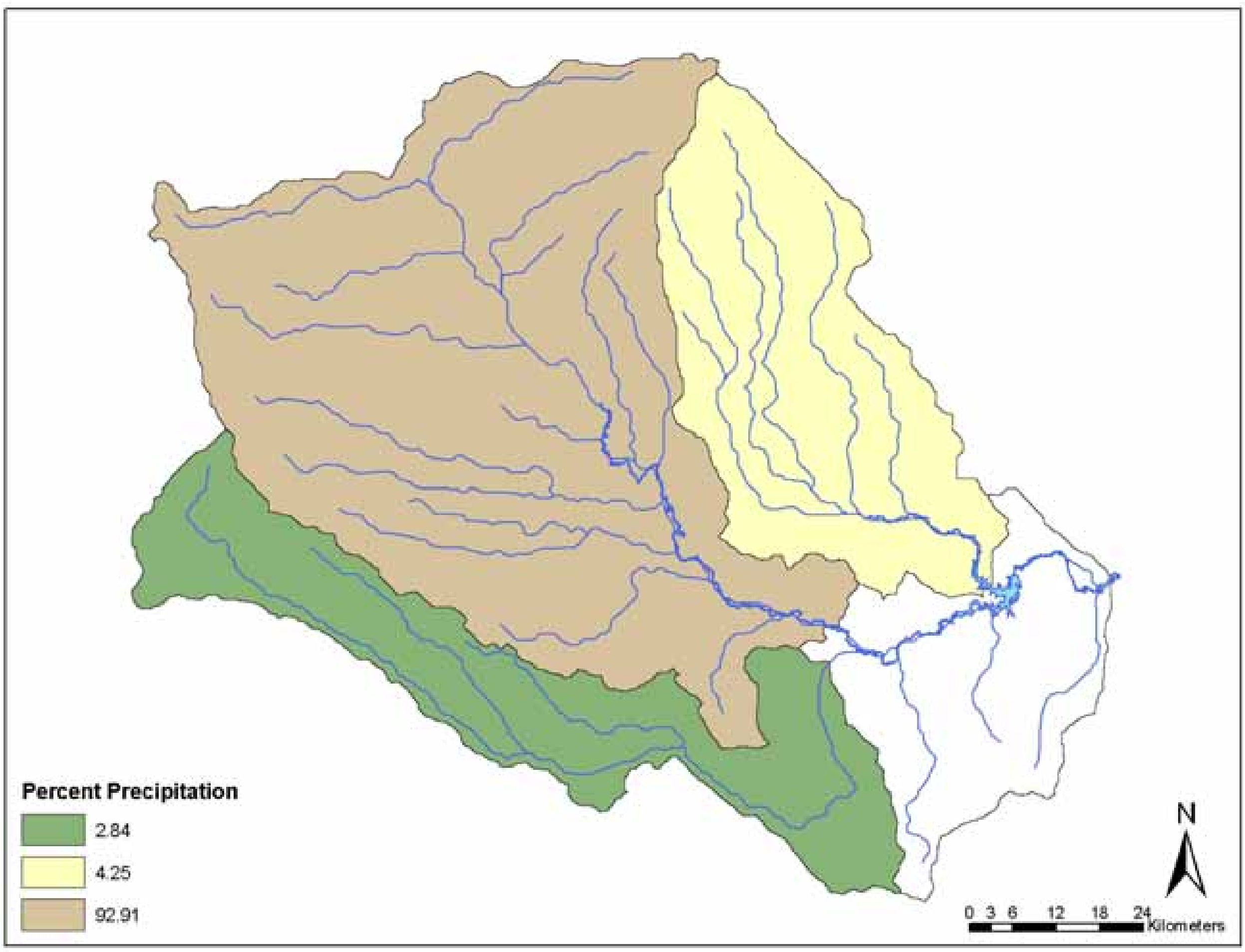

Figure 41. Percent rainfall from the three main reservoir channels.

As for runoff, the Tana subbasins account for 51.66%, Thiba accounts for 40%, and Thika accounts for the remaining 8.34% (Figure 42). It stands to reason then that the percent sediment load from the three channels is very similar to the percent runoff. Tana accounts for 50.36% of the sediment load to the reservoir, whereas Thiba adds 43.81%, and Thika adds the remaining 5.83% (Figure 43).

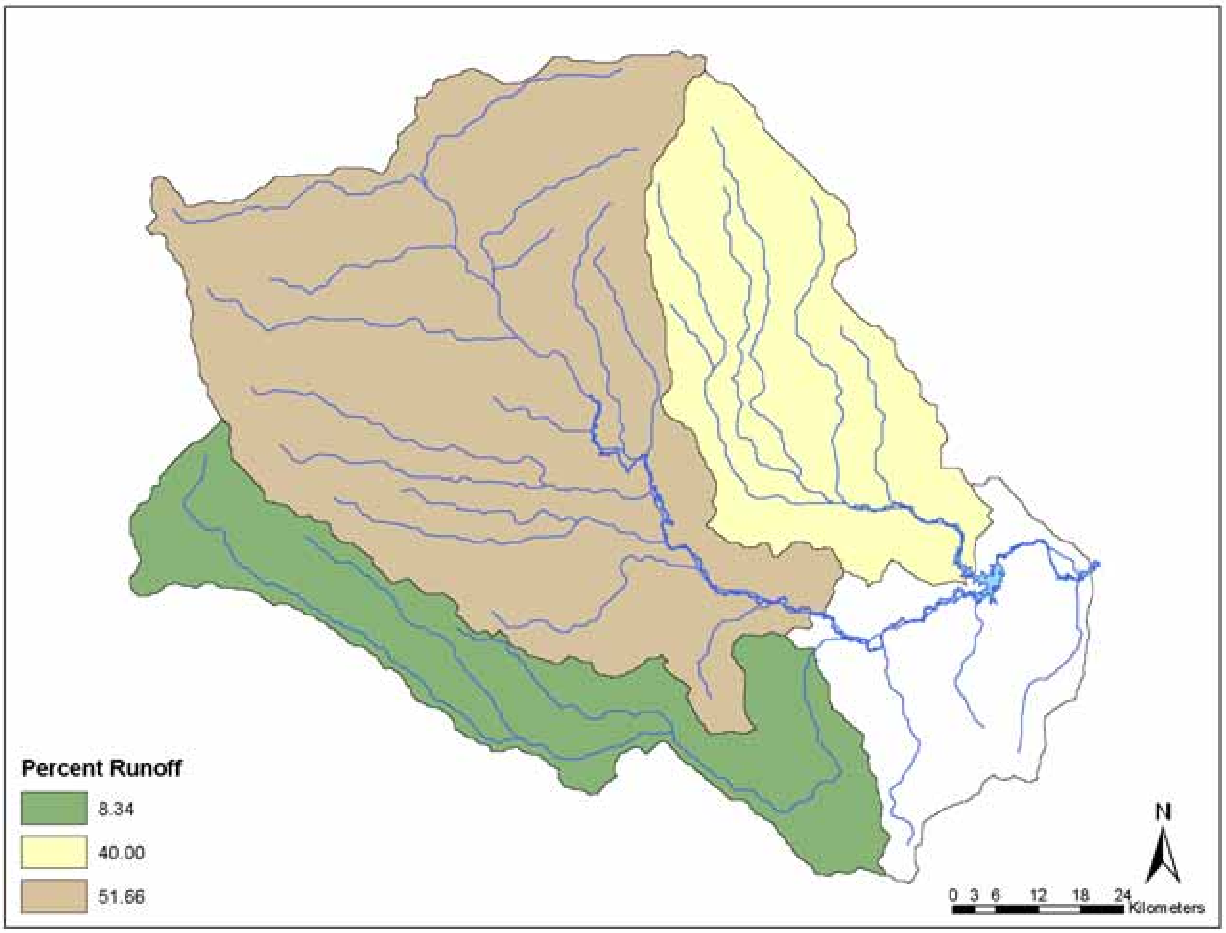

Figure 42. Percent runoff from the three main reservoir channels.

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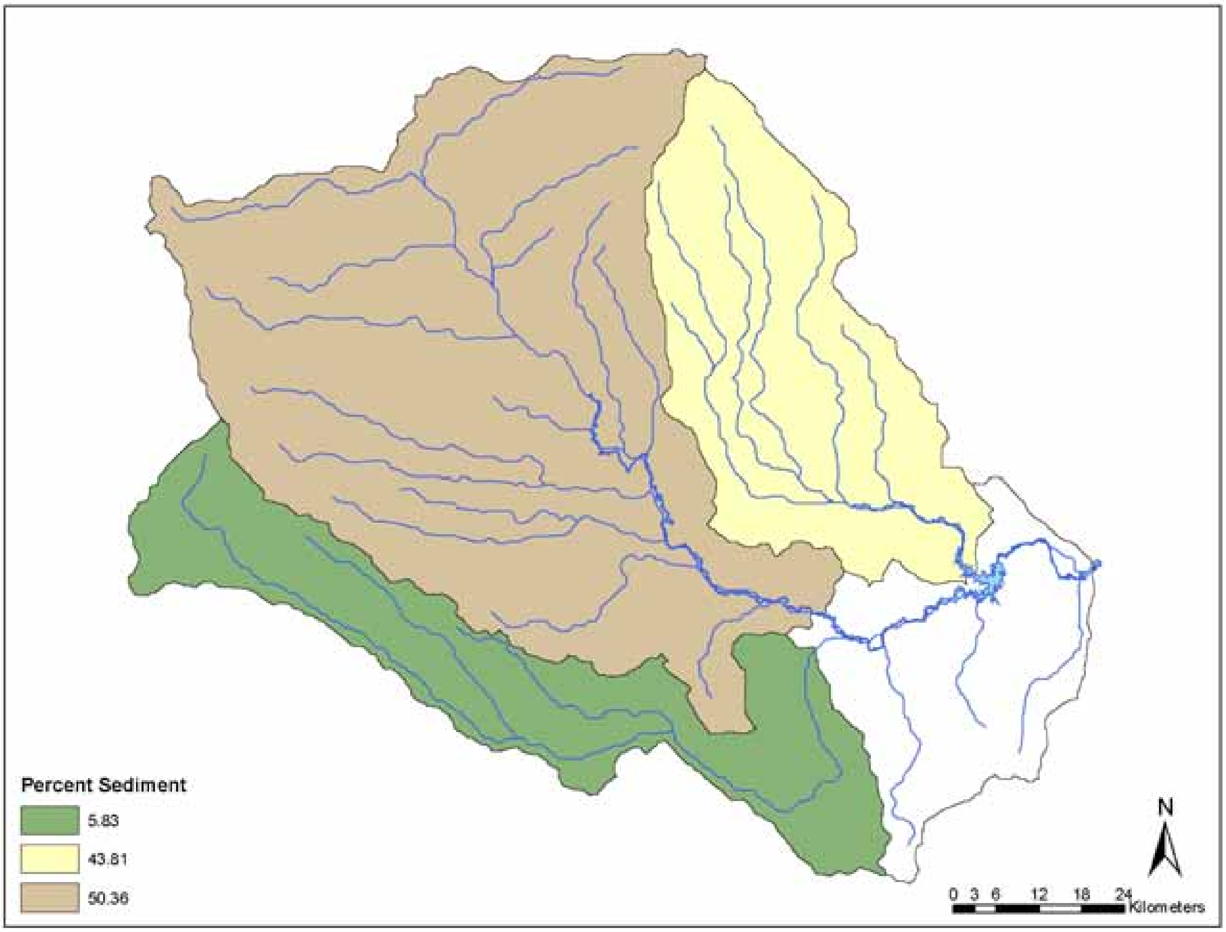

Figure 43. Percent sediment load from the three main reservoir channels.

Figure 44 shows the monthly average flow contribution of the three stream channels as well as the total flow into the reservoir over the 15 year study period. The cumulative total flow for the 15 years is 70.937 million m^3 (Figure 45).

Figure 46 shows the monthly average sediment load for the same time period and breaks down the contribution from each stream channel as well as the total sediment load for the reservoir. The cumulative total sediment load for the study period is 46.392 million tons of sediment (Figure 47).

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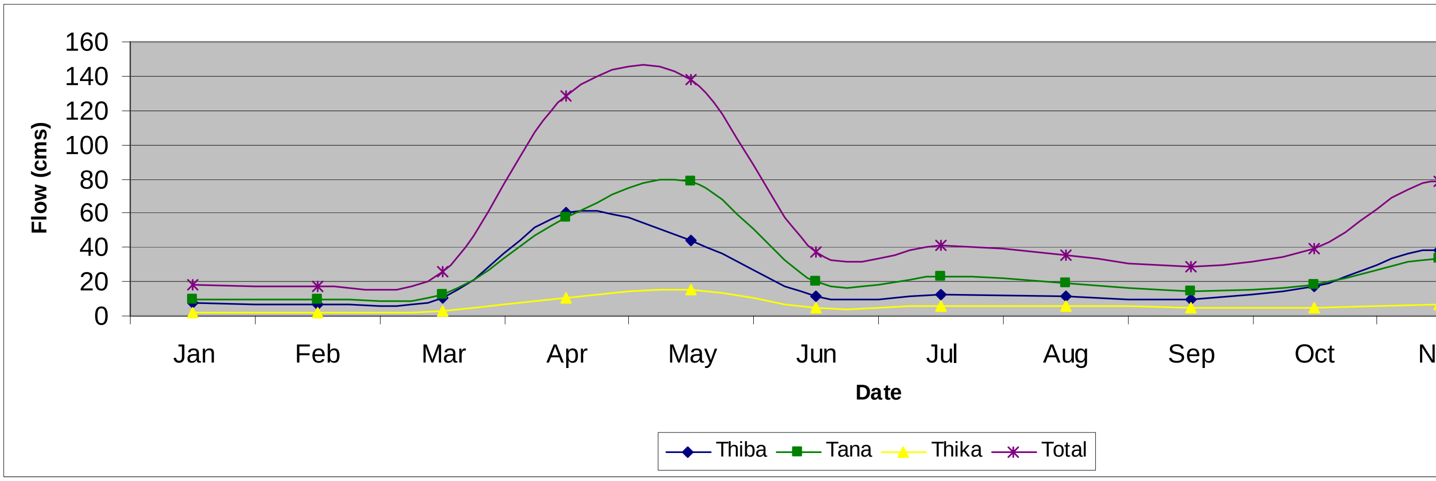

Figure 44. Average monthly reservoir inflow for 15 year study period from 1981 – 1995.

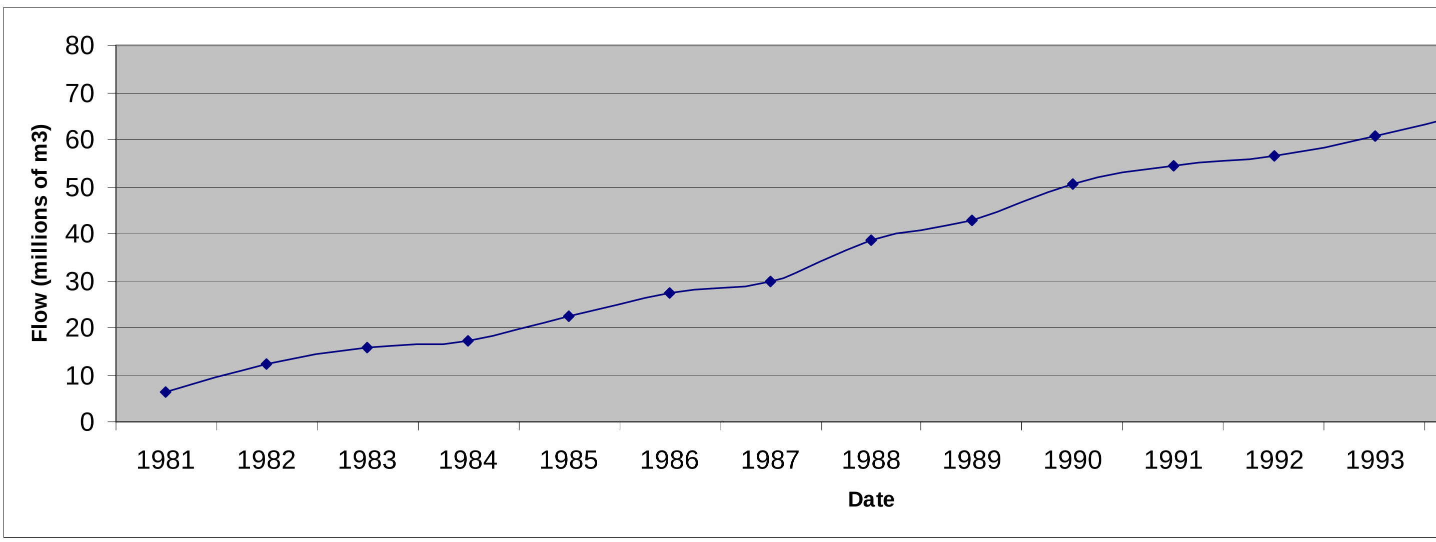

Figure 45. Cumulative reservoir inflow over 15 year study period from 1981 – 1995.

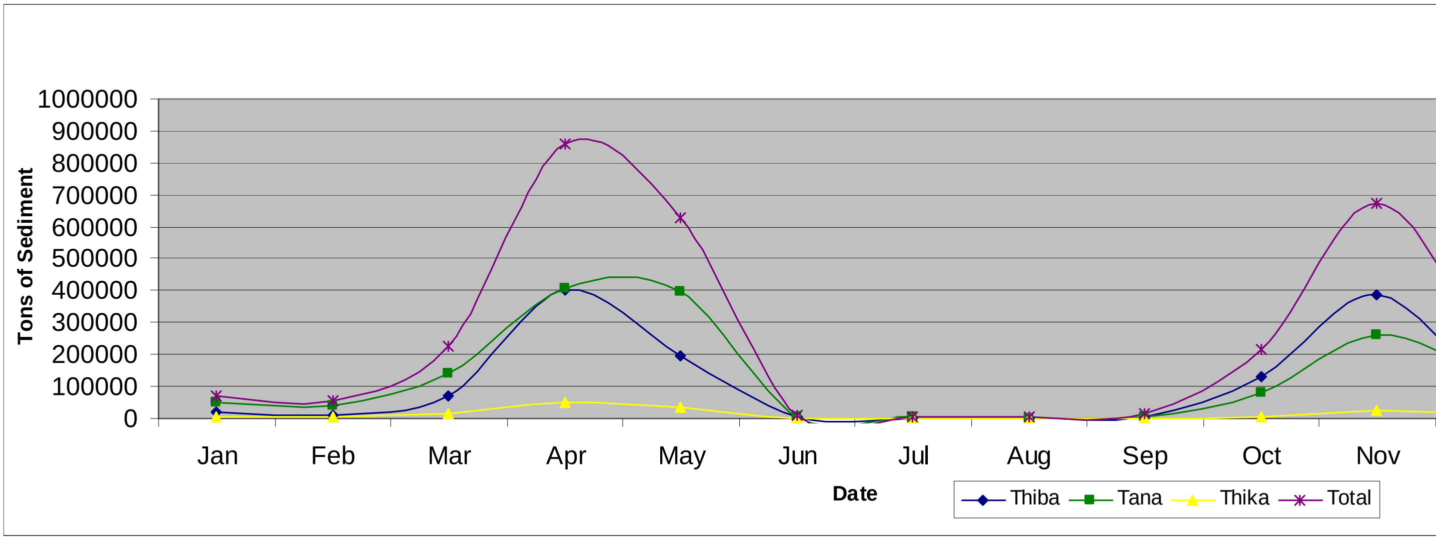

Figure 46. Average monthly reservoir sediment load for 15 year study period from 1981 – 1995.

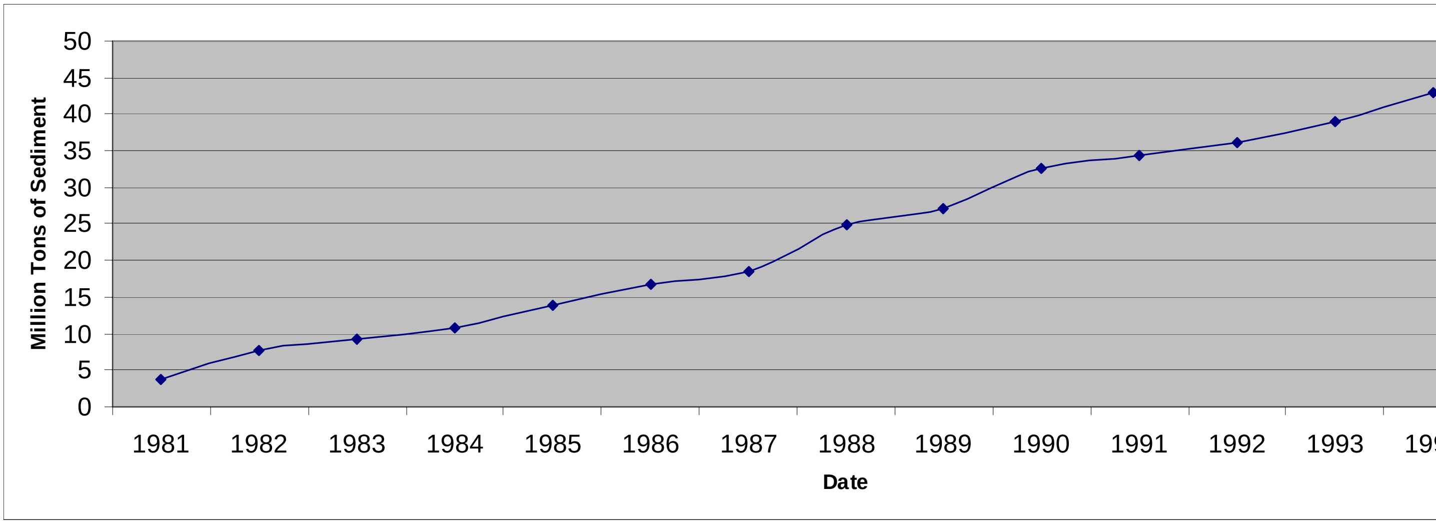

Figure 47. Cumulative reservoir sediment load over 15 year study period from 1981 – 1995.

Reforestation Scenarios

Most of the land over 1,800 m asl in the study has been either legally or illegally acquired since 1958. The land over 1,800 m asl is characterized by high slopes and is therefore susceptible to erosion when tree cover is removed. Before independence this land was all under forest, but over time there has been a gradual encroachment as population pressures have increased (Imbernon, 1999). The introduction of cash crops has had a significant impact on land use in the upper zones. Recent forest cover maps indicate that forest lands are found above the 2,000 m elevation contour; therefore, we proposed a graded reforestation scenario of the 2,000, 1,950, 1,900 and 1,850 m elevation zones.

To implement the change in land use across the elevation bands for scenario modeling, a displacement model was used in the GIS. Using the base land use grid (Figure 10) and the digital elevation model (Figure 3), a conditional replacement series was developed to generate the data layers for each of the reforestation scenarios. For the base scenario, the areas designated as forest were left intact as were all of the other land uses. For the 2,000 m scenario, all of the land uses having elevations greater than 2,000 m, regardless of type were displaced with the forests. This procedure was repeated for each of the reforestation scenarios (Figure 48).

The base (1997) land use grid in the original SWAT simulation was replaced with the various modified land use grids in order to develop scenario models. Each successive land use grid was used to create a new SWAT simulation with forest cover gradually increasing from the 2,000 m contour line to the 1,850 m contour line, in 50 m intervals, in the Mt. Kenya and Aberdare Range areas of the catchment.

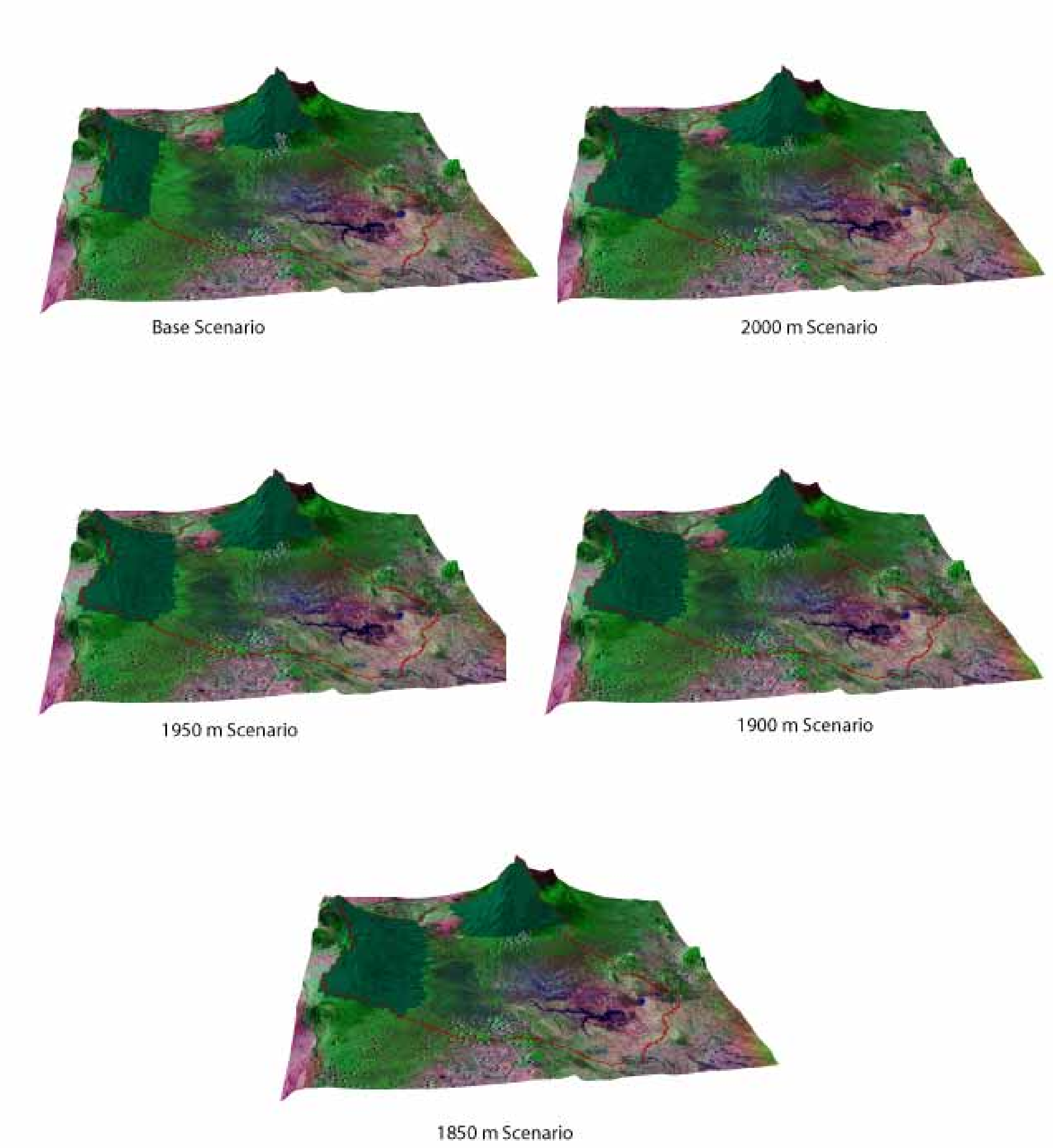

Figure 48. Depiction of the reforestation scenarios used in the study of the Upper Tana River basin. The base scenario represents 1997 forest cover conditions. The remaining scenarios represent land use displacement by forests down to the elevation described in the scenario name.

For the current, or baseline, condition simulation forest cover was estimated to be approximately 2,216.448 km^2. It should be noted that this current forest cover condition is based on the best available spatial data and is thought to be much greater than the actual forest cover area in the basin, thereby creating the potential for an under estimation of benefit from forest restoration. For the 2,000 m interval simulation, forest cover was 2,932.7612 km^2. Forest cover increased over each successive simulation with the 1,950 m, 1,900 m, and 1,850 m intervals with 3,077.222 km^2, 3,253.478 km^2 and 3,453.235 km^2 forest area, respectively.

In general, grazing lands and tea were the main land use types to be displaced by forest restoration activities at all contour intervals (Table 5). In addition, areas of displaced maize and coffee increased with each successive scenario.

Table 5. Forest restoration land use displacement for various scenario simulations.

Scenario 2000		Scenario 1950		Scenario 1900		Scenario 1850	
Land Use	**Percent Area**	**Land Use**	**Percent Area**	**Land Use**	**Percent Area**	**Land Use**	**Percent Area**
Grazing	63.93	Grazing	49.22	Grazing	52.51	Grazing	41.07
Tea	16.01	Tea	24.88	Tea	18.53	Tea	18.77
Maize	9.05	Maize	11.66	Maize	12.1	Maize	15.71
Woodlot	6.6	Woodlot	6.92	Coffee	6.48	Coffee	13.83
Bush	3.35	Coffee	3.35	Woodlot	5.62	Woodlot	4.89
Coffee	0.65	Bush	2.69	Bush	4.05	Bush	3.7
Other*	0.41	Other*	1.58	Other*	1.05	Other*	2.17

*other consists of banana, hedges, maize-banana, and roads

Reforestation Scenario Results

After careful examination of the change in runoff over the various scenarios, it was determined that this change was relatively insignificant and was not evaluated further. For the Tana subbasins, flow increased by 0.4%, whereas variance decreased by 4.5%. Flow for the Thiba subbasins decreased by 0.7% with a 0.5% decreased in variance. The Thika subbasins showed a 2.4% increase in flow with a 7.4% decrease in variance. However, the change in sediment load to the reservoir over the scenarios was noticeable. It should be noted that the change in both of flow and sediment yield would most likely be greater than what was achieved here if the current condition of forest cover was established to be lower than the area used for the initial land use classification.

The average annual sediment yield for the catchment generally decreased with each successive scenario and added forest cover. This is true for both the yield per hectare (Figure 49) and overall yield for the catchment (Figure 50). However, there is a slight increase in sediment load from the 2,000 m simulation to the 1,950 m simulation. This could be due, in part, to the large area of tea that is displaced in the 1,950 m scenario (Table 5). The tea plantations could provide more tightly packed canopy cover than the forests do, thereby preventing more sediment loss. The 1,900 m and 1,850 m scenarios return to the expected levels of decrease in sediment load for the catchment.

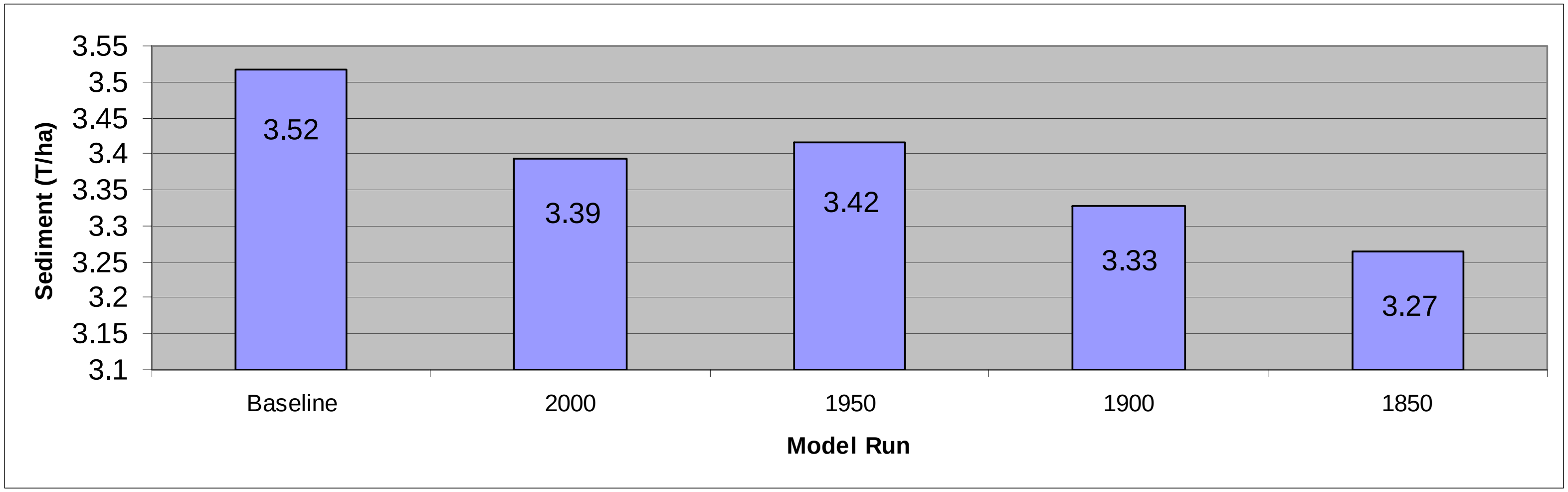

Figure 49. Average annual sediment yield per hectare.

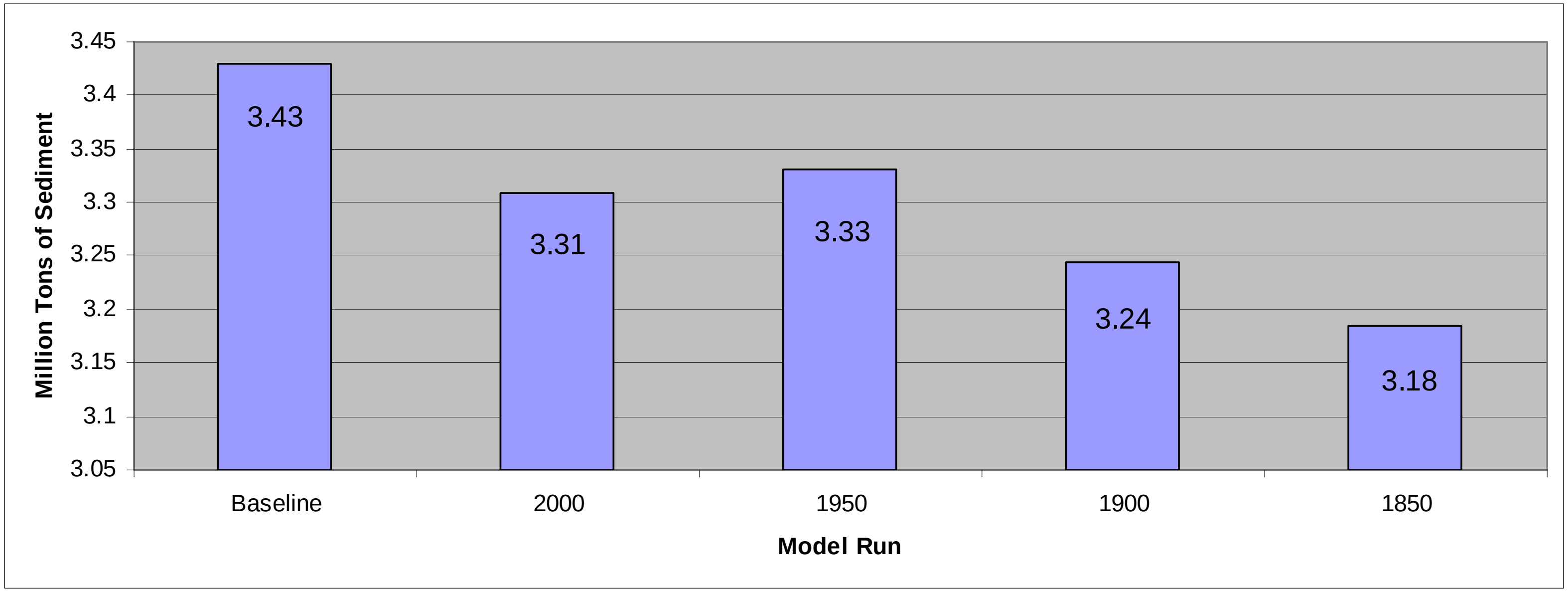

Figure 50. Average annual sediment yield for the catchment.

The percent cumulative sediment change from the baseline simulation for the various scenarios behaved similarly. There is a general increase in percent change over each successive scenario except in the 1,950 m interval. Again the increased sediment yield for this scenario was most likely caused by the displacement of tea. For the 15 year study period the least change in sediment yield is in the 2,000 m scenario with an approximately 3% decrease, whereas in the 1,850 m scenario, the decrease in more on the order of 7% (Figure 51).

Further comparison of the current, or baseline, condition simulation to the most productive simulation at the 1,850 m interval provided more evidence of the benefit of forest restoration. Under current conditions, the cumulative total sediment load to the reservoir was approximately 46.39 million tons of sediment in 1995. Had forest cover been established up to the 1,850 m contour interval for this same period since 1981 (the same time the reservoir was established) to 1995, the sediment load would have decreased to 42.95 million tons (Figure 52). Again, it is important to note that the decrease in sediment would most likely be greater than what was simulated here in that the original land use does not capture the full extent of deforestation in the region.

The increase in forest cover provided more benefit during peak rainfall events than drought conditions as would be expected. Again, the years 1984 and 1988 are representative of these conditions. In 1984, during a drought period, the current, or baseline condition sediment yield amounts to approximately 1.57 million tons. At the same time, forest cover under the 1,850 m scenario would have allowed for 1.44 million tons of sediment loss. On the other hand, in 1988 under higher rainfall conditions, the baseline sediment yield was 6.4 million tons, whereas the 1,850 m scenario was 5.86 million tons (Figure 53).

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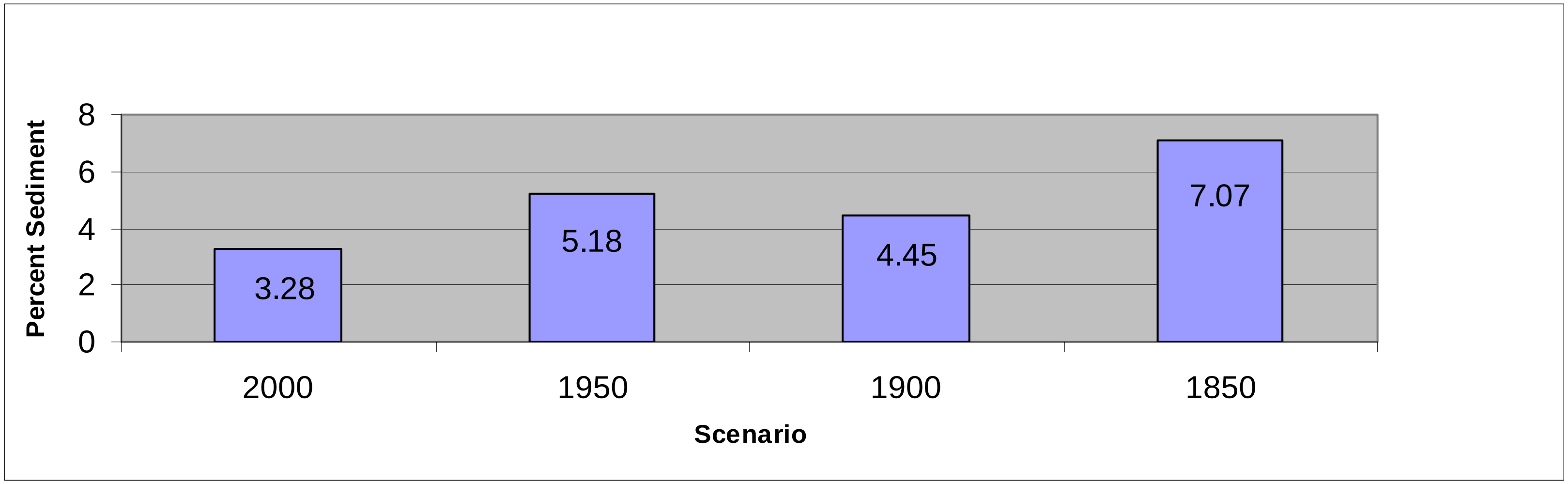

Figure 51. Percent cumulative sediment change for various scenarios with respect to the current conditions simulation.

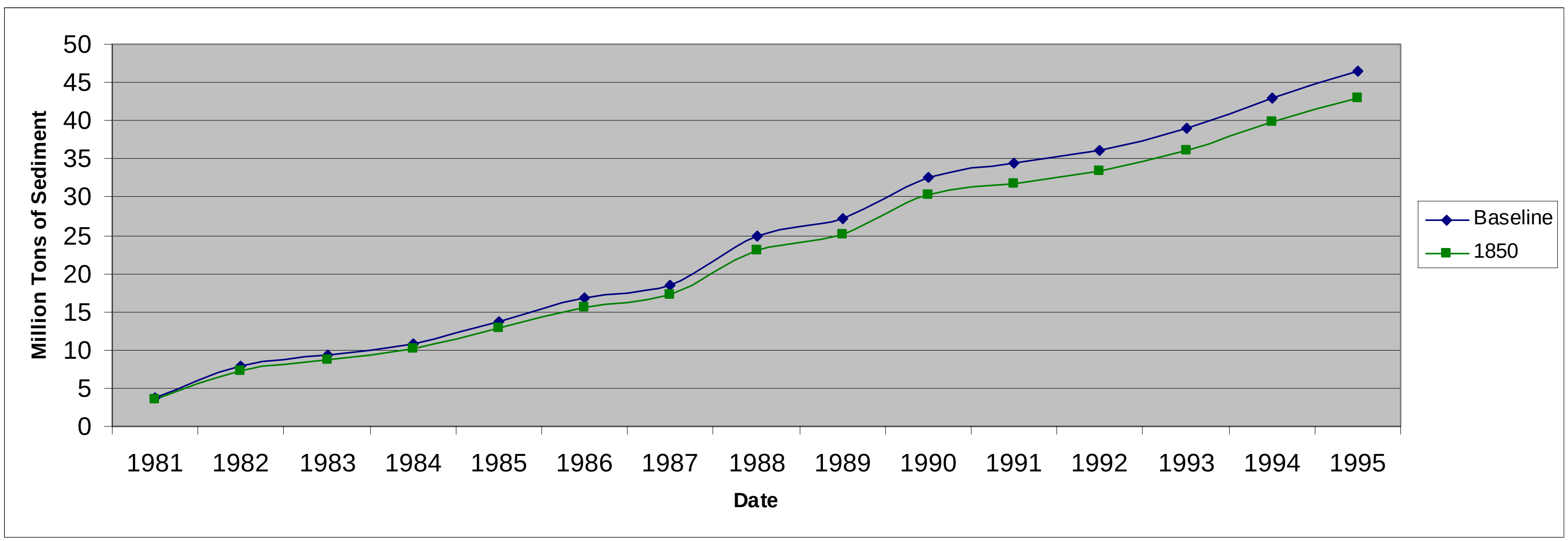

Figure 52. Cumulative sediment load under current condition vs. the 1850 m scenario from 1981 – 1995.

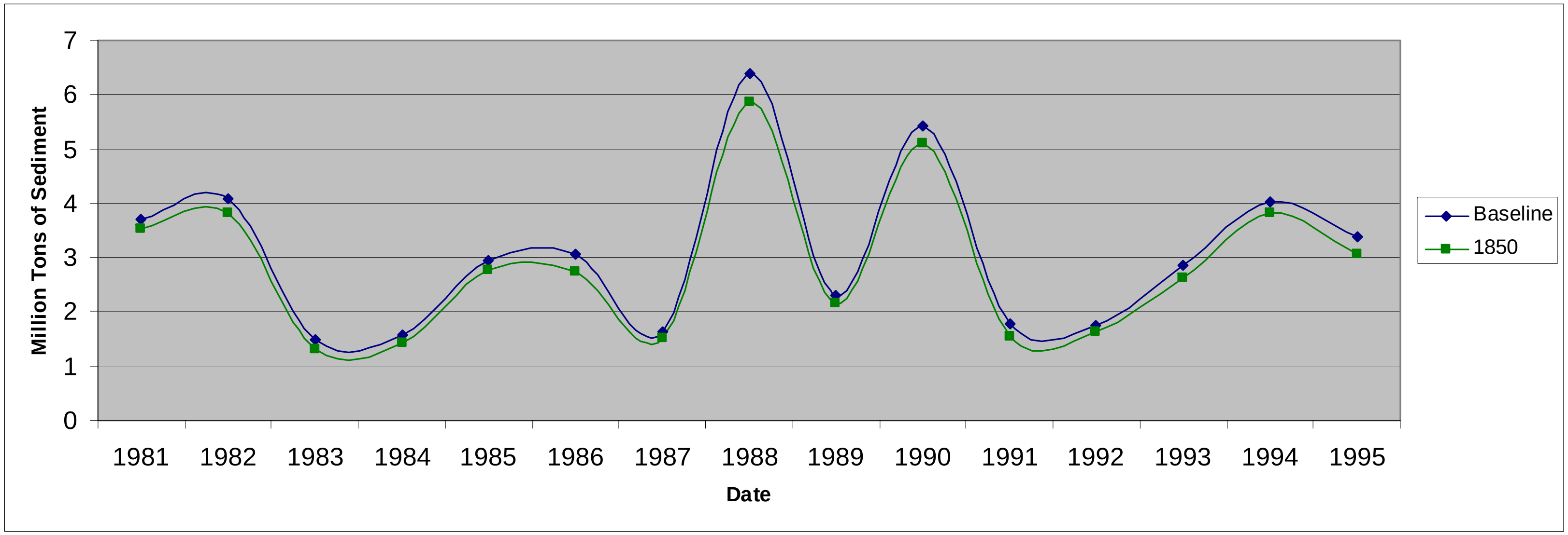

Figure 53. Sediment load under current conditions vs. the 1850 m scenario from 1981 – 1995.

Economic Implications

Subbasin average sediment reduction costs have three sharply contrasting regions (Figure 54). In each scenario, there is an initial region with a high degree of elasticity in sediment reduction. In the 1,850 m scenario, for instance, the initial up to about 150,000 tons/year of sediment could be reduced at a cost much less than $1/ton. To prevent additional sediment from reaching the downstream users, costs would increase linearly at the rate of about $1 for every 10,000 tons of sediment reduced. This linear portion would end around 240,000 tons of sediment reduction. Above this level, sediment reduction costs would increase nearly exponentially with only marginal reductions in sediment loading.

The other three reforestation scenarios (2,000 m, 1,950 m, and 1,900 m) have similar sediment reduction costs curves (Figure 54). The elastic portions of the sediment reduction extend out to 70,000 tons/year, 140,000 tons/year, and 110,000 tons/year, respectively, which reflect the amount of sediment that can be reduced at low costs to the upper watershed user groups. The linear portions extend from the end of the elastic portion by about 60,000 tons/year, 30,000 tons/year, and 35,000 tons/year, respectively. These segments represent modest costs that are likely to satisfy the efficiency criterion (Equation 2) under a reasonable set of dredging costs. The near exponential section, where costs rise quickly with only marginal changes in sediment reduction, represent the practical limit for sediment reduction in each scenario. This implies that the largest sediment reduction achievable from and economically efficient perspective is 110,000 tons/year, 160,000 tons/year, and 140,000 tons/year, respectively.

The subbasin average analysis shows that the 1,950 m scenario would provide more efficient resource allocations than the 1,900 m scenario (Figure 54). Even though the area targeted for reforestation is less in the 1,950 m scenario, the greater presence of tea provides more efficient sediment reduction due to the enhanced land-cover/protection service that tea provides.

The utility of the subbasin average HEM is that it is able to select which subbasins to include within a particular reforestation scenario, and leave intact land uses that fail to satisfy economic efficiency. In this case, since the HEM is used mainly to complement the hydrologic modeling activities, the decision variables, X_i, can be determined just as easily using a GIS derived map of the sub-basin average sediment reduction costs. The HEM remains useful, however, in calculating the net economic gains to the watershed from optimal reforestation.

The use of GIS provides an improved visualization of the spatial complexity as it transforms a 2-D figure (Figure 54) into a color-coded map that represents sub-basin specific sediment reduction costs (Figure 55). Sub-basins targeted for reforestation can be found using Equation 2, which requires that benefits be greater than costs. For dredging costs less than \$2/ton, only the dark-green shaded subbasins would be included in the optimal reforestation; these are the subbasins in the upper reaches of the watershed that contain large tracts of marginal lands that and deforested areas left in disrepair. Both land use types have very low opportunity costs associated with reforestation, and since these are high slope, erosive prone areas they provide significant environmental services to downstream users through reduced sediment loading. Subbasins with costs greater than \$2/ton would remain intact in their baseline land use.

Five subbasins would be included in the optimal reforestation if dredging benefits were between \$2/ton and \$10/ton (Figure 55). These are the modest-cost subbasins that likely contain a mixture of marginal lands, maize, and cash crops (coffee and tea), and are found at the mid-elevation portions of the watershed. The remaining subbasins, shown using two shades of red, are the high cost subbasins that correspond to the near-exponential portions of the cost curve (Figure 55). In these areas, satisfying the efficiency criterion (Equation 2) has more academic rather than practical significance since the amount of sediment reduction they provide downstream users is negligible.

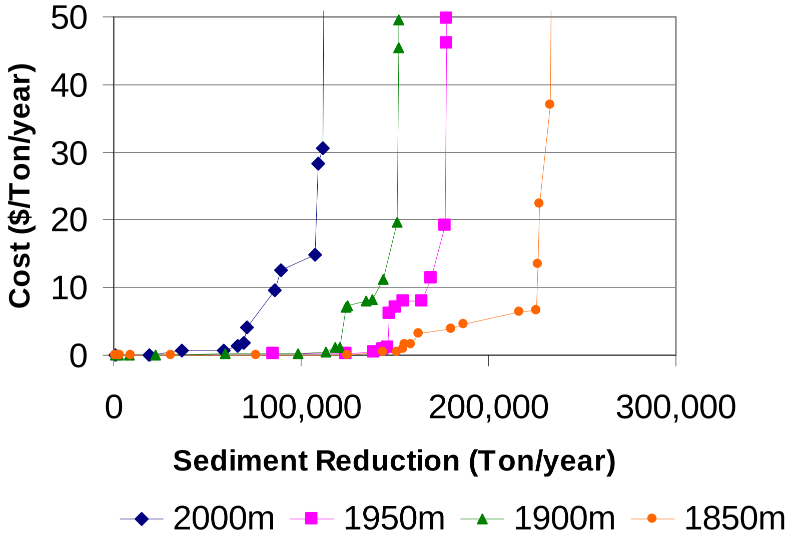

Figure 54. Subbasin average sediment reduction costs.

Figure 55. Map of sediment reduction costs.

DISCUSSION AND CONCLUSIONS

Given the demonstrated verification that SWAT provided acceptable estimates of baseline response in the Upper Tana River catchment, the reforestation strategy explored in this study should provide useful insights into the impact on runoff and sediment loading into the Masinga Reservoir. We found the use of an elevation gradient strategy to be practical as it reflected not only the changes in environmental conditions along the toposequence from the dam to the upper reaches of Mt. Kenya and the Aberdare Range, but also reflected the normal course of land use change over time. Using the baseline forested area of 2,216 km^2, there was a 32.4, 38.9, 48.8 and 55.8% increase in land area dedicated to reforestation using the elevational changes from the baseline level to 2,000, 1,950, 1,900, and 1,850 m elevation contours.

Reconnaissance trips in the catchment revealed that the 1,850 m demarcation corresponded to the level where long-term settlement of smallholder farmers was dominating the landscape. Reforestation above these levels would minimize the impact on farmer livelihoods in the region and relegate growing of trees to agro-ecological zones that present more difficult growing environments for food crops. The major land use above 1,850 m was tea plantations and grazinglands which are constrained by available water for livestock. There is some maize production in that zone as well. However, the reforestation program could face problems associated with illegal logging, growing of illicit drug crops and some farm squatters in the upper reaches of the watershed.

The Upper Tana River catchment was comprised of three river subsystems of which the Tana was the largest (92.1%). However, a proportionally lower amount of runoff and sediment was yielded by this part of the catchment into the Masinga reservoir, 51 and 50%, respectively. The Thiba River subsystem only accounted for 2.8% of the land area but 40% of the runoff and 44% of the sediment load into the Masinga reservoir. The Thika River subsystem made up 4.2% of the catchment yet only produced 8% of the runoff and about 6% of the sediment load.

The reforestation strategy pursed in this study generally resulted in a reduction of sediment loading as tree plantings moved down the mountain with similar levels of runoff and return flow of less variance within years. However, there was a small increase in sediment as reforestation was advanced in the 2,000 m to 1,950 m elevational band as tea plantations were displaced by forests. This would suggest that reforestation is not advisable for any of the existing tea plantations located above 1,850 m unless there is a restructuring of the tea industry where profitability is significantly lower or risk much higher. After grazinglands, maize production was the next major land use to be displaced.

Overall the reforestation strategy in this study would have reduced sediment loading to the Masinga Dam by 7.3% per year or approximately 0.25 million tons of sediment per year if the same weather sequence occurred as was observed between 1981 and 1995. The reforestation of the full extent of elevation change resulted in an 8.3% reduction in sediment lost during drought and 8.5% during high rainfall years. The mean annual variance is reduced yet more. Therefore, reforestation appears to be able to sustain water yields of higher quality and less variation in this catchment.

Given these findings, the question remains, what are the ecological implications to the Masinga Reservoir ecosystem and the lowland Tana River ecosystem. In the recommendation of Pacini *et al.* (1998), they called for a lowering the level of the reservoir to allow more natural flow patterns in the river system and suggested less than 3.5 m amplitude in changes in lake levels based on the work of Bernasek (1984). The lower flux in lake levels allows greater stability of shoreline vegetation and shallow water fish habitats. The Maingi (1991) estimated that Masinga Dam trapped 90% of all sediment flowing into the reservoir. However, Masinga Reservoir is a bottom-withdrawal, monomictic reservoir which leads to strong stratification of the water column with a cold-water underflow to the turbines, especially during flood periods. This allows a high surface area to volume ratio that causes the upper layers of water to increase in temperature and due to higher evaporation, increases salinity. The hydro-chemical impact is confinement of phosphorus at lower depths and restriction of algal biomass in the critical epilimnion zone of the lake needed for fisheries development. Once a peak rainfall event occurs, the high flushing rate removes suspended sediment from the reservoir, reducing further the nutrient mixing needed for proper ecosystem function in the lake, particularly in the epilimnion.

If the government would decide to reduce lake levels to improve ecosystem function in the lake itself and attempt to restore flooding cycles to some degree in the lower Tana River system, then the reforestation strategy would be critical to reducing the overall sediment loading and facilitate ecological restoration of the epilimnion. Lowered lake levels can only be sustained if there is stable recharge or flow to the lake and greater mixing of nutrients coming in with the runoff and return flow. The ideal situation would be to create an upstream biological system that allows a less variable flow that would increase the changes for lake level management which in turn would result in a more stable shoreline and inlet delta vegetation system that leads to a more stable nutrient distribution in the lake and improved overall ecosystem function. Greater ecosystem function then leads to greater downstream control in water levels needed for sustaining riverine forests and nutrient loading at the delta of the Tana River into the Red Sea which has a major Mangrove Forest ecosystem.

Clearly, the management of the lake levels and ecosystem function are not the only concerns. The social pressures for illegal logging, illicit drug plant cultivation and farmer squatters need to be addressed as a unified policy. Downstream benefits in terms of clean stable water for drinking, electricity and fisheries need to feed back from society to those people displaced by the policy. A greater connectivity of the people and value that the ecosystem serves needs to be part of public awareness campaigns in order to allow the government to effectively implement reforestation policies.

The proposed strategy would ultimately require plantation of 30 million trees over 123,700 ha, clearly the infrastructure for developing tree nurseries will have to be a critical part of any reforestation policy. However, the solution is collaboration between those that manage the engineering aspects of the Tana Reservoir system, forestry specialist who develop the appropriate genetics for the upper watershed reforestation, natural resource managers who work with the forestry people to insure that wildlife habitat is considered and alternative forage resources can be developed for livestock producers and agronomists and soils specialist who work with farmers to implement appropriate soil conservation practices in their cropping systems. In addition, extension officers and community leaders need to come to understand the complexity and needs of the total watershed and help educate the populace and promote a dialogue to seek solutions. Viable ecosystem management approaches are required to address this problem to avoid the failure of a single-technology infusion approach to try and solve a complex ecosystem problem.

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