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Soil Erosion, Sediment Transport and Reservoir Sedimentation Relations Observed at Pantabangan and Magat Reservoirs in the Philippines

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ABSTRACT. Reservoir sedimentation survey data revealed that, the annual sediment delivery rates at Pantabangan and Magat reservoirs in the Philippines were 112 and 25 t/ha, respectively. The percentage of total sediment deposited in the dead storage was about 50%; which was more than the predicted value by the Empirical Area-Reduction Method, particularly due to annual reservoir draw downs resulting from seasonal rains. The annual sediment yield was dependent on the transport capacity of the stream-flow, rather than on the supply of material from the watershed; and therefore a decrease in sediment delivery ratio with increasing watershed area was not observed. Much of the material eroded from the land in the past was readily available for remobilization. and sediment delivery was a function of stream-flow. Therefore, control of sediment inflow from major rivers by soil conservation measures in the watershed seemed impractical, except in the case of small drainage basins, which discharge almost the entire sediment supply directly into the Pantabangan reservoir. In the case of the Magat Reservoir, the present sedimentation rate is critical for its future performances. Under such circumstances, the only economical alternative to sediment control seems to be the allocation of adequate reservoir capacities at the design stage for future sediment deposits.

INTRODUCTION

The objective of this study was to evaluate and assess sedimentation of the Pantabangan and Magat Reservoirs in the Philippines, and its impact on the reservoirs' capabilities to sustain their functions of hydroelectric power generation and irrigation water supply.

These dams have been designed for an economic lifespan of about 100 years. The useful life can be defined as the period of time which will elapse before the usefulness of volume allocated for a particular purpose is seriously impaired or destroyed. Most of the modern dams of large reservoirs are engineered to have a practically unlimited life as far as the structure itself is concerned, provided it is maintained reasonably well. The exceptions are due to the remote chances of foundation failures or earthquake destructions. However, long before the dams themselves reach a stage of significant deterioration, the functions are affected, mainly by the deposition of sediment, most of which is transported by inflowing streams.

MATERIALS AND METHODS

In this study, available historic time series data of stream-flow and sediment yield were used. The sources of data and methodologies employed to analyze the data are given with the results and discussion.

RESULTS AND DISCUSSION

The results of the data analysis are discussed separately for the two cases studied.

Sedimentation of the Pantabangan Reservoir

Quantities and distribution of reservoir sediment deposits

In the Pantabangan Reservoir, pre-impoundment capacities of conservation storage and dead storage were $1{,}731 \times 10^6$ and 197×10^6 m^3, respectively, between elevation 170-216 m and below 170 m (Figure 1). Reservoir sedimentation surveys revealed that the total reservoir sedimentation in 1985, or 12 years after impoundment, was 84.74×10^6 m^3, and that in 1989 or 15 years and 5 months after impoundment was 105.25×10^6 m^3. The long term average annual sedimentation rate during 1973-1989 was 6.75×10^6 m^3 despite the assumption of 1.13×10^6 m^3 at the project design stage. The percentages of sediment deposited in dead storage were 52.7% and 51% of the total, respectively, during the 1985 and 1989 surveys. The rest was in the conservation storage.

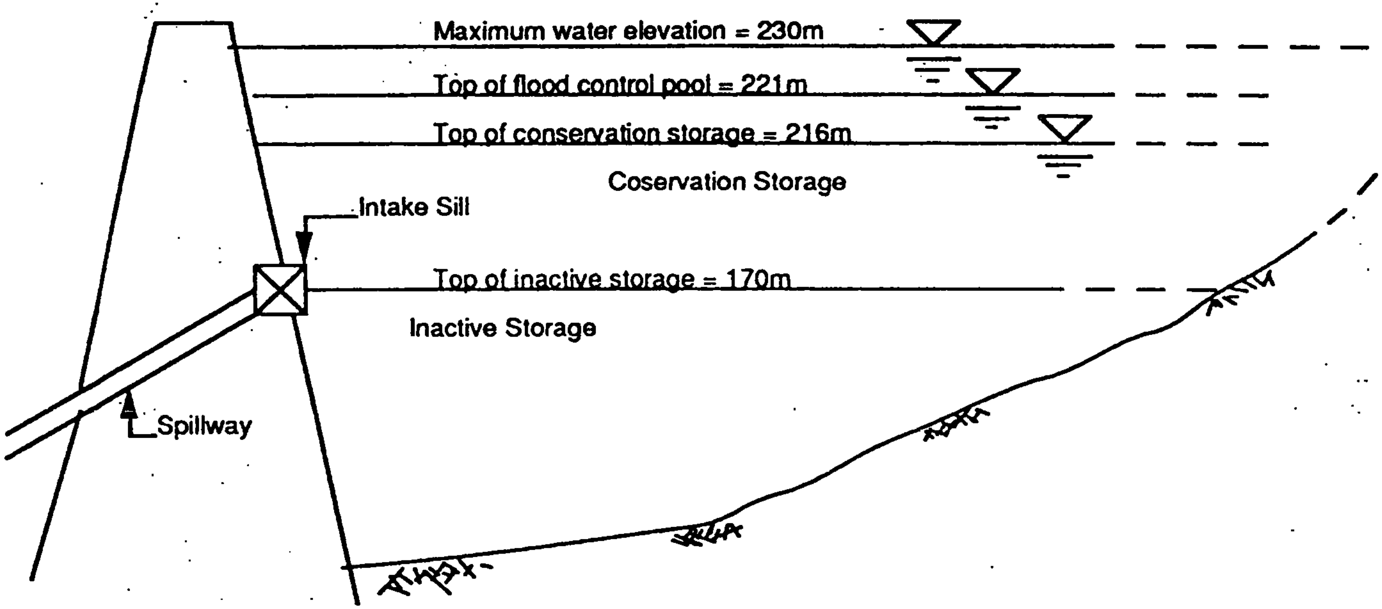

Figure 1. Schematic diagram showing the elevations of designed storages at Pantabangan dam.

If the observed long term average rate of sedimentation and the ratio of sediment distribution between dead and conservation storage continue; sediment deposits at the face of the dam will reach the intake level at 170 m elevation, after about 58 years of dam operation from its impoundment. Once sediment deposits at the dam reach the intake sill elevation, power generation cannot continue further, and the irrigation water released from the reservoir will carry more sediment. At the design stage, Empirical Area-Reduction Method (EARM) revised by Lara (1962) was used to predict the locations of future sediment deposits. Following the procedure recommended by Anonymous (1975), and using actual sedimentation rate and a mean level of dam operation at elevation 190 m (which is a reasonable assumption since during about 50% of the total time reservoir water levels were below this elevation) as input data, EARM predicted the time required by sediment to level at intake to be 70 years. This is because EARM gives satisfactory results under dam operation conditions, with less fluctuations in the water level. During excessive draw downs in the reservoir, previously deposited material at higher water stages tend to be eroded and transported to lower elevations in the reservoir. As a result, the actual proportion of sediment deposited in the dead storage can exceed that predicted by EARM under conditions of dam operation similar to that observed in the Pantabangan Reservoir, where wide fluctuations in water level were evident (Figure 2).

Sediment yield

In the calculation of reservoir sedimentation, only the volume of material trapped in the reservoir was taken into account. Based on the Brune's generalized trap efficiency envelop curve for estimating trap efficiency of storage type reservoirs (Brune, 1953); trap efficiency of the Pantabangan Reservoir, with 2.2 capacity-inflow ratio, was estimated at 98%. At this trap efficiency level, the measured reservoir sedimentation revealed an average annual sediment yield of $7.20\text{x}10^6$ m^3 during the 1973-1985 period and $5.84\text{x}10^6$ m^3 during the 1986-1989 period, with a long term average of $6.89\text{x}10^6$ m^3. Based on the total catchment area of 827.5 km^2 and sediment bulk density of 1,320 kg/m^3, the average annual sediment production rate of the Pantabangan watershed was 117.04 t/ha during the 1973-1985 period and 93.16 t/ha during the 1986-1989 period, with a long term average of 111.52 t/ha.

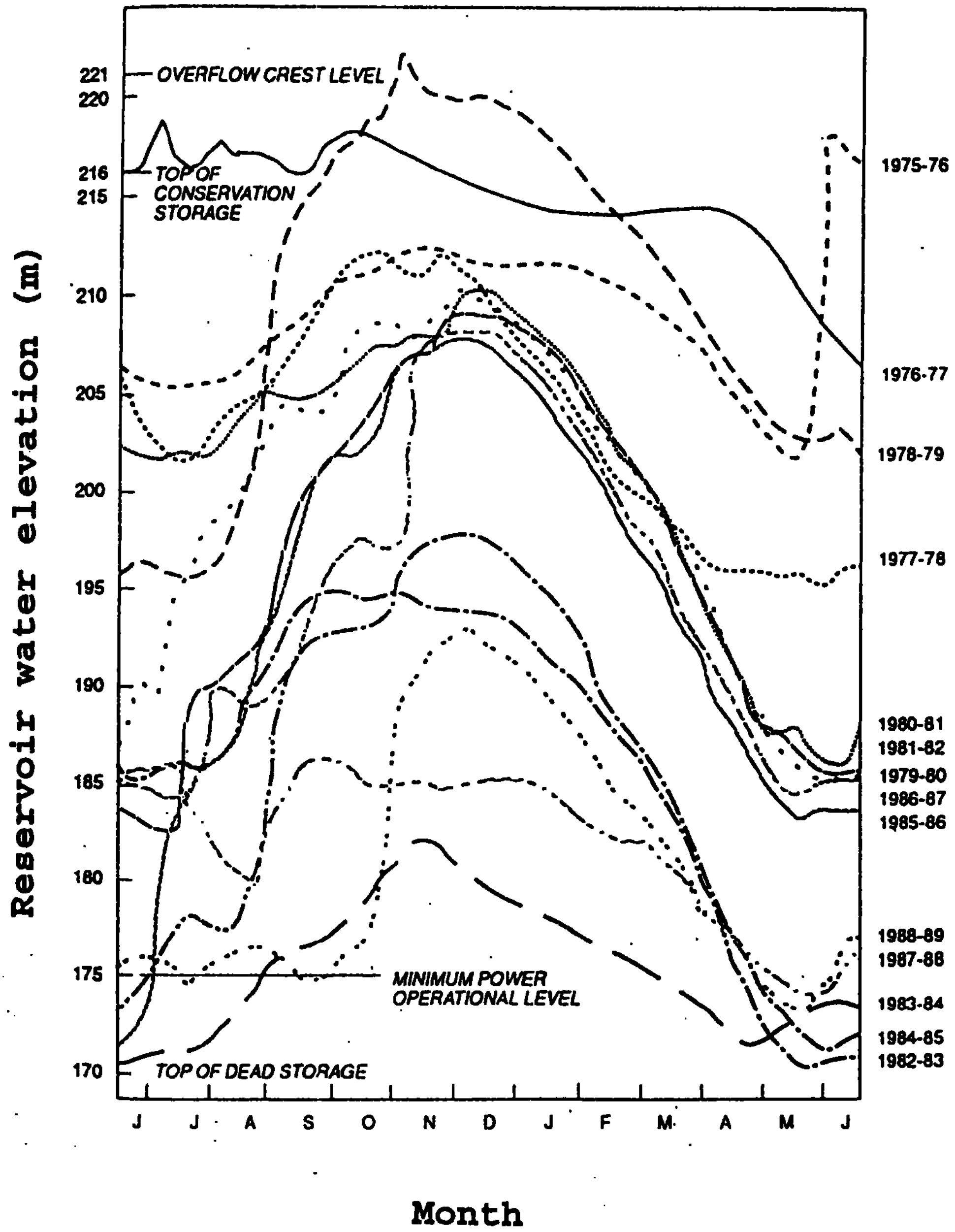

Figure 2. Actual water levels observed in Pantabangan reservoir.

Stream-flow discharge and sediment yield relations

The average annual reservoir inflows during the 1973-1985 and 1986-1989 periods were 1,386.05x10^6 and 979.94x10^6 m^3, respectively. The ratio of average annual sediment yield for these two periods was about the same as the ratio of corresponding average annual discharge, indicating a high correlation between sediment yield and stream-flow discharge. This seems to be due to the fact that most of the annual sediment transport occurs with peak flows brought about by southwest monsoon and typhoons from July to November, during which more than 80% of the total annual flow occurs. This observed functional relationship between sediment and water discharges implies the dependence of total sediment load on the transport capability of the stream-flow, rather than on the supply of material from the catchment. This is because the wash load is entirely supply dependent and not a unique function of the stream discharge of the reach (Einstein, 1964). Einstein further stated, that a considerable amount of temporary deposition and scour can correct the supply to follow the bed load function of the river, which is discharge dependent. This became clear when large volumes of sediment deposits were observed in the river channels discharging into the reservoir, particularly in their lower reaches with mild slopes.

Sediment supply from the watershed and delivery process

On the average, the rate of annual sheet and rill erosion of the watershed was estimated at 108 t/ha by David (1987) using a modified form of the Universal Soil Loss Equation. This high soil erosion was due to steep slopes with disturbed grasslands and more erosive rains. Field observations revealed that sliding, slumping, and gullying in the watershed were very extensive. Most probably the rate of soil erosion from such sources was higher than that of sheet and rill erosion. It is now well recognized that the net soil loss is substantially less than the gross erosion due to deposition losses during the conveyance from the source, depending on the hydro-physical conditions (Walling, 1988). However, because of the dominance of steeply sloping to steep hilly and rugged mountainous landscape dissected by narrow flat bottom valleys formed by streams, much of the eroded material from the watershed can be expected to end up in stream channels of a different order. As a result of these conditions, the total annual sediment supply from the watershed can be expected to exceed the annual transport capacity of the river system (estimated to be 111.52 t/ha at the reservoir). This clearly explains the dependence of sediment yield on the transport capacity of the flow rather than on the supply.

Control of reservoir sedimentation

Any change in the sediment carrying capacity of the river system could result mainly from changes in fluvial geometry or changes in stream-flow pattern. Possibilities for such changes are meager due to the greatly limited meandering belt *etc.*; and therefore it is reasonable to expect the long term sediment yield to continue at the calculated rate. Control of reservoir sedimentation is important to prolong the power generation beyond 60 years and to mitigate any adverse effect on irrigation during the later part of the dam's life. Since sediment yield in the river system is a function of the carrying capacity of stream-flow and much of the already eroded material from the watershed accumulated in river channels are available for further movement, any reduction in the soil erosion rate of the catchment would most probably have no effect on reservoir sedimentation rate even in the long term. Improvements in land use to establish a good vegetal cover as well as other soil and water conservation practices could significantly reduce the sediment yield, only if such measures are capable of reducing the sediment carrying capacity of streams through modulation of peak flows. However, for watersheds of Pantabangan size, changes in river flow pattern by land use transformation is quite unlikely. This is because in large drainage basins, the effect of channel storage is so pronounced that sensitivities to land use are generally suppressed (Ven Te Chow, 1964). Larger catchments become progressively more linear in their response with increasing catchment area, as channel travel time increasingly dominate the hydrograph (Kirkby, 1988).

The control of sediment yield at the Pantabangan Reservoir could therefore be achieved effectively only through artificial interferences along the river channels. These are river training and controlling to reduce flood peaks, flood retarding structures, stream bank revetment, sill or drop structures for stream bank and bed stabilization; or by incorporation of artificial sedimentation basins or check dams into the river system, which would be prohibitively costly.

The above discussed sediment delivery processes and their influences on sediment control are essentially applicable to major rivers and streams discharging into the reservoir. The drainage network of the watershed is dendritic and there are many small streams which discharge directly into the reservoir. Most of these small streams have incised narrow cross sections with coarse beds of steep gradients. Therefore, flow velocities can be very high with little channel storage of sediment. Their annual sediment yield can be expected to be almost equal to sediment supply under normal conditions. Aya Creek, which has a drainage area of 2.4 km^2 and a highly erodible young geologic formation provides an example for sediment delivery from smaller basins. A detailed geology and sediment survey on the Aya Creek delta at the reservoir revealed that 85,500 t of accumulated sediment were deposited primarily during typhoon Didang and subsequent storms in 1976, representing a sediment yield of 356 t/ha for the two month period (Anonymous, 1978a). Typhoon Didang stalled in the watershed for six days and brought a total rainfall of about 1,200 mm, and consequently there were excessive landslides in the drainage area.

Considering the above discussed factors, it is clear that soil conservation practices including gully control measures could greatly reduce the sediment yield resulting from small streams, which have drainage basins of only few square kilometers; and this is directly drained into the reservoir. Such basins are devoid of a good vegetal cover and most of the grasslands are annually burnt. The reforestation programme has been a great failure; mainly because of poor survival due to burning and other human interferences by about 30,000 inhabitants living in the watershed, whose overriding priority is food production. Further, in implementing the reforestation programme, no emphasis has been placed on the actual sediment delivery processes and their impact on reservoir sedimentation. Consequently, the required priority has not been given for conservation of small drainage basins, which are crucial in sediment delivery into the reservoir. If grasslands are undisturbed, soil erosion could be reduced dramatically. The results of plot experiments conducted by Kellman (1969) on 20% slope in Mount Apo and by the Anonymous (1978b) on 36 to 70% slopes in Mount Makiling have shown, that good grass cover is nearly as good as primary forest and perhaps better than a secondary forest, as far as the control of sheet and rill erosion are concerned. Plantations of suitable tree species would minimize landslides in geologically young formations with weathered or fractured parent material by mechanically binding potential failure blocks to stable slopes with deeply penetrating roots, and also by decreasing soil water content through evapotranspiration. Where drainage areas are about 5 km^2 or less, the sediment contribution can be reduced by as much as 95% through intensive conservation measures (Anonymous, 1975). In small drainage basins of 0.26 and 0.15 km^2, on 20 to 50% slopes of the Dallao sub-catchment planted to 2 to 6 yr old Ipil-Ipil (*Leucaena* *leucocephala*), Yamane (*Gmelina arbota*) and Japanese Acacia (*Acacia auricaliformis*), the measured annual sediment yield for a three and a half year period was less than 0.6 t/ha (Amphlett and Dickinson, 1989). In small watersheds, under good cover conditions, sediment yield comes mainly from channel erosion, and it may be the case in the Dallao study as sediment yield was observed to be a function of the stream-flow capacity only.

Sedimentation of the Magat Reservoir

Quantities and distribution of reservoir sediment deposits

Pre-impoundment capacities of the conservation and dead storage were $1,129.42 \times 10^6$ and 191.35×10^6 m^3, respectively, between elevation 193-147 m and below elevation 147 m. Reservoir sedimentation surveys showed that the total reservoir sedimentation in 1985 or two years after impoundment was 7.42×10^6 m^3, and that in 1989 or six years after impoundment was 43.04×10^6 m^3. Therefore, on the average, annual sedimentation rates were 3.71×10^6 m^3 for the 1982-1985 period and 8.91×10^6 m^3 for the 1986-1989 period. For the entire period, the average value was 7.17×10^6 m^3, as against the feasibility estimate of 5.5×10^6 m^3. In both surveys, 48% of the total sediment were in the dead storage. If, sedimentation and distribution of deposits continue at the observed rates, sediment deposits at the dam will reach the intake sill at an elevation of 147 m after 56 years of dam operation from impoundment. Using the actual rate of sedimentation and dam operation levels as input data, EARM underestimated the sediment deposits in dead storage by about 50%.

Sediment yield

At 92% trap efficiency estimated by using the capacity - inflow ratio of 0.18 on the Brune's median curve, sediment bulk density of 1,320 kg/m, and the total catchment area of 4,123 km^2; the average annual sediment production rates of the catchment were computed to be 12.90 t/ha for the 1982-1985 period and 30.99 t/ha for the 1986-1989 period. The average for the six year period from 1982 to 1989 was 24.94 t/ha and it was almost the same as that estimated near the dam site by various researches during the 1970's and 1980's, prior to the construction of the dam.

Stream-flow discharge and sediment yield relations

The average annual reservoir inflows during the 1982-1985 and 1986-1989 periods were 3,631x10^6 m^3 and 5,772x10^6 m^3 respectively. The corresponding annual sediment yield data showed a dependency of sediment yield on stream discharge. This functional relationship has been demonstrated clearly in studies on sediment transport of the Magat River. The measured suspended sediment load in the Magat River, 5 km upstream of the reservoir, during the 1986-1987 period, showed the following relationship between the river discharge, Q in m^3/s, and the sediment concentration, Q_s in g/l (Dickinson *et. al.*, 1990). For 113 samples of coarse fraction of sediment with particle diameter more than 0.063 mm, 98% of variation in Q_s was explained by the relation:

$$Q_s = 8\,(10^{-5}\,Q^{1.41})$$

For 297 samples of wash load with particle diameter less than 0.063 mm, 97% of the variation in Q_s was explained by the relation:

$$Q_s = 2.9\,(10^{-4}\,Q^{1.33})$$

This functional relationship between sediment discharge, even when only wash load is concerned, and water discharge; indicate the dependence of sediment yield on transport capacity of the steam-flow, rather than on sediment supply. It was also observed that in 1986, about 90% of the annual total sediment load was carried during five major storms, and sediment flux during low steam-flow was almost negligible in comparison (Amphlett *et. al.*, 1987). This shows the importance of large storm events or typhoons, which in turn control the annual river discharge, in transporting the annual sediment yield.

Sediment supply from the watershed, fluvial morphology and delivery process

The average annual sheet and rill erosion from the watershed was estimated at 50 t/ha by David and Collado (1987) using a modified form of the Universal Soil Loss Equation. There were many gullies but landslides were not so extensive. The topography varying from hilly or mountainous in the highlands to level or undulating in the alluvial valleys give an opportunity for much of the eroded material from the watershed to deposit on overland flow areas, where the slopes change from steep to mild, before reaching the river system. However, considering all forms of soil erosion and estimated annual sediment yield at the reservoir, the supply of material can be expected to be greater than the sediment yield estimated at 25 t/ha.

There was strong evidence that the sediment supply was in excess of the carrying capacity of the river system, or else it had been so in the past. One piece of evidence was the enormous volume of sediment deposits particularly along the major river system. Another physical manifestation was the active meandering of the river, and also the braided river channels at some locations. Albert and Simons (1964) explained that, sediment deposition resulting from loads exceeding that required for stability, initiate meandering under suitable conditions; and this was observed in the laboratory by Ackers (1988).

The head reach of the Magat River above Santa Fe has a non alluvial and fairly stable coarse bed with a steep gradient ranging up to a 3% slope. Flow velocities in this incised narrow cross section can be expected to be high with little channel storage. The sediment yield in this section can be expected to almost equal the supply from the watershed, with little channel erosion. As the river flows downstream, the river channel becomes alluvial, and near Aritao the gradient falls to about 0.6%. Here the river valley consists of a wide alluvial floodplain with a more recent floodplain or a terrace at a lower elevation, within which the river presently meanders. As the river reaches further downstream, floodplain becomes wider, and the meandering river becomes braided in places and the gradient falls to about 0.3% at Baretbet near the reservoir. As the mean slope of the river progressively decreases beyond Santa Fe, the river seems to change its morphological regime to increase its sediment carrying capacity by changing its plan form. Nevertheless, the river has failed to transport all the sediment supplied and it has resulted in further channel aggravation on the whole; despite the local channel bed and bank scour in many places. As a result, river islands and mounds of river washing were continuously formed.

During the period 1986-1991, NIA and HRL monitored the suspended sediment flux in the main channel of the Magat River at three monitoring stations, which represented three nested sub-catchments (Figure 3). The results showed a great variation in annual sediment yield between years depending on the occurrence of typhoons and large storm events (Table 1). Sediment yield at Santa Fe showed a supply dependence. When sediment concentrations were plotted against the stream discharge, a considerable

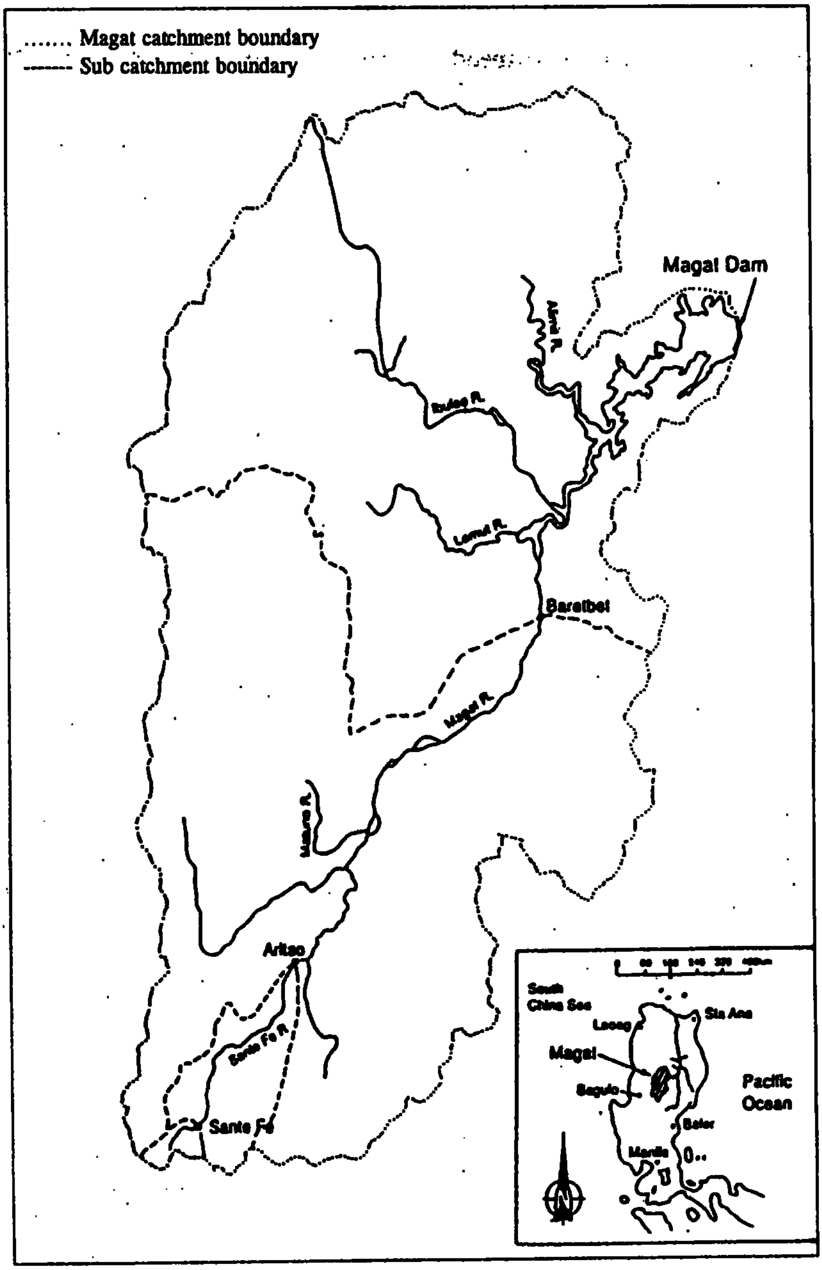

Figure 3. Locations of sediment measurement stations in the Magat river.

Table 1. Result of suspended sediment flux monitoring at three gauging stations along the Magat river.

Gauging	Drainage area (km^2)	Total suspended sediment station yield (t/ha/yr)					
		1986	1987	1988	1989	1990	1991
Santa Fe	18.9	39.7	1.5	5.42	21.2	-	41.3
Aritao	159.2	22.0	0.6	3.41	-	-	-
Baretbet	2041.0	25.3	4.0	20.80	-	22.9	6.0

Sources: Amphlett *et. al.*, 1987, Amphlett and Blyth, 1989, Dickinson *et. al.*, 1990, Bradbury et.al., 1993.

scatter was evident compared to other monitoring stations. Furthermore, in 1987, the largest sand concentration occurred with the flood event ranked third in magnitude among the events of the year, which was but the first storm after a long dry period (Amphlett and Blyth, 1989).

It was difficult to discern any possible drastic changes in sediment yield due to variation in land use among the three sub-catchments. Therefore, a decrease in net soil loss is expected as the catchment size increases, due to the decrease in the mean slope of the catchment by incorporation of more lowlands and floodplain. However, such a relation (*i.e.* decreasing sediment delivery ratio or sediment yield to gross erosion ratio with increasing catchment area) was not observed between Aritao and Baretbet station, indicating the non-dependence of sediment yield on supply from the watershed.

On July 16, 1990 a major earthquake struck the watershed causing massive landslides around Santa Fe and Aritao areas. Although the sediment yield at Santa Fe is expected to be equal to the sediment supply, the deposited sediment volume was so large that only a fraction of it could be transported. As a result, the river bed at Santa Fe monitoring station was raised by 2 m in the following month. Sediment yield estimated at Santa Fe in 1991 was much greater than that estimated prior to the earthquake. As expected for transport dependency, sediment yield measured at Baretbet was not affected by enhanced sediment supply at head reaches of the river, and the suspended yield measured in 1990 and 1991 showed no significant difference compared to that measured prior to 1990 (Table 1).

The analysis of sediment concentration, C, and water discharge, Q, for individual hydrologic events showed hysteresis effects in most cases, when C/Q ratios at a given discharge on the rising and falling limbs were compared. The observed behaviour of coarse fraction of sediment in the river showed a very prominent counterclockwise loop, but occasional clockwise loops were observed at Santa Fe (Figure 4). The clockwise loops can be attributed to depletion or flushing out of available sediment before water discharge has peaked due to limited availability from supply, as explained by Wood (1977). Changes in water discharge tend to travel with wave velocity, which is somewhat faster than the mean flow velocity for many streams. As suspended sediment tend to travel at a velocity closer to the mean flow velocity, the sediment flux tends to lag behind the flood wave (Heidel, 1956); and the lag time increases with distance downstream. This may explain the counterclockwise loops observed with progressively increasing lag between the stream-flow discharge and sediment peaks with increasing distance downstream. For fine sediment, a single-valued-line C-Q relation was observed, and Wood (1977) attributed such C-Q relations to an uninterrupted sediment supply throughout the flood. These possibilities clearly demonstrate the supply dependency of sediment yield at head reaches and non-supply dependency at lower reaches of the river.

Control of reservoir sedimentation

Historic sediment yield estimations and reservoir sedimentation data showed that the long term mean annual sediment yield has remained almost constant during the last few decades. Control of this sedimentation rate could prolong the reservoir life for power generation beyond 56 years. Also it could reduce severe irrigation shortages predicted by simulation studies, particularly to occur after about 70 years of dam operation. Similar to the case of Pantabangan Reservoir, any reduction in soil erosion rate in the watershed could not reduce the reservoir sedimentation rate. Such practices could effectively control sediment inflow from smaller streams discharging into the reservoir. However, such streams drain only less than 10% of the entire catchment. An effective control of sedimentation could be achieved only through costly artificial interferences in the river system. The alternative measure to sediment control is the removal of silt from the

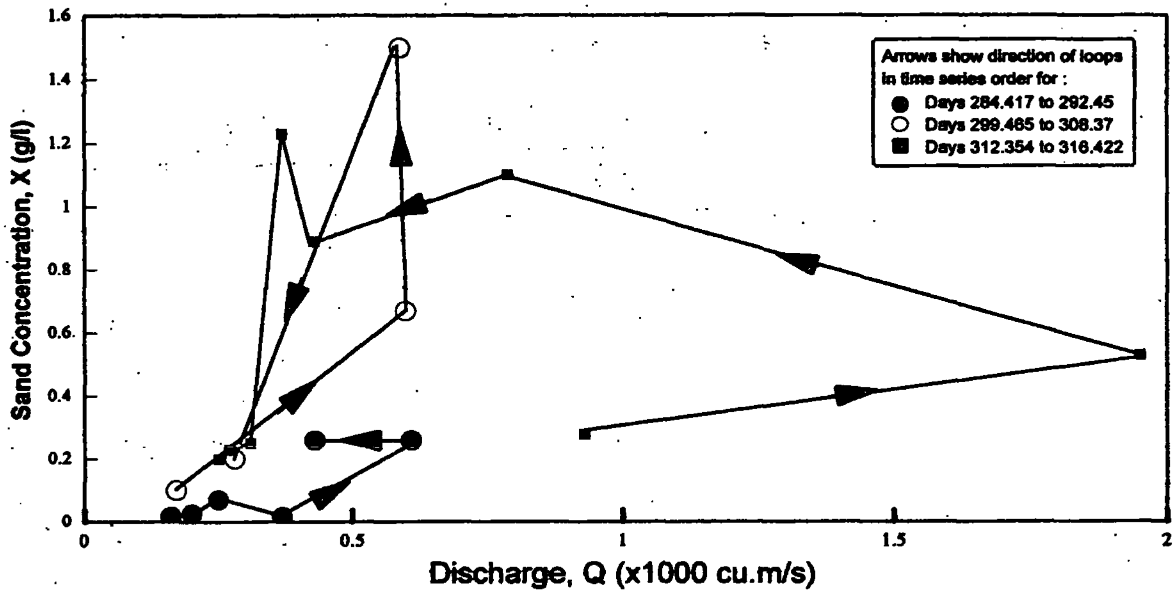

Figure 4. Examples of hyterisis loops in sand rating at Baretbet in 1986 (from Dickinson *et al.*, 1990).

reservoir through a low level outlet by sluicing; which is seldom practical, because every such attempt has resulted in the scouring of a deep narrow channels into the deposit, leaving most of the sediment intact (Anonymous, 1975). Generally, the cost of mechanical excavation is prohibitive, and a location to deposit them is usually unavailable. Therefore, the most appropriate alternative to sediment control should have been the provision of a sufficient storage capacity during the design stage for sediment storage within the reservoir.

CONCLUSIONS

There is considerable evidence that the economic life of the reservoirs would be less than that designed, owing to more than anticipated rates of sedimentation, particularly, within the dead storage. This has resulted mainly from serious under-estimation of sedimentation rate, as well as, the application of Empirical Area-Reduction Technique to predict sediment distribution during the design stage. There is an impracticability of applying these analytical techniques, developed on the basis of empirical work in western countries, to tropical countries with monsoonal climates; where most of the annual sediment yield is transported in few flood peaks and greater reservoir draw downs are experienced.

Watershed soil loss rate did not necessarily equate stream sediment delivery rate, when spatial variations in sediment transport and yield were manifested as channel storage and remobilization of stored sediment. Sediment delivery rate seemed to depend more on transport capacities of the stream-flow, when a considerable volume of sediment was already in transit along the river system. Under such circumstances, prediction of sediment delivery ratio at drainage basin scale became complicated due to temporal discontinuity in the sediment delivery system.

If soil conservation measures are introduced in the watershed they cannot control or greatly reduce the sediment inflow into a reservoir. This is because much of the sediment eroded from the land in previous years has been deposited in river channels or other areas, and is available for further movement as a function of flow capacity. Under such circumstances, the alternative sediment control measures would most probably be uneconomical. The only economical alternative in such instances is to allocate sufficient storage in reservoirs at the design stage, for future deposition of sediment. This will demand reliable estimates of sediment yield data over a period of time (preferably 10 years or more as recommended by the ASCE). It is also important to note that soil conservation practices must be selected only after a thorough identification of the sediment delivery process at play, if they are meant only for reducing sediment yield.

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