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The nature and controls on downstream change of channel sediment along the Shiyang River, Northwest China

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The grain size composition and distribution of river sediments are important for understanding regional geomorphological evolution, source-sink processes and drainage ecology. The Shiyang River basin, an inland river system in northwestern China, provides an environmental context within which to investigate the relationship between sediment particle size and environmental factors. Based on the analysis of the grain size characteristics of modern riverbed sediments, basin geomorphological parameters and lithology, it is found that the median grain size (Md) of river sediments shows a decrease trend from upstream to downstream in the basin. One of the tributaries named the Jinta River shows an obvious downstream fining trend (exponentially decreasing) of Md, which is related to the old geomorphological development stages and relatively homogeneous lithology in the basin. The downstream fining trend of Md along the Xiyang River, another tributary, shows complex fluctuations, which might be affected by the tectonically active, young geomorphic development stage, complex lithology of the basin, and the sediment confluence of tributaries. The gravel-sand transition zone occurs in the plain section of the river about 28 km out of the mountain, which is related to the combination of regional geomorphological features, river morphology and hydraulic sorting.

KEYWORDS

river sediment, median grain size, downstream fining, gravel-sand transition, Shiyang River

Introduction

The grain size composition of sediments and its distribution characteristics along the river are important indicators for regional geomorphic evolution, deconstruction of basin analysis, and evaluation of watershed ecological health (Allen, 2008; Duller et al., 2010). River sediment grain size is one of the characterizing indicators of river hydrodynamic conditions and transport environment (Knighton, 1999), and its size and distribution characteristics are related to many factors such as regional geology, geomorphology, climate and hydrology (Allen, 2008; Duller et al., 2010; Blom et al., 2017). Fluvial abrasion and sorting of the reconstituted population, in the absence of further inputs, often produces relatively systematic downstream fining trends (Sternberg, 1875; Yatsu, 1955; Gale et al., 2019; Ivan and Tomáš, 2021a). Sternberg (1875) suggested that abrasion is the main cause of sediment decomposition and grain size refinement. Moreover, the

hydraulic sorting effect, i.e., the preferential downstream transport of fine-grained material, is also an important factor in the refinement of river sediments (Krumbein, 1941; Leopold and Maddock, 1953). The difference in slope lithology determines the initial grain size of river sediments and is an influential factor controlling the variation of grain size along the river (Yatsu, 1955; Kodama, 1994a; Rice, 1999). In addition, factors such as channel slope, width, depth, and flow velocity can also affect the transport capacity and sediment distribution characteristics of a river. Disturbed by tributaries and other lateral source factors and influenced by human activities will break the natural river sediment grain size along the refinement trend, showing complex segmental changes (Williams and Wolman, 1985; Rice, 1999; Surian, 2002).

Shulist (1941) proposed that the channel slope is the main factor affecting the distribution of particle size along the river, and it determines the transport capacity, when the gradient decreases, the transport capacity of the river is limited, and only finer particles can be transported. Leopold and Maddock (1953) argued that the gradient is not the only factor affecting the sediment size, and that the influence of channel morphology on the grain size variation characteristics is equally important. Alternatively, lateral material may also be important factors in causing irregular variations in sediment size along the channel, such as tributaries, slope-forming material, and land use (Knighton, 1980; Rice and Church, 1996; Surian, 2002; Dawson, 2010; Church and Kellerhals, 2011). In recent years, human activities have greatly altered the natural properties of the river channel and become an important factor affecting the distribution of grain size along the channel (Williams and Wolman, 1985; Surian, 2002). In addition, many studies have found that gravel-sand transitional reaches often occur during the process of grain size changes, with the change of river channel slope and channel morphology (Ferguson, 2003; Jerolmack and Brzinski, 2010; Frings, 2011; Miller et al., 2015).

However, the impact of these environmental factors on the grain size change along the river is still controversial (Blom et al., 2017). For example, affected by the characteristics of the tributary sediments, the inflow of the tributary can cause the coarsening or refinement of the

main stream channel sediment (Blom et al., 2017; Ivan and Tomáš, 2021b). Abrasion and sorting also have different effects on the refinement of river sediments in different river sections (Gale et al., 2019). The Shiyang River Basin (SYRB), which is an inland river system in Northwestern China, provides a good case for comprehensive comparative analysis of the impact of the above factors on the channel sediments. In this paper, we aim to analyze the influencing factors in combination with the geomorphic parameters, lithology and other environmental factors in the basin, so as to improve our understanding of river sediment grain size variation. This study can provide specific cases to explore the variability of sediment grain size characteristics among different rivers, and provide some ideas to reveal the general process of river sediment transport and deposition.

Study area

The Shiyang River originates from the northern slope in the eastern Qilian Mountains with an altitude of above 4,500 m above sea level (asl), flows through the Hexi Corridor at an altitude of 1,500 m, and finally disappears in the Tengger Desert. The topography is high in the south and low in the north, with a relief of 3,000 m (Figure 1A). The geomorphic units consist of the Qilian Mountains in the south, the Hexi Corridor in the center, and the low hills and desert areas in the north. The geological structure in the Basin is complex, mainly includes active Minle-Damaying Fault (M-D), Huangcheng-Shuangta Fault (H-S), Wuwei Basin South Fault (WWBS) and the Lenglongling Fault (LLL) (Figure 1B). The upper reaches of the basin are mainly Ordovician metamorphic rocks, while the middle and lower parts are dominated by loose deposits of the Quaternary (Figure 1B). In the Qilian Mountains, the upper Shiyang River is composed of eight major tributaries from west to east, including the Xida, Dongda, Xiyang, Jinta, Zamu, Huangyang, Gulang, and Dajing Rivers. The tributaries come out of the mountains and converge near Wuwei to form the main stream of the Shiyang River, which together constitute an important ecological safeguard for the Hexi Corridor and prevent the convergence of the Badain Jaran and Tengger Deserts (Figure 1A).

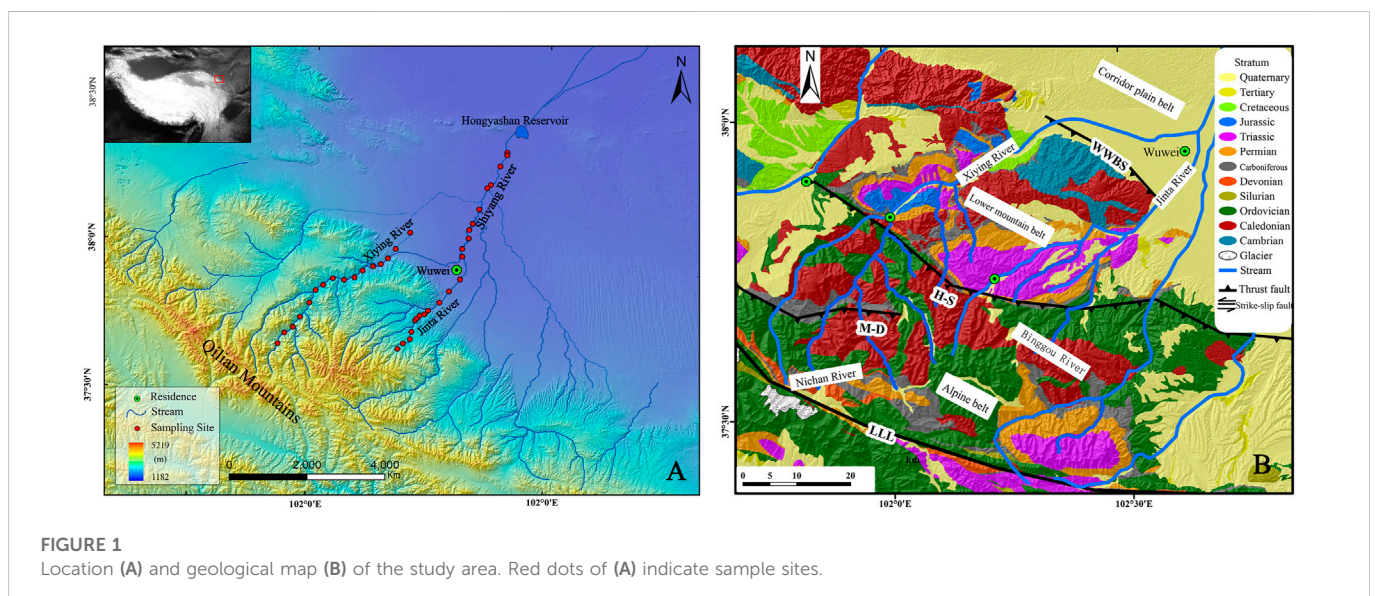


FIGURE 1 Location (A) and geological map (B) of the study area. Red dots of (A) indicate sample sites.

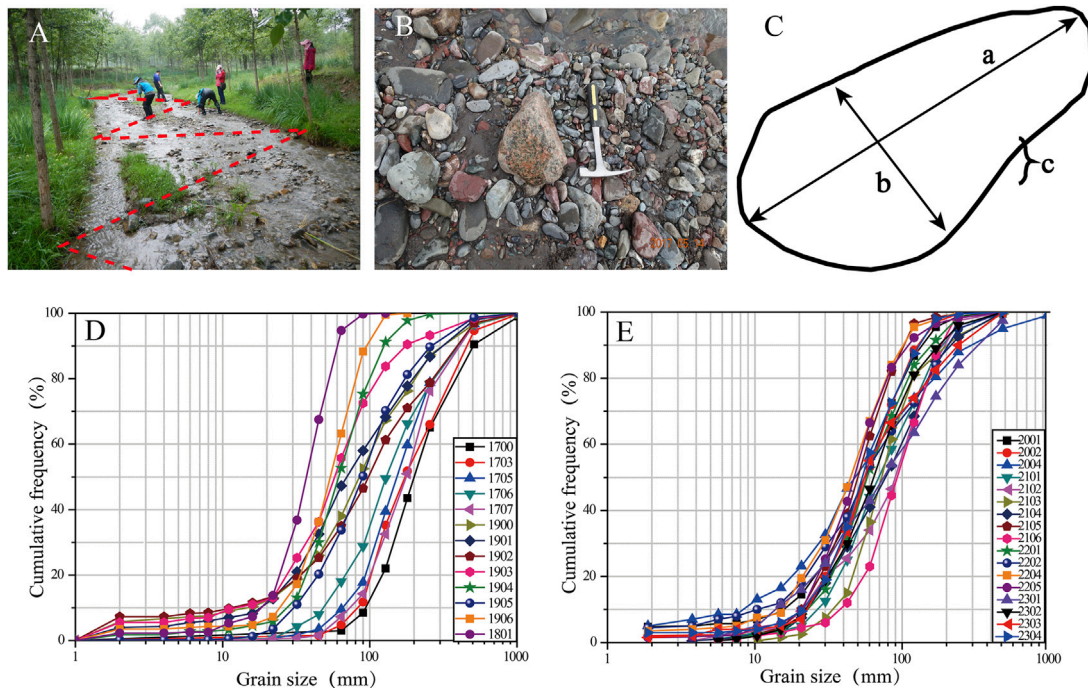


FIGURE 2

Diameter measurement method and field photographs of channel sediments. (A,B) show field survey methods and photos; (C): Measuring shaft "B" axis; (D,E) indicate frequency accumulation curves of the samples.

The SYRB, located at the intersection of the East Asian monsoon and westerly wind belts (Chen et al., 2008), possesses a typical continental arid and semi-arid climate. The spatial distribution of annual precipitation is characterized by less in the north and more in the south, more in the mountains, and less in the plains (Kang et al., 2009). Due to the large vertical height difference, the vegetation cover types and soil types in the study area are diverse. The area above 4,300 m asl is an alpine ice and snow zone, with sparse vegetation and a maximum precipitation of 600 mm. The altitude between 4,300 and 4,000 m asl is dominated by alpine sub-ice and snow sparse vegetation. It is mainly alpine dormant vegetation and alpine meadow vegetation between 4,000 and 3,500 m asl, and a mountainous forest zone dominated by cold temperate coniferous forest at 3,500–2,700 m asl. There are mainly mountain grassland, mountain desert steppe at 2,700–2,400 m and 2,300–2,000 m asl, respectively. The Hexi Corridor plain area in the middle reaches of the Basin is 1,500–2,000 m asl, with an annual precipitation of 150–300 mm. The elevation of the Minqin Basin in the lower reaches of the Basin is 1,300–1,500 m asl, and the annual precipitation is less than 150 mm. The main vegetation type is semi-shrub salt desert.

Methods

The median grain size (Md) of river sediments is the most basic characteristic parameter to measure river transport capacity, indicating the central tendency of sediment grain size frequency distribution and the average kinetic energy condition of flowing water. In this paper, the upstream mountain tributaries Jinta River, Xiyang River and the main stream of Shiyang River (Shiyangdahe) in the plain area are selected as the research areas. The material composition of the river was measured

using the "Wolman gravel counting method" (Wolman, 1954). The Jinta River-Shiyang River section was selected from the upper tributary Binggou River to Hongyashan Reservoir, and a total of 24 sample points were selected. For the Xiyang River, the study section is near the Ningchan River to the mountain pass in the upper reaches of the basin (Figure 1A), a total of 16 samples were selected.

Bed materials were sampled at approximately equal interval along each river channel. With the sediments consisting primarily of particles larger than 2 mm in size, sampling was conducted according to the procedures outlined by Wolman (1954). In river sections, take one bank at the full bank level as the starting point, walk along the jagged path in the river (Figure 2A) a photograph of the gravel in the field is shown in (Figure 2B), select the gravel in which the toe of the index finger steps in each step, and measure the middle axis of the gravel, i.e., the b axis, with a tape measure (Figure 2C). The distance between measurements along the river section is about 3–4 km, and at least 200 gravels were measured for each cross section. Then the measured data were processed in Excel for statistical analysis and grain size classification, and the Md of the section was calculated and obtained (Figures 2D, E). For the sandy river in the lower reaches of the Basin, after collecting samples in the field, the particle size was measured and analyzed using a Malvern Mastersizer 2000 laser particle sizer in the laboratory.

Results

Grain size distribution

The statistical results show (Figure 3A) that two channel types, i.e., gravelly and sandy channels, can be identified along the river

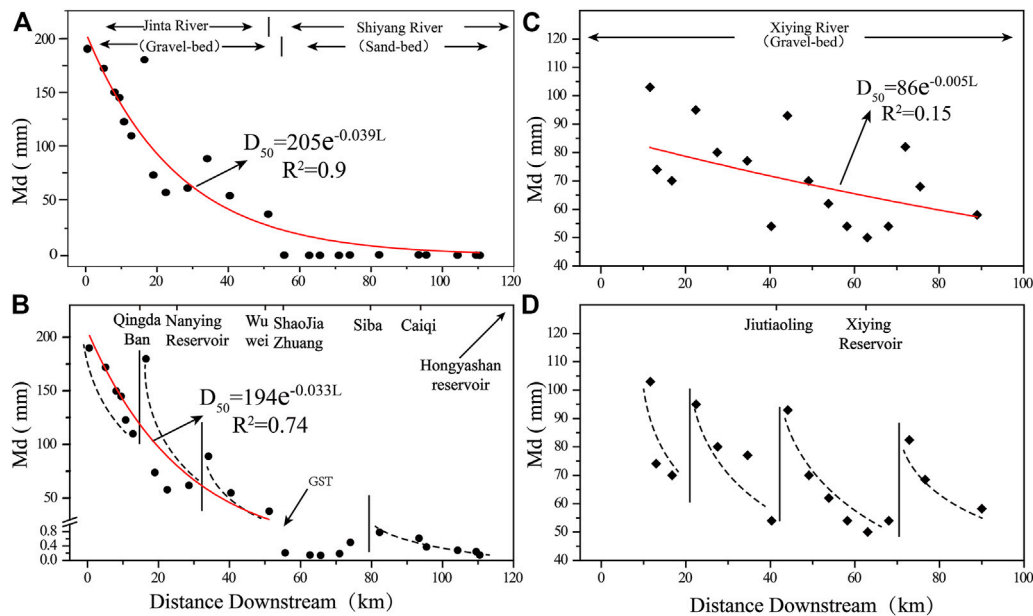


FIGURE 3

The variation characteristics of Md in channel sediments along the channel; (A,B): The variation of Md along Jinta - Shiyang River. (C,D): The variation of Md along Xiying River. The black solid line is the demarcation of the phase change, and the black dashed line is the general trend. Red solid line is the fitting result.

section from the Jinta River to Hongyashan Reservoir. The section of the Jinta River from its source to Shaojiazhuang is a gravelly channel with a Md of 38–190 mm and an average of ~106 mm (Figure 3B); the section from Shaojiazhuang to Hongyashan Reservoir is a sandy channel with a Md of 0.13–0.62 mm (Figure 3B). The modern riverbed sediments in the Xiying River are mainly gravels, with a Md of 50–103 mm and an average of 70.6 mm (Figure 3C).

Downstream changes in riverbed sediment

As the distance from the river source increases, the particle size of the river sediment generally decreases exponentially, as shown in Formula Eq. 1:

$$D_i = D_0 e^{-\partial L} \quad (1)$$

where D_i is a characteristic linear dimension at some distance L , D_0 is the characteristic dimension at $L = 0$, L is the distance from the river source, and ∂ is a size diminution coefficient that expresses the rate of grain-size decreases toward downstream.

In general, there is a strong exponential relationship ($R^2 = 0.9$) between the sediment Md and the distance L in the reach from Jinta to Shiyang Rivers, and the ∂ is about 0.039 (Figure 3A). In the gravelly section of Jinta River, there is a significant exponential decreasing relationship between Md and the distance L , and the ∂ is about 0.033 (Figure 3B). In the sandy section of the Shiyang River, the refinement trend of Md is not obvious with the increase of distance L , which shows a fluctuating change of increasing first and then decreasing. The exponential decreasing relationship between Md and river length of the Xiying River is relatively weak, with a low coefficient R^2 of 0.15, and a ∂ of 0.005 (Figure 3C).

The Md of riverbed sediment in the Shiyang River section showed a general trend of gradual decrease from upstream to downstream, which is consistent with the trend of refinement along the grain size in most studies (Table 1). A comparison of the global stream sediment refinement model (Figure 4A) shows that most of the gravelly channels are less than 10^2 km long, while the sandy channels can stretch for thousands of kilometers, indicating that the transport distance of gravel in the channel is limited, generally not more than 100 km. The fining coefficient of gravelly river is generally greater than 0.01, while that of sandy river is generally lower than 0.01, that is, the refinement trend of gravelly channels is more obvious than that of sandy channels (Figures 4B, C). In addition, the fining coefficient α of river sediments was inversely correlated with river length (Figure 4A), which probably attributed to the fact that the longer the river, the more complex the response of river sediment grain size to factors such as landforms, climate, and tributary confluence, thus showing a more complex change trend.

Abundant studies suggest that the downstream fining of river bed materials can be attributed to sorting and abrasion. However, lateral inputs of coarse sediment, basin geomorphic development stage, lithology, human activities and tributary confluence may break the downstream fining trend (Figure 3). For example, in the Jinta River, there is a sudden increase in the Md of river sediment near Qingdaban and below the Nanying Reservoir. The sudden change in Md of river sediment in the Xiying River mainly occurs at about 20 km from the source, near Jiutiaoling, and at the head of the Xiying River canal (Figures 3B, D), and the occurrence of these sudden change in grain size makes the distribution of river sediment along the river show an obvious segmental decreasing trend.

TABLE 1 Fining coefficient of clasts in rivers.

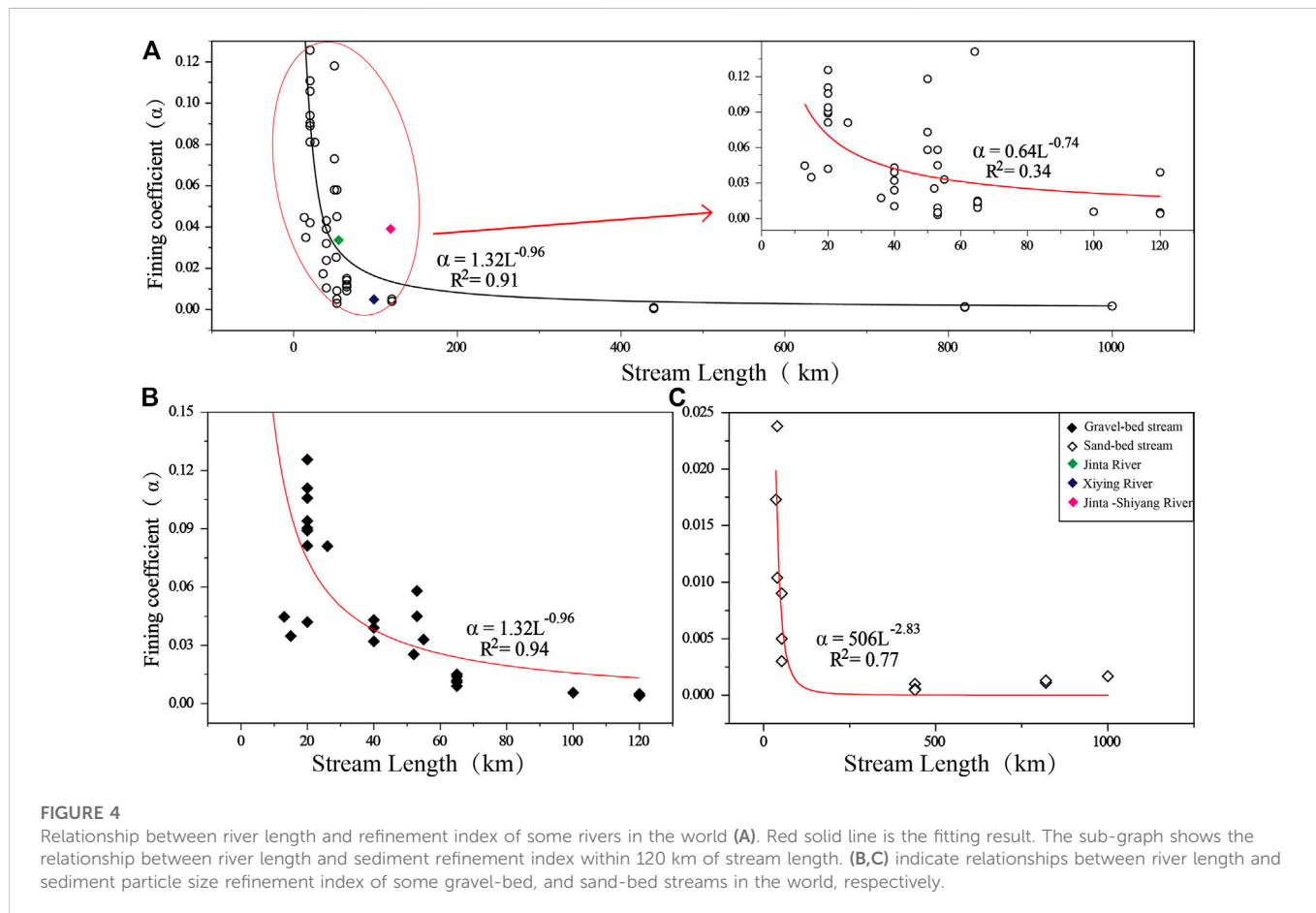
Location	River length (km)	Slope (%)	Characteristic dimension	Particle size (mm)	Riverbed type	α	References	
Knik River, Alaska	0-26	0.55	\bar{D}	44-330	B/G	0.081	Bradley et al. (1972)	
Mississippi, Vicksburg	440	/	D ₈₅	0.3-0.9	S	0.0010	Rana et al. (1973)	
			D ₅₀	0.2-0.55	S	0.00055		
			D ₁₅	0.18-0.33	S	0.00045		
North Saskatchewan River, Canada	0-1,000	/	D ₉₀	0.03-0.24	S	0.00168	Hoey and Bluck, (1999)	
Squamish, British Columbia	40	/	D ₈₄	53-610	B/G	0.043	Brierley and Hickin, (2010)	
			D ₅₀	37-300	B/G	0.039		
			D ₁₆	18-120	B/G	0.032		
Amazon, from Iquitos	3,300	/	D ₅₀	0.15-0.50	S	Slightly negative	Nordin et al. (1980)	
Bollin-Dean, Cheshire	0-50	/	\bar{D}	0.33-67	G/S	0.118	Knighton, (1980)	
Noe, Derbyshire	0-20	/		29-69	G	0.042		
Piave River, Italy	0-120	0.2-1.05	D ₈₄	22-183	G	0.005	Surian, (2002)	
			D ₅₀	12-84	G	0.004		
Niger River, Western Africa	0-300	/	D ₅₀	0.43-0.82	S	1.38×10^{-6}	Deigaard and Fredsee, (1978)	
Ringarooma River, Northeast Tasmania	0-65	1.45	D ₉₅	83-220.53	G	0.012	Knighton, (1999)	
			D ₈₄	61.5-161.5	G	0.011		
			D ₅₀	21.69-68.38	G	0.009		
			D ₁₆	6-30.1	G	0.015		
			D ₅	2.45-7.75	G	0.014		
	65-118	0.16	D ₉₅	5.5-53	G	0.058		
			D ₈₄	2.5-27.5	G	0.045		
			D ₅₀	0.9-2.5	S	0.009		
			D ₁₆	0.6-1.1	S	0.003		
			D ₅	0.4-0.8	S	0.005		
Kinu River, Japan	0-52	0.36	D ₅₀	20-70	G	0.0253	Yatsu, (1955)	
	60-100	0.11		0.4-0.9	S	0.0238		
Kiso River	0-15	0.19		35-70	G	0.0348		
	15-55	0.04		0.4-0.6	S	0.0104		
Nagara River	0-13	0.1		25-40	G	0.0446		
	13-49	0.04		0.7-1.2	S	0.0173		
Watarase, Japan	0-20	0.45	\bar{D}	4-65	G	0.089		Kodama, (1994b)
Mayan River, NE Iran	0-20	4.5	F060D	2.5-15	G	0.0812		Moussavi-Harami et al. (2004)
			D ₅₀	3-17.5	G	0.0903		
Dehbar River	0-20		\bar{D}	2.5-20	G	0.1108		
			D ₅₀	2-25	G	0.1256		
Jaghargh Rive	0-25		\bar{D}	1.5-15	G	0.094		

(Continued on following page)

TABLE 1 (Continued) Fining coefficient of clasts in rivers.

Location	River length (km)	Slope (%)	Characteristic dimension	Particle size (mm)	Riverbed type	α	References
			D ₅₀	2–17.5	G	0.1058	
Ningmeng section of the Yellow River, China	820	0.012	D ₈₄	0.166–0.192	S	0.0013	Ta et al. (2011)
			D ₅₀	0.055–0.137	S	0.0011	
			D ₁₆	0.031–0.096	S	0.0013	
Liyuan River, China	0–50	0.1–1.56	D ₈₄	26–530	G/S	0.058	Chen et al. (2018)
			D ₅₀	12–272	G/S	0.073	
Jinta-Shiyang River, China	0–120	0.067–0.001	D ₅₀	0.134–190	G/S	0.039	This paper
Jinta- River, China	0–55		D ₅₀	38–190	G	0.033	
Shiyang River, China	55–120		D ₅₀	0.13–0.62	S	Slightly	
Xiying River	0–100	0.054–0.006	D ₅₀	50–103	G	0.005	

Note: B, G and S indicate Boulder-bed, Gravelly-bed and Sandy-bed, respectively.



The gravel-sand transition

The results show that the Gravel-Sand Transition (GST) is evident in the Hexi Corridor area at about 28 km downstream from the outlet of the Jinta River (Figure 3B). Previous studies

have shown that the GST of river sediments is usually related to slope, local base level, excessive sand supply or gravel wear, selective sorting, etc., (Yatsu, 1955; Gregory et al., 1995; Knighton, 1999; Dubille and Lavé, 2015; Ferguson and Ashworth, 2010; Ehda et al., 2021). Especially after the rivers

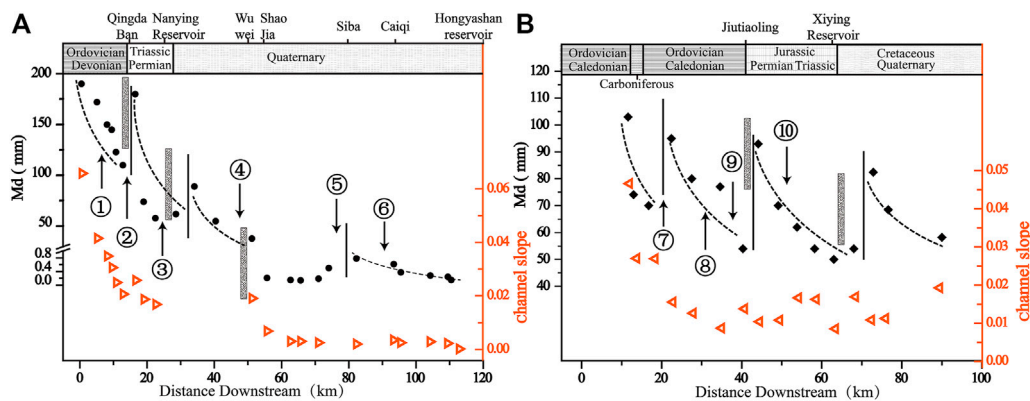


FIGURE 5

The relationship between slope, tributary inflow and Md of sediments in Jinta—Shiyanghe River (A,B) Xiying River. ①–⑩ indicate Xigou, Binggou, Dashui, Yangjiaba, Baita, Hongshui, Qingyang, Tuoluo, Shuiguan, and Xiangshui Rivers, respectively. The gray strips indicate human settlements and reservoirs.

flow out of the mountain, the channel is not limited laterally by topography, and the rapid decrease in sand transport capacity of the river is the main reason for the formation of the GST zone. In addition, the GST is accompanied by a shift in channel planform from multi-channel to single-channel (Dubille and Lavé, 2015), e.g., gravelly reaches in the upper part of the gravel-sand transition zone are usually braided streams with a large channel slope (Gregory et al., 1995; Venditti and Church, 2014), while downstream channels typically evolve into single-channel sandy streambeds (Frings, 2011; Dubille and Lavé, 2015; Dingle et al., 2020). From the mountain pass of Jinta River to Wuwei City, the landforms are dominated by alluvial fans, wide and shallow river channels. The river channel presents a braided river style, with the channel slope of 0.02. In the Hexi Corridor plain area, it is dominated by narrow and deep meandering rivers, with a slope of less than 0.005 (Figure 5). The GST occurs at the distance of about 10–40 km downstream from most river outlets (Dingle et al., 2017; Ehda et al., 2021), suggesting that the gravel transport distance is related to the geomorphic characteristics of the watershed, sediment supply, and the transport capacity of flowing water.

It was suggested that the GST occur at the distance of about 10–40 km downstream from the mountain pass (Dingle et al., 2017; Ehda et al., 2021), indicating that the gravel transport distance is limited downstream the outlet. After the river exits the mountain pass, the stream gradient decreases rapidly in the lower reaches, and the channel is no longer restricted, accelerating lateral swings, resulting in large deposits of coarse gravel and continued transport of fine-grained material (Paola et al., 1992). And in the GST region, the presence of some gravel further promotes the fragmentation of matter and the production of fine particles (Bradley, 1970; Kodama, 1994a). Therefore, under the condition of river hydraulic separation, fine particles are preferentially transported faster and farther downstream than coarse particles. In addition, some rivers passing through Wuwei City have been artificially channelized, which will also affect the original transport process of river sediments.

Discussions

Influence of tributary inflow on sediment downstream fining

River sediments are mainly originated from the slope process, tributary inflow and river bank erosion along the river. Tributary confluence generally leads to a sudden increase in sediment grain size (Ichim and Radoane, 2010; Brewer and Lewin, 1993; Rice, 1998). If the transport capacity of the confluence section is weak, the coarse-grained materials will be deposited on the riverbed (Lane, 1995), and this deposition will in turn lead to a reduction in the channel slope in the confluence section, resulting in a reduction in runoff shear stress and deposition of fine-grained material (Dawson, 2010). Our results show that the confluence of Binggou River, Dashui River and Baita River, tributaries of the Jinta River, showed coarsening of the grain size of the riverbed material in the confluence section (Figure 5A). In addition, the confluence of Qingyang River and Shuiguan River, tributaries of the Xiying River, similarly caused an increase in the sediment particle size of the main channel (Figure 5B).

Especially the larger the volume of an input and the greater the grain size disparity between it and the main stem material, the greater is the expectation that the main-stem texture is changed notably. At confluences the situation is complicated by the concomitant influx of water which, if sufficiently large, modifies ambient stresses and, in turn, the bed material. A tributary which introduces a significant quantity of water but little sediment could, by increasing the capacity of the main stem, produce a significant change in texture. Therefore, the relative volume of a sediment input, its size characteristics relative to the recipient channel and, at tributaries, the relative contribution of water, may be controls on the occurrence of particle size discontinuities. The volume of material carried by tributaries depends on the volume of sediment supplied to the river and the ability of the stream transport, while the volume of water flowing out of the basin depends mainly on the climate, vegetation and watershed area (Knighton, 1980; Rice, 1998). In the Qilian Mountains, the Xiying and Jinta Rivers are located in the same climatic unit, the vegetation difference is small, and the watershed area can be used to indirectly reflect the tributary flow (Table 2). For example, probably influenced by flow and

TABLE 2 Drainage area of some tributaries of the Jinta and Xiyang Rivers.

Watershed	Jinta River			Xiyang River			
	Xigou	Binggou	Dashui	Qingyang	Tuoluo	Shuiguan	Xiangshui
Drainage area (km ²)	47	130	482	176	117	242	104

TABLE 3 Comparison of geomorphic parameters of Jinta and Xiyang River Basins.

River basin	Dd	HI	Bs	Vf
Jinta	0.40	0.39	1.5	2
Xiyang	0.33	0.45	2	0.43

sediment size, some of the tributary confluences, such as the Xigou, Tuoluo, and Xiangshui Rivers, cannot break the along-channel refinement of the river sediments (Table 2).

After the confluence of the tributaries, the sorting action and abrasion process of the water flow will continue to act on the river sediments. Except for the area near the confluence, the overall pattern of longitudinal changes in river sediments is basically not affected, and the overall trend is decreasing.

Influence of lithologic composition on sediment downstream fining

Watershed lithology is an important factor influencing the sediment yield, which determines the initial grain size of the river sediment and the anti-erosion ability (Rice, 1999). The lithology of the Jinta River basin is distributed uniform, with Ordovician metamorphic rocks and Caledonian granites in the source area, Carboniferous-Permian and Triassic sedimentary rocks in the upstream area, and Quaternary loose sediments in the middle and downstream areas. The lithology of the Xiyang River basin is complex, with Ordovician metamorphic rocks and granites dominating, Silurian granites and Triassic granites and sedimentary rocks distributed locally, with a few Carboniferous and Permian strata exposed near the watershed; some Cretaceous and Cambrian strata are distributed near the outlet (Figure 1B). From the viewpoint of the stratigraphic lithology along the river channel, the distribution of lithological resistance strength and weakness along the Jinta River channel is uniform, which indicates that the lithology of the source of sedimentary material in the river channel is relatively uniform. However, the distribution of lithological resistance in the Xiyang River channel is more complex, which indicates that the sources of sedimentary material are diverse, thus the grain size changes are more complex along the channel.

Influence of the geomorphic evolution stage on sediment downstream fining

The geomorphic parameters that reflect the development stage of the basin geomorphology (Bull and Mcfadden, 1977; Keller and

Pinter, 2002; Peters and Balen, 2007), such as drainage density (Dd), hypsometric integral (HI), basin shape index (Bs), and valley width-to-height ratio (Vf) of the basin, are shown in Table 3. The Vf values in the Jinta River basin are larger than those in the Xiyang River, while the HI and Bs values in the Jinta River basin are smaller than those in the Xiyang River, indicating that the regional tectonic activity in the Xiyang River is more active than that in the Jinta River basin. Moreover, the geomorphic development stage in the Jinta River basin is tend to a mature stage, and the river longitudinal profiles tend to be graded (Yatsu, 1955). Therefore, in the Jinta River basin, which is relatively tectonically stable and has a relatively mature development stage, the refinement of river sediment shows an obvious exponential decreasing, while in the Xiyang River basin, which is relatively tectonically active and has a relatively young development stage, the trend of refinement of river sediment grain size is often broken.

Influence of channel slope on sediment downstream fining

The decrease of channel slope will weaken the transport capacity of the river and lead to the accumulation of coarser fractions in the river sediment. By comparison, it was found that the change of channel slope in the Jinta-Shiyang Rivers generally showed a decreasing downstream trend, which basically followed the same trend as the change of river sediment grain size. For example, the gravel-sand transition zone near Wuwei corresponds to a decrease in channel slope (Figure 5A), which may be due to the fact that this area is a transition area from mountainous to plain area, and the lower channel slope reduces the transport capacity of the river, which can only transport finer fractions of material downstream, so that there is an obvious gravel-sand transition zone downstream. Similarly, the Xiyang River channel shows a general trend of fluctuating lowering of channel slope downstream, and the fluctuating change corresponds to the area of sudden increase of grain size (Figure 5B), indicating that, except for strong tectonic activities, the along-channel change of channel slope has a significant influence on the change of grain size of river sediments.

Influence of human activities on sediment downstream fining

Increasing human activities, such as village settlements and the construction of dams and reservoirs, can regulate river runoff, breaking the original water-sand balance of the river, for example, leading to a reduction in the transport capacity of the river, and inability to transport coarse-grained material downstream (Surian,

2002). For example, in the upstream of the Xiyang River near Jiutiaoling (Figure 5A), the construction of houses and bank stabilization have led to an obvious coarsening of river sediment grain size along the river. In addition, the construction of reservoirs, has changed the river environment and weakened the river transport capacity, and the downstream river sediment grain size of reservoirs has also coarsened (Figure 5B).

In addition, the construction of Tianma Lake near Wuwei reduced the riverbed sediment transported downstream, breaking the original refinement pattern of river sediment grain size, and an obvious abrupt change area of gravelly sand transformation appeared in the area below Wuwei. Below Tianma Lake, the impact of human activities decreased, and the grain size of river sediments gradually increased and continued to show a refinement trend below Siba.

Conclusion

Based on the analysis of the variation of river sediment grain size along the Shiyang River basin in northwestern China, it was found that the river particle size generally shows a trend of refinement along the river channel. The refinement index of gravelly channels is generally larger than that of sandy channels. And the GST zone occurs at about 28 km downstream from the outlet of the Jinta River in the Hexi Corridor area. The tributary confluence is the main reason why the sediment refinement trend is broken, and the difference of geomorphic development stage and lithology in the basin is also the main reason why the sediment grain size distribution along the two tributary channels of Jinta and Xiyang Rivers is different. Human activities, such as sand and gravel extraction, bank stabilization and damming, reservoir storage, change the natural properties of local rivers and affect the distribution of sediment grain size along the rivers.

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Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

Project administration and experimental design: GH Writing, original draft: PL, and HG Writing, review and editing: all authors. Methodology and investigation: HG, PL, ZL, YW, and FL.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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