

Effects of Cascade Reservoir Systems on the Longitudinal Distribution of Sediment Characteristics: A Case Study of the Heihe River Basin

Yu Wang (✉ wangyu-mike@163.com)

Lanzhou University of Technology <https://orcid.org/0000-0001-5621-6052>

Bao-long Li

Lanzhou University of Technology

Juan-juan Liu

Lanzhou University of Technology

Qi Feng

Northwest Institute of Eco-Environment and Resources

Wei Liu

Northwest Institute of Eco-Environment and Resources

Xu Wang

Lanzhou University of Technology

Yu-hua He

Lanzhou University of Technology

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Abstract

Spatial variations in grain-size parameters can reflect river sediment transport patterns and depositional dynamics. Therefore, 22 surficial sediment samples taken from the Heihe River and its cascade reservoirs were analyzed to better understand the impact of cascade reservoir construction on sediment transport patterns in inland rivers in China. The results showed that the longitudinal distribution of sediment grain size in the Heihe River was significantly affected by the influence of the cascade reservoirs. The grain size of the reservoir sediments within the cascade reservoir system was much lower than that of sediments in the natural river section, and the sediments in the natural river were well sorted, exhibiting leptokurtosis and positive or very positive skew. The lower reaches of the dammed river experienced strong erosion, and the grains of the bed sediments were coarse and poorly sorted; the grain-size distributions were more positively skewed and exhibited leptokurtosis. The backwater zone of the reservoir was influenced by both backwater and released water, and the sediment grain size was between the grain size of the natural river and that of the lower reaches of the dam; these sediments were moderately well sorted and had a positively skewed, leptokurtic grain-size distribution. Sedimentary environmental analysis revealed that the characteristics of the sediment grain size in an upstream tributary of the Heihe River were more influenced by source material than by hydrodynamic conditions, while the grain-size characteristics of the mainstream sediments were controlled mainly by hydrodynamic conditions.

Introduction

River sediments are a significant component of the river ecosystems created by soil erosion in the river basin (Bravard et al., 2014), and their grain-size distribution are affected by multiple factors, including sediment source, and hydrodynamic conditions (Snelder et al., 2011, Zhu et al., 2014, Pan, et al., 2015). Grain-size characteristics of sediments can intensively reflect local the sedimentary environment, such as its hydrodynamic conditions and changes in water levels, sediment transport and redistribution processes (Folk, 1966, Pejrup, 1988). Different sedimentary condition has specific sediment grain-size parameters and their assembly characteristics (Sun et al., 2002, Vandenberghe et al., 2018). Therefore, grain-sizes analysis is extensively applied in environmental studies and used to reveal the origin of sediments (Zanella, et al., 2012), identify sedimentary environment types (Halls, 1967, Friedman, 1979), reflect hydrodynamic conditions during deposition, infer sediment diffusion, transport and deposition processes (Ma et al., 2014, Rosenberger et al., 2016).

Cascade reservoirs not only generate electricity to alleviate the energy crisis, but also control flood and adjust the uneven spatiotemporal distribution of water resources. Nevertheless, such large artificial lake can have significant negative effects on a river's hydrodynamic conditions, including water level fluctuations (Lu and Siew, 2006; Wang et al., 2013) and decreased velocity (Klaver et al., 2007, Wei et al., 2008). Subsequent to the reservoir impoundment, such changes of hydrodynamic conditions significantly affect the compositions and transport fluxes of sediment in the reservoir area and downstream river (Walling and Fang, 2003, Willis and Griggs, 2003). A global estimate reveals that greater than 50% of basin-scale sediment flux in regulated basins is potentially trapped in artificial impoundments (Vörösmarty et al., 2003). Moreover, river sediments are important carriers of chemicals such as nutrients, salt, and pollutants. The nutrients adsorbed onto sediment particles, especially phosphorus, will accumulate with the sedimentation of river sediments (Muller et al., 2007), which may lead to algal blooms in reservoir areas (Yang et al., 2018, Zhou et al., 2013). However, the lower reaches of dammed rivers, which have relatively clear water, often experience bed incision and bank collapse; these effects can further adversely impact riparian infrastructure and riverine ecosystems and cause the drawdown of the alluvial water table (Vörösmarty et al., 2003, Minear and Kondolf, 2009, Ran et al., 2013). Therefore, it is important for the ecological restoration of river basins and the rational

operation of reservoirs to study how the spatial distribution of sediment grain size is correlated with water and sediment changes in rivers in which reservoir cascade systems have been constructed.

The Heihe River Basin (HRB), the second largest inland river basin in China, is located in a very important strategic position. The middle reach of the basin is located on the ancient "Silk Road" and the current Asia-Europe Continental Bridge, and it has become one of the top ten commodity grain bases in China in addition to its long history of agriculture; the Ejina Oasis in the lower reach of the basin is an important ecological security barrier in China (Li et al., 2020). Thus, rivers have undoubtedly played a vital role in the agricultural development of the middle reaches of the HRB and the maintenance of a healthy oasis system in the lower reach. However, a cascade of eight hydropower dams with a river distance of 100 km has already been constructed in the mainstream and tributary reaches of the upper Heihe River, and another, larger-capacity reservoir ($4.01 \times 10^8 \text{ m}^3$) is in the construction stage in the upper reach of the river. The intensive cascade reservoir system in the upstream region of the Heihe River has greatly changed the relationship between water and sediments, and this change has influenced several factors, including the evolution of the river course in the middle and lower reaches, the riverine ecosystem, and even the development of agriculture in the Hexi Corridor. Previous studies have focused mainly on the analysis of river sediment sources (Derbyshire et al., 1998; Ta et al., 2004; Zhang et al., 2020), and there have been few studies on the influence of human activities on the characteristics of river sediment transport. In this study, we systematically collected surface sediment samples from a typical river and cascade reservoir system in the Heihe River. The aims of this study were to analyze and quantify the extent to which environmental factors and processes such as cascade reservoir construction affect riverine sediments.

Study Area

The HRB is located in northwestern China, within the range of $96^{\circ}42'-102^{\circ}04' \text{ E}$, $37^{\circ}45'-42^{\circ}40' \text{ N}$ (Fig. 1). The core drainage area is approximately $143,000 \text{ km}^2$, with a mainstream length of 821 km. The HRB can be divided into three segments (Zhang and Dong, 2015). The upper reach flows within the Qilian Mountains and down to Yingluo Gorge (the outlet of the river in the Qilian Mountains) and is characterized by a steep gradient and a narrow channel. The elevation of the upper reach ranges from 2600 to 5500 m, and the mean annual precipitation varies substantially with altitude, increasing from 250 mm in the lower mountainous zone to 700 mm in the higher mountainous zone. The middle reach flows through the Hexi Corridor, from Yingluo Gorge to Zhengyi Gorge. The elevation of this segment decreases from 2600 m to 1400 m, and the mean annual precipitation decreases from 250 mm to $< 100 \text{ mm}$. The lower reach of the river flows northwards from Zhengyi Gorge and terminates in the Juyan Lakes (the east and west branches, respectively). The reach has a mean altitude of 1000 m and a mean annual precipitation of $< 50 \text{ mm}$ (Zhu et al., 2008).

Most of the runoff in the HRB and its tributaries is generated from rainfall and ice-snow melting in the upstream mountainous area; precipitation is the main source (Wang et al., 2009). The hydrological station at Yingluo Gorge (the outlet of the river in the Qilian Mountains) recorded a multiyear average runoff amount (1955–2015) and sediment flux (1968–2015) of $1.65 \times 10^9 \text{ m}^3/\text{yr}$ and $2.06 \times 10^6 \text{ t/yr}$, respectively (Zhang et al., 2020). The sediment in the Heihe River comes mainly from the upstream mountainous area and is formed by the erosion of surface soils by precipitation and runoff. Most of the sediments in the middle reaches of the river have been transported there from the upper reaches, but some originate locally when large floods result in riverbed and riverbank erosion. In addition, a small amount of the sediment in the middle reaches is carried in water that returns to the river after being used for irrigation.

The Heihe River originates on the northeastern margin of the Tibetan Plateau. The upstream mainstream channel has a large elevation drop and contains large amounts of water energy. The upper reaches of the river comprise 106.88×10^4 kW, with an exploitable capacity of 52.8×10^4 kW and an annual electricity output of 38.48×10^8 kW/h. To meet flood control and power generation needs, a series of cascade reservoir and water diversion projects (e.g., Baoping, Sandaowan, Erlongshan, Dagushan, Xiaogushan, Longshou II, and Longshou I, Table 1) have been conducted in the Heihe River in the past decade. The Longshou I reservoir, built in 2001, was the first reservoir built on the mainstream of the upper reaches of the Heihe River. The Baopin reservoir, one of the largest reservoirs on the river, began operations in 2012 and had an initial total storage capacity of 2.15×10^8 m³.

Table 1
Hydropower development on the mainstream of the upper Heihe River

| Hydropower station | Installed capacity (10^4 KW) | Average annual electricity yield ($\times 10^8$ KW·h) | Total capacity (10^8 m ³) | Operation time |
|--------------------|------------------------------------|---|---|---------------------|
| Dipanzi (DPZ) | 1.60 | 0.72 | 0.0028 | 2004.09 |
| Huangzangsi (HZS) | 4.90 | 2.03 | 4.03 | In the construction |
| Baoping (BP) | 12.30 | 4.10 | 2.150 | 2012.07 |
| Sandaowan (SDW) | 11.20 | 4.00 | 0.053 | 2009.05 |
| Erlongshan (ELS) | 5.05 | 1.74 | 0.811 | 2007.09 |
| Dagushan (DGS) | 6.50 | 2.01 | 1.410 | 2009.07 |
| Xiaogushan (XGS) | 10.20 | 3.91 | 0.014 | 2006.07 |
| LongshouⅠ (LS Ⅰ) | 15.70 | 5.28 | 0.862 | 2004.08 |
| LongshouⅡ (LS Ⅱ) | 5.20 | 1.98 | 0.132 | 2002.04 |
| Longqu (LQ) | 1.60 | 0.85 | – | 2002.12 |

Materials And Methods

Field sampling

After the impoundment of a reservoir, the hydraulic factors of the river such as the water surface slope and flow rate decrease, and the water level in the reservoir area increases. As a river approaches the base level of a reservoir, its water and sediment dynamics are affected by a transitional reach known as the variable backwater zone (Zheng et al., 2019). Sediments in the reservoir and in the variable backwater zone exhibit different erosion and sedimentation characteristics. At low flows, flow deceleration and in-channel sedimentation occur in variable backwater zones, but at high flows, flow acceleration and erosion occur. In addition, sedimentation in the reservoir causes the discharge water flow to erode and scour the downstream riverbed, thereby coarsening the particle size of the river sediments. To analyze the effects of hydropower development on the erosion and sedimentation characteristics of sediment in the mainstream of the Heihe River, the field sampling in this study was performed at four location types: the natural river, the backwater zone, the lower reaches of the dam, and the reservoir.

Riverbed sediments were collected from 22 sites in the mainstream of the Heihe River (Fig. 1). Nine sites (H₁, H₃, H₄, and H₁₇–H₂₂) were established on the mainstream of the natural river based on the distribution of hydrological stations, the confluence of rivers, and administrative boundaries. Four sites (H₅, H₆, H₁₅ and H₁₆) were established in the lower reaches of the dam on the mainstream. Four sites (H₇, H₈, H₁₀ and H₁₂) were established in the backwater zone, and five sites (H₂, H₉, H₁₁, H₁₃ and H₁₄) were established in the mainstream and tributary of the reservoir. Samples from the natural river, the lower reaches of the dam, and the backwater zone were collected in January 2018. Samples from the reservoir area were collected in August 2018 because the surface of the river was frozen during the January sampling period. Surface sediments were collected at a sampling depth of less than 5 cm from the banks of the natural river, the lower reaches of the dam, and the backwater zone. Three parallel sediment samples were collected from each sampling area using a Petersen mud extractor. The samples were packed into polyethylene bags and taken back to the laboratory for analysis. Moreover, since the reservoir is emptied during the winter dry season to clear out sediments, stratified sampling was performed at a depth of 3 m at sampling site H₂ (labelled H₂₋₁, H₂₋₂ and H₂₋₃).

Grain size experiment

The samples were pretreated with 10% H₂O₂ and 10% HCl to remove organic matter and biogenic carbonate, respectively. Then, the samples were dispersed with 0.5% (NaPO₃)₆ and subsequently dispersed ultrasonically. The grain size was measured with a Malvern Mastersizer 2000 laser particle size analyzer (Malvern Instruments Ltd., UK), with a measuring range from 0.02 to 2000 μm, a particle resolution of 0.01, and a relative error of <2%.

The grain-size and sorting parameters of the sediments were calculated following the formulae devised by Folk and Ward (Folk and Ward, 1957). In the calculations, the grain size was measured using phi (φ) units (φ, where φ is the grain size in millimeters) and described using the parameters mean grain size (M_z), standard deviation (σ), skewness (S_k), and kurtosis (K_G), as determined by the following formulae:

$$M_z = \frac{\varphi_{16} + \varphi_{50} + \varphi_{84}}{3} \quad (1)$$

$$\sigma = \frac{\varphi_{84} - \varphi_{16}}{4} + \frac{\varphi_{95} - \varphi_5}{6.6} \quad (2)$$

$$S_k = \frac{(\varphi_{84} + \varphi_{16} - 2\varphi_{50})}{2(\varphi_{84} - \varphi_{16})} + \frac{(\varphi_{95} + \varphi_5 - 2\varphi_{50})}{2(\varphi_{95} - \varphi_5)} \quad (3)$$

$$K_G = \frac{(\varphi_{95} - \varphi_5)}{2.44(\varphi_{75} - \varphi_{25})} \quad (4)$$

where φ₅, φ₁₆, φ₂₅, φ₅₀, φ₇₅, φ₈₄ and φ₉₅ represent the 5th, 16th, 25th, 50th, 75th, 84th and 95th percentiles, respectively, on the cumulative curve. The grain-size parameters were classified by the standards of Folk and Ward (Folk and Ward, 1957) (Table 2).

Tab.2 Grain-size grades parameter

| Standard Deviation | σ | Skewness | S_K | Kurtosis | K_G |
|-------------------------|--------------|----------------------|----------------|---|--------------|
| very well sorted | 0.35 | very negative-skewed | -1.00 -0.30 | very platykurtic | 0.67 |
| well sorted | 0.35 0.50 | negative-skewed | -0.30 -0.10 | platykurtic | 0.67 0.90 |
| moderately sorted | 0.50 1.00 | nearly symmetrical | -0.10 0.10 | mesokurtic | 0.90 1.11 |
| poorly sorted | 1.00 2.00 | positive-skewed | 0.10 0.30 | leptokurtic | 1.11 1.50 |
| very poorly sorted | 2.00 4.00 | very positive-skewed | 0.30 1.00 | very leptokurtic | 1.50 3.00 |
| extremely poorly sorted | 4.00 | | | extremely very leptokurtic leptokurtic | 3.00 |

Results

Grain-size composition

Table 3 provides the grain-size composition of the river (natural river, lower reaches of the dam and backwater zone) sediments. The mean values from the channel samples show that the natural river sediments were composed mainly of fine sand (59.11%), followed by very fine sand (21.29%) and medium sand (10.44%), with very little very coarse sand or clay content. However, the sediment composition in the backwater zone was relatively balanced between fine sand (35.13%) and medium sand (32.46%), followed by coarse sand (15.46%), very fine sand (6.91%), gravel (5.14%), silt (2.46%), and very coarse sand (2.44%). The sediments from the lower reaches of the dam were composed mainly of coarse sand (34.92%), followed by gravel (23.90%), medium sand (18.17%) and very coarse sand (11.48%), and contained almost no clay. Table 3 also shows that the sediments from the reservoir of the mainstream were composed mainly of very fine sand (34.86%) and silt (34.18%) and a small amount of fine sand (19.01%) and clay (10.40%), with almost no coarse sand and gravel. The sediment composition in the reservoir of the tributary was much different from that in the reservoir of the mainstream and was composed mainly of coarse sand (26.62%), medium sand (25.08%) and some gravel (24.24%).

Table 3
Grain-size compositions (%) (average and range) of river and reservoir sediments at the Heihe River

| Sampling types | Clay | Silt | VFS | FS | MS | CS | VCS | GR |
|--|-------------------|--------------------|---------------------|---------------------|---------------------|---------------------|--------------------|---------------------|
| natural river | 0.54 (0-4.82) | 3.58 (1.43-6.13) | 21.79 (7.11-62.49) | 59.16(32.05-78.44) | 10.44 (0.18-25.71) | 3.27(0.07-4.32) | 0.74 (0-4.40) | 1.02 (0-3.47) |
| lower reaches of dam | 0 (0-0) | 1.33 (0.60-2.15) | 1.33 (0.91-1.78) | 8.87 (5.25-16.23) | 18.17 (9.60-30.00) | 34.92 (18.08-51.38) | 11.48 (5.93-14.43) | 23.90 (11.68-33.55) |
| backwater zone | 0 (0-0) | 2.46 (1.77-3.67) | 6.91 (3.93-12.32) | 35.13 (21.76-58.28) | 32.46 (24.87-37.52) | 15.46 (2.19-22.79) | 2.44 (0.04-4.02) | 5.14 (0.23-11.77) |
| reservoir of tributary | 0 (0-0) | 1.66 (0.17-3.61) | 2.99 (0.17-7.41) | 9.91 (0.75-20.84) | 25.08 (12.40-47.20) | 26.62(4.60-41.13) | 9.50 (4.50-18.64) | 24.24 (6.44-45.92) |
| reservoir of mainstream | 10.40(6.37-16.36) | 34.18 (7.57-54.05) | 34.86 (19.82-42.15) | 19.01 (1.75-43.82) | 1.55 (0-4.19) | 0 (0-0) | 0 (0-0) | 0 (0-0) |
| Note: Clay, >7.64 ϕ ; Silt, 3.99-7.64 ϕ ; VFS (very fine sand), 3.00-3.99; FS (fine sand), 2.00-3.00 ϕ ; MS (medium sand), 1.00-2.00 ϕ ; CS (coarse sand), 0-1.00 ϕ ; VCS (very coarse sand), 0 - -1.00 ϕ , Gravel, < -1.00 ϕ . | | | | | | | | |

Grain-size parameters of river and reservoir sediments

Table 4 provides the grain-size parameters of the sediments from the different sampling points in the Heihe River. The for the natural river samples averaged 2.52 ϕ (0.174 mm), with a range of 3.18-1.52 ϕ (0.110-0.349 mm), indicating that the natural river sediments were composed mainly of fine sand. However, the in the samples from the lower reaches of the dam was -0.06 ϕ (1.007 mm), with a range of -0.46 - 0.44 ϕ (1.376-0.737 mm), which is larger than that in the backwater zone (average of 1.54 ϕ (0.344 mm), with a range of 2.32-0.97 ϕ (0.203-0.507 mm)). The sorting values of the natural river sediments measured by the standard deviations of ϕ (σ) ranged from 0.04 to 0.31 (average of 0.10), which is considered to represent very well sorted sediments. The standard deviations of the backwater zone sediments ranged from 0.11 to 0.64 (average of 0.37), and the value indicated moderately well sorted sediments. However, the standard deviations of the sediments from the lower reaches of the dam ranged from 0.62 to 1.10 (average of 0.94), which is greater than that of the natural river, implying that the sediments at the lower reaches of the dam are less well sorted than those in the natural river. The of the natural river sediments ranged from -0.08 to 0.60 (average of 0.33) and was mostly positive. The of the backwater zone sediments varied between 0.40 and 0.66 (average of 0.53) and was mostly very positive skew. The of the lower reaches of the dam sediments varied from 0.46 to 0.77 (average of 0.58), indicating very positive skew that was more positive than that of the natural river. The mean K_G values of the sediments from the natural river, lower reaches of the dam and backwater zone sediments were 1.46, 1.25 and 1.89, respectively; these sediment distributions were very leptokurtic largely due to the narrow grain-size range.

Table 4

Grain-size parameters (average and range) of river and reservoir sediments at the Heihe River (in phi units)

| Sampling types | M_z | σ | S_K | K_G |
|-------------------------|--------------------|------------------|------------------|------------------|
| natural river | 2.46 (1.52–3.23) | 0.10 (0.04–0.31) | 0.33(-0.08-0.60) | 1.46(0.77–2.47) |
| backwater zone | 1.45 (0.98–2.30) | 0.37 (0.11–0.64) | 0.53 (0.40–0.66) | 1.89 (1.10–2.50) |
| lower reaches of dam | -0.16 (-0.46-0.44) | 0.94 (0.62–1.10) | 0.58 (0.46–0.77) | 1.25 (0.74–2.53) |
| reservoir of tributary | -0.15 (-0.21-0.94) | 0.87 (0.44–1.26) | 0.56 (0.20–0.64) | 1.93 (0.55–3.13) |
| reservoir of mainstream | 3.92(3.00-4.45) | 0.05 (0.04–0.07) | 0.48 (0.17–0.86) | 1.71 (1.07–2.33) |

The M_z of the sediments from the mainstream reservoir averaged 3.98 ϕ (0.064 mm), with a range of 4.32-2.94 ϕ (0.046-0.125 mm), which is smaller than that of the sediments from the tributary reservoir (average of -0.013 ϕ (1.007 mm), with a range of -0.63-0.94 ϕ (1.155-0.310 mm)). The standard deviations of the sediments from the mainstream reservoir averaged 0.05, which is smaller than the average of those of the sediments from the tributary reservoir (0.87), indicating that the sediments in the mainstream reservoir are very well sorted. The of the mainstream reservoir and tributary reservoir sediments included only two gradations; very positively skewed samples predominated (71.43%), followed by positively skewed samples (28.57%). The K_G values of the mainstream and tributary reservoir sediments were 1.71 and 1.93, respectively, which indicate high leptokurtosis. In addition, the sediment grain-size parameters in the tributary reservoir showed strong differences with increasing sediment depth. With increasing sampling depth, increased, the sorting worsened, became more positive, K_G and gradually flattened (Fig. 2).

Longitudinal distribution of the sediment grain-size parameters in the Heihe Rivers

Fig. 3 shows the longitudinal distribution characteristics of the sediment grain-size parameters at each sampling point on the Heihe River. The average values of the Heihe River sediments in terms of longitudinal variability can be ranked as follows: the upper mainstream (cascade reservoir area), 1.82 ϕ (0.283 mm) > the middle reaches, 2.02 ϕ (0.247 mm) > the upper tributary reaches, 2.33 ϕ (0.199 mm). This trend reflects that the of the sediments in the reaches with the cascade reservoir was greater than that in the upper tributary reaches and middle reaches, presumably due to the clean water released from the reservoir causing more intense scouring of the riverbed. The sediments in the upper tributary and middle reaches of the Heihe River are well sorted (averages of 0.16 and 0.26, respectively), while the poorest sorting was found in the upper mainstream (average of 0.45). In addition, the of the sediments in the upper tributary reaches and middle reaches was positive (averages of 0.41 and 0.36, respectively), but the of the sediments in the upper mainstream was more extremely positive (average of 0.57). The of the sediments showed a leptokurtic trend in the longitudinal direction (averages from the upper tributary reaches to the middle reaches, 1.62, 1.62 and 1.36, respectively).

Discussion

Impacts of cascade reservoir construction on the longitudinal distribution of sediment grain size

Rivers continuously transport substances downstream, and these transport processes are essential to driving biogeochemical processes in river ecosystems (Beaulieu et al., 2014; Borges et al., 2018). Dams convert rivers into lentic reservoirs, causing a subsequent decrease in flow velocity and increases in hydraulic residence time and suspended particle settlement (Maeck et al., 2013). In this study, the of the reservoir sediments was smaller than that of the sediments in the natural river and the lower reaches of the dam. In addition, due to the change in hydrodynamic conditions in the reservoir, a large amount of sediments was deposited in the reservoir, creating bedding at different

sediment depths. Sediments with a larger grain size were deposited first, and sediments with a smaller grain size were deposited on the surface. However, sediments with high values were found in the lower reaches of the dam, which shows that cascade reservoirs create conditions where clean water released from the reservoir causes a relatively rapid coarsening of the gravel riverbed in the downstream channel. The reach of the Heihe River in which a cascade reservoir system was constructed is at a high altitude, which results in a relatively high flow velocity and intense hydrodynamic conditions. The released clean water has thus resulted in the accumulation of significantly coarser sediments in the lower reaches of the dam. This effect was also indicated by the sorting values. The standard deviations of the sediment sorting values in the lower reaches of the dam at sampling sites H₁₅ and H₁₆ and at site H₆ are as high as 1.10 and 0.95, respectively. Compared with the natural river, the sorting values of sediment grain sizes decreased, with the skewness tending to be very positive-skewed and the kurtosis flatter.

The water surface gradient, flow velocity, and hydrodynamic conditions in the Yeniugou River (Fig. 1), a tributary of the upstream Heihe River, were greater than those in the middle reaches of the Heihe River. Theoretically, the of the sediments in Yeniugou River should be larger, their should be more positive and their should be leptokurtic. However, the sediments in the Yeniugou River had a smaller than those in the middle reaches of the natural river (Fig. 3). The main reason for this phenomenon is that the upstream tributary of the Heihe River is wide and shallow, and the average annual flow over several years is only 23.67 m³/s (Wang et al. 2019). In addition, with the implementation of a series of ecological construction and protection projects in the Heihe River in recent years, soil and water loss has been reduced. As a result, the riverbed in the middle reaches is mostly gravel, and the sediment concentration in the river has been reduced.

The survey in this study showed that the of the backwater zone sediments was larger than that of sediments in natural rivers but smaller than that of sediments in the lower reaches of the dam (Table 4). The and were also characterized by the same pattern, indicating that because the backwater zone of the Heihe River is influenced by both the backwater of the reservoir and the clear water released from the reservoir, erosion and sedimentation both occur. These two influences are the main reason that the grain-size parameters of sediments in the backwater zone of the reservoir are between those of natural rivers and those in the lower reaches of the dams.

Analysis of the sedimentary environment in the Heihe River

Previous studies have shown that changes in material sources and hydrodynamic properties can lead to different depositional environments (Morris & Williams, 1999). Conversely, different sedimentary environments can be inferred based on the sediment composition and grain-size parameters (Frings, 2008; Curtis et al., 2010, Guo et al.,2020). According to Church's research showing that riverbed sediments tends toward fining downstream, the grain size of the riverbed sediments is compatible with the hydrodynamic conditions of the river. The stronger the hydrodynamic conditions are in a river, the larger the of the sediment will be, and vice versa (Church and Kellerhals, 1978, Rice and Church, 1998). Generally, the more downstream a river is, the lower the slope of the water surface, the lower the flow velocity, and the finer the corresponding riverbed sediments. However, the longitudinal distribution of sediment grain-size parameters in the Heihe River determined in this study showed that downstream-fining trends in the sediments were only a macroscopic phenomenon. We found that the longitudinal distribution of the sediment grain size was significantly influenced by sediment material sources and cascade reservoir interception, which makes the trend of sediments toward downstream fining even more complicated. The total length of the upstream tributary of the Heihe River investigated in this study is approximately 175 km, with a slope of 8.5‰ and a mean flow velocity of 3 m/s. The overall length of the middle reach of the Heihe River is approximately 185 km, with a slope of 2.03‰ and a mean flow velocity of 0.93 m/s. The hydrodynamic conditions of the upstream tributary are more intense than those of the middle reaches of the Heihe River, but the of the sediments in the upstream tributaries is smaller than that in the

middle reaches. These trends indicate that the grain size of sediments in the upstream tributaries is more significantly affected by material sources than by hydrodynamic conditions. In each river segment, the of the sediments in the reservoir was smaller than that in the backwater zone, which means that when the sediment material source was the same, the hydrodynamic conditions in the reservoir of the Heihe River were weaker than those in the backwater zone. Our analysis of sediment grain-size parameters in the natural river and the lower reaches of the dam shows that the hydrodynamic conditions in the lower reaches of the dam are stronger than those of the natural river when the sediment source for the river is not substantially different.

Conclusions

(1) The cascade reservoirs in the upper reaches of the Heihe River strongly impact the longitudinal distribution of sediment grain size. The survey in this study shows that the sediments in the natural river were composed mainly of fine sand, those in the reservoir were mainly silt and fine sand, and those in the lower reaches of the dam contained more coarse sand.

(2) The grain size of reservoir sediments was much lower than that of the natural river sediments. The sediments from both areas were well sorted, exhibiting leptokurtosis and positive or very positive skew. The lower reaches of the dam suffered from strong erosion; the sediments were coarse and poorly sorted, and the grain-size distributions were more positively skewed and leptokurtotic. The backwater zone of the reservoir was restricted by both backwater and released water, and the sediment grain size was between those of the natural river and the lower reaches of the dam. The sediments were moderately well sorted sediments, with a positively skewed, leptokurtic grain-size distribution.

(3) Sedimentary environmental analysis showed that the grain size of the sediments in the upstream tributaries of the Heihe River was more significantly affected by material sources than by hydrodynamic conditions; in the mainstream Heihe River, the grain size of the sediments was affected mainly by hydrodynamic conditions. In addition, the hydrodynamic conditions in the mainstream reservoir were weaker than those in the backwater zone, but the hydrodynamic conditions in the lower reaches of the dam were stronger than those in the natural reaches.

Declarations

Ethics approval and consent to participate

All studies did not involve human or animal ethics, and involving sampling investigations of water and sediment were approved by the Research Ethics Committee of Lanzhou University of Technology and Northwest Institute of Eco-Environment and Resources (Lanzhou, China).

Consent to Publish

This manuscript hasn't contained any individual person's data in any form.

Authors Contributions

Yu Wang: Writing - original draft, Methodology, Formal analysis, Conceptualization, Supervision, Project administration, Funding acquisition. **Bao-Long Li:** Writing - review & editing, Data curation, Formal analysis, Software, Investigation. **Juan-juan Liu:** Formal analysis, Methodology. **Qi Feng:** Methodology, Formal analysis, Conceptualization. **Wei Liu:** Formal analysis, Software. **Xu Wang:** Investigation, Data curation, Formal analysis. **Yu-hua He:** Data curation, Formal analysis.

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and materials

The data and materials used in the study are available from the corresponding author by request.

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Figures

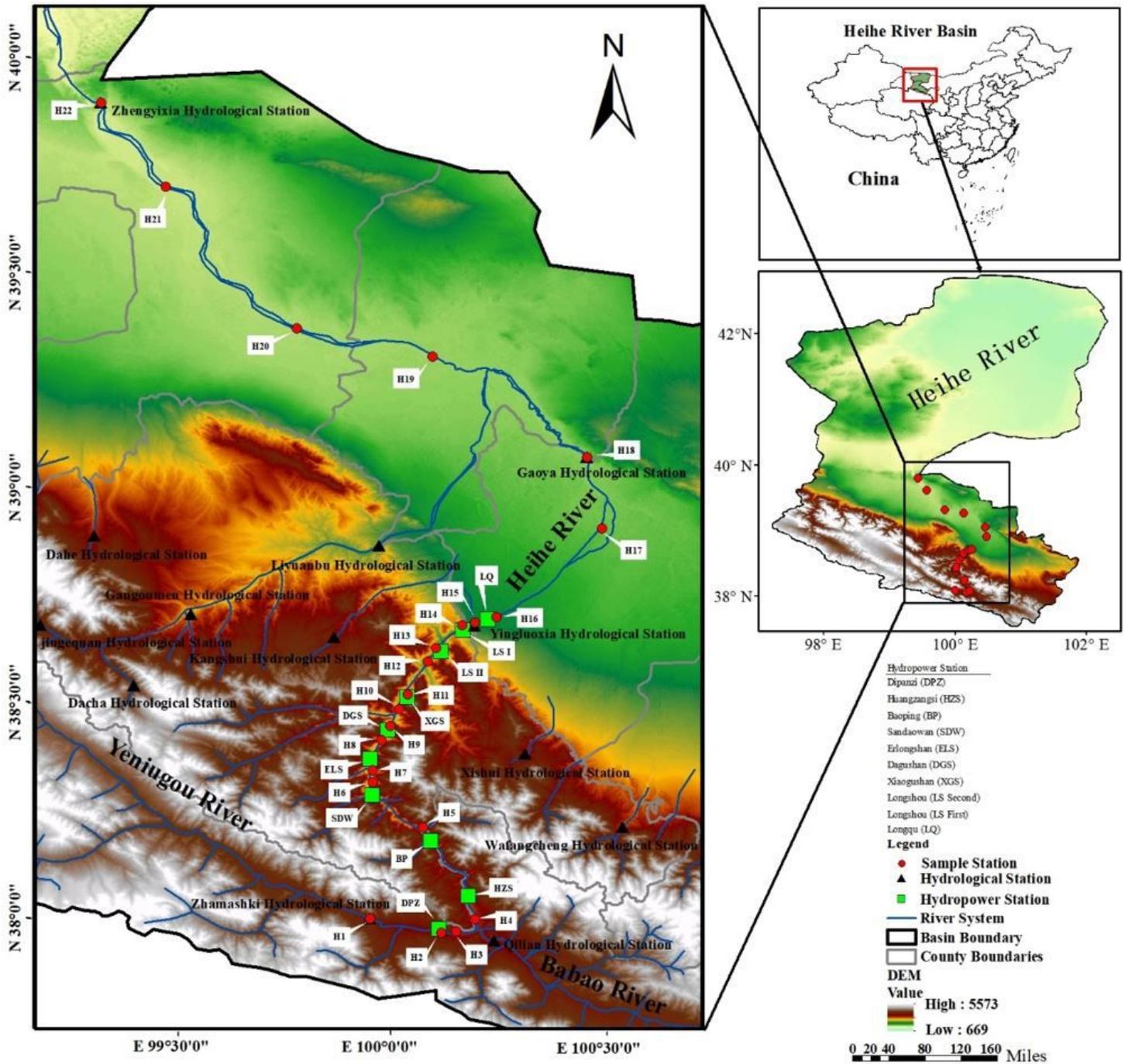


Figure 1

Map of the study area showing the sampling stations. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

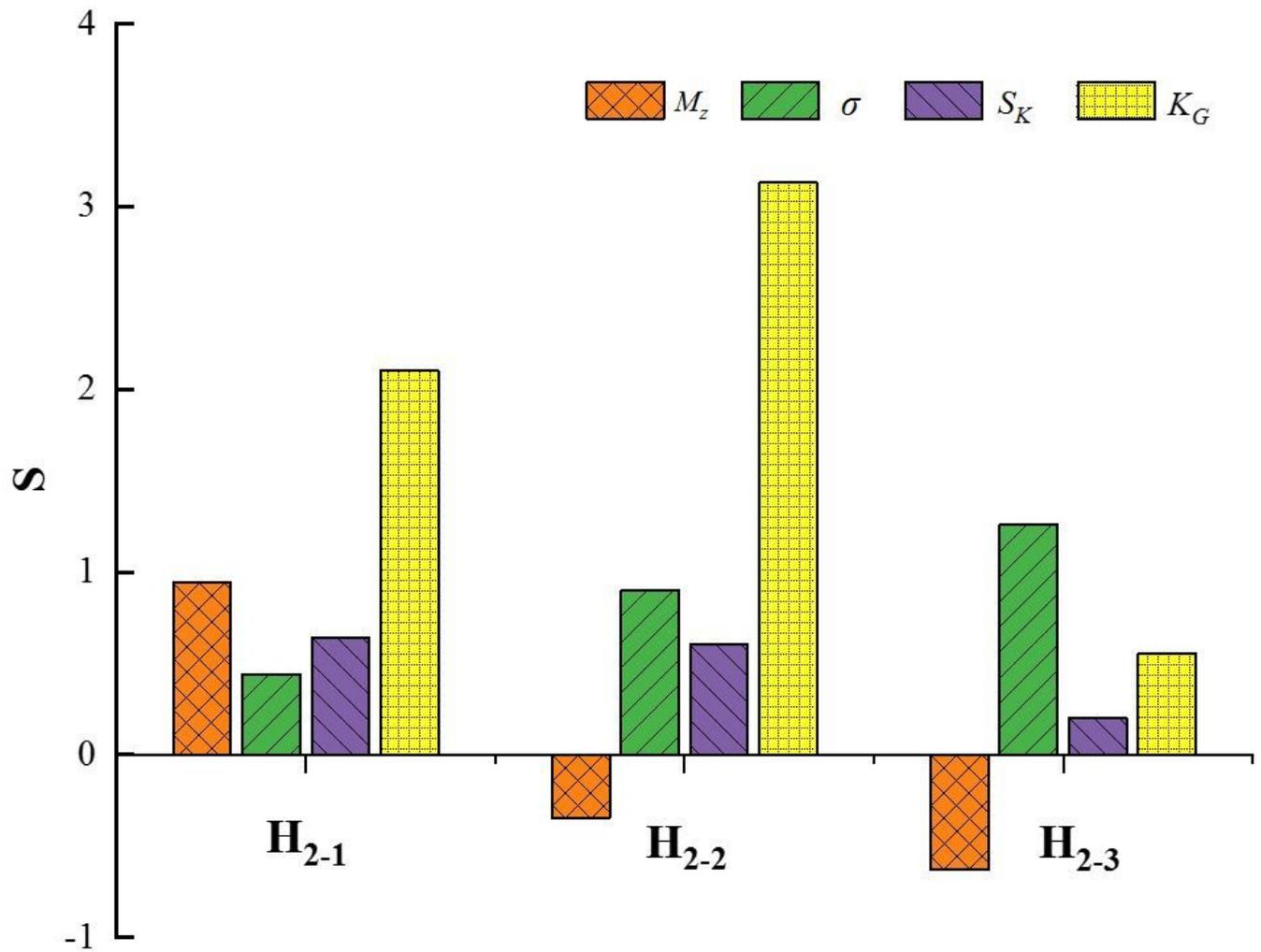


Figure 2

Grain-size parameters of different sampling depth in tributary reservoir The H₂₋₁ is the surface sediments, the H₂₋₂ is the intermediate sediments, and the H₂₋₃ is the bottom sediments.

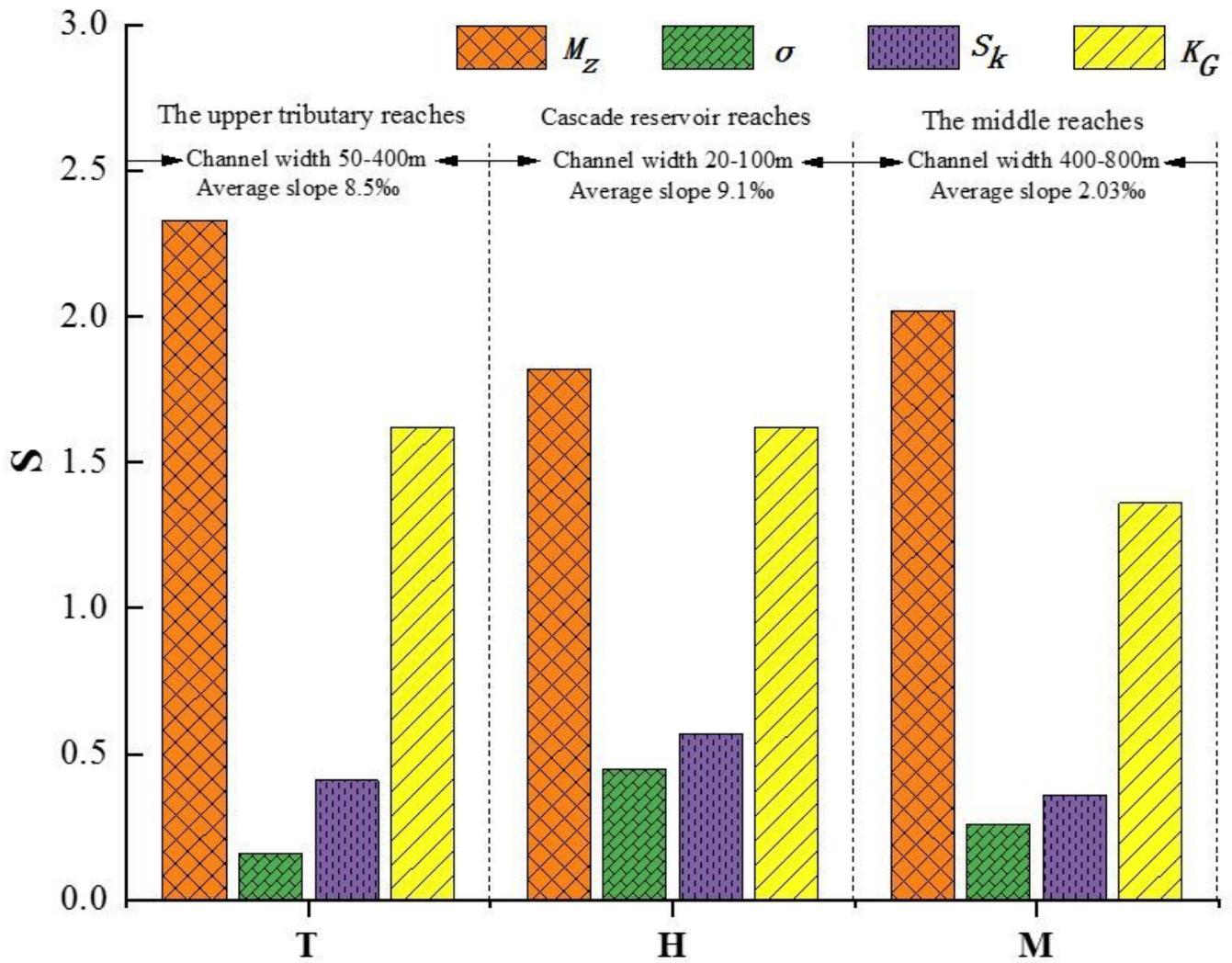


Figure 3

Grain-size parameters of Heihe Rivers sediments change along the longitudinal direction The T is upstream tributary, the H is upper main stream, and the M is middle stream.