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Specific sediment yield and drainage basin scale

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Abstract Investigations of specific sediment yield have provided important insights into the effects of climate, relief, soil type, vegetation, and land use on sediment fluxes and continental denudation. Considerations of spatial scale play an important role in explanations of specific sediment yield. The following points should be taken into account in an analysis of the relationship between spatial scale and specific sediment yield. First, correlations of specific sediment yield with drainage area may be spurious because they involve correlating a fraction with its denominator. Spurious correlations can be avoided by correlating sediment yield with drainage area and evaluating the exponent of the power function describing the relationship. Second, yield and specific yield of suspended sediment are controlled by supply conditions rather than by transport capacity. As a result, the relationship between sediment yield and basin scale is complex because, unlike transport capacity, supply conditions may not change in a straightforward manner with basin scale. Third, lack of overlap in the periods of record for stations may distort the relationship between sediment yield and basin scale. Care should be taken to ensure that observed changes in sediment yield with spatial scale are not artefacts resulting from a comparison of data for different periods with different precipitation and runoff characteristics. Fourth, sediment sources in a basin may be decoupled and sediment may be contributed by only a fraction of the basin area. Consequently, expressing sediment yield per unit drainage area becomes increasingly misleading and less meaningful as basin scale increases.

INTRODUCTION

Specific sediment yield is a measure of sediment export per unit area, for example in Mg km^{-2} $year^{-1}$. Specific sediment yield is given in the same units as, and has been related to, rates of soil loss from erosion studies, and investigations of specific sediment yield as affected by climate, relief, soil type, vegetation, and land use have led to important insights into the effects of these controlling factors on sediment fluxes and continental denudation (e.g. Walling & Webb, 1983). Because specific sediment yield is also affected by drainage area, considerations of scale play an important role in explanations of specific sediment yield. The objective of this paper is to review the relationship between basin scale and specific sediment yield, and to point out the various pitfalls which may adversely affect analysis results.

BASIN SCALE AND SPECIFIC SEDIMENT YIELD – PITFALLS

There are four basic problems which should be considered in an analysis of specific sediment yield and basin scale. The following sections will outline these problems, using published data from various sources.

Spurious correlations

The standard model of the variation of specific sediment yield with basin scale states that specific yield decreases with increasing drainage area as a result of gentler hillslope gradients, sediment storage within the basin, and a decreasing percentage of basin area contributing sediment to the stream. Figures showing this inverse relationship have been published in a number of textbooks and papers (e.g. Chorley *et al.*, 1984; Ritter *et al.*, 1995). Waythomas & Williams (1988) pointed out that because specific sediment yield (Mg km^{-2} $year^{-1}$) is calculated as sediment yield (Mg $year^{-1}$) divided by drainage area (km^2), correlations between specific sediment yield and drainage area are spurious since the two variables have a common term. In a rigorous analysis, Kenney (1982) showed that correlations of variables with common terms are not necessarily spurious, and provided tests to establish whether or not a correlation is spurious. Kenney (1982) advised, however, that to be absolutely safe, correlations of variables with common terms should be avoided.

In the relationship of specific sediment yield and drainage area the latter variable is a measure of basin scale. Various authors have explored the use of alternative measures of basin scale such as main stream length and total stream length. Waythomas & Williams (1988) proposed plotting annual sediment yield (Mg $year^{-1}$) on the ordinate against either distance downstream (km) or drainage area (km^2) on the abscissa to avoid spurious correlations. Both types of plot will provide insight into the effect of basin scale on sediment transfer. As an example, Fig. 1 presents data from Guyot *et al.* (1994) for

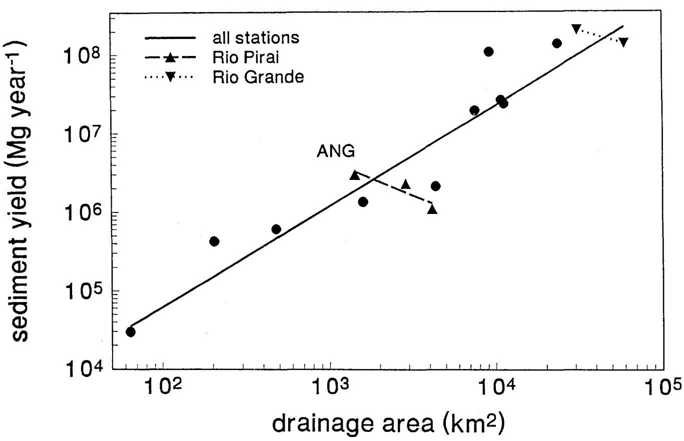

Fig. 1 Relationship between drainage area and annual sediment yield for the Rio Grande, Bolivia. Data from Guyot *et al.* (1994). Regression lines are for all stations (solid line) and for selected stations along short reaches (dotted and dashed lines).

the Rio Grande, a Bolivian Amazon drainage basin. The relationship between annual sediment yield and drainage area for all stations is described by the power function

$$Y = 168.3\,A^{1.28} \qquad (1)$$

($r^2 = 0.87$, $n = 15$) where Y is annual sediment yield (Mg year^{-1}) and A is drainage area (km^2). Because annual sediment yield and drainage area have no common terms, there is no possibility of spurious correlation. The effect of basin scale on specific sediment yield (Mg km^{-2} year^{-1}), however, is indicated by the exponent in equation (1). An exponent with a value less than 1 indicates that drainage area increases faster than sediment yield, resulting in a downstream decrease of specific sediment yield. Since in this example the exponent has a value of 1.28, i.e. is greater than 1, annual sediment yield increases faster than drainage area so that the specific sediment yield increases downstream.

Spatial scale transference

The Rio Grande data in Fig. 1 can also be used to illustrate a second point about the relationship between basin scale and specific sediment yield, namely that data from only a few stations may provide a misleading view of the relationship for the whole region. For the entire Rio Grande data set, the exponent in equation (1) indicates an increase in specific sediment yield with drainage area. For selected, smaller portions of the drainage basin, however, both sediment yield and specific sediment yield decrease downstream. For example, along selected reaches of the Rio Grande and one of its tributaries, the Rio Pirai, sediment yield decreases downstream, which is indicated in Fig. 1 by the downward slope of the two short regression lines. Guyot *et al.* (1994) attribute this decrease to sedimentation on the Amazon flood plain, just downstream of the Andean piedmont. For suspended sediment, yield and specific yield are controlled predominantly by supply conditions, with transport capacity fulfilling a secondary role. As a result, the relationship between sediment yield and basin scale is complex because, unlike transport capacity, supply conditions may not change in a straightforward manner with basin scale owing to changes both in the contributions of sediment sources and in the effectiveness of sediment sinks, in response to downstream changes in morphology and process rates. Hence, conclusions drawn at one specific scale cannot be extrapolated to other scales without testing.

Lack of overlap in the periods of record

Many organizations operate sampling stations for only a few years before moving the limited resources to another station. As a result, the periods of record for the various stations in a drainage basin only rarely overlap and a comparison of sediment yields between stations frequently involves comparing different periods with different precipitation and runoff characteristics. The downstream decrease in sediment yield along the Rio Pirai (Fig. 1) is partly explained by the effect of the catastrophic flood of March 1983. Data collected at one station (coded ANG in Fig. 1) resulted in a greatly increased sediment yield for that station (Guyot *et al.*, 1994). The data sets for the other stations, however, did not include the March 1983 catastrophic flood so that the sediment yield at station ANG is overestimated relative to the yields at the other stations.

Scale-related changes in sediment source contributions and erosional processes

Over the last 10 to 15 years, a clear appreciation of the limitations of concepts such as specific sediment yield and sediment delivery ratio has developed (e.g. Walling, 1983), to a large extent because it was increasingly appreciated that these concepts provide average values for drainage basins, but give no indication of the variability of process rates and sediment source contributions within the drainage basin. It is now clear from a number of studies that the processes and factors controlling sediment transfer can change dramatically between scales so that the relationship between spatial scale and specific sediment yield may not be straightforward.

As an example, Fig. 2 presents soil loss and sediment yield data at a range of spatial scales for the prairie region of southern Saskatchewan from studies of snowmelt erosion (Nicholaichuk & Read, 1978; Forster, 1995), ^{137}Cs distribution (Pennock & de Jong, 1987, 1990; Martz & de Jong, 1990, 1991; Sutherland & de Jong, 1990a,b; Sutherland *et al.*, 1991) and suspended sediment loads (Ashmore, 1990, 1992). The snowmelt data indicate that snowmelt runoff can make a significant contribution to farmland erosion. ^{137}Cs provides an estimate of soil loss over 20 to 30 years so that the ^{137}Cs data typically indicate the cumulative effect of snowmelt, rill and inter-rill erosion, wind erosion, and tillage. The contribution of wind erosion to soil loss was quantified by measuring ^{137}Cs depletion at level sites where erosion by surface runoff was negligible (Sutherland & de Jong, 1990a,b; Sutherland *et al.*, 1991). One of the main conclusions of the ^{137}Cs research on the Canadian prairies has been that most soil erosion results in redistribution rather than in net loss. This is a direct consequence of the geomorphology of the region which typically contains large areas of hummocky moraine with abundant closed depressions and poorly integrated drainage networks. As a result, even for small basins, only a small portion of the eroded soil is actually exported (Martz & de Jong, 1990, 1991). Excluding the snowmelt data, the relationship between sediment yield and drainage area in Fig. 2 is given by the power function

$$Y = 224.0\,A^{0.73} \qquad (2)$$

($n = 11$, $r^2 = 0.92$). Equation (2) can be interpreted as indicating that net soil loss and specific sediment yield vary inversely with spatial scale owing to the storage of mobilized sediment in the landscape. In this region, however, the increase in spatial scale is accompanied by a shift in dominant erosional process and sediment source. At the smallest scale of the farm field or portion thereof, the processes causing soil loss are rill and inter-rill erosion, wind erosion, and tillage. At the scale of the Assiniboine River basin, however, the dominant process is bank and bed erosion of the reworked glacial, glaciofluvial, and glaciolacustrine sediments deposited on the main valley floor by mass movements and gulley erosion. Consequently, sediment sources at small and large scales are decoupled (Phillips, 1995) in the Assiniboine River basin, which is confirmed by a marked change in suspended sediment characteristics with spatial scale (Crosby & De Boer, 1995). Because of sediment source decoupling and because sediment yield at large scales is predominantly controlled by in- and near-channel processes (i.e. is derived

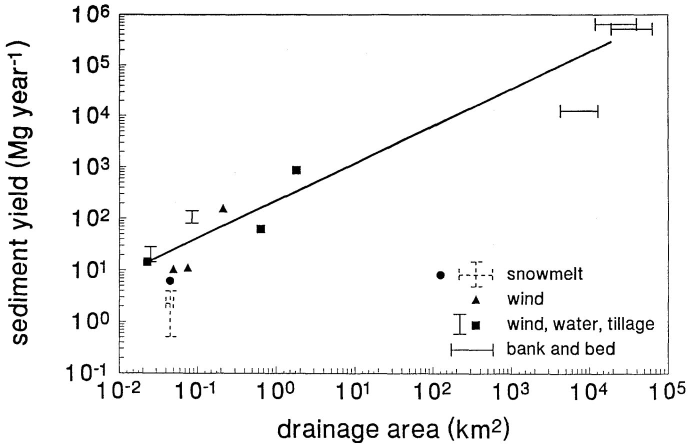

Fig. 2 Relationship between drainage area and annual sediment yield for the southeastern prairie region of Saskatchewan, Canada. Symbols and error bars indicate dominant erosional process. See text for references.

from only a fraction of the drainage area), expressing sediment yield per unit drainage area becomes less and less meaningful as scale increases.

CONCLUSIONS

Analysis of the effect of basin scale on sediment yield and specific sediment yield provides insight into the factors controlling the downstream transfer of sediment in the channel network. The following points, however, must be considered to make such an analysis meaningful:

- Spurious correlations, involving variables with common terms, should be avoided if at all possible. Thus, correlating specific sediment yield (Mg km^{-2} $year^{-1}$) with drainage area is unwise since both variables contain the term drainage area. It is worth noting that correlations of sediment yield and discharge may also be spurious since discharge is used to calculate sediment yield.
- For suspended sediment, yield and specific yield are controlled predominantly by supply conditions, with transport capacity fulfilling a secondary role. As a result, the relationship between sediment yield and basin scale is complex because, unlike transport capacity, supply conditions may not change in a straightforward manner with basin scale owing to changes in both the contributions of sediment sources and the effectiveness of sediment sinks, in response to downstream changes in morphology and process rates. Hence, sediment yield data for short reaches may provide a misleading picture of the larger scale patterns of sediment yield, and vice versa, owing to the effect of local sediment sources and sinks controlled by factors such as channel slope and valley morphology. Care should be taken in extrapolating results obtained at one specific spatial scale to other scales.
- Lack of overlap between the periods of record for the stations analysed may distort the relationship between sediment yield and basin scale. Care should be taken to

ensure that observed changes in sediment yield with spatial scale are not artefacts resulting from a comparison of data for different periods with different precipitation and runoff characteristics.

- Sediment sources in a basin may be decoupled (Phillips, 1995) so that the sediment yield measured at small spatial scales is not transferred down the drainage network. Furthermore, at large spatial scales, sediment may be contributed by riparian sources accounting for only a fraction of the drainage area. Consequently, expressing sediment yield per unit drainage area becomes increasingly misleading and less meaningful as basin scale increases.

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