A programme of monitoring sediment transport in north central Luzon, the Philippines

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ABSTRACT Monitoring sediment transport through the 4000km² Magat catchment in Luzon, the Philippines, between 1986 and 1988, is described. Three catchments nested one within the next were monitored, each being an order of magnitude greater, the smallest being 20km². Sediment measurements were taken daily at each catchment outlet, by means of pump sampling systems. Wash load and bed material load were monitored independently from up to four verticals per site with up to three points per vertical. Results suggest that for calculation of annual sediment loads, sediment ratings to fill data gaps are not recommended. Ratings are shown to vary with time and to exhibit strong hysterisis effects through individual storm events.

INTRODUCTION

Magat catchment

The Magat catchment is located approximately 350km north-east of Manila in North Central Luzon, the Philippines. The catchment is bounded on three sides by major mountain systems which have a high relief and steeply dissected topography. The Magat River originates at an elevation of 1200m and flows through a broad alluvial valley in a north-easterly direction for about 135km, before it joins the Cagayan River. The Magat Dam, which was built in 1975, impounds a total of $1090 \times 10^6 m^3$ for irrigation and power generation purposes. The catchment area commanded by the dam is approximately 4123km². Average inflow to the reservoir is equivalent to a flow of $200m^3s^{-1}$, although a peak flow of $20\ 000m^3s^{-1}$ has been experienced.

Rainfall in the Philippines is dominated by two tropical monsoon seasons: November to April and June to November. Average annual catchment rainfall has been estimated to be 2500mm, but is possibly much higher, up to 4000mm, in the Cordillera Mountains. On average one typhoon per year will cross this area of Central Luzon bringing maximum 24 hour rainfall of around 300mm. Typhoons can 'stall' or remain stationary for several days giving total rainfall of over 1000mm.

Catchment soils are generally shallow, acidic, of a fine loamy to clayey texture. The geomorphology is characterised by active erosion, with landslides being common on steeper slopes. Increasing levels of traditional subsistence farming and cultivation of steep slopes, due to population pressure, together with forest and grass fires and unregulated logging operations have exacerbated erosion.

For the construction of the Magat Dam an annual sediment yield of 2000t km⁻² was predicted. Subsequent work has shown that this estimate is heavily dependent upon the method of data analysis used and a

revised estimate of 3200t km⁻² was later made from the same data.

Monitoring in the Magat catchment

In 1984 a programme of collaborative field work was initiated between
the Overseas Development Unit (ODU) of HR Wallingford, and the National
Irrigation Administration (NIA), Government of the Philippines, to
quantify the effectiveness of reforestation in controlling sediment
yield within the Magat catchment, and hence to predict future sediment
deposition in the reservoir. This followed the reforestation of part
of the catchment by NIA. Initially the field monitoring consisted of a
hydrographic survey of the reservoir, which estimated an annual rate of
sedimentation equivalent to 3800t km⁻² (Wooldridge, 1986). Two
experimental sub-catchments were then established to measure runoff and
soil loss in the reforested area. Between 1984 and 1987 the annual
sediment yield from these did not exceed 61t km⁻² (Amphlett and
Dickinson, 1989).
   The field work was extended in 1985 to include a programme of
sediment monitoring at three river sites on the Magat River, in order
to obtain information on sediment transport and delivery processes.
These three catchments were nested one within the next, each being an
order of magnitude greater, the smallest Santa Fe being 19km², the next
Aritao 160km² and the largest Baretbet 2040km². Mean channel slopes at
the three sites are 1.7%, 0.6% and 0.3% respectively. Monitoring at
these sites was carried out from June 1985 to December 1988 (Dickinson
et al, 1990). The results are currently being used to calibrate a
GIS-based model of catchment and to study sediment delivery processes.

EQUIPMENT AND MEASUREMENT TECHNIQUES

General

The primary objective of the field monitoring exercise was to obtain an
estimate of the annual sediment load passing each of the monitoring
sites. To obtain this, instantaneous sediment flux is calculated as
the product of sediment concentration and liquid discharge at different
locations in the cross-section for each sampling occasion. Integration
across the section gives the instantaneous sediment discharge from
which a flow-weighted mean concentration can be obtained. Given a
continuous record of sediment discharge, time integration allows the
determination of sediment load for a specified period; in this case
annually. The analysis difficulties discussed in this paper arise
because it is rarely possible to maintain a sufficiently intensive
field data programme to generate a continuous sediment hydrograph.
   Bed material load and wash load were measured and calculated
separately (Sanmuganathan and Bolton, 1984). Wash load is expected to
be uniformly distributed through the cross-section and thus readily
calculated as the product of a single measured concentration and mean
discharge at the time of sampling. Suspended bed material particles
are not uniformly distributed through the depth, concentration normally
decreasing with height above the bed. Measurements are thus required
at a number of discrete points in a vertical in order to define the
sediment concentration profile. In this study the non-suspended load,

normally referred to as 'bed load', was assumed to be small (less than 10% of the suspended bed material load) and no attempt was made to measure it separately. The distinction between wash load and bed material load is not well defined, an arbitrary split being made at 63μm.

The theoretical basis for the measurement programme assumes that bed material transport is largely governed by hydraulic parameters and consequently that data collection can be simplified by developing a form of 'sediment rating curve' relating mean sediment concentration to discharge based on short periods of data collection. By contrast, since wash load is generally not dependent on hydraulic parameters, the method recognises that reliable estimates can only be made by continuous monitoring. Analysis of the Magat data, particularly for 1988, has placed a question over the reliability of bed material load estimates based on rating curves in certain situations.

Field measurements

The sampling technique adopted for sediment concentration measurements was that of pump sampling (Brabben et al, 1991). For suspended bed material load, its improved accuracy over other methods has been demonstrated (Atkinson and Bolton, 1988). Water is pumped through a nozzle positioned in the flow along a hose to the river bank where it is passed through a 63μm sieve, the filtrate being collected and its volume measured. The sediment retained on the sieve (suspended bed material), along with a sample of the filtrate water (containing only wash load), are transported to the laboratory where their concentrations are determined.

On each sampling occasion, except in low flows, a target strategy was set of three samples per vertical, to account for variations in suspended bed material concentration, and three, or at larger sites, four verticals per section. It was not always possible to adhere to this. At the two upstream sites suspension equipment was used, consisting of a movable carriage, suspension cable and sinker weight. At Baretbet the section is very wide and here the road bridge was used as a platform for sediment monitoring.

Current metering was undertaken at each monitoring site to establish the relationship between stage and discharge. Standard staff gauges were also used at all sites for the measurement of water level. Readings were taken manually three times a day and more frequently during peak flood events or periods of sediment sampling. Due to the additional monitoring complexity it was decided not to make detailed velocity measurements in conjunction with pumped sampling and, therefore, measured variations of velocity with depth could not be utilised in calculating sediment flux. However, in a numerical experiment based on the year of highest flows, 1986, it was shown that the maximum error in the estimate of sediment discharge resulting in an assumption of uniform velocity is of the order 3.5%.

DATA ANALYSIS

Rating curve development

To convert staff gauge records to flow hydrographs stage-discharge

ratings were developed. Attempts were also made to fit
sediment-discharge ratings as a means of interpolation in periods
without concentration data. An important feature of the analysis was
that all ratings were developed by means of an allometric nonlinear
regression model. An allometric model is one in which the dependent
and independent variables are related by an expression of the form:

$$Y = a\ X^b$$

where a and b are derived constants

By contrast, in much of the published literature, variables have
been transformed with logarithms after which a linear regression has
been used. This tends to under-emphasise the higher residuals, a
tendency which is reinforced by a predominance of middle and lower
values, due to the greater ease and likelihood of collecting data at
these values. Jansson (1985) proposed a method based on class mean
values which partially addressed this problem. Nonlinear regression
based on untransformed variables provides a method which is
statistically more sound and therefore believed to be more accurate
unless the underlying (allometric) model is inappropriate.
Development of the stage-discharge rating curve for Aritao was
complicated by a major storm on 2nd-3rd July 1986 during which a 0.6m
change in bed level and mean water surface elevation occurred. This
was associated with a very distinct change in the channel section and
discharge rating. The channel subsequently reverted to its 1985 form
during another large storm in late October 1988. Uncertainty over the
precise timing of the change has meant that the 1988 discharge volume
has been estimated as lying between two extreme values which differ by
30%.

Discharge hydrographs

The stage-discharge ratings were applied to the time series of staff
gauge readings to obtain instantaneous discharge hydrographs.
Integration of these provided the annual discharge volumes for each
site.

Site	Area (km²)	Discharge Volume (m³ x 10⁶)			Runoff (m)		
		1986	1987	1988	1986	1987	1988
Santa Fe	18.9	68	19	41	3.6	1.01	2.17
Aritao	159.2	266	71	(149-196)	1.67	0.45	(0.94-1.23)
Baretbet	2041	4049	2204	4599	1.98	1.08	2.25

Blyth and White (1990) found, from annual rainfall between 1968 and
1987, for gauges throughout Magat, that the annual rainfall for all
sites was consistently below average from 1984 onwards. This suggests

that the measured discharges for 1986 to 1988 may be lower than for an
average rainfall year and this is consistent with local opinion.

Bed material load (sand load)

For the analysis of the 1986 and 1987 data, measured values of
flow-weighted mean concentration at each section had been plotted
against corresponding instantaneous values of river discharge to
produce sediment rating curves. These were used with discharge
hydrographs to provide estimates of bed material load. During 1988,
particular care was taken to monitor the changes in concentration
occurring through a number of major storms. These data indicated that
the sediment rating approach would not be the most reliable method of
analysis.
     Unfortunately, using the simplest alternative, direct integration
of sediment hydrographs, errors may arise in the estimation of annual
sediment loads due to the use of linear interpolation between occasions
on which concentration data are available, irrespective of the elapsed
time period. A new method was, therefore, developed in which linear
interpolation is used only during periods in which the discharge
hydrographs indicate that the sampling frequency has been adequate to
monitor the likely changes in sediment discharge through flood events.
Where this is not the case a gap is left in the sediment hydrograph.
At the end of the year an estimate of the 'missed' sediment is made by
increasing the measured sediment load by the ratio of the total annual
(liquid) discharge to the discharge during periods when sediment was
adequately measured. This approximation is only valid if the full
range of flow conditions is represented in the monitored data. At two
sites in 1988 the measured load accounted for 40% of the estimated
annual total whilst at Santa Fe, 98% of the load was measured. The new
method was applied alongside sediment rating curve analysis and the
results of the two methods compared.

Wash load (silt load)

Silt is regarded as being evenly distributed in the flow and entirely
supply dependent, although the analysis of the 1986 and 1987 data
showed an apparent dependence on transporting capacity as with sand
load. In analysing wash-load data, therefore, the possible existence
of a sediment rating relationship was examined alongside the preferred
method of sediment hydrograph integration as described above.

DISCUSSION OF RESULTS

Sediment rating relationships

The large scatter observed in the data renders the rating method
unsuitable for use in the present study (Figure 1). Data from
individual storm events studied show a hysterisis effect, in most
cases, when concentrations are plotted against discharge in time order
(Figure 2). A review of hysterisis by Williams (1989) provides a
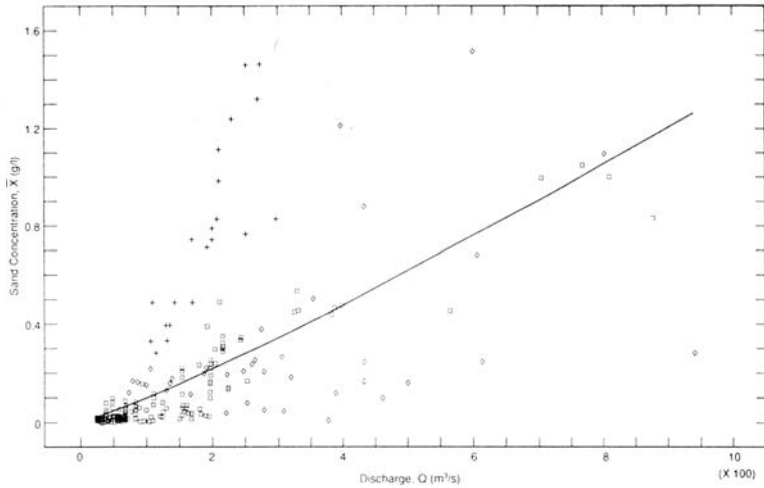framework against which results can be compared. In the present study

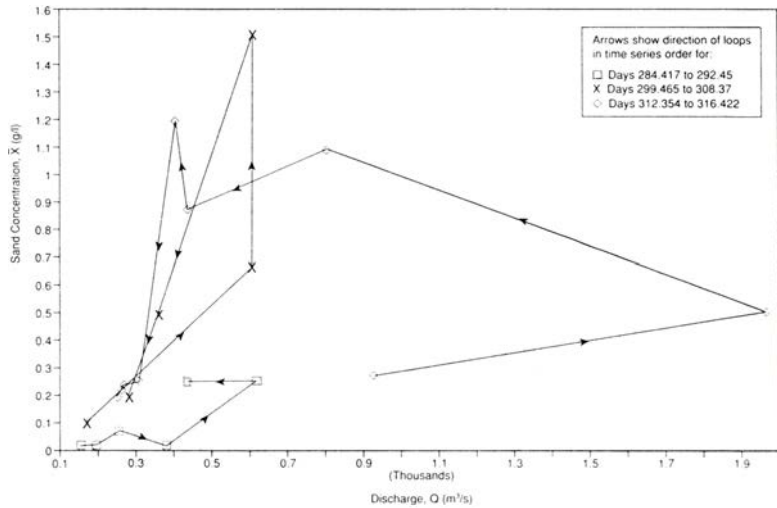FIG. 1   Attempted sand concentration rating, Baretbet.

FIG. 2   Example of hysterisis in concentrations measured
in three storms at Baretbet, 1988.

the hysterisis loops at Baretbet were negative with the peak discharge
being reached prior to the peak concentration. The lag between the two
peaks was most marked at the largest catchment outlet and less so at
the smallest, (ie there appears to be a progressively increasing lag
with increasing area). At the most upstream site, Santa Fe, the
hysterisis loop occasionally went in a positive direction.

At the largest catchment scales results indicated that the
hysterisis effects were more pronounced with the sand load than with
the silt. This may explain why some researchers have, contrary to

expectations, reported better rating correlations on silt than sand.

Even where hysterisis effects occur the use of rating correlations might still be possible if the data fall evenly about a stable curve. For the 1988 Magat data, however, the mean gradient through the hysterisis varies greatly from storm to storm so that a regression based on the complete data set may over-estimate yield for some storms whilst for others it would under-estimate yield (Figure 1). Moreover, there appears to be no consistent relationship between storm size and the mean gradient of the loop. Comparison between the rating method and integration of sediment hydrographs for the 1988 data showed that the rating curve approach over-estimates annual suspended bed material load by over 100% at all sites.

In view of the poor rating relationships found for bed material discharges, the following approach was proposed in estimating annual loads from the Magat basin. If there is a large amount of discharge and concentration data spread evenly throughout the year enabling a consistent sediment hydrograph to be derived, then simple integration of the sediment hydrograph should be the most reliable method. If, however, there are some missing periods of concentration data then, provided that a good discharge hydrograph exists and sufficient of the large storm events have been monitored, estimation of the ratio of measured to unmeasured discharge based on study of the flow hydrograph is probably the most appropriate method. If a large proportion of the data for the year is missing the only recourse is to a rating method but large errors in the result might then be expected.

Concentration profiles

A subsidiary study of the variation of sand concentration with depth was made for the 1988 data set which included a large number of occasions in which sampling at three points in each vertical had been possible. The results showed frequent occasions on which concentration profiles were only weakly developed and about 25% of all cases in which their apparent slope showed increasing concentrations towards the surface. Although the preferred method for calculating instantaneous suspended bed material discharge is to measure concentrations at a minimum of three points per vertical and to fit a concentration profile to the data, reduced field effort may be possible in certain situations if a uniform concentration across the entire section can be assumed. Estimates of annual bed material load based on the assumption of uniform concentrations differed by a maximum of only 10% at Baretbet, 4% at Aritao and 1% at Santa fe from corresponding estimates based on fitted concentration profiles.

Annual sediment loads and sediment yield

At Santa Fe, the smallest catchment outlet, an almost complete sediment hydrograph is available for 1988 suggesting that good results can be obtained from time series integration. The annual totals (3.3×10^6 kg for sand and 6.9×10^6 kg for silt) are strongly influenced by a single large event which carried 30% of the annual discharge.

At Aritao, a major shift in channel section in 1988, as already described, introduced considerable uncertainty into the analysis. This

was most evident in the analysis methods which used a sediment rating
curve. For this reason, and the fact that a study of individual storms
cast doubt on the existence of a stable rating relationship, time
series integration was again the preferred method. Unlike Santa Fe,
however, sand concentration data were missing for approximately 60% of
the annual discharge (including the largest storm) so the annual sand
totals must be regarded with caution (8 to 20 x 10^6kg). The annual
silt load estimate (46 to 90 x 10^6kg) is more reliable.

At Baretbet the situation was similar to Aritao in that time series
integration was preferred but, although most large events were
adequately monitored in 1988, concentration data were missed for 60% of
the discharge for both sand and silt particles. The best estimates for
the 1988 annual totals, are 1200 x 10^6kg for sand and 3000 x 10^6kg for
silt.

Combined sand and silt loads were used to calculate sediment
yields. Only the results for 1988 were calculated using the methods
outlined above since the nature of the 1986 and 1987 data sets
prevented any improvement on the earlier results which had been based
on rating relationships.

SITE	AREA	SEDIMENT YIELD		
	(km^2)		(t ha^{-1})	
		1986	1987	1988
Santa Fe	18.9	39.7	1.5	5.42
Aritao	159.2	22.0	0.6	$(3.41-6.95)^2$
Baretbet	2041.0	$(17.0-33.5)^1$	4.0	20.8

Note: [1] Uncertainty due to problem of choosing gradient of sand
          concentration rating curve.
        [2] Uncertainty due to unknown time when discharge ratings
          changed.

It is of interest to note the ratio of wash load (particles under
63 μm) to total measured sediment load. In 1988 the wash load ratio
was high, varying from 67% to 85% for the different measurement sites.
In 1987 the ratio varied from 50% to 92% whilst in 1986 it was much
lower at between 8% and 38%. The much lower wash load ratios in 1986
are what might be expected given the higher discharges that year.

CONCLUSIONS

A summary of three years of sediment measurement at three river gauging
sites in the Magat basin has been presented with particular discussion
of the analysis of the 1988 data set which is the most detailed of the
three years. The measurement programme, using pumped sampling, was
designed to enable wash load to be measured separately from suspended
bed material load. Sediment discharges showed strong hysterisis
effects through storm events and marked inter-storm variability thus
preventing the use of sediment rating equations to fill data gaps.
Integration of a time series of sediment discharges was therefore used
as the basis for annual sediment load estimation for both wash load and

suspended bed material load at these sites.

Discharge rating equations are required to relate staff gauge readings to flow and these have been developed using allometric nonlinear regression. This method is recommended as preferable to linear regression of logarithmically transformed variables. A major shift in channel section at Aritao, leading to a completely new rating equation, complicated the analysis and indicates the unsuitability of this site for long-term monitoring.

The results have implications for future measurement programmes. The observed hysterisis effects, which appear to be more pronounced with sand particles than with silt and become more strongly negative as catchment size increases, suggest that, in mountainous regions, continuous monitoring of both sand and silt may be required since sediment rating curves developed from instantaneous values may be unreliable. A subsidiary study showed that a relatively small improvement in accuracy is obtained by fitting concentration profiles to account for depth variations in bed material discharge at these sites. This does not necessarily mean that sufficient accuracy can be achieved with a reduced number of samples per vertical. However, further study of the optimum number of samples per section might enable reductions in monitoring effort to be made particularly at small (20km²) catchment outlets on steep (>1%) channels.

The annual sediment yield values obtained over the three year period do not allow precise estimation of long-term mean values but are consistent with the yields estimated at the time the Magat Dam was built (2000 to 3200 t km⁻² year ⁻¹ at the largest catchment outlet).

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