SUSPENDED SEDIMENT TRANSPORT CHARACTERISTICS OF UPPER KALEYA RIVER, SOUTHERN ZAMBIA

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Abstract

Soil erosion has many negative impacts on agriculture and other land related activities and so there is an urgent need to find ways of controlling it. In a bid to increase the understanding of soil erosion and sediment transport processes in Zambia, a project, which was funded by the UK Department for International Development, was conducted in the Upper Kaleya River catchment, southern Zambia, between 1997 and 2000. Being primarily concerned with sediment budgeting, this project necessarily involved the collection of discharge and suspended sediment load data for estimating sediment yields from the study river. This paper reports the suspended sediment transport characteristics of Upper Kaleya River during the study period. Analysis of the data collected at the study catchment outlet, at Roadbridge, revealed that discharge ranged from zero, during some dry season months, to 3.65 m^3 s^{-1}, with a daily mean discharge of 0.406 m^3 s^{-1}. The corresponding suspended sediment loads ranged from zero to 253.9 tonnes, with a mean of 3.15 tonnes per day. Magnitude-frequency analysis revealed that the flow responsible for transporting most of the suspended sediment load was 1.44 m^3 s^{-1}. This discharge represented 1.5 % of the time. During the study period, the total cumulative discharge was estimated at 34.8 million m^3, whilst the total suspended sediment load was estimated at 3,130 tonnes. It is concluded that, though the Upper Kaleya River catchment is small, measured discharge and suspended sediment fluxes are reasonably high. Ways of controlling soil loss and of improving water resource protection should therefore be encouraged among the local farmers. There is also an urgent need to conduct this type of research in larger catchments in Zambia and in southern Africa region in order that national and regional sediment-related control measures can be designed and implemented.

KEY WORDS: Catchment, effective discharge, magnitude-frequency analysis, river discharge, soil erosion, suspended sediment load.

Introduction

The Upper Kaleya River flows through one of the most productive areas of Zambia and provides water for domestic and agricultural usage (Figure 1). Although local yields of coffee, maize and paprika are high, soil erosion and sediment-related environmental problems are widespread, with the result that there is an urgent need to protect soil and water resources from pollution and over-use. Without such management strategies, sustainable agricultural production is seriously threatened. The provision of improved sediment control policies is, however, dependent upon a better understanding of suspended sediment transport regimes. In a bid to increase the understanding of sediment transport and to assist the provision of management strategies for dealing with such problems in Zambia, a collaborative research project was conducted in the Upper Kaleya catchment. In a bid to increase the understanding of soil erosion and sediment transport processes in Zambia, a project, which was funded by the UK Department for International Development, was conducted in the Upper Kaleya River catchment, southern Zambia, between 1997 and 2000. Preliminary results of this project were reported in Sichingabula *et al*. (2000).

Theoretical background

Conventional methods for discharge and sediment transport monitoring and analysis have previously been described by a range of contributions (e.g. Leopold et al., 1964; Gregory and Walling, 1973; Briggs, 1977; Walling, 1977; 1983). The most widely used approach for the analysis of effective discharge, with respect to suspended sediment transport, was first introduced by Wolman and Miller (1960). They argued that the amount of sediment transported by flows of a given magnitude depends upon the form of the relationship between discharge and sediment concentration, as well as on the form of the discharge frequency distribution. Moderate flows of low frequency were predicted to be the most effective in the transportation of suspended sediment loads. This approach has subsequently been applied to a number of rivers around the world (e.g. Benson and Thomas, 1966; Pickup and Warner, 1976; Wolman and Gerson, 1978; Beven, 1981; Webb and Walling, 1982; Hickin and Sichingabula, 1988; Ashmore and Day, 1988; Sichingabula, 1993).

However, Ashmore and Day (1988) argued that the concept of a simple effective discharge was not applicable to many streams and that, in many cases, effective discharge histograms did not consist of the unimodal distribution envisaged by Wolman and Miller (1960). More recently, Sichingabula (1999a) has demonstrated the limitations of this approach with respect to determining the number of classes used in the calculation of effective discharge. As an alternative, this work proposed 'event-based' and 'seasonally-based' approaches as possible alternatives to the work of Wolman and Miller (1960). In this paper, the applicability of an 'event-based' approach is partly assessed in the Upper Kaleya catchment.

Discharge and sediment monitoring are the bases for construction of catchment sediment budgets (cf. Phillips, 1991; Trimble 1981, 1995). More recently, Walling *et al*. (2001) applied the integrated assessment of catchment sediment budgets approach in the Upper Kaleya catchment and found that soil loss from the catchment was 21 t km^{-2} yr^{-1}. Such research results are important both for local farmers and planners for purposes of designing and implementing soil conservation measures at local and national levels. Other more recently conducted studies on Zambia rivers also exists (cf. Gilvear *et al.* 2000; Sichingabula, 1999b, Collins *et al.* 2001; Walling *et al*. 2003).

Study area

The Upper Kaleya River is located near Mazabuka, in the Southern Province of Zambia (Figures 1 and 2). It originates in the Chikankata Hills and flows in a southwest direction before joining the Kafue River north of Mazabuka. The catchment area at the Roadbridge (4-943) monitoring station is 63 km^2 (Water Affairs, 1982). This monitoring station, which was used as the catchment outlet for this study, was opened in 1958 and is located at 16^o 10' South and 28^o 01' East. The Kaleya valley, receives about 800 mm of rainfall from November to April, with an average daily temperature of about 22 ^oC (Hutchinson, 1974). The valley is characterised by undulating surfaces with isolated hills. Soils are dominated by red clays which are clay to sandy in texture and which are well drained (Brammer, 1976). However, rock and rubble occur on steeper hillslopes. Local geology comprises limestone and other rocks rich in ferromagnesian minerals (Smith, 1963; Drystal et al., 1972).

In terms of land use, the Upper Kaleya catchment is covered by natural savannah vegetation, which, in most areas has been cleared for commercial and subsistence cultivation. These represent the major economic activities of the area. Most of the lower study catchment is under commercial farming, whilst the headwaters remain under small-scale subsistence farming. Immediately upstream of the study catchment outlet, is the Upper Kaleya settlement, where emergent farmers are engaged in agricultural production with limited irrigation and soil conservation (Figure 2).

Methodology

Sources and types of data

Data analysis involved the historical discharge record obtained from Water Affairs (1972-1994) as well as recent discharge and suspended sediment load data collected by the project over the period 1997-2000.

Project monitoring activities

Water levels at the Roadbridge monitoring station were measured continuously by a Campbell PDCR 1830 water pressure transducer at 15 minute intervals. These records were subsequently converted into corresponding discharge records using stage-discharge ratings based upon velocity-area measurements undertaken by the Zambian Department of Water Affairs. The latter were conducted on a weekly basis during the wet season and on a bi-weekly or monthly basis during the dry season. In addition, water level was also monitored three times a day using manual gauge readings. Suspended sediment concentrations were monitored continuously using a Partech IR40-C turbidity sensor, which was cleaned at regular intervals. Turbidity records were calibrated using suspended sediment concentration-turbidity ratings derived from a comprehensive filtration programme based upon the collection of 6 (3 manual and 3 Epic samples) water samples per day.

Data analysis

For the purpose of this paper, the continuous 15 minute records of discharge and suspended sediment load were reduced to daily values. Daily suspended sediment load (SSL) was determined as the product of instantaneous discharge (Q) ($m^3\ s^{-1}$) and sediment concentration (C) (mg l^{-1}), multiplied by 86,400 (the number of seconds in a day). Daily volumes of discharge were determined in a similar manner. The effective discharge, defined as the discharge which transports the highest sediment load in a given period of time (cf. Pickup and Warner, 1976) was determined in three steps: (i) by dividing the discharge range into 12 arbitrary classes; (ii) determining the duration of each discharge class; (iii) by multiplying the mid-point discharge of each class by the corresponding mean sediment load, and finally; (iv) multiplying the result given in (iii) by the duration. Thereafter, a plot of discharge versus sediment load was constructed. The mid-point discharge of the class with the highest sediment load was taken to be the effective discharge.

Results and discussion

Hydrological and sediment transport characteristics

Analysis of discharge data revealed that instantaneous flows on the Upper Kaleya River at the Roadbridge monitoring station ranged from zero, during some dry seasons, to a maximum of 3.65 $m^3 s^{-1}$, with a daily mean of 0.406 $m^3 s^{-1}$ (Figure 3a). The drying up of the river in 1997 was caused by excessive water abstraction. Daily suspended sediment loads in the catchment ranged from zero to 253.9 tonnes, with a daily mean of 3.15 tonnes (Figure 3b). Most of this sediment load was transported during flood events, which occurred on a few days of each year. The highest flood during the study period occurred on 6 December 1999, with a peak discharge of 3.65 $m^3 s^{-1}$. This event alone transported 111.9 tonnes of suspended sediment. Other events with discharges greater than 1.5 $m^3 s^{-1}$, represented 1.7% of the time and in combination transported 1,236.7 tonnes or 60% of the total sediment load (3,130.4 tonnes) recorded between 1997 and 2000.

The relationship between either suspended sediment concentration or load and discharge was found to be weak (see Figures 4a and 4b). Figure 4a presents the relationship ($r^2 = 0.236$) between suspended sediment concentration and discharge ($n = 993$). Figure 4b examines the relationship ($r^2 = 0.382$) between suspended sediment load and discharge ($n = 993$). All these were significant at 0.001 level of significance. As expected, each relationship comprises considerable scatter about the regression line, reflecting the influence of a number of factors other than discharge on suspended sediment concentrations and loads e.g. sediment supply and exhaustion, hysteresis and storm lag effects (cf. Gregory and Walling, 1973).

Magnitude-frequency characteristics of suspended sediment transport

The mean monthly discharge and sediment loads for the Upper Kaleya River during the period 1972-1994 at Damsite gauging station are shown in Figure 4c. These data indicate that low flows occur in September and October whilst peak flows are recorded in March. The most important months in terms of discharge and sediment flux are January to March, i.e. the local wet season.

Magnitude-frequency analysis was used to divide discharges into classes. Figure 4d shows that different classes of discharge are responsible for transporting contrasting amounts of suspended sediment. Although suspended sediment concentrations are high at the beginning of the rainy season, when loose soil on slopes is mobilised and routed to the river channel, corresponding sediment loads are low, due to the small discharges recorded during this period of wetting up (Figure 3a). At the peak of the rainy season, higher sediment loads are recorded because of higher flows. However, because the higher flows are infrequent, most of the suspended sediment load is transported by moderate flows of moderate frequency.

Figure 4d shows that the flow responsible for transporting most of the suspended sediment load is 1.44 $m^3 s^{-1}$. This represents just 1.5% of the time and is the effective discharge for suspended sediment transport on the Upper Kaleya River at Roabridge. Using an event-based approach, it was found that a daily discharge of 1.32 $m^3 s^{-1}$ was responsible for transporting the highest daily sediment load of 253.9 tonnes, compared to 111.9 tonnes transported by the highest recorded instantaneous discharge (3.65 $m^3 s^{-1}$). The explanation for this observation could be that, the highest recorded instantaneous discharge occurred at the end peak of the seasonal hydrograph and at the time when most of the loose sediment on catchment slopes had already been evacuated. Conversely, the event-based effective discharge occurred on the rising limb of the hydrograph when sediment recruitment from slopes was at its highest. The event-based sediment analysis result seems to reflect real time pictures of sediment mobilization and transport in river catchments.

Over the duration of the study period, the total cumulative discharge was estimated at 34.8 million m^3, whilst the corresponding total suspended sediment load was estimated at 3,130 tonnes.

Some commercial farmers in the study area welcomed the study and based on the research findings they have since then embarked on soil conservation measures. But small-scale farmers have difficulties in implementing soil conservation measures such that more efforts are required to sensitize them on the soil erosion problem and on types of conservation methods to apply in the Upper Kaleya Settlement area. In the same, vein it can also be said that sediment transport measurement and monitoring is not very common in Zambia and in the sub-region for a number of reasons. But one reason could be the problem of the low number of people trained and/or interested in sediment studies.

Conclusion

The Upper Kaleya River, though small in size, is characterized by reasonably high discharges and suspended sediment loads. The latter should be a major cause of concern for sustainable agricultural development in the area and strategies for controlling soil loss and water utilization must be encouraged among the local resource users. In addition, there is a clear need to conduct this type of research in other parts of the country, in order that national sediment-related control measures can be designed and implemented. Lastly, there is need for capacity building in sediment research and sediment monitoring among local and regional researchers and practitioners to ensure that sediment monitoring is done as a routine activity in various developmental projects.

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FIGURE CAPTIONS

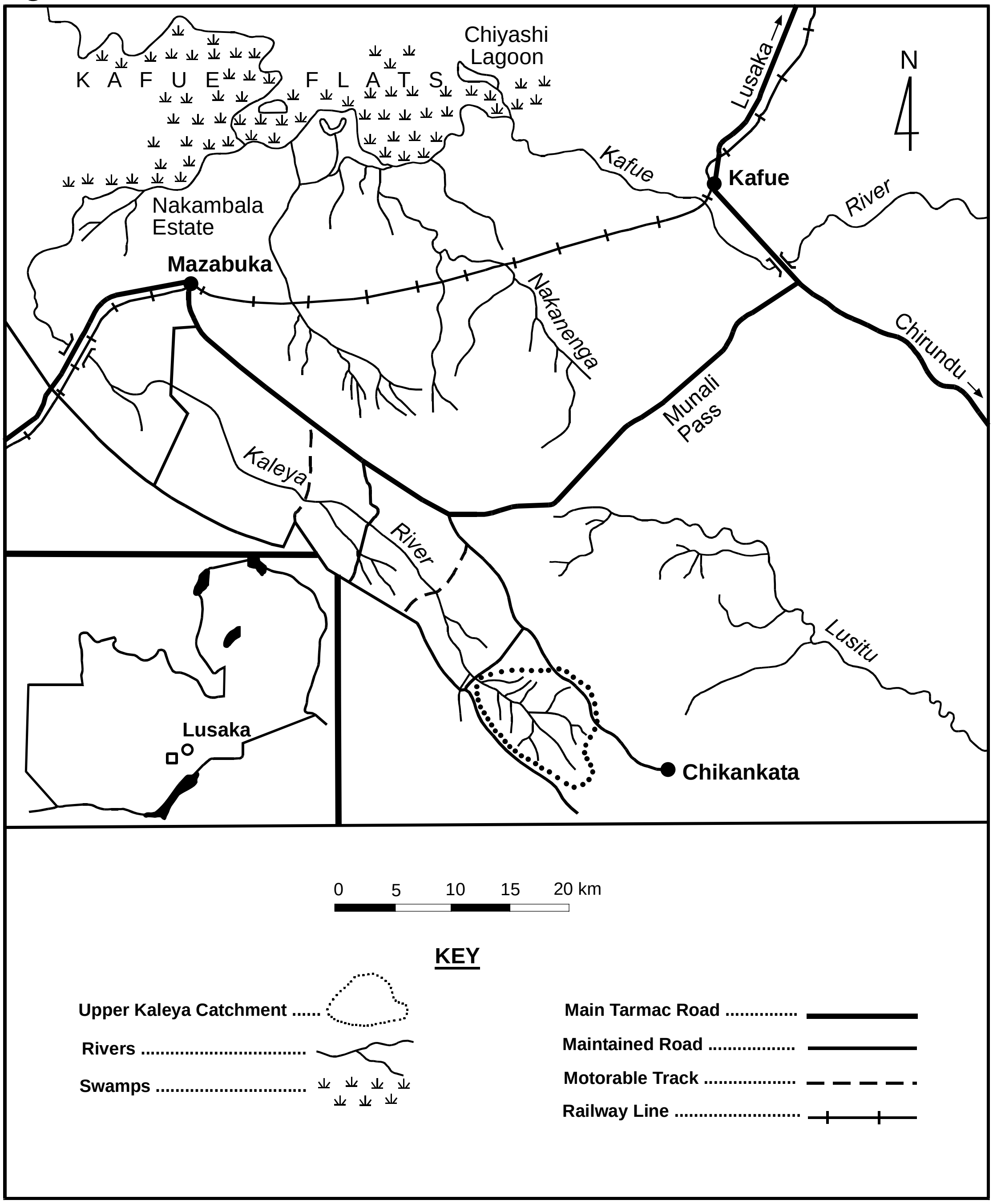
Figure 1. Location map of Kaleya River catchment in Mazabuka District, southern Zambia.

Figure 2. Locations of gauging stations and settlements in Upper Kaleya catchment.

Figure 3. Variations in time of (a) monitored discharge and (b) suspended sediment load on Upper Kaleya River at Roadbridge station, 1997-2000.

Figure 4. Relationships between (a) discharge and suspended sediment concentration, and (b) discharge and suspended sediment load; and variations in (c) monthly mean discharge (1992-1994) and (d) effective discharge for suspended sediment load, Upper Kaleya River, 1997-2000.

Figure 1



Chiyashi Lagoon
K A F U E F L A T S
Lusaka
N
Kafue
Kafue
River
Nakambala Estate
Mazabuka
Nakanenga
Chirundu
Munali Pass
Kaleya
River
Lusitu
Lusaka
Chikankata
0 5 10 15 20 km
KEY
Upper Kaleya Catchment ......
Rivers ....
Swamps ....
Main Tarmac Road ....
Maintained Road ....
Motorable Track ....
Railway Line ....

Figure 2

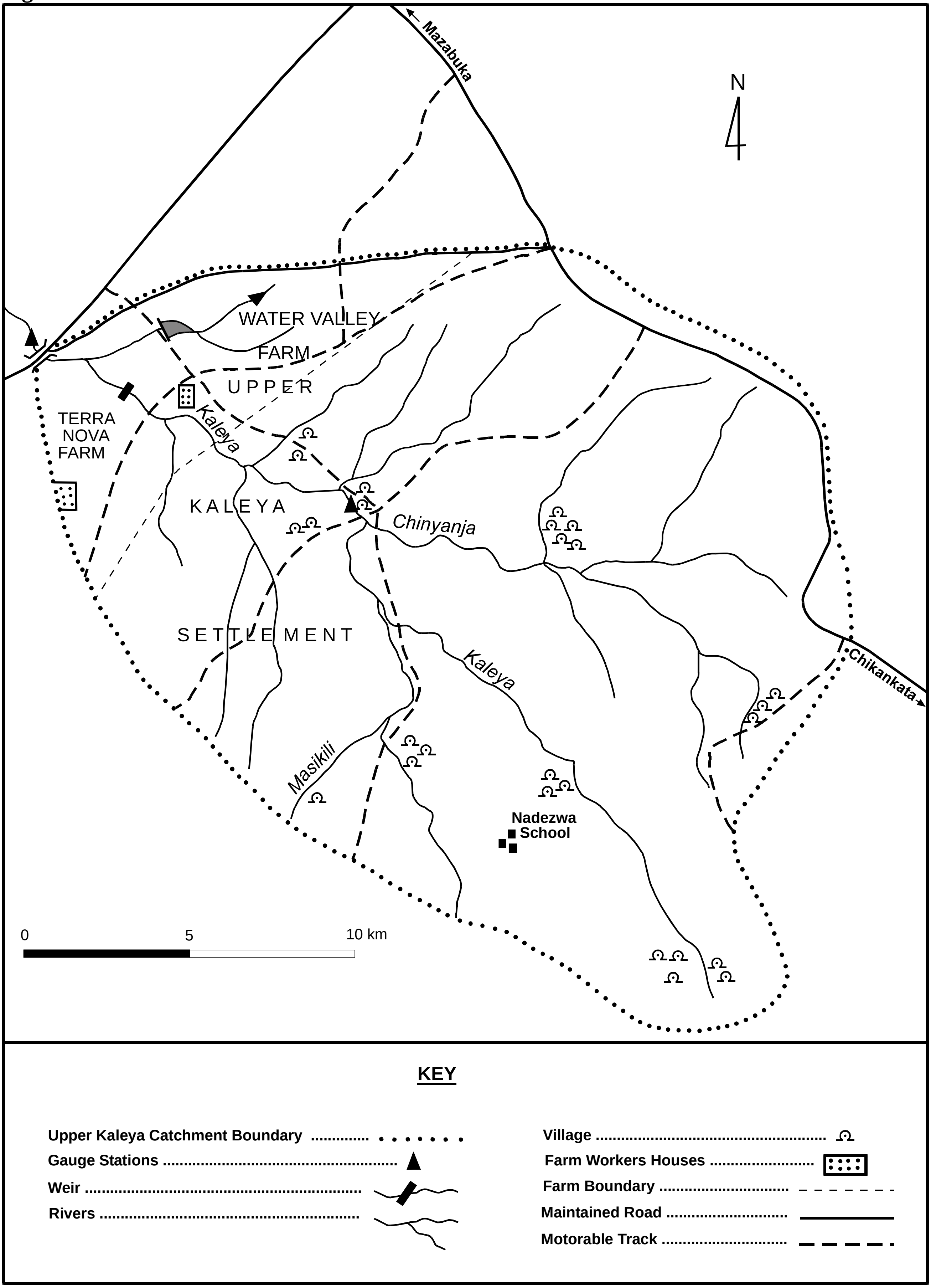

Mazabuka
N
WATER VALLEY
FARM
UPPER
TERRA
NOVA
FARM
Kaleya
KALEYA
Chinyanja
SETTLEMENT
Kaleya
Chikankata
Masikili
Nadezwa
School
0
5
10 km
KEY
Upper Kaleya Catchment Boundary
Gauge Stations
Weir
Rivers
Village
Farm Workers Houses
Farm Boundary
Maintained Road
Motorable Track

Figure 3

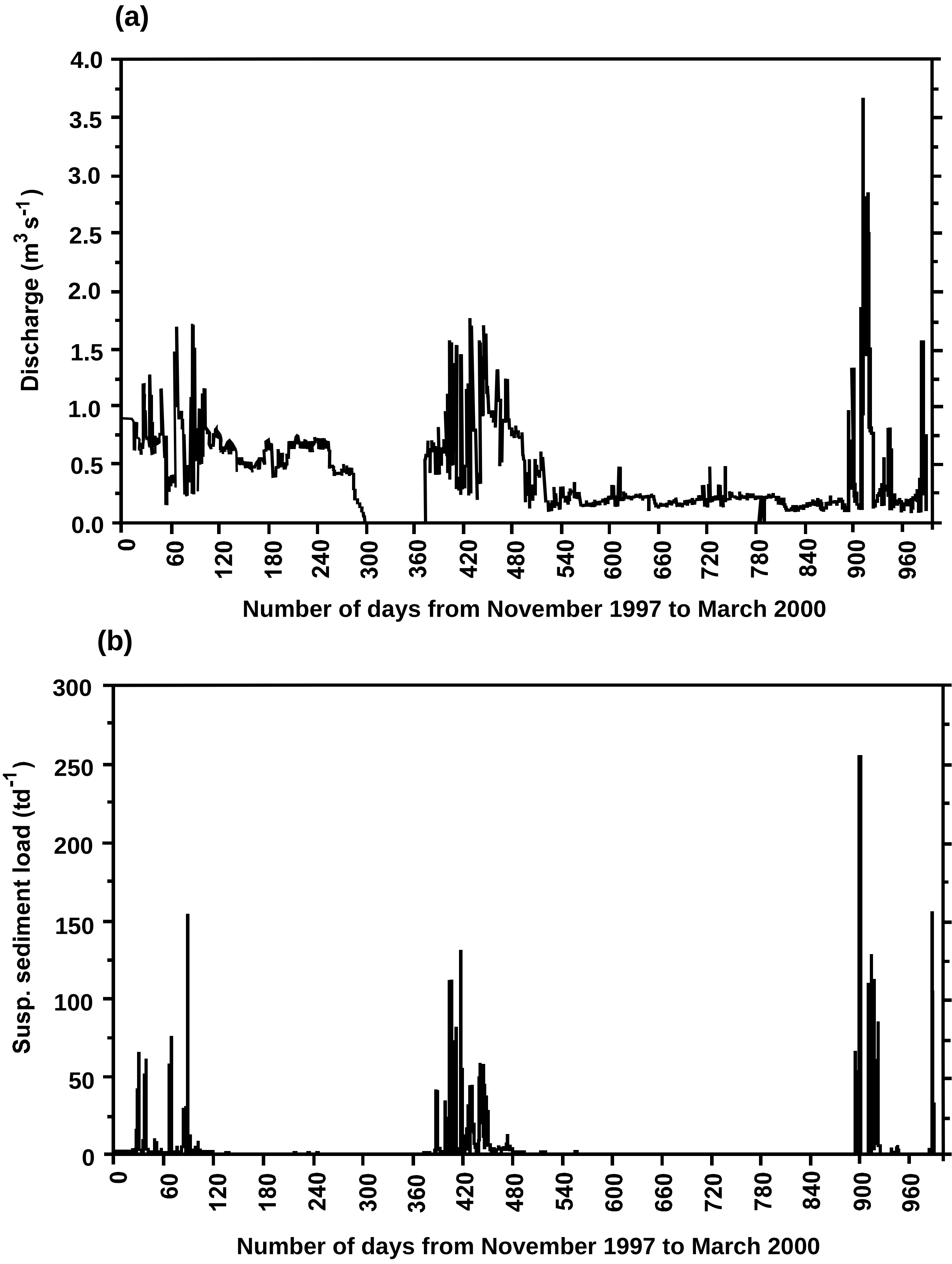
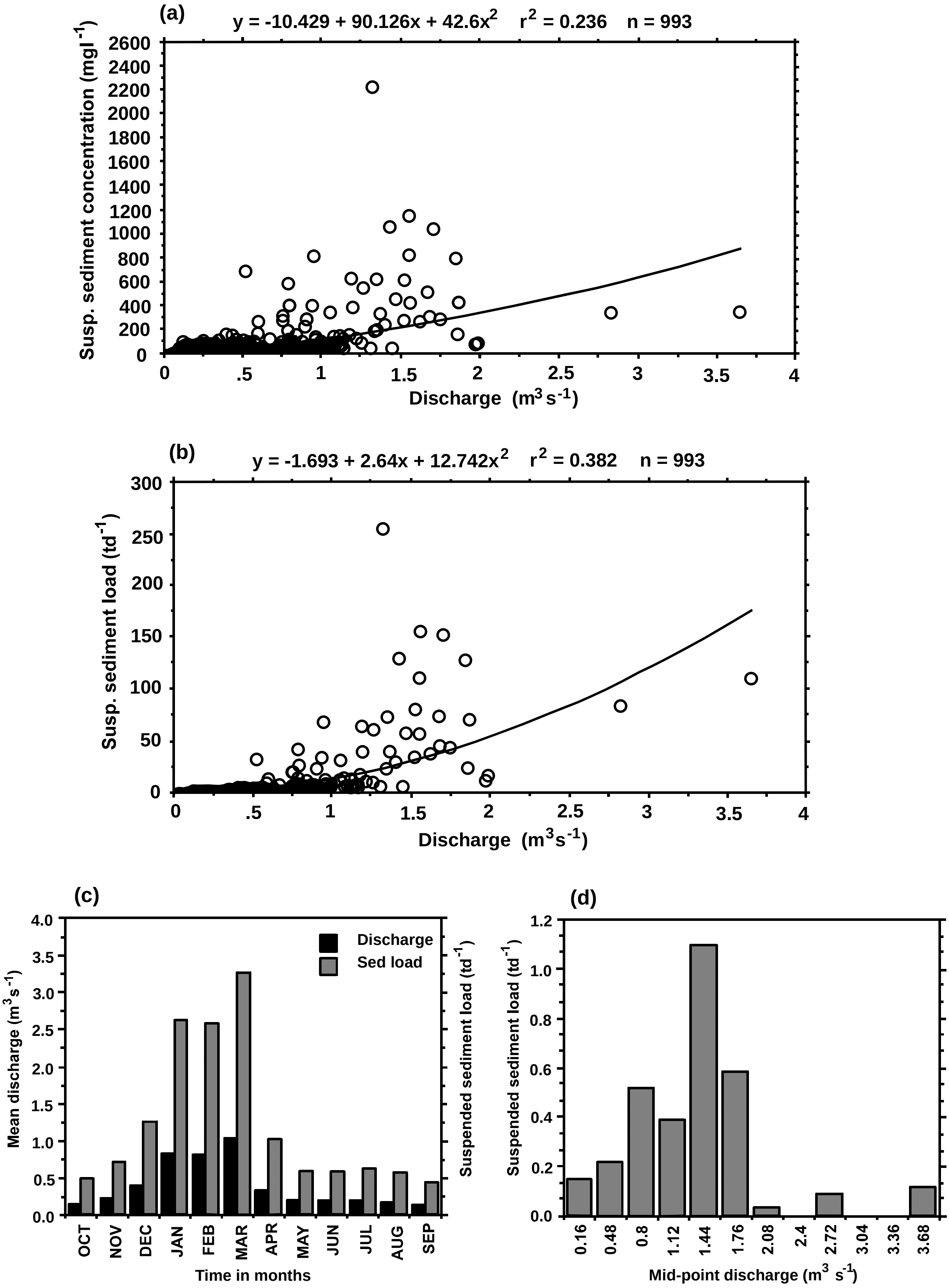

(a)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Discharge (m3 s-1)
0
60
120
180
240
300
360
420
480
540
600
660
720
780
840
900
960
Number of days from November 1997 to March 2000
(b)
300
250
200
150
100
50
0
Susp. sediment load (td-1)
0
60
120
180
240
300
360
420
480
540
600
660
720
780
840
900
960
Number of days from November 1997 to March 2000

Figure 4


(a)
y = -10.429 + 90.126x + 42.6x2 r2 = 0.236 n = 993
Susp. sediment concentration (mgl-1)
Discharge (m3 s-1)
(b)
y = -1.693 + 2.64x + 12.742x2 r2 = 0.382 n = 993
Susp. sediment load (td-1)
Discharge (m3s-1)
(c)
Discharge
Sed load
Mean discharge (m3s-1)
Suspended sediment load (td-1)
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP
Time in months
(d)
Suspended sediment load (td-1)
0.16 0.48 0.8 1.12 1.44 1.76 2.08 2.4 2.72 3.04 3.36 3.68
Mid-point discharge (m3 s-1)