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Spatial and depth variability of streambed vertical hydraulic conductivity under the regional flow regimes

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Abstract

This study investigated the influence of the regional flow on the streambed vertical hydraulic conductivity (K_v) within the hyporheic zone in three stream reaches of the Weihe River in July 2016. The streambed K_v with two connected depths was investigated at each test reach. Based on the sediment characteristics, the three test reaches could be divided into three categories: a sandy streambed without continuous silt and clay layer, a sandy streambed with continuous silt and clay layer, and a silt–clay streambed. The results demonstrate that the streambed K_v mainly decreases with the depth at the sandy streambed (without continuous silt and clay layer) and increases with the depth at the other two test reaches. At the sandy streambed (with continuous silt and clay layer) where streambed K_v mainly decreases with the depth, the regional upward flux can suspend fine particles and enhance the pore spacing, resulting in the elevated K_v in the upper sediment layers. At another sandy streambed, the continuous silt and clay layer is the main factor that influences the vertical distribution of fine particles and streambed K_v. An increase in streambed K_v with the depth at the silt/clay streambed is attributed to the regional downward movement of water within the sediments that may lead to more fine particles deposited in the pores in the upper sediment layers. The streambed K_v is very close to the bank in the sandy streambed without continuous silt and clay layer and the channel centre in the other two test reaches. Differences in grain size distribution of the sediments at each test reach exercise a strong controlling influence on the streambed K_v. This study promotes the understanding of dynamics influencing the interactions between groundwater and surface water and provides guidelines to scientific water resources management for rivers.

KEYWORDS

clogging level, regional flow, spatial and depth variability, streambed grain size, streambed vertical hydraulic conductivity (K_v)

1 | INTRODUCTION

The water exchange between groundwater and surface water plays an important role in the discharge of contaminants (Chapman, Parker, Cherry, Aravena, & Hunkeler, 2007; Flewelling, Herman, Hornberger, & Mills, 2012) and the movement and transformations of nutrients (Brunke & Gonser, 1997; Pretty, Hildrew, & Trimmer, 2006) and also has an important influence on microbial and invertebrate assemblages (Boulton, Findlay, Marmonier, Stanley, & Valett, 1998; Malcolm, Youngson, Greig, & Soulsby, 2008). Due to the natural complexity of the groundwater–surface water system, it is difficult to characterize and quantify the extent and variability of groundwater–surface water exchange (Kalbus, Reinstorf, & Schirmer, 2006). Streambed vertical hydraulic conductivity (K_v) can be used to predict groundwater–surface water exchange (Anibas, Buis, Verhoeven, Meire, & Batelaan, 2011; Birkel et al., 2015; Kalbus, Schmidt, Molson, Reinstorf, & Schirmer, 2009). Estimation of K_v may be simpler than measurements of other streambed attributes and could thus serve to quantify groundwater–surface water exchange. Field measurement methods (i.e., in situ permeameter) are very useful to estimating K_v. Kalbus et al. (2006) summarized a wide array of field methods for investigating streambed K_v. The most commonly used methods for measuring K_v including slug tests (Binley et al., 2013; Conant, 2004), pumping tests (Kelly & Murdoch, 2003), field permeameter tests (Chen, 2004; Genereux, Leahy, Mitasova, Kennedy, & Corbett, 2008; Jiang et al., 2015; Landon, Rus, & Harvey, 2001; Sebok, Duque, Engesgaard, & Boegh, 2015; Song et al., 2016), seepage metre measurements (Kennedy et al., 2010; Rosenberry, 2008), and temperature-dependent method (Wang, Pozdniakov, & Vasilevskiy, 2017).

Spatial variability of streambed vertical hydraulic conductivity and its influencing factors have been widely studied (Genereux et al., 2008; Jiang et al., 2015; Sebok et al., 2015; Song et al., 2016; Wang et al., 2016). For example, Genereux et al. (2008) reported the highest K_v in the centre of the channel. Streambed K_v values were found higher at the erosional outer bend and close to the middle of the channel (Sebok et al., 2015). Some researchers have also observed that there was a decreasing trend of streambed K_v with depth (Chen, 2011; Min, Yu, Liu, Zhu, & Wang, 2013; Song et al., 2016; Song, Chen, Cheng, Summerside, & Wen, 2007; Song, Chen, Cheng, Wang, & Wang, 2010; Wu, Shu, Lu, & Chen, 2016). The flow moving through the streambed sediments basically proceeds in two ways: groundwater flows through the sediments into the stream (gaining stream) or stream water infiltrates through the streambed into the groundwater (losing stream; Chen, Dong, Ou, Wang, & Liu, 2013; Kalbus et al., 2006). Chen et al. (2013) found that streambed K_v decreased with depth in gaining reaches whereas increased with depth in losing reaches using in situ permeameter tests at the Platte River and its tributaries in Nebraska, USA. Chen et al. attributed the contrasting patterns of streambed K_v with depth in the two types of streams to the differences of flow direction during groundwater–surface water exchange. In gaining reach, fine particles are winnowed by the upward flow, which will increase the pore spacing in the upper parts of the streambed and result in higher K_v in upper parts of streambed (Song et al., 2007). Conversely, in losing reach, downward water flow through the streambed carries fine particle into the coarse sediment matrix, partially leading to the pores clogged. Rosenberry and Pitlick (2009) also found that the upward flow can enhance the hydraulic conductivity and downward flow can reduce hydraulic conductivity. Several authors have also reported local-scale relationships between percent fine particles and streambed vertical hydraulic conductivity (K_v; Dong, Chen, Wang, Ou, & Liu, 2012; Genereux et al., 2008; Jiang et al., 2015; Song et al., 2007). Nevertheless, the accurate relationship between streambed percent fine sediments and K_v at different reach scales is poorly understood.

In this study, permeameter tests were conducted at three reaches that were either predominantly losing or predominantly gaining conditions on the regional scale. This contributes to better understanding of the spatial or depth variability of streambed vertical hydraulic conductivity across the channels and from upstream to downstream. We determined the regional losing and gaining conditions for the study sites based on the measurements of the stream water temperature, streambed temperature, and groundwater temperature. We conducted in situ permeameter test for measuring streambed K_v within two connected sediment layers (0–30 cm and 30–60 cm). Then, we analysed spatial or depth variability of streambed K_v values and related their variability to different flow directions on the regional scales. We also used statistical methods to test whether streambed K_v values from different depths or from different test sites belonged to different populations. Furthermore, we discussed the effects of sediment grain size distribution on streambed K_v based on statistical methods.

2 | STUDY SITES

The study was conducted in the Weihe River, the largest tributary of the Yellow River, China (Figure 1a). The Weihe River originates from the Niaoshu Mountain at Weiyuan County of Gansu Province, runs across 818 km through the provinces of Gansu, Ningxia, and Shaanxi, and finally flows into the Yellow River at Tongguan County of Shaanxi Province (Figure 1b). The drainage area of the Weihe River is 1.34×10^5 km^2, accounting for 17.9% of the total amount of the Yellow River basin. The river is the major source of water supply for the Guanzhong Plain, which has a typical semiarid climate. It is also well known as the Mother River of the Guanzhong Plain. This river plays an important role in the development of Western China and the ecosystem health of the Yellow River.

On the north side of the Weihe River in Shanxi Province, the river is joined by several long tributaries such as the Jinghe River, Beiluo River, and Shichuan River draining the vast Loess Plateau, known as one of the largest and thickest loess deposits in the world. The annual erosion rate in the Loess Plateau can be as high as 5,997 ton/km^2 (Jiao, Ma, Wang, & Wang, 2004). Consequently, the sediments from the northern tributaries of the river consist of the enormous amount of loess and fine particles, then which was transported into the Weihe River. On the south side, numerous short tributaries originating from the high and well-vegetated Qinling Mountain have steep gradients and large flow velocity and carry coarse materials (sand and gravel or cobbles) into the Weihe River (Chen et al., 2014).

Field investigations were performed in three reaches (Meixian, Caotan, and Huaxian; Figure 1b) of the Weihe River in July 2016. The width of the Weihe River channels varies from one test site to another (Table 1). At the Caotan site, the Weihe River divided into two channels, and the average width is about 221 m. The river is not braided at the Meixian and Huaxian test sites, and the average width is about 302 and 122 m, respectively. Streambed measurements were carried out at the right side of the river channel (Figure 1c–e) because of the limitation of the equipment and large water depth. The Topcon GTS-102N total station was used to detect the streambed topography (streambed elevation in metres). The detection of angle is obtained by two horizontal and one vertical measurements (the accuracy is ± (2 mm + 2 ppm × D) mean squared error).

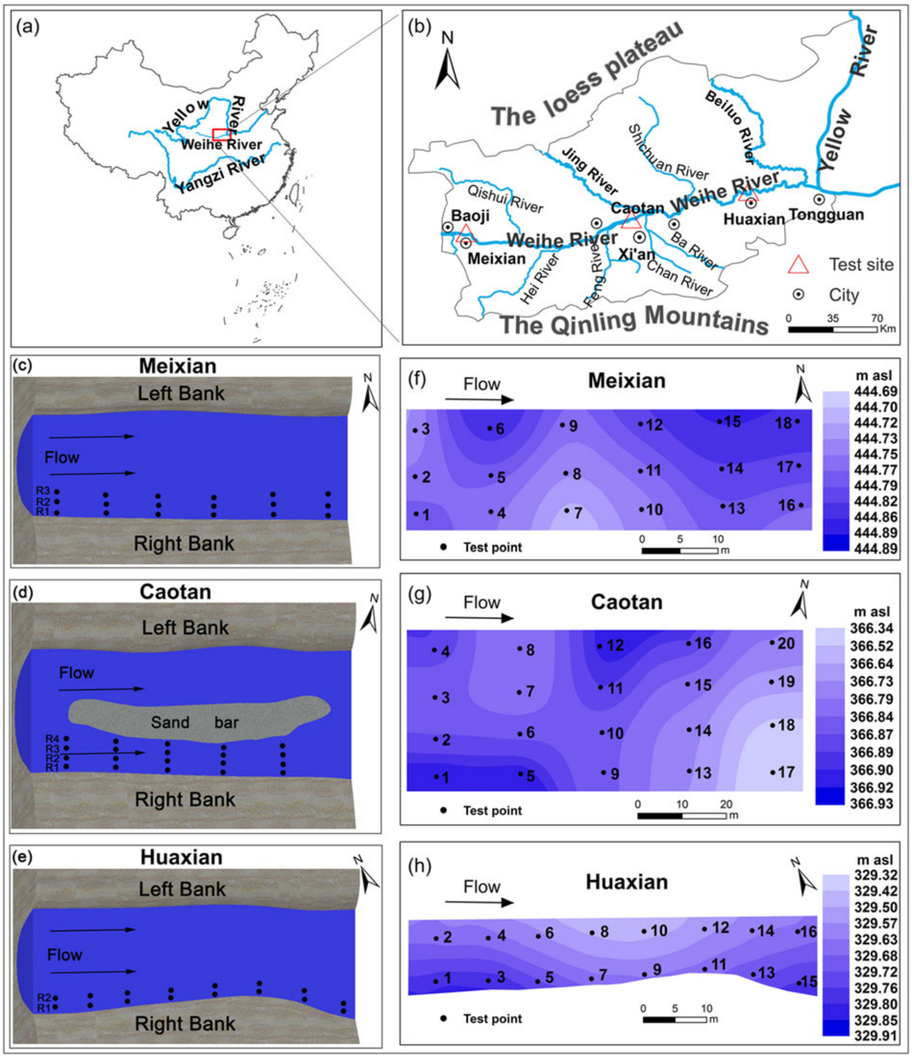

FIGURE 1 (a,b) Map of the three study sites within Shaanxi Province, China. The conceptual diagrams of the (c) Meixian site, (d) Caotan site, and (e) Huaxian site, and test locations are shown. Streambed topography and test locations are also shown at the (f) Meixian site, (g) Caotan site, and (h) Huaxian site. (c,d,e) The test position from the bank towards the channel across the stream is shown (R1, R2, R3, and R4)

TABLE 1 Hydrological characteristics of each test site

	Site		
Parameter	Meixian	Caotan	Huaxian
Test date	July 9, 2016	July 12, 2016	July 10, 2016
Number of measurements	18	20	16
Average channel width (m)	302	221	122
Site length (m)	50	80	70
Max. water depth (cm)	31	66	67
Average water depth (cm)	21.9	20.3	35
Max. stream velocity (m/s)	0.058	0.92	1.875
Average stream velocity (m/s)	0.033	0.28	0.60
Streambed description	Streambed sediment contains large part of silt and clay and a small part of sand.	Stream flow is divided into two branches by a 128-m-long sand bar. Test site is located in the right bank of an anabranching channel. Streambed sediment contains large part of sand but with a continuous silt and clay layer (approximately 5–10 cm thick) at about 25- to 35-cm depth.	Streambed sediment contains large part of sand and a small part of silt and clay particles, with the exception of test Locations 15 and 16, where streambed sediment contains large part of silt and clay.

Fifty-four points were selected to conduct in situ streambed tests to determine the K_v. At the Meixian site, 18 test points were arranged in six transects across the channel with three positions along each transect (Figure 1c,f). At the Caotan site, 20 test points were arranged in five transects across the channel with four positions along each transect (Figure 1d,g). The 16 test points at the Huaxian site were arranged in eight transects across the channel with two positions along each transect (Figure 1e,h). During the permeameter tests, the streambed sediments at the Huaxian site are rather uniform and consist predominantly of sand (Figure 2c), which provide a good connection between the Weihe River and the adjacent aquifers. However, the streambed sediments at the Meixian site consist mainly of silt and clay (Figure 2a). At the Caotan site, the in situ tests were conducted at sandy streambed, which has a continuous silt and clay layer (approximately 5–10 cm thick) at about 25- to 35-cm depth (Figure 2b). The distance between each cross section was approximately 10 m. The investigated reach was approximately 70 m in each study site. The latter two types of sediment structure can significantly reduce the hydraulic connection between the river and the adjacent aquifers. Table 1 summarizes stream hydrological characteristics and data collection date.

3 | METHODS

3.1 | Determination of regional losing and gaining pattern

The flow directions between groundwater and surface water strongly influence the natural temperature distribution in the streambed (Anibas et al., 2011; Conant, 2004; Silliman, Ramirez, & McCabe, 1995). In summer, for gaining stream reaches, the sediment temperature is close to the regional groundwater temperature due to the flow of groundwater towards the stream, whereas the stream water temperature is higher because of high atmospheric temperature (Chen et al., 2013; Silliman et al., 1995). In contrast, for losing stream reaches, the sediment temperature more closely reflects the stream water temperature, but not in close agreement with the groundwater temperature (Silliman et al., 1995; Wang et al., 2017). During the study, stream water temperatures and groundwater temperatures were measured using a portable multiparameter water quality analyser (HACH HQ40d). Groundwater temperature was measured in a nearby well of each test site. A vertical temperature probe was used to measure the temperatures at 0.8-m depth in the streambed at very close location with in situ Darcy measurements.

3.2 | Streambed vertical hydraulic conductivity (K_v) within two connected sediment layers

The in situ falling head permeameter test (Song et al., 2007) was applied to measure streambed K_v within two connected sediment layers. The procedure for the method is described as follows. Figure 3 is a schematic diagram showing an in situ falling head permeameter test. A 160-cm-long and 5.4-cm internal diameter transparent PVC standpipe with an open top and end was vertically pushed into about 30-cm depth below the streambed; thus, the lower part of the pipe was filled with a sediment column of 30-cm length. Then, the clarified stream water was carefully added into the upper part of the pipe until it was full. With the falling of the hydraulic head inside the pipe, a series of hydraulic head readings at given times were recorded. After the permeameter test at 0- to 30-cm depth was completed, the pipe was pressed to around 60-cm depth. Again, a permeameter test at 0- to 60-cm depth was conducted. After the tests, the streambed K_v can be calculated using the following formula (Hvorslev, 1951), which has been developed by Pozdniakov, Wang, and Lekhov (2016).

$$K_v = \frac{\frac{\pi D}{11m} + L_v}{t_2 - t_1} \ln(h_1/h_2), \tag{1}$$

where L_v is the length of the sediment column in the pipe; D is the interior diameter of the pipe (5.4 cm); h_1 and h_2 are the hydraulic heads inside the pipe measured at times t_1 and t_2, respectively; and $m = \sqrt{K_h/K_v}$. K_h is the horizontal conductivity of the streambed sediment around the base of the sediment column. If the ratio (L_v/D) is larger than 5, Chen (2004) modified Equation (1) to a simplified

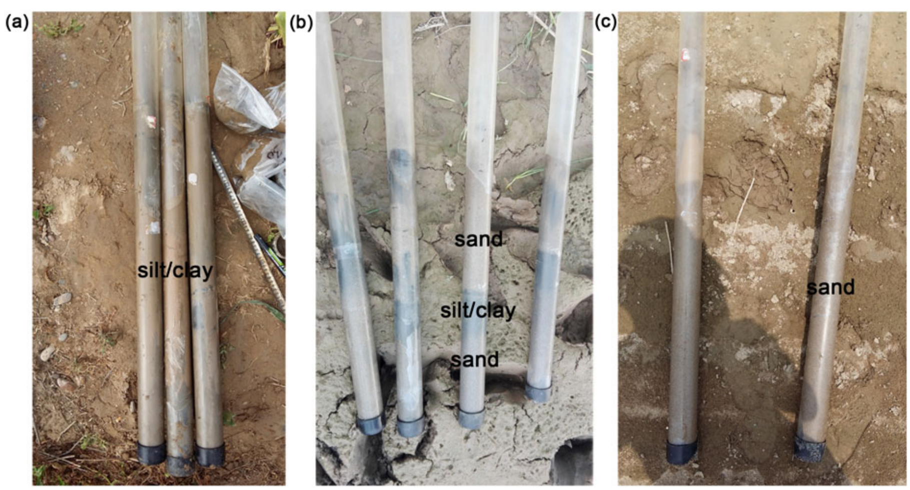

FIGURE 2 Typical cores of (a) mainly uniform silt and clay or (b) sand with a continuous silt and clay layer or (c) sand without silt and clay layer. The cores shown on the pictures are test locations (a) MX10–MX12, (b) CT13–CT16, and (c) HX3–HX4

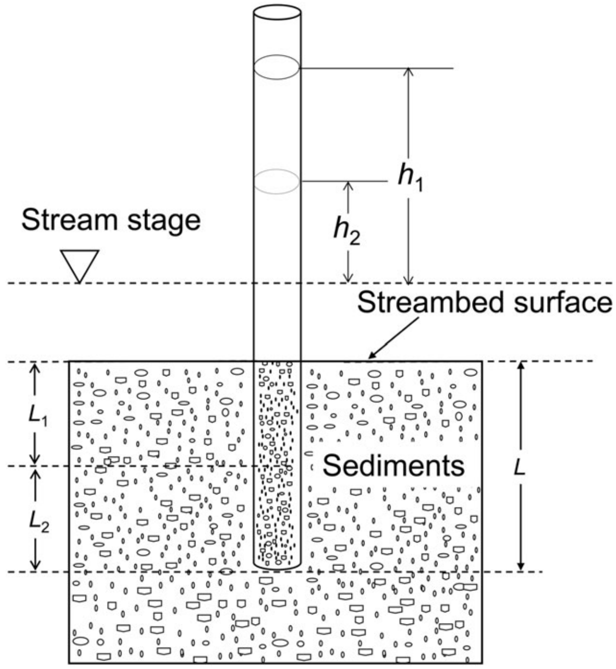

FIGURE 3 Schematic diagram showing an in situ permeameter test to determine streambed K_v

Equation (2) and the error of the modified equation less than 5% requires m > 1.14 or K_h/K_v > 1.3. At each test location, the lengths of the sediment column L_v for the two permeameter tests were respectively 30 and 60 cm; thus, the ratio (L_v/D) is larger than 5, ensuring relatively small errors of the simplification.

$$K_v = \frac{L_v}{t_2 - t_1} \ln(h_1/h_2). \tag{2}$$

In this equation, there is a linear relationship between $\ln(h_1/h_2)$ and t. The values of tanθ indicated K_v/L_v (Figure 4). During in situ K_v test for each point, several pairs of h and t data were collected. Each tanθ indicates each recorded result of $\ln(h_1/h_i)$ versus Δt (Figure 4). Different tanθ mainly caused by measurement errors. Therefore, the mean value of K_v was calculated based on the least squares method.

After sediment K_v values of the depths from 0–30 cm to 0–60 cm were calculated, the K_v values of 30- to 60-cm depth can be calculated using the following equation (Freeze & Cherry, 1979):

$$K_{v2} = L_2/(L/K_v - L_1/K_{v1}), \tag{3}$$

where K_{v1}, K_{v2}, and K_v represent vertical hydraulic conductivities for sediment column L_1 (0 to 30 cm, the upper sediment layer), L_2 (30 to 60 cm, the lower sediment layer), and L (0 to 60 cm), respectively.

3.3 | Sediment sampling and grain size analysis

After sediment K_v tests at each test location were completed, the streambed sediment cores were collected. The top open of the pipe was sealed with a rubber cap to disconnect the pipe from the atmosphere, and then the pipe with the sediment column inside was carefully pulled out. Then, the two sediment layers in the pipe were separated and placed into sampling bags.

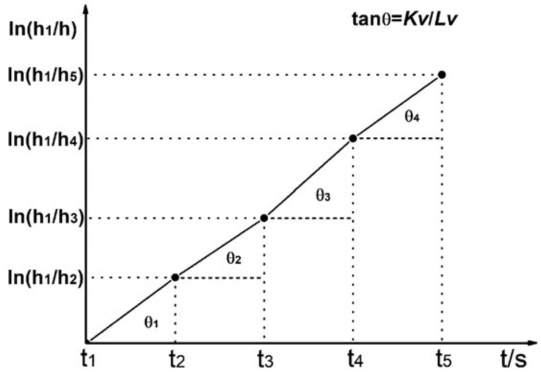

FIGURE 4 Typical graph showing $\ln(h_1/h)$ versus t for K_v test of each point

Sediment samples in the laboratory were air dried and sieved using 15 grades. In this study, the finest sieve size was 0.075 mm, and the coarsest sieve size was 5 mm. The particle was categorized into three groups: silt or clay (size < 0.075 mm), sand (0.075 mm ≤ size ≤ 2 mm), and gravel (size > 2 mm).

3.4 | Statistical analysis

All statistical analyses were done using the statistical software program R 3.2.1 (RC Team, 2015). The nonparametric Kruskal–Wallis test (Helsel & Hirsch, 1992) was used to determine the similarity of the streambed K_v values between the upper and lower sediment layers and to identify streambed K_v values that differ significantly among three test sites. The test null hypothesis is that streambed K_v values from two samples are from the same population, and the alternative hypothesis is that data from two samples are not the same.

A nonparametric Spearman's rank correlation test (Helsel & Hirsch, 1992) was used to verify if silt–clay or sand contents of the sediment are significantly correlated to the streambed K_v.

4 | RESULTS

4.1 | Stream water temperature, streambed temperature, and groundwater temperature

The stream water temperatures vary between 25.2°C and 28.2°C (average = 26.7°C) at the Meixian site, between 28.7°C and 36.6°C (average = 30.5°C) at the Caotan site, and between 28.7°C and 29.8°C (average = 29.2°C) at the Huaxian site. The observed streambed temperatures at 0.8-m depth also vary spatially between 23°C and 24°C (average = 23.6°C) at the Meixian site, between 22.3°C and 26°C (average = 23.9°C) at the Caotan site, and between 18.6°C and 22°C (average = 20.4°C) at the Huaxian site. Groundwater temperature is respectively 16.3°C at the Meixian site, 21.4°C at the Caotan site, and 18.8°C at the Huaxian site. Hence, the sediment temperatures at the Caotan site and Huaxian site are close to the groundwater temperatures. Thus, the Caotan site and Huaxian site are determined to be gaining streams on the regional scale. Whereas the sediment temperatures at the Meixian site are close to the stream water temperatures, the Meixian site is determined to be a losing stream on the regional scale, and the fluctuation of water exchange caused by downward flux may influence fine particles transported in the upper layer.

4.2 | The depth variability of streambed vertical hydraulic conductivity

The calculated K_v value and the contents of silt and clay or sand in the upper and lower layers of sediment at each location are shown in Figures 5, 6, and 7. At the Meixian site, the streambed K_v values for the upper sediment layer and the lower sediment layer range from 0.01 to 0.27 m/day (median = 0.04 m/day) and from 0.02 to 0.32 m/day (median = 0.10 m/day), respectively. At the Caotan site, the streambed K_v values for the upper sediment layer and the lower sediment layer range from 0.02 to 5.58 m/day (median = 0.05 m/day) and from 0.05 to 1.73 m/day (median = 0.13 m/day), respectively. At the Huaxian site, the streambed K_v values for the upper sediment layer and the lower sediment layer range from 0.12 to 34.9 m/day (median = 15.4 m/day) and from 0.22 to 21.0 m/day (median = 1.69 m/day), respectively. Generally, these statistical results indicate that streambed K_v values at the Meixian site and Caotan site display a weak increasing trend with depth, whereas streambed K_v values at the Huaxian site display a significant decreasing trend with depth. Streambed K_v values from the two layers are compared using the Kruskal–Wallis test. The results show that there are significant differences between the K_v values from the two layers at the Meixian site (p = 0.0031) and Huaxian site (p = 0.0014). The p value for the two layers of K_v values at the Caotan site is 0.07. The p value suggests that there is weak evidence that the two populations are also different. The median values of K_v in both upper and lower layers in Huaxian site are the highest among three sites.

The Weihe River is a losing stream at the Meixian site and becomes gaining streams at the Caotan site and Huaxian site on the regional scale, as evidenced by measurements of stream water temperature, streambed temperature, and groundwater temperature. At the Meixian site, the streambed consists mainly of silt and clay and is not very permeable. The K_v values are generally smaller than 0.4 m/day. In the two gaining stream reaches, the streambeds mainly consist of sand. At the Huaxian site, the streambeds are very permeable. The K_v values are often greater than 1 m/day and could be as high as 34.9 m/day. The median K_v value for the upper layer and lower layer is 15.4 and 1.69 m/day, respectively. However, at the Caotan site, the permeability of the streambed is severely influenced due to the existing of a continuous silt and clay layer. The median K_v value for the upper layer and lower layer is only 0.05 and 0.13 m/day, respectively.

4.3 | Spatial variability of streambed vertical hydraulic conductivity

Generally, at the Meixian site, the higher and lower K_v values for the upper sediment layer and the lower sediment layer are both observed at the upstream part and the downstream part, respectively (Figure 8a,b). The highest and lowest K_v values for the upper layer and the lower layer show contrary spatial distribution across the channel (Figure 9a,b). For the upper sediment layer, the highest values are observed towards the channel centre and the lowest values are observed towards the bank (Figure 9a). The highest and lowest K_v values for the lower sediment layer are observed towards the bank and the channel centre, respectively (Figure 9b). At the Caotan site, K_v values for the upper sediment layer show large spatial variability with higher values observed towards the centre of the channel and at the downstream part and lower values near the bank (Figure 8c). For the lower sediment layer, streambed K_v values also show large spatial variability with higher values observed at the beginning of upstream

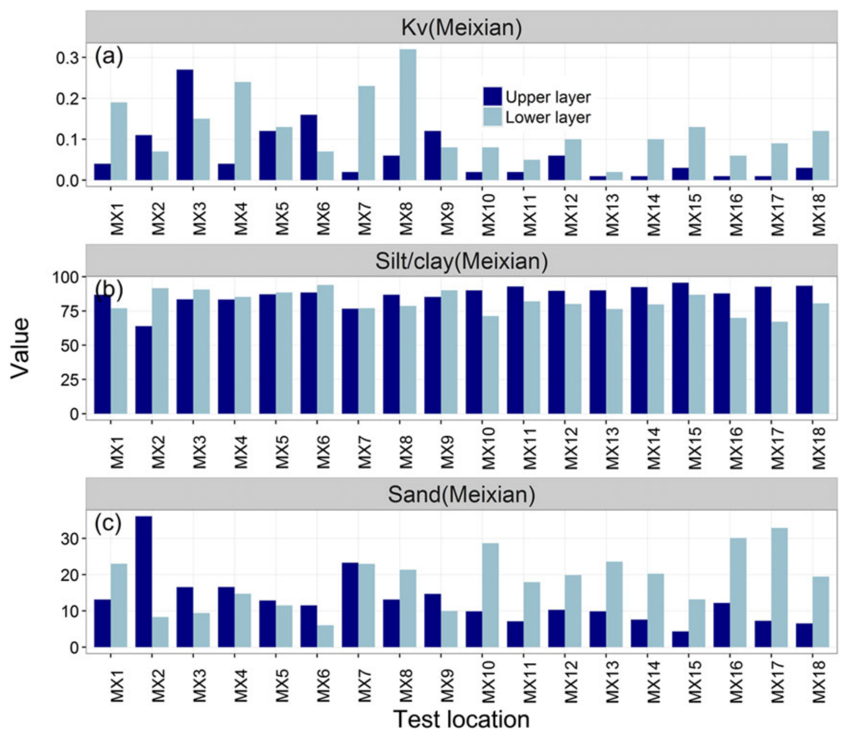

FIGURE 5 The bar plots of the (a) K_v value, the contents of (b) silt/clay, and (c) sand in the upper and lower layers of sediments at each location of the Meixian site. All K_v magnitudes are in metres per day. The magnitudes of all contents of silt/clay and sand are in percent

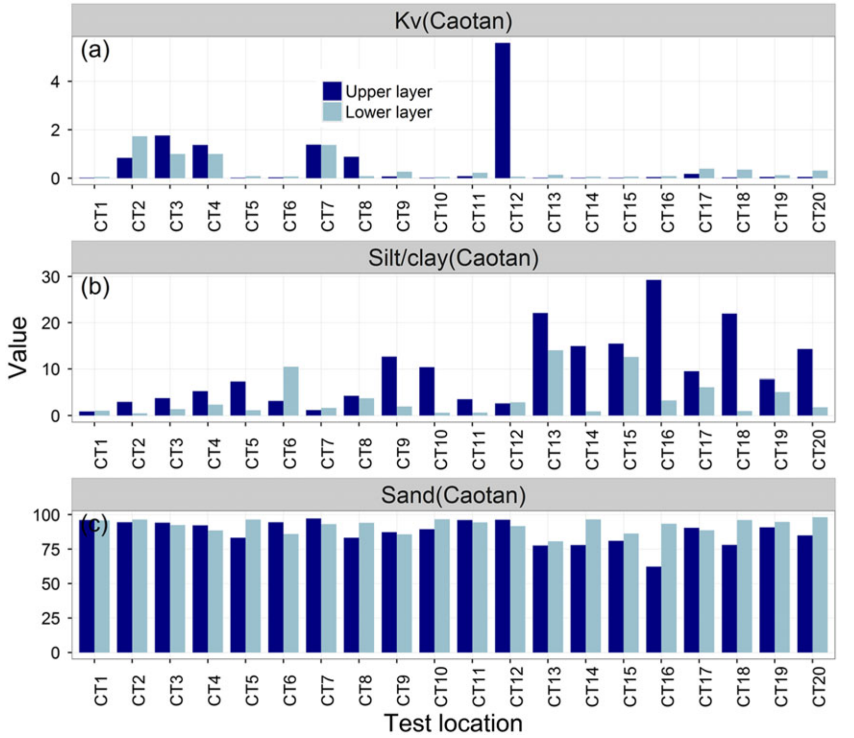

FIGURE 6 The bar plots of the (a) K_v value, the contents of (b) silt/clay, and (c) sand in the upper and lower layers of sediments at each location of the Caotan site. All K_v magnitudes are in metres per day. The magnitudes of all contents of silt/clay and sand are in percent

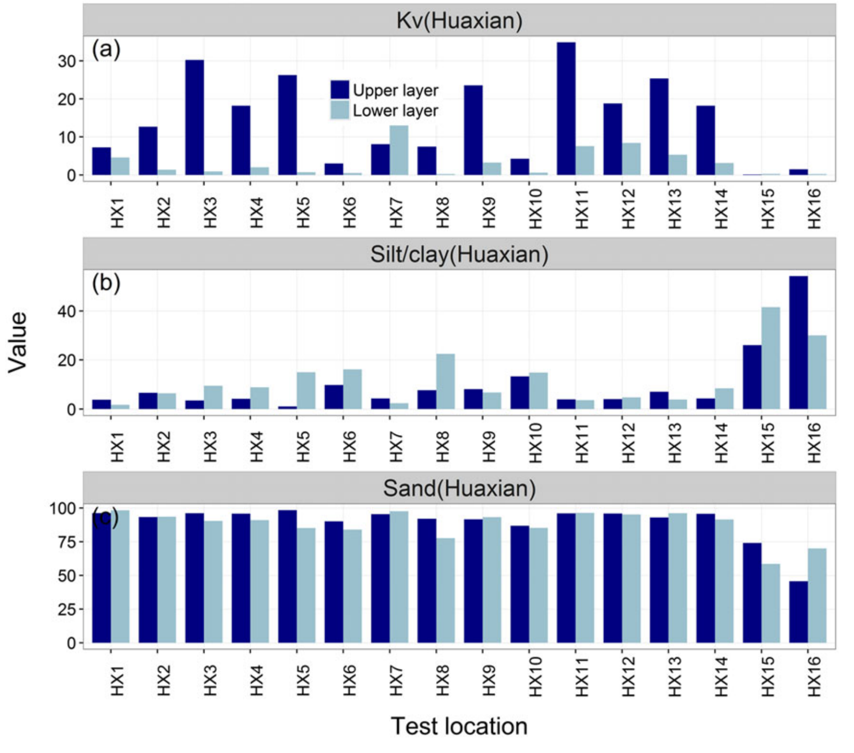

FIGURE 7 The bar plots of the (a) K_v value, the contents of (b) silt/clay, and (c) sand in the upper and lower layers of sediments at each location of the Huaxian site. All K_v magnitudes are in metres per day. The magnitudes of all contents of silt/clay and sand are in percent

part and at the end of the downstream part and lower values in the middle of the reach (Figure 8d). The highest and lowest values for the two sediment layers of the Caotan site are both observed towards the channel centre and near the bank, respectively (Figure 9c,d). At the Huaxian site, K_v for both the two sediment layers shows higher values closer to the bank and lower values at the end of the reach (Figures 8e,f and 9e,f). The results of the Kruskal–Wallis test at 0.05 level indicate that the K_v values from each layer of the Meixian site and Caotan site are not significantly different (p = 0.24 for the upper layer and p = 0.51 for the lower layer) but differ from K_v values from the Huaxian site (each p value is almost equivalent to 0). Nevertheless, much lower K_v values are observed at the Meixian site and Caotan site, whereas the average and median K_v values and their range are consistently higher at the Huaxian site than at other two sites (Figure 10a,b).

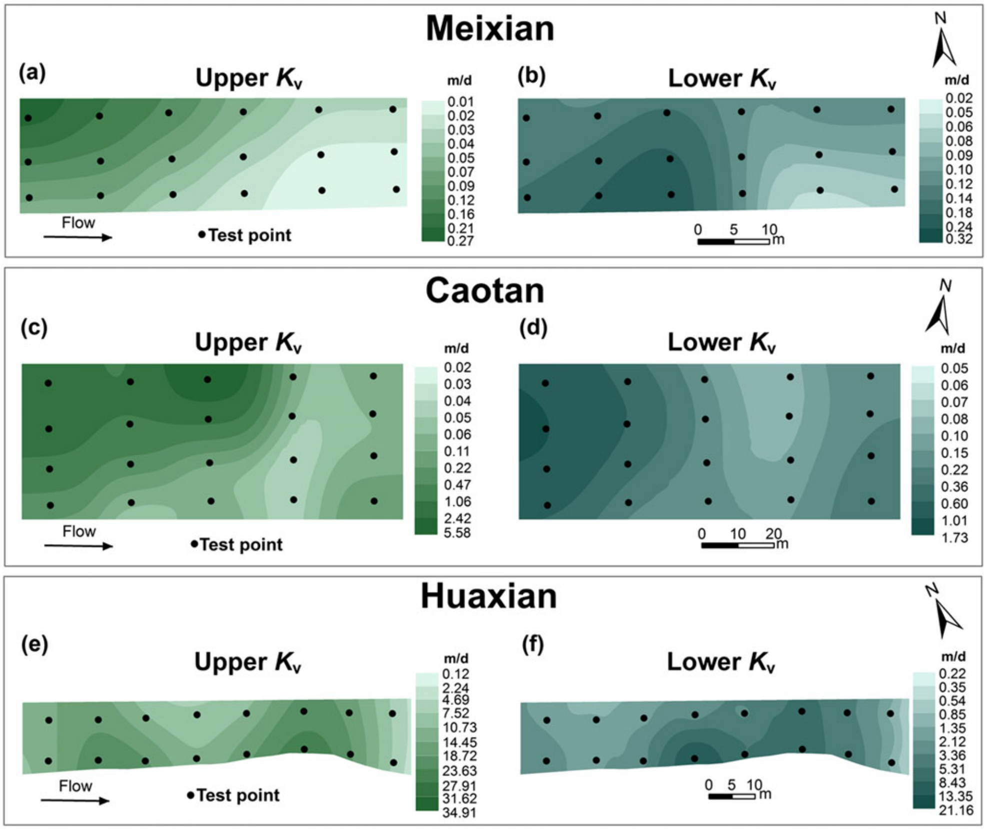

FIGURE 8 Interpolated contour maps of K_v in the upper and lower layers for each test site along the Weihe River: (a,b) Meixian site, (c,d) Caotan site, and (e,f) Huaxian site. The test location is shown in Figure 1f–h

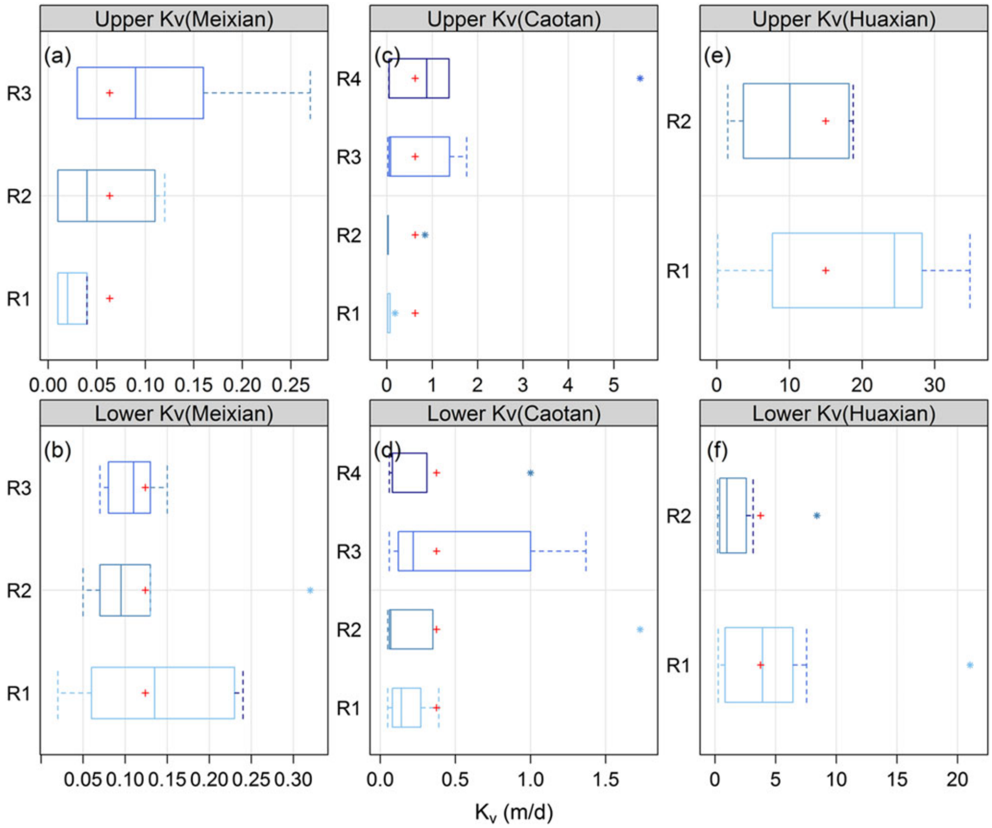

FIGURE 9 Box plots of K_v in the upper and lower layers for each position across the stream at each test site: (a,b) Meixian site, (c,d) Caotan site, and (e,f) Huaxian site. All K_v magnitudes are in metres per day. + indicates the mean value. * indicates outliers

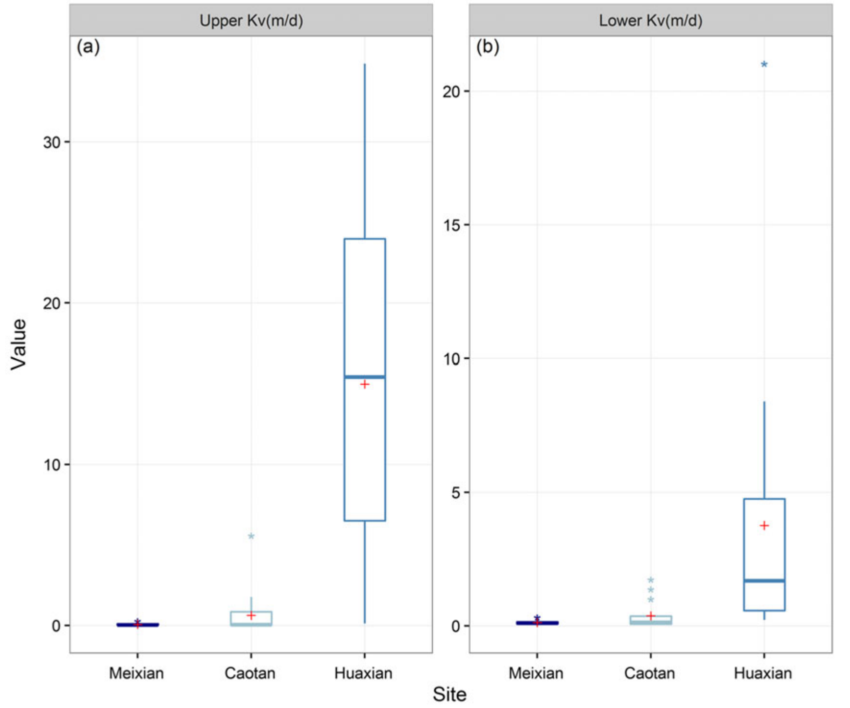

FIGURE 10 Box plots of (a) K_v in the upper layers and (b) K_v in the lower layers for all locations at each test site. + indicates the mean value. * indicates outliers

5 | DISCUSSION

5.1 | The variability of streambed K_v with depth

The Kruskal–Wallis tests show differences of the K_v values between the upper layer and lower layer of each test site. At the Huaxian site under the regional upward flow patterns, streambed K_v values generally decrease with increasing depth (Figure 7a). The decreasing trend of streambed K_v values with depth has also been reported by many studies (Binley et al., 2013; Chen, 2011; Rosenberry & Pitlick, 2009; Song et al., 2007; Wu et al., 2016). Chen et al. (2013) also observed a decreasing trend of streambed K_v values with depth in gaining streams. In gaining streams, the fine particles are stirred by the upwards flow and into streams and then washed away by stream currents, thus inducing larger streambed K_v in the top layer of streambeds (Chen et al., 2013). The Spearman's rank correlation tests also confirm this winnowing process of streambed sediments. The Spearman's rank correlation tests show that at the Huaxian site, the streambed K_v values for the two layers have a significant negative and positive correlation with silt–clay content and sand content of the sediment, respectively (Table 2). This suggests that the differences in grain size distribution (sand, silt, and clay) for the two layers could be a cause of streambed K_v decreasing with depth. At most locations of the Huaxian site, the content of fine materials (silt/clay) tends to increase with depth (Figure 7b); these fine-grained particles fill the interstices of coarse-grained sediments and in consequence lowering the K_v in the lower layer of streambed. Nonetheless, the differences in streambed K_v in the upper and lower sediment layers do not completely result from the differences in grain size distribution. For example, at some test locations (HX1, HX9, HX13, and HX16), the weight percentage of silt–clay relative to total sample weight in the upper layer of the streambed is higher than that in the lower layer of the sediment (Figure 7b). However, the streambed K_v value in the upper layer is also much higher than that in the lower layer at these test locations (Figure 7a). At these test locations, the decrease in streambed K_v with depth is probably associated with three hyporheic processes (inflow–outflow exchange, bioturbation, and gas burst). Song et al. (2007) suggested that the three hyporheic processes are very effective in enlarging streambed K_v. Water upward and downward movement can expand pore size and make sediment more unconsolidated and permeable in the upper layer (Song et al., 2007), whereas invertebrate bioturbation (such as burrowing and feeding) and gas bursts from redox processes could create larger pore spaces and induce higher permeability in the upper layer of sediments.

TABLE 2 Correlations between grain size and K_v values from the two layers of each test site

Pair	Silt–clay content—K_v			Sand content—K_v		
Site	Meixian	Caotan	Huaxian	Meixian	Caotan	Huaxian
n	36	40	32	36	40	32
r	0.07	−0.19	−0.54***	−0.07	0.14	0.55***
p value	0.553	0.09	3.29e-06	0.553	0.21	2.87e-06

***$p < 0.001$.

Compared with the decreasing trend of streambed K_v with depth at the Huaxian site, there is an increasing trend of K_v with depth at most test locations of the Meixian site and Caotan site (Figures 5a and 6a). In this study, although no significant correlations between streambed K_v values and sediment silt–clay content or sand content are found at the $p = 0.05$ level (Table 2), however, streambed sediments in the upper layers do have higher content of silt and clay compared with those in the lower layers at most test locations of the Meixian site and Caotan site (Figures 5b and 6b). This may be the main reason for lower K_v values in the upper layers at the two test sites.

Furthermore, for streambed sediments of the Meixian site with high content of silt and clay (Figure 5b), differences in silt–clay content do not generally cause significant changes in streambed K_v values. For example, an obvious difference of silt–clay content in the two layers exists at test location MX2 (Figure 5b); however, there are similar low K_v values (0.11 m/day in the upper layer and 0.07 m/day in the lower layer; Figure 5a). Moreover, the Meixian site at the investigation time was under regional losing condition. Downward flux caused suspension of fine particles within the upper layer of the streambed, and the concentration of suspended fine particles decreases gradually with time (Chen et al., 2013). Blaschke, Steiner, Schmalfuss, Gutknecht, and Sengschmitt (2003) also found the uppermost parts of sediment are more easily clogged. Thus, the upper layer of streambed sediments due to the clogging may have a smaller K_v than the lower layer of streambed sediments, in keeping with similar finding of Chen et al. (2013) in the losing streams. Nonetheless, at some test locations (MX2, MX3, MX6, and MX9), lower content of silt and clay (Figure 5 b) and higher K_v values (Figure 5a) in the upper layers are observed compared with those in the lower layer. Chen et al. also found a decreasing trend of K_v with depth when the stream is under regional losing condition.

Although the Caotan site is under regional gaining condition, the winnowing process of streambed sediments that happened at the Huaxian site seems not act at the Caotan site. This is mainly due to the continuous silt and clay layer. Especially at some test locations (e.g., CT5, CT9, CT10, and CT14), regional upward flows do not result in lower content of silt and clay in the upper layer due to the continuous clogging layer. On the contrary, higher content of silt and clay is observed in the upper layers of these locations (Figure 6b), which cause lower K_v values compared with the lower layers (Figure 6a). At test locations (e.g., CT3, CT4, and CT8), three hyporheic processes (Song et al., 2007) may also play very important role in enlarging streambed K_v in the upper layers.

Moreover, the lower layers of sediments are compressed by the weight of upper sediment layers; this may cause differences in the porosity and streambed K_v in the two sediment layers at the three test sites.

5.2 | Factors influencing K_v values

The streambed K_v for the upper layer indicates that the higher values of the streambed K_v are close to the channel centre (i.e., Meixian and

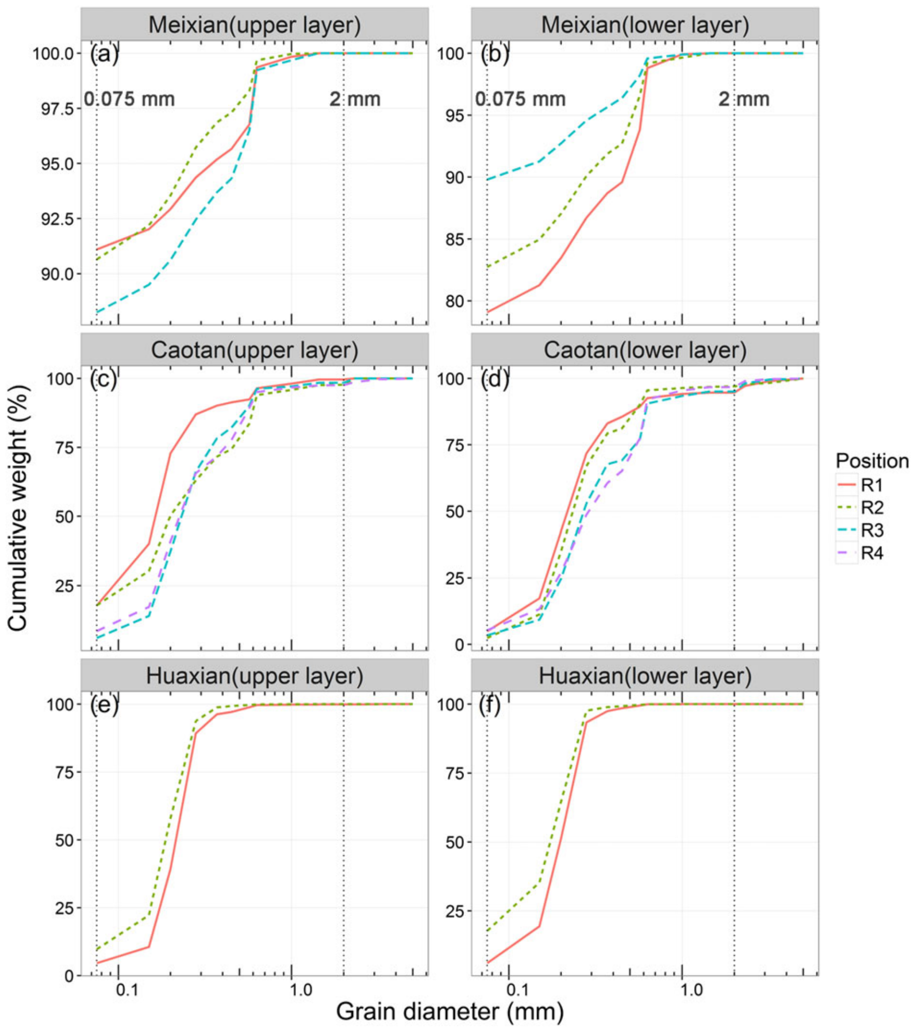

FIGURE 11 The grain size distributions of streambed sediment cores for each position across the stream from (a) the upper layer of the Meixian site, (b) the lower layer of the Meixian site, (c) the upper layer of the Caotan site, (d) the lower layer of the Caotan site, (e) the upper layer of the Huaxian site, and (f) the lower layer of the Huaxian site

TABLE 3 Sediment grain size distributions for three test sites

Grain size			Meixian R1	Meixian R2	Meixian R3	Caotan R1	Caotan R2	Caotan R3	Caotan R4	Huaxian R1	Huaxian R2
Upper layer	Median value of cumulative percentage in weight (%)	<0.075 mm (silt + clay)	89.7	89.1	87.3	9.5	10.4	3.8	5.3	4.2	7.2
		<2 mm	100	100	100	99.7	97.7	98.4	97.6	99.9	100
	Average median grain size	d50 (mm)	<0.075	<0.075	<0.075	0.17	0.20	0.23	0.23	0.22	0.19
Lower layer	Median value of cumulative percentage in weight (%)	<0.075 mm (silt + clay)	76.7	80.9	88.4	2.0	0.9	1.6	2.9	5.4	11.9
		<2 mm	100	100	100	94.7	97.0	95.1	96.7	100	100
	Average median grain size	d50 (mm)	<0.075	<0.075	<0.075	0.22	0.24	0.27	0.29	0.20	0.17

Caotan sites in upstream and middle stream, respectively) or the bank (i.e., Huaxian site in downstream) positions of the river. Genereux et al. (2008) speculated that higher streambed conductivities in the channel centre locations primarily resulted from the much less fine particles deposited towards the channel centre compared with the channel sides. At each test site, the grain size distribution varies significantly at different positions across the channel (Figure 11; Table 3), and this could result in different distribution of streambed K_v. The sediment grain size is larger closer to the channel centre of the Meixian site and Caotan site and the bank of the Huaxian site (Figure 11; Table 3), where the lower content of silt/clay may be a factor leading to higher streambed K_v. The results of the Spearman's rank correlation tests also confirm this, showing a significant negative correlation between silt–clay content of the sediment and streambed K_v and a significant positive correlation between sand content of the sediment and streambed K_v at each test site (Table 4). Such links are also suggested by Song et al. (2016), who found a negative correlation between hydraulic conductivity and the proportion of clay and silt and a positive correlation between hydraulic conductivity and the weight of sand. Similarly, Roque and Didier (2006) also found a negative exponential relationship between hydraulic conductivity and the proportion of clay and silt. Therefore, grain size distributions of the sediments at the three test sites play a major influencing role in streambed K_v. Among the three test sites, the significant higher streambed K_v values are observed at the Huaxian site (Figure 10a,b), mainly due to relatively large uniform particles of streambed sediments (Figure 7b,c).

The clogging degree of the streambed can also influence the magnitude of streambed K_v values (Chen et al., 2013). Among the three test sites, the smallest streambed K_v values occur at the Meixian site whereas the highest streambed K_v values occur at the Huaxian site. The streambed K_v values at the Caotan site fall between the former and the latter. The results of in situ permeameter tests indicate that the streambed at the Caotan site and Huaxian site is under partially clogged conditions, whereas the Meixian site is reaching the completely clogged stage. At the Meixian site, the channels are mainly covered by fine silt and clay (Figure 5b; Table 3). This large amount of fine-grained sediments is consistent with the lower streambed K_v at this site. Streambed K_v values at the Meixian site are all less than 0.4 m/day (Figure 5a). Streambed sediment at the Huaxian site has higher contents of coarse-grained sand and patches of silt/clay (Figure 7b,c) and thus shows a large spatial variation in K_v values. The highest K_v value is about four orders of magnitude higher than the smallest K_v value at each measurement depth (Figure 7a). For example, the tests at locations HX15 and HX16 encountered higher content of silt/clay (Figure 7b), and their K_v value for the upper layer is 0.12 and 1.5 m/day, respectively (Figure 7a). The other 14 tests were conducted in the medium-coarse sand, and their K_v values for the upper layer range from 3.03 to 34.9 m/day, indicating relatively high permeable sediments compared with the other two sites. Although the streambed sediments at the Caotan site have similar high contents of coarse-grained sand like at the Huaxian site (Figures 6c and 7c), in situ permeameter tests were carried out on a sandy streambed that was mostly covered by a continuous clogging layer, and K_v values for the upper layer and lower layer are mostly lower than 0.9 and 0.4 m/day, respectively (Figure 6a). It should be noticed that the continuous clogging layer has very strong influence on streambed K_v, as demonstrated by Landon et al. (2001), Chen (2004), and Min et al. (2013) in the other rivers. Moreover, especially at the Huaxian site, the regional upward flux also winnows sediments and increases the pore spacing, causing higher K_v values in the upper layers of the streambed.

TABLE 4 Correlations between grain size and K_v values from the upper layer of each test site

Pair	Silt–clay content—K_v			Sand content—K_v		
Site	Meixian	Caotan	Huaxian	Meixian	Caotan	Huaxian
n	18	20	16	18	20	16
r	−0.51*	−0.50*	−0.72**	0.51*	0.57**	0.69**
p value	0.03	0.02	0.002	0.03	0.009	0.004

*$p < 0.05$. **$p < 0.01$.

6 | CONCLUSION

In this study, streambed attributes of K_v within two connected sediment layers were observed at 54 locations in three stream reaches (Meixian, Caotan, and Huaxian) of the Weihe River in July 2016. Streambed K_v at each test site shows large spatial or depth variability related to streambed materials and stream regional flow patterns.

There are spatial and depth variability of K_v, and grain size distribution of the sediment is one of controlling factors in streambed K_v. The K_v varies from upper layer and lower layer. Generally, the K_v values from the Huaxian site show a significant decreasing trend with depth, whereas the K_v values from the Meixian site and from the Caotan site both show a weak increasing trend with depth. For each test site, the main effect in the difference between streambed K_v

values from the upper layer and lower layer is due to the difference in their sediment grain size distribution, which is mainly affected by the regional flow patterns and the sediment transport balance of deposition and erosion. At the Meixian site, with the regional downward movement of water within the sediments, fine particles were more easily deposited in the pores in the upper layers of the streambed. At the Caotan site, the continuous silt and clay layer seems to be responsible for a weak increasing trend of K_v values with depth. However, at some test locations of each site, the three hyporheic processes (inflow–outflow exchange, bioturbation, and gas burst) may also have an impact on the variation in streambed K_v with depth, but their influence cannot be examined with the available data here.

This study highlights the important influence of the effect of grain size and clogging pattern on the K_v. Nonetheless, all K_v tests were performed at only a few locations across the channels due to deeper water table depths. To improve understanding the spatial or depth variability of streambed K_v in the Weihe River, further representative streambed K_v measurements across the channel of the Weihe River are encouraged.

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