Variability in Stream Erosion and Sediment Transport (Proceedings of the Canberra Symposium, December 1994). IAHS Publ. no. 224, 1994.

Land-use effects on magnitude-frequency characteristics of storm sediment yields: some New Zealand examples

D. MURRAY HICKS
Climate Division, National Institute of Water and Atmospheric Research, PO Box 8602, Christchurch, New Zealand

Abstract Magnitude-frequency relationships for storm suspended sediment yield were analysed at four small basins under various land uses near Auckland, New Zealand. Relationships between storm sediment yield and storm peak flow rate were combined with continuous records of streamflow to derive (a) the return periods of given storm sediment yields, (b) the long-term average sediment yield, (c) the proportion of the long-term yield carried by storms of various return period. The results showed that an urbanizing basin yielded much more sediment with larger rarer storm events, and the bulk of its long-term average sediment yield was carried by events with longer than annual return periods. In contrast, in a nearby mature urban basin storm yields increased little with larger storm flows, and it was the weekly-monthly events that carried the most sediment in the long term. For pasture and market-gardening basins, the sub-annual and super-annual events were of approximately equal importance in carrying the long-term yield. These patterns of storm sediment yields probably relate mainly to landuse controls on erosion processes and sediment supplies. The results suggest different approaches for the most cost-effective controlling of basin sediment exports.

INTRODUCTION

Greater public interest and improved legislation for resource management in New Zealand over recent years has increased the need for knowledge of stream sediment loads and sediment exports from small basins. Traditionally, measurements of basin sediment exports have focussed primarily on obtaining an estimate of the long-term average (or mean annual) yield. Often, in climatic regimes containing considerable interannual variability, the time constraint for obtaining planning information conflicts with the length of time required to obtain sediment yield data that are representative, and results in quite uncertain estimates of the "long-term average" sediment yield. Also, while a basin sediment yield value is useful to manage sediment problems downstream, such as sediment supplies to a reservoir, or to suggest how basin exports might change after a land-use conversion, it is less useful where there is a need to manage sediment routing within a basin, since in-basin sediment problems tend to arise on an event basis.

Sediment yields from individual storms and their magnitude-frequency characteristics are rarely assessed, yet they have the potential to enable better estimates of the long-term basin yield and to identify the return periods of the events that transport the most sediment in the long-term. For example, is more sediment exported in the long term by a few large rare storms or by the relatively small but frequent events that occur monthly to several times yearly? Such knowledge could then be used to design the most cost-effective means of sediment management.

This paper presents results from analysis of individual storm sediment yields in four small basins under various land uses but experiencing the same climatic regime. The purposes are to present an alternative method for estimating a long-term representative basin sediment yield, to show how the magnitude-frequency characteristics of the storm sediment yields differ, to discuss the possible reasons for this, and to explore some implications for in-basin sediment management.

DATA AND ANALYSIS

Study basins

Data are used from four basins in the greater Auckland area (Table 1). Pasture, mature urban, developing urban, and market-gardening land uses are represented. Basin size is small, ranging from 0.3 to 2.2 km^2.

Table 1 Study basin characteristics, flow records, and sediment yield estimates.

Basin	Land use	Area (km^2)	Flow records (year)	Storms sampled	Storm rating regression coefficient	Yield by storm rating (t km^{-2} $year^{-1}$)	Yield by frequency analysis (t km^{-2} $year^{-1}$)	T_{50}* (year)
Alexandra	Urbanizing	2.2	1.2	22	0.97	960	2370	3.0
Wairau	Mature urban	1.5	6	17	0.79	107	100	0.2
Whangapouri	Market gardening	1.8	3	34	0.78	49	52	0.4
Manukau	Pasture	0.3	17	14	0.92	49	46	0.8

* T_{50} Return period at which 50% of long-term sediment yield is moved by storms of shorter return period.

Data collection

Data collection procedures were essentially the same at all basins. At each basin outlet, streamflow was monitored by continuously recording water levels at a "V-notch" weir. A nearby auto-sampler was triggered to collect samples of water from storm flows for determination of suspended sediment concentration. The samplers became activated when the water level exceeded a threshold value, then continued to sample through-out the storm event at either fixed intervals of time or changes in water level. The records of suspended sediment concentration and water discharge collected in this fashion were then combined to calculate the discharge of suspended sediment over the storm event. At Alexandra basin, depth-integrated samples were collected over a range of discharges and sediment concentrations in order to establish a relationship between the point concentration at the auto-sampler intake and the mean cross-section concentration.

There, the mean/point concentration ratio was found to be 0.95 $\pm$ 0.05 and this was applied during the calculation of storm yield. At the other basins, a 1:1 relationship between point and mean concentration was assumed. Automatic tipping-bucket-type rain gauges were operated within the basins to record storm rainfalls.

Analysis methods

Determining sediment yields In practice, because of malfunctions and the limited number of sample bottles with the auto-samplers, not all storms could be sampled for suspended load. Accordingly, the strategy was to measure accurately the sediment yield from a sampling of storms and from these determine relationships between storm sediment yield and storm peak flow, with these relationships then being used to estimate the yields in unmeasured events over the complete flow record. Least-squares regression was used to parameterize these relationships. When calculating the sediment yield over the period of flow record, storms were distinguished on the basis of discrete quickflow events. The yields from very small events were ignored if the event quickflow was less than a threshold value. Separate threshold quickflows were identified for each basin.

A previous study by Hicks (1990), in which storm sediment yields at a number of small New Zealand basins were related to total runoff during the storm, quickflow runoff, peak discharge, Williams' (1975) runoff factor (i.e. the runoff * peak flow product), storm rainfall, rainfall energy, and Wischmeier & Smith's (1958) EI_{30} rain erosivity factor, showed that storm sediment yields correlated best overall simply with the storm peak discharge.

Magnitude-frequency relationships Analysis of storm event frequencies involved first compiling a peaks-over-threshold series of all peaks in the flow record. This series was then transformed to one of storm sediment yields by applying the storm sediment yield ratings described above. After assigning return periods to the elements of the storm yield series (using the Gringorten formula), an Extreme Value model (type 2) was fitted to the magnitude-frequency distribution. The goodness-of-fit was tested using the method of Hosking *et al.* (1985). Working with the EV model over a recurrence interval band from 0.1 to 20 years, the 20-year average annual yield transported by events in 0.1

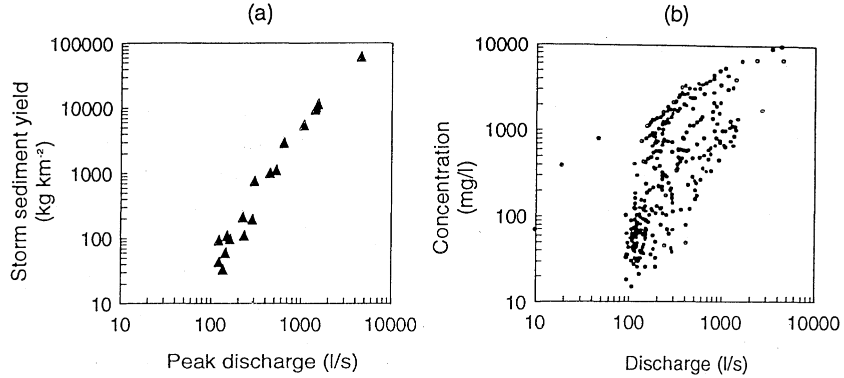

Fig. 1 Relationships between (a) storm sediment yield and peak flow and (b) instantaneous sediment concentration and water discharge for Alexandra site.

year increments of return period was determined by multiplying the probability-of-occurrence of events in that increment by the storm yield corresponding to the mid-point of the return period increment. Summing the yields over all increments provided an estimate of the 20-year average annual sediment yield.

The 20-year time base used in this study was considered to be an acceptably long period to represent the "long-term" yet did not require excessive extrapolation of the magnitude frequency relationship. Any arbitrary time base could be used with the approach.

RESULTS AND DISCUSSION

Storm yield *vs.* peak flow

The storm sediment yield *vs.* peak discharge "ratings" were "crisp", with high regression coefficients for the logarithmically transformed data (Table 1). At all four basins, the statistics of the storm yield ratings were superior to those for instantaneous sediment concentration and water discharge ratings. A typical storm sediment yield rating and instantaneous concentration rating are compared in Fig. 1. It appeared that while the instantaneous concentration could vary by up to a factor of one hundred for a given discharge at most basins, due to apparently random supplies of sediment to the stream, this "noise" tended to be averaged-out over the storm event.

Magnitude-frequency characteristics

The storm sediment yield magnitude-frequency relationships varied among the study basins (Fig. 2), with the largest variations appearing to be related to land use. The overall position of the magnitude-frequency relationships on Fig. 2 is indicative of the relative sediment yields from the basins, while the steepness of the lines indicates the relative yields between frequent and rare events.

The relationship for the urbanizing Alexandra basin (28% bare ground, 18% scrub and trees, 52% pasture, and 2% urban at the time of the study) shows that, compared to the other basins, it yields more sediment from storms over all return periods. Moreover, its steepness shows that the sediment yield increases exponentially as the storm magnitude increases, with extremely high yields predicted for rare events. In

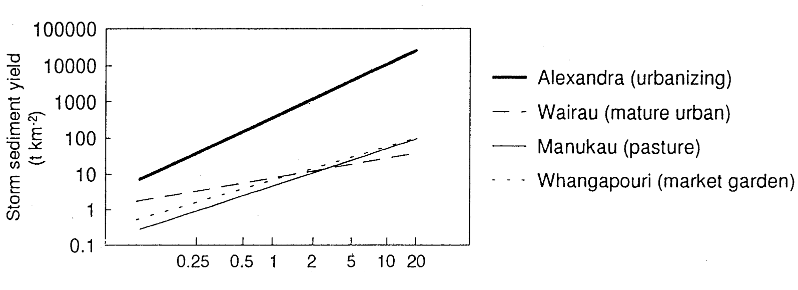

Fig. 2 Magnitude-frequency relationships for storm sediment yields.

comparison, the relationship for the "mature" totally urban Wairau basin is relatively flat, indicating that not a great deal more sediment is yielded from large, rare runoff events than is yielded by events that occur several times per year. This behaviour can be related to the ground cover. The large degree of paving in the urban basin limits sediment sources, and the sediment supply is probably exhausted early during the larger storms. Conversely, the supply of sediment from exposed soil slopes in the urbanizing basin is relatively unrestricted, with gullying and sheet erosion processes expected to intensify during larger events.

The "crossover" of the relationships for the urban Wairau basin and the pasture basin at Manukau shows that the urban basin yields more sediment during events occurring more frequently than 2-yearly, but the pasture basin yields more from less frequent events. Again, this is consistent with a sediment-source/erosion-process effect, with slope erosion only becoming relatively more important in the pasture basin during bigger, rarer events, while sediment supplies in the urban basin appear to be limited for all but the most frequent events.

The market-gardening Whangapouri basin responds in a similar fashion to the pasture basin. The relatively low yields from the market-gardening basin were surprising in light of the expected high erosion rates in the tilled fields, and point to a very low sediment delivery ratio.

Figure 3 shows the cumulative proportions of the 20-year average sediment yields carried by events with return periods less than the plotted value for the four basins. It is derived from the relationships in Fig. 2 weighted by the cumulative probability of occurrence of events in any one year. It shows that in the urbanizing Alexandra basin, the 20-year average sediment yield is carried relatively equally by events of short and long return period – for example, the 20-year event does a similar amount of work as does the annual event. This contrasts with the other three basins, where the most effective events at exporting sediment in the long term are those that occur several times per year. In the mature urban Wairau basin, it is the weekly-monthly events that carry the most sediment in the long term.

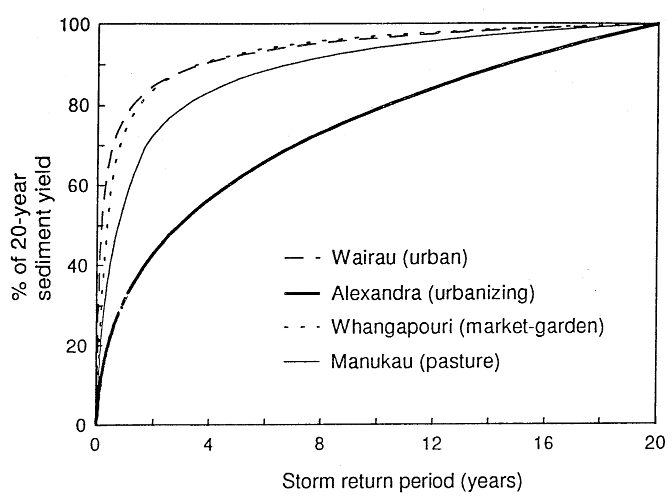

Fig. 3 Cumulative proportions of 20-year average sediment yield carried by storms of given return period.

A useful index of the relative geomorphic importance of shorter and longer return period events was found to be the return period at which events of that recurrence interval and less carried 50% of the long-term (i.e. 20-year) yield. The values of this "T_{50}" index for the four basins are compared in Table 1. A T_{50} of 0.2 years (2-3 months) for the mature urban basin clearly indicates the predominance of the frequent events, while a T_{50} of 3.0 years for the urbanizing basin points to the much greater importance of the rarer events. For both the rural basins, the sub-annual and super-annual events are of more equal importance. Again, as discussed above, these results appear to relate to the influence of land use on erosion processes and sediment availability.

Long-term average yield estimates

The "long-term average" basin sediment yields estimated by both the "storm yield rating" approach and by using the storm yield magnitude-frequency approach are compared in Table 1. The agreement between the two approaches varies. For example, the 20-year time-base figure for Alexandra basin (2370 t km^{-2} $year^{-1}$) is more than a factor of two higher than the yield estimated simply by using the storm yield rating over the one year of record (960 t km^{-2} $year^{-1}$). While partly due to the uncertainties in modelling the storm yield ratings and the magnitude-frequency relationships, the differences in the results from the two methods also highlight the uncertainty that can occur when the "long-term" yield of a basin is based on a record for only one or two years.

For basins with a "steep" magnitude-frequency relationship, such as Alexandra, the actual yield during any short (one or two year) period will be very dependent on what events occur then. Even for less responsive basins, the random occurrence of storms can lead to considerable inter-annual variability in sediment yields. An idea of how variable the sediment yield can be from year to year in the Auckland region is indicated in Fig. 4, which shows annual yields and also 3- and 5-year running means over the 16 years of record at the pasture basin at Manukau. The annual variability ranges over a factor of 10, while even the 5-year mean varies by a factor of two.

These figures indicate that considerable caution should be used when comparing estimates of mean annual sediment yield among basins where the yields are based only on short non-concurrent periods of record.

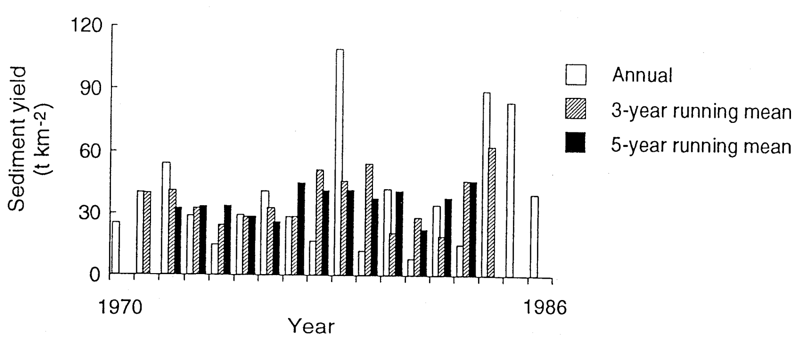

Fig. 4 Annual sediment yields at Manukau site, plus 3- and 5-year running means.

Generally, if it can be assumed that basin land use remains stable, the yield determined with the magnitude-frequency approach provides a fairer means of comparing yields among basins with flow records of varying length, since the estimate is based on a standard time base for all basins (i.e. 20-years for this study) and incorporates the contributions from events of return period longer than the record period. For cases where land use is changing, such as with the urbanizing basin, the yield determined by the magnitude-frequency approach is only a potential yield keyed to the condition of the basin during the period of record. In reality, as a basin is urbanized, its storm yield magnitude-frequency response will change, and so its actual long-term average yield will be less than if it had been left in its disturbed state.

Implications for basin sediment management

A clear conclusion from this frequency analysis is that the long-term average sediment yields from the basins in established land use are not excessively influenced by extreme events. Conversely, the yield from a basin whose soils have been temporarily exposed for urban development and are easily eroded will depend very much on the magnitude of the largest event that occurs before the ground is covered again. This contrast suggests different approaches for in-basin sediment management. Thus for basins with stable land use, particularly the urban ones, the best return would likely be achieved by targeting the very frequent sub-yearly storms. For urbanizing basins, the rare events should be targeted when designing sediment control structures and basin development should be scheduled to minimise the probability of an extreme event occurring while the basin remains vulnerable to erosion. Thus development work should be done quickly, and areas with exposed soil should not be left for extended periods. Possibly also, ground clearing could be restricted to certain seasons if a seasonal affinity for extreme events could be shown.

CONCLUSIONS

Conclusions from the study are:

(a) The study basins showed good relationships between storm sediment yield and storm peak flow.

(b) The urbanizing basin yields much more sediment with larger rarer storm events than do the basins under stable land use. The mature urban basin yields little more sediment as storm events get larger. These different sediment yield responses to different return period events probably relate to differences in sediment supplies and erosion processes among the basins. In particular, while sediment supplies probably become exhausted during large storms in the mature urban basin, sediment supplies appear to increase dramatically during larger events in the urbanizing basin due to intensifying gully and sheet erosion.

(c) In the urbanizing basin, the bulk of the long-term average sediment yield is carried by events with longer than annual return periods. For both the pasture and market-gardening basins, the sub-annual and super-annual events are of approximately equal importance. In the mature urban basin, it is the weekly-monthly events that carry the most sediment in the long term.

(d) There can be considerable uncertainty in estimates of basin sediment yield when the yield is averaged over only a few years of record. Estimating the average annual yield over a standard time base, such as 20 years, using the storm-yield magnitude-frequency relationship provides a fairer means of comparing sediment yields among basins with stable land use.
(e) For controlling sediment yields from basins with stable land use, the greatest benefit would probably be derived from targeting the relatively frequent, small events. In urbanizing basins, the largest events should to be targeted and the ground surface should be uncovered for as short a time as possible in order to minimise the probability of large events occurring and causing catastrophic erosion.

Acknowledgements Approval to use data collected for the Auckland Regional Council is gratefully acknowledged. Data collection at the Whangapouri site was jointly funded by the Auckland and Waikato Regional Councils and by the Foundation for Research Science and Technology under Contract no. CO9204.

REFERENCES

Hicks, D. M. (1990) Suspended sediment yields from pasture and exotic forest basins. In: *Proc. 1990 N.Z. Hydrol. Soc. Symp.* (Taupo, November 1990).

Hosking, J. R. M., Wallis, J. R. & Wood, E. F. (1985) Estimation of the General Extreme value by the method of probability weighted moments. *Technometrics* **27**, 251-261.

Williams, J. R. (1975) Sediment yield prediction with Universal Equation using Runoff Energy Factor. In: *Present and Prospective Technology for Predicting Sediment Yields and Sources*, 244-252. US Dept of Agric., Agricultural Research Service Publ. no. ARS-S-40.

Wischmeier, W. H. & Smith, D. D. (1958) Rainfall energy and its relationship to soil loss. *Trans. AGU* **39**, 285-291.