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Influence of Different Particle Sizes of Sediments on the Lower Reaches of the Basin and its Significance in the Liao River Governance

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ABSTRACT

Based on the sand volume and sedimentation volume data for different particle size (PS) groups, the relationship between the annual scouring and silting amount of the Juliu River-Liujianfang section and the yearly sediment volume entering the downstream river channel was established. The critical values of sediment storage and release for the downstream river channel were obtained. It was found to decrease with an increase in the sediment particle size. The correlation coefficient between the annual scouring and silting amount of the Juliu River-Liujianfang section and the annual sediment volume entering the downstream river channel increased with the coarsening of sediment PS. It indicated that the sediment size was proportional to the sediment amount (SA) entering the river channel. As the sediment size increased, the deposition amount increased due to the variation of unit sediment amount. Based on the treatment and achievement of source areas with sediment sizes larger than 0.05 mm, it is significant to concentrate on treatment areas with sediment sizes larger than 0.10 mm.

INTRODUCTION

The PS characteristics of sediment transport and its impact on river sedimentation are important theoretical issues. Many studies have been carried out that have played an important role in solving the siltation in the lower reaches of rivers (Schumm 1977, Walling & Kane 1984, Walling & Moorehead 1987). The sediment deposition in the lower reaches of rivers depends on the SA from the midstream and the granular composition of the sediments. Based on data statistics, Qian obtained the discharge ratio of sediments with different particle sizes. Moreover, the sedimentation laws of the Yellow River were proposed for sediments of sizes greater than 0.10 mm, 0.05-0.10 mm, 0.025-0.05 mm, and less than 0.025 mm (Ning 1980). Xu suggested that 0.455t of sediment was deposited in the lower reaches of the Yellow River for each ton of sediment from the coarse sediment areas (Xu 2008, 2007). It was also found that the sedimentation amount in the lower reaches of the Yellow River was 0.154t, almost three times as large as the delicate sediment areas. By restricting the coarse and fine discharge through Xiaolangdi Reservoir and reducing the coarse sediment into the lower reaches of the Yellow River, the siltation in the lower reaches of the Yellow River was reduced.

Similarly, it is important to solve the sediment siltation in the lower reaches of the Liao River. Our research is aimed at studying the erosion and siltation behavior of sediments of different sizes in the lower reaches of the Liao River.

An Overview of the Research Area

The area of study is the lower reaches of the Liao River. It begins from the Juliu River and ends at Liujianfang, with a length of 119.8 km. The middle and lower reaches of the Liao River were originally flooded by the river and accumulated over a long time. Therefore, the terrain is flat, and the river channel ratio ranges from 0.14 to 0.3‰. According to the multi-year average, before the construction of Shifo Reservoir, the sediment into the downstream channel was 1316×10^4t per year, with only 987×10^4t sediment entering the sea and 329×10^4t sediment accumulating on the riverbed. The main siltation site is Liukou delta, below Xinmin Station, which rises at a rate of 4~8cm per year and becomes a suspended river. With regard to the entire downstream river channel, there is no tributary recirculation. Only the Liu River in the upper part of the Liao River enters. The water and sediment in the interval have little influence on the sedimentation process. Therefore, the river channel in the lower reaches of the Liao River provides an ideal place for studying the response process of the river channel deposition to input water and sediment (Fig. 1).

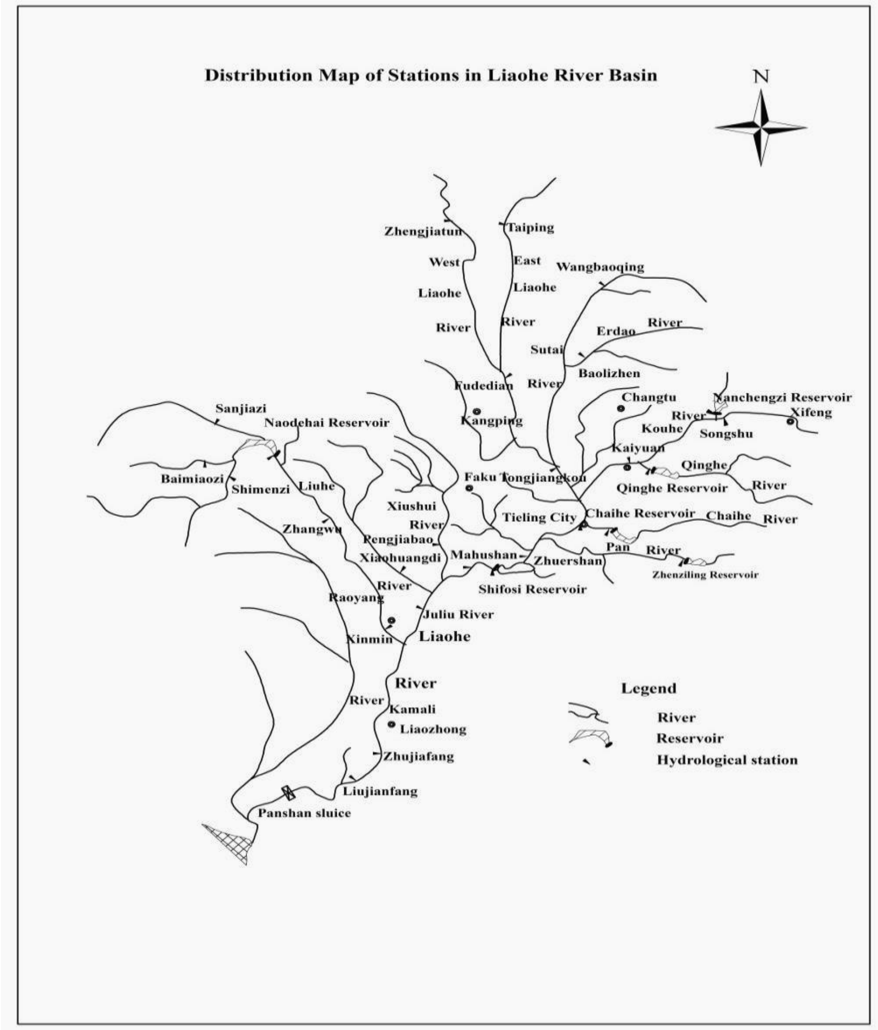

Fig. 1: The map depicting the river network and the hydrometric stations for the middle and lower reaches of the Liao River.

MATERIALS AND METHODS

Source of Data

The Juliu River station is the water and sediment inlet control station for the mainstream in the lower reaches of the Liaohe River. Liujianfang is the entering sea control station, and the section tributary is the Liu River. The amount of water and sediment in the sink is represented by Xinmin Station. According to the principle of sediment balance (Xu 2007, Hao et al. 2015), the amount of sedimentation-siltation in the lower reaches of the Liao River is obtained by the following equations:

Dep = Input sediment amount – output sediment amount

$$= Q_{s,j} + Q_{s,x} - Q_{s,l}, \quad \ldots(1)$$

Where $Q_{s,j}$ the sediment amount is in JuLiuRiver station, Xinmin station, and Liujianfang station, respectively. The total amount of sediment scouring and silting with different particle sizes can be calculated by the input sediment amount (ISA) and output sediment amount with different PSs, namely:

Dep_i = Input sediment amount of particle size i

- Output sediment amount of particle size i …(2)

$$= Q_{s,j,i} + Q_{s,x,i} - Q_{s,l,i}$$

Where $Q_{s,j,i}$, $Q_{s,x,i}$, $Q_{s,l,i}$ are the SA of PS i for JuLiu River station, Xinmin station, and Liujianfang station, respectively. As the hydrological stations are in the lower reaches of Liao River, the PS of suspended sediment can be divided into the following six levels: (1) <0.007mm (2) 0.007mm~0.01mm; (3) 0.01mm~0.025mm; (4) 0.025mm~0.05mm (5) 0.05mm~0.10mm; (6)>0.10mm. Moreover, i represents any one of these grades.

The hydrological, sediment and sediment PS data used in this paper were all obtained from the above hydrological stations. Sediment particle size data collection was limited to the year 2005 as the Shifo Reservoir was built in the middle reaches of the Liao River after that. It is also important to note that, for the downstream river sections, the construction of rubber dams and other water conservancy projects have greatly affected the natural process of river sediment transport. Therefore, the data period of this paper is from 1988 to 2005.

Research Methodology

This paper uses statistical methods to study the effect of sediment PS on sediment deposition in the lower reaches of the Liao River. The sedimentation for the five particle sizes below JuliuRiver-Liujianfang is calculated by using the sediment-receiving amount and the suspended sediment PS data of each station: (1)>0.007mm; (2)>0.01mm; 3)>0.025mm; (4)>0.05mm; (5)>0.10mm. There were 6 groups of data obtained by adding the annual silt amount. The ISAs of the above six groups were obtained according to the PS group, i.e., the sum of SAs for the JuLiu station and the Xinmin station. The relationship between the annual sluicing amount and the ISAs of the six groups was then established. Thus, the relationship between the sediment deposition in the Liao River's lower reaches and the PS group's PS variation is discussed, and the critical points can be determined (Xu et al. 2006, Chang 2003, Yan & Zhang 2007).

RESULTS AND DISCUSSION

The Relationship Between the Scouring-Silting Amount and the ISA with Six Particle Size Groups

As shown in Fig. 2, the relationship between the annual scouring-silting amount of Julihe-Liujianfang and the input sediment volume of PS groups was ascertained. The regression equation's linear regression and the correlation coefficient's squared value were also ascertained. The significance of the correlation coefficient was tested, and the results showed that the correlation is significant while the significance probability is less than 0.01. The results of the statistical analyses are listed in Table 1. The linear fitting equation in each graph is shown as follows:

$$Dep = aQ_{s,input} - b, \quad \ldots(3)$$

where *Dep* is the sluicing amount, $Q_{s,\ input}$ is the ISA, and a and b are the positive constants. After differentiating two ends of the upper type, we obtain:

$$dDep/dQ_{s,input} = a. \quad \ldots(4)$$

This indicates that the coefficient a of the regression equation can represent the change in the amount of deposition caused by the change in the amount of input sediment per unit, that is, the amount of sediment per ton of sediment.

As shown in Fig. 2, each regression line has an intersection with the line of Dep=0, and the ISA corresponding to the intersection leads to zero sedimentation amount. The intersection point can be regarded as the critical point of erosion and siltation. This can be called the storage-release critical point. The corresponding ISA is the critical ISA. When the ISA is greater than the critical ISA, the river channel appears silted, with the sediment storage increasing. The river channel is scoured when the ISA is less than the critical ISA, and the sediment storage is reduced. As Dep in equation 3 becomes zero, we can obtain the ISA corresponding to the storage-release critical point of sediment:

$$Q_{s,input} = b/a. \quad \ldots(5)$$

According to the above method, the sedimentation amount per ton of sediment and the sedimentation threshold corresponding to the sediment storage release (the critical value of the input sediment without sluicing) are obtained in Table 1.

Figs. 2(a)-(f) show the results of subtracting a finer PS group from the whole sediment. A comparison can be used to ascertain how the channel responds to the gradual thinning of sediment. The following recognition can be obtained according to Fig. 2 and Table 1.

(1) The correlation coefficient between the annual scouring-silting amount of the JuLiu River-Lijianjian section and the annual amount of sediment entering the downstream channel increases with the coarsening of the sediment PS group. As the sediment size increases, the relationship between SA and river siltation increases. The correlation coefficient with sediment size is shown in Fig. 3. It can be seen that for the three sediments of whole sediment, >0.007 mm and >0.01 mm, the correlation coefficient slightly increases with the coarsening of PS at a low rate. As for three coarser-grade sediments of >0.025 mm, >0.05 mm, and >0.10 mm, this correlation coefficient rapidly increases as the PS increases. For sediments of >0.05 mm and >0.10 mm, the square of correlation coefficient R2 is 0.7898 and 0.9256. It is suggested that the coarse sediment of >0.05mm is closely related to the sedimentation of the lower reaches of the Liao River, while the coarse sediment of >0.10mm is even closely related to the sedimentation of the lower reaches of the Liao River.

(2) The sedimentation amount variation caused by the unit amount variation of input sediment increases as the PS increases (Fig. 4). As for three sediments of whole

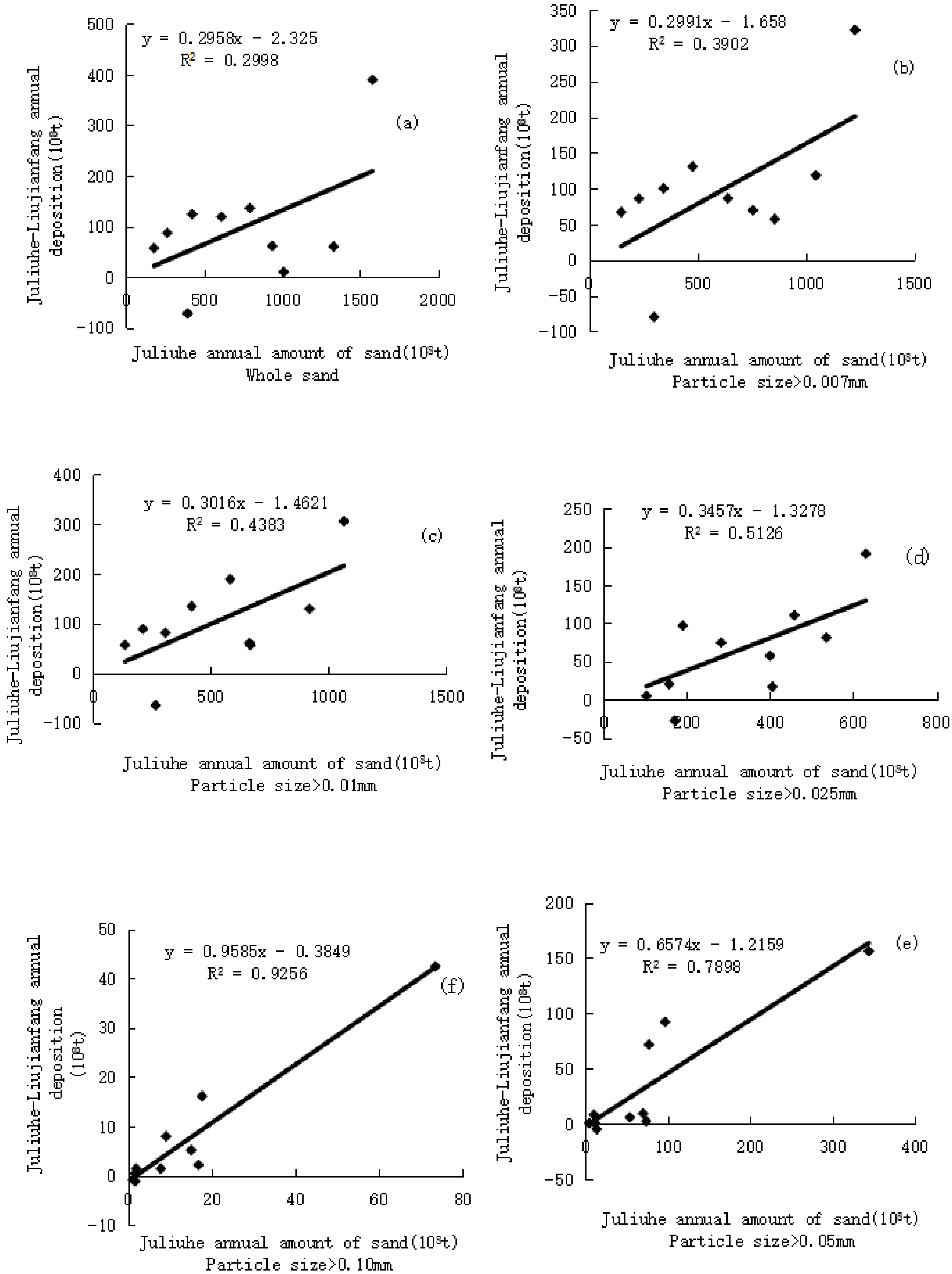

Fig. 2: The relationship between the annual deposition of JuLiu River to Liujianfang with 6 size groups and the annual sediment amount of the corresponding group. Comment: (a) whole sediment; (b) particle size > 0.007 mm; (c) particle size > 0.01 mm; (d) particle size > 0.025 mm; (e) particle size > 0.05 mm; (f) particle size > 0.10 mm.

Table 1: The relationships and the results of statistical analysis between annual deposition (y) of group size six and sediment input (x) of the corresponding group.

Project	Regression equation	Correlation coefficient squared value R2	Correlation coefficient squared value	Critical value of input sediment that does not rush and does not deposition	Deposition amount of per ton input sediment [t]
Suspended whole sediment	y=0.2958x-2.325	0.2998	<0.01	7.860	0.2958
>0.007 mm Sediment	y=0.2991x-1.658	0.3902	<0.01	5.543	0.2991
>0.01 mm Sediment	y=0.3016x-1.4621	0.4383	<0.01	4.848	0.3016
>0.025 mm Sediment	y=0.3457x-1.3278	0.5126	<0.01	3.197	0.3457
>0.05 mm Sediment	y=0.6574x-1.2159	0.7898	<0.01	1.616	0.6574
>0.1 mm Sediment	y=0.9585x-0.3849	0.9256	<0.01	0.402	0.9585

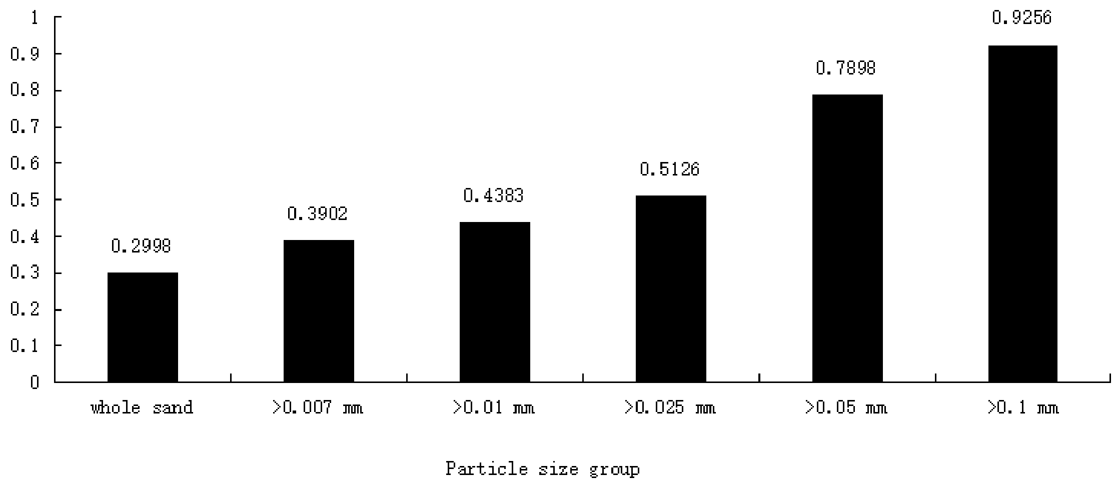

Fig. 3: The correlation coefficient changes pertaining to annual deposition and the amount of annual sediment entering the river course in the lower reaches of the Liao river following the particle size group.

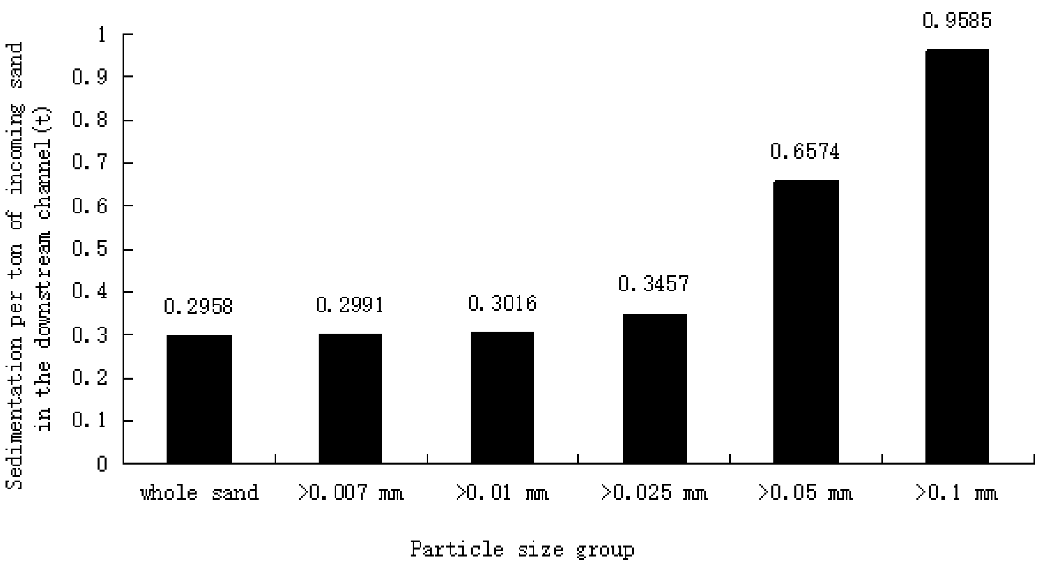

Fig. 4: The changes of the volume per ton sediment deposition of the various size groups in the river course of the lower reaches of Liao river with group size.

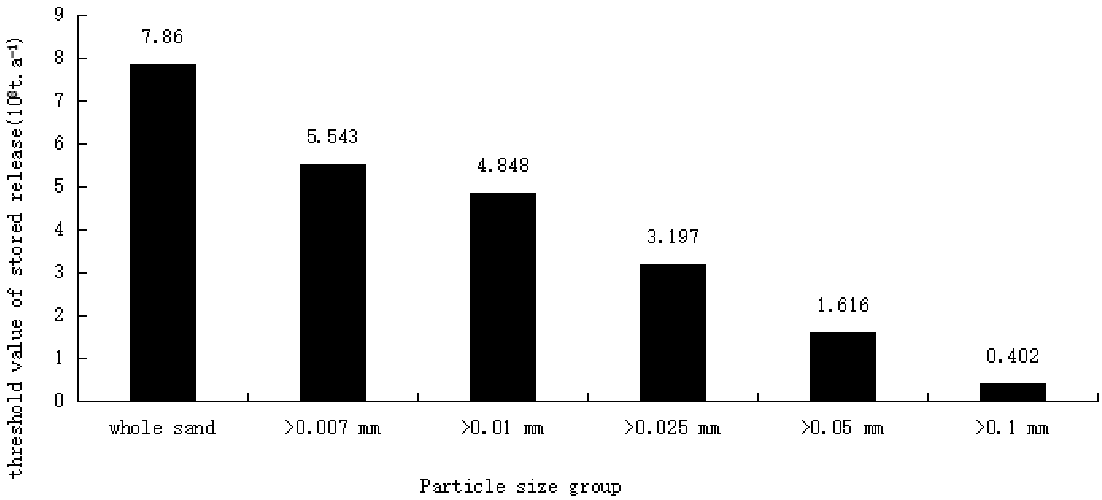

Fig. 5: The changes in the critical value of the incoming sediment from storage to release, with a sediment-size group.

sediment, >0.007mm and >0.01mm, the correlation coefficient between the amount of sedimentation and siltation is not high, so the SA is returned according to the amount of sedimentation and siltation. The SA variation caused by the unit amount variation of input sediment, estimated by the equation, is selected for reference. There is not much change in the value for the three fine PS groups, approximately 0.3 t. As for three coarser-grade sediments of >0.025mm, >0.05mm, and >0.10mm, this value rapidly increases with the PS increase, which is 0.3457t, 0.6574t, and 0.9585t, respectively. It is found that 34.57% of sediment >0.025mm, 65.74% of sediment >0.05mm, and 95.85% of sediment >0.10 mm entering the downstream channel is deposited in the channel. In the upper and middle reaches, the reduction effect of sediments greater than 0.10 mm is 1.458 times larger than 0.05mm and 2.773 times larger than 0.025mm.

The sediment transportation ability of water is closely related to the PS of sediment. Under the same hydraulic conditions, the transportation ability of water for fine sediments is stronger than for coarse sediments. Zhang (1961) associated the sediment-capturing capacity ρ with the flow velocity v, the water depth h with the sedimentation velocity ω, and obtained the following sediment-splitting capacity equation (Zhang 1961):

$$\rho = k\left(\frac{v^3}{gh\omega}\right)^m \quad \ldots(6)$$

Where g is the gravity acceleration and ω is the sinking sediment rate. As the PS increases, the sinking speed ω increases, and the sediment-capturing capacity ρ decreases. Therefore, an increase in PS can lead to the reduction of water sedimentation capacity. As the amount of sediment is constant, the river siltation can increase. It is suggested that the deposition amount variation caused by the unit amount variation of input sediment is proportional to the PS. According to the principle of sediment movement mechanics, the suspended sediment can be divided into two parts: the bed material sediment and the washed sediment. The former consumes adequate energy of water flow, which is sensitive to the intensity of water flow. The latter does not consume adequate energy for water flow, which is irritated the river and makes it insensitive to the water flow's intensity (Ning & Hui 1983). As for the lower reaches of Liao River, the sediment of >0.025mm is generally the bed material sediment, and the sediment of <0.025mm is used for wash sediment. As for three particle sizes, including the whole sediment, the sediment >0.007mm and the sediment >0.01mm, the scouring-silting amount is not high. As for the sediment >0.025mm, >0.05mm, and> 0.1mm, these three grades do not contain the coarse PS of wash sediment, and the correlation between the slag amount and the SA is significant.

(3) The critical value of sediment from the storage to the release in the downstream river is reduced as the sediment PS increases (Fig. 5). As shown in Table 1, it can be seen that the sediment in the downstream river is not silted, and the annual SA of whole sediment should be lessthan7.860×10^8t.To prevent silting of sediments >0.007mm, >0.01mm, >0.025mm, >0.05mm, and >0.10mm in the downstream river channel, the annual SA should be less than 5.543×10^8t, 4.848×10^8t, 3.197×10^8 t, 1.616×10^8t, and 0.402×10^8t, respectively.

It can be seen that the damage to the river channel by the sediment entering the lower reaches of Liao River increases with the particle size increases. As for various particle size grades, sediments >0.10 mm are the most harmful, followed by sediment sizes >0.05 mm and >0.025 mm.

The Relationship between the Sedimentation-Siltation Amount and the ISA, As Well As the Input Water Amount for Six Particle Size Groups

The relationship between the sedimentation amount and the ISA for six size groups is discussed above. The sedimentation-siltation amount of sediment is not only related to the ISA but also related to the input water amount (IWA). The former is the river load, while the latter is the power for sediment transportation. The power of sediment transportation is related to the total runoff amount and depends on the runoff process. As a preliminary approximation, the annual runoff is used to express the sediment transportation power. Based on the hydrological year data of six particle sizes, the binary linear regression equation is established for the sedimentation-siltation amount Dep_i from JuLiu River to Liujianfang and the ISA $Q_{s,i}$ of each particle size group as well as the IWA from the downstream river, which is shown as follows:

$$Dep_i = a + bQ_{s,i} + cQ_w \quad \ldots(7)$$

Where the subscript *i* represents any particle size group. The established equations are listed in Table 2, and the negative correlation coefficient varies between 0.878 and 0.974, which is highly significant.

In the equation, 7 Q_w is assumed to keep constant with $Q_{s,i}$ changes, and when the partial derivative of two ends is conducted, the following equation can be obtained:

$$\delta Dep_i/\delta Q_{s,i} = b \quad \ldots(8)$$

The equation means the sedimentation increment of any group with the sediment addition of 1×10^8t and the IWA keeping constant. Equation 7 $Q_{s,i}$ is assumed to keep constant with Q_w changes, and the following equation can be obtained after the partial derivative:

$$\delta Dep_i/\delta Q_w = c \quad \ldots(9)$$

As the ISA keeps constant, the sedimentation increment of any group is calculated according to the above two equations, which is caused by the runoff of 1×10^8m^3, as given in Table 2.

Since the variable magnitudes in equation 7 differ greatly, the contribution magnitude of each variable cannot be directly determined from the magnitude of the regression coefficient. Thus, the data can be normalized, which changes between 0 and 1, and the regression is recalculated. Moreover, a linear regression equation is established with a constant term of 0, which is shown as follows:

$$Dep_i = cQ_{s,i} + dQ_w \quad \ldots(10)$$

It is assumed that the contribution rate of the two variables at the right to Dep_i is proportional to the absolute values of regression coefficients *c d*. Also, it is assumed that the total contribution rate is 100%, the contribution rate of $Q_{s,i}$ to Dep_i is $c/(|c|+|d|)$, and the contribution rate of Q_w to Dep_i is $d/(|c|+|d|)$. The results are also shown in Table 2 (Hu & Guo 2004, Xu et al. 2006, Wang et al. 2006).

As shown in Table 2, after adding the input water variable, it can be seen that the complex correlation coefficient is significantly higher than the simple correlation coefficient between the sedimentation-siltation amount and the ISA, especially for the finer PS group. It can also be seen that the contribution rates of ISA and IWA to the sedimentation-siltation amount, and the sedimentation-siltation amount caused by 1t sediment as well as the 10^{10} m^3 runoff, present a regular variation with the particle size changing. As shown in Table 2 and Fig. 6, it is indicated that as the particle size increases, the contribution rate of erosion amount to sedimentation increases, and the contribution rate of IWA to sedimentation decreases. As the particle size is more significant than 0.025 mm, the variation rate of the scouring amount is significantly accelerated. The contribution rate of the SA to the sedimentation amount increases with an increase in particle size, and the transportation of coarse sediment can consume more water energy, so the siltation probability increases. The contribution rate of the input water to the siltation amount decreases with an increase in particle size. It is suggested that the variation of IWA significantly influences sedimentation and has little influence on coarse sediment erosion. As shown in Fig. 7, as the input water is constant, the amount of silt caused by increasing 1t sediment increases with an increase in the particle size. The sedimentation amount of a certain group of sediment caused by the decreasing 10^{10} m^3 runoff decreases with increased particle size. This further indicates that the sedimentation amount of coarse sediment is more sensitive to the amount change of coarse sediment, and is less sensitive to the change of input water volume. The sedimentation amount of fine sediment is less sensitive to the SA change of fine sediment, which is sensitive to the change of IWA. This is mainly because the fine silt is mainly deposited on the beach. As the deposition occurs in the floodplain, the input water mount reduces the chance of floodplain, which can significantly reduce the sedimentation of fine silt. The coarse sediment is mainly deposited in the main tank. As the flow rate is reduced, the flow rate reduction of the main tank is smaller

Table 2: Regression analysis results between the amount of sedimentation and the amount of sediment in each particle size group and the amount of water coming from the particle size group a.

Particle size group	Regression equation 1. Based on raw data 2. Based on standardized data	R	r_s	r_w	A_s/%	A_w/%	B_s/t	B_w/10^8t
Whole sand	1. $Dep_i = 4.198 + 0.387Q_{S,I} - 0.0175Q_W$ 2. $Dep_i = 0.659Q_{S,I} - 0.717Q_W$	0.936	0.537	-0.562	49.52	50.48	0.387	1.75
>0.007mm	1. $Dep_{>0.007} = 1.974 + 0.302Q_{S>0.007} - 0.0098Q_W$ 2. $Dep_{>0.007} = 0.649Q_{S>0.007} - 0.638Q_W$	0.901	0.573	-0.519	51.53	48.47	0.302	0.98
>0.01mm	1. $Dep_{>0.01} = 1.793 + 0.231Q_{S>0.01} - 0.0079Q_W$ 2. $Dep_{>0.01} = 0.626Q_{S>0.01} - 0.542Q_W$	0.897	0.614	-0.543	51.87	48.13	0.231	0.79
>0.025mm	1. $Dep_{>0.025} = 1.872 + 0.351Q_{S>0.025} - 0.00536Q_W$ 2. $Dep_{>0.025} = 0.191Q_{S>0.025} - 0.172Q_W$	0.878	0.693	-0.469	57.92	42.08	0.351	0.536
>0.05mm	1. $Dep_{>0.05} = 1.002 + 0.782Q_{S>0.05} - 0.00357Q_W$ 2. $Dep_{>0.05} = 0.171Q_{S>0.05} - 0.197Q_W$	0.965	0.831	-0.451	63.34	36.66	0.782	0.357
>0.10mm	1. $Dep_{>0.1} = 0.105 + 0.941Q_{S>0.1} - 0.00137Q_W$ 2. $Dep_{>0.1} = 0.124Q_{S>0.1} - 0.179Q_W$	0.974	0.963	-0.508	82.85	17.15	0.941	0.137

a: *Dep* for the amount of scouring and silting (10^8t/a), Q_s is the annual water quantity (10^8t.a^{-1}), and Q_w is the annual water quantity (10^8m^3.a^{-1}).In the subscript, i is all sediment, >0.007 means >0.007mm particle size group, and the rest is analogous; R is the negative correlation coefficient, r_s is the correlation coefficient between the amount of scouring and silting in a certain particle size group and the amount of sediment in the particle size group, and r_w is the correlation coefficient between the amount of scouring and silting of a certain particle size group and the amount of input water is the contribution rate of the change of the amount of erosion and sedimentation in the input sediment, A_w is the contribution rate of the change of the flushing and silting amount of the input water change; B_s is the sediment of a certain group of 1t when the input water is constant. The amount of sedimentation in the sediment caused by this group, $B_{w,}$ is the amount of sedimentation of a certain group of sediment caused by the decrease of 10^{10} m^3 runoff when the input sediment is constant.

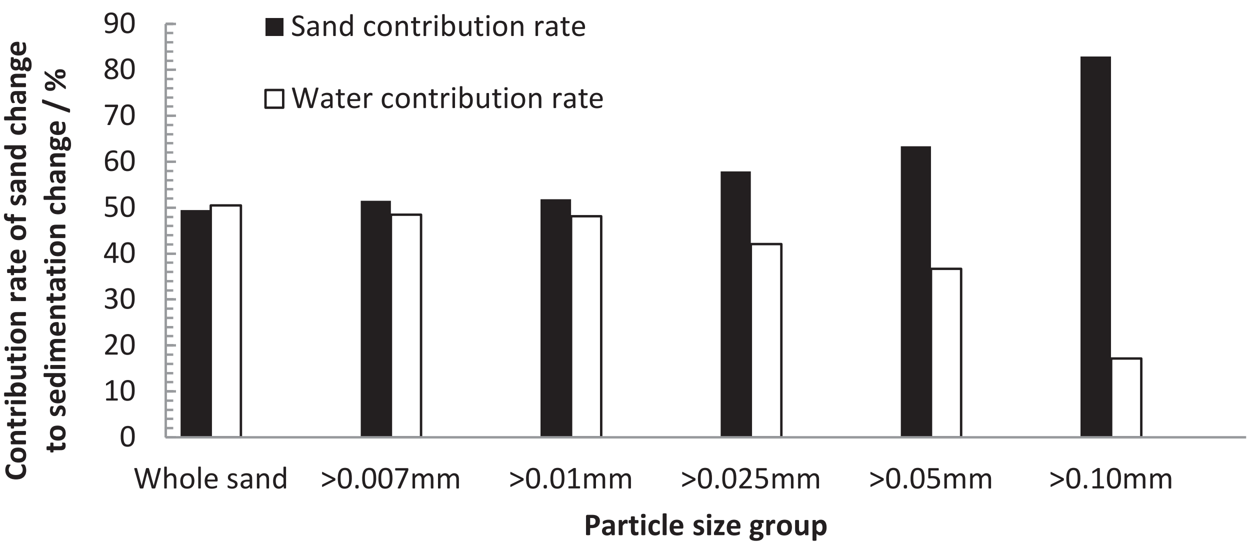

Fig. 6: Comparison of contribution rate of variation of scour and siltation in sediment and water changes in different particle size groups.

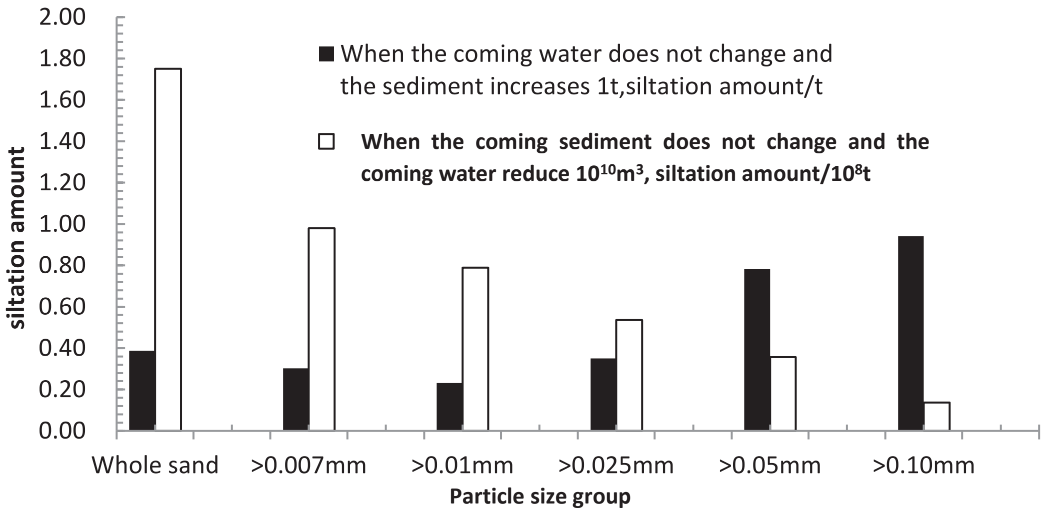

Fig. 7: Comparison of sedimentation changes in water and sediment change in different particle size groups.

than that of the beach. Therefore, the amount of reduction of coarse sediment is not large.

CONCLUSIONS

(1) The correlation coefficient between the annual sedimentation-siltation amount of the JuLiu-Liujianfang section and the annual SA entering the downstream channel increases with an increase in the sediment particle size. As the sediment particle size increases, there is an increased correlation between the sediment and the river siltation. The threshold value of sediment from the storage to the release in the downstream river is reduced as the sediment particle size increases.

(2) The deposition amount caused by the unit amount change of input sediment increases as the particle size increases. The damage to the river channel caused by the sediment entering the lower reaches of Liao River increases with the increased sediment particle size. When the various particle size grades are taken into consideration, it is found that sediment >0.10 mm is the most harmful, followed by >0.05 mm and >0.025 mm sediments.

(3) It was found that the thicker the particle size, the greater the contribution rate of sediment to the amount of erosion and siltation. On the other hand, the contribution rate of input water to the amount of erosion and sedimentation decreased. As the IWA is constant, the amount of silt caused by each additional 1t of sediment increases with the increased particle size. As the ISA is constant, each 10^{10} m^3 of runoff is reduced. The amount of silt reduction decreases as the particle size increases.

The research results of this paper are important for the governance of the Liao River. This study shows that 34.57% of sediment >0.025 mm, 65.74% of sediment >0.05 mm is silt in the channel, and 95.85% of sediment >0.10 mm entering the downstream channel is deposited in the river. For the upper and middle reaches, the reduction effect of sediment >0.10 mm is reduced 1.458 times and 2.773 times compared with the reduction effect of sediment>0.05 mm and >0.025 mm, respectively. Based on the treatment and effectiveness of the source area with coarse sediment >0.05 mm, managing the production area of sediment >0.10 mm is of great significance.

The analysis of this paper is based on data from 1988 to 2005. The statistical relationship and critical values obtained in this paper only apply to a certain range of input water from 1988 to 2005. In this period, the maximum annual flood runoff is 20.99×10^8 m^3, the minimum annual flood runoff is 5.57×10^8 m^3, the maximum annual runoff is 29.25×10^8 m^3, and the minimum annual runoff is 7.79×10^8 m^3. Since 2005, the construction of Shifo Reservoir in the middle reaches of the Liao River, the construction of rubber dams and other water conservancy projects in the middle and lower reaches of the Liao River, and the implementation of river improvement engineering measures have caused some changes in the river boundary conditions. Therefore, the results of this study may not be entirely suitable for the situation after 2005. As the data after 2005 has not been collected, it cannot be further analyzed. However, this study's methodology is important and can be used for further studies.

The scouring-silting process in the lower reaches of the Liao River is affected by many factors related to the quantity, particle size composition, and change process of input sediment, the quantity and process of input water, and the shape and variation of the Liao River. This paper has obtained a single-factor criticality, and the direction of future studies should reveal the multi-factor composite criticality, including the above factors that influence the scouring-silting process.

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