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Erosion, sediment delivery and sediment yield patterns in the Philippines

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Abstract The physical environment of the Philippines is extremely fragile. Steep topography, shallow soils, erosive rainstorms and large flood events provide ideal conditions for accelerated soil erosion and rapid sediment transport. Once the natural forest vegetation is disturbed, this is indeed the picture that emerges. The situation is not irredeemable, but in some cases it is too late to employ conventional land management techniques such as reforestation as a means of reducing sediment yield. Results from sediment yield measurements at various scales and with various land uses in the Magat catchment of northern Luzon are discussed. Using the data from Magat, a theory for an erosion-sediment delivery system in the Philippines is put forward. The combination of frequent intense thunderstorms and less intense but more widespread and persistent cyclone related rainfall appear to be the controlling factors. The results of sediment yield measurements at different scales are also considered in terms of sediment delivery ratios, which do not appear to be directly applicable in the Philippines. This is also discussed in relation to the suggested erosion-sediment delivery system. Finally, important implications of these results for sediment yield assessment, especially where new dams or catchment management schemes are planned, are noted.

INTRODUCTION

The Republic of the Philippines is made up of 7107 islands with a total land area of 299 404 km^2. Of these islands only 2000 are inhabited and 500 are less than 1 km^2 in size. The two largest islands are Luzon, to the north and Mindanao to the south, both consisting of mountain ranges whose peaks also form the intervening islands. The area is one of active mountain building, and includes several active volcanoes. Elevations of over 2000 m.a.m.s.l. occur in many locations, and slopes often exceed 50%. Geologically the area ranges from sandstones, to coralline limestones and basalt; soils are generally shallow and easily degraded. Natural vegetation in this area is forest, but a combination of population pressure and exploitation of forest resources for timber has resulted in clearance of large areas.

MEASUREMENT PROGRAMME

From 1984 to 1988 an intensive field measurement programme was carried out in the Magat catchment in northern Luzon (Fig. 1). Data were collected at many catchment scales, ranging from small single use catchments at Aritao and Dallao to river sites at Santa Fe, Aritao and Baretbet and measurements in the Magat reservoir.

Small catchments

At the beginning of the Magat field programme data were already available from a set of three study catchments at Aritao for a number of events. These three areas (2.35, 2.69 and 6.31 ha) represented the degraded end of the catchment spectrum, with

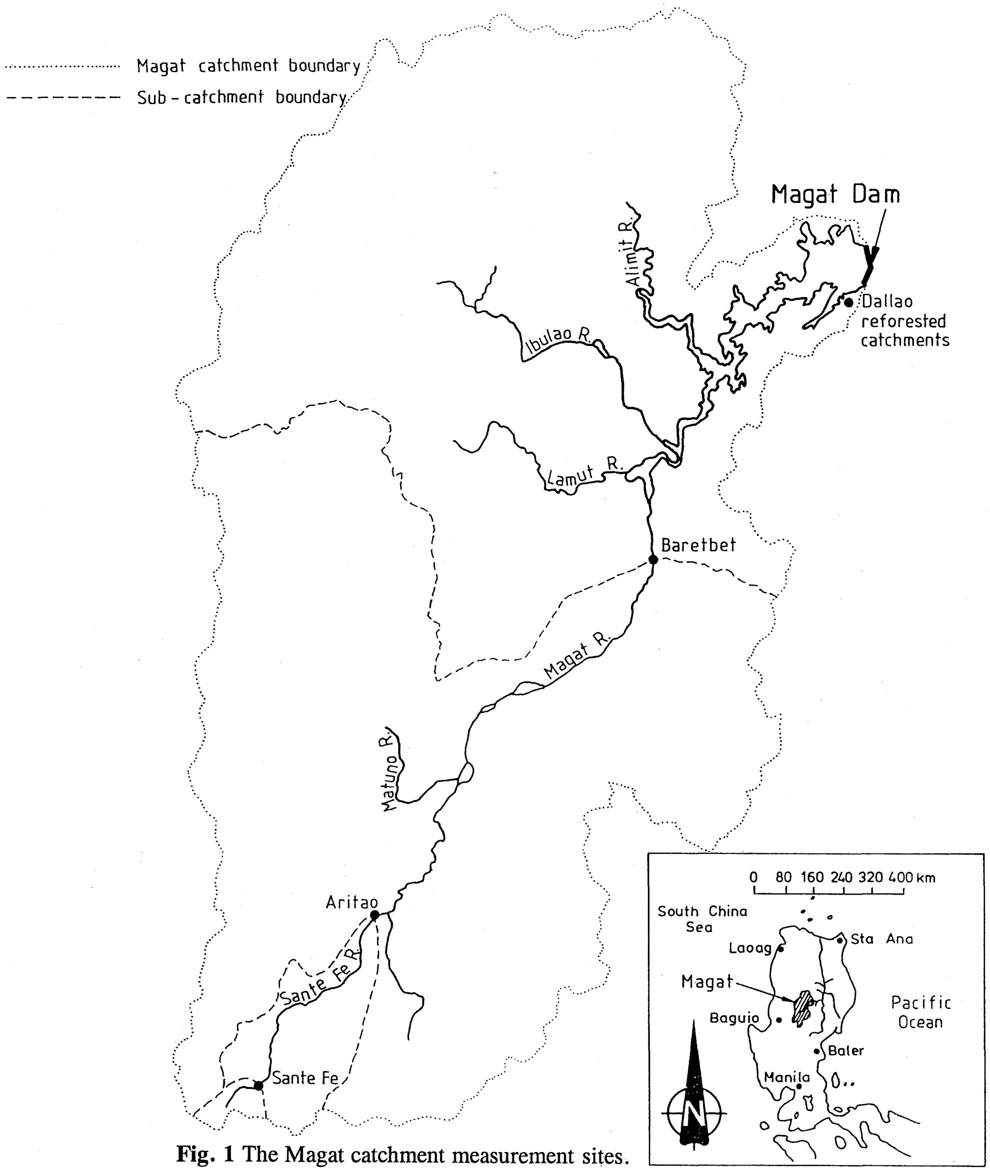

Fig. 1 The Magat catchment measurement sites.

overgrazed grasslands, pasture and annual burning, and ungrazed grassland, respectively. In contrast, the two small catchments at Dallao (26.5 and 15.3 ha) represented the best scenario in terms of catchment restoration. Both were replanted with trees (Ipil-Ipil with Yemane and Ipil-Ipil with Japanese Acacia, respectively) in 1982, and by 1984 had developed a good tree and under canopy vegetative cover. Data from Aritao were available on an event basis for four, three and two storms, in the three catchments respectively. Data from Dallao were collected on a continuous basis from June 1984 to December 1987 (Amphlett & Dickinson, 1989). In both locations rainfall, discharge and sediment yield data were gathered.

River sites

The three nested river measurement sites at Santa Fe (18.9 km^2), Aritao (159.2 km^2) and Baretbet (2041 km^2) provided the means to compare discharge and sediment yield for catchments of different sizes along the same river system. Data were collected from 1985 to 1988, at specified time intervals during daylight hours, with more frequent data collection during high flows (Dickinson *et al.*, 1990). Data collection at night and during the largest floods was impossible for logistical and safety reasons. At all sites flow level was monitored and converted to discharge through the use of discharge rating curves, derived from a series of current metering exercises. In spite of changes in the channel configuration at the two downstream sites, rating relationships were relatively stable. Longer term discharge data (1977 to 1981) were available for the Baretbet site.

Sediment yield was measured as wash load ($< 63\ \mu m$) and suspended bed material load ($> 63\ \mu m$). Sediment samples were pumped from a number of depths on vertical profiles across the river and separated into wash load and suspended bed material load by filtering on site. A sample of water and wash load was then taken from the pumped and filtered sample and the suspended sediment was removed from the filter and stored in a bottle. Both were later analysed in a laboratory. As available sediment data increased, it was possible to derive rating relationships between sediment concentration and discharge for both wash load and suspended bed material load. In practice this meant that rating relationships were revised after each year of data collection.

Magat reservoir

The downstream end of the data collection programme was the Magat reservoir itself. The dam at Magat was impounded in 1982, and the first echo-sounder survey of reservoir capacity was carried out in 1984 (Wooldridge, 1986). Comparison of cross-sections from the echo-sounder survey with pre-impoundment data allowed an estimation of sediment yield to the reservoir during the two years of operation.

Water inflow to the reservoir was not available for this period. However, pre-impoundment data were available as monthly totals and peak discharges from 1948 to 1977.

RESULTS

Table 1 summarizes the discharge and sediment yield data gathered from the Dallao catchments and the river sites. By comparison, average sediment yield to the reservoir (catchment area 4143 km^2) estimated from the 1984 echo-sounder survey was 3800 t km^{-2} $year^{-1}$ for the 2 years since impoundment.

From these results it can be clearly seen that conventional ideas about decreasing sediment yield with catchment area (e.g. ASCE, 1975) are not generally applicable in this catchment. The only sites where a sediment delivery ratio approach seems to be justified are the Dallao catchments, where the larger catchment B consistently shows both lower runoff and sediment yield, even with the slightly higher rainfall (around 10%) in this catchment seen in all years.

For the river sites, in spite of the many problems of data collection, results consistently show higher sediment yield at Santa Fe than at Aritao, related in part to the higher runoff depth for the former catchment. In turn, Aritao sediment yields and runoff depths are consistently lower than those seen at Baretbet. Sediment yield at the reservoir (approximately twice the catchment area of Baretbet) appears to be consistent with that measured at Baretbet.

In order to understand these results it is necessary to consider the combination of factors which affect erosion and sediment transport in and from each of these areas. Of these, land use and climate are proposed as the dominant controlling factors.

Table 1 Annual rainfall, runoff and sediment yield data for the Magat catchment measurement sites.

	Rainfall (m)	Discharge (m^3 x 10^6)	Runoff (m)	Sediment yield (t km^{-2} $year^{-1}$)	Area (km^2)
1984					
Dallao C	0.864	0.0109	0.0714	16	0.153
Dallao B	0.938	0.0187	0.0705	9	0.265
1985					
Dallao C	1.834	0.0522	0.3414	61	0.153
Dallao B	2.035	0.0891	0.3362	40	0.265
1986					
Dallao C	1.624	0.0312	0.2038	35	0.153
Dallao B	1.792	0.0651	0.2455	24	0.265
Santa Fe	-	68.0	3.60	3970	18.9
Aritao	-	266.0	1.67	2200	159.2
Baretbet	1.0	4049.0	1.98	3350	2041.0
1987					
Dallao B	1.187	0.0343	0.1294	17	0.265
Santa Fe	-	19.0	1.01	130	18.9
Aritao	-	71.0	0.45	60	159.2
Baretbet	0.966	2204.0	1.08	400	2041.0
1988					
Santa Fe	-	40.0	2.17	780	18.9
Aritao	-	149 .0	0.94	650	159.2
Baretbet	-	4599.0	2.25	3030	2041.0

Land use

The effects of land use on sediment yield can be clearly seen by comparing the runoff and sediment yield from the reforested Dallao catchments with data from the river and reservoir sites. In addition the limited event data from the Aritao grassland catchments (Table 2) support the view that under natural forest and in reforested areas, runoff and sediment loss are dramatically reduced. Sediment yields from a single event at any of the Aritao catchments exceed the annual yields from Dallao. This may, however, also be influenced by the smaller catchment size, and thus potentially more efficient delivery system of the Aritao catchments. The results also show a general trend of decreasing sediment yield with catchment area, although the limited data availability means that these results are very tentative.

Table 2 Rainfall, runoff and sediment yield data for four events at the Aritao agricultural catchments.

Date and catchment no.	Rainfall (mm)	Runoff (mm)	Sediment yield (t km^{-2})	Area (km^2)
2.4.78				
1	21.6	2.6	130	0.0235
2	18.9	1.9	40	0.0269
12.4.78				
1	33.8	7.2	260	0.0235
2	32.8	5.0	160	0.0269
3	35.5	4.6	120	0.0631
22.4.78				
1	42.8	14.9	620	0.0235
25.5.78				
1	25.4	8.8	410	0.0235
2	37.4	11.5	190	0.0269
3	45.2	13.4	540	0.0631

In the Magat catchment deforestation has been rapid and extensive. Land use classification from a Landsat Thematic Mapper image (White, 1992) showed around 50% of the catchment under primary or secondary forest. Cleared areas are concentrated around the valleys, although in the south and north of the catchment forest has been replaced almost entirely by poor quality grasslands with some rice terraces. It is difficult to judge when, or how quickly, the forests of Magat were cleared. Land use maps from 1978, 1980 and 1983 show primary forest increasing (an impossibility) and then decreasing again. However, it is likely that rapid forest clearance took place in the period of most rapid population growth. For Magat this happened between 1948 and 1975, with an average annual increase in population of 3%. This followed a period of population decline during and following the second world war (1939-1948). In the period 1975 to 1980, the population growth rate slowed to 0.3% per annum. Neighbouring, undeveloped catchments such as Casecnan (White, 1987) still show high percentage forest cover.

Climate

Rainfall in the Magat catchment ranges from around 1500 mm per year in the southeast of the catchment to 4500 mm in the northwest. There is no real dry season in Magat, but rainfall is higher from May to November inclusive. Much of the rainfall is due to convective thunderstorm events which occur in the afternoons. The catchment has between 140 and 180 rain days per year, of which 60 to 70 are days with thunderstorms. Rainfall totals show a strong relationship with elevation, although this relationship varies from year to year (Blyth & White, 1990). Annual precipitation is greatly affected by the occurrence of tropical cyclones, especially those which stall over the area.

The Philippines lie in the area of the world most affected by tropical cyclones, and the Magat catchment is within the worst affected area of the Philippines (Flores & Balagot, 1969). On average, between 2.7 and 3.5 cyclones per year cross the Magat catchment (White, 1992). Such events result in spatially widespread rainfall, and high total rainfall volumes. However, rainfall intensities may not be higher than those normally observed (White, 1990).

The combination of thunderstorms and cyclones can be used to understand the patterns of runoff and sediment yield seen at the various catchment scales. For the small

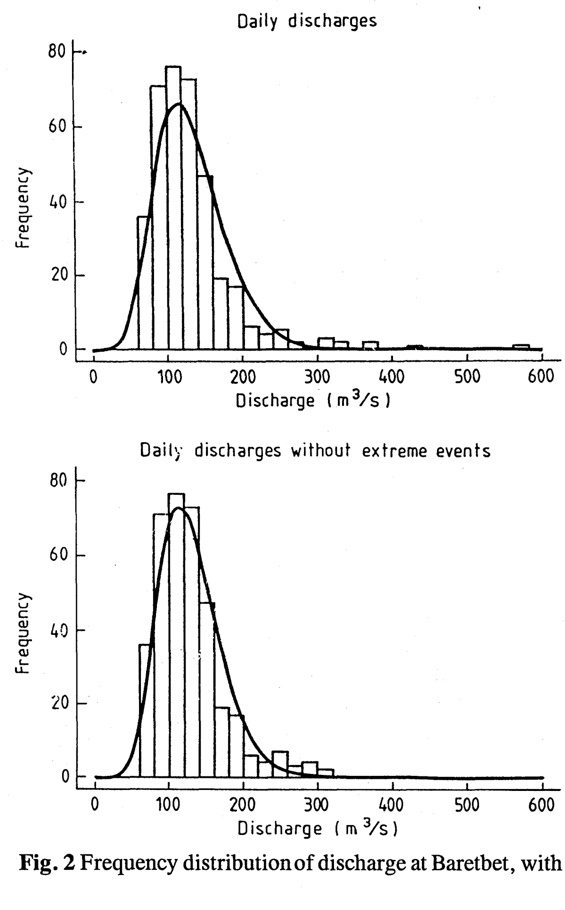

Fig. 2 Frequency distribution of discharge at Baretbet, with and without cyclone events.

Dallao catchments, it is difficult to separate thunderstorm events from cyclone events simply by studying rainfall, runoff and sediment yield records. However, for the Baretbet catchment cyclones are clear statistical outliers to the general distribution of flows (Fig. 2) (White, 1992). This can be understood by considering the spatial extent of thunderstorm and cyclone events. Although rainfall generally shows high spatial variability, a thunderstorm event is likely to affect most or all of the catchments at Dallao, causing rapid runoff with considerable sediment transporting capacity. Thus in spatial and temporal extent it is not dissimilar to a cyclone event passing over the catchments. For the larger Baretbet catchment there are likely to be a number of thunderstorm events occurring on any one day within the area. However, their impact on discharge and sediment transport at Baretbet will be minimal unless the storm occurs very near to the measurement point. On the other hand, cyclones may cause rainfall over the majority of the catchment, and although they normally pass over the catchment in a day or less, the combined rainfall and runoff from the whole catchment area can greatly influence flow at Baretbet. This does not, however, mean that cyclones are the only important events in terms of sediment transport at Baretbet. Few cyclones occur each year, and some years have none. Furthermore, cyclones sometimes affect only a part of the catchment. Thus, in 8 of the 10 years for which flow data were available at Baretbet, it was calculated that the majority of the sediment transported through the site was moved in non-cyclone wet season flows (White, 1992).

Hypothetical flow routing studies were carried out using data scaled to represent events at Santa Fe and the river channel to Aritao (Baldwin & White, 1991). This showed that flood waves resulting from thunderstorms within the Santa Fe catchment were attenuated before they reached Aritao. Thus, sediment removed from the Santa Fe catchment would be deposited in the river reach between Santa Fe and Aritao. When a cyclone occurs, this normally results in higher peak flows and/or longer flood events for the river reach between Santa Fe and Aritao, and these will mobilize the sediment, carrying it to and beyond Aritao. Evidence of extreme channel mobilization at Aritao was seen in cyclone events (White, 1992). Thus, frequent thunderstorms ensure a consistent supply of sediment to the channel system and the rarer cyclone events provide the energy to move this sediment downstream.

DISCUSSION AND CONCLUSIONS

The combination of a fragile environment, rapid forest clearance and thunderstorm and cyclone events provide an extremely efficient sediment supply and transport system in the Magat catchment. The implications for sediment yield estimation, catchment management and reservoir sedimentation are vast, but four main points will be raised here:

(a) In an area affected by cyclones, traditional sediment yield estimation methods using meam monthly or annual flows will not give a true picture of potential sediment delivery. Discharge must be considered at a daily level at least.

(b) Because cyclones are relatively rare events the need for a long time series of data (possibly between 50 and 100 years) for statistical analysis must be emphasized. Equally, it is clear that such data series do not exist, and therefore sensitivity analyses of predictions are essential.

(c) In degraded catchments, where sediment has already been supplied to the river system, catchment management programmes to reduce downstream sediment yield are likely to have limited effect. This is because runoff during cyclone events from forest areas, although less than that from grasslands, is still high enough to mobilize sediment stored in the river channel.

(d) For undisturbed catchments where new dams are planned it is important to realize that the best protection against sedimentation of the reservoir is the conservation of the soils *in situ* in the catchment. This also has obvious benefits for the indigenous population.

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