

Accuracy of estimating basin denudation processes from suspended sediment measurements

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ABSTRACT It is obvious that estimations of denudation rate have a systematic (negative) error resulting from not having taken into account (a) bed and dissolved load, and (b) that part of the denudation product which does not reach rivers but remains in storage in the landscape. These estimations have random errors which depend on the method used to measure suspended load, the method of calculating sediment concentration, the method of calculating sediment yield etc. By establishing the elementary random errors by statistical analysis it is possible to calculate the accuracy of denudation indices. An assessment is presented using data from Polish rivers, both for simple basins (source to measuring point) and incremental basins (between measuring points); errors are 4 times larger for the latter calculation.

Exactitude de l'estimation des résultats des processus qui suivent la mise à nu du sol des bassins, à partir des mesures de transports solides en suspension

RESUME Il est évident que l'estimation des résultats de la déforestation présente une erreur systématique (négative) du fait que n'ont pas été pris en compte (a) le charriage de fond et les matières dissoutes et (b) la partie des produits de l'érosion qui n'atteignent pas la rivière mais s'accumulent sur les versants. Ces estimations présentent en outre des erreurs aléatoires qui dépendent de la méthode de mesure de la charge en suspension, de la méthode de calcul de la concentration en sédiments, et de la méthode de calcul du transport total de sédiments. En déterminant les erreurs élémentaires aléatoires par l'analyse statistique il est possible de déterminer l'exactitude des indices de dénudation. Une évaluation est présentée pour des données concernant des rivières polonaises, à la fois pour des bassins élémentaires (origine du point de mesure) et pour des bassins plus grands (en interpolant entre les points de mesure); les erreurs sont 4 fois plus fortes pour ce dernier genre de calcul.

INTRODUCTION

If one agrees with the opinion that the sediment yield of rivers is the reflection of the operation of denudation processes in

drainage basins, then the results of measuring river sediments can be used for estimating the rate of operation of sedimentary processes. Such an opinion has been expressed by numerous investigators: Fournier, Tixeront, Cormary, Quesnel, Lopatin, Poliakov, Guy, Piest, Gazzalo, Bassi, Diaconu, Reniger, Dębski. Denudation estimates may be made, based on measurements of suspended sediment only. Most products of denudation reach the river in such a fine form that they are transported in suspension. It should be noted, however, that denudation estimates made on the basis of suspended sediments have a systematic error resulting from the fact that traction load and dissolved sediments are not considered.

In this paper I would like, however, to deal with random errors, which occur while taking measurements and in data processing. The sources of error are: measuring instruments, methods of observation, methods of determining sediment concentration and operator variability. Knowing the magnitude of these random errors it is possible to estimate, by statistical analysis, the accuracy of denudation estimates determined on the basis of suspended sediment concentrations.

MEASUREMENT AND CALCULATION OF SUSPENDED SEDIMENT YIELD

The major method of suspended sediment measurement applied in Poland consists of multi-point measurements in conjunction with single-point ones. Multi-point measurements are taken across the whole river cross section and as a result of such measurements one obtains the probable suspended sediment concentrations (P) in mg l^{-1} . Single-point measurements consist of taking a single 2 l sample at a definite spot in the cross section. In this case an estimate of suspended sediment concentrations (P') is obtained. The relation between these two values can be expressed:

$$P = k P' \quad (1)$$

For estimates of annual sediment yield, first the daily values of suspended sediment transport are calculated from the formula

$$U_i' = 10^{-3} P_i' Q_i \quad (2)$$

where U_i' is daily sediment transport (kg s^{-1}); P_i' , suspended sediment concentration (mg l^{-1}); and Q_i , discharge ($\text{m}^3 \text{s}^{-1}$).

Mean monthly suspended sediment transport (U') is calculated as the arithmetic mean of the daily values, but monthly sediment yield is derived from the relationship:

$$r' = 10^{-3} 86400 n U' \quad (3)$$

where r' is monthly suspended yield (t); 86400 is the number of seconds in a day; and n , the number of days in the month. By summing monthly sediment yield (r') we obtain the annual sediment yield (R').

In the last expression the variables with primes refer to sediment transport calculations made on the basis of single-point measurements. To get the effective values, i.e. those which concern the whole river cross section, it is necessary to

multiply each such variable by the proportionality coefficient k used in expression (1). The value for coefficient k is determined by the method of least squares. Then an effective sediment yield is:

$$R = k R' \quad (4)$$

CALCULATION OF DENUDATION INDICES

Denudation indices may be calculated from a simple relationship:

$$d_o = \bar{R}/A \quad (5)$$

where d_o is the index of denudation (in the calculation of this index, only those denudation products are included which are irretrievably lost from the basin) ($t \text{ km}^{-2} \text{ year}^{-1}$); \bar{R} , annual mean from many years of sediment yield measurements (t), expressed per unit area of the drainage basin - A (km^2).

For the case when two or more observation posts are installed on a river, denudation indices may be defined for each basin section. For the simple (upper) basin (from the source to the first observation post) the denudation index is calculated from formula (3), but for increments of basin area (between two successive observation posts on the same stream) it may be found from a more complex expression:

$$d_o = (\bar{R}_i - \bar{R}_{i-1}) / (A_i - A_{i-1}) = \Delta \bar{R}_i / \Delta A_i \quad (5a)$$

where \bar{R}_i is annual mean sediment yield in the section of basin concerned; \bar{R}_{i-1} , sediment yield from the basin segment located upstream of the one considered; A_i and A_{i-1} , total basin area draining to the two successive observation posts.

Expressions (5) and (5a) are simple to use; there is some difficulty in the evaluation of the denudation index in cases where reservoirs occur on a stream, since the part of the sediment yield of the river trapped in the reservoir should also be taken into account. Annual mean sediment yield trapped in a reservoir may be evaluated by measurements of the rate of siltation, by balancing sediment yields at the inflow and outflow of the reservoir, or by using any of the well known empirical formulae. For the conditions in Poland formulae by Brune (1953) and Lopatin (1965) are recommended. An example of the evaluation of denudation indices for a basin including reservoirs may be found in the paper by Brański (1980).

THE ACCURACY OF DENUDATION INDICES

In the case of simple (upper) basins it may be assumed that the accuracy is equivalent to that of determining the sediment load at the basin outlet (it may be assumed that the basin area term is not loaded with error). When estimating accuracy one may use mean quadratic errors (s) and thus for the denudation index in upper basins it may be written:

$$s_{d_o}/d_o = s_R/\bar{R} \quad (6)$$

i.e. $S_{dO} = S_R$. Referring to expressions (3) and (4) it may be written:

$$S_R^2 = S_k^2 + S_U^2 \quad (7)$$

where S_{dO} is the relative probable quadratic error of the denudation index; S_R , the relative probable quadratic error of annual mean suspended sediment yield; S_k , the relative probable quadratic error of proportionality coefficient k ($S_k = s_k/k$); and S_U , the relative probable quadratic error of suspended sediment transport ($S_U = s_U/\bar{U}$). Values S_k and S_U are calculated by the following expressions:

$$S_k = \frac{1}{k} \left[\frac{\sum P^2 - k \sum (PP')}{(N-1) \sum (P')^2} \right]^{1/2} \quad (8)$$

$$S_U = \left[\frac{S_P^2 + S_Q^2 + 2r_{PQ} \cdot S_P S_Q}{n} \right]^{1/2} \left[\frac{1+r_U}{1-|(n-2)/n| r_U} \right]^{1/2} \quad (9)$$

where N is the number of multi-point measurements used for estimating k ; S_P , the relative mean (probable) quadratic error of measurement of suspended sediment concentration; S_Q , the relative probable quadratic error of daily discharge Q ; r_{PQ} , the correlation coefficient between daily values of P and Q ; r_U , the correlation coefficient between daily values of U ; n , the number of days in the period for which mean discharge and suspended sediment yield were calculated.

S_Q is accorded a value of 0.10 (10%). Error S_P depends on the suspended sediment concentration and volume of sample taken (thus indirectly it depends on the time of sample and on the type of silt sampler used). Values of such errors were determined for measuring conditions in Poland, i.e. for 2 l samples taken using the bottle silt sampler PIHM-1. Values of the errors are as follows (Brański, 1967):

P ($g\ m^{-3}$)	5	10	20	50	100
S_P	0.477	0.265	0.200	0.194	0.178

Values of correlation coefficients r_{PQ} and r_U were defined and given in the paper by Brański (1975). In practice $r_{PQ} = 0.46$ and $r_U = 0.58$ may be assumed. In fact errors S_R scarcely differ from errors S_k , because in general values of S_U are small compared with S_k and for long records of R (15 years and more) it may be assumed that $S_R = S_k$, provided that values of S_k are large enough, e.g. greater than 0.03.

For the case of incremental basin areas, the denudation index is calculated from expression (5a) and then we have:

$$s_{dO}/d_O = s_{\Delta R}/\bar{\Delta R} \quad (10)$$

i.e. $S_{dO} = S_R$. Since $\bar{\Delta R} = \bar{R}_i - \bar{R}_{i-1}$ if we assume that value \bar{R}_i and \bar{R}_{i-1} are defined by independent measurements and have independent variations, the relationship with variation $\bar{\Delta R}$ may be written as the variation difference in the following form:

$$s_{\Delta R}^2 = s_{R_i}^2 + s_{R_{i-1}}^2 \quad (11)$$

assuming further

$$\bar{R}_{i-1}/\bar{R}_i = m \quad \bar{R}_{i-1} = m \bar{R}_i \quad (12)$$

and

$$s_{R_i} = S_{R_i} \bar{R}_i \quad (13)$$

$$s_{R_{i-1}} = S_{R_{i-1}} \bar{R}_{i-1} \quad (13a)$$

and after substituting these expressions in formula (11) and transforming it we obtain:

$$S_{\Delta R} = \alpha S_{R_i} \quad (14)$$

where

$$\alpha = (1-m)^{-1} \left[m^2 \left(\frac{S_{R_{i-1}}}{S_{R_i}} \right)^2 + 1 \right]^{\frac{1}{2}} \quad (15)$$

In the above expression probable quadratic errors were denoted by s , relative values of these errors were denoted S ; suffix i refers to the measurements taken downstream and $(i-1)$ upstream of the incremental basin.

From analysis of expressions (12) and (15) two significant conclusions result: (a) errors of denudation indices calculated for incremental basins are very variable, with values from near zero to very great values, (b) the errors are greater when small increments of basin area are used and in fact this is the case where $\bar{\Delta R}$ is smaller for the considered basin.

In practice errors $S_{d_o} = S_{\Delta R}$ rarely reach very high values. This may be found from denudation estimates made for Poland during the period 1956-1970 (15 years). For incremental basins (25 such basins were selected) values of errors S_{d_o} are within the interval 0.07-0.55 (7-55%), and only in two cases did they reach very large values i.e. c. 660% and 4800%. In both cases m nearly equals one (0.978 and 0.997), and the growth of sediment yield in these incremental basins is barely 2%. For simple basins (48 such basins were selected for Poland) values of errors S_{d_o} (for the 15 year period) are between 0.02 and 0.14 (2-14%); so they are 4 times smaller, on average, than errors for incremental basins.

The method of assessing errors in denudation indices involves a number of simplifications (e.g. it was assumed that during the whole period at one observation post constant suspended sediment concentrations were recorded (equal to the mean in this period). The following assumptions were also made: (a) all measurements of suspended sediment concentration were taken with the bottle silt sampler PIHM-1, (b) over the whole period, uniform measuring methods were used, with operating rules scrupulously observed, (c) the missing values of daily sediment concentrations determined by interpolation have the same error as the measured ones and (d) over the whole period in one profile, one coefficient k was operative.

CONCLUDING REMARKS

(a) The accuracy of estimating the operating rate of denudation processes based on measurements of sediment transport is sufficiently high in simple (upper) basins, if the results from a

period of 5 years or more are available.

(b) The accuracy of denudation estimates in incremental basins is on average 4 times lower than in simple basins.

(c) An improvement in estimation accuracy may be gained by extending the observation period, increasing measurement accuracy and improvements in the calculation of sediment yield.

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