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Suspended sediment yields in the Nairobi area of Kenya and environmental controls

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Abstract As part of a regional water resources study of the Nairobi area of Kenya, a survey of suspended sediment yields was carried out as a basis for assessing sedimentation rates of potential reservoirs. The study area comprised over 6000 km^2 in the upper Tana and Athi river basins, extending from the Aberdare Mountains in the northwest, to a rolling plateau in the south. Rainfall, runoff, land use and vegetation, which are described, show related altitudinal sequences. The diversity of the physical environment provided an ideal opportunity for assessment of factors controlling sediment yield. The zone of highest yield occurs where annual rainfall ranges from 1000 to 1600 mm and runoff lies between 350 and 700 mm. This coincides with the zone of smallholder coffee cultivation. At higher elevations with higher rainfall, sediment yield is of an order of magnitude lower, both in the indigenous forest and in the zone of smallholder tea cultivation, where soils have high structural permeability and generate little surface runoff. On the lower dry plateau, mean sediment concentration is high but sediment yields are comparatively low since annual runoff is limiting.

INTRODUCTION

Soil erosion annually exacts an enormous toll on the resources of tropical Africa, both at the point of its removal, where it destroys agricultural potential, and at the point of its deposition where it may reduce the capacity of reservoirs and canals.

The scale of the problem in Kenya is illustrated by Wooldridge (1984) who used hydrographic survey data to estimate a sediment inflow of 357 m^3 km^{-2} year^{-1} to the Kamburu reservoir on the Tana River. This represents a loss in storage volume of 17 million m^3 (12%) in 18 years. This estimate is in reasonable accord with estimates by Dunne & Ongweny (1976) based on suspended sediment measurements which indicated an inflow of 315 t km^{-2} year^{-1}. Their analysis showed large differences between the main sub-basins of the Tana River, but each sub-basin contained a wide range of topographic and land use types, and doubtless concealed even greater variations within each basin.

A survey of the water resources of the Nairobi region was carried out in 1985 to provide a basis for long term planning of water resources development (Howard Humphreys and Partners, 1986). As part of that survey, sedimentation rates at potential reservoir sites throughout the region were investigated. Existing sediment load data were reviewed and were supplemented at key locations by a further program of sediment sampling. The area investigated in the upper Tana and Athi river basins covers a wide range of climate, topography and land use and provided an unusual opportunity for the environmental controls on suspended sediment yield to be evaluated. Bed load transport rates were not measured but are believed to be a very small component of the total load.

THE AREA

The study area lies just south of the equator and extends approximately 70 km north and south of the city of Nairobi (Fig. 1). The Aberdare Mountains reaching over 4000 m, are the dominant topographic feature, formed by volcanic activity on the margin of the Rift Valley, which forms the western boundary of the study area. The eastern slopes are drained by the southern tributaries of the River Tana (Mathioya, Maragua, Thika and Chania) and the northern tributaries of the River Athi (Ndarugu, Thiririka, Ruiru and Nairobi). These streams form a dense parallel drainage network, deeply incised at higher

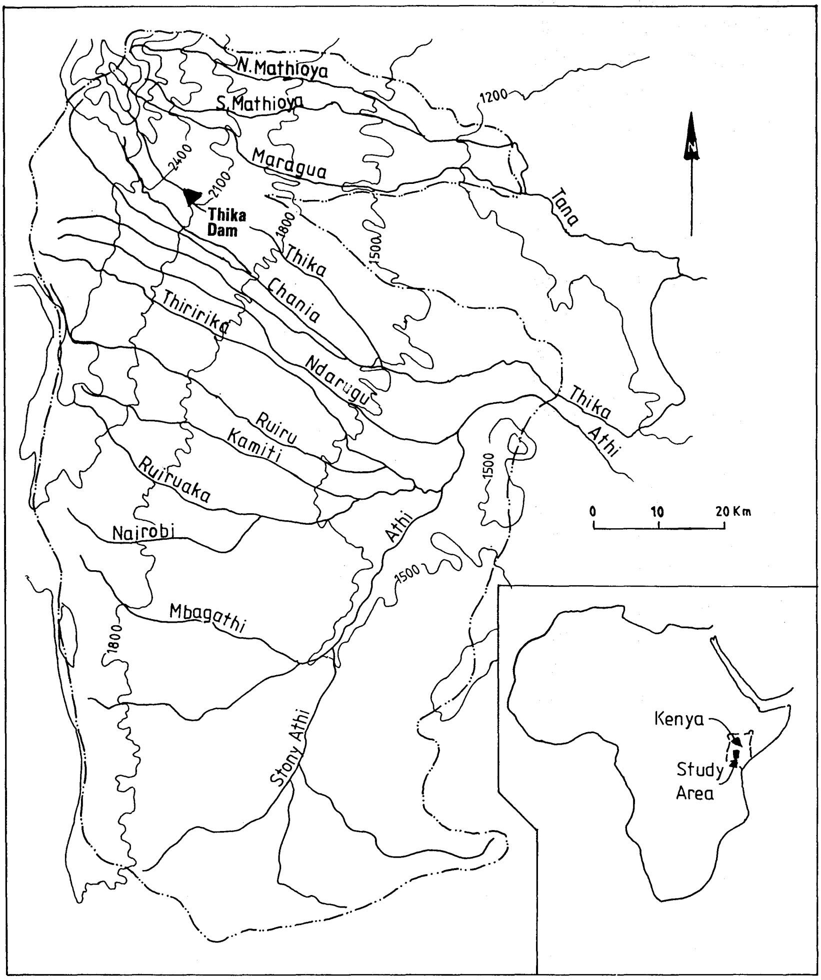

Fig. 1 Relief and drainage network of the upper Tana and Athi Rivers, Kenya, and, *Inset*: location of the study area.

levels. They emerge on a rolling plateau at an elevation of 1200 to 1600 m. The plateau is predominantly underlain by deeply weathered gneiss and schists and is drained by the intermittent southern headwaters of the River Athi (Stony Athi, Mbagathi), with a low drainage density.

Rainfall

Climate and topography are closely related. Annual rainfall is defined by over 200 daily raingauges. Average annual rainfall reaches a maximum of about 2500 mm, a little to the east of the Aberdare Mountains divide (Fig. 2). Totals fall off rapidly towards the Rift valley and more slowly toward the south and east and reach less than 500 mm on the plateau south of Nairobi.

The rainfall year may be divided into four seasons, the long rains from March to June, the short rains from October to December and the intervening dry seasons. Data on short period storm rainfall intensity, which defines soil erosivity, were not available, but surrogate values of daily maxima show a general increase with annual rainfall. Two-year return period daily maxima range from 65 to 90 mm and ten-year return period from 105 to 145 mm.

Land use, soils and vegetation

The sequence of land use, soil and vegetation zones is closely related to altitude and rainfall (Fig. 3). Above 2300 m a dense indigenous forest still exists, replaced locally by commercial conifer plantations. Below this level the forest has largely been cleared and the land is given over to mixed smallholder farming with perennial tea, pasture and a range of annual crops. Commercial tea plantations also occur, mainly to the west of Nairobi.

Downslope, smallholder coffee makes an appearance at about 1900 m and there is a narrow zone where mixed tea and coffee cultivation occurs, before tea is replaced completely by coffee as the principal cash crop. Valley floors are extensively used for growing vegetables and bananas. Cultivation in both tea and coffee areas occurs on very steep slopes (up to 70%) with variable, but usually limited, application of conservation measures. Coffee estates, which unlike the smallholder coffee are usually irrigated in the dry seasons, take up flatter land on lower slopes.

The slopes of the Aberdares, down through the coffee estates are mantled with a deep weathering layer. In spite of steep slopes, bedrock is rarely seen at higher levels, except in river beds; outcrops are a little more frequent at lower levels. The soils are dark red clay loams.

Runoff

Assessment of runoff variations in space and time is essential for evaluating sediment yields. Over 80 gauging stations have operated in the study area. These were assessed for quality and 16 base stations were selected for extension of daily record sets by

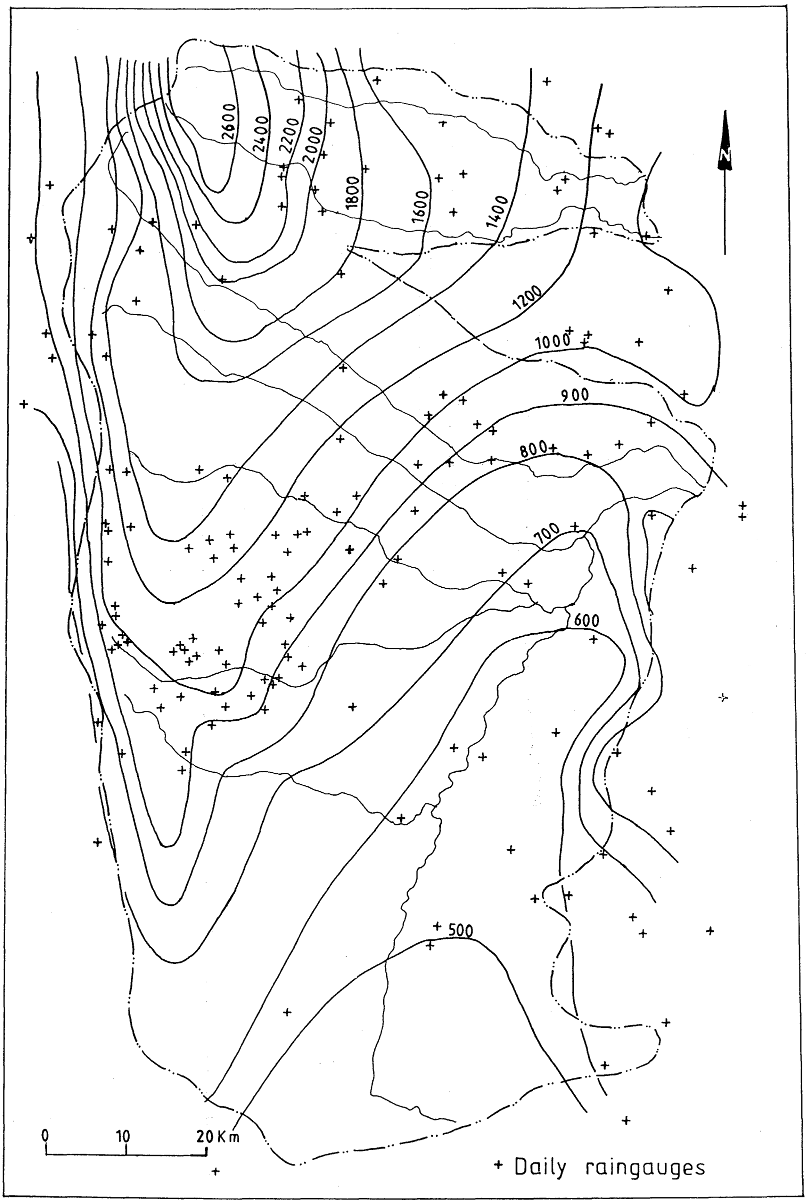

Fig. 2 Mean annual rainfall (mm) in the upper Tana and Athi river basins, Kenya.

regression to a common period, 1949-1986 for the Tana basin and 1956-1986 for the Athi basin. These data were supplemented by a reassessment of published information (e.g. Edwards & Blackie, 1981; WHO, 1973), with adjustments made to short records based on the ratio of runoff for the abbreviated and full record at adjacent base stations.

Annual runoff distribution (Fig. 4) closely resembles that of annual rainfall. Maxima of over 1500 mm occur in the upper Maragua and Mathioya basins. Like rainfall, the maximum occurs east of the topographic divide. In some instances, e.g. the Chania,

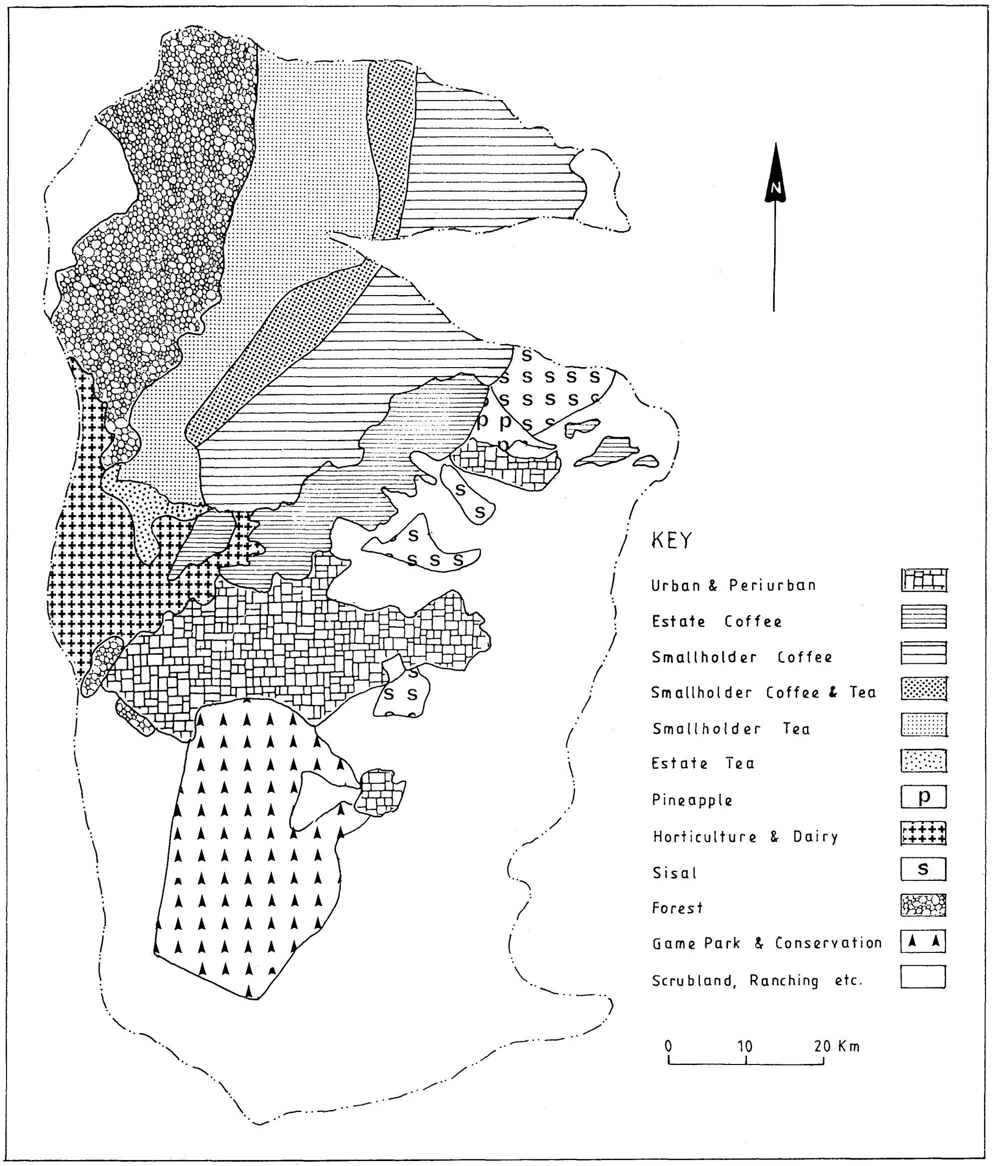

Fig. 3 Vegetation and land use in the upper Tana and Athi river basins, Kenya.

flows in the middle reaches are strongly influenced by spring flows. Runoff declines to the east and south and falls to less than 100 mm in most of the southern part of the area.

The seasonal pattern is again bimodal throughout the area, but there are great differences in basin response characteristics. Storm rainfall response is very damped on catchments originating in the Aberdares. In spite of periodic intense rainfall on steep slopes, wet season hydrographs of tributary basins, especially those of the Mathioya, Maragua and Thika, show a prolonged seasonal rise with only minor fluctuations, and a slow recession more typical of much larger basins. This applies not only to rivers

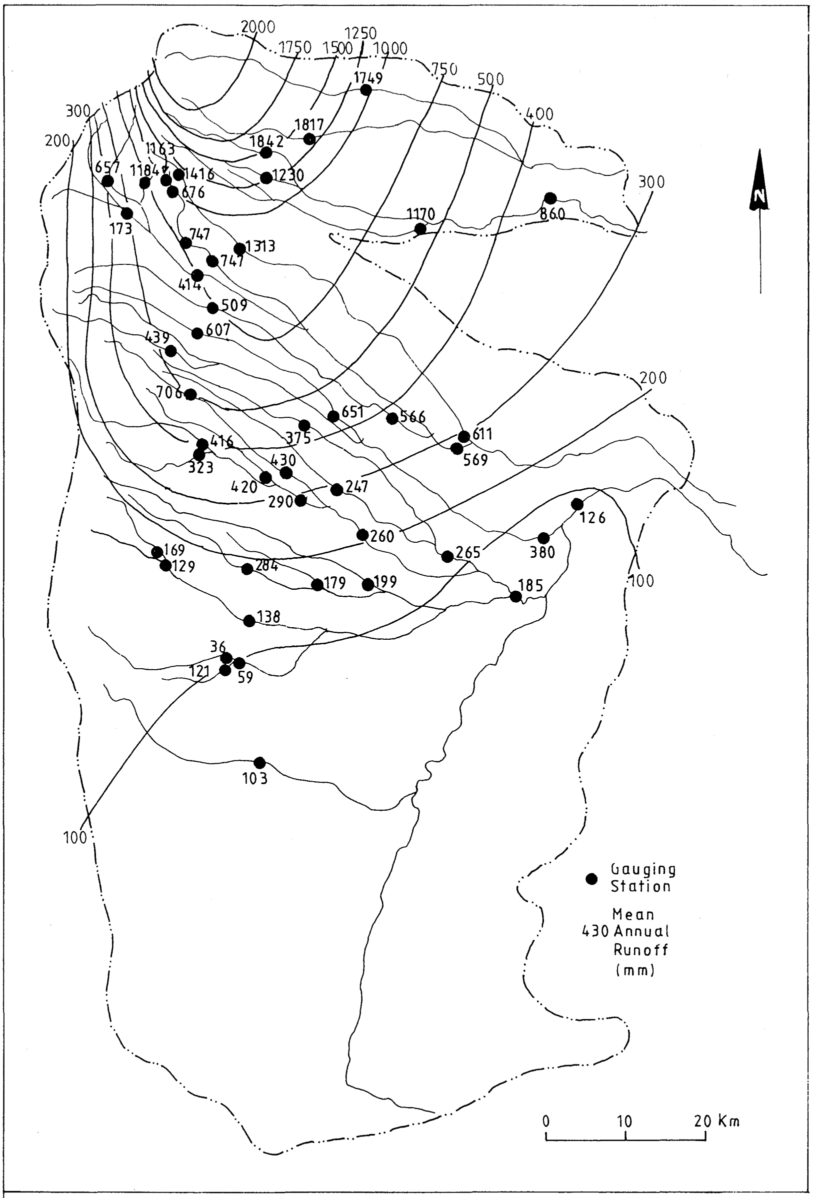

Fig. 4 Estimated mean annual runoff (mm) in the upper Tana and Athi river basins, Kenya.

originating in the forest, but also to a lesser extent to those predominantly on lower cultivated zones. Good dry season flows are maintained and quite small tributaries remain perennial. In contrast, towards the south, the rivers become more flashy and in the extreme case, tributaries in the upper Athi may have discontinuous flow even in the rainy season.

SUSPENDED SEDIMENT DATA

Data up to 1985 were obtained from two principal sources.

- The Ministry of Water Development (and predecessors) of the Kenya Government. Data were collected with varying intensities since 1948. Data to 1965 were reported by Dunne (1974). More extensive sampling was carried out after 1981 on downstream reaches of rivers in the study area to assess rates of sediment accretion in major reservoirs.
- A sampling programme as part of the project, supplemented information at existing stations and established new stations at higher elevations where there was a need for data to determine sediment inflow to potential water supply reservoirs. Data from both sources were predominantly obtained using USDH 48 or D49 samplers as the discharge weighted mean of three samples.

COMPUTATION OF SEDIMENT YIELD

Graphical relationships between measured suspended sediment load Q_s (t day^{-1}) and stream discharge Q (m^3 s^{-1}) were established at 20 locations. In the past a single relationship has frequently been used, of the form:

$$Q_s = a\, Q^b$$

where a and b are regression constants.

The establishment of this relationship and subsequent extrapolation over the streamflow record is subject to many theoretical and practical difficulties (Walling & Webb, 1981; Ferguson, 1986) and an empirical procedure was adopted which it is believed would improve accuracy and reduce bias in the estimated yields.

There is little theoretical justification for the application of a single logarithmic relationship through the full range of flow. Many plots show curvature, and as the greatest number of samples is usually taken at low discharges, the fit at high discharges may be least satisfactory. Good fit at high discharges is essential because it is at the upper range of flow that the greater part of the load is carried. Dunne (1979) shows that for Kenyan basins the highest 10% of flows carries an average of 80% of the mean annual yield and the highest 1% carries an average of 41% of the yield.

For this study, relationships have been determined by eye to provide satisfactory fit over the highest range of discharges, and, where appropriate, the relationship has been segmented over different ranges of flow or partitioned by season. Sediment rating curves have been combined with flow records to estimate average annual sediment load (Q_s) and annual sediment yield (t km^{-2} year^{-1}). Two different procedures were adopted depending on the nature of the available record:

(a) Daily flow records compiled for this study were combined with the adopted sediment rating curve to give daily and annual sediment loads through the period of record. This applies to 13 stations.

(b) Sediment rating relationships were combined with flow duration curves (World Health Organization, 1973) where daily flow sequences were not readily available. In the published flow duration plots, probability is shown on an arithmetic scale and it is therefore difficult to assess accurately flows of low exceedance probability, when most sediment is carried. Considerable error is therefore possible in calculated yields at individual stations, but anomalies should emerge when values are mapped. This procedure was adopted for seven stations.

Average annual sediment concentration (C)(mg l^{-1}) was calculated as:

$$C = 0.0137\ Q_s/Q \qquad (1)$$

where Q is the mean annual flow ($m^3\ s^{-1}$).

SPATIAL VARIATIONS IN SEDIMENT TRANSPORT

Regional variations in average annual sediment concentration and yield are shown in Fig. 5. In spite of the several potential sources of error, the maps show coherent regional distributions which are in keeping with observed patterns of soil erosion and stream turbidity. Where two or more sampling stations occur in a basin, the mean concentration and yield from intervening reaches may be calculated. In some instances, for example on the Maragua catchment, the resulting yield and concentration are higher than the measured values for the gauged catchments.

Concentrations are generally low in the west at higher elevations and higher rainfalls. There is a marked increase in downstream concentration by more than an order of magnitude. Sediment yields similarly increase downstream, but they decline again towards the drier south and east.

ENVIRONMENTAL CONTROLS ON SEDIMENT PRODUCTION

Rates of sediment removal from a drainage basin depend on those factors which promote or inhibit the detachment of particles and their transport to and within the river channel. Such factors are very numerous and include rainfall amount and intensity, slope steepness, a range of many soil properties which influence infiltration capacity and resistance to particle detachment, vegetation and land use, and runoff. Catchment runoff provides the means of conveyance of detached and delivered particles and may be limiting especially in semi-arid areas.

These factors show complex interactions such that the weight which attaches to a factor in one area may not apply in another. Thus prediction of sediment yields using multivariate equations relating sediment yield to climatic and catchment characteristics may give misleading estimates when applied outside their area of derivation. Prediction of yields through prior estimation of local erosion rates, for example using the Universal Soil Loss Equations (Wischmeier & Smith, 1965) suffers further from inadequate local information on delivery ratios (Walling, 1983). Examination of relationships and their variations within a limited region is essential to improve conceptual understanding. In this study an attempt is made to relate the spatial variations of observed yield and concentration (Fig. 5) to the distribution of potential controls (Figs 1-4), and associated observations.

In a previous study over a broader area of southern Kenya, Dunne (1979)

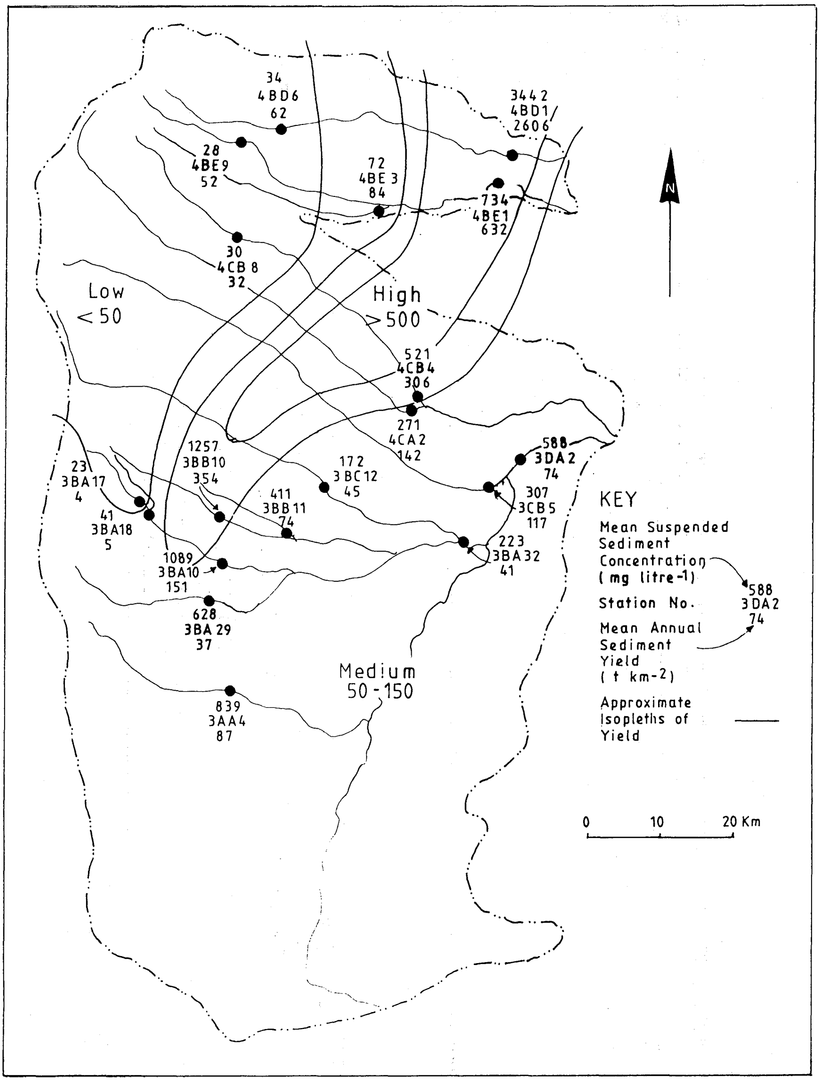

Fig. 5 Estimated mean annual sediment concentration and yield in the upper Tana and Athi river basins, Kenya.

investigated sediment yields and concluded that land use was the dominant control, although the influence of runoff and topography could also be recognized. He proposed equations to determine yield for four land use categories: (a) forested; (b) forest > 50%; remainder cultivated; (c) agricultural land > 50%, remainder forested; (d) rangeland. Yield from the agricultural land and grazed land was significantly greater than from partially or completely forested basins. However there was great variability within each land use class and especially in cultivated catchments. This is also evident in this study.

In the Aberdare forest, the dense vegetation cover provides protection against erosion and overland transport, and sediment yields are low. But very low sediment yields also prevail in the upper cultivated zone roughly down to the limit of tea production. This result is supported by measurements on five basins. This may be due in part to the protection given by the dense perennial tea crop, but this rarely occupies more than 50% of the area and, even where there are significant areas of annual crops, the sediment yield is much lower than expected from the application of Dunne's equations. Thus for one potential reservoir site near the lower margin of tea production, the estimated sediment yield on the basis of these equations was 339 t km^{-2} year^{-1}, but the measured yield was an order of magnitude lower. This observation is further confirmed by catchment experiments carried out within the forest (Edwards & Blackie, 1981). This showed continued low sediment yield in a basin cleared of indigenous forest and converted to smallholder agriculture. The reason is believed to reside in the high infiltration capacity of the soil, resulting primarily from vertical structural cracks which remain effective even after prolonged seasonal rainfall.

High structural permeability was demonstrated by pit permeability tests carried out at the Thika Dam site (Fig. 1). Twin pits were dug on a steep valley side slope and water pumped into the upper pit. Although the downslope pit remained dry, demonstrating low pore permeability, the vertical infiltration rate was such that the pit could not be completely filled. Thus most runoff reaches the channel by subsurface routes and carries little sediment load. The existence of limited surface runoff is also supported by damped flood response and prolonged recession on these steep basins.

Downstream, at a point roughly coinciding with the boundary of the smallholder tea and coffee land use zones, there is a rapid change in basin sediment yield as shown by visibly increased turbidity over a comparatively short reach of channel in the rainy seasons and confirmed by the much increased measured sediment yields downstream. Perennial coffee offers a much greater bare soil surface to rain impact than tea, and cultivation is on steep slopes where only limited protection is provided by terracing. In addition, there is a significant area of horticulture in tributary valley bottoms leaving soil exposed adjacent to the channels. During the dry season, valley bottom cultivation in this zone provides the principal source of sediment and dry season concentrations are commonly greater here than peak rainy season loads further upstream. Associated observations suggest that land use changes are accompanied by changes in soil infiltration characteristics. Gullies and areas of exposed bare subsoil occur in this zone but are rarely observed at higher elevations. They are most common in the lower reaches of the Maragua and Mathioya basins where the sediment yields are also the highest observed.

Erosion is ameliorated to some extent in the coffee estate zone by gentler slopes, better land use practices and less cultivation adjacent to the channel. However the relative sediment contribution from smallholder and estate coffee areas during the rainy seasons remains uncertain and requires further study.

Towards the south and east, where annual rainfall and runoff become low, the grassland vegetation offers less protection against raindrop impact. However, slopes are usually gentle and the drainage density low, and it seems likely that only a small proportion of the detached material reaches the river channel. Although the average concentration is high, sediment yields are comparatively low since the annual runoff is small.

In general, the sediment yield may be viewed as the product of average sediment concentration and annual runoff, which are inter-related through association with vegetation and soils. Thus low sediment yields are also observed in the higher Aberdares where high runoff combines with very low concentrations. It is in the intermediate zone where significant areas are exposed to soil detachment and transport, and runoff is moderately high, that the greatest sediment yields occur. Typically the zone of maximum sediment yield has an annual runoff of from 350 to 700 mm and an annual rainfall of from 1000 to 1600 mm.

CONCLUSIONS

In spite of the potential errors in the sediment yield estimates, the results obtained show a regionally coherent spatial pattern which results from interactive environmental controls. Land use has an important influence, though not necessarily an overriding one. The upper tea cultivation zone, although cultivated for several decades shows little change in sediment yield from the natural forest. This appears to be due to the continued high soil infiltration capacities and low surface runoff. It is in this zone that the most suitable sites for public water supply reservoirs to supply Nairobi under gravity, are situated. Under present conditions these are unlikely to suffer any serious siltation problems. However, the stability of the soil structures may be at risk in the event of more intense or mechanical cultivation practices and efforts should be directed to devising systems that preserve the structures and sustain infiltration.

It is uncertain whether the soils at lower altitudes in their natural state enjoyed similar moderating structures or whether they became immediately vulnerable on first cultivation. However, conditions of rainfall, soil, slopes and land use now combine to create serious erosion problems. A more radical approach to soil conservation is required in these areas both to maintain present levels of agricultural productivity and to protect the main stem reservoirs on the River Tana.

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