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The response of sedimentary record to catchment changes induced by human activities in the western intertidal flat of Yalu River Estuary, China

SHI Yong[1, 2], LIU Zhishuai[1, 2], GAO Jianhua[2*], YANG Yang[2], WANG Yaping[2]
[1] National Ocean Technology Center, Tianjin 300111, China
[2] Ministry of Education Key Laboratory for Coast and Island Development, Nanjing University, Nanjing 210093, China

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Abstract

The response to the catchment changes of the sedimentary environment of the western intertidal flat of Yalu River Estuary was investigated by analyzing the vertical variations of the grain size of sediment cores, along with the hydrologic data and human activities in the catchment. The results demonstrated a stepwise decreasing trend for the variations of both the sediment load and water discharge into the sea, which could be divided into three stages as 1958–1970, 1971–1990 and 1991–2009. Reservoir construction and the changes of catchment vegetation coverage turned out to be the two predominant contributors to the changes. There are four periods for the variation of the sensitive components of the sediment cores from 1940 to 2010, i.e., 1940–1950, 1951–1980, 1981–1990 and 1991–2010. The vertical distribution of grain size in the cores mainly varied with the changes of vegetation coverage in the catchment and reservoir construction from 1960 to 1980, whereas it varied depending on the intensity of water and soil erosion in the catchment from 1980 to 1990. Despite the further reduction of the water and sediment input into the sea from 1990 to 2009, this period was characterized by coarsening trends for the grain size of sediment in the estuarine intertidal flat and correspondingly, the significantly increased silt contents of the sensitive component.

Key words: runoff and sediment load, human activities, sediment record, sensitive component, Yalu River

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1 Introduction

Sediment flux into the sea has attracted a widely attention in recent years, as approximately 95% of global terrestrial sediments are transported into the ocean by rivers (Syvitski, 2003). Since the last century, the drainage basin and estuarine coastal environment have suffered drastic changes as a result of the collective effects of natural factors and human activities (Syvitski et al., 2005), e.g., the increase in soil loss induced by overgrazing and deforestation and the decrease of riverine sediment owing to reservoir constructions (Gao et al., 2015a, b).

Since the late 20th century, numerous studies have been conducted on the riverine sediment flux at global or regional scales (Milliman and Syvistski, 1992; Milliman et al., 1999; McCarney-Castle et al., 2010; Syvitski, 2011), most of which were focused on the large rivers in the globe owing to the large quantity of information that is available regarding to the connections between large deltas and large rivers (Syvitski and Saito, 2007). Rivers of small scales, by contrast, have received little attention due to the corresponding submerged deltas of smaller scales and the lack of long-term historical data (Milliman and Meade, 1983; Gao et al., 2011; McCarney-Castle et al., 2012). Although large rivers are commonly characterized by large amount of discharges, it is the input from small rivers that predominates the total quantity of fresh water discharging into the ocean (Milliman et al., 1999). Therefore, it is necessary and beneficial to study the changes of flux from small sized rivers and the behaviors of the estuarine systems responding to human activities in the coastal zones.

The Yalu River, China, is such a small-scaled river, where the quantity and the temporal and spatial distributions of water and sediment discharge of the whole catchment changed owing to the intensive human activities (Gao et al., 2012). Abundant information regarding to the catchment change was expected recorded in the sediment of the estuarine tidal flat, which is a typical geomorphology unit in a small-scaled estuarine system, potentially bearing a good deal of environmental evolution information in the basin (Yamamuro and Kanai, 2005; Jia et al., 2012). Hence, this study aims to reveal the response of the sedimentary environment to the catchment changes in the western intertidal flat of the Yalu River Estuary through the comprehensive analysis of the vertical variations of grain size of the sediment cores, the hydrologic data and human activities in the catchment.

2 Regional settings

Located at the boundary between China and North Korea, the Yalu River, is a representative mountainous river flowing into the North Yellow Sea (Figs 1a and b). The river has a total drainage

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*Corresponding author, E-mail: jhgao@nju.edu.cn

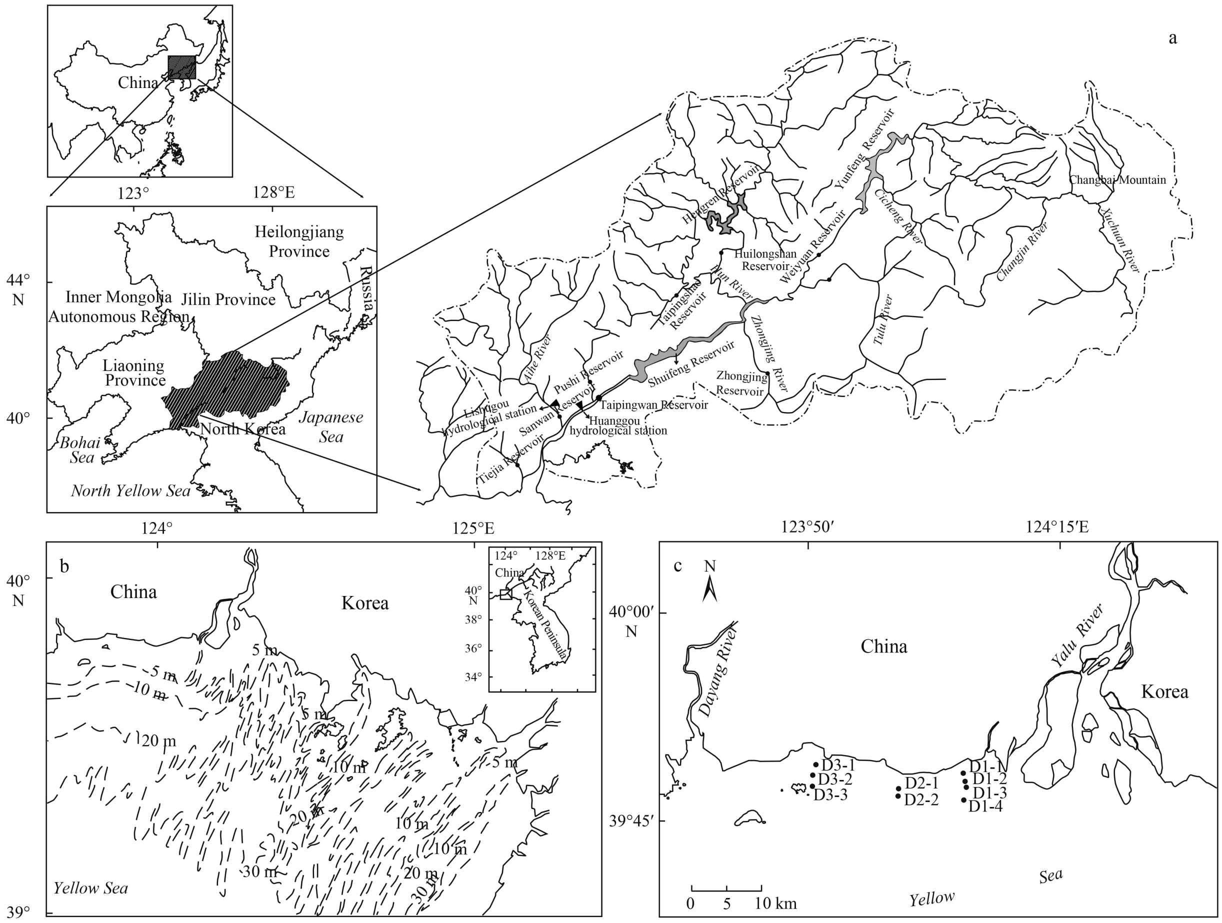

Fig. 1. Map of sampling stations of the Yalu River Estuary. a. The distribution of the reservoirs in the catchments of the Yalu River, b. the tidal current sand ridge system of the outer Yalu River Estuary and c. the sampling stations in 2010 and 2011.

area of 6.45×10^4 km^2 and a length of 790 km. The mean annual runoff and sediment discharge are 289×10^8 m^3 and 1.13×10^6 t, respectively (Gao et al., 2003). The seasonal distributions of the runoff and sediment load are imbalanced: over 33% of the freshwater discharge and 80% of the sediment load are transported into the estuary during the flood season from June to September (China Bays Compiling Committee, 1998). The Yalu River Estuary is characterized by a high suspended-sediment concentration, strong tidal currents, and the presence of prominent turbidity maxima (Gao et al., 2004).

Among the 41 reservoirs that were built in the Yalu River catchment on China side since the construction of the Shuifeng Reservoir in 1940, 13 reservoirs are relatively large with a larger storage capacity and 28 are small sized reservoirs (Fig. 1a, Table 1). The constructions of reservoirs led to a continuous reduction of the sediment discharge into the coastal waters and tremendous changes of the estuarine geomorphology (Gao et al., 2012).

Table 1. The major large reservoirs of the Yalu River Estuary

Reservoir name	Building time (year)	Water storage capacity/10^8 m^3	Reservoir capacity index/%
Shuifeng$^{1)}$	1940	146.00	57.25
Tiejia$^{1)}$	1965	2.34	0.92
Yunfeng$^{1)}$	1967	45.80	17.96
Huilongshan$^{1)}$	1972	6.00	2.35
Hengren$^{1)}$	1975	36.40	14.27
Weiyuan$^{1)}$	1978	6.26	2.45
Taipingshao$^{1)}$	1982	2.00	0.78
Taipingwan$^{1)}$	1984	1.70	0.67
Pushihe$^{1)}$	1993	0.42	0.16
Shuangling$^{2)}$	2004	1.33	0.51
Jinshao$^{2)}$	2004	1.00	0.38
Linjiang$^{2)}$	2007	18.35	7.15
Sanwan$^{2)}$	2008	1.54	0.60

Note: $^{1)}$ The data from Song (1997); $^{2)}$ the data from Song and Fu (2008).

3 Materials and methods

3.1 *Sample and data collection*

Nine sediment cores were collected from the intertidal zone of the western Yalu River Estuary in July 2010 and October 2011 (Fig. 1c). At Section 1 located sediment Cores D1–1, D1–2, D1–3 and D1–4, with lengths of 2.2 m, 2.25 m, 2.5 m and 2.48 m, respectively. At Section 2, sediment Cores D2–1 and D2–2 with lengths of 2.79 m and 2.8 m, respectively. At Section 3, sediment Cores D3–1, D3–2 and D3–3, with lengths of 2.82 m, 3.23 m and 3.07 m, respectively.

The elevations of the three sections were surveyed using the GPS RTK Z-Max measurement system (Thales Navigation) with a real-time differential correction to ensure planimetric and altimetric precisions of 0.5 cm, +0.5 ppm (parts per million) and 1 cm, +0.5 ppm, respectively. Two signal receivers were employed in the measurement. A position with a given elevation of 10 m was selected as a reference datum for all the measured elevations. One receiver served as the basement station, which was the benchmark for all the measurements and the other was a rover to survey the topography. The measurements were taken in August 2011.

The consecutive monthly data of the water and suspended sediment discharge at the Huanggou and Lishugou stations from 1958 to 2009 were mainly collected from the hydrological yearbooks of the People's Republic of China, compiled by the Ministry of Water Resources of China (MWRC, 2009). The water samples were taken across the full water column at a fixed gauging section and the flow discharge was recorded at certain times. The river's sediment discharge was measured based on the Chinese national standard criterion.

3.2 *Laboratory analysis*

The sediment cores were sliced at different intervals for the grain size analysis: 2 cm for sediment Cores D1–2, D1–3, D1–4, D2–2 and D3–2, 1 cm for sediment Core D3-1 and 0.5 cm for sediment Cores D1–1, D2–1 and D3–3.

We derived the deposition time by conducting the ^{210}Pb isotopic analysis and a subsequent series of calculations, in preparation to estimate the sedimentation rates in the following. In specific, the isotopic analysis includes: (1) preprocessing the sediment samples (aqua regia extraction and electro deposition), (2) measuring the ^{210}Pb activity in each layer with the 576A Alpha Spectrometer, (3) calculating the amount of excess ^{210}Pb ($^{210}\mathrm{Pb}_{\mathrm{ex}}$) by subtracting the background ^{210}Pb activity from the ^{210}Pb activity in each layer. In a Constant Initial Concentration Model (CIC), based on Goldburg and Koide (1963), the radioactivity of excess ^{210}Pb ($^{210}\mathrm{Pb}_{\mathrm{ex}}$) can be expressed as

$$N_t = N_0 e^{\lambda t}, \tag{1}$$

where N_t refers to the radioactivity of $^{210}\mathrm{Pb}_{\mathrm{ex}}$, N_0 refers to the initial radioactivity of $^{210}\mathrm{Pb}_{\mathrm{ex}}$, t refers to age and λ refers to the decay constant of ^{210}Pb (0.031 a^{-1}).

The grain size distributions of the sediment samples were analyzed utilizing Mastersizer 2000, a particle size analysis instrument with a measurement range of 0.02–2 000 μm and a relative error of less than 3% for replicated measurements. The grain size parameters were calculated with the moment method (McManus, 1988).

4 Results

4.1 *^{210}Pb dating*

The deposition rates could not be calculated for sediment Cores D1–1 and D3–3, as the ^{210}Pb activities appeared as a disordered vertical distribution without apparent decaying and background region (Fig. 2). The sediment Core D3–1 exhibited a normal vertical distribution pattern of ^{210}Pb activities: the decaying region of the ^{210}Pb activities ranged from the surface layer to 100 cm, and the background region was below 100 cm. Similar trends were observed for the vertical distribution of the ^{210}Pb activities among sediment Cores D1–2, D1–3, D1–4, D2–1 and D3–2. There was an obvious mixing layer from the surface to 20 cm in depth, which was followed by an exponential decaying region and a background region of ^{210}Pb activities were recorded below the depth of 200 cm.

We extended upward the decaying trend lines of the excess ^{210}Pb activities in the exponential decaying region and obtained the deposition rates of sediment Cores D1–2, D1–3, D1–4, D2–1 and D3–2 as 0.97 cm/a, 1.71 cm/a, 1.44 cm/a, 1.07 cm/a, 1.78 cm/a and 1.44 cm/a, respectively.

4.2 *Grain size*

The nine sediment cores were mainly composed of brown sand, gray-brown sand and silt. The contents ranged from 68.83% to 29.73% for sand, 23.49% to 58.83% for silt and 7.68% to 11.43% for clay (Fig. 3). The mean grain size of the sediment cores varied from 5.45Φ to 3.96Φ. Section 1 was close to the estuary, where the grain size variations of the four sediment cores were greatly influenced not only by the changes of the water and sediment discharge but also by the geomorphological evolution in the estuary, resulting in the more complicated vertical sediment environment in Section 1. The grain size of D1-1 appeared a discontinuous distribution from the bottom upwards until the depth of 20 cm, above which the grain size increased upwards to the surface. This complicated variation might be attributed to anthropogenic disturbances or an extreme weather conditions (Cheng, 1988) given that the sediment core D1-1 was close to the Dadong Harbor.

It seemed similar of the mean grain size variation trends of the sediment cores in Sections 2 and 3. In spite of the different deposition rates that contribute to the odd similarity of variation trend in the mean grain size at different depths, the general vertical change trends of D2-1, D2-2, D3-1 and D3-2 were consistent. From the depth of 150 cm, the mean grain sizes of these four sediment cores became finer upwards to the surface, whereas fluctuations were found downwards, which were replaced eventually by increasing trends. Despite a variation trend of the mean grain size similar to that of the other four sediment cores from the depth of 150 cm to 25 cm, the mean grain size of D3-3 appeared a continuous decreasing trend from the depth of 25 cm up towards the surface.

4.3 *Variations of sediment load and water flux*

The Huanggou and Lishugou hydrometric stations were located at the downstream of the mainstream and an important tributary (Ai River) of the Yalu River, respectively (Fig. 1a). The sum of the sediment/water flux at the two stations represented the whole influx from the Yalu River catchment into the sea (Fig. 4). The drainage area of the Ai River is approximately 5 902 km^2, accounting for only 9.12% of the whole catchment. From 1958 to 2009, the average annual runoff and sediment load of the Huanggou station was 226.66×10^8 m^3 and 76.00×10^4 t, respectively. Although the mean annual runoff of the Lishugou station was merely 28.21×10^8 m^3, its average annual sediment load reached as high as 71.44×10^4 t, which was nearly equal to that of the Huanggou station, due to fewer dam constructions in the Ai River catchment.

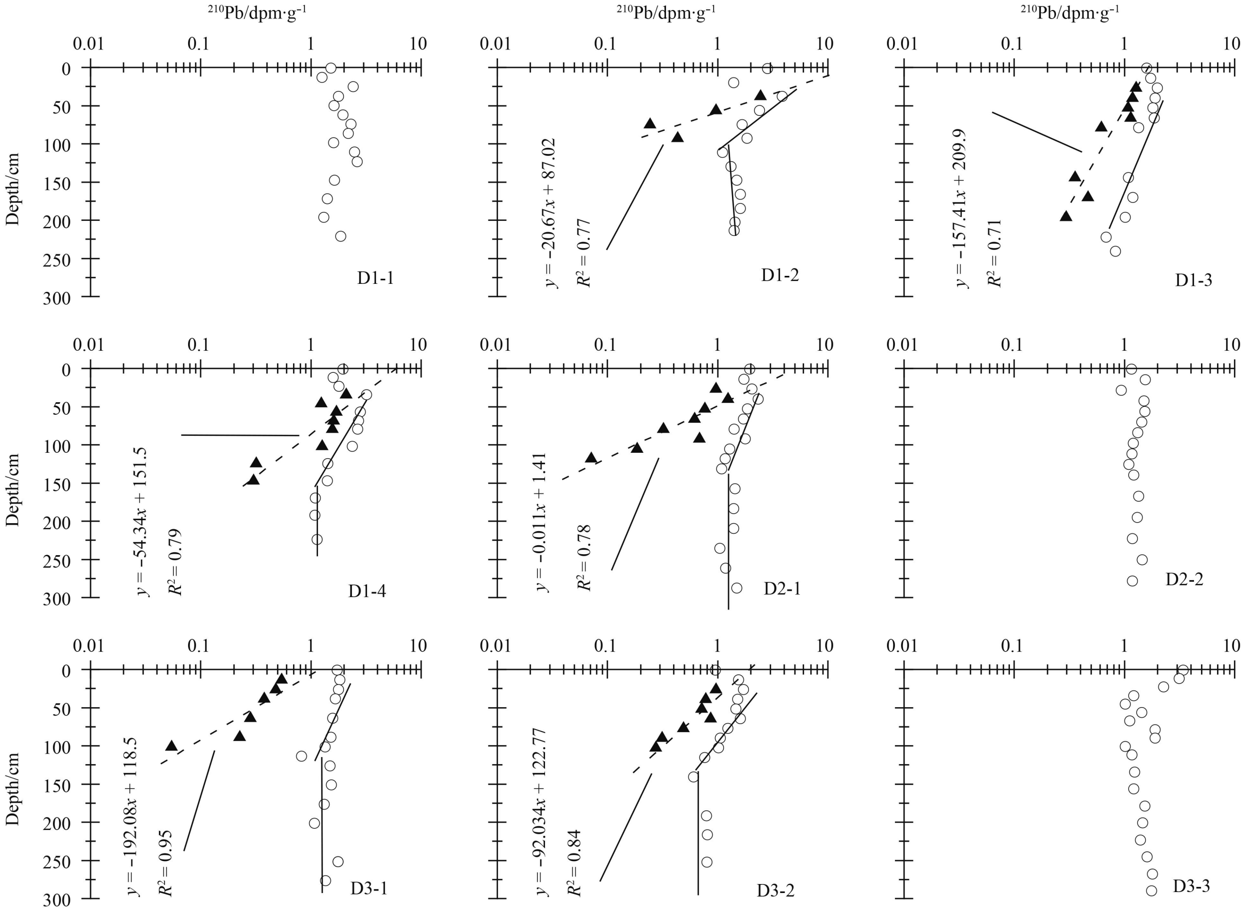

Fig. 2. Profiles of ^{210}Pb activity (○) and excess ^{210}Pb activity (▲) in the nine sediment cores.

The variation of water discharge into the sea displayed an overall stepwise decreasing trend that could be divided into three stages: 1958–1970, 1971–1990 and 1991–2009. In contrast, the sediment load into the sea during 1958–1970, in terms of the average value of 207.29×10^4 t/a, was obviously higher than that during the rest periods in the study, i.e., 1971–2009. The sediment load remained relatively stable from 1971 to 2000 whereas decreased rapidly during 2001–2009 (with a mean value of 55.82×10^4 t/a). Given that a catastrophic flood occurred in the Yalu River in 1995, the sediment load exhibited a variation trend similar to runoff and could also be classified into three stages (i.e., 1958–1970, 1971–1990 and 1991–2009) if the sediment load of 1995 were excluded. As a whole, common as the reduction trend was observed for both the runoff and sediment load into the sea from 1958 to 2009, the decrease of sediment load was more significant than that of runoff.

5 Discussion

5.1 *Variations of sediment flux into the sea caused by human activities*

The runoff and sediment flux from the Yalu River into the sea displayed three stepwise reduction stages, which is closely related to the construction of reservoirs in the catchment. Currently, the reservoir capacity index (RI, the ratio of the total reservoir storage capacity to the average annual runoff) of the 13 relatively large reservoirs within the Yalu River basin as a whole was up to 105.45%. In addition, the RI value of the Shuifeng Reservoir (built in 1940) reached 57.25%, suggesting that the Shuifeng Reservoir had a significant impact on the sediment load variation of the entire catchment. In this study, RI was calculated every ten years from 1960 to 2009, taking ten years as a cycle unit. The increase of the RI in the 1960s and 1970s were 18.88% and 19.07%, respectively, whereas the RI remained stable in the 1980s and 1990s before rapidly increasing to 8.64% in the 2000s. To further quantify the relationship between reservoir construction and the reduced sediment discharge, we performed correlation analysis between the cumulative RI and the average annual sediment discharge (Fig. 5a). The result revealed that the reduction of average annual sediment discharge was highly correlated with the increment of the cumulative RI (r^2=0.93). That is, the reservoir construction was a predominant contributor to the reduction of the sediment flux after the 1960s. The result (Fig. 5b) also illustrated that the influencing degree of reservoir construction on the sediment flux arranged in a sequence from high to low as 1960s, 1970s, 2000s, 1980s and 1990s.

5.2 *The response of suspended sediment grain size variations to human activities*

Generally, the sediment load and the grain sizes of the suspended sediment into the sea will correspondingly increase with the reduction of vegetation coverage of the catchment and decrease with the opposite circumstance (Van Dessel et al., 2008). The suspended sediment load during the flood season accounted for 80% of the entire year; therefore, the mean grain size of the suspended sediment during the flood season at the Huanggou and Lishugou stations measured in 1962–1985 was adapted to analyze the response of the grain size of suspended sedi-

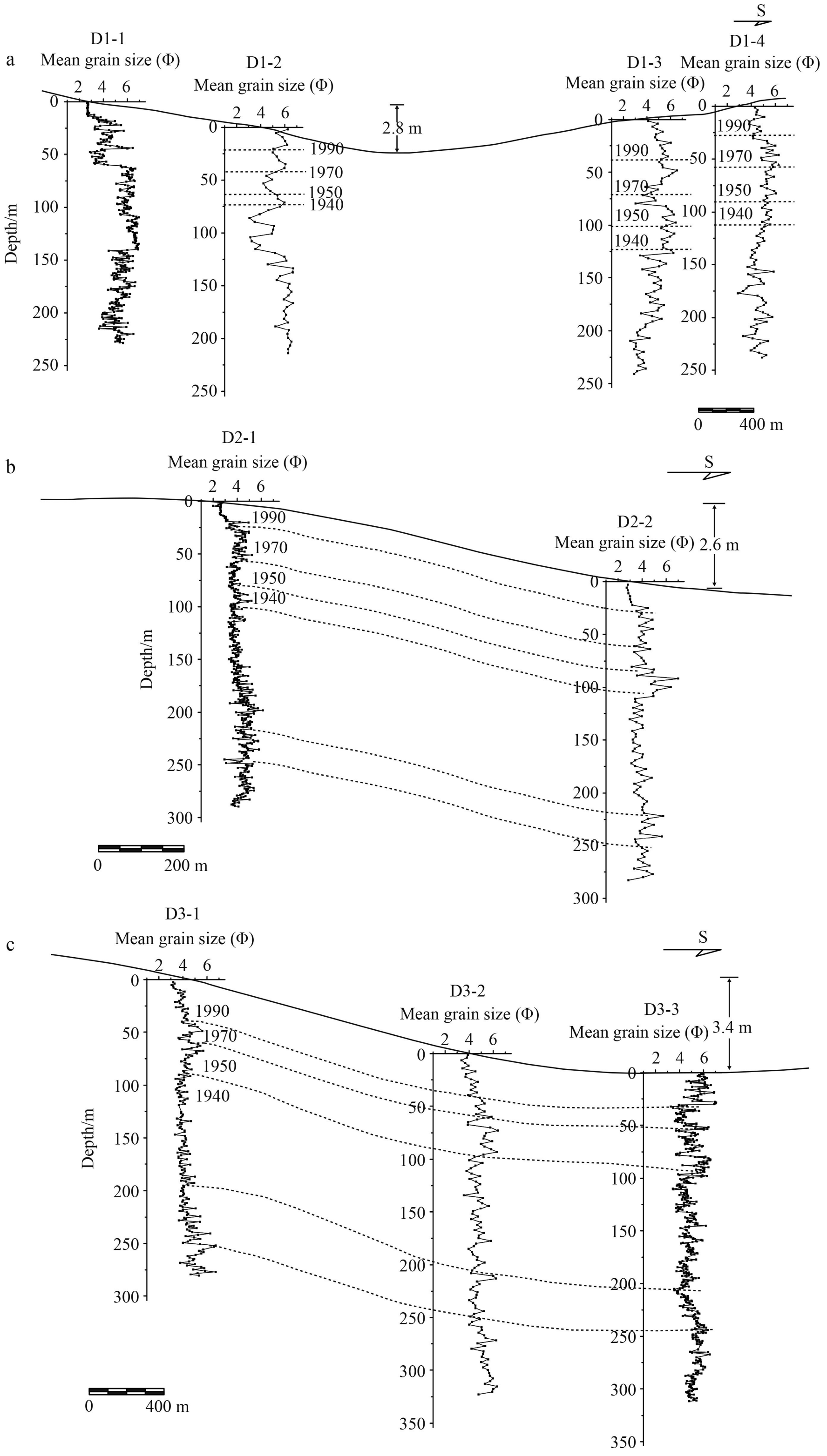

Fig. 3. Vertical variations of the average particle size in the core samples. a. Section 1, b. Section 2 and c. Section 3.

ment to the catchment changes. The results (Fig. 6a) showed that the mean grain size of the suspended sediment at the Huanggou and Lishugou stations both displayed gradually increasing and then decreasing trends in the 1960s and 1970s, which was closely related to human activities in the whole basin.

Due to deforestation, the forest resources were seriously damaged in the 1950s and 1960s, and the forest coverage in the middle and lower reaches of the Yalu River decreased from 1.67×10^6 hm^2 to 0.54×10^6 hm^2 (Yin et al., 2001). The rapid decline of forest coverage not only lowered the functions of water and soil conservation of the catchment but also increased the flood frequency. Only two floods occurred from 1937 to 1958 downstream of the Yalu River catchment; however, four floods occurred from 1958 to 1979. Although the rainfall intensity of every

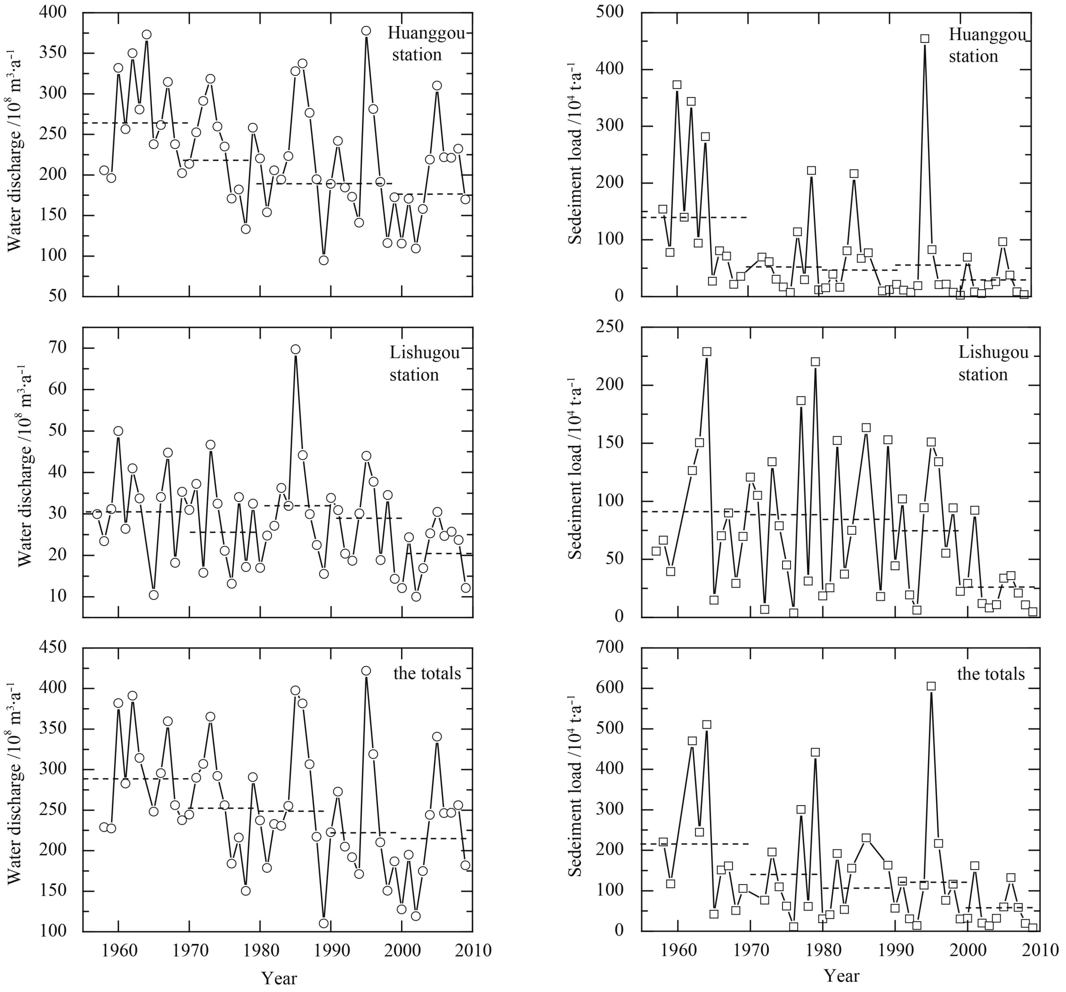

Fig. 4. Annual sediment load and water discharge at the Huanggou station and the Lishugou station, as well as the total sediment load and water discharge into the sea, from 1958–2009. The black dash line denotes the mean value of sediment load/water discharge for every ten years.

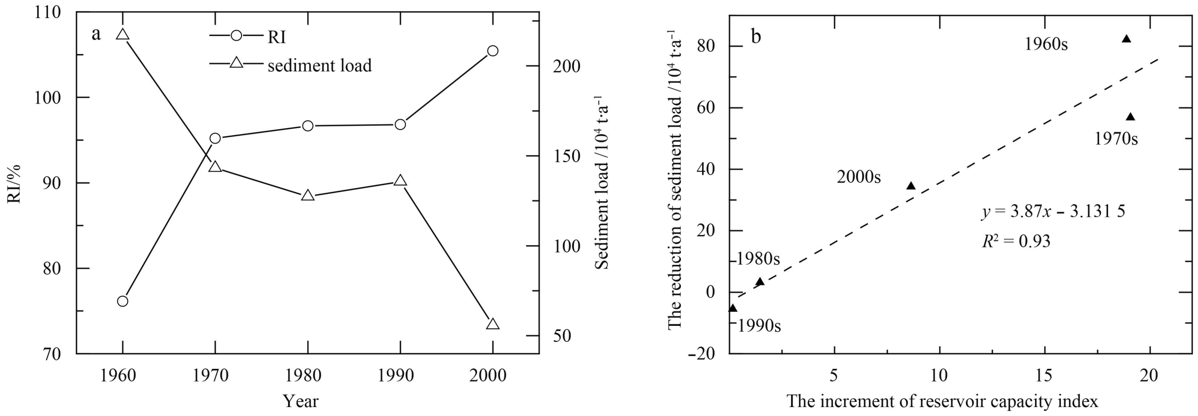

Fig. 5. The impact of reservoir construction on the decrease of sediment load into the sea. a. The variation of cumulative RI and sediment load in the 1960s, 1970s, 1980s, 1990s and 2000s; and b. the relationship between the reservoir capacity index increment and the sediment reduction in the 1960s, 1970s, 1980s, 1990s and 2000s.

flood continuously decreased (482 mm in 1958, 462 mm in 1966, 456 mm in 1977 and 443 mm in 1979), the degree of the flood damage became more serious (Editorial Committee of Liaoning Forest, 1990). The decreased vegetation cover and increased floods resulted in serious soil erosion in the entire catchment, and the grain size of the suspended sediment into the sea gradually rose in the 1960s. Afforestation and the protection of forests were implemented in the entire Yalu River catchment during the 1970s, and the forest coverage gradually recovered. The forest coverage increased 1.83 times from 1973–1982 to 1961–1972

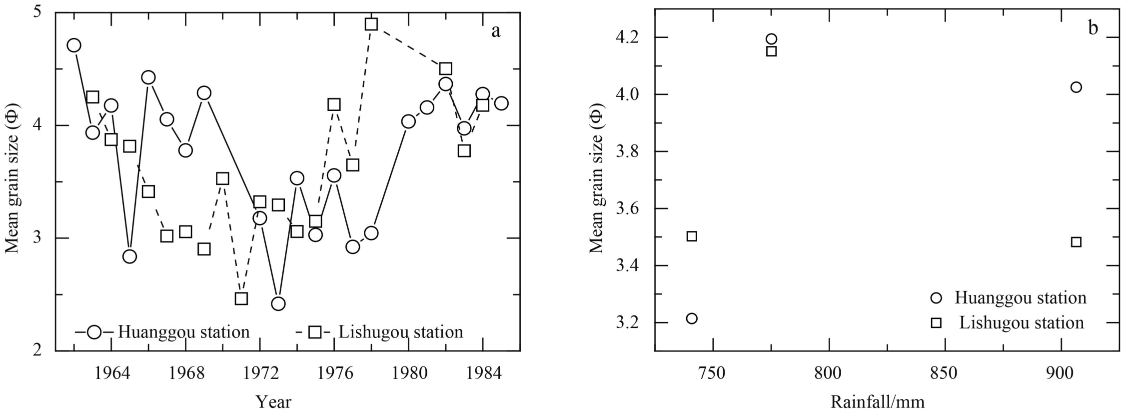

Fig. 6. The mean grain size variations of the suspended sediment at the Huanggou and Lishugou stations measured in July and August from 1962 to 1986 (a); the relationship between rainfall and the grain size of suspended sediment during 1962–1970, 1971–1980 and 1981–1985 (b).

(Wang et al., 2010). The increased forest coverage improved the soil and water conservation capacity, and the soil erosion degree was also reduced. Therefore, the mean grain size of the suspended sediment at the Huanggou and Lishugou stations has gradually decreased since the 1970s. Although the variation of rainfall could also change the grain size of the suspended sediment into the sea, no relationship was observed between these two parameters (Fig. 6b). Therefore, the variations of the suspended sediment grain size may mainly be the result of land use/cover changes.

5.3 *Sediment records of intertidal flat responding to the sediment discharge reduction*

One portion of the sediment originating from the Yalu River catchment was transported towards the open sea, the rest was conveyed to the west and supplement to the western tidal flat of the Yalu River Estuary (Cheng, 1988). A linear correlation was observed between the mean grain size of sediment in Cores D1–4, D2–1, D3–1, D5–2 and the suspended sediment (Fig. 7), implying that the grain sizes of the sediment in the intertidal flat were affected by the variation in the sediment discharge of the catchment. Noticeably, the variation the mean grain size of sediment in Cores D1–4, D2–1, D3–1 and D5–2 is out of phase from that the suspended sediment. The 1 or 2 years lagging is likely to be caused by the certain amount of suspension time before the sediment eventually deposited in the intertidal flat (Wang et al., 1999). In comparison, the mean grain sizes of sediment in Cores D1–1 and D1–2 demonstrated poor correlations to that of the suspended sediment, suggesting that the sediment variation of the western intertidal flat of the Yalu River being influenced by other factors (such as geomorphology evolution) in addition to the variation of water and suspended sediment flux.

A sensitive components analysis was used for the grain size of the suspended sediment of the Yalu River in July and August from 1962 to 1985. Two sensitive components of silt and clay fractions were observed, variations of which were considered the

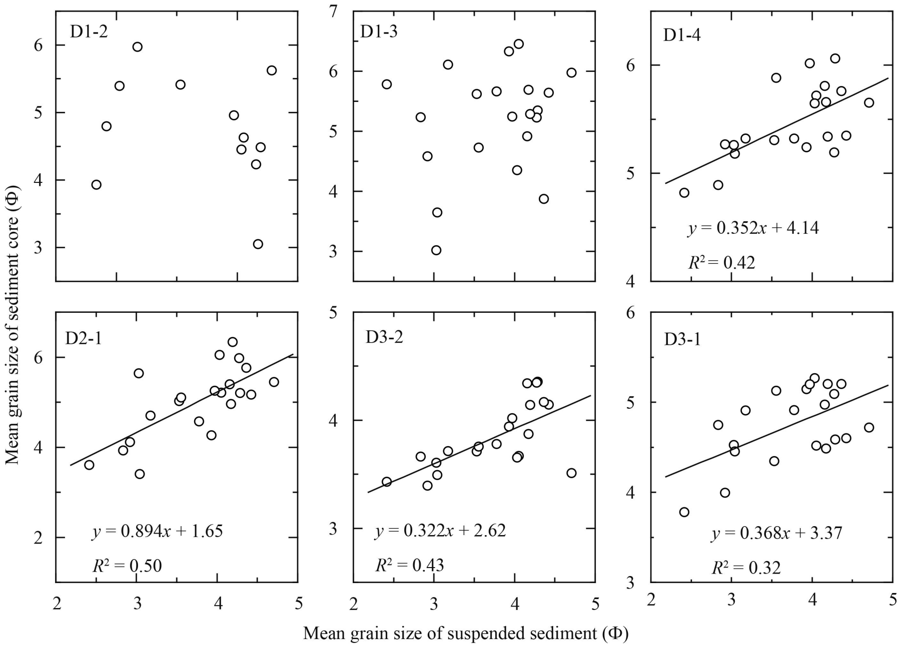

Fig. 7. The relationships between the mean grain size of the suspended sediment transported into the sea and that of the sediment samples in the six sediment cores.

major factors influencing the changes of sediment grain size in this area (Fig. 8). Two sensitive components were also identified for sediments in the intertidal flat of the Yalu River, ranging from 1.75Φ–2.75Φ and 6.75Φ–7.75Φ (Fig. 9), indicating that the content of the silt sensitive component turned out to be greater than that of the clay sensitive component and that the sensitivity of the silt fraction was higher than that of the clay fraction.

Considering that the dramatic changes in the runoff and sediment load after the construction of the Shuifeng Reservoir in 1940, we analyzed the silt sensitive components of the sediment cores during 1940–2010 to determine the response of the grain size of sediment in the intertidal flat to human activities in the catchment. As illustrated in Fig. 10, the content variations of the silt sensitive components of sediment Cores D2-1, D3-1 and D3-2 were divided into four periods from 1940 to 2009: 1940–1950, 1951–1980, 1981–1990 and 1990–2010. The contents of the silt sensitive components fluctuated during 1940–1950, probably reflecting the inter-annual variation of the suspended sediment flux of the whole basin into the sea. During the period of 1950–1980, the contents of the silt sensitive component of the three cores gradually increased before significantly decreased. The reduction of vegetation coverage induced by human activities in the 1950s and 1960s led to the increase of the suspended sediment grain size. During the period of 1940–2010, the peak rainfall occurred in the 1960s. Correspondingly, the contents of the silt sensitive component of the three sediment cores gradually increased during this period. With the recovery of the vegetation coverage in the catchment in the 1970s, the grain size of the suspended sediment into the sea gradually became finer. As the largest reservoirs being constructed during the 1960s and 1970s, a large quantity of coarse-grained sediments was trapped in reservoirs, reducing the grain size of the suspended sediment into the sea (Mahmood, 1987; Poulos et al., 2008; Gao et al., 2015b). The reduction in the contents of the silt sensitive components in the sediment cores served as an independent proof for such a tendency to become thinner. In a word, the collective influences of land use/cover variation, rainfall and the construction of reservoirs in the catchment accounted for grain size variations of sediment in Sections 2 and 3.

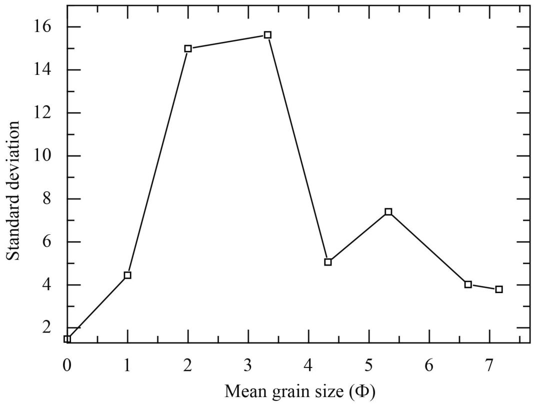

Fig. 8. Grain-size (Φ) versus standard deviation of the suspended sediment measured in July and August from 1962 to 1985.

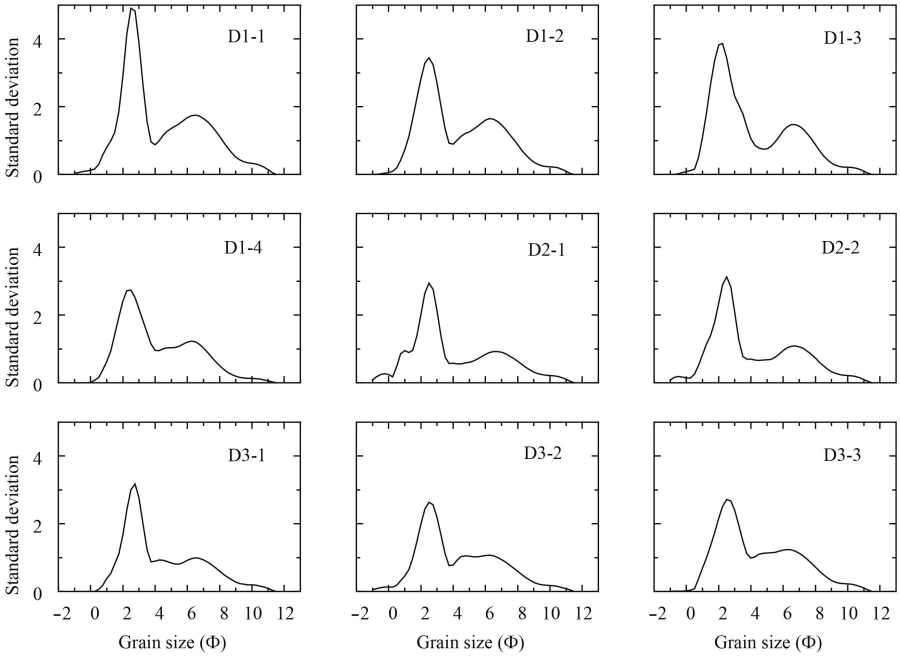

Fig. 9. Grain-size (Φ) versus standard deviation of the sediment samples in the nine sediment cores.

From 1980 to 1990, only small reservoirs were constructed and the recovered vegetation coverage underwent no significant changes in the catchment. During the period when the catchment vegetation decreased continuously, same amount of runoff was likely to result in different quantities of water and soil loss (Bakker et al., 2005; Zhu et al., 2008; Gao et al., 2015c), whereas during the period when the vegetation coverage was stable in the catchment, different soil erosion intensities may reflect the magnitude of runoff (Jordan et al., 2005; Szilassi et al., 2006). Due to the large quantity of sediment trapped in the reservoirs of the main stream, the tributary Ai River had less reservoir construction and contributed more sediment to the whole catchment. The linear correlation was observed between the runoff of the Ai River from 1980 to 1990 and the contents of the silt sensitive component of sediment Cores D2-1, D3-1 and D3-2 (Fig. 11). The mean grain size of the sediment cores still fell behind the runoff for 1–2 years, indicating that the grain size variation of the sedi-

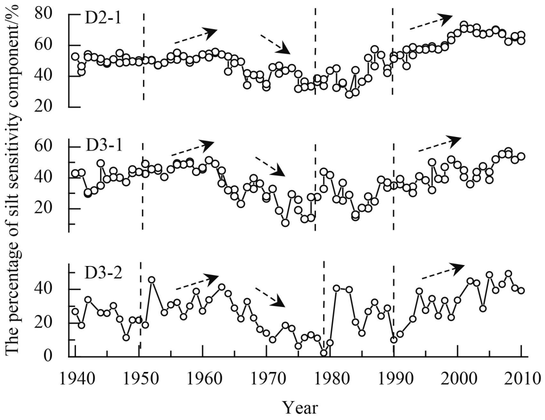

Fig. 10. The variations of the contents of the silt sensitivity component for sediment samples in Cores D2-1, D3-1 and D3-2.

ment cores in Sections 2 and 3 mainly reflected the erosion intensity caused by the runoff of the Ai River catchment from 1980 to 1990.

During the period from 1990 to 2009, particularly from 2000 to 2009, another peak of reservoir construction occurred in the Yalu River catchment, which resulted in the further reduction of water and sediment flux into the sea. The sediment load into the sea decreased to 8.29×10^4 t in 2009, which only accounted for 3.99% of the sediment load in the 1960s. In turn, coarsening trends were discovered for the mean grain sizes of sediment in Cores D1–1, D1–3, D2–1, D2–2, D3–1 and D3–1 after 1990, the corresponding contents of the silt sensitive component also increased significantly.

6 Conclusions

The variations of the runoff and sediment load into the sea were characterized by a stepwise reduction from 1958–2009, which was divided into three stages: 1958–1970, 1971–1990 and 1991–2009. Although the runoff and sediment load into the sea both showed reduction trends, the decrease in the sediment load was more significant than that in the runoff. Reservoir construction was the key factor that is responsible for the reduction of the sediment load of the entire Yalu River catchment since the 1960s. Vegetation coverage changes in the catchment on account of human activities also impacted the variations of the sediment load into the sea, as reflected by the gradual increase trends of suspended sediment grain size into the sea during the 1960s, which was followed by the decrease in the 1970s.

The variation of the sediment load was recorded by changes in the grain size of the sediment cores. The content variations of the sensitive components of the sediment cores from 1940 to 2010 were divided into four periods: 1940–1950, 1951–1980, 1981–1990 and 1991–2010. The contents of the silt sensitive components displayed a fluctuation during 1940–1950, as a possible refection of the inter-annual variation of the suspended sediment flux of the whole catchment into the sea. The sediment grain size variation was greatly influenced by the combinational effects of the land use/cover variation and reservoir construction from 1960 to 1980. The grain size variation was ascribed to the erosion intensity, which in turn was the increasing runoff in the catchment from 1981 to 1990. Despite the further reduction of the water and sediment flux into the sea, the period of 1990–2009 bore a coarsening trend for the grain size of sediment in the estuarine intertidal flat and significantly increasing silt contents of the sensitive component.

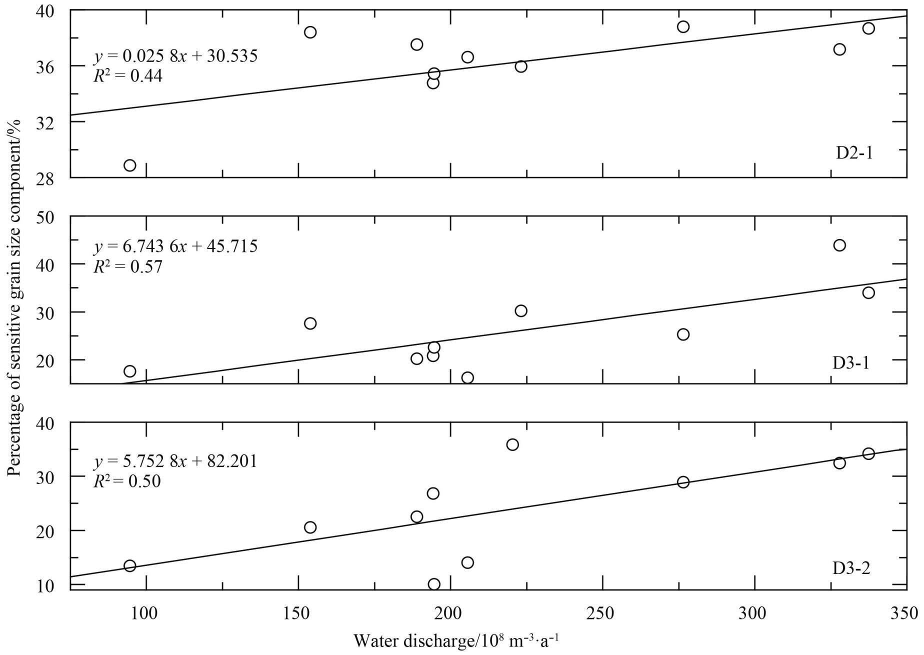

Fig. 11. The relationship between water discharge and the content of silt grain-size populations for sediment samples in Cores D2-1, D3-1 and D3-2.

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