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A study of the total load transport by the Yellow River

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Abstract Analysis of data obtained from field measurements revealed considerable discrepancies in the amount of deposition computed by the range survey method and from the difference between the sediment load at the two end sections of a river reach. The results obtained from range surveys are consistent with actual river conditions and are relatively more reliable than those obtained from the load difference method. Differences between the two methods are mainly caused by errors in the measurement of sediment load related to the "unsampled load" which includes both the unsampled suspended load and bed load. In order to overcome this problem, studies have been undertaken to develop a method suitable for computing total sediment load in the Yellow River.

Une l'étude de la charge totale de sédiments transportée par le Fleuve Jaune

Résumé L'analyse des données obtenues par des mesures de terrain a mis en évidence des différences considérables dans l'importance des dépôts calculée par la méthode du "range survey" et par les différences entre les charges de sédiments aux deux extrémités d'un bief du fleuve. Les résultats obtenus par la méthode du "range survey" sont compatibles avec les conditions actuelles du fleuve et sont relativement plus sûrs que ceux qui résultent de la méthode des différences de charges. Les différences entre les résultats de ces deux méthodes résultent principalement d'erreurs dans la mesure de la charge en sédiment relatives à la partie de la charge échappant aux prélèvements qui comprend à la fois une partie de la charge en suspension et du charriage de fond. En vue de résoudre ces problèmes des études ont été entreprises en vue de mettre au point une méthode valable pour estimer la charge totale en sédiments du Fleuve Jaune.

PROBLEMS

It is well known that the Yellow River transports a very high sediment load. About 1600 million tonnes of sediment enter the Lower Yellow River each year, and about 20–25% of this is deposited in the lower reaches, causing the level of the river bed to rise by almost 2 m in the past four decades.

There are two methods for determining the amount of sediment deposition or erosion in a river reach. The first involves range surveys and the second analyses differences in the inflow and outflow sediment loads. The results obtained by these two methods in the Yellow River can differ considerably as shown in Table 1 (Long *et al.*, 1982).

Table 1 *A comparison of sediment deposition/erosion determined by two methods*

River reach	*Period*	*Length of reach (km)*	*Deposition ($m^3 \times 10^6$)*	
			Load difference method	*Range survey method*
Tungkuan-Sanmenxia	*Sept. 1960 –Oct. 1978*	*120*	*+1510*	*+2810*
Tiexie-Huayuankou	*Oct. 1952 –Sept. 1960*	*100*	*+1626*	*+492*
Luokou-Lijin	*1954–1977*	*174*	*–366*	*+290*

Several questions are raised by this comparison. One is which result should be used in the evaluation of sedimentation problems in river management?, another is whether or not the existing procedure for computing sediment transport in the lower reaches is reliable, because the previous practice for assessing such transport used data obtained from sediment load measurements.

DATA ANALYSIS

In order to answer these questions, some analyses have been undertaken on the three river reaches listed in Table 1. Their location is shown in Fig. 1. We found that:

(i) Variation between the methods reflects systematic error

Figure 2 shows a comparison of the amounts of deposition/erosion determined by the two methods at Sanmenxia Reservoir. In which:

$$\Delta S = W_r - W_d$$

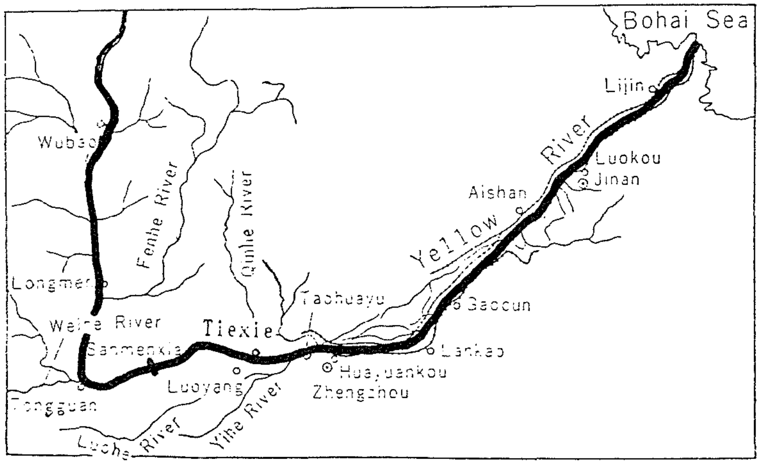
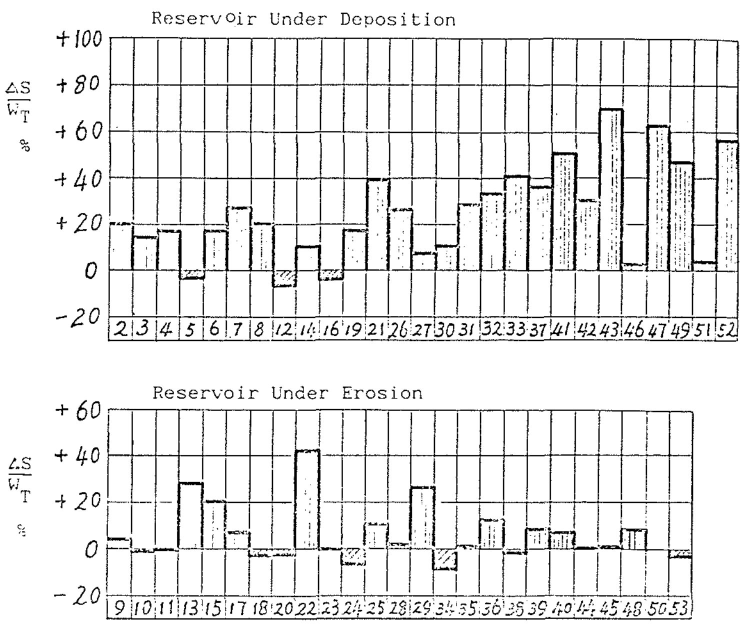


Fig. 1 *The middle and lower course of the Yellow River.*



Remarks: numbers noted in horizontal axis represents number of period between two successive surveys.

ΔS= difference of amount of deposition expressed in volume as determined by two methods.

W_T= total sediment load entering into the reach at Tungkuan gauging station.

Fig. 2 *Percentage of deviation of the volume of deposition determined by the two methods.*

where W_r is the volume of deposition/erosion determined by the range survey method, and W_d is that determined from the difference in the sediment loads at the two end sections. The upper graph shows the results when the reservoir was undergoing deposition, and the lower graph shows the results when the reservoir was experiencing erosion. It can be clearly seen that ΔS is positive in most cases, regardless of whether the reservoir was experiencing deposition or erosion.

Table 2 shows a comparison of the amounts of deposition/erosion determined by the two methods for the reach between Tiexie and Huayuankou. The ΔS values for this river reach are all negative.

Table 2 *Amount of deposition/erosion within the reach from Tiexie to Huayuankou*

Period	*Amount of deposition/erosion ($m^3 \times 10^6$)*		
	Load difference method	*Range survey method*	ΔS
Oct. 1952–Sept. 1960	*+1626*	*+492*	*−1134*
July 1960–Oct. 1964	*−394*	*−700*	*−306*
Nov. 1964–Oct. 1975	*+1055*	*+323*	*−732*

Table 3 shows the comparison for the reach between Luokou and Lijin. Here all the ΔS values are positive with only one exception.

A comparison of the results from the two methods for each measuring period on the three river reaches indicates that there is a common trend in the deviations, i.e. systematic error must exist in the field measurements.

(ii) The range survey method is more reliable than the load difference method

A comparison of the results from the range survey and load difference methods with river stage and topographic survey data indicates that the results from the range survey method are closely related to the variation of river stage and the topographic survey data. The systematic error associated with the range survey method is therefore less, although the random errors may be larger.

Figure 3 presents water level data for the reach between Tiexie and

Table 3 *A comparison of sediment deposition/erosion determined by two methods in the reach between Luokou and Lijin, in* $m^3 \times 10^6$

Method	*Number of period:* 1	2	3	4	5	6	7	8	9	10
Range survey	−28.8	+6.0	+41.1	−22.1	+51.0	+130.0	+23.5	+69.9	+18.9	+289.5
Load difference	−323.2	−7.6	−94.9	−32.3	+93.1	+79.1	−82.0	−6.4	+7.9	−366.3
ΔS	+294.4	+13.6	+136.0	+10.2	−42.1	+50.9	+105.5	+76.3	+11.0	+655.8

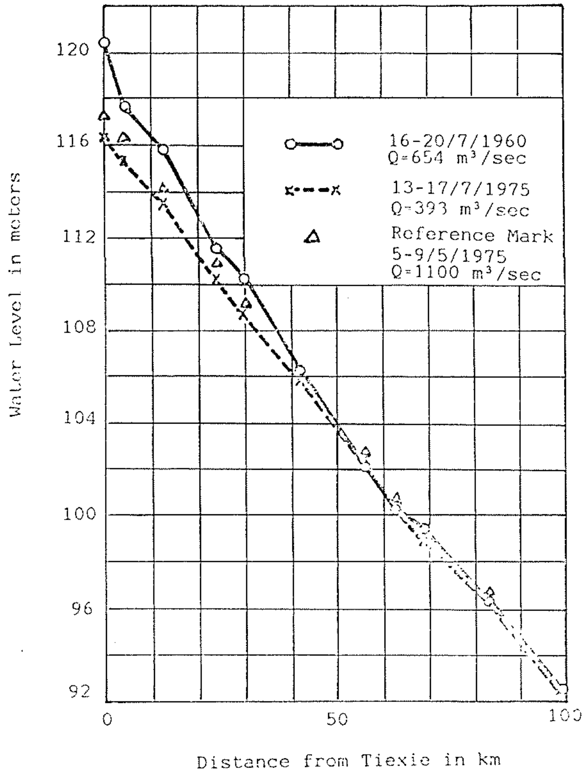


Fig. 3 Water surface levels in the reach between Tiexie and Huayuankou.

Huayuankou. The range survey results presented in Table 2 indicate that 700 million m^3 of sediment was scoured from this reach from July 1960 to October 1964, and that only 323 million m^3 of sediment was redeposited from November 1964 to October 1975, representing 46% of that eroded in the previous period. However, according to the load difference method, only 394 million m^3 of sediment was scoured during the first period, and as much as 1055 million m^3 was redeposited during the latter period, representing 270% of that mobilized in the first period. Figure 3 indicates that the results from the range survey method are basically consistent with the variations in river stage, but the results provided by the load difference method deviate substantially.

Data relating to the variation of river stage and the volume of deposition/erosion in the reach from Tiexie to Huayuankou are given in Table 4. It can be seen that the results obtained from the range survey method are consistent with the increase or decrease of river stage for equivalent discharges.

Table 5 shows the rate of channel deposition/erosion in the reach from Gaocun to Lijin. Again the results from the range survey method are seen to be in close agreement with those obtained from river stage data.

Table 4 *Variation of river stage in the reach from Tiexie to Huayuankou*

Period no.	*H* (m)	W_r ($10^6 m^3$)	W_d ($10^6 m^3$)
1	+0.14	+41	+43
2	−0.09	−61	+49
3	+0.55	+159	+200
4	+0.27	+140	+261
5	−0.26	−71	+208
6	+1.28	+446	+621
7	−0.62	−111	+96

$H = H_e$ (river stage at end of period) − H_b (river stage at beginning of period), and both H_e and H_b are stages for the same discharge.
W_r is the amount of deposition/erosion determined by range survey.
W_d is the amount of deposition/erosion determined by load difference.

Table 5 *Rate of channel deposition/erosion in the reach from Gaocun to Lijin (m year^{-1})*

Period		*Reach from Gaocun to Aisan*	*Reach from Aisan to Lijin*
Pre-Sanmenxia	1	+0.11	−0.01
Reservoir	2	+0.04	−0.12
(1951–1960)	3	+0.11	+0.02
Post Sanmenxia	1	+0.06	+0.06
Reservoir	2	−0.02	+0.02
(1960–1977)	3	+0.04	+0.07
	1	+0.07	+0.04
Total	2	−0.00	−0.03
(1951–1977)	3	+0.07	+0.05

1 = The rate determined by range survey method.
2 = The rate determined by load difference method.
3 = The rate determined by the river stage at equivalent discharges.

THE MAIN CAUSES OF THE DEVIATION

The above analysis indicates that the results provided by the range survey method are consistent with the actual river conditions, and are relatively more reliable than those obtained by load difference calculations.

Inconsistency between the two methods must, therefore, be mainly caused by errors in the measurement of sediment load.

Many observations have been made of the distribution of sediment concentration in the vertical for different size ranges at various gauging stations. It is well known that: (a) the concentration in the vicinity of the river bed is high; and (b) the coarser the sediment, the larger the gradient of the concentration distribution in the vertical. In addition, from measurements of the lateral distribution of concentration for different size ranges in a cross section, it is known that the coarser the sediment size, the more uneven is the lateral distribution of concentration.

Because simplified methods of sediment sampling are employed in routine work, such as the use of one or three verticals in a cross section and sampling at one, two or three points in a vertical, the accuracy of the sediment measurements will be affected, leading in general, to underestimation of the sediment load and prediction of a finer sediment composition by computations based on the load difference method.

Considering a river reach, the incoming and outgoing sediment loads can be denoted by W_{Ii} and W_{Oj} respectively, and the ratios of the unsampled to the total sediment load can be correspondingly denoted by a_{Ii} and a_{Oj}, where: i and j denote the number of gauging stations for measuring the sediment entering and leaving the river reach respectively (including stations for measuring input of sediment from tributaries and withdrawals of sediment from the reach). Using the sediment mass balance, and the results from the range survey method, which are considered to be relatively reliable, a relationship can be established as follows:

$$\sum_{i=1}^{n} (1 + a_{Ii})\, W_{Ii} - \sum_{j=1}^{m} (1 + a_{Oj})\, W_{Oj} = \Delta W_r \qquad (1)$$

where ΔW_r is the amount of deposition determined by the range survey method converted into mass units, n is the total number of inflow sediment gauging stations, and m is the total of outflow sediment gauging stations.

In the case of the river reach from Tungkuan to Sanmenxia, no appreciable error would be introduced by neglecting sediment entering or withdrawn from the river reach between the upstream and downstream measuring sites. Equation (1) can therefore be simplified as follows:

$$(1 + a_T)W_T - (1 + a_S)W_S = \Delta W_r \qquad (2)$$

where a_T and a_S denote the ratio of unsampled sediment to the total at the Tungkuan and Sanmenxia gauging stations respectively, W_T represents the amount of sediment passing the Tungkuan gauging station, and W_S the amount of sediment passing the Sanmenxia gauging station. A field study indicated that the vertical distribution of sediment concentration in the sampling cross section of the Sanmenxia station, which is only several hundred metres from the outlet exits, is very uniform, because water and sediment are very well mixed by turbulence. Therefore, $a_S \approx 0$. From equation (2), we have

$$(1 + a_T)\, W_T - W_S = \Delta W_r \quad (3)$$

$$(W_T - W_S) + a_T W_T = \Delta W_r \quad (4)$$

$$\Delta W_d = W_T - W_S \quad (5)$$

where ΔW_d denotes the amount of deposition determined by the load difference method.

From equations (4) and (5), we get

$$\Delta S = W_r - W_d = a_T W_T \quad (6)$$

Because

$$a_T > 0 \text{ and } W_T > 0 \quad (7)$$

Therefore,

$$\Delta S = a_T W_T > 0 \quad (8)$$

This is the reason why the ΔS shown in Fig. 2 is positive. Using the same approach, similar results may be obtained for other river reaches.

It could be concluded that differences in the magnitude of the unsampled sediment load in a vertical at the two end sections of a river reach is the major cause of deviation between the results of the range survey method and the load difference method.

Figure 4 shows a typical set of data extracted from Sanmenxia Reservoir during the cited period. No sediment was sluiced out of the reservoir, and the sediment load entering the reservoir at Tungkuan gauging station was all deposited in the reservoir. A comparison of the size grading curves and the amount of deposition for each size class, indicates that the unsampled sediment is primarily coarse sediment. For instance, the particle diameter involved in this case is >0.1 mm, and in most cases it is >0.05 mm.

An analysis of measurement data undertaken by Lin (1982) showed that the ratio of unsampled sediment load to the total load at the Tungkuan gauging station was larger than that at Sanmenxia. However, in the Lower Yellow River the ratio becomes increasingly smaller from Huayuankou to Lijin because of the preferential deposition of coarse sediment along the downstream course.

COMPUTATION OF TOTAL LOAD

In the case of Lower Yellow River, the unsampled sediment load, including part of suspended load and all of the bed load, only constitutes a small proportion of the total load. However, it is this small part of the sediment load that constitutes the major part of the deposition in the channel of the

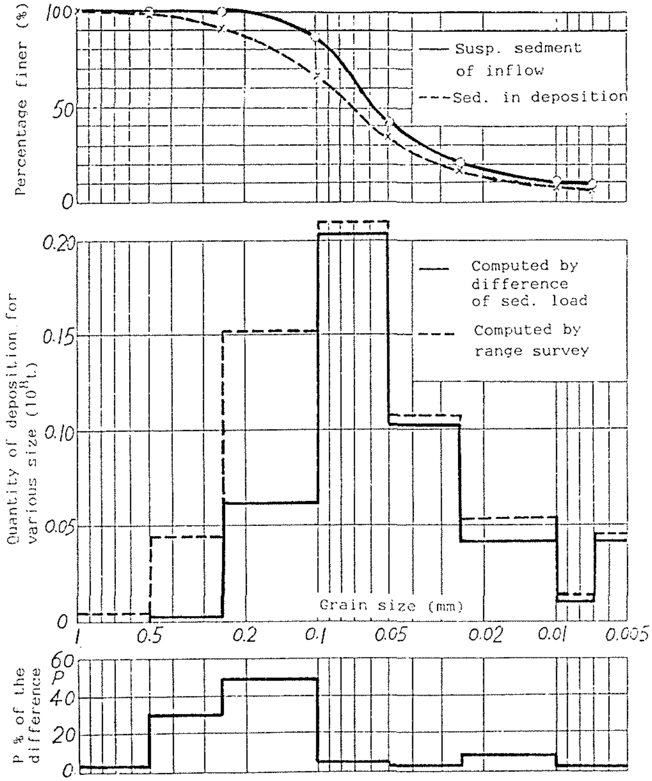


Fig. 4 Differences in the amount of deposition calculated for various size fractions, March–June 1976, at Sanmenxia Reservoir.

Lower Yellow River. For example, 60% of the deposition in the Lower Yellow River channel is composed of sediment sizes coarser than 0.05 mm. Therefore, special attention should be paid to this unsampled sediment load. However, the conventional concept of the so-called "unsampled sediment load" used for depth-integrating suspended sediment sampling is somewhat different from that needed for point-integrating suspended sediment sampling. In point-integrating measurements the deviation of measured sediment load from its real value of total load reflects not only the unsampled load due to the position of the measuring point in the vertical and the position of the measuring verticals in the cross section, but also the method of data processing.

What is the best way to determine the so-called "unsampled sediment load" correctly? Many studies (e.g. Qian, 1952; Qian & Wan, 1956; Lin, 1981) have been undertaken since the 1950s to provide procedures for correcting the observed data. The available approaches can be divided into two types.

Direct methods

Using the observations of both flow and sediment, an exponential velocity profile or sediment concentration profile for the vertical may firstly be determined. Then the total load for the vertical can be evaluated by integrating the product of velocity and sediment concentration obtained from these two formulae for which the Z value, an exponent of suspended sediment distribution, should also be determined empirically from the sediment observations. Xiong & Huang (1984) have successfully used this method to correct the measured suspended load in the Yellow River. The basic requirement of this type of method is one that is generally not met by routine work. A sufficient number of measurements of velocity and sediment concentration distribution in the verticals should be made to provide a sound basis for establishing appropriate formulae to represent the vertical distribution of the relevant parameters.

Indirect methods

The indirect methods differ from the direct methods in terms of the measured data required in the computation. It is necessary to take measurements of the flow and the size distribution of the bed material for the indirect methods instead of collecting suspended sediment samples. Here the formulae used for the vertical velocity and concentration distributions are for general conditions, and so is the Z value. Using the measured flow data and the size distribution of the bed material in association with these general laws developed statistically, the total load can be predicted. For example, Lin (1982) has proposed a modification coefficient method, based on Einstein's method, to estimate the total load by using data obtained by several simplified methods of measuring suspended sediment discharge in a vertical, as shown in Fig. 5. Using the data from the flow and sediment measurements, the value of a for each simplified sampling method can firstly be determined. The total load can then be computed using the following formula:

$$Q_{st} = (1 + a)\, Q_{sm} \tag{9}$$

In which Q_{st} is the total sediment discharge (including bed load), and Q_{sm} is the measured sediment discharge in suspension.

Many studies have also been undertaken by US scientists (cf. Bureau of Reclamation, 1955; Toffaleti, 1968; Stevens, 1985) and methods for computing total bed material load have been developed and widely used in both small and large rivers. Due to the difficulties involved in direct measurement of bed load on the silt or fine sand dominated bed of the Yellow River and also the existence of large deviations in the measurements of suspended load, Lin *et al.* (1987) have undertaken a number of studies to see whether or not these methods (Einstein, 1950; Toffaleti, 1968; Stevens, 1985; etc.) developed originally for sand-dominated US rivers, could be transferred directly to the silt- and fine sand-dominated Yellow River. All results (Qian *et al.* 1980; Lin, 1981, 1982; Lin & Liang, 1987) indicate that there is considerable potential for applying these methods to the Yellow River and several

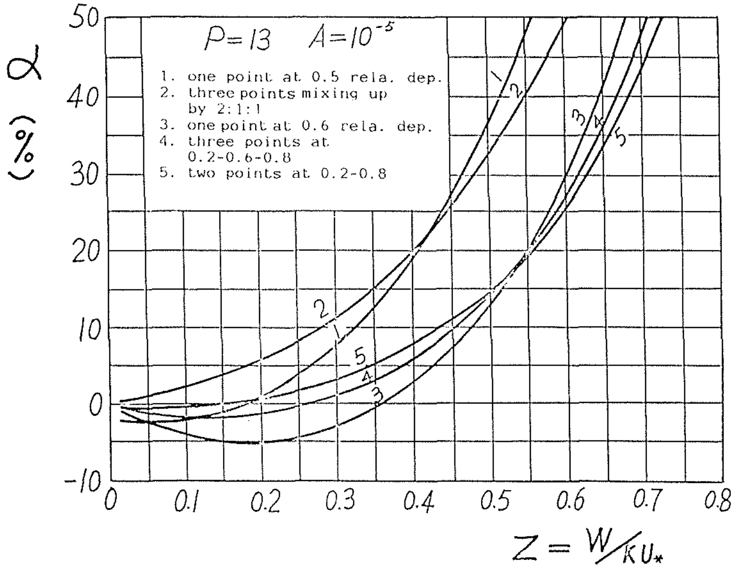


Fig. 5 Computed value α vs. Z for different simplified measuring methods.

empirical curves were modified by data collected from the Yellow River.

Sixty seven sets of measurements obtained from eight gauging stations on the main stem and the tributaries of the Yellow River were used for these evaluations. Plots of computed *vs.* measured sediment discharges are shown in Figs 6 and 7. The results obtained using the Toffaleti (1968) and Stevens (1985) procedures conform closely to the direct measurements.

CONCLUSION

The problem of unsampled load in measurements of sediment exists not only in depth- but also in point-integrating suspended sediment sampling. The coarser the sediment grain size, the larger the unsampled sediment load. The unsampled load represents only a very small proportion of the total load, but it constitutes a major component of the deposition in the channel of the Lower Yellow River. The accuracy and reliability of sediment measurements will directly influence any attempt to determine the amount of deposition/erosion in a river reach by the load difference method.

Comparisons of the amount of deposition/erosion computed by well-spaced range surveys with that estimated using the load difference method applied to the sediment loads measured at the two ends of the reach indicates that the systematic error associated with the range survey method is less, although the random error may be larger due to the relatively crude surveying technique employed in range surveys. The amount of deposition/erosion in a river reach determined by the range survey method is found to

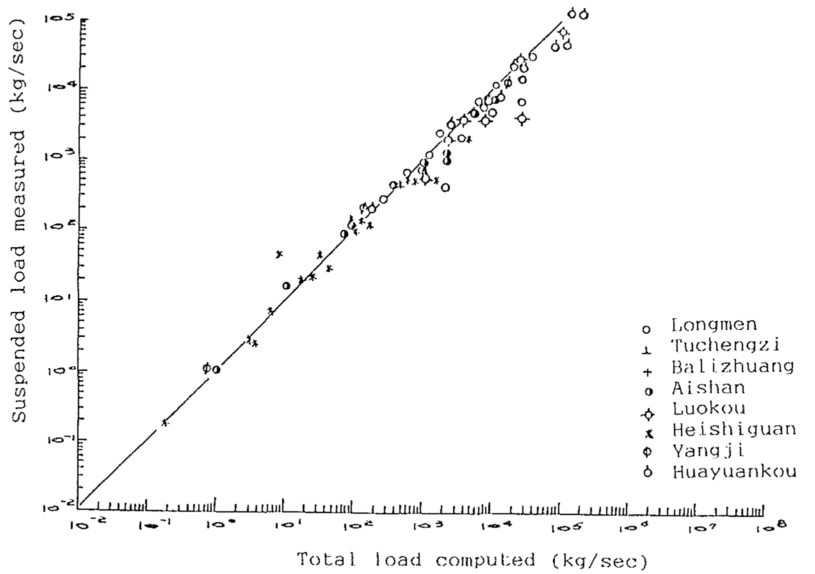


Fig. 6 *Comparison of the total load computed by the Toffaleti procedure with the measured suspended load.*

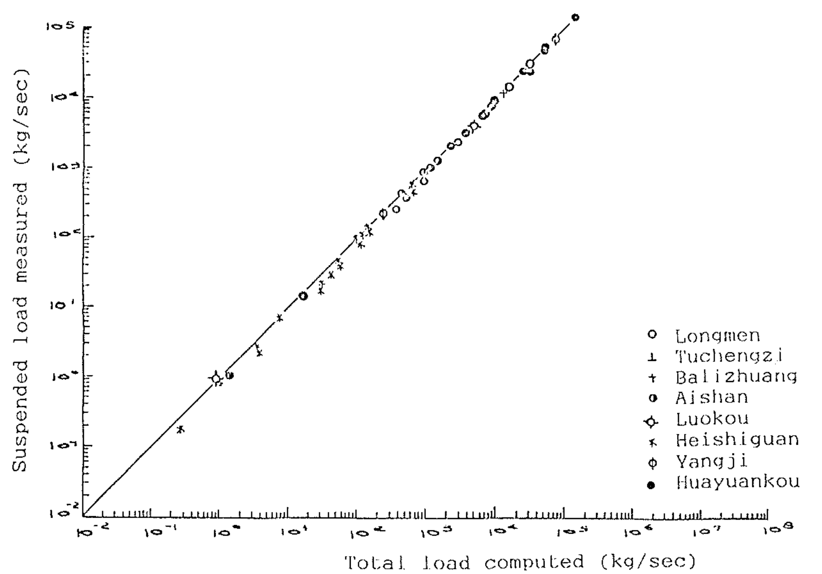


Fig. 7 *Comparison of the total load computed by the Stevens procedure with the measured suspended load.*

be in close agreement with the actual conditions in the river. The main cause of deviations between the sedimentation estimates provided by the range survey and load difference methods is the different proportion of the sediment load unsampled, or improperly taken account of, in the vertical, at the two end sections of the river reach.

The best way to assess the accuracy and reliability of sediment measurements at a gauging station is to compare the quantity of deposition/erosion in a river reach computed by the load difference method, with that estimated by the range survey method, through an examination of the sediment balance of the reach, using a sediment balance equation. For this purpose, it is suggested that range surveys should be carried out in a river reach between two adjacent gauging stations which can be used for studying methods of total load computation.

It is necessary to correct the magnitude of observed sediment loads to take account of the unsampled load associated with routine suspended load measurements and the absence of data on bed load, which is very difficult to measure especially in large rivers. It will save considerable time and effort if some of the flow and sediment measurements can be used to correct the measured sediment load.

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