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Estimation of colluvial reservoir life from sediment budgeting, Katiorin experimental basin, Kenya

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Abstract Field studies of sediment entrainment, storage and transport in channel systems within a small, semiarid Kenyan drainage basin (0.30 km^2) have been in progress since 1984. The study area was subject to overgrazing, drought and locust invasions in the 1920s and 1930s. The present paper reports the results of field experiments carried out during 1986, which had two principle objectives. The first was to quantify the total amount of sediment within the colluvial-hillslope zone of the Katiorin basin, and the second was to determine the net change in storage within this reservoir using a sediment budget approach. These data are necessary to assess erosion rates in the study basin. Results indicated a net sediment loss of 6150 t km^{-2} $year^{-1}$ from the colluvial reservoir during 1986. Once the material reached the channel network, it was efficiently removed from the basin. Results suggest that at current rates of colluvium loss, 70% of the Katiorin basin will approach colluvial exhaustion in 150 years. The sediment budget approach is of great practical value, since it identifies the most significant areas of sediment loss and areas where rehabilitation measures should be implemented.

Evaluation de la durée de vie d'un réservoir de colluvion à l'aide de la technique du bilan sédimentaire, au bassin expérimental de Katiorin, au Kenya

Résumé Des études sur le terrain de l'érosion, du transport, et de l'accumulation de sédiments dans le réseau hydrographique à l'intérieur d'un petit bassin hydrologique semi-aride Kenyan sont en cours depuis 1984. La région sous étude a été soumise au surpaturage, à la sécheresse, et à des invasions de sauterelles dans les années 1920 et 1930. La présente étude fait état des résultats d'expériences sur le terain qui ont eu lieu en 1986. Ces expériences comportaient deux objectifs principaux: premièrement, déterminer avec précision la quantité totale de sédiments présents dans la zone de colluvion sur la pente du bassin de Katiorin; et en second lieu, mesurer la variation nette en terme d'accumulation de sédiments à l'intérieur du réservoirs à l'aide de la technique du bilan sédimentaire. Ces données sont nécessaires pour déterminer les vitesses d'érosion dans les bassin étudié. Les résultats obtenus indiquèrent une perte nette de 6150 t km^{-2} $annee^{-1}$ de sédiments en provenance du réservoir de colluvion durant l'année 1986. Les sédiments étaient aisément évacués du bassin hydrographique dés qu'ils atteignaient le réseau hydrographique. Les résultats suggèrent qu'au taux courant de perte de colluvion, la réserve de colluvion sera presque épuisée dans 70% du bassin de Katiorin d'ici 150 ans. La technique du bilan sédimentaire s'est révélée être très utile, puisqu'elle permet d'identifier les zones où la perte de sédiments est la plus sérieuse, et les zones où des mesures de réhabilitation des sols devraient être mises en oeuvre.

INTRODUCTION

Soil erosion and fluvial transport have been studied in Africa for more than 50 years (cf. Walling, 1984; Lal, 1985). However, many of these studies have focussed on either small hillslope plots or drainage basins. Basin-scale erosion studies tend to be input-output oriented (i.e. "black-box", cf. Walling & Webb, 1983). Little is known about the local transfers or storages of material within drainage basins. Richards (1987), emphasized this point when he stated that the focus on "output" series has delayed geomorphological contributions to the modelling of sediment and solute delivery processes.

Sediment output studies provide an indirect and very imprecise measure of erosion occurring above a given point in a drainage basin. It is necessary to establish closer links between erosion from source areas, storage and transport in channel systems (Wolman, 1977). The construction of sediment budgets can provide information on the links between hillslope erosion (plot) studies, sediment transfer, storage and output from a drainage basin.

Sediment budgets for drainage basins must incorporate inputs, storage changes and sediment outputs. The general sediment budget equation is a continuity equation:

$$\text{inputs} = \text{outputs} \pm \text{change in storage} \tag{1}$$

The change in storage is the most poorly understood component of the system (Swanson *et al.*, 1982). This results largely from the difficulty in defining and quantifying amounts of sediment in colluvium (Dietrich *et al.*, 1982, Lehre, 1982), flood plains, and in-channel deposits (Leopold *et al.*, 1966). The net change in sediment storage in these reservoirs is critical to the understanding of the linkages between sediment inputs and outputs from drainage basins. If the net change in sediment storage is negligible during a monitoring programme, then there is an efficient transport of sediment from source areas to the basin outlet. Disequilibrium within a drainage basin occurs when there is significant aggradation or degradation of stored sediment. Sediment outputs from drainage basins can only be used to make reliable estimates of basin denudation when there is no significant change in sediment storage (Trimble, 1977), or when changes in storage occur over time scales an order of magnitude different than the period for which the budget is being estimated (Phillips, 1986).

Critical areas of drainage basin erosion can be identified through constructing fluvial sediment budgets. An understanding of sediment source areas is necessary to implement techniques to reduce soil loss and off-site damage, such as reservoir sedimentation. Sediment budgets can thus provide information which is needed by decision-makers to plan effective strategies to reduce soil loss.

The present drainage basin study uses a fluvial sediment budget approach to identify source areas and sediment reservoirs. Information from this study may be used to model sediment changes within a system, and allow drainage basin planners to concentrate their conservation efforts on the most appropriate areas.

STUDY AREA

The study area is located in the Baringo District, Rift Valley Province, Kenya (Fig. 1). The Baringo District has long been recognized as an example of misuse of land resources (Thom & Martin, 1983). The causes of environmental degradation in the area include inappropriate land use techniques and overgrazing, combined with natural disasters such as drought and locust invasions (Anderson, 1981).

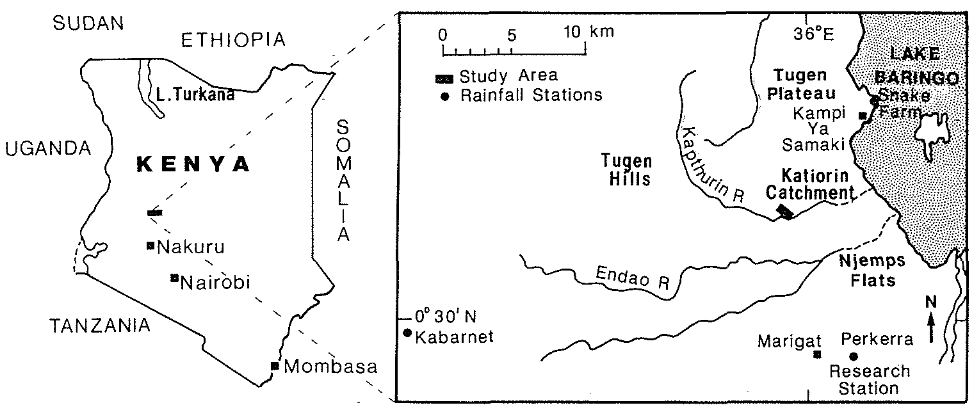

Fig. 1 Location map of the Katiorin experimental basin, Kenya.

The data were collected in the Katiorin experimental basin, located west of Lake Baringo, in a semiarid, tropical environment ($0^{\circ}33'$N, 36°E). The Katiorin basin is considered to be representative of the area west of Lake Baringo and is a manageable size for hydrological and geomorphological research. The Katiorin basin is located in the Gregory rift zone, which comprises the eastern arm of the Tertiary rift system of East Africa (Rosendahl, 1987). The geological units exposed in the drainage basin are members of the Kapthurin Formation, which is a fluvio-lacustrine sequence, interbedded with tuffs (Tallon, 1978).

Average annual rainfall in the area is approximately 650 mm (arithmetic mean) and the median annual rainfall is 680 mm. Rainfall is extremely variable in space and time, and is generated mainly during convective storm events. Annual rainfall may vary by 3 times in successive years. The rainfall regime is bimodal, with peaks in April and May (27% of annual rainfall) and July and August (28% of annual rainfall). Potential evapotranspiration in the area, calculated by the Penman method, is approximately 1700 mm $year^{-1}$.

The vegetation in the Katiorin basin is open woodland (*Acacia* thorn-scrub) and is formed on the residual soils of the area. Canopy coverage estimated from aerial photographs is less than 30%. Ground cover in the basin is mainly composed of annual grasses which occupy less than 5% of the total basin area.

The Katiorin basin is a fourth-order basin, with a planimetric area of 0.30 km^2. The ephemeral stream network has a fine drainage density of approximately 27 km km^{-2}, and a mean bifurcation ratio of 5.3. The Katiorin basin may be divided into an upper basin and a lower basin (Fig. 2). The upper basin is characterized by relatively steep slopes (i.e 10 to 26°), and slope lengths less than 50 m. A colluvial mantle covers the hillslopes from midslope to footslope, and the surface texture is silty clay with minor sands and a residual lag of gravels. The lower basin is characterized by mudstone units with a thin colluvial covering, and a coarse-grained fan deposit near the basin outlet.

EXPERIMENTAL DESIGN

Sampling scheme

General sediment budgets must integrate hillslope and channel subsystems. Inputs of sediment from primary source areas within the hillslope subsystem were identified. Primary source areas were defined as all hillslope areas not mantled by colluvium (i.e. exposed bedrock, parent material and regolith). Sheetwash was assumed to be the most important hillslope transport process, while mass wasting and subsurface flow were considered to be of minor importance. Colluvium was identified as the main temporary hillslope storage reservoir. Erosion of the colluvial reservoir formed an input to the channel subsystem. Temporary storage within the channel subsystem included flood plains, streambank deposits and in-channel deposits. Outputs from the basin included suspended sediment discharge, and bed load discharge.

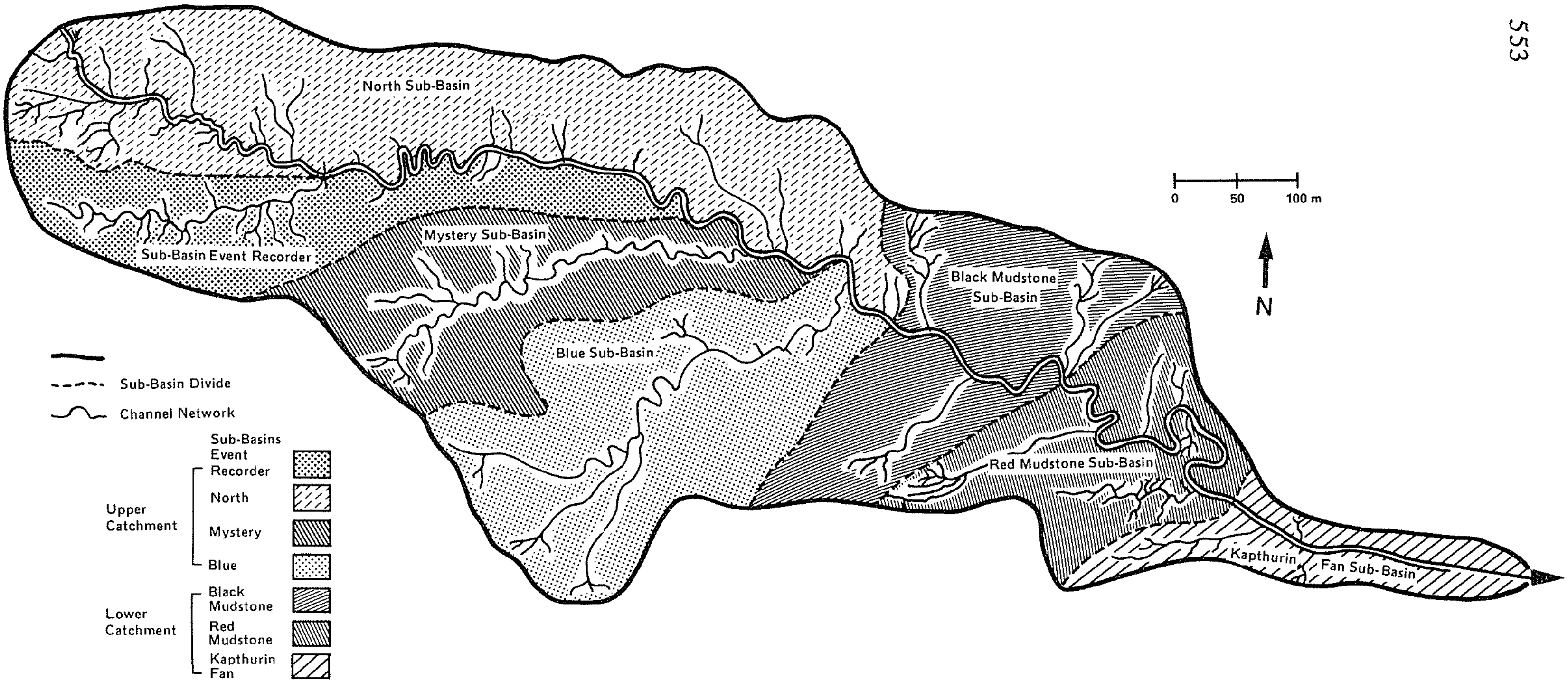

Fig. 2 Stream channel network and sub-basins of the Katiorin experimental basin.

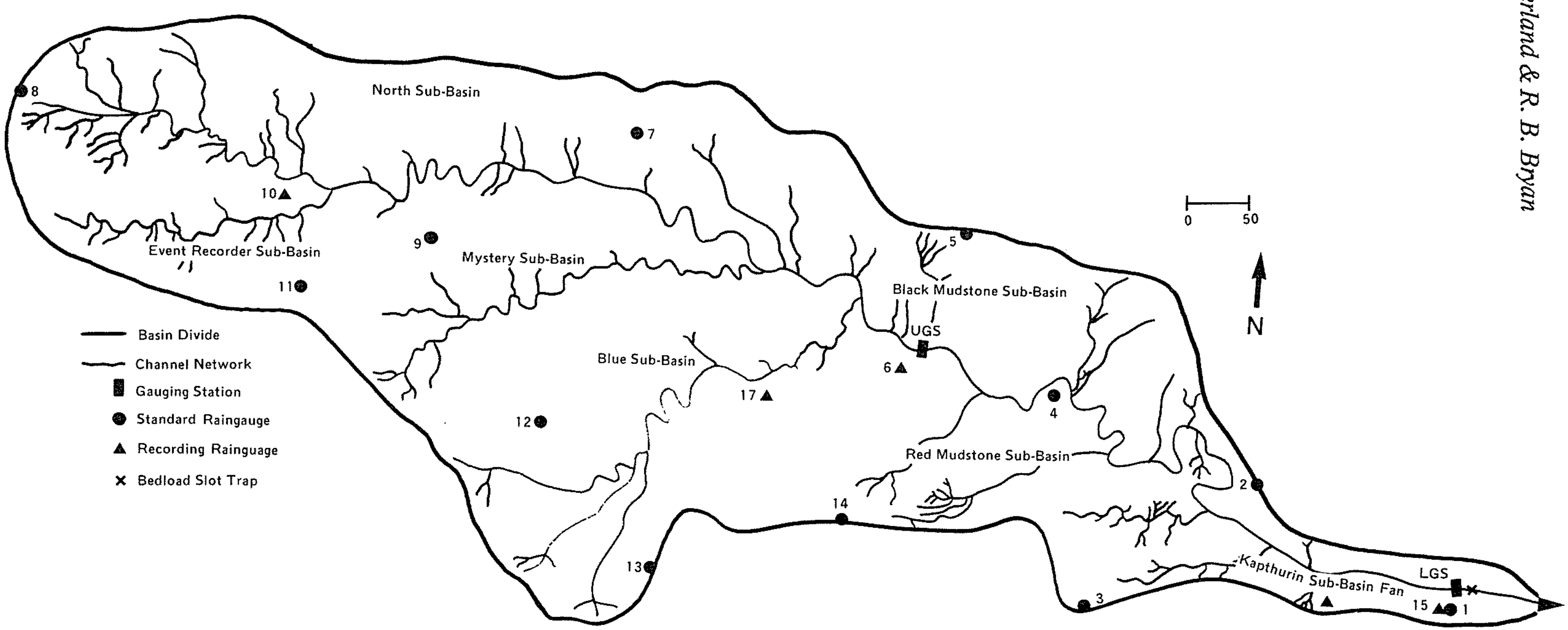

Fig. 3 *Location of gauging stations and raingauges in the Katiorin experimental basin.*

General instrumentation

Seventeen raingauges were located in the basin, of which 12 were non-recording gauges, measured after each rainfall event, and five were tipping-bucket raingauges (Fig. 3). Two streamgauging stations were established to aid storm event sampling. An upper station was located immediately downstream from the junction of major tributaries, draining an area of 0.21 km^2 (Fig. 3). At each station, a Campbell CR-21 data logger was installed. Two channels on each data logger recorded rainfall amounts, and one channel was used to measure water depth with a Druck PDCR 10/D pressure-transducer. A 5-min sampling interval was used for instantaneous water depth measurements. Water velocity was determined using a Montedoro Whitney PVM2A electromagnetic flowmeter. A stage-discharge relationship was established for the lower gauging station:

$$Q = 94.4\ (h)^{2.43} \qquad (2)$$

where Q is the discharge ($m^3\ s^{-1}$), and h is the stage (m). The coefficient of determination of equation (2) was significant at the 5% level (r^2 = 0.86, n = 50).

Depth-integrated water samples were collected using an Uppsala-type suspended sediment sampler (Nilsson, 1969). Samples were analysed for suspended sediment concentration by filtration. Bed load was sampled using a hand-held, Helley-Smith pressure-differential sampler. A sampling interval of 30–60 s was used, and samples were taken from one point in the channel.

Seventeen hillslope erosion pin networks were installed within primary source areas (i.e. non-colluvial) and colluvial areas (370 pins). Fifteen flood plain erosion pin networks were established using 71 pins. Eleven lateral corrasion arrays (cf. Düysings, 1985) were established on the main third-order and fourth-order channels, to monitor streambank erosion. Thirteen Gerlach troughs were installed to monitor runoff and erosion from small hillslope plots (<5 m^2).

The net change of in-channel sediment storage during a runoff year (12 storm events) was determined using 87 cross sections, surveyed on the three major third-order tributaries and on the main fourth-order channel,

Net change in colluvial storage was determined from repeated erosion pin measurements. The total storage of colluvium in the basin was determined by surveying 59 profiles with an Abney level and excavating 121 pits. Colluvial slope widths were determined from aerial photographs. The volume of colluvium stored within each sub-basin was converted to a mass by using mean colluvial bulk densities from each sub-basin.

RESULTS AND DISCUSSION

In-channel storage change

During 12 runoff events of 1986, there was a net increase of 164 ± 17 t km^{-2}

year^{-1} of sediment within the in-channel reservoir (i.e. bed-sediments and channel-margin bars). Increase in sediment within the in-channel reservoir was minor (<0.6%) compared to the total size of the reservoir (28800 ± 350 t km^{-2}). The channel sediment reservoir was essentially in equilibrium during the study period, and played only a minor role in regulating output of coarse-grained sediments >0.25 mm from the basin.

Flood plain storage outputs

The net change in flood plain storage could not be determined because of major pin disturbance. However, since they were discontinuous, formed less than 1% of the basin area, and because no overbank events occurred during 1986, it was assumed that flood plains were of minor importance in regulating sediment output. If there was a storage change in this reservoir it was probably small and was governed by surface inputs form the hillslope subsystem, and outputs by sheetwash.

Lateral corrasion of streambanks

Sediment production from channel banks to the main channels of the Katiorin basin was estimated as 67 ± 13 t km^{-2} year^{-1}. The sediment loss was supplied from about 10% of the total streambank length within the basin. Lateral corrasion was spatially variable, with only minor amounts eroded from the cohesive red and black mudstone streambank sections.

Mass wasting

Past episodes of rapid mass wasting in the form of slides and slumps was evident in the field. However, many of these now appeared to be stabilized, with a good vegetation cover, and no signs of rilling or gullying. Bank collapse was noted on several occasions, but volumes produced were minimal, and were not included in the sediment budget.

Evidence of soil creep was apparent within the basin, but could not be reliably measured during a one year study. Thus, the method of Dietrich & Dunne (1978) was used to estimate the creep contribution, using a reasonable mean creep velocity of 2.5 mm year^{-1} (e.g. Lewis, 1976). The estimated creep contribution from hillslope areas was only 40 ± 14 t km^{-2} year^{-1}.

Sediment input from primary source areas

Denudation of primary source areas resulted in a net loss of 922 ± 319 t km^{-2} year^{-1} (Table 1). The loss of sediment was spatially variable, with only a minor loss from the Kapthurin fan sub-basin (12.6 ± 8.2 t km^{-2} year^{-1}), but

Table 1 Estimation of primary source area erosion and colluvial erosion by sheetwash, Katiorin basin, 1986

Sub-basin	Primary source area denudation* ($t\ km^{-2}\ year^{-1}$)	Colluvial denudation ($t\ km^{-2}\ year^{-1}$)
Blue	371 ± 61.4	3220 ± 530
Mystery	102 ± 54.8	319 ± 145
Event Recorder	31.4 ± 16.8	215 ± 97.1
North	217 ± 63.9	3040 ± 592
Black Mudstone	142 ± 86.8	66.3 ± 18.7
Red Mudstone	46.0 ± 27.1	59.7 ± 15.5
Kapthurin Fan	12.6 ± 8.2	110 ± 56.5
Totals	922 ± 319	7030 ± 1450

*Based on planimetric area of the Katiorin basin.

sediment loss was significantly higher from the blue sub-basin (371 ± 61.4 t km^{-2} $year^{-1}$).

Colluvium storage change

The total loss of sediment from the colluvial reservoir was 7070 t km^{-2} $year^{-1}$ of which 7030 ± 1450 t km^{-2} $year^{-1}$ was removed by sheetwash erosion (Table 1) and 40 ± 14 t km^{-2} $year^{-1}$ by soil creep. The net loss of sediment from the colluvial reservoir was 6150 ± 1140 t km^{-2} $year^{-1}$ and incorporates an input of 922 ± 319 t km^{-2} $year^{-1}$ from the primary source areas.

The total mass of colluvium within the basin was estimated to be 2.31×10^5 t (±27%). The upper basin was the dominant reservoir with 6 to 7 times more colluvium than the lower basin. The net losses of colluvium from sub-basins in the upper catchment were extrapolated to determine the time period necessary for colluvium to approach exhaustion (Table 2). Results indicated that 63% of the colluvium in the upper basin (0.21 km^2) would be lost in less than 15 years. The blue sub-basin (0.060 km^2) would approach total exhaustion during the same time period. These calculations are only approximations, as they assume that:

(a) the net changes in colluvial storage determined in 1986, can be extrapolated to all successive years,

(b) the decrease in slope of the colluvial surface due to erosion will not cause a decrease in transport rates,

(c) no exogenous inputs are received from such sources as volcanic eruptions, and

(d) all colluvium is fine-grained (<0.25 mm) and is transported mainly by sheetwash.

Table 2 Estimation of colluvial exhaustion times, upper basin, Katiorin

Sub-basin	*CS_{NC} (t year^{-1})*	*CS_T (t)*	*Mass of colluvium remaining after a given time period:* 13 year	43 year	120 year	150 year
Blue	*–855*	*10 800*	*~0*	*~0*	*~0*	*~0*
Mystery	*–65.3*	*7 700*	*6 870*	*4890*	*~0*	*~0*
Event Recorder	*–55.0*	*8 150*	*7 460*	*5790*	*1670*	*~0*
North	*–847*	*36 400*	*25 700*	*~0*	*~0*	*~0*
% of initial storage remaining			*63*	*17*	*2.6*	*~0*

CS_{NC} *is the net change in colluvial storage, 1986.*
CS_T *is the total mass of stored colluvium.*

Drainage basin sediment output

Suspended sediment was the dominant mode of sediment transport within the Katiorin basin. During 1986, 96% of the total sediment discharge was transportedin suspension (6780 ± 1350 t km^{-2} year^{-1}). Bed load discharge was 290 ± 73.6 t km^{-2} year^{-1}, thus total sediment discharge for 1986 was 7070 ± 1420 t km^{-2} year^{-1}.

Sediment budget

Input of sediment from the hillslope subsystem and from streambanks to the channel subsystem was 7140 ± 1480 t km^{-2} year^{-1}. Outputs from the basin were 7070 t km^{-2} year^{-1}, and net storage increase within the in-channel reservoir was 160 t km^{-2} year^{-1}. There was a net imbalance of approximately 90 t km^{-2} year^{-1}, which is within the experimental error of the budget.

Results of the sediment budget suggest that remobilization of stored colluvium is the main source of sediment within the Katiorin basin. The mean denudation rate for the basin was 4.7 ± 1.0 mm year^{-1}, computed using sediment output data and a mean bulk density of 1.5 t m^{-3}. However, this value underestimates the actual denudation within the colluvial reservoir (i.e. 5.8 ± 1.1 mm year^{-1}), and overestimates denudation within the primary source areas (i.e. 3.0 ± 1.1 mm year^{-1}). Sediment from the colluvial zone was efficiently delivered to the channel subsystem, and from the basin. The efficient translation of sediment resulted from the dissected nature of the basin, short, steep slopes and the erodible fine-grained materials (i.e. 98% of the suspended sediment transported was silt and clay).

CONCLUSIONS

The area to the west of Lake Baringo has been degraded since the 1930s. Construction of a fluvial sediment budget for this degraded area provided the data necessary to assess present rates of local denudation, and sediment transfer, storage, and output from a 0.30 km^2 drainage basin. Results showed high current denudation rates within the basin. Net denudation of stored colluvial material approached 6 mm for the 12 storm events of 1986 (return periods <1.8 years) and erosion from non-colluvial areas was approximately 3.0 mm $year^{-1}$. Changes within the in-channel reservoir were minor, and thus had little influence in regulating sediment flux from the basin. Remobilization of stored colluvium from the hillslope subsystem produced mainly fine-grained sediments to the channel subsystem, which were efficiently transported from the drainage basin.

Exhaustion of colluvial material in the upper basin was predicted by extrapolating 1986 net colluvial denudation data, and estimating the total store of colluvium. Results suggest that the upper basin may approach colluvial depletion within 150 years. This is geomorphologically significant since the entire basin system would have to adjust to the new equilibrium condition of an altered stream load. Basin adjustment could involve an increase in channel degradation or increase in lateral corrasion of streambanks, and could cause an accompanying increase in mass wasting. Therefore the suspended-load channel which is presently in equilibrium with supply conditions, may develop into a braided bed load channel as the supply of fine-grained sediments decreases and coarse-grained sediments increases. In this way colluvial depletion may result in river metamorphosis (cf. Schumm, 1969, 1985).

Fluvial sediment budgets are necessary to improve understanding of the linkages between local denudation rates, transfer processes and outputs. Sediment budgets are also needed to develop predictive models of soil loss. Simple black-box, input-output basin studies must be developed to include net storage change components to identify critical source areas for implementation of conservation measures.

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