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A suspended sediment budget for the Liu River basin, China

HAOMING FAN[1,2] & QIANGGUO CAI[1]

1 *Institute of Geographical Sciences & Natural Resources Research, CAS, Beijing, Building 917, Datun Road, Anwai 100101, China*
fanhaoming@163.com

2 *Department of Water Conservancy, Shenyang Agricultural University, Shenyang 110161, China*

Abstract A mass budget for the suspended sediment load of the Liu River was established for a period of 36 years (1968–2003). The approach was based on analysing the amount of sediment contributed by the different tributaries and the sediment storage in different reaches, using data available for six gauging stations on the Liu River. The findings indicate that nearly 50% of the suspended sediment flux from upstream tributaries was stored on the downstream riverbed, with almost 75% of this storage occurring in the reach extending from the Nao Dehai Station to the Zhang Wu Station. About 50% of the suspended sediment coming from upstream reached the catchment outlet. The key controls on the sediment budget of the river basin have been investigated. The findings reported in this paper have important implications for understanding suspended sediment dynamics and sediment control in river basins.

Key words controls; Liu River basin, China; sediment budget; sediment delivery system

INTRODUCTION

The sediment budget affords an effective conceptual framework for quantifying sediment mobilization, transport, deposition and storage within, and sediment output from, a drainage basin (Walling *et al.*, 2002). Many studies have demonstrated that land use can exert an important influence on sediment supply and sediment fluxes in drainage basins (Lang & Honscheidt, 1999; Evans *et al.*, 2000; Van Rompaey *et al.*, 2002), and sediment budget studies can define the impact of human activities on sediment storage and sediment routing (Roberts & Church, 1986). The space and time scales used in sediment budgeting have a major influence on the conclusions reached (Church, 1980; Trimble, 1983). This paper reports the establishment of a mass suspended sediment budget for a 6759 km^2 sandy river basin over the period 1968–2003. The key controls on the sediment budget have been identified.

The study area is shown in Fig. 1. The Liu River basin, which is characterized by the highest mean annual suspended sediment concentration in northeast China, is a tributary to the Liao River, that drains to the Bohai Sea in Liaoning province and the province of Inner Mongolia. The mean annual rainfall is 400–600 mm, and increases from upstream to downstream (Song, 1995). Three tributaries (the Kou Hezi River, the Yang Xumu River and the Tie Niu River) dominate the upstream area of the Liu River basin, and most of its sediment load originates from these tributaries. The lower Liu River is impacted by excess sediment deposition and many reaches have become "above ground rivers" similar to those found in the lower Yellow River of China.

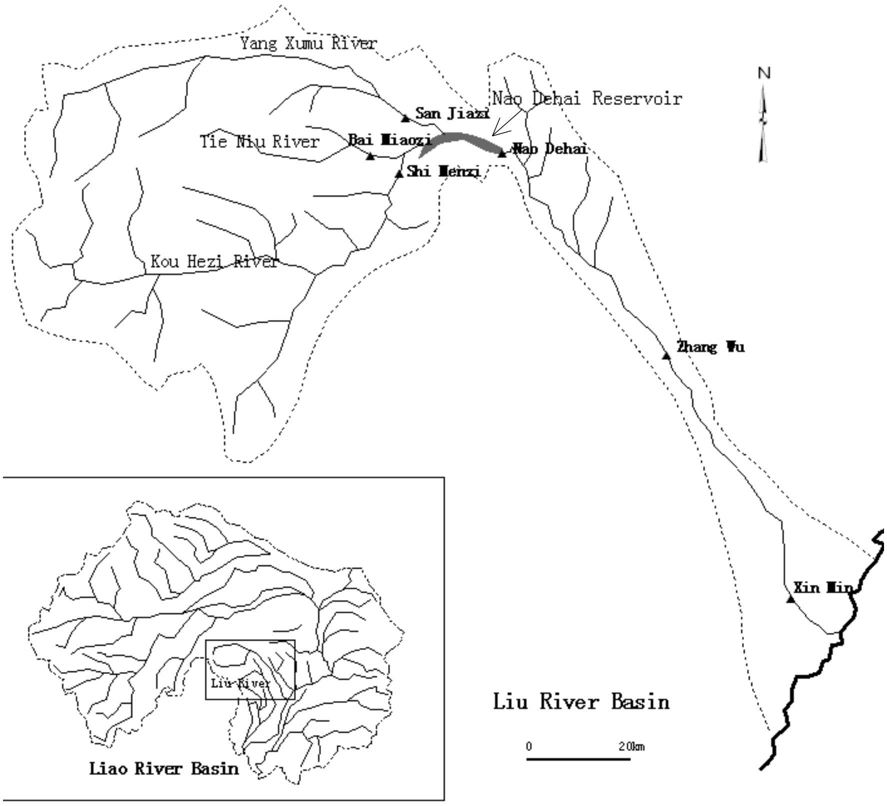

Fig. 1 Location of the study basin and the position of the gauging stations.

Within the Liu River basin, the Nao Dehai Reservoir is the largest hydraulic engineering work. This reservoir was constructed in 1942 as a flood detention reservoir and its sediment storage was filled within about 20 years.

DATA SOURCES

There are six hydrometric stations on the Liu River. The data on suspended sediment discharge, suspended sediment concentration, sediment grain size and water discharge, used in this study were obtained for the hydrometric stations established and managed by the Songliao River Water Conservancy Commission. The Chinese Ministry of Water Resources has produced and issued operational manuals and national standards for flow measurement, river water sampling, and suspended sediment concentration and grain size analyses. In this study, we did not undertake measurements of water and sediment discharge, river water sampling or sediment analysis. Emphasis was placed on analysis of existing records and data. The measurements of river stage, water discharge and suspended sediment concentration, and the analyses of grain size and suspended sediment concentration undertaken at all stations followed national standards issued by the Ministry of Water Conservancy and Electric Power (1962, 1975). The procedures used for hydrological surveys, water sampling and laboratory grain-size analyses at the hydrometric stations are essentially the same as those used internationally (see Yan, 1984, for details).

RESULTS

Sediment sources

The main sediment contributing area of the Liu River basin is the zone above the Nao Dehai Station. Almost all sediment comes from three tributaries (the Kou Hezi, Tie Niu and Yang Xumu rivers) in the upper reaches of the Liu River basin. The Kou Hezi River is the largest of these three tributaries. Half of its catchment is characterized by low-relief terrain and half belongs to the hilly and gully area. As shown in Table 1, although the Kou Hezi River basin has the lowest mean annual erosion modulus and suspended sediment concentration of the three upstream tributaries, it contributed nearly 50% of the suspended sediment load entering the downstream reaches. This major contribution reflects its large catchment area and the erodible soils found in the basin. The Yang Xumu River is located in the south of the Korqin Sandy Land, where there are extensive fields of moving dunes. Wind erosion is dominant in this basin in spring and the particles deposited on the slopes and in the channels are transported downstream by the flows occurring in summer and autumn. Most of Tie Niu River basin is located in the hilly and gully area and part is located in an area of flat sandy hills. Table 2 shows that in the Tie Niu River, tilled land accounts for 50.6% of its overall area and its population density (105 people km^{-2}) is significantly higher than

Table 1 Suspended sediment and runoff characteristics at each gauging station in the Liu River basin (1968–2003).

Gauging station	River	Area (km^2)	*Q* (10^8 m^3)	*HQ* (10^8 m^3)	*HQ*/*Q* (%)	*D* (10^4 t)	*HD* (10^4 t)	*HD*/*D* (%)	*C* (kg m^{-3})	*E* (t km^{-2})
San Jiazi	Yang Xumu	825	0.7632	0.3035	39.77	178.99	140.57	78.54	21.1	2169.69
Bai Miaozi	Tie Niu	341	0.1376	0.0953	69.26	132.84	129.11	97.19	72.7	3898.26
Shi Menzi	Kou Hezi	2405	0.9971	0.6721	67.41	330.71	306.04	92.54	23.0	1376.58
Nao Dehai	Middle of Liu	4051	2.0572	1.1638	56.57	773.98	733.92	94.82	29.9	1910.75
Zhang Wu	Lower of Liu	6100	2.3237	1.3142	56.56	486.63	393.39	80.84	18.2	797.75
Xin Min	Mouth of Liu	6759	2.3415	1.3923	59.46	388.02	296.82	76.49	13.6	589.43

Q: mean annual runoff; *HQ*: runoff in the month of 6–9; D: mean annual suspended sediment discharge; *HD*: suspended sediment discharge in the month of 6–9; *C*: mean annual suspended sediment concentration; *E*: mean annual erosion modulus.

Table 2 The physical geography and socio-economic conditions in the upland of Liu River Basin.

River	Topography	Soil type	Erosion	*LR* (km)	*SR* (‰)	*GA* (km^2)	*TA* (km^2)	*TA*/*GA* (%)	*GL* (km^2)	*GL*/*GA* (%)	*FL* (km^2)	*FL*/*GA* (%)	*P*	*PD* (people km^{-2})
Yang Xumu	Flat sandy hill	Wind-blown soil	Wind Water	112.0	2.70	973	272.8	28.0	197.6	20.3	267.3	27.5	31549	32
Tie Niu	Hilly and gully area Flat sandy hill	Chestnut soil	Water Wind	54.7	4.07	374	189.4	50.6	70.4	18.8	96.7	25.9	39133	105
Kou Hezi	Low-relief terrain Hilly and gully area	Brunisolic, Cinnamon and Chestnut soils	Water	145.2	2.11	2504	749.3	29.9	535.9	1.4	714.3	28.5	155639	59.8

LR: length of river; *SR*: slope of river; *GA*: gross area; *TA*: tilled area; *GL*: grazing land; *FL*: forest land; *P*: number of people; *PD*: population density.

that found in the Yang Xumu River basin (32 people km^{-2}) and the Kou Hezi River basin (59.8 people km^{-2}). Intensive gully erosion is the main erosion type in the Tie Niu River basin although and wind erosion occurs in the upstream area in spring. Although it has the largest erosion modulus of the three upstream tributaries, the Tie Niu River contributes the least sediment to the downstream basin by virtue of its small catchment area. As shown in Table 1, most of the sediment transport in the upstream basin occurs during months 6–9. All the sediment coming from upstream accumulates in the Nao Dehai Reservoir and is then sluiced downstream.

The spatial and temporal distribution of sediment deposition

Sediment deposition on the riverbed is one of the most important problems in the lower Liu River. Deposition affects flood transmission by reducing the cross section of the channel. Figure 2 shows that from 1968 to 2003, sediment deposition occurred in the lower Liu River during most years. The scouring of deposited sediment only takes place every few years and only a small proportion of the deposited sediment has been transported out of the Liu River basin. Most of the deposited sediment is stored in the sector stretching from the Nao Dehai Station to Zhang Wu Station. Overall, it might be expected that most sediment deposition will occur at times of high water discharge, but as shown in Fig. 2, the highest deposition rates do not coincide with the highest water discharges.

Several factors can affect the deposition of suspended sediment. According to the investigation conducted by the Liaoning Institute of Water Resources and Hydraulic Research, the 0.05–0.1 mm fraction accounts for 50–70% of the bed material in the lower reaches and this size fraction therefore dominates the bed material. The sediment transported out of the reach is dominated by the <0.05 mm fraction, which accounts for 68–89% of the suspended sediment load. The particle size composition of suspended sediment has been investigated and the results are presented in Table 3. The Yang Xumu River and the Tie Niu River contribute a greater proportion of deposited

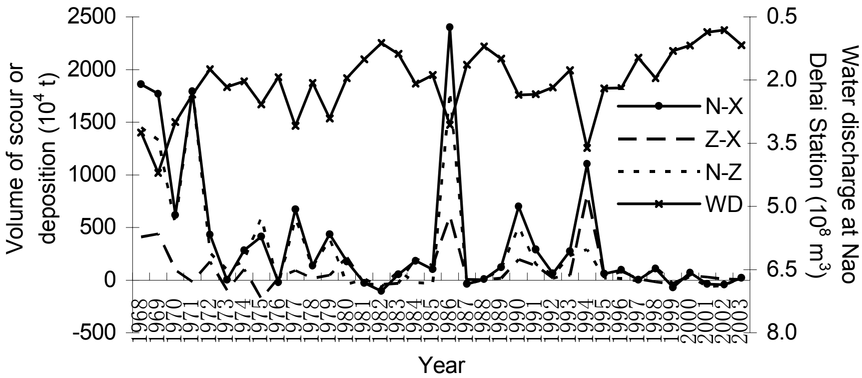

Fig. 2 The spatial and temporal distribution of sediment deposition and scour in the lower Liu River. Positive values indicate deposition and negative values indicate scour. N-X: the suspended sediment deposition between Nao Dehai Station and Xin Min Station; Z-X: the suspended sediment deposition between Zhang Wu Station and Xin Min Station; N-Z: the suspended sediment deposition between Nao Dehai Station and Zhang Wu Station; WD: water discharge at the Nao Dehai Station.

Table 3 Summary information on the particle size characteristics of the suspended sediment samples collected from the gauging stations (1968–1999).

Station (river)	Sample size	d_{50} (mm)	<0.05 mm (%)	>0.05 mm (%)
San Jiazi (Yang Xumu)	788	0.0548	48.8	51.2
Bai Miaozi (Tie Niu)	673	0.0588	46.3	53.7
Shi Menzi (Kou Hezi)	1058	0.0439	58.2	41.8
Nao Dehai (middle Liu)	969	0.0491	54.5	45.5
Zhang Wu (lower Liu)	667	0.0343	66.7	33.3

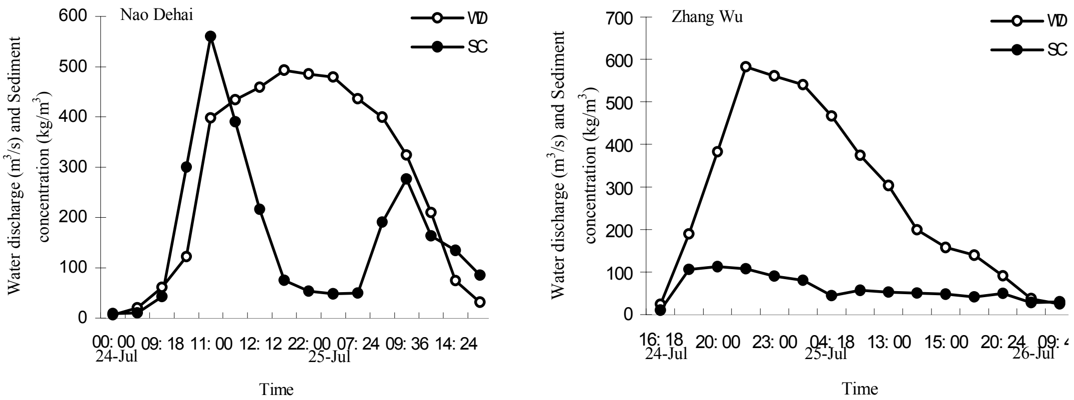

Fig. 3 The flood and sediment hydrographs at Nao Dehai and Zhang Wu stations for 24 July 1977. WD: water discharge; SC: suspended sediment concentration.

sediment to the downstream reaches. The suspended sediment load shows evidence of downstream fining due to the size selective deposition of coarser particles. The long-term median size (d_{50}) of suspended sediment decreases from 0.0491 to 0.0343 mm between Nao Dehai Station and Zhang Wu Station, and the percentage >0.05 mm decreases from 45.5 to 33.3%, as a result of intensive deposition within this reach (Table 3).

Hydraulic engineering works and their operation have exerted an important influence on sediment behaviour in the lower river reaches. Before the Nao Dehai Reservoir was constructed, the flood peak and the sediment peak were almost synchronous. After the reservoir was constructed, the flood wave was attenuated by the Nao Dehai Reservoir, resulting in a lag of the first sediment peak. With increasing water levels, the large-scale overtopping of the dam crest would lead to the second sediment peak at Nao Dehai Station (Fig. 3). For the Zhang Wu Station, only one sediment peak can be seen in a given flood, compared to the two peaks observed for the same flood at the Nao Dehai Station (Fig. 3). This means that most of the suspended sediment transported with the second sediment peak at Nao Dehai Station is deposited in the reach between the Nao Dehai and Zhang Wu stations, because the second sediment peak at Nao Dehai corresponds with a relatively small water discharge.

Before 1972, the operating mode for the Nao Dehai Reservoir was to discharge flow freely through the discharge orifices at times of relatively low water level, and when the reservoir filled the floodwater would be released via the dam spillway. This operation mode is termed “freely overbrim” (FO). After 1972, the operation mode was modified to close the gates on the discharge orifices from October to April, in order to impound water for irrigation, and to then empty the reservoir in May to create storage capacity for floods occurring between June and September. During that time the gates of the discharge orifices were open continuously. This operation mode is termed "storing clear and releasing sediment (SCRS)". During the low-stage season, the riverbed in the lower reaches would experience sedimentation during the operation of FO, but under the operation of SCRS, scouring would take place during the same season. The reason behind the scouring is that most of the sediment coming from upstream would be stored in the reservoir and the clean flows released from the dam would result in remobilization of the bed material in the lower reaches. However, only a small portion of the remobilized sediment is transported out of the basin; most of the remobilized sediment would be redeposited on the riverbed further downstream. During the flood season, the operation of SCRS would result in the remobilization of more sediment than with the operation of FO, because the large amounts of sediment deposited in the reservoir at low water stages would be remobilized during the flood season. Under the operation of SCRS more sedimentation would take place than with FO during the flood season.

The suspended sediment budget

The suspended sediment budget for Liu River basin has been calculated as follows:

$$Sn - SDnz - SDzx = Sx \, (773.9 - 287.34 - 98.61 = 388.02) \tag{1}$$

$$Sn = Ss + Sb + Ssh + So \, (773.98 = 178.99 + 132.84 + 330.71 + 131.44) \tag{2}$$

where *Sn*, *Sx*, *Ss*, *Sb*, *Ssh* are annual suspended sediment flux at Nao Dehai, Xin Min, San Jiazi, Bai Miaozi, Shi Menzi; *SDnz* and *SDzx* are annual suspended sediment deposition from Nao Dehai to Zhang Wu, and from Zhang Wu to Xin Min; and *So* is other sediment inputs source flowing into the Nao Dehai Reservoir (unit: 10^4 t year^{-1}).

The results indicate that nearly 50% of the suspended sediment coming from upstream was stored on the riverbed, and that about 75% of this storage occurred within the sector extending from Nao Dehai Station to Zhang Wu Station. About 50% of the suspended sediment coming from upstream is transported out of the Miaozi, Shi Menzi reach and into the Nao Dehai Reservoir.

CONCLUSIONS

A mass suspended sediment budget has been established for the Liu River basin for the period from 1968 to 2003. The major findings may be summarized as follows:

(a) Most of the suspended sediment comes from the upstream areas of the Liu River during months 6–9.
(b) Sediment sources are affected by several factors, such as the physio-geographical conditions, the type and extent of erosion, the local social conditions, human behaviour, and the density of the vegetation cover.

(c) The particle size fraction <0.1 mm and >0.05 mm is the main component of the sediment load leading to sediment deposition on the riverbed in the lower reaches of the basin.
(d) The Nao Dehai Reservoir and its operation mode have had a major effect on the spatial and temporal distribution of suspended sediment deposition.
(e) Nearly 50% of the suspended sediment coming from upstream was stored on the riverbed, and about 75% of the deposited sediment was stored in the sector stretching from the Nao Dehai Station to Zhang Wu Station. About 50% of the suspended sediment coming from upstream reached the outlet of the Liu River basin.

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