Multi-scale estimates of erosion and sediment yields in the Upper Tana basin, Kenya

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Abstract This paper summarises the main findings of a project on soil erosion and sediment yield in the Upper Tana basin, Kenya. A multi-scale approach was taken in order to produce: a revised estimate of the rate of sediment input to Masinga Dam, and a regional erosion hazard map, to locate the major sources of sediment yield and investigate rainy-season erosion processes. The new sediment yield estimate is lower than some previous estimates, but it is sensitive to climatic variation. The sediment is largely generated from one morpho-climatic zone in the basin. In this tropical foothills zone further conservation measures should focus on paths, tracks and roads as point sources of runoff and sediment. At the regional scale of the Upper Tana basin there is no internal relationship between sediment yield and area due to variations in climate, relief and soil type, so a multi-scale approach to the assessment of regional rates of erosion and sediment yield is essential.

INTRODUCTION

Erosion rates and sediment transport processes are far less well known in tropical catchments than in temperate or even semiarid catchments despite the fact that they provide the majority of the sediment delivered to the oceans. One of the principal reasons for this is the difficulty of monitoring transport rates in regional-scale basins in the tropics during the rainy season when most erosion occurs. As part of a project concerned with the economic development of the Masinga Dam in central Kenya, estimates were required of sediment and nutrient input from the Upper Tana basin. The Upper Tana is a regional basin covering 7950 km^2 with a relative relief of 4143 m (base level 1056 m a.s.l.) and with a variety of subregional climates including semiarid, humid tropical and alpine.

Despite large differences between published sediment yield estimates for the Upper Tana, previous work by Dunne (1975) and others (Dunne & Ongweny, 1976; Ongweny, 1979) had suggested that it was the humid foothills of the Aberdare Mountains and Mt Kenya that were the major sources of the sediment entering Masinga Dam (Fig. 1). It was therefore decided to concentrate on the Aberdare foothills using a multi-scale sampling strategy. The three scales were; the Upper Tana subcatchments, a typical small

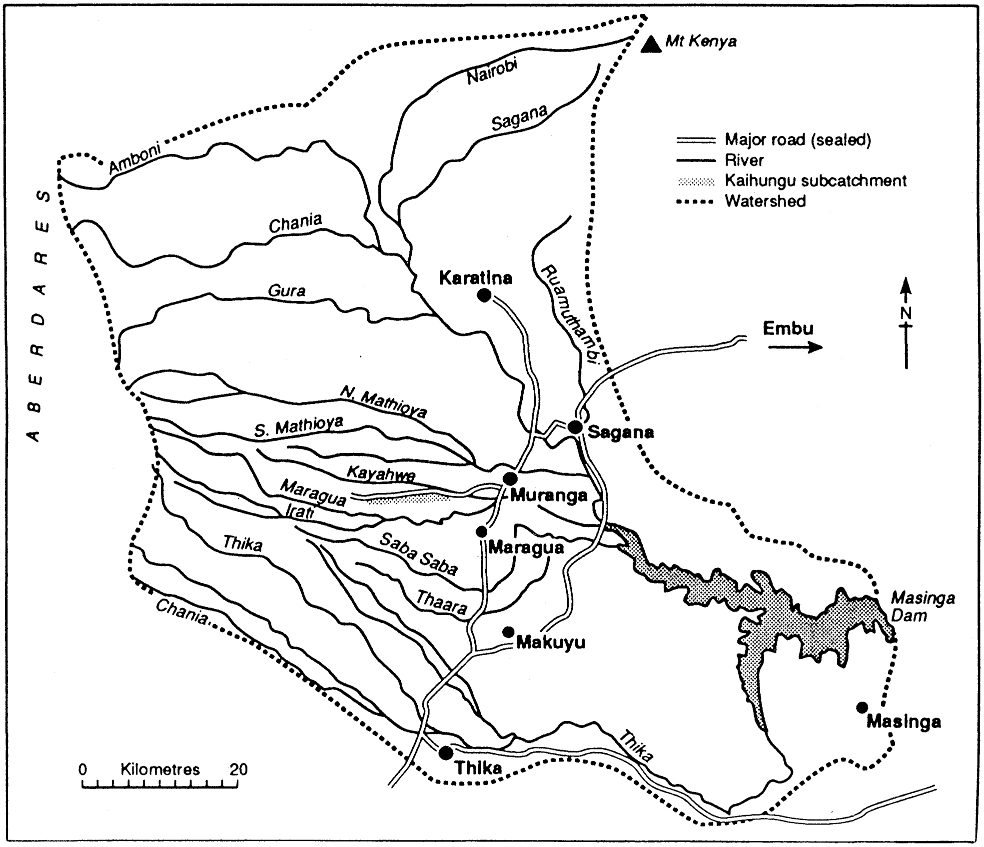

Fig. 1 A map of the Upper Tana basin and the location of the Kaihungu catchment.

headwater catchment (the Kaihungu basin) and the plot and gully scale. Table 1 shows how these monitoring scales were matched by different data sources for sediment monitoring and vegetation data collection. It was hoped that the multi-scale approach

Table 1 The multi-scale approach.

Scale	Erosion/sediment	Vegetation and topographical data	Analysis and modelling
Upper Tana subcatchments (total area 7950 km^2)	(1) monthly suspended sediment monitoring (2) rating curve estimation	(1) Landsat (2) agro-ecological maps	(1) GIS erosion hazard modelling (2) sediment load estimation
Kaihungu catchment (24 km^2)	(1) suspended sediment monitoring (2) flood monitoring	(1) Landsat (2) air-photos (3) topographic maps	(1) sediment load estimation (2) hydrograph analysis (3) urban catchment approach
Plots and gullies (<0.1 km^2)	(1) Gerlach traps (2) spot suspended sediment sampling	(1) cover estimation (2) ground radiometry (3) ground survey	(1) erosion estimation (2) statistical analysis

would reduce the task to manageable proportions, whilst still incorporating the full range of processes operating in the catchment, and downstream linkages.

Previous estimates were largely based on occasional suspended sediment sampling and rating curves and they varied by more than an order of magnitude (Table 2). The reasons for this are essentially due to variation in the sampling locations, methodology, sampling interval and variation in the period over which the sampling took place (Schneider, 1993). Since this wide variation alters dramatically the projected life of the Masinga Dam and would effect any cost-benefit analysis of the Seven Forks Hydro-electric Power Scheme, it was a priority to try and produce a new estimate based on recent data which included rainy season monitoring. This was also the first study in the Upper Tana basin to monitor flood events at the hillslope and small catchment scale. Data were collected during the long and short rains in 1991 and 1992.

Table 2 Previous estimates of sediment yield from the Upper Tana River basin.

Author(s)	Load (t $year^{-1}$)
Gibb (1959) 1947-1958 *Q* records	280 000
ILACO (1971) 1948-1965 *Q* records	250 000
Dunne (1975) 1956-1970 *Q* records	1 283 000
Dunne and Ongweny (1976) 1956-1970 *Q* records	568 547
Edwards (1979) 1956-1970 *Q* records	334 730
Ongweny (1978) 1956-1970 *Q* records	4 580 000
Maingi (1991) 1970-1984 *Q* records	7 470 000

SEDIMENT YIELD FROM THE UPPER TANA BASIN

Because of the limitations of the 1991-1992 data, such as an inevitably smaller range of flow variation in comparison with decadal variations, the data at the subcatchment scale have been combined with those of earlier sampling programmes in order to improve the rating curves. The loads estimated using the revised rating curves were compared with those derived using the old rating curves for equivalent discharges. For the Chania, Thika, Maragua and Sagana rivers no significant difference was found (using Mann-Whitney "U" test at the 0.05 probability level). For the others, Saba Saba and Ruamuthambi, the difference was significant but probably due to changes in sampling location and earlier problems with the discharge estimates (Schneider, 1993). The revised rating equations were used to estimate the combined mean annual load entering Masinga Dam over the period 1970-1988 using the two rating curves based on 1979-1984 data augmented by the 1991-1992 data and different runs of discharge data (Table 3).

These calculations which are relatively similar suggest that for the first seven years of the dam's operation (1981-1988), the mean annual input of sediment to the reservoir was of the order of 0.6-0.9 $\times$ 10^6 t $year^{-1}$. At this level, there is no danger that the reservoir lifespan is being significantly reduced from that given by the design proposals (520 years). The estimates for the principal subcatchments produced by application of

Table 3 New sediment load estimates for the Upper Tana River basin. Estimates vary due to the use of different initial rating curves (DHV, Maingi) and different periods of discharge data.

Sediment data	Discharge data	Mean annual load (t year^{-1})
1979-1984 (DHV)	1970-1984	665 000
1979-1984 (Maingi)	1970-1984	686 000
1979-1984 (DHV)	1981-1988	836 000

the revised curves are significantly lower than a number of previous estimates (an order of magnitude lower than some), despite the inclusion of rainy season data. Comparison of 1991-1992 data with 1979-1983 data suggests the largest cause of variation is discharge variation. The coefficients of inter-annual variation are high for all subcatchments varying from 95% to 57% over the estimated period 1981-1988. This illustrates the influence of high inter-annual flow variability and the practicality of using rating curves with synthetic "worst case" discharge estimates. The comparison of the relative magnitude of sediment yield from the subcatchments within the basin confirms that the rivers that contribute most to the Upper Tana load are those that drain the densely populated, intensively cultivated tropical foothills zone (100-300 t km^2 year^{-1}) and not the semiarid zone of the basin (50-100 t km^2 year^{-1}). At this scale using all the data, there is no significant relationship between sediment yield and drainage area, as inter-basin variations in climate, relief, erosivity and land use are too great. However, it is the foothills zone that should be the focus of soil conservation in order to reduce off-site impacts.

Soil loss measurements

Soil loss was measured in the Kaihungu catchment during the long and short rains of 1992 using 29 Gerlach traps located on a sample of slopes and vegetation types. The results (Fig. 2) clearly show the fallacy of the belief that the highest losses occur in the long rainy season, since erosion in the short rainy season can be greater due to a lack of vegetation growth (the short rains are too short for crop cover to increase sufficiently to reduce the erosion rate) and the intensity of the storms. This was also found to be the case by Lewis (1985) in the Kiambu and Murang'a districts. The soil loss measurements indicate a high susceptibility of the soil to detachment and transport on steep cultivated slopes when crop/vegetation cover is low, but there is a significant hillslope storage component, with physical conservation structures providing sites for deposition and sediment storage. During storms, the sediment observed to be reaching the stream was transported along a dense network of tracks, paths and associated gullies, which act as an extension of the drainage network. Material conveyed through this network was derived from the paths themselves, splash from adjacent fields and overland flow from poorly maintained soil conservation structures.

The Kaihungu catchment

The sediment yield estimated for this catchment from monitoring through both rainy

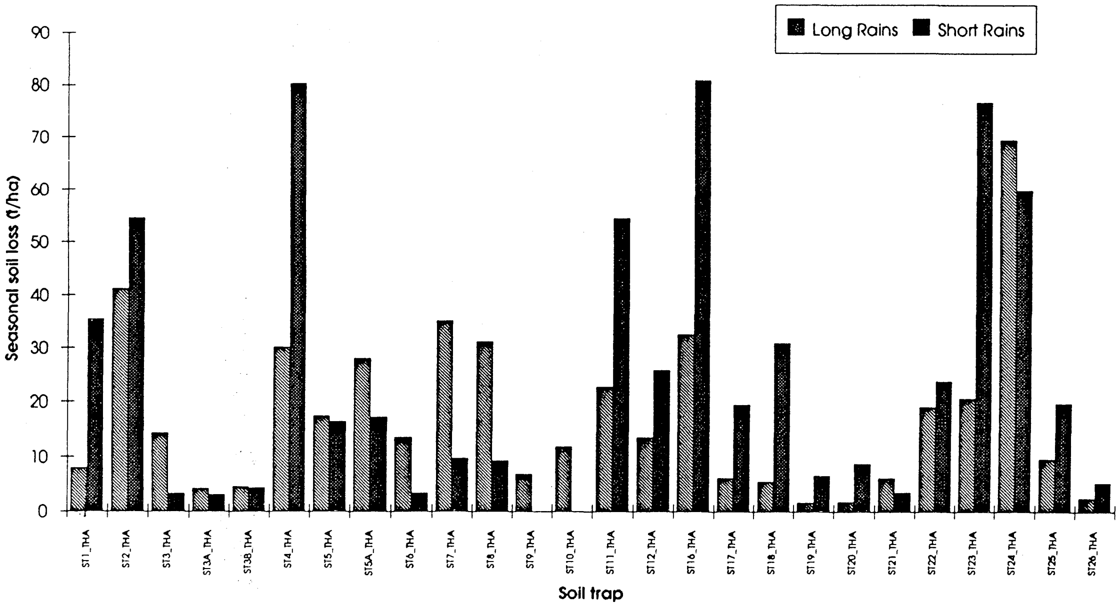

Fig. 2 Total measured soil loss in the Kaihungu plots in t ha^{-1} for the long and short rains of 1992.

seasons in 1992 was 156 t km^2 $year^{-1}$ which is comparable to the estimated unit yield of the Maragua subcatchment as a whole (140 t km^2 $year^{-1}$). This tends to confirm an earlier suspicion by Dunne (1975) that the headwaters of the tropical Tana serve as conduits with relatively little floodplain or channel storage. The Kaihungu stream has a flashy hydrological response as illustrated by the almost instantaneous response of flow to rainfall and the short recession limb. The catchment is composed of thousands of small agricultural units, artificial slopes (e.g. terraces and soil erosion control structures) and a conduit system of paths, tracks and roads. Under these circumstances the use of standard catchment models, such as the Universal Soil Loss Equation or computer models such as TOPMODEL based upon map-derived slopes and flow pathways, is inappropriate. Paths and other infrastructure cover 20% of the catchment (measured using ground survey and aerial photographs) and these areas are semi-impervious. The catchment behaves like an urban catchment, as can be shown using a simple engineering approach such as the rational or time area method. If we apply this method to a typical hydrograph with a peak discharge of 38 m^3 s^{-1} and assume no contribution from plots at all (i.e. 100% infiltration loss) then the predicted peak discharge is 40 m^3 s^{-1}.

CONCLUSIONS

Revised estimates using rainy season data suggest an average input of sediment to the Masinga dam of 0.6-0.9 $\times$ 10^6 t $year^{-1}$ for the first seven years of its operation. This is lower than some previous estimates. However the largest cause of inter-annual variation is discharge variation, making the life-span of the dam more dependent on future climate trends than changes in land use. Plot and subcatchment data indicate that the short rains produce proportionately more erosion than the long rains, due to a lack of vegetation cover. Comparison of the major subcatchments confirms that the highest yields are from the intensively cultivated relatively steep tropical foothills zone and not the semiarid zone of the basin. Although the erosion rates within this zone are high (100-300 t km^{-2} $year^{-1}$), the situation is probably sustainable given the deep soils and high productivity of the terrace/plot agriculture. Further soil conservation measures should be focused on paths, roads and tracks as they are the major areas of runoff generation and the point sources of runoff with high suspended concentrations.

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