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Calculation of Water Volume for Sediment Transport in the Sediment-laden River of the Main Stream of Liaohe River, Northern China

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ABSTRACT

The water volume for sediment transport affects the distribution of sediments in rivers and offers important guidance for river dredging, management and remediation. In this paper, with daily water and sediment data of major hydrological stations of main stream of Liaohe River from 1988 to 2010, we calculated the average water volume and unit water volume for sediment transport of the year with the methods of sediment discharge, sediment concentration and erosion and silting ratio correction that are based on net water volume method. We analyzed the relations between change process of water volume for sediment transport and its impact factors to identify the critical water volume for sediment transport for non-scouring and non-silting situation. The results showed that (1) according to the calculation with the hydrological data from the major hydrological stations in Tongjiangkou, Tieling, Mahushan, Ping'anpu and Liujianfang, the average water volume and the unit water volume for sediment transport during the flood season of the year were $13.88\times10^8 m^3$ and $1136.62 m^3/t$ respectively; (2) According to the theoretical calculation, the water demand model for hydraulic sediment dredging in the major reaches of the main stream of Liaohe River was determined and there was linear function relationship between the sediment discharge and the water demand. When the channel kept the sediment from silting, the water demand at Tieling was $\geq 18.73\times10^8 m^3$, $\geq 5.49\times10^8 m^3$ at Mahushan, $\geq 2.90\times10^8 m^3$ at Ping'anpu and $\geq 10.97\times10^8 m^3$ at Liaozhong. In a word, net water volume method can accurately calculate the amount of sediment transport in sediment-laden rivers with a prospect of broad application.

INTRODUCTION

As the largest river in the southern part of Northeast China, Liaohe River extends its catchment to nearly 20 cities with its downstream reaching as far as the most industrially and economically developed areas in China. The Liaohe River has a large sediment concentration, second only to the Yellow River and Haihe River, and is the third in China. The sand-laden Liaohe River suffers severe soil erosion as there are large hilly and semi-desert areas and sparse vegetation along the western part of its catchment. The heavy rains and floods in the Liaohe River are rapid in speed and repetitive in scouring and silting and often have a significant sediment-carrying capacity. Between 1985 and 1996, large floods occurred many times, resulting in dramatic erosion and siltation (Xiong et al. 2005). Currently, the main stream of the Liaohe River is still characteristic of having wide bench land but a narrow groove in the river channel, being shallow and curved and slow water flow. In order to strengthen the management and planning and utilization of the Liaohe River, it is urgent to identify the reasonable sediment transport volume of the Liaohe River.

So far, many scholars around the world have studied the relationship between water volume and sediment. Based on the fundamental formula of "the more is the incoming sediment, the more the sediment discharged", Wu et al. (2015) proposed a general expression of sediment discharge. And with measured water and sediment data of the Inner Mongolian section of the Yellow River from 1953 to 2010, they fitted for the annual sediment discharge formula of the Sanhukou and Toudaoguai reaches and then further figured out the year-by-year scouring and silting amount of major reaches by sediment transport rate method. After analysing the calculation results with the collected hydrological data from the stations at Xiaolangdi, Huayuankou etc., Zhao et al. (2017) found that the water volume for sediment transport generally increases as the runoff, the flow and incoming sediment go up and decreases and tends to be stable as the sediment concentration and incoming sediment coefficient fall and that the proportion of water volume for sediment transport in the runoff increases and tends to be stable as the sediment concentration and incoming sediment coefficient rise. In the lower reaches of the Yellow River, the amount of sediment transported during the flood season is relatively stable with the sediment transport volume being small and the sediment transport efficiency being high. Yan et al. (2013) set up a generalized movable bed model for the lower reaches of the Yellow River by summarizing the relevant results of the sediment transport efficiency in the lower Yellow River and simulated the sediment transport process of the lower Yellow River channel under different fluctuating flows after water and sediment adjustment at Xiaolangdi. They found that with the standard deviation of 4.03 L/s in the model experiment (i.e., the fluctuation ratio was 0.375), the 1 hour period water-sediment process witnessed the highest sediment transport efficiency. Shao-lei et al. (2015) used physical model tests to predict the trend of erosion and siltation in the lower Yellow River. Based on the water and sediment data from the lower reaches of the Yellow River from 1960 to 2012, statistical methods were used to analyse the sediment transport in the lower reaches of the Yellow River in the situations of different flows and different sediment concentrations. They found that reasonable water and sediment regulation is a necessary measure to avoid later siltation. And the discharge and sediment concentration in the Huayuankou section should change within the ranges of $3000\ m^3/s < Q < 4000\ m^3/s$ and $20\ kg/m^3 < S < 60\ kg/m^3$ respectively, so that the equilibrium sediment transport can be achieved. Tu et al. (2017) applied coupling models constructed with two-dimensional hydrodynamic sediment transport and morphology to evaluate the effects of different watershed management strategies on flood inundation, sediment transport dynamics and morphological changes in different extreme flood events.

Water and sediment are very important elements for the good regulation or operation of the natural rivers or reservoirs. Watershed management requires accurate discharge and sediment predictions (Fasikaw et al. 2018). So far many researches have been conducted with regard to the relationship between water demand or volume and sediment. Toffolon & Vignoli (2007) used to discuss the limitations of the depth-averaged approach for suspended sediment transport. Castro et al. (2008) researched on the numerical approximation of bed-load sediment transport because of the shallow layer flows on unstructured meshes, and proposed the technique that gave expression to several empirical bed-load formulas in the form of grass Model with a complex bed-load coefficient. Many scholars have conducted researches on the problem of sedimentation in the lower Yellow River based on water-sediment regulation. Hu et al. (2012) and Liu et al. (2016) summarized that the average annual erosion rates vary from 5000 to 10000 Mg $km^{-2}yr^{-1}$. Arabkhedri et al. (2010) resorted to sediment rating curves for the estimation of sediment load. Some ancillary data like time-weighted SSC, suspended sediment load, stream data, instantaneous flow discharge, and erosivity density as per Kinnell et al. (2010) and Panagos et al. (2016, 2015, 2017), were either obtained or calculated based on the available data. Jothiprakash & Garg (2010) used BPNN, the back propagation neural network to evaluate sediment trap efficiency in a reservoir and found that the BPNN model shows better accuracy in results compared to that by regression analysis. Han (2011) and Peng (2011) found that the equilibrium sediment transport is more viable than balanced sediment transport in the lower reaches of the Yellow River. Benkhaldoun & Seaïd (2011) came up with a new numerical method to solve the equations of coupled sediment transport and bed morphology by free-surface water flows. As reported by Chao et al. (2012) in the inflow of supplemental sand-laden river water, the supplement water flow renders the key factor in the determination of the sediment load into lakes, and it brings influences to the lake hydrodynamics and sediment transport. Yesuf et al. (2014) proposed that models are necessarily in need if wanting to predict reliable quantity and sediment transport rate from land surface into streams, rivers and water bodies, to identify erosion problem areas within a watershed and to propose the best management practices to reduce erosion impact. Zhao et al. (2011) applied a three-dimensional numerical model to make a simulation of sediment transport in water bodies influenced by wind-induced currents and waves in shallow oxbow lakes. Kisi et al. (2015) proposed that river sediment transport can be put into model either by physical modelling, which required several efforts and information or conceptually using intelligence models. Benjankar & Yager (2012) made a comparison between the sediment transport model simulated suspended sediment concentrations (SSCs) and measured concentrations at a gage station. Erosion and deposition processes were simulated with two sediment transport equations and five hydrograph scenarios as a function of high and low SSC. Yaseen et al. (2015) came to the conclusion that intelligence models have been found an appeal in accordance to their advantages (e.g., accurate models, simplicity, less time consuming and less required information). A three-dimensional hydrodynamic and suspended sediment transport model was established by Liu et al. (2016) in order to simulate temporal and spatial variations in suspended sediment in a subalpine lake. Chiang & Hsiao (2011) found if correctly removed from the transport equation of the diffusion term, the Courant number boundary value can be exceeded. The grain saltation was used to perform the essential role in initiating the motion of sediment (Bialik & Czernuszenko 2015). Cavalli et al. (2013) applied the spatially explicit modelling of the watershed via sediment connectivity models and found its potential to reflect the actual three-dimensional landscape to clarify concentrated pathways of sediment transport and zones of active erosion. Climate change impact on water and sediment regulation has also been touched upon. Leong & Donner (2015) evaluated climate change impacts on annual flow, centroid of flow, and timing of spring runoff at a station downstream of oil-sands region of the ARB, including impacts on low-flow frequency. Adem et al. (2016) discovered a synergetic response of increases in temperature and precipitation on mean annual sediment yield in the Upper Gilgel Abay catchment, Blue Nile Basin, in Ethiopia. However, Rodríguez-Blanco et al. (2016) found non-linear responses between changes in climatic variables and sediment concentrations in the Corbeira catchment, Spain as a result of complex interactions between atmospheric carbon dioxide level, climatic forcing, water yield, streamflow, and biomass. Milhous (2005) studied the relationship between the climate change and the corresponding changes in sediment transport capacity in the Colorado Plateau. Yang (2005, 2007) made an analysis of the sediment transport capacity in rivers and the correlations between the total sediment discharge and hydraulic parameters of various conditions.

Among the researches that have been conducted so far, there is generally no differentiation made between the water volume for sediment transport and the net water volume (the net volume of water left with the sediment volume removed from net flow of water), and it is not clear how much water from the total water volume is used to transport the sediment. With the actual water and sediment data (flow, sediment transport, sediment concentration, etc.) measured by the main hydrological stations of the main stream of Liaohe River from 1988 to 2010, this paper used sediment transport method, sediment concentration method and erosion and sedimentation ratio correction method to calculate the amount of sediment transport in different periods of Tongjiangkou, Tieling, Ping'anbao and Liujianfang, and figured out critical water volume for sediment transport in the non-scouring and no-silting situation, attempting to provide some reference for the production practices such as river dredging and management remediation.

SURVEY OF STUDY AREA

The Liaohe River is located between 117°00′-125°30′ east longitude and 40°30′-45°10′ north latitude. It is one of the seven major rivers in China with many tributaries. The Liaohe River originates from the Guangtou Mountain in the Qilaotu Mountain Range in Hebei Province. The upstream is named the Laoha River. It flows northward through Dayushu bordered on with the city of Chifeng and the city of Tongliao in Inner Mongolia and is named the West Liaohe River. The West Liaohe River flows eastward and the Dongliao River flows in Liaoning. After the confluence of the Fudedian in Changtu County, Tieling City, it was named Liaohe River. The Liaohe River flows through cities of Tieling, Shenyang, Anshanand and Panjin in Liaoning Province, and flows into Bohai Sea from Dayi County in the city of Panjin. Fig. 1 shows the map of Liaohe River basin (Qiang et al. 2019).

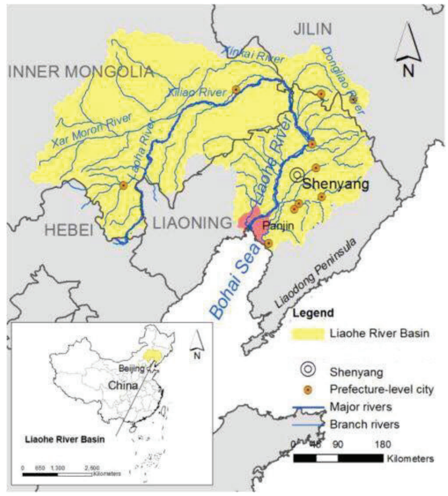


Fig. 1: Map of Liaohe River Basin.

Liaohe River has a high concentration of sediment, ranking the third highest sediment concentration river in China and only next to the Yellow River and Haihe River. As measured by the hydrological station in Tieling reach of Liaohe River, the average annual sediment discharge from 1954 to 2000 was 13.8 million tons and the average annual sediment concentration was 3.09 kg/m^3. The measurement data of the hydrological station in the Zhujiafang reach of Liaohe River shows its average annual sediment discharge was 6.94 million tons from 1969 to 2000 and the average annual sediment concentration is 2.19 kg/m^3. The main stream of Liaohe River is generally categorized as sediment-laden river with less runoff and too much sediment.

IDENTIFICATION OF WATER VOLUME FOR SEDIMENT TRANSPORT USING NET WATER VOLUME METHOD

Calculation Formula

From the correlation between sediment transport efficiency and water volume for sediment transport, following equation is used to calculate the water volume for sediment transport:

$$W' = \eta^{\alpha} \cdot W_{\omega}\text{, in which } W_{\omega} = W - W_s / \gamma_s \qquad \ldots(1)$$

In the equation, W′ is the water volume for sediment transport (m^3), η is sediment transport efficiency, α is exponent (decided by η), W_{ω} is net water volume (m^3), W is the runoff (m^3), W_S is sediment discharge(10^8t), γ_S is sediment volume-weight (usually taken as 2.65t/ m^3).

Here, the calculation method of water volume for sediment transport can be divided into sediment transport method, sediment concentration method and erosion and silting ratio correction method. The sediment transport efficiency η and coefficient α can be determined according to sediment transport method, sediment concentration method and erosion and silting ratio correction method.

The sediment transport efficiency η_1 in the sediment transport method and the sediment transport efficiency η_2 in the sediment concentration method can be expressed by the following formulas:

$$\eta_1 = W_{s;entrance} / W_{s;exit} \qquad \ldots(2)$$

$$\eta_2 = S_{entrance} / S_{exit} \qquad \ldots(3)$$

In which, $W_{s;\ entrance}$ and $W_{s;\ exit}$ are sediment discharge at the river entrance and exit (t), $S_{entrance}$ and S_{exit} are sediment concentration at the river entrance and exit (kg/m^3). When $\eta_1<1$, the sediment discharge of the river entrance $W_{s;entrance}$ being less than that of river exit $W_{s;exit}$, the river reach was scoured and α=1; when $\eta_1\geq1$, sediment transport of river entrance $W_{s;entrance}$ being more than or equivalent to that of river exit $W_{s;exit}$, it came to the sedimentation or scouring and silting balance at the river reach and α=0. When $\eta_2<1$, sediment concentration of river entrance being less than that of river exit, the river reach was scoured and α=1; when $\eta_2\geq1$, sediment concentration of river entrance being more than or equivalent to that of river exit, the river reach saw the sedimentation or scouring and silting balance and α=0.

The balance of scouring and silting is a range, which is generally difficult to accurately grasp. So, for the silting channel in the lower reaches of the Liaohe River, the requirements for the equilibrium state between scouring and silting can be appropriately relaxed. For example, if the sediment deposition ratio is equal to 0.1 or 0.2 and the river channel is approximately in equilibrium state between the scouring and silting (that is, $\eta'_{critical}$ = 0.1 or 0.2), and the correction coefficient A of the scouring-silting ratio associated with the $\eta'_{critical}$ is introduced, and the water volume for sediment transport at different sediment deposition ratios can be calculated by the following formula:

$$W' = (A \cdot \eta)^{a} \cdot W_{\omega}\text{, in which } A = 1 - \eta'_{critical} \qquad \ldots(4)$$

The net water volume W_{ω} and sediment transport efficiency in the scouring-silting ratio correction method can be calculated by formula (2) and formula (3), sediment deposition ratio η′ can be obtained through the following formula:

$$\eta' = \Delta W_s / W_{s;\text{entrance}} = (W_{s;entrance} \cdot W_{s;exit}) / W_{s;entrance} \qquad \ldots(5)$$

In which, $W_{s;entrance}$ is sediment transport volume of river entrance (t), $W_{s;\ exit}$ is sediment transport volume of river exit (t). The correlation between the scouring-silting ratio η′ and sediment transport efficiency η can be found as follows:

$$\eta = 1/(1-\eta') \qquad \ldots(6)$$

When the critical value of η′ is taken as 0.1, according to formula (6), $\eta_{critical}$ equals to 1.11. When $\eta_1<1.11$, α=1; when $\eta_1\geq1.11$, α=0. When the critical value of η′ is taken as 0.2, according to formula (6), $\eta_{critical} = 1.25$, when $\eta_1<1.25$, α stands as 1; when $\eta_1\geq1.25$, α = 0.

Similarly, the unit water volume for sediment transport is calculated based on the amount of water required for every-ton sediment discharge and the computation expression is as follows:

$$q' = W / W_s \qquad \ldots(7)$$

In which, q′ is unit water volume for sediment transport (m^3/t), W′ is water volume for sediment transport (m^3), W_S is sediment discharge (t). Corresponding with the calculation method of water volume for sediment transport, that of unit water volume for sediment transport is also divided into sediment transport volume method, sediment concentration method, and scouring-silting ratio correction method. In the sediment transport method, the calculation of the sediment transport efficiency η is expressed further as follows:

$$\eta = \frac{W_{s;\text{entrance}}}{W_{s;exit}} = \sum_{i=1}^{n} \begin{bmatrix} (Q_{entrance;i} \cdot S_{entrance;i} \cdot t_i) / \\ (Q_{exit;i} \cdot S_{entrance;i} \cdot t_i) \end{bmatrix} \qquad \ldots(8)$$

In which, $W_{s;entrance}$ is the sediment discharge of the entrance station (t); $W_{s;exit}$ is the sediment discharge of exit station (t); i is period unit serial number; $Q_{entrance}$ and $Q_{exit;.i}$ are in-flow rate and out-flow rate (m^3/s); $S_{entrance;i}$ and $S_{exit;i}$ are the sediment concentration of entrance station and exit station (kg^3/m); t_i is the time duration of the first period (s).

Data Sources and Application

According to the collected water and sediment data (flow, sediment transport amount, sediment concentration, etc.) from the five major hydrological stations of the main stream in the Liaohe from 1988 to 2010, the formula (2) was used to calculate the net water volume at each station. With the measured water and sediment data, the relationship can be obtained between water volume for sediment transport and unit water volume for sediment transport at each hydrological station of the main steam of Liaohe River and the average flow rate, average sediment concentration and the incoming sediment coefficient from the Fudedian station.

According to the analysis of the measured water and sediment data in the river channel, the average sediment concentration range during the flood seasons of the Liaohe River in different periods of time can be obtained. The sediment transport amount of each station can be calculated with runoff data of the main hydrological stations.

RESULTS AND ANALYSIS

Correlation Analysis of Water Volume for Sediment Transport of the Year and its Impact Factors

Water volume for sediment transport is defined as the volume of water used to transport certain amount of sediment to next reach of river under certain conditions of water, sediment and river boundary. There is water volume for sediment transport as long as there is transport of sediment, the former refers to the amount of water used for sediment transport in the net water, and the former is a part or the whole of the latter at a ratio closely related to water and sediment conditions as well as sediment transport efficiency. If the entire reach is scoured, the former is less than the latter; if there is a balance of scouring and silting for the reach, the former equals to the latter for all the net water is used for sediment transport.

Water Volume for Sediment Transport of the Year

The results of periodical water volumes for sediment transport at major hydrological stations in the lower reaches of Liaohe River are given in Table 1.

It can be seen from the Table 1 that the average annual water volumes for sediment transport of hydrological stations of Tongjiangkou, Tieling, Mahushan, Ping'anpu and Liujianfang during the flood seasons from 1988 to 2010 were 6.9, 11, 17.6, 16.2 and 17.7×10^8 m^3, respectively; the water volumes for sediment transport during the non-flood seasons were 3, 3.9, 7.5, 5.3 and 9×10^8 m^3, and the annual water volumes for sediment transport were 9.9, 14.9, 25, 21.4 and 26.7×10^8 m^3. The ratios of net water volume to runoff during the flood seasons were 74.3%, 64%, 95.2%, 79.55% and 84.2%, respectively. The ratios of net water volume to runoff during the non-flood seasons were 89.2%, 58.5%, 98.8%, 69.86% and 83.7%; and the ratios of net water volume to runoff on the annual basis were 78.22%, 62.5%, 96.3%, 76.95% and 93.6%, respectively.

From 1988 to 2010, the water volumes for sediment transport recorded by the hydrological stations in the lower reaches of the Liaohe River in the flood seasons, non-flood season and on the whole year basis showed a downward trend with the passage of time. Especially after 1996, the reduction level was significant. From the statistical results of water volumes for sediment transport by periods, since 2000, the period of 2000 to 2005 and 2006 to 2010 witnessed high water volumes for sediment transport and their annual average water volumes for sediment transport varied significantly.

The changes of water volumes for sediment transport of different periods of in lower reaches of Liaohe River were as follows: The Fudedian-Mahushan section had an increasing trend; and the Mahushan-Liujianfang section had a smaller trend along the way. Among them, water volumes for sediment transport during the non-flood season had the most significant increase along the river, and the water volumes for sediment transport on the whole year basis went second and the water volumes for sediment transport in the flood season had a relatively small change along the river.

Table 1: Periodical water volumes for sediment transport at major hydrological stations in the lower reaches of Liaohe River (sediment transport method).

Year	W' Flood Seasons/10^8m^3					W' Non-Flood Periods/10^8m^3					W' Whole Year Periods/10^8m^3				
	Tongjiangkou	Tieling	Mahushan	Ping'anpu	Liu Jianfang	Tongjiangkou	Tieling	Mahushan	Ping'anpu	Liu Jianfang	Tongjiangkou	Tieling	Mahushan	Ping'anpu	Liu Jianfang
1988~1993	10.7	15.7	19.8	18.7	20.6	5.5	7.6	9.8	7.6	10.2	16.2	23.3	29.6	26.3	30.8
1994~1999	13.6	22.6	60.4	61.8	30.4	3.4	2.5	14.0	13.6	14.1	17.0	25.1	74.3	75.4	44.5
2000~2005	0.5	2.7	6.9	5.4	7.8	0.2	1.2	2.2	0.9	3.3	0.7	3.8	9.1	6.3	11.1
2006~2010	3.5	3.9	16.9	14.9	13.2	1.3	2.2	8.7	4.9	5.7	4.8	6.1	25.6	19.8	18.9
1988~2010	6.9	11.0	17.6	16.2	17.7	3.0	3.9	7.5	5.2	9.0	9.9	14.9	25.0	21.4	26.7

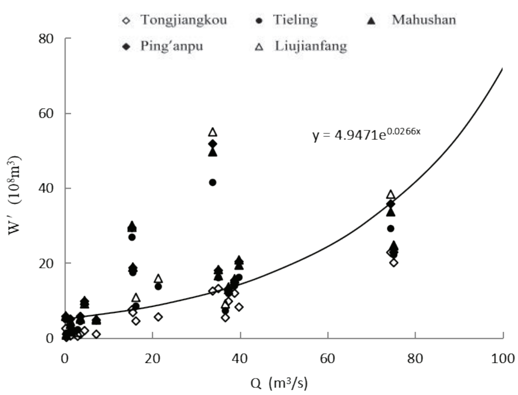
Correlation of Water Volume for Sediment Transport in the Flood Seasons of the Year and its Impact Factors

Fig. 2 shows the correlation between the water volume for sediment transport at the hydrological stations in the lower reaches of the Liaohe River and the incoming sediment at Fudedian station based on the measured water and sediment data. It can be seen from the figure that the water volumes for water transport at the stations during the flood seasons, non-flood periods and whole year periods were exponential with the average flows of the Fudedian station; the water volumes for sediment transport at the hydrological stations increased with the increase of sediment concentration, and decreased with the increase of the incoming sediment coefficient. When the average sediment concentration is greater than 1kg/m^3 or the incoming sediment coefficient is bigger than 0.06, the water volumes for sediment transport at each station during the flood seasons were relatively stable at about $10\times10^8 m^3$.

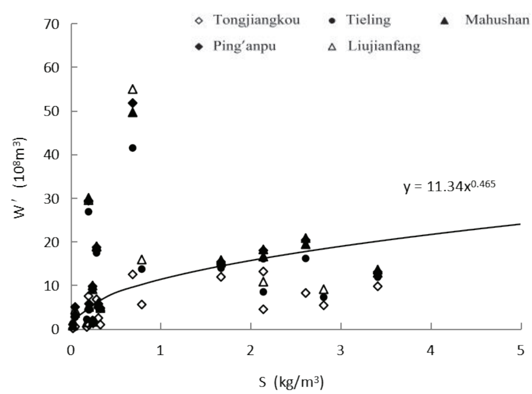
In Fig. 2, the correlation between water volumes for sediment transport at the hydrological stations and the incoming sediment of Fudedian station can be expressed by the following formula:

$$w=-4.9\ln S/Q+2.201 \quad \ldots(9)$$

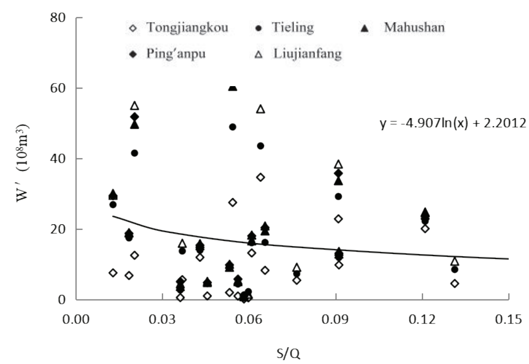
In which, W' is water volumes for sediment transport at the hydrological stations ($10^8 m^3$); Q is the average flow at Fudedian station during the flood seasons (m^3/s); S is the average sediment concentration at Fudedian station during



(a)



(b)



(c)

Fig. 2: The correlation between water volume for sediment transport at the hydrological stations along the lower reaches of Liaohe river and the incoming sediment of Fudedian station from 1988 to 2010: (a) The correlation between water volume for sediment transport and the average flow; (b) The correlation between water volume for water transport and the average sediment concentration; (c) The correlation between water volume for sediment transport and incoming sediment coefficient

the flood seasons (kg/m^3); S/Q is the incoming sediment coefficient at Fudedian station during the flood seasons.

The annual average unit net water volume of the stations of Tongjiangkou, Tieling, Mahushan Ping'anpu and Liujianfang between 1988 and 2010 were 1780.7, 2098.8, 2183, 1534.1 and 1563.4m^3/t in flood seasons, and 6653.9, 4581.5, 6154.6, 1801.4 and 3130m^3/t in non-flood seasons, and 1242.8, 2274.9, 2740.4, 1325.7 and 1541.5m^3/t on the whole year basis. The change of unit net water volume of each station in the flood season, non-flood period and on the whole year basis corresponded with the change law of the average sediment concentration in their corresponding periods. Generally, the lowest happened in the flood seasons; the highest took place in the non-flood period and the change on the whole year basis was between them. The year-on-year changes did not show a significant increased or decreased trend.

Correlation Analysis of Unit Water Volume for Sediment Transport and its Impact Factors

Unit water volume for sediment transport is defined as the volume of water used to transport unit amount of sediment to next reach of river under certain conditions of water, sediment and river boundary, which is directly related to water volume for sediment transport and volume of sediment transport, as well as sediment transport efficiency and net water volume per unit. Because water volume for sediment transport is influenced by many factors, such as volume of runoff, sediment transport, average runoff volume, average sediment concentration, coefficient of incoming sediment, sediment quantity of scour-silt, volume and ratio of scouring and silting, sediment transport efficiency, fluvial facies coefficient, and grain composition, etc., especially with a close relationship with runoff volume. Under natural circumstances, runoff volume of the same reach changes a lot at different times, therefore water volume for sediment transport often fluctuates greatly, by contrast, unit water volume for sediment transport is relatively stable which reflects the relationship between water volume for sediment transport and volume of sediment transport and is more capable of reflecting the sediment transport features of the reach.

Unit Water Volume for Sediment Transport

The result of periodical unit water volumes for sediment transport at major hydrological stations in the lower reaches of Liaohe River (sediment transport method) are given in Table 2.

Sediment transport at major hydrological stations in the lower reaches of Liaohe River by sediment transport method (Table 2), it can be found that: The annual average unit water volume for sediment transport of stations at Tongjiangkou, Tieling, Mahushan Ping'anpu and Liujianfang from 1988 to 2010 were 935.5, 776.4, 1870.6, 1001.5 and 1099.1m^3/t in flood seasons; 2970.6, 1984.2, 5140.8, 907.7 and 2830.7m^3/t in non-flood periods; and 772.1, 899.9, 2551.5, 809.5 and 1310.9m^3/t in unit year. The proportion of the annual average unit water volumes for sediment transport to the unit net water volumes at each of the hydrological stations from 1988 to 2010 were 52.53%, 36.99%, 85.69%, 65.28% and 70.3% in flood seasons; 44.64%, 43.31%, 83.53%, 50.39% and 90.44% in non-flood seasons and 62.12%, 39.56%, 93.11%, 61.06% and 85.04% on the whole year basis.

The unit water volumes for sediment transport at each station along the lower reaches of the Liaohe River from 1988 to 2010 displayed an increasing trend with the passage of time in the flood seasons, non-flood seasons as well as on the whole year basis. The increase turned more significant after 2002.

The unit water volumes for sediment transport at the low-

Table 2: Periodical unit water volumes for sediment transport at major hydrological stations in the lower reaches of Liaohe River (sediment transport method).

Year	q' Flood Seasons (m^3/t)					q' Non-Flood Periods (m^3/t)					q' Whole Year Periods (m^3/t)				
	Tongjiangkou	Tieling	Mahushan	Ping'anpu	Liu Jianfang	Tongjiangkou	Tieling	Mahushan	Ping'anpu	Liu Jianfang	Tongjiangkou	Tieling	Mahushan	Ping'anpu	Liu Jianfang
1988-1993	199	239	400	310	479	902	784	1503	420	1172	201	334	506	374	496
1994-1999	382	636	2003	1127	710	534	554	735	1053	2088	373	516	351	477	766
2000-2005	1386	1626	1714	851	1566	6326	6005	11736	690	10209	629	1592	3899	510	2271
2006-2010	1902	825	3666	1861	1750	4718	1066	6868	1580	1869	2029	1132	4368	1637	1630
1988-2010	935	776	1871	1002	1099	2971	1984	5141	908	2831	772	900	2551	810	1311

er reaches of Liaohe River showed little change in different time periods along the river. There was a slight increasing trend for unit water volume for sediment transport in flood seasons, non-flood seasons and on the whole year basis, with Mahushan station showing the more significant change than others, thus indicating a stronger river sediment transport capacity in the lower reaches of Liaohe River.

Correlation of Unit Water Volume for Sediment Transport in the Flood Seasons and its Impact Factors

Fig. 3 shows the correlation between water volumes for sediment transport at the hydrological stations during flood seasons and the incoming sediment of Fudedian station based on the measured water and sediment data. It can be found that the water volumes for water transport at the stations during the flood seasons, non-flood periods and whole year periods were logarithmically related to the average flow of Fudedian station in the flood seasons. The water volumes for sediment transport decreased with the increase of incoming sediment coefficient and that trend was most significant in terms of unit water volume for sediment transport and the corresponding incoming sediment coefficient. When the average sediment concentration at the Fudedian station was less than 4 or incoming sediment coefficient was less than 0.15, there was a smaller value range for unit water volume for sediment transport at the hydrological stations and the point group was more concentrated. When the average sediment concentration of Fudedian station was larger than 40kg/m^3, the water volumes for sediment transport at each station during the flood season remained relatively stable, and the value was about 450m^3/t.

As shown in Fig. 3, the correlation between the unit water volumes for sediment transport at the stations during the flood seasons and the average flow, average sediment concentration and incoming sediment of Fudedian station can be expressed by following formulas respectively:

$$q' = -189\ln(Q) + 1025 \quad \ldots(10)$$

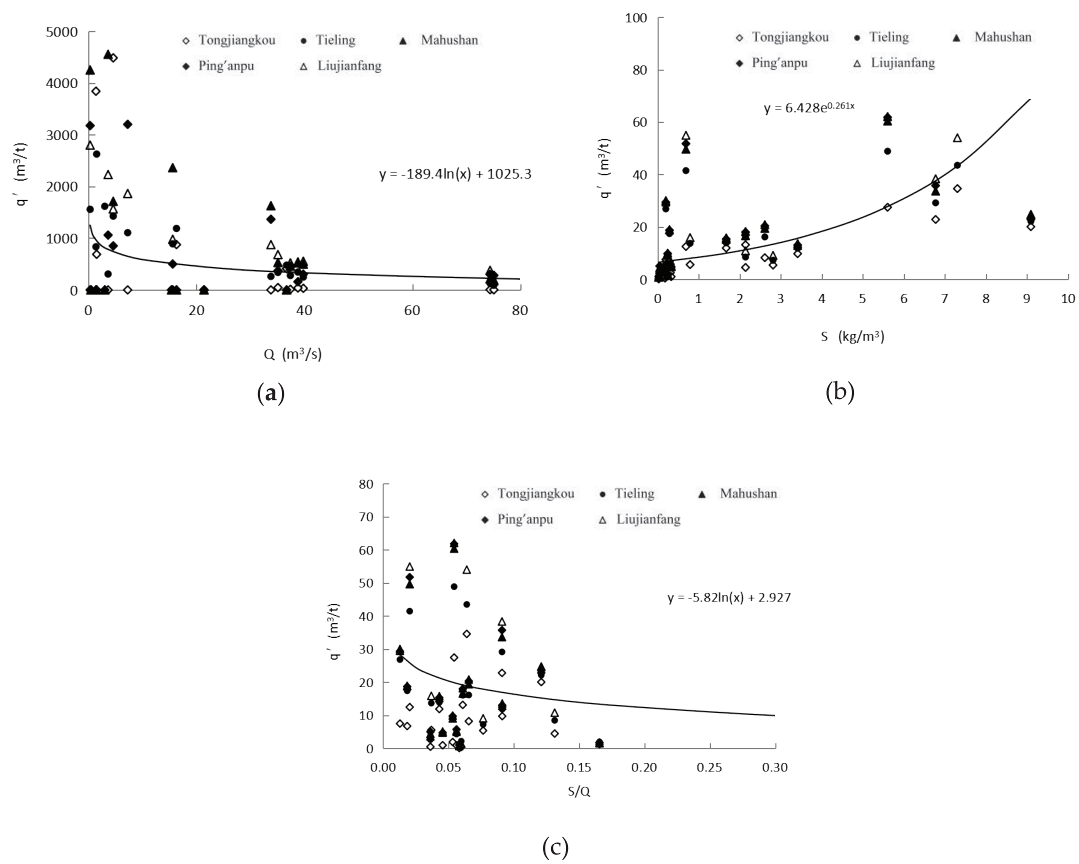


Fig. 3: The correlation between water volumes for sediment transport at the hydrological stations during flood seasons and the incoming sediment of Fudedian station based on the measured water and sediment data from 1988 to 2010: (a) The correlation between water volume for sediment transport and average flow; (b)The correlation between water volume for sediment transport and average sediment concentration; (c) The correlation between water volume for sediment transport and incoming sediment coefficient.

$$q' = 6.428e^{0.261S} \quad \ldots(11)$$

$$q' = -5.82\ln(S/Q) + 2.927 \quad \ldots(12)$$

In which, q is water volume for sediment transport at the stations during the flood seasons (m^3/t); Q is the average flow of Fudedian station during flood seasons (m^3/s); S is the average sediment concentration of Fudedian station during flood seasons (kg/m^3); S/Q is the incoming sediment coefficient of Fudedian station during the flood seasons.

Non-Scouring and Non-Silting Critical Water Volume for Sediment Transport of Typical Reaches of the Main Stream of Liaohe River

There are many factors influencing the sediments in the main stream of Liaohe River. As the main source of sand in the downstream of Liaohe River, Liuhe River's sand is not only large in amount but also coarse in size, which constitutes the major reason for the main stream being sand-laden and sediments in the river channel. Therefore, we prioritize our research on the influence of afflux of Liuhe River on sediments in the river channel and referred to the nearby 4 hydrological stations: Tieliang, Mahushan, Ping'anpu and Liaozhong for data (Fig. 4 for the major hydrological stations in the main stream of Liaohe River). Using the sediment discharge and runoff data of each station, we applied the knowledge on water volume for sediment transport and sediment transport efficiency to calculate the sediment discharge of the four hydrological stations with relevant formulas. The four stations' water volumes for sediment transport were worked out by calculation with diameters. We also established the relationship between scouring and silting volume and water volume for sediment transport and determined the critical points of water volume for sediment transport in the non-scouring and non-silting situation. When the water volume is equitable to or more than the value, the sediment will not be deposited. The result can provide some reference for the work of river channel dredging.

The correlation between the annual scouring and silting amount and water volume for sediment transport measured at the four hydrological stations is given in Table 3. Table 4 shows the regression equations established through linear fitting and the squared value of the relevant coefficients.

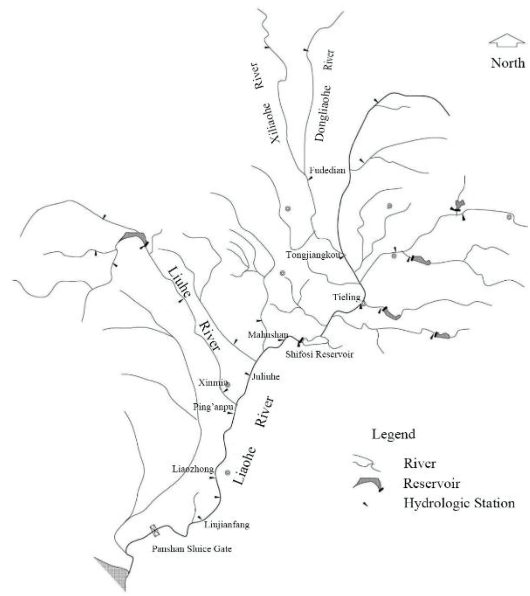


Fig. 4: Distribution diagram of the major hydrological stations in the main stream of Liaohe River.

Sediment discharge method was used to calculate the annual scouring and silting amount of each hydrological station, the relations between water volume for sediment transport and scouring and silting amount are shown in Fig. 5. The formula of the linear fitting for Fig. 5 is:

$$Dep = aQ - b \quad \ldots(13)$$

In which Dep is sediment discharge; Q is water volume for sediment transport; a, b are positive constants. Through differential on the two ends of the formula, the following was obtained:

$$dDep/dQ = a \quad \ldots(14)$$

The a in the formula represents the quantity of sediment transported by the water volume for sediment transport.

As is shown in Fig. 5, each regression line has an intersection with the straight line Dep=0, and water volume for sediment transport corresponding to the intersection makes the scouring and silting amount be zero. The intersection point can be regarded as the critical point of scouring and silting, and the corresponding water volume for sediment

Table 3: Water volume for sediment transport of the hydrological stations in the main stream of Liaohe River after the afflux of Liuhe River (in $10^8 m^3$).

Year	Annual Water Volume for Sediment Transport ($10^8 m^3$)			
	Tieling	Mahushan	Ping'anpu	Liaozhong
1988-1999	24.18	36.02	34.72	36.13
2000-2007	3.61	10.32	12.17	7.02
1988-2007	15.95	23.17	23.45	25.41

transport is the critical water volume for sediment transport. When the amount of the incoming water to transport sediment is more than the critical water volume for sediment transport, the river channel is seen as scoured, i.e. the sediment storage is reduced; when the amount of incoming water to transport sediment is less than the critical water volume for sediment transport, there is a silting in the river channel, i.e. the sediment storage increases. When letting the left end of the formula (13) be 0, the formula can work out the water volumes for sediment transport at the critical points of sediment storage and discharge as:

$$Q = b/a \tag{15}$$

Using the above method, we figured out the scouring and silting amount of per ton sediment and the critical water volume for sediment transport, i.e. non-scouring and non-silting critical water volume for sediment transport (Table 4).

Based on the net water volume method to calculate the amount of water required for sediment transport as above-mentioned and according to the hydrological characteristics of different reaches of the river, we proposed the corresponding hydraulic sediment dredging model as guidance for practical projects of hydraulic sediment dredging. The core of the technology is to use the years of data on sediment transport to work out the critical water volume for sediment transport with which the water amount required for hydraulic sediment transport can be determined. When the incoming water volume for sediment transport is larger than the critical water volume for sediment transport, the river channel is scoured, i.e. the storage of sediment decreased in the channel. When the incoming water volume for sediment transport is less than the critical water volume for sediment transport, the river channel is silted, i.e. there is an increase of sediment storage in the channel.

According to the analysis, floods of Liuhe River, which

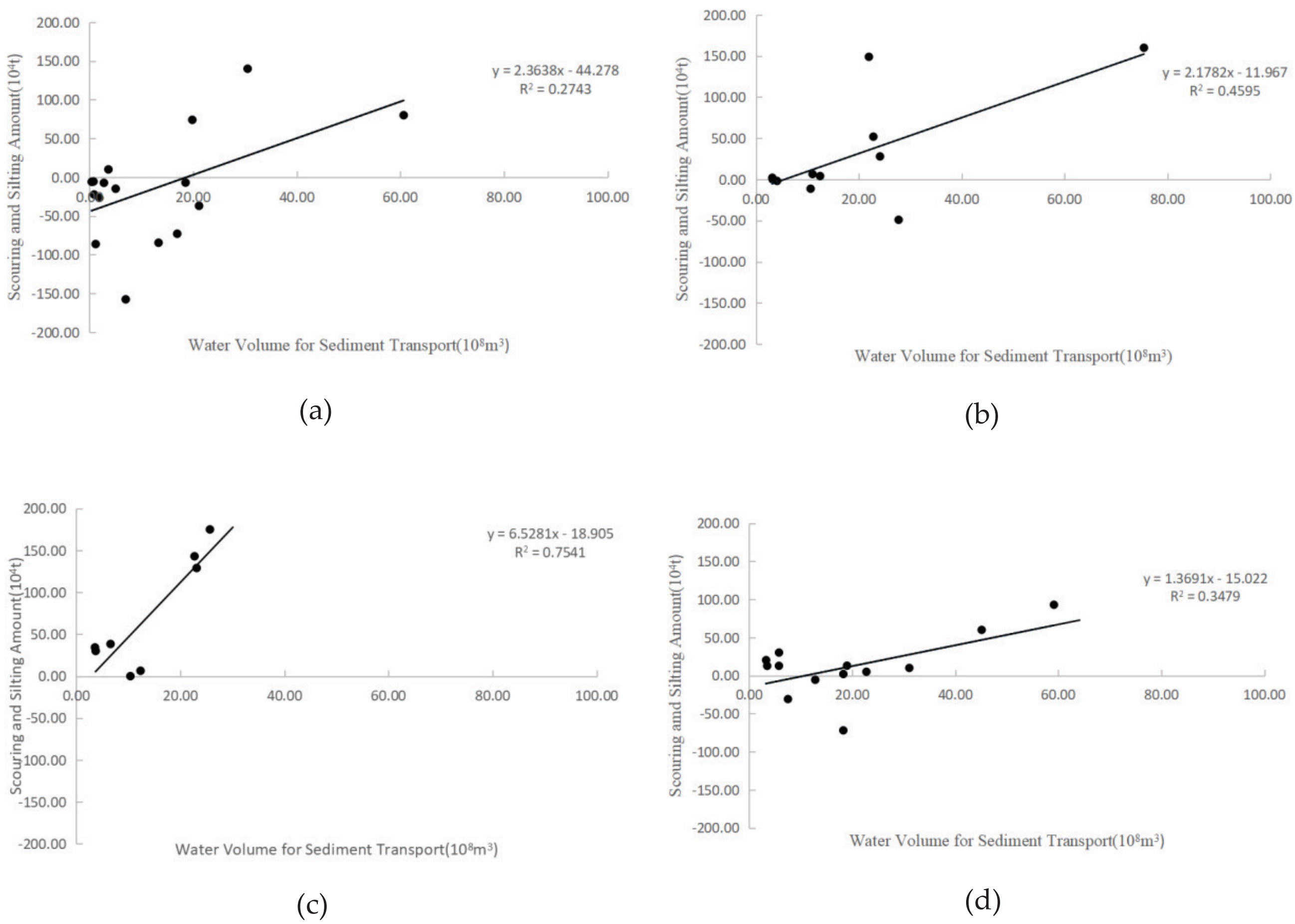


Fig. 5: The relationship between the water volume for sediment transport and scouring and silting amount in each hydrological station: (a) Tieling station; (b) Mahushan station; (c) Ping'anpu Station; (d) Liaozhong Station

Note: The positive value of the ordinate in each figure is the amount of sedimentation, Negative value is the amount of flushing.

Table 4: Model of water demand for hydraulic sediment dredging in the major reaches of the main stream of Liaohe River.

Reach	Regression Equation	Squared Value of Relevant Coefficient, r^2	Non-scouring and Non-Silting Critical Water Volume for Sediment Transport (10^8m^3)	Sediment Discharge by Unit Water Volume for Sediment Transport (10^4t)
Tieling	y=2.364x-44.278	0.274	18.73	2.364
Mahushan	y=2.178x-11.967	0.460	5.49	2.178
Ping'anpu	y=6.258x-18.905	0.754	2.90	6.528
Liaozhong	y=1.369x-15.022	0.348	10.97	1.369

Note: The function in the table indicates the relationship between the sediment deposition of per ton incoming sand and the critical water demand for sediment transport.

are highest in sediment concentration, normally would not meet with the floods of the upstream. The sand of Liuhe River going into Liaohe River often clogged the river channel. Though the sand could be washed away afterwards by the floods of the main stream, it would often silt up the Liaohe River channel at the upstream and downstream of Liuhe River mouth. According to the theoretical calculation, the water demand model for hydraulic sediment dredging in the major reaches of the main stream of Liaohe River was determined and there is linear function relationship between the sediment discharge and the water demand. Specifically, when the water amount in the Tieling reach is more than $18.73\times10^8m^3$, in the Mahushan reach more than $5.49\times10^8m^3$, in the Ping'anpu reach more than $2.90\times10^8m^3$, and in Liaozhong reach more than $10.97\times10^8m^3$, the channel can keep sediment from silting.

DISCUSSION

The water volume for sediment transport of Liaohe River, a sediment-laden river, is influenced by various factors, such as its sediment discharge, rainfall and stream discharge and so forth. The average water volume for sediment transport during flood seasons for Liaohe river from 1988 to 2010 is $13.88\times10^8m^3$, and that during non-flood seasons is $5.74\times10^8m^3$. The research of Yan et al. (2004) showed that the average water volume for sediment transport in downstream of the Yellow River during flood seasons from 1950-2000 is $182.37\times10^8m^3$, and that during non-flood seasons is $107.84\times10^8m^3$. There is a difference in water volume for sediment transport of the two rivers with a method of net water volume, indicating that the results are influenced by rivers' sediment concentration. Meanwhile, both of the water volumes for sediment transport of the two rivers during flood seasons is higher than that during non-flood seasons, indicating that water volume for sediment transport is influenced by rainfall. The annual precipitation in downstream of the Yellow River is around 435mm (Wu et al. 2000), while that of Liaohe River is 700mm, the comparison of water volume for sediment transport of the two rivers shows that the water volume for sediment transport of the Yellow River during flood seasons is 10 times as much as that of Liaohe River, and 20 times during non-flood seasons, indicating that the water volume for sediment transport is influenced by rainfall, and is related to the fact of higher sediment concentration and greater gravity of stream.

By calculation, there is an exponential relationship between the annual water volume for sediment transport in main stream of Liaohe River no matter in flood or non-flood seasons and the average water discharge in Fudedian station in flood seasons, and a logarithmic relationship for unit water volume for sediment transport. Yan et al. (2004) took the same method and drew the conclusion that there is an obvious linear relationship between the annual water volume for sediment transport as well as unit water volume for sediment transport of the Yellow River no matter in flood or non-flood seasons and the average water discharge in Xiaolangdi station in flood seasons. Therefore, we can conclude that there is a different relationship with the same method being applied to different rivers, and the different results are caused by rivers' sediment concentration and other features.

The average annual unit water volume for sediment transport is a good indicator of river sediment conditions. By calculation, it is $1136.62m^3/t$ in Liaohe River during flood seasons and $2766.8m^3/t$ during non-flood seasons, while $28.90m^3/t$ and $84.89m^3/t$ in the Yellow River respectively. The study of Yan et al. (2004) shows that the unit water volume for sediment transport of the Yellow River is 40 times as much as that in Liaohe River, because the Yellow River carries a great volume of sediment which ranks the top of the world, with an annual sediment discharge of $37.8kg/m^3$, and an average annual volume for sediment transport up to 16×10^8t (http://www.waterpub.com.cn/jhdb/DetailRiver.asp?ID=8, 2015). Meanwhile, the average sediment concentration in the main stream of Liaohe River is $3.6kg/m^3$, the annual sediment transport volume is 2.1×10^7t (http://www.yellowriver.gov.cn/hhyl/hhgk/qh/szyl/201108/t20110814_103518.html, 2011), the results show that there is quite a higher sediment concentration in the Yellow River. Silt carrying stream has a better sediment carrying capacity than clean stream, the above mentioned results also confirm that the net water volume method is applicable to the calculation of sediment transport volume in sediment-laden rivers.

CONCLUSIONS

The calculation results using the net water flow method show that:

1. According to the hydrological data of the hydrological stations of Tongjiangkou, Tieling, Mahushan, Ping'anbao and Liujianfang from 1988 to 2010, the annual average water volume for sediment transport and unit water volume for sediment transport of the main stream of Liaohe River are calculated to be $13.88\times10^8 m^3$ and 1136.62 m^3/t respectively.
2. From 1988 to 2010, the unit water volume for sediment transport of the main stream of the Liaohe River in the flood season, non-flood period and whole year showed an increasing trend with time, and it was logarithmically related to the mean flow of the Fudedian station in the flood season. The water volume for sediment transport decreases with increase of the average water flow and coefficient of incoming sediment and increases with the increase of sediment concentration.
3. When the average sediment concentration in the Fudedian station is less than 4 kg/m^3 or the incoming sediment coefficient is less than 0.15, the unit sediment water volume for sediment transport has a smaller value range. When the average sediment concentration is more than 40kg/m^3, the water volume for sediment transport of each station is relatively stable during the flood seasons, and the value was about 450m^3/t.
4. According to the model of water demand for dredging of the main reaches of the main stream of the Liaohe River, there was a functional relationship between sediment transport volume and its water demand. If the river keeps sediment from silting, the water demand of the Tieling section needs to be larger than $18.73\times10^8 m^3$. And the number needs to be larger than $5.49\times10^8 m^3$ at Mahushan reach, larger than $2.90\times10^8 m^3$ at Ping'anpu reach, and larger than $10.97\times10^8 m^3$ at Liaozhong reach.

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