Use of reconnaissance measurements to establish catchment sediment budgets: a Zambian example

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Abstract The sediment budget of a catchment represents a key tool for understanding its sediment dynamics and for developing effective sediment management and control strategies. To date, however, there are few, if any, reliable procedures for predicting the sediment budget of an ungauged catchment. In the absence of such prediction procedures, recourse must be made to direct measurements to provide the necessary information to synthesize the sediment budget. An intensive programme of field measurements would be needed to obtain a detailed sediment budget for a catchment, but reconnaissance measurements can provide sufficient information to synthesize a generalized sediment budget that will be adequate for many requirements. An approach employing such reconnaissance measurements has been developed by the authors and tested in a small (63 km^2) catchment in southern Zambia. The key components involve: establishing the catchment sediment yield, use of sediment fingerprinting techniques to establish the relative importance of different sediment sources, and use of caesium-137 measurements to obtain information on gross and net soil loss under different land-use types and on rates of flood plain sedimentation. The resulting data can be used to synthesize the catchment sediment budget.

Key words caesium-137; deposition; erosion; reconnaissance measurements; sediment budget; sediment source fingerprinting; sediment storage

INTRODUCTION

In many developing countries, sustainable land use and water resource development are threatened by soil erosion and sediment related problems (cf. Johnson & Lewis, 1985). The development of effective sediment management and control strategies requires an understanding of the sediment dynamics of a catchment and, more particularly, the links between sediment mobilization from the catchment surface, sediment delivery to the channel network and through that network, sediment storage, and the sediment yield at the catchment outlet, and the magnitude of the fluxes involved. The catchment sediment budget concept affords an effective framework for assembling such information on sediment sources, sinks, storage and output (e.g. Reid & Dunne, 1996; Walling, 1998a). To date, however, there are no reliable procedures for predicting the sediment budget of an ungauged catchment. In the absence of such prediction procedures, direct measurements must be employed to provide the necessary information to synthesize the sediment budget. An intensive programme of field measurements would be needed to obtain a detailed sediment budget for a catchment (cf. Walling *et al*., 2002), but such intensive programmes will be well beyond the scope of any investigation undertaken within an essentially ungauged basin. There is a need to develop reconnaissance measurement techniques that are able to assemble sufficient information to synthesize a generalized, but nevertheless meaningful, sediment budget for a catchment in a rapid and cost effective manner. An approach involving such reconnaissance measurements has been developed by the authors and its application has been tested in a small (63 km^2) catchment in southern Zambia (cf. Walling *et al*., 2001). The key components involve: establishing the catchment sediment yield, use of caesium-137 measurements to obtain information on gross and net soil loss under different land-use types and on rates of flood plain sedimentation, and use of sediment fingerprinting techniques to establish the relative importance of different sediment sources. The resulting data can be used to synthesize the catchment sediment budget. Further details regarding the study area, the approach developed and the results obtained are provided below.

THE STUDY AREA

The approach developed has been tested in the Upper Kaleya River basin located near Mazabuka in southern Zambia. The 63 km^2 catchment (Fig. 1) is underlain by limestones and calc-silcrete formations, which are associated with ferruginous tropical laterite soils, with skeletal soils and regolith on the steeper slopes. The local climate is characterized by distinct wet (November–March) and dry (April–October) seasons and the mean annual precipitation lies in the range 800–900 mm. Altitudes range from 1240 m at the catchment outlet to 1400 m in the headwaters, and slopes are commonly in the range 2–5°. Communal agriculture occupies 69% of the study catchment and is characterized primarily by the cultivation of maize, cotton, groundnuts and sunflowers. Bush grazing and commercial farming of coffee and crops, such as potatoes, mange-tout peas and wheat, occupy the remaining 29% and 2% of the catchment area, respectively.

THE APPROACH AND DATA COLLECTION

The approach comprises three key components. The first involves estimation of the sediment yield at the catchment outlet, either by direct monitoring or by using appropriate prediction procedures. The second employs caesium-137 measurements (cf. Ritchie & McHenry, 1990; Walling, 1998b; Walling & He, 1997) to obtain representative estimates of medium-term (*c*. 40 year) erosion and deposition rates on the catchment slopes and to quantify overbank deposition rates on the small areas of flood plain bordering the channel near the catchment outlet. The third makes use of sediment fingerprinting procedures (cf. Collins *et al*., 1998; Walling & Woodward, 1995) to establish the primary sources of the suspended sediment load at the catchment outlet and to permit estimation of the conveyance losses associated with the transfer of

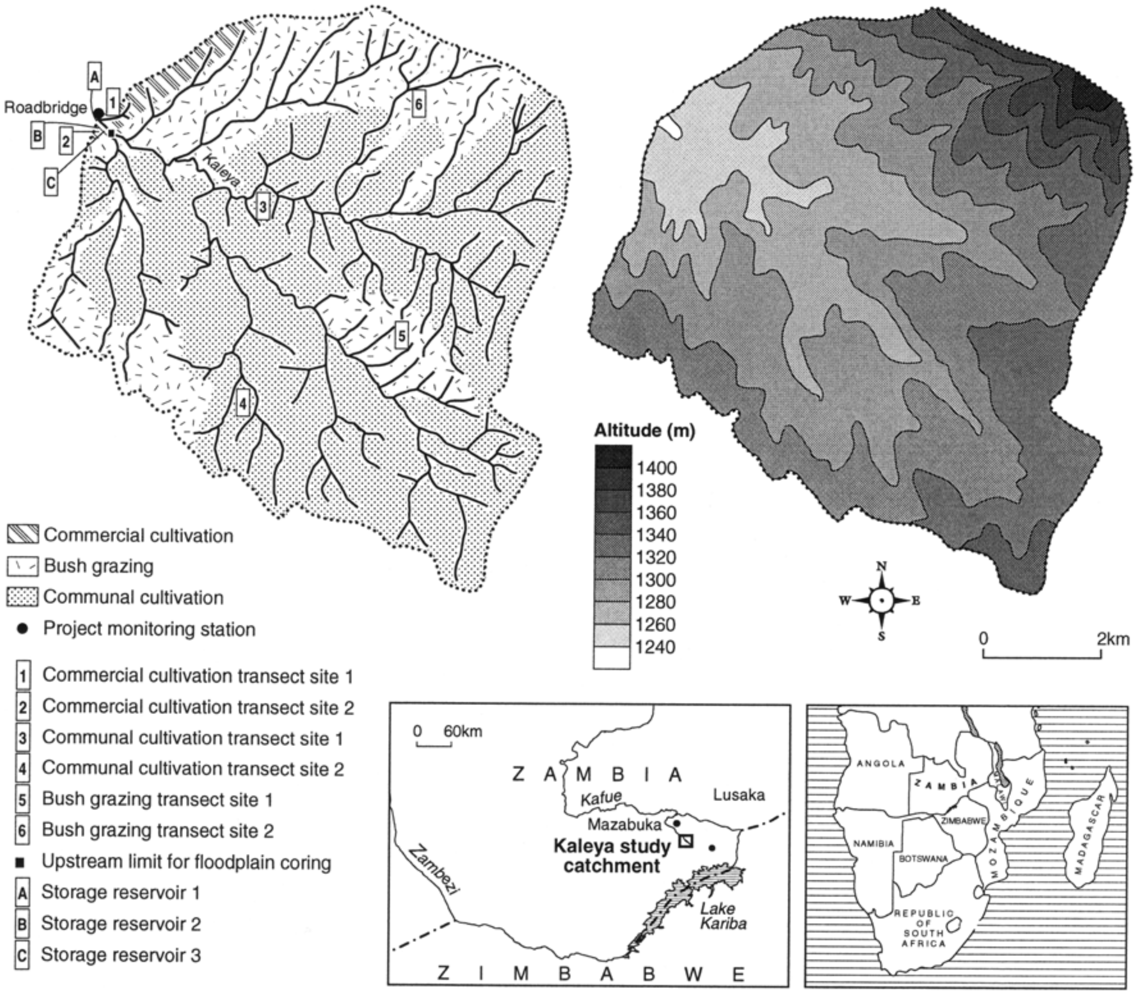

Fig. 1 The Upper Kaleya study catchment, showing its location, generalized maps of its land use and relief, the location of the small off-stream reservoirs and the area of river flood plain investigated by coring, and the position of the slope transects.

sediment from the catchment slopes to the channel network. In addition, the existence of three small off-channel reservoirs in the lower part of the study catchment necessitated estimation of the rates of sedimentation in those reservoirs.

Estimating the mean annual suspended sediment yield

In the case of the Upper Kaleya catchment, measurements of the sediment yield at the project monitoring station at the catchment outlet (Fig. 1) were undertaken during the period extending from November 1997 to April 2000. Flow data were obtained using a continuously recording pressure sensor coupled to a data logger to record stage, and combining the resulting stage records with a stage/discharge relationship. Suspended sediment concentrations were continuously recorded using a turbidity probe coupled to the data logger and calibrated against direct measurements of sediment concentration in the river cross section. Suspended sediment loads were computed by combining the water discharge and suspended sediment concentration records at 15-minute intervals. The estimate of the mean annual suspended sediment yield for the study period, which included three wet seasons, was 21 t km^{-2} year^{-1}. Taking account of the likely intra-annual variability of the sediment yield according to annual rainfall and the relatively dry conditions associated with the study period, the longer-term (i.e. *c*. 40 year) mean annual suspended sediment yield of the study catchment was estimated to be 42 t km^{-2} year^{-1}.

In other reconnaissance studies it likely that direct measurements of suspended sediment yield will not be available and in these circumstances the yield would need to be estimated using available prediction procedures or by extrapolation of available data.

Using caesium-137 measurements to estimate gross and net rates of soil loss from the catchment slopes and rates of flood plain sedimentation

The use of caesium-137 (Cs-137) measurements to estimate soil erosion rates is now well documented (Ritchie & McHenry, 1990; Walling, 1998b). The key advantages of this approach to documenting erosion rates include its potential to provide retrospective estimates of erosion and deposition rates, and thus gross and net erosion rates, on the basis of a single site visit, and its applicability to a wide range of environments (cf. Walling, 1998b). In view of its essentially uniform underlying geology and topographic characteristics, the key factor influencing rates of soil loss in the Upper Kaleya catchment was judged to be land use. As indicated above, the catchment was dominated by three main land-use types, namely: bush grazing, communal cultivation and commercial cultivation. In order to obtain representative estimates of rates of gross and net soil loss associated with each of these three land-use types, two parallel downslope transects were established within each of two representative locations for each land use type (Fig. 1, sites 1–6). Two replicate soil cores were collected at equidistant (~10 m) sampling points along each transect and these were bulked into a single bag. The transects comprising each pair were typically 30–40 m apart and each was surveyed using a level. This sampling programme yielded a total of 206 bulked cores. The cores were collected to depths of ~40 cm using a 6.9 cm steel core tube driven into the ground by a motorized percussion corer and extracted using a portable winch. By measuring the Cs-137 inventories associated with the bulked cores and comparing these to the local reference inventory, it was possible to derive estimates of erosion and deposition rates for the individual sampling points (cf. Walling *et al.*, 2001). Integration of these estimates of erosion and deposition rates along the transects provided estimates of gross and net erosion rates for the individual transects, which were subsequently averaged to provide representative estimates of gross and net erosion rates for the individual land use types. The results are presented in Table 1.

Table 1 Mean gross and net erosion rates for transects representative of the main land-use types in the study catchment.

Land use	Gross erosion rate (kg m^{-2} year^{-1})	Net erosion rate (kg m^{-2} year^{-1})
Bush grazing	0.34	0.29
Communal cultivation	0.70	0.25
Commercial cultivation	0.27	0.43

Caesium-137 measurements were also used to obtain estimates of medium-term (*c*. 40 year) rates of overbank sedimentation (cf. Walling & He, 1997), associated with the flood plain areas bordering the main channel in the lower reaches of the study catchment (Fig. 1). Data were assembled for four parallel transects selected to be representative of the local microtopography. These transects were located perpendicular to the main channel and ~250 m apart. Four bulked cores and one sectioned core were collected along each transect, with two bulked cores being collected on either side of the river, one adjacent to the channel and one further away. Estimates of the mean sedimentation rate (g cm^{-2} $year^{-1}$) were obtained for the sectioned core from each transect, based on the position of the Cs-137 peak in the depth profile. This value was then used in association with the inventory for the sectioned core and the inventories measured for the bulk cores collected at other points along the same transect, to estimate the sedimentation rates at those points, by assuming that the deposition rate is directly proportional to the magnitude of the excess inventory and taking account of differences in particle size composition between the cores (cf. Walling *et al*., 1998). The sedimentation rates estimated for the individual cores ranged from 0.54 g cm^{-2} $year^{-1}$ to 1.90 g cm^{-2} $year^{-1}$. The mean sedimentation rates for each of the three transects and the overall mean sedimentation rate for the areas of flood plain investigated are listed in Table 2.

Table 2 Estimates of flood plain sedimentation rates based on Cs-137 measurements.

Transect	Mean sedimentation rate (g cm^{-2} $year^{-1}$)
i	0.70
ii	0.90
iii	0.60
iv	1.10
Mean	0.83

Use of sediment fingerprinting procedures to establish sediment sources and to estimate the conveyance losses associated with slope channel transfer

The quantitative composite fingerprinting technique documented by Collins *et al*. (1998) was used to establish the importance of the four potential sources of the suspended sediment load passing the catchment outlet. These represented surface soils beneath each of communal and commercial cultivation and bush grazing, and channel banks/gullies. Twenty representative source material samples were collected from each of the four potential sediment sources and these were sieved to <63 µm, in order to make them more directly comparable with the suspended sediment samples, which typically had a d_{50} of ~5.9 µm. In order to characterize the suspended sediment flux from the study catchment, bulk suspended sediment samples (n = 65) were collected from the catchment outlet during flood events using a bucket suspended from a rope. The sediment was recovered from the bulk samples by settling, decantation and air drying. Following recovery and pre-processing, all source material and suspended sediment samples were analysed for a range of fingerprint properties and the results were used to derive a composite fingerprint, for use in establishing the relative contribution of the four potential sources to each of the bulk samples collected from

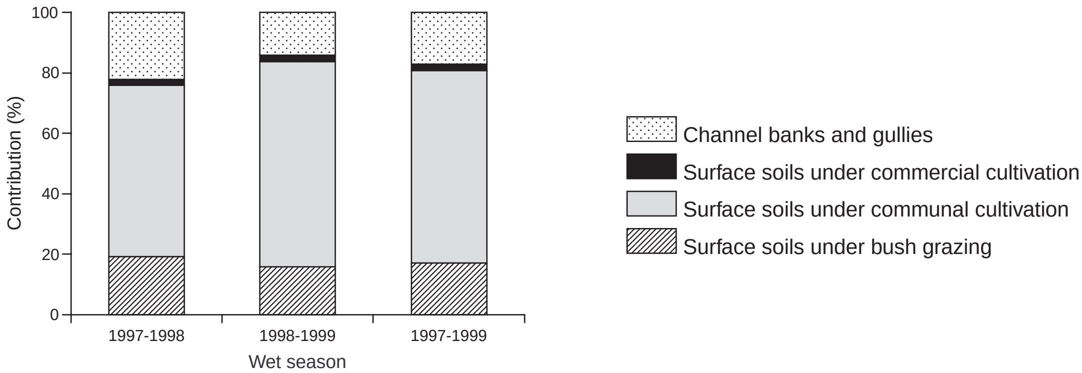

Fig. 2 Load-weighted mean relative contributions from each main sediment source to the sediment samples collected during each wet season and over the entire study period.

the catchment outlet (cf. Collins *et al*., 2001). The estimates of the relative contributions from the four potential sources obtained for the individual sediment samples were weighted according to the suspended sediment load at the time of sampling (cf. Walling *et al*., 1999), in order to estimate the mean contributions from the individual sources for the individual wet seasons and the 2-year period covered by the suspended sediment sampling (Fig. 2). For the latter, the load-weighted mean contributions from the four potential sources were in the order: communal cultivation 64%, channel banks and gullies 17%, bush grazing 17% and commercial cultivation 2%.

The estimates of net rates of soil loss from the catchment slopes presented in the previous section relate to zones characterized by the three land-use types rather than complete slope profiles extending from the divide to the channel, and they have been designated *within zone* erosion rates. In constructing a sediment budget, it is also necessary to take account of deposition of sediment during transfer or conveyance from these zones to the channel network. This has been termed the *zone-channel* deposition or conveyance loss. An estimate of the magnitude of this deposition or conveyance loss can be obtained by taking the estimate of the suspended sediment load at the catchment outlet, scaling this up to provide an estimate of the total sediment input to the channel system, by taking account of losses of sediment due to channel and flood plain deposition and reservoir sedimentation, apportioning this value of total sediment input to the channel system to the four potential sources, by using the results of the source fingerprinting investigation (Fig. 2), and finally comparing the estimates of sediment input to the channel from the catchment surface under the three land-use types with the estimates of net soil loss from these areas. The net soil loss will exceed the equivalent sediment input to the channel, reflecting the deposition losses associated with zone-channel conveyance or transfer.

Reservoir sedimentation

Estimates of mean annual sedimentation rates in the three off-stream reservoirs were obtained by comparing pre-impoundment surveys of the reservoir basins with the present bottom of the reservoirs defined by surveyed cross-profiles. The cross-profiles were surveyed by sounding from a boat. The results of these surveys are presented in Table 3.

Table 3 Estimates of reservoir sedimentation rates.

Reservoir	Construction date	Surface area (m^2)	Mean depth of sediment accumulation (m)	Mean annual deposition rate (cm $year^{-1}$)
1	1973	60 000	75.0	3.0
2	1986	15 000	30.0	2.0
3	1986	80 000	50.0	4.0

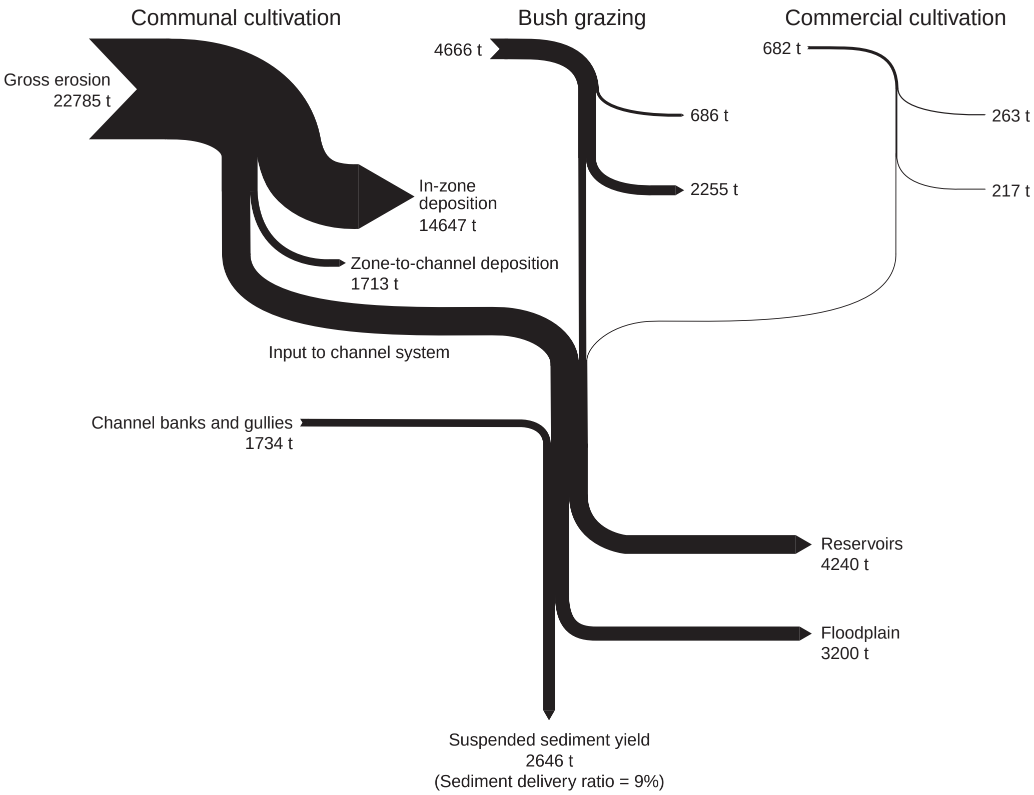

Fig. 3 The suspended sediment budget for the Upper Kaleya study catchment.

CONSTRUCTING THE SEDIMENT BUDGET

The information on the individual components of the sediment budget of the Upper Kaleya catchment provided by the measurements outlined above can be combined to construct a sediment budget. Since the budget (Fig. 3) is based on the total mass of sediment mobilized, transported and stored within the catchment, it is necessary to convert estimates of erosion and sedimentation rates to values of mass by taking account of the areas involved. Thus, the areas occupied by the three land-use types are multiplied by the mean gross and net erosion rates obtained for those land-use types to estimate the total mass of sediment mobilized from the catchment slopes, the proportion of that sediment deposited within the individual land-use zones and the net transfer of soil towards the channel network. Although the transects used for Cs-137 sampling had been selected to be representative of areas of erosion and deposition within the catchment, there were some areas under each land use, albeit of limited extent, where there was no evidence of erosion or deposition. Field inspection indicated that these areas occupied about 25% of each land use type. It was therefore assumed that the erosion rates estimated for the three land-use zones were applicable to 75% of the area of these zones and that the remaining areas were characterized by negligible erosion and deposition. The total mass of sediment mobilized, stored and transferred from the individual land use zones is shown on Fig. 3.

The estimate of the mean annual deposition rate for the flood plain areas in the lower reaches of the catchment (i.e. 0.83 g cm^{-2} $year^{-1}$) was extrapolated to the total area of the flood plain to estimate a total annual conveyance loss or storage of 3200 t $year^{-1}$. Since sediment mobilization by bank erosion, and therefore remobilization of flood plain deposits by channel migration has been included in the sediment budget (see later), this estimate represents the net increase in sediment storage on the flood plain during the period covered by the Cs-137 measurements (i.e. the past *c*. 40 years). The estimates for the sedimentation rates in the three small reservoirs (Table 3) were used to derive an estimate of the total annual deposition of sediment in the three reservoirs of 4240 t $year^{-1}$. A mean bulk density of 0.8 g cm^{-3} was assumed. Since field observations suggested that only limited amounts of fine sediment were stored in the channel system of the study catchment and, more importantly, that there was little net change in the amount of channel storage from year to year, channel storage was excluded from the annual sediment budget. Summation of the estimates of mean annual sediment output from the catchment, conveyance loss associated with flood plain sedimentation and sediment deposition in the small reservoirs provides an estimate of the total sediment input to the channel system of the study catchment. This value was apportioned using the information on the relative contributions of each potential sediment source provided by the fingerprinting investigation, to estimate the magnitude of the sediment input to the channel network from each land use zone and from eroding channel banks and gullies. The difference between the estimate of mean annual net soil loss from an individual zone and the mass of sediment derived from this zone entering the channel network was attributed to the conveyance loss associated with the zone-channel transfer.

As indicated in Fig. 3, the overall sediment delivery ratio for the Upper Kaleya catchment is estimated to be ~9%. This value is consistent with existing understanding of sediment delivery from small to medium-sized catchments (cf. Walling, 1983).

PERSPECTIVE

The results presented above demonstrate the potential for using reconnaissance measurements to synthesize the sediment budget for a small or medium-sized catchment. Since the study of the Upper Kaleya catchment used to demonstrate this potential was originally undertaken to develop and test an integrated approach to the assessment of catchment sediment budgets (cf. Walling *et al*., 2001), the amount of data available for constructing the budget is arguably greater than might be generated by a truly reconnaissance investigation. In many cases, for example, direct measurements of sediment yield will not be available, but it may be possible to estimate this component of the budget using empirical prediction techniques or similar approaches. Equally, in many cases, it will be impossible to undertake an intensive programme of storm sampling to provide a large number of samples for source fingerprinting. Use of simple time-integrating suspended sediment samplers (e.g. Russell *et al*., 2000) could provide a less demanding alternative approach to collection of the sediment samples required for source fingerprinting. Equally, if direct sampling is precluded by considerations of cost, accessibility or the time available, it may be possible to use recent overbank flood plain deposits as a surrogate for suspended sediment samples (e.g. Bottrill *et al*., 2000). If the latter approach was adopted, and the catchment sediment yield was estimated, rather than measured, it should be possible to assemble the information required to synthesize the sediment budget relatively rapidly, since the Cs-137 measurements could be undertaken within a single intensive field campaign. The viability of the Cs-137 approach to providing information on rates of soil loss from the catchment slopes will, however, be strongly influenced by the heterogeneity of the catchment terrain and land use. In the example presented, the relatively uniform terrain and the existence of only three major land use units limited the number of transects required.

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