The influence of tropical cyclones as soil eroding and sediment transporting events. An example from the Philippines

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ABSTRACT During a four year study of rainfall, runoff and sediment yield in the Philippines, it has become increasingly apparent that tropical cyclones, which on average occur twice a year in this region, are indeed extreme events in terms of rainfall and discharge. It follows that they are also the events which erode and transport most sediment. However, it is extremely difficult to collect data in the physical environment of the Philippines, especially during such large storms. A lack of data means that all estimates of long-term erosion and sediment yield rates rely on large extrapolations from the monitored data set. Given this, certain techniques of analysis are needed to make the best possible use of available data, and to make the most reliable estimates for future catchment management plans.

INTRODUCTION

The prediction of long term erosion and sediment yield rates is often hampered by a lack of data. This is exacerbated in an area where extreme rainfall and runoff events occur frequently. Such a situation is found in the Philippines where tropical cyclones occur on average 19 times a year (Flores and Balagot, 1969). The area of the country affected by cyclones varies throughout the year, with the cyclone band moving from south to north and then returning south again. This means that most regions of the country will only be affected by two or three cyclones per year.

In a study of two river basins in northern Luzon, rainfall, discharge and sediment yield have been monitored at a number of scales, and for varying durations. In the Magat catchment three river sites have been used for an intensive monitoring programme over four years. The maximum discharge monitored at the largest of these sites, Baretbet, has been 1400 m$^3$/s, whilst sediment data has only been collected up to a discharge of 744 m$^3$/s. This lack of data at high flows is not due to any incompetence of the monitoring staff, but simply reflects the extreme difficulty of measuring sediment movement in velocities exceeding 4 m/s, when the whole river section has itself become unstable. Basically, it is not safe for anyone to be near the river during a cyclone, and anything which is put into the river to collect data automatically will be damaged or washed away, or will be left high and dry as the river course changes completely during the flood. Therefore, until
some way of measuring sediment load at high flows is found, any estimate of long term sediment yield will depend on how we treat these cyclone events.

Typically sediment yield estimates for planned or existing reservoirs are based on a sparse data set. The usual analysis procedure then involves averaging most of the parameters involved before using them to make estimates. For example, often such a small amount of sediment data is available that an average concentration is used. Samples are typically from the low end of the flow range. This mean calculation is multiplied by mean annual discharge to calculate the sediment load delivered to a downstream point. An alternative is to use a rating curve derived from the sediment samples. This approach has merit, but only if used in conjunction with daily discharges. Often mean monthly or annual flow is used instead. This type of analysis may be suitable for rivers where discharge shows gentle increases and decreases through the year, or even where there are months which are consistently wetter than others. But, in an area such as the Philippines where cyclones can cause a rise in discharge of 100 fold in less than 24 hours, and where post cyclone flows can just as quickly decrease to pre-flood levels, averaging can lead to dangerous under estimates of sediment transport. The occurrence of such cyclones follows no set pattern - they are more likely to happen in certain months in a given area, but can happen in other months as well. Cyclones do not affect an area every year, but in some years one river basin may be affected by as many as six. Sometimes these cyclones can follow one another within a matter of days.

A standard hydrological analysis technique is to look at statistical distributions of rainfall or discharge in order to make longer term predictions. In the developing world, reliable data sets of a length to allow statistical analysis are often not available. In an area where cyclones are a feature of the climate, statistical analysis also becomes fraught with difficulties, as only a few cyclones will have been monitored. These few events will appear as outliers on a statistical distribution (Fig. 1) thus making standard analysis techniques impossible.

Areas of the world which are subject to cyclones also tend to be the most environmentally fragile. Slopes are steep, rainfall intensity is high, soils are often of volcanic origin and thus extremely erodible. These areas have some of the highest and most rapidly increasing populations in the world, thus increasing the pressure on the natural resources. It is therefore vital that these resources are properly managed, and for this to happen it is necessary to be able to predict the outcome of possible management interventions. In the foreseeable future, at least, reliable means of analysing sparse data sets in areas with frequent extreme events must be found. Some ideas on how this can be done, and the varying answers from different analysis techniques are now discussed.
EROSION PREDICTION

Continuously recorded rainfall data is often not available in developing countries. An effort has therefore been made to collect and analyse rainfall data from various sites around the river basins of interest in the Philippines. Four recording gauges have been installed in the Magat basin, two near to the Magat reservoir, one at Santa Fe, and one at Aritao near to the river monitoring sites. Daily data are also available for a longer time span for many sites in the area. There were, therefore, two main tasks in the analysis of the recorded rainfall data. The first was to find any relationship between rainfall amount and rainfall energy, in order to have some measure of erosivity. Some energy parameter is needed in all reliable erosion prediction techniques. The second task was to discover if rainfall in cyclones was distinguishable from other storm rainfall by amount or intensity. Or, in other words, to discover if cyclone events are likely to cause more erosion at a point than other rainfall.

There are several relationships which relate storm rainfall to rainfall energy (Wischmeier and Smith, 1978; Zanchi and Torri, 1981; Hudson, 1971). None of these has been derived for an area affected by cyclones, and indeed most are expected to over estimate rainfall energy at high intensities (Kinnell, private communication, 1988). This is mainly a function of unjustified extrapolation - it is known that at high intensities raindrop impact results in smaller drops of lower energy - the formulae however assume an ever increasing raindrop size. Because no techniques have been developed for estimating the energy of tropical rainfall, one must use the formulae that are available, whilst remembering that over estimates are likely at high rainfall intensities.
A plot of storm energy against storm rainfall is shown in Fig 2. This shows the typical linear relationship between these two parameters, with energy being some constant multiple of rainfall. For data from the Philippines the constant is between 22 and 26, depending on the site and the amount of data available. This is higher than the constants found in areas of southern Africa, of around 18 to 20 (Stocking, 1987). So it appears that an estimate of rainfall energy can be made from measurements of daily or annual rainfall.

![Graph showing storm energy against storm rainfall](image)

**Fig 2 Storm rainfall versus storm energy**

Given such an estimate of rainfall energy, and some information about soils, slopes and land use throughout the river basin, it is possible to make an estimate of the potential erosion rates. Calculations can also be carried out for possible future land use scenarios, assuming for instance that forest clearance will continue, or that soil conservation techniques may be implemented. These calculations will allow estimates of future sediment supply to the river system. One should also of course consider the effect of changing land use on runoff coefficients and discharge patterns, but this is outside the scope of this paper.

The other point of interest from Fig. 2 is the way that cyclones, indicated by squares, are seen through the range of storm rainfalls and energies. Although the highest intensity storm at this site was a cyclone related event, the next three events, in terms of rainfall amount are not cyclones. When one studies values of the maximum 30 minute rainfall intensity in different events, again the cyclones do not cover the whole range of high values. It is thus clear that some high rainfall, high energy events are due to other phenomena, such as thunderstorms. Cyclones are typified by long duration fairly high intensity rainfall, whereas thunderstorms tend to be of shorter duration and higher intensity. Cyclones are also more
likely to affect a large proportion of the river basin, so although at the small scale cyclone related floods cannot be distinguished from non-cyclone floods, at the larger river monitoring sites peak flows are all due to cyclones. The eroding power of cyclone rainfall is thus due to the areal extent of rain rather than high intensities.

SEDIMENT YIELD CALCULATION

A four year set of daily discharges from a river in the Philippines, together with 50 sediment samples taken from the river were supplied to ODU in order that estimates of long term sediment yield could be made. The sediment data coincided with times of relatively low flow in the river, and was clustered around a small range of discharge. This sort of data set is not unrepresentative of those often used to predict sediment yield, in fact being considerably better than many cases where no data from the relevant river basin is available. There is often scope to collect such data during the pre-feasibility stage of projects which can go on for many years. This opportunity is rarely used, and organisations responsible for water resources and catchment management must be encouraged to collect such valuable data whenever possible. Data shown in Fig 3 represents two river sites in neighbouring river basins, and indicates the dangers in using data from other basins to make sediment yield predictions.

Given such a data set as that from site, there are many ways in which it could be analysed. Perhaps the most frequently used is the technique of multiplying mean sediment concentration by mean discharge, thus calculating an average annual yield. Alternatively one could attempt to produce a rating curve, relating sediment concentration to discharge, this can then be used to predict sediment yield from daily, monthly or annual discharge figures. These techniques give widely varying answers as shown below.

Table 1 Calculations of annual suspended bed material load in tonnes

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<tbody>
<tr>
<td>Mean sediment concentration</td>
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<td></td>
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<td></td>
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<tr>
<td>Mean daily, monthly or annual discharge</td>
<td>57768</td>
<td>26440</td>
<td>45435</td>
<td>50187</td>
<td>44958</td>
</tr>
<tr>
<td>Rating curve</td>
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<tr>
<td>Daily discharge</td>
<td>1331508</td>
<td>12575</td>
<td>287792</td>
<td>441558</td>
<td>518358</td>
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<tr>
<td>Mean monthly discharge</td>
<td>161906</td>
<td>10588</td>
<td>52346</td>
<td>62579</td>
<td>71859</td>
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<tr>
<td>Mean annual discharge</td>
<td>47691</td>
<td>8545</td>
<td>28026</td>
<td>34996</td>
<td>29815</td>
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</table>

The technique of multiplying mean sediment concentration by discharge gives results which are generally lower than those
predicted by the rating curve approach with daily or monthly discharges. However, the results for 1979 are higher than those predicted with the rating curve, suggesting that 1979 was a year of relatively low flows, whose sediment transport capacities are below those of the sampled flows.

It should also be noted that the predictions for 1979, using the rating curve approach, do not show as much variation as those for the other years. The main reason for this is that the area was not affected by any cyclones in 1979, whereas in 1978 and 1980 there were three, and in 1981 there were two. The main differences in sediment yield predictions for 1978, 1980 and 1981, using the rating curve, are due to the averaging of extreme cyclone flows over a month or a year. This has a profound effect on the sediment yield predictions because sediment concentration is related to discharge by a power law such that:

\[ C = a Q^b \]

where \( C \) = concentration
\( Q \) = discharge
\( a \) and \( b \) are constants for a given river site

So, how does one decide which of the predictions given above are correct? It is known that higher discharges carry higher concentrations of sediment given a sufficient supply. We have also seen that the high rainfall storm events in the Philippines typically input more rainfall energy to the system and are therefore more erosive, although the cyclones are not responsible for the most erosive events. The sediment samples which were collected were from a limited range of low flows, unrepresentative of the complete flow distribution. It is thus impossible to justify use of a mean sediment concentration to calculate sediment yield.

The rating curve approach also raises some problems, not least of which is deciding how to extrapolate from the low to high flows. There are various options open, as shown in Fig 3. Fitting a best fit line by least squares regression gives a line which has a very shallow slope compared with other river sites in the neighbouring catchment. The value of 0.6 for \( b \), the power to which discharge is raised, is also low when compared with the typical value of 1.2 found from both measurement and theory (Vanoni, 1977; Lawrence, 1986). In the work carried out it was, therefore, decided to fit a line through the mean of the sampled concentrations and discharges with a 'b' factor equal to 1.2. This is shown on Fig 3.

Such a rating equation gives a sediment concentration of 2800ppm at the highest monitored discharge (\( Q = 2400 \) cumecs). This seems rather high, and can be checked by plotting the sediment and discharge data in a different way. If sediment load is plotted against daily discharge on logarithmic scales, it can be seen that the lines for many of the monitored river sites curve over at their top end, towards a constant sediment concentration (Fig 4). This is a recognised phenomena (Vanoni, 1977) thought to be due to sediment supply limitations. We can therefore investigate the effect of different cut-off concentrations on predictions of sediment yield.
The calculations in Table 1 were carried out with no limit to sediment concentration. In fact, such a limit only makes a difference to the predictions from daily discharges, as averaging discharge over a time period removes high flows from the record. Using a 200ppm cut-off concentration to the rating curve reduces the predicted annual sediment yield from the daily discharges to 201 313 tonnes.

One thing which is certain is that where daily discharge data is available it should be used to assess sediment yield. In these days of programmable calculators and micro-computers there really can be no excuse for averaging discharge data over a longer time span. This is especially important in areas of high flow variability.

SEDIMENT YIELD PREDICTION

If one wishes to make long term predictions using the data and relationships given above, it is necessary to find some means of extending the monitored data. One way to do this is by simply assuming that the pattern of discharges monitored over four years are repeated again and again. This is obviously unrealistic, as it is certain that flows outside the range of those monitored will occur, and as high flows have such a profound effect on the sediment yield it is important that these are represented realistically. It is also desirable to find a predictive technique where the sensitivity of assumptions can be tested. Both of these requirements can be satisfied by looking at the statistical distribution of discharge and sediment load within the monitored
data set. This standard hydrological technique allows predictions to be made which maintain the statistical parameters of the data. Tests can also be done using statistical parameters which vary from those of the monitored data set. In this way a sensitivity analysis can be carried out, allowing the parameters of most importance to sediment yield prediction in the given situation to be defined. It is likely that in different areas different parameters will be critical, dependent on the range of flows that have been sampled, the distribution of discharge and the relationship between sediment concentration and discharge.

As seen earlier (Fig 1) a frequency distribution for the four years of monitored flow results in a smooth curve for most of the discharge range, with a few outliers in the high flow range. These high discharges are all cyclone related events and can be considered separately from the non-cyclone flows. This is a recognised procedure in statistical analysis, where distributions are split into as many component parts as necessary to allow sensible analysis. Typically this is done for wet and dry season flows, and indeed our data record could be further sub-divided in this way. This is, however, stretching the information available from such a limited data set to its limit, and it was thus considered wise to use just a cyclone and non-cyclone division of discharge data.

Cyclones can be removed from the data record by a form of baseflow separation (see eg. Linsley, Kohler and Paulhus, 1975). The first step is to identify a threshold discharge, which when exceeded is indicative of a cyclone. This can be done by looking at the annual flow hydrograph in conjunction with a record of cyclone occurrence. For the site at which this analysis is being carried out a threshold of 260 cumecs is reasonable. Cyclones are then removed by extending the pre-cyclone discharge to beneath the flow peak, and then joining that point to another $N$ days after peak flow, where:

$$N = A^{0.2}$$

$A =$ river basin area in square miles

Sediment transport in cyclone events must be calculated as the difference between the transport in the total cyclone discharge and that in the flows represented by the baseflow separation line. This is because of the non-linear relationship between sediment concentration and discharge, which means that the differences between discharges cannot be used.

In this way it is possible to look at sediment transport in cyclone and non-cyclone flows independently, and to study the variations in these. For the set of data used above, the mean suspended bed material load in cyclones can be calculated, and the frequency distribution of cyclone sediment loads can be determined. It is also possible to derive statistical relationships for the frequency and timing of cyclone occurrence in a certain area. For the Philippines this is facilitated by a comprehensive set of cyclone reports produced by PAGASA, the Philippines meteorological service. Using these
statistical relationships and a similar distribution for the non-cyclone flows, a hypothetical set of future sediment transport rates can be developed. This is done using random number generation, maintaining the statistical properties of the original data set (White, 1987). Of course it is now possible to test variations of the statistics from the original data set - eg. what happens if the true mean sediment load in cyclones is higher than that estimated from the limited data set? Such calculations are easier to carry out than complete recomputation of sediment load using different ratings or different cut-off concentrations. This approach also allows one to attach different weightings to each step of the analysis. For example, there is much more uncertainty about the amount of sediment transported by cyclones, than by non-cyclone flows. These high discharges also account for the majority of sediment transport, and thus variations from the monitored data have a great effect on predicted sediment yield. Such uncertainty should be considered if believable predictions are to be made.

A final point to make is that even if different analysis techniques give widely differing predictions of annual sediment yield, the variation in the final item of interest may not be of great importance. In the case described above, sediment yield predictions were needed in order to estimate the useful life of a planned reservoir. A simple model of sediment supply to the reservoir, sediment deposition patterns and fluctuating reservoir water level was developed. The model calculated sediment deposition in the reservoir on a monthly basis, and could either be supplied with monthly sediment yield figures, or would aggregate daily yields to give a monthly sediment input. The various techniques of sediment yield prediction could then be used to estimate reservoir life. This gave answers as shown below (Table 2) varying between 50 and 139 years. The final recommendation of the study was that a reservoir life of around 89 years was most likely, but that this would be reduced if forest clearance was allowed to continue in an uncontrolled manner.

Table 2 Predicted reservoir life from different sediment analysis techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Estimated life (years)</th>
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<tbody>
<tr>
<td>Mean daily discharge + rating curve</td>
<td>63</td>
</tr>
<tr>
<td>Mean monthly discharge + rating curve</td>
<td>113</td>
</tr>
<tr>
<td>Mean sediment concentration</td>
<td>139</td>
</tr>
<tr>
<td>Cyclones analysed seperately (no cut-off)</td>
<td>50</td>
</tr>
<tr>
<td>Cyclones analysed seperately (200ppm cut-off)</td>
<td>89</td>
</tr>
<tr>
<td>Cyclones analysed seperately (100ppm cut-off)</td>
<td>98</td>
</tr>
</tbody>
</table>
DISCUSSION

It has been shown that even with limited rainfall and discharge data sets it is possible to make sensible estimates of long-term erosion and sediment yield. In areas affected by cyclones attention must be paid to the effect of such high rainfall events which may affect a large proportion of the river basin. In terms of rainfall amount and intensity at a point cyclones are indistinguishable from other storm events. Rainfall energy is related to rainfall amount for all events, with cyclones covering the range of rainfall records. Similarly for small river basins, cyclone related floods cannot be easily identified from the flow record. The impact of cyclones is due to the large areas which they affect, resulting in high discharges in the main rivers. This phenomena provides the opportunity to analyse cyclones seperately from other flows at the large scale.

Using statistical distributions to represent the amounts of sediment transported by cyclone and non-cyclone flows, and the frequency of cyclone occurrence, estimates of long term sediment yield can be made. By analysing the cyclones apart from the other discharges, different accuracies can be assigned to the distributions, representing the greater uncertainty related to a small cyclone data set.

REFERENCES


