Sediment Budgets (Proceedings of the Porto Alegre Symposium, December 1988). IAHS Publ. no. 174, 1988.

Uncertainties in defining the suspended sediment budget for large drainage basins

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Abstract Toxic material tranported in association with suspended sediment has increased interest in the sediment budgets of large rivers and has emphasized concerns about uncertainties in these accounting methods. A sediment budget within a reach can be defined as a closed system by considering the measured sediment transport from upstream, from intervening tributaries, and from the outlet of the reach. The residual in this calculation is sediment that is eroded or deposited in the reach, although natural variability may cause this residual to be masked by error. On the Missouri River main stem, the standard errors of mean annual suspended-sediment discharge increase in a downstream direction. Tributaries have greater standard errors for the mean annual values than main stem stations. In the reach between Omaha, Nebraska, and Nebraska City, Nebraska, the variance in the residual term of the sediment budget accounts for 13% of the mean sediment discharge at Nebraska City.

Les incertitudes constatées lors de la détermination du budget de sédiments en suspension pour les grands bassins de drainage

Résumé Les matériaux toxiques transportés par les sédiments en suspension ont augmenté l'intérêt que l'on porte aux budgets de sédiments des grands fleuves et ils ont accentué aussi les problèmes relatifs aux incertitudes liées aux méthodes de décomtes. Un budget de sédimente dans un bief d'une rivière peut être défini comme un système fermé en considérant le transport mesuré des sédiments en amont, des tributaires dans le bief, et à l'extremité aval du bief. Le résidu dans ce calcul est le sédiment qui est érodé ou déposé dans le bief, bien qu'une variation naturelle puisse masquer ce résidu. Pour la branche principale du Missouri l'erreur standard sur le transport de sédiments en suspension, moyenne annuelle croît vers l'aval. Les tributaires ont des erreurs standards, pour la moyenne annuelle, plus grandes que celles des stations de la branche principale. Dans le bief entre Omaha, Nebraska et Nebraska City, Nebraska, la variance du terme résiduel du budget de sédiment explique 13% de déversement du transport de sédiment à Nebraska City.

NOTATION

C_v	=	coefficient of variation
E	=	standard error of the mean suspended-sediment discharge (%)
n	=	number of years of record
N	=	number of tributaries within a given reach
QS_I	=	a series of annual suspended-sediment loads at the input of a reach (t)
QS_O	=	a series of annual suspended-sediment loads for the outlet of a reach (t)
ΔQS_R	=	the change in storage (aggradation or degradation) within a reach (t)
QS_T	=	a series of annual suspended sediment loads for a tributary in a reach (t)
r	=	correlation coefficient
s	=	standard deviation

INTRODUCTION

The transport of radioactive materials, pesticides, metals, and nutrients in association with fluvial sediment has empasized a need for suspended-sediment data and the application of these data to sediment budgets. Concern for small quantities of material sorbed to the suspended sediment leads to questions about the uncertainties associated with the sediment data. Often the construction of a sediment budget leaves nagging doubts about the uncertainties contained in the values used.

The uncertainties in suspended-sediment data result from natural variability, sampling error, and inaccurate extrapolation or interpolation of the sampled data in time. Errors from sampling and extending data in time are difficult to evaluate. However, if it is assumed that sampling procedures are adequate to define the sediment discharge in the channel cross section, the largest component of error that remains is from procedures used to interpolate sediment data in time (Walling & Webb, 1981). This study uses data from daily sediment stations in order to reduce this temporal error or at least to make it consistent among stations.

This paper examines some uncertainties in the suspended-sediment budget that result primarily from natural variability. It is recognized that error is incorporated in the data used to an unkown extent. Sediment data for the Missouri River and its principal tributaries from Yankton, South Dakota, downstream from Gavin's Point Dam, to Hermann, Missouri, near the confluence with the Mississippi River are used as an example (Fig. 1). Within this reach suspended-sediment load increases in the Missouri River from about 1.1 million t year^{-1} (1957–1968) to about 80 million t year^{-1} (1957–1981) primarily from the addition of material from intervening tributaries.

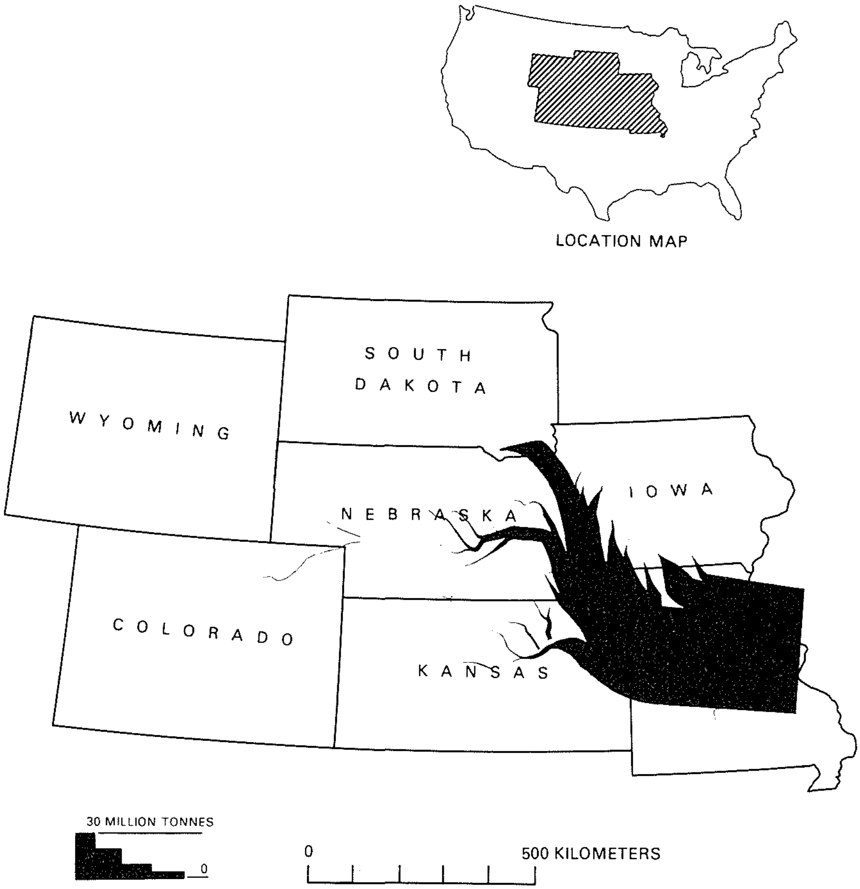

Fig. 1 Average annual suspended-sediment discharge of the lower Missouri River basin (circa 1980). Discharge less than 0.5 million tonnes per year not shown.

DATA AVAILABLE

The daily suspended-sediment stations for the main stem Missouri River and stations near the mouths of the major tributaries are listed in Table 1. In some cases the tributary stations may be located some distance from the outlet. For example, the Grand River has a drainage area greater than 18 000 km^2 (US Geological Survey, 1971) but the three tributary stations have a combined total drainage area of 5011 km^2. Similarly, the Gasconde River, which has a drainage area greater than 8300 km^2, has two gauged upstream tributaries that drain 1564 km^2.

These daily stations on the tributaries have variable lengths of record. The data collection varies within the general period 1935 to the present (1988). Few of these tributaries have stations with concurrent records.

The main-stem Missouri River stations have concurrent records, and several of these stations have records beginning in the 1940s. A series of

Table 1 Daily suspended-sediment stations on the Missouri River main stem and near the mouths of tributaries for the reach between Yankton, South Dakota and Hermann, Missouri (adapted from Keown et al., 1981)

Index Number	Stream	Station	Period of record	Drainage area (km^2)
1.	Missouri R.	Yankton, S. Dak.	1940-1968	724 009
	(a) James R.	Yankton, S. Dak.	1982-1983	53 354
	(b) Big Sioux R.	Akron, Iowa	1941-1951	23 388
2.	Missouri R.	Sioux City, Iowa	1955-1976	814 814
	(a) Floyd R.	James, Iowa	1969-1973	2 284
	(b) Monoma-Harrison Ditch	Turin, Iowa	1958-1969	2 331
	(c) Little Sioux R.	Turin, Iowa	1959-1969	9 132
	(d) Soldier R.	Pisgah, Iowa	1940-1951	1 054
	(e) Boyer R.	Logan, Iowa	1940-1951	2 255
3.	Missouri R.	Omaha, Ne.	1940-1976	836 052
	(a) Platte R.	Louisville, Ne.	1957-1981	229 992
4.	Missouri R.	Nebraska City, Ne.	1958-1976	1 073 296
	(a) Nishnabotna R.	Hamburg, Iowa	1940-1951	7 268
	(b) Tarkio R.	Blanchard, Iowa	1935-1939	518
	(c) Big Nemaha R.	Falls City, Ne.	1950-1967	3 470
	(d) Nodaway R.	Burlington Junction, Mo.	1970-1976	3 212
5.	Missouri R.	St. Joseph, Mo.	1949-1981	1 098 937
	(a) Platte R.	Sharps Station, Mo.	1979-1987*	6 164
	(b) Kansas R.	Desota, Kans.	1949-1985	155 213
6.	Missouri R.	Kansas City, Mo.	1949-1981	1 267 028
	(a) Grand R.			
	(1) Thompson R.	Mount Moriah, Mo.	1963-1970	2 308
	(2) Weldon R.	Mill Grove, Mo.	1964-1969	1 279
	(3) Locust Cr.	Linneus, Mo.	1964-1971	1 424
	(b) Chariton R.	Rathbun Lake, Iowa	1970-1974	1 422
	(c) L. Chariton	Huntsville, Mo.	1963-1970	570
	(d) Blackwater R.	Blue Lick, Mo.	1971-1974	2 900
	(e) Moreau R.	Jefferson City, Mo.	1970-1972	1 453
	(f) Osage R.	Osceola, Mo.	1972-1976	21 290
	(g) Gasconde R.			
	(1) Osage Fork	Dryknob, Mo.	1971-1975	1 046
	(2) L. Piney Cr.	Newburg, Mo.	1971-1974	518
7.	Missouri R.	Hermann, Mo.	1949-1981	1 368 038

**Periodic record only.*

upstream dams give a distinct nonstationarity to the total period of record. Fort Peck Dam was closed in 1937, and the most downstream dam, Gavin's Point, was closed in 1955. These dams and four intervening structures introduce a trend to the suspended-sediment data. Examination of the annual sediment loads of the Missouri River at Omaha, Nebraska, indicates that to avoid problems with these anthropogenic effects, the data must be limited to 1957 and after (Mellema, 1986).

SEDIMENT BUDGET

By using the data available from the stations listed in Table 1, Keown *et al.* (1981) computed mean annual sediment loads for the main stem Missouri River stations and for the contributions from the major tributaries. Additional suspended-sediment data from sites upstream in the tributaries can be used to provide a sediment budget of the average annual sediment discharge of the lower Missouri River basin (Fig. 1). This sediment budget shows the average annual sediment discharge by width of line. The diagram probably defines the average loads within the uncertainties in the data.

The diagram provides useful information about the sources of suspended sediment transported to the reach. First, the increases in sediment discharge to the main stem are derived primarily from the tributaries rather than from the main stem upstream. The biggest contributors of sediment among the tributaries drain loess deposits in Iowa and Missouri.

Sediment loads are derived primarily from the more humid parts of the basin. Those streams that drain the western part of the basin contribute little sediment to the Missouri River main stem. This probably results from the increases in streamflow that are available in the more humid regions of the basin and from the number of reservoirs constructed upstream in the two principal tributaries that drain the more arid sections of the basin, the Platte and Kansas Rivers.

The sediment budget also shows reaches along the Missouri River main stem, such as near the downstream end of the reach, as a decreasing width of line. That is, the sum of average annual sediment loads from upstream tributaries and the main stem is larger than the load for the main stem station downstream. This decrease suggests aggradation within these reaches.

If attention is given to the main stem Missouri River and those data at or near the mouths of the tributaries, a suspended-sediment budget for a reach of the main stem could be written:

$$\bar{Q}S_O = \bar{Q}S_I + \Sigma_{i=1}^{N} \bar{Q}S_{T_i} + \Delta\bar{Q}S_R \qquad (1)$$

Each term in equation (1) is represented by the mean annual suspended-sediment load. The aggradation shown as a decreasing width of line in Fig. 1 is reflected in equation (1) by a minus value for ΔQS_R Because equation (1) represents a closed system and the terms of the equation are represented by the mean, the results are dependent on the natural variability that is part of each term.

VARIABILITY OF DATA

In the sediment budget above, the average sediment loads are derived from the annual series of suspended-sediment loads. If it is assumed that each year of the annual series is independent, the standard error of the mean (E), in %, is defined (Hardison, 1969) as:

$$E = 100\ C_v / \sqrt{n} \tag{2}$$

The standard error of the mean is a relative index of variability and uses the coefficient of variation (C_v), which is an index of the variability of the time series, and the length of record (n). These are the two characteristics on which the accuracy of the estimate of the mean value of sediment load depend (Adamowski *et al.*, 1986).

The coefficient of variation (C_v) was computed for the data from each of the seven stations on the main stem of the Missouri River (Table 1) for the period being investigated (1957 to the end of record). Then the standard error of the mean was computed with n varying from 1 to the number of years of record (Day & Spitzer, 1985). The resultant curve defines the decrease in the standard error of the mean sediment discharge with increasing number of years of record (Fig. 2). The number of years of record range from 12 to 25.

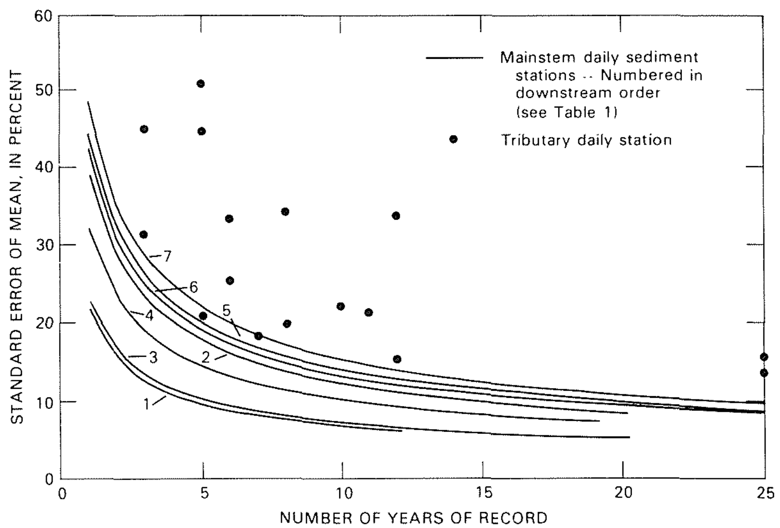

Fig. 2 Relation between standard error of the mean and number of years of record for Missouri River main stem stations and for major tributaries.

With increasing number of years of record, the standard error of the mean decreases to between 5.2 and 9.7% when all n years of record are used. It seems that additional data collection would not substantially reduce this standard error.

With a few exceptions, the curves shown in Fig. 2 for the seven stations on the main stem are arranged in downstream order. The most upstream station (Yankton, South Dakota; curve 1) has the smallest standard error, and the most downstream station (Hermann, Missouri; curve 7) has the largest standard error, for a given number of years of record. Thus, even if all the stations had equivalent lengths of record, the standard error increases generally in a downstream direction. This is not surprising, because the increase in sediment downstream results from contributions of the tributaries. Each additional tributary can add to the variability (standard error) by changes in the quantity and timing of the sediment contributed. Thus, both sediment discharge and relative variability increase downstream along the main stem of the Missouri River. Included in Fig. 2 are the tributaries listed in Table 1 that have records within the time frame of the main-stem stations (1957 through 1981). The tributary stations are shown for their individual periods of record. Standard errors for all the tributaries except one plot above all the lines drawn for the main-stem stations and indicate that no matter what period of record is available, the tributaries would have a standard error of the mean that is larger than that of the main-stem stations. Nordin & Meade (1981) suggest that to obtain the same relative accuracy, longer records are required for small rivers than for large rivers. This need results from the greater variability identified in smaller rivers and because the effect of sediment discharge of extreme events in large rivers is not as great as in small rivers. Two tributaries have lengths of record (25 years) comparable to those of the main-stem stations. These stations are near the mouths of the Platte and Kansas Rivers, which are both large tributaries. However, in both cases, the standard error of the mean is larger than that for any of the main-stem stations.

The discussion above suggests that in evaluating each term in equation (1), the contribution from tributaries ($\Sigma_{i=1}^{N} QS_{T_i}$) has more relative variability associated with it than two terms associated with the main stem (QS_O and QS_I). This result probably is not unique to the Missouri River basin. Unfortunately, in the case of the Missouri River basin, the tributaries are the principal suppliers of the sediment to the total reach studied here (Fig. 1).

SEDIMENT BUDGET FOR A REACH

The terms in equation (1) can be rearranged and the residual variables (or those not measured — in this instance the change in storage within the reach, ΔQS_R) placed on the left side of the equation:

$$\Delta QS_R = QS_O - QS_I - \Sigma_{i=1}^{N} QS_{T_i} \qquad (3)$$

Equation (3) represents a closed system and it should be possible to solve for the residual (ΔQS_R). The sign of this residual term will reflect aggradation (negative sign) or degradation (positive sign).

The uncertainty in each of the terms in equation (3) contains error from measurement and natural variability. Although these two components cannot be separated at present, their sum can be estimated by using the variance of each term. Because the terms in equation (3) are undoubtably correlated and because each term may have a different length of record, the variance estimate for the storage term ΔQS_R can be derived from:

$$\text{var}(\Delta QS_R) = \text{var}(QS_O) + \text{var}\ (QS_I) + \text{var}(\Sigma_{i=1}^{N} QS_{T_i})$$

$$- 2\ \text{cov}(QS_O, QS_I) - 2\ \text{cov}(QS_O, \Sigma_{i=1}^{N} QS_{T_i})$$

$$+ 2\ \text{cov}(QS_I, \Sigma_{i=1}^{N} QS_{T_i}) \quad (4)$$

where the covariance (cov) is calculated by:

$$\text{cov}(x_1,x_2) = r(x_1,x_2)\ \sqrt{\text{var}(x_1)}\ \sqrt{\text{var}(x_2)} \quad (5)$$

where x_1 and x_2 represent terms from equation (4) and r is the correlation coefficient.

The reach between Omaha and Nebraska City has data at the upstream and downstream ends (Table 1). There is only one major tributary in the intervening reach, the Platte River. In this example concurrent records are available from 1958 through 1976. Using the mean values for the concurrent period of record in equation (3), the mean value for ΔQS_R is +2.62 million t. The plus sign suggests that there is erosion of this amount within the reach or that there is contribution of sediment by unmeasured tributaries, and that it is transported past the downstream gauge.

The variance of ΔQS_R as calculated from equation (4) yields a standard deviation of 5.11 million t. This standard deviation of the residual term is about 13% of the downstream mean sediment discharge (QS_O). This standard deviation of the residual term occurs in a reach that has only one major tributary, and the sediment discharge is determined for 99% of the drainage area of the downstream gauge. The statistics are calculated using 19 years of concurrent data. Even with this sizeable amount of information there remains a substantial amount of variability.

With the natural variability, the question remains whether the mean value of +2.62 million t for ΔQS_R is significant. The 95% confidence interval of the mean value of ΔQS_R (assuming a student's t = 2) is shown for increasing number of years of record in Fig. 3. It is assumed that the variance is derived from the total 19 years of record. It is also assumed that ΔQS_R is normally distributed which seems reasonable (histogram in inset, Fig. 3). For the first 14 years of record, the mean value of ΔQS_R is not significantly different from zero.

An examination of Table 1 shows that even with the amounts of data available in this study section, there is not another reach in which the terms of equation (3) can be rigorously defined. In many cases the period of record is not concurrent and the derivation of the covariance would have to be done with data extrapolated in time, which introduces an unknown component of error. In some instances, the tributaries are defined by periodic record, and the extension of these data to annual totals presents another component of

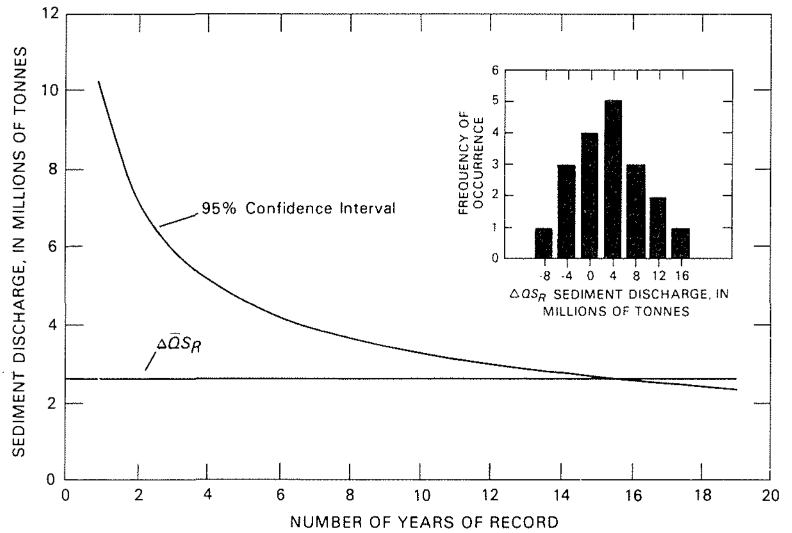

Fig. 3 The relation between the 95% confidence interval of the mean $\Delta \bar{Q}S_R$ and years of record for the reach of the Missouri River between Omaha, Nebraska, and Nebraska City, Nebraska. Inset is histogram of ΔQS_R for the reach.

error that is unknown. Finally, there are those reaches with major tributaries ungauged or gauged far upstream in which case the data at the gauge do not represent the sediment discharge of the river at the mouth.

Few rivers in the world have as much data as the Missouri River. This sequence of daily sediment stations provides a unique data base; however, even with this amount of data the natural variability provides substantial uncertainty in the terms of the sediment budget. In addition, errors generated from estimates that must be made from periodic record, insufficient concurrent record, or lack of data, at present cannot be incorporated into the assessment of uncertainty.

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