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Spatial variability of streambed vertical hydraulic conductivity and its relation to distinctive stream morphologies in the Beiluo River, Shaanxi Province, China

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Abstract Streambed vertical hydraulic conductivity (K_v) is a key parameter in the analysis of interactions between streams and aquifers, and of stream ecosystems. However, knowledge of the streambed hydraulic conductivity associated with different stream morphologies is relatively scarce. An in-situ standpipe permeameter test method was used to determine the spatial variability in streambed K_v measured along 18.5 km of stream reach in the Beiluo River, Shaanxi Province, China. The 59 total measurements were conducted at four test sites in three different stream morphologies: straight channel, anabranching channels and a nearby meander bend. There was great spatial variability in K_v among the four test sites and three K_v distribution patterns can be determined: (1) higher K_v values appear on the erosional bank in contrast to lower K_v values on the depositional bank at the two sites near meander bends; (2) the K_v distribution in straight channels shows that the higher K_v values occur in the center of the channel; (3) the K_v values are generally highest on the branch with more alluvial forms in the anabranching channels. Moreover, grain-size analysis results illustrate that the average grain-size distributions of streambed sediments are significantly different on each side of the channel. The erosional and depositional forms are one of the driving dynamics for the distribution of streambed grain size that trigger the differences in the distribution of the K_v.

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Introduction

Accurate estimation of streambed hydraulic conductivity (K) is of significance in the analysis of the magnitude and extent of water exchange and contaminant transfer between groundwater and surface water, and is even important in dealing with a number of geotechnical problems involving the management of groundwater and surface water (Cardenas et al. 2004; Chen et al. 2008; Song et al. 2009; Sebok et al. 2014). Streambed K can be measured through a variety of approaches and techniques which have been discussed by Landon et al. (2001) and Kalbus et al. (2006). It should be taken into account, however, that each method has its own limitation because of measurement scale and field conditions (Kalbus et al. 2006; Min et al. 2013). It is known that the streambed vertical hydraulic conductivity (K_v) always varies spatially; some studies have revealed that the K_v has large variations along a river transect (perpendicular to the river flow direction; Chen 2005; Min et al. 2013). Streambed K_v is spatially variable in a river and the occurrence of the largest K_v is in the center of the stream channel (Genereux et al. 2008). Landon et al. (2001) and Chen (2005) reported that K_v variation could occur on a scale as small as 3 m. In addition, even over a short distance (less than hundreds of meters), the K_v can change appreciably (Chen 2004; Genereux et al. 2008). Moreover, hydraulic conductivity decreases with increasing depth according to the study results of Song et al. (2010) and Min et al. (2013).

The channel morphologic features are important factors in the analysis of the hydraulic relationship between streams and aquifers (Cardenas et al. 2004; Käser et al. 2009; Sebok et al. 2014). Hyporheic interaction is controlled by variable pressure heads in the streambed sediments and its environmental conditions (Koch et al. 2011). Stream morphologies create the pressure variations, including meanders (Nowinski et al. 2011), cobbles (Edwardson et al. 2003), bedforms (Bardini et al. 2013), riffles and pools (Käser et al. 2009), and beaver dams (Genereux et al. 2008). The across-stream gradient can be induced by flow along meander bends, which is enhanced by the natural alignment of large stream K along the direction of maximum gradient (Cardenas et al. 2004). Compared to homogeneous bedform, small-scale permeability heterogeneity produces more irregular flow patterns (Bardini et al. 2013). Downwelling and upwelling flow paths can be caused by bedform and sinuosity at small scale (1–100 m), and width and depth of bedrock at large scale (km; Malard et al. 2002). For a pool–riffle sequence, exchange between channel and hyporheic water can induce rapid downwelling at the head of riffles and varies upwelling in riffle tails (Edwardson et al. 2003). Furthermore, regional groundwater-flow attributes are predominately controlled by stream geomorphology such as channel gradient, sinuosity, width/depth ratio, streambed hydraulic conductivity and so on (Larkin and Sharp 1992). It has been reported that either bankfull cross-sectional area or bankfull width are significant for all peak discharges (Lawlor 2004). High hydraulic conductivity produces saturated subsurface flow (Irvine et al. 2012). The interaction of streams and aquifers can be enhanced by growth of meander length and reduced by decrease in river sinuosity (Boano et al. 2006). Due to the transport of fine materials, the hydraulic conductivity of shallow alluvial aquifers under condition of sinuosity-driven hyporheic flow is dynamic (Nowinski et al. 2011).

A meandering stream is one of the important sedimentological forms that connects regional aquifers and streams (Dong et al. 2012). Sebok et al. (2014) demonstrated that there are more variable streambed features in the meander bend than in the straight section. The existence of several orders of magnitude in range of streambed anisotropy values has been observed close to stream banks (Sebok et al. 2013). The water exchange in the main channel can move into slower pools by anabranch diversions, and promotes the exchange process into the subsurface (Koch et al. 2011). A combined study of the K_v and erosion and deposition processes of streambed sediments has been conducted by Genereux et al. (2008) and Levy et al. (2011). Bardini et al. (2013) showed that the bedform is an important hydrologic factor impacting hyporheic water exchange. The streambed and point bars influence the process of water exchange and solute transport between streams and surrounding groundwater systems (Dong et al. 2012). Those previous studies suggested that there are many influences on hydraulic conductivity including stream morphology and geomorphology attributes, riverbed forms, erosion and deposition process, and the riverbed sediments. However, knowledge of the streambed hydraulic conductivity for different stream morphologies is relatively scarce. In the present study, the study focuses on an investigation of spatial variability in streambed K_v spanning 18.5 km of stream reach in the Beiluo River, Shaanxi Province, China. An in-situ field standpipe permeameter was utilized to collect 59 total measurements using 4 test sites in 3 stream morphologies (one in the straight stream channel, one in anabranching channels and two near distinctive meander bends). All sediment samples were collected after the K_v tests and they were used for grain-size analysis.

The objectives of this study were to (1) investigate spatial variability in streambed hydraulic conductivity (2) determine the links between this variability and stream morphologies, bedforms and water depth, and (3) analyze the relationship between the distribution of vertical hydraulic conductivity and the sediment grain size.

Study area

The field study was conducted in the Beiluo River, which is one of the tributaries of the Weihe River, and is a meandering stream located in Shaanxi Province, China. The river system has a feather-like distribution with a total length of 680.3 km, and the total area of the Beiluo River Basin is approximately 26.9 km^2. It covers two Chinese topographic regions, the Loess Plateau and the Guanzhong Basin. Its flow is from northwest to southeast and empties into the Weihe River. The study area is located in a continental monsoon climate area and has a mean annual precipitation of 541.7 mm and a mean temperature of 13.2 °C. Seasonal variations in precipitation are distinctive and non-uniform. The majority of floods occur from July to October. The river system has a stream gradient of 1.98 ‰ and the average stream flow is 14.99 m^3/s. This area is in the transition region between the Loess Plateau and the Guanzhong Basin. The streambed sediment is alluvial loess sandy clay and sand-gravel stratum of Pliocene and Holocene Epoch. Meandering channel morphologies occur because of the change from an erosional regime to a depositional regime.

The Beiluo River is an important local river that provides water supplies for agricultural activities and human consumption (Zhang et al. 2007). However, because of a long history of wastewater drainage and platform runoff from nearby rapidly developed petroleum industries, the natural environmental systems have been affected. In this process, the Beiluo River has received contaminants and has been influenced by the input of a large amount of organic matter and heavy metals (Shi et al. 2008). Furthermore, the annual average amount of runoff for the Beiluo River has markedly decreased, especially from spring to autumn, during the period from 1964 to 2008 (Dong et al. 2014). Therefore, determination of the hydraulic conductivity of the Beiluo River's riverbed is essential for estimating the water discharge from groundwater into rivers and the management of water resources.

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Field measurements were conducted in an 18.5 km section of the Beiluo River at the meander bend 1 (MB1) site, anabranching channel (AC) site, straight channel (SC) site, meander bend 2 (MB2) site. The stream flows from north to south with many sharp bends in the channel. Because of those bends, one stream bank is being eroded, while depositional processes occur at the other bank and those processes have resulted in steep banks that project 0.5–4 m above the stream. Both stream banks are covered with trees and shrubs and the surrounding environment is covered with cultivated fields. It can be hypothesized that the composition of sediment particles may have significant difference among test sites, which can induce considerable distinctive spatial variability of K_v.

All sites were suitable for conducting the field experiments to establish the relationship between spatial variability of streambed hydraulic conductivity and differences in stream morphologies. All in all, the distribution of 60 measurements at 4 test sites in different stream morphologies (Fig. 1) was determined. In the field study, the testing points were determined by the submerged streambed width and river-water depth (Fig. 2). The distribution of test sites in MB1 is different from other sites because the stream velocity was relatively high and the water is deeper on the left bank (Table 1). Measured points were labeled by a letter (L, C, R, R1 or R2) to indicate left side, center, or right side of the channel (Fig. 2). Because the first test location along the stream flow for left side of MB1 site was inundated by stream water in the afternoon (Fig. 2a), the value for this point was discarded in this study.

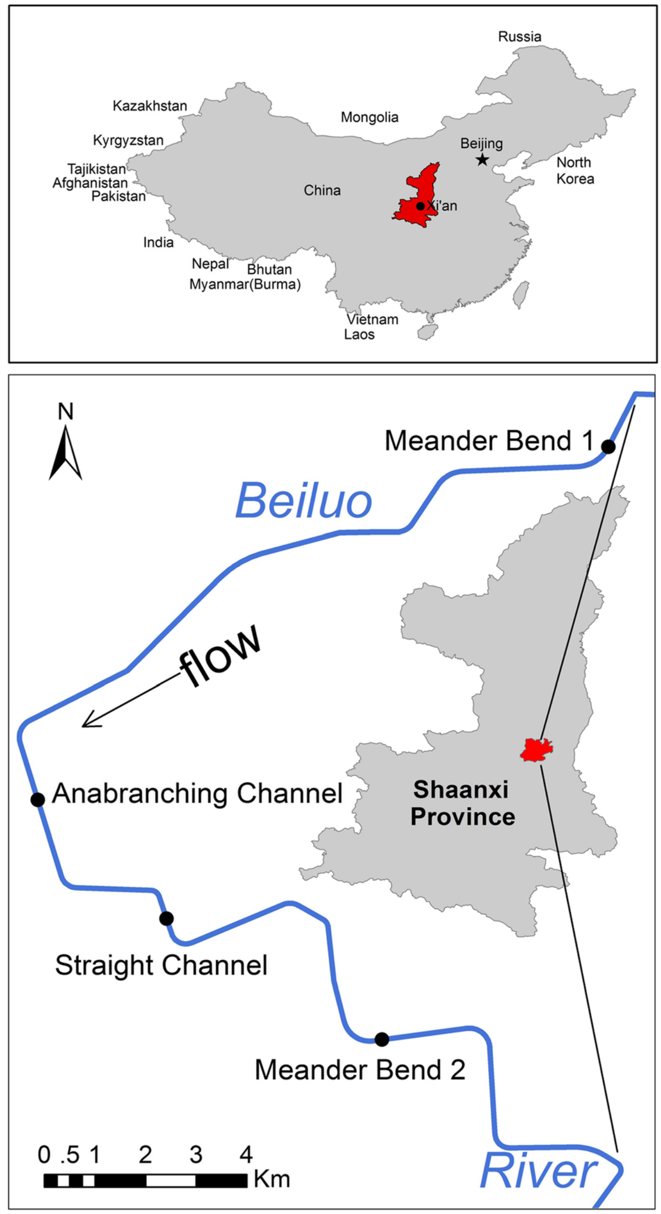

Fig. 1 The location of the study area along the Beiluo River

Methods

Vertical hydraulic conductivity

A field permeameter method for measuring vertical hydraulic conductivity has been applied and discussed in previous studies (Chen 2005; Genereux et al. 2008; Song et al. 2010; Dong et al. 2012). This method is used to determine the streambed hydraulic conductivity (K_v) by inserting a pipe vertically into the streambed (Fig. 3), filling the pipe with water, and measuring the rate of decline of the water level inside the pipe. After doing this several times the K_v can be calculated from this rate. In this study, polyvinyl chloride pipe with an inner diameter of 5.4 cm and length 160 cm was used. The pipe was inserted into the streambed sediments, ensuring that the length of the sediment column was approximately 40 cm. A measuring tape was used to measure water levels, with accuracy of 1 mm. A track level bar was used to ensure that the pipe is vertical. During the test, water was added at the top open end of the pipe to form a hydraulic head. The head was then allowed to fall in the pipe. During the water-level falling process (inside the pipe) for each permeameter test, hydraulic head measurements were collected at regular intervals. In this study, hydraulic head and time were recorded at a water-level declining interval of 1 cm, and hydraulic head measurements were collected more than 5 times. Any pairs of measured data of hydraulic head and time were used to calculate the K_v value using the equation of Hvorslev (1951).

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

where D is the inner diameter of the pipe, m is the square root of the ratio of the horizontal conductivity K_h to the vertical conductivity K_v (i.e., $m = \sqrt{K_h/K_v}$), L_v is the length of the sediment column, h_1 and h_2 are hydraulic head inside the pipe measured at times t_1 and t_2, respectively. Generally, K_h is larger than K_v. A modified Hvorslev solution has been developed by Chen (2004) and

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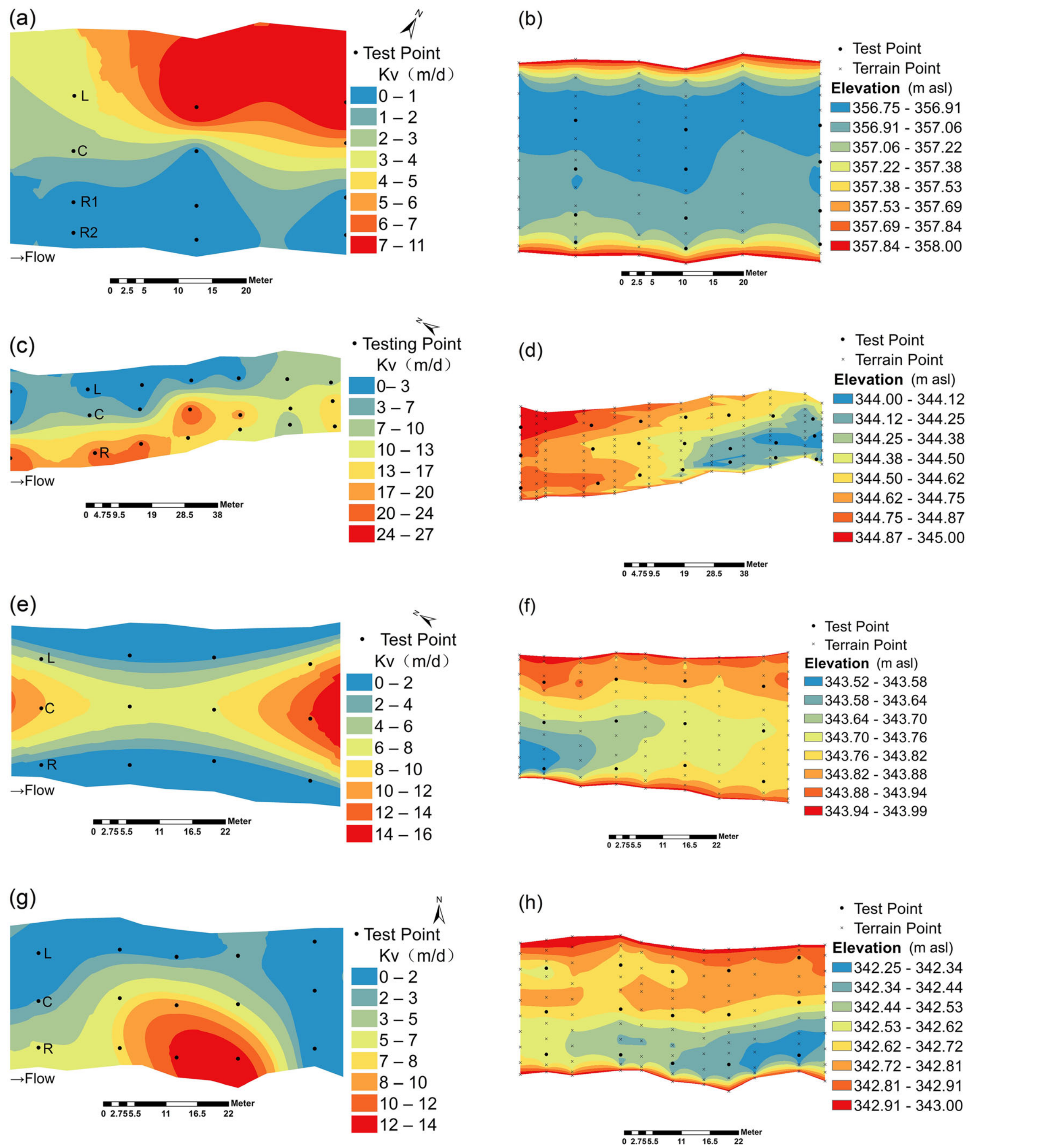

Fig. 2 The spatial distribution of K_v and bedforms (streambed elevation in meters above sea level) by Kriging for each test site along the Beiluo River. **a**–**b** Meander bend 1 (MB1), **c**–**d** anabranching channel (AC), **e**–**f** straight channel (SC), and **g**–**h** Meander bend 2 (MB2)

Song et al.(2009) to determine the K_v when L_v is much larger than D:

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

However, the error in K_v from the formula provided by the modified Hvorslev equation (Eq. 2) is linked to the ratio (L_v /D) of the measured sediment length (L_v) to the inner diameter (D) of the polyvinyl chloride pipe. When $1<m<5$, if the ratio (L_v /D) is larger than 5, the error of the modified calculation will be less than 5 % (Chen 2004). For this reason, the appropriate inner diameter and measured sediment column length should be selected carefully. In this study, the length of the measurements of sediment column in the in-situ permeameter tests ranged from 37.5 to 48.1 cm and the inner diameter of the sediment column was 5.4 cm, so the ratio L_v /D was greater than 5, ensuring a relatively small error using these measurements.

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Table 1 Hydrological condition and geomorphologies of test sites

	MB1	AC	SC	MB2
Test date	June 23, 2014	June 17, 2014	June 18, 2014	June 27, 2014
Number of measurements	12	21	12	15
Average channel width (m)	32.2	25.1	27.5	25.8
Site length (m)	50	95	54	55
Average stream velocity (m/s)	0.785	0.482/0.415[a]	0.311	0.415
Max. water depth (cm)	120	68	48	70
Average water depth (cm)	98.9	24.6	21.4	38.5
Stream gradient (m/m)	2.4 ‰	1.8 ‰	1.8 ‰	1.6 ‰
Sinuosity	1.17	1.08	1.04	1.21
Average thickness of measured sediment (cm)	39.5	44.6	43.8	41.2
Mean water depth of L/C/R (R_1/R_2)[b] (cm)	107.9/98.9/(86.9/86.4)	12.9/36.9/34.7	14.9/25.2/27.3	27.2/26.3/50.5
Site description	Test site is near a meander bend. Streambed sediment contains medium sand, silt and clay particles	Stream flow is divided into two branches by a 20-m sand bar. Streambed sediment contains large part of sand and a small part of gravel	Riverbanks are covered with shrubs. Streambed sediment contains medium sand, silt and clay particles	Test site is near a meander bend with a point bar. Streambed sediment contains medium sand, silt and clay particles

[a] Average stream velocity in left and right side in an anabranching channel, respectively

[b] (R_1/R_2) indicates two test locations at right side channel of MB1 site

Bedform

Bedforms reflect not only the influence of the different stream morphologies on the riverbank and the degree of erosion and deposition, but also correspond well with the water depth. Chen (2005) and Min et al. (2013) explained that the K_v has a positive correlation with the water depth. The Topcon GTS-102 N Construction Total Station was used to collect the data to detect the bedform. The detection of angle is by 2 horizontal and 1 vertical, and the prism mode-of-measurement accuracy is ±(2 mm+ 2 ppm×D) mean squared error (MSE). The maximum range is 2,000 m. The data processing for spatial analysis was performed using ArcGIS 10.0 (Genereux et al. 2008).

Sediment sampling and grain-size analysis

The sediment samples were collected after the completion of the K_v test. The top opening of the pipe was sealed using a rubber cap to disconnect the pipe from the atmosphere, and then the pipe with the sediment column inside was pulled out. This procedure prevented sediments from exiting at the bottom end of the pipe (Song et al. 2009). The sediments were placed into labeled sampling bags after the water was poured out. Ultimately, the sediment samples were used for grain-size analyses in a laboratory at Northwest University, China. The sieving method was used. After the samples were dry, each sample was poured into a roto-tap for shaking and was separated into 13 grades. The finest sieve size was 0.075 mm and the coarsest one was 10 mm. Particle sizes <0.075 mm were classified as silt and clay for this study, particle sizes of 0.075–2.0 mm as sand, and particle size >2.0 mm as gravel (Song et al. 2010).

Results and discussion

Spatial variability of K_v

The K_v values of the total of 59 measurements covered 4 orders of magnitude, from 0.01 to 26.9 m/d (Table 2; Fig. 4), which is within the range of K_v values reported by a number of researchers (Genereux et al. 2008; Min et al. 2013) for studies conducted in sediment-laden alluvial rivers that are similar to Beiluo River.

Generally, the K_v values are highest on the right erosional bank and the lowest K_v values occur close to the depositional bank at the sites MB1 (Fig. 2a) and MB2 (Fig. 2g). At the SC site, the K_v values are higher in the center of the channel (Fig. 2e). This result was consistent with the research results of Genereux et al. (2008) for West Bear Creek (USA), which suggested that the greatest K_v generally occurs in the center of the channel. In the anabranching channels, the sand bar in the center, on its upstream end, divides the stream into two parts which leads to different patterns of K_v distribution than at the other sites. The K_v values are generally higher on the right side, and smaller K_v values appear on the left bank (Fig. 2c).

The values for the coefficient of variation for each test site are 1.27, 0.82, 1.21 and 0.92 (Table 2), for MB1, AC, SC,

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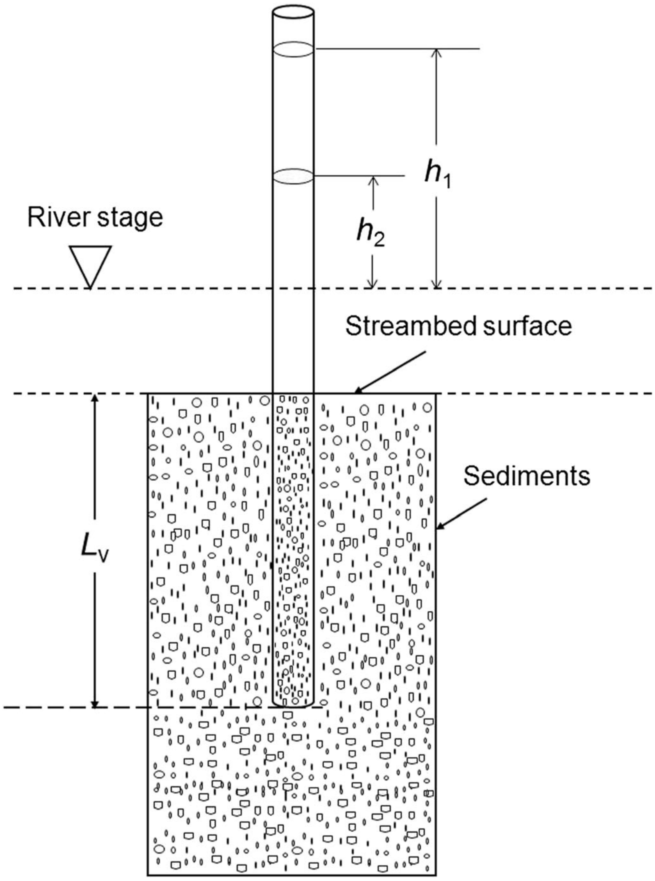

Fig. 3 Schematic diagram showing an in situ permeameter test to determine streambed K_v

and MB2 respectively. The values indicate that streambed attributes are more variable at the MB1 site than those close to the meander bend. This may be because of the more dynamic environment at MB1, which has the greatest water velocity and average channel width (Table 1) and the greatest erosion and deposition of the streambed (Fig. 2). There is more variability in streambed materials there, including more silt/clay compared to the lower coefficient of variation values at the AC site that has more sand and gravel (Table 3). Chen (2005) reported that the coefficient of variation values in sediments with more silt/clay is larger than in sediments containing mostly sand and gravels.

In the results of this study, the streambed K_v distribution showed great spatial variability for each test site and that K_v distribution could be linked to the differences in grain size in streambed sediments as discussed by Song et al. (2010). Sebok et al. (2014) found that streambed attributes in the meander bend were more variable than in the straight channel. Dong et al. (2012) reported that the K_v values in point bars were lower than those in the streambed. Käser et al. (2009) studied the potential relationship between K and geomorphology in a riffle-step-pool sequence and showed that the mean value of hydraulic conductivity is smaller in the pool than in the riffle, which might be related to excess fine sediments settling preferentially in pools where stream velocity was lower. Other studies showed that the variability of K_v values was related to the erosion and deposition of streambed sediments (Genereux et al. 2008; Levy et al. 2011) and regional variations in streambed characteristics, including sedimentary texture and sedimentary structure (Leek et al. 2009; Min et al. 2013). Therefore, streambed sediment grain size, which in turn can be related to different stream morphologies, bedforms, and erosional and depositional regimes, correlates with K_v values.

Each test site has a different stream morphology. SC is located in a straight stream channel that is broader and straighter than the channel at the AC site (Table 1; Fig. 2). Among all the test sites, the water velocity and water depth are the lowest at the SC site (Table 1). In particular, there is a sand bar with a 20 m length near the bridge pier, and this structure leads to a division of the stream flow into two channels.

At the MB1 site, it is shown that the erosional process increases from the right bank to left bank in the K_v measurement area (Fig. 2b). The streambed profile at the MB2 site is opposite that of the MB1 site (Fig. 2h). At the SC site, the lowest streambed elevation occurs on the right bank and towards the center of the channel, which suggests that the erosion process is mainly concentrated in the center of the channel towards the right side (Fig. 2f). The elevation on the left bank is relatively higher at the AC site. This indicates that the majority of erosional locations are on the right bank of the channel (Fig. 2d). The configuration of this stream, which is characterized by anabranching, is mainly controlled by one or two major anabranches because such structures result in the greatest transport efficiency (Huang and Nanson 2007).

The study shows that distinctive stream morphologies have resulted in bedforms that correspond to erosion and deposition of the channel at each test site. Those contrasting erosion and deposition patterns led to different sediment distributions and spatial variability for K_v values at each test site (Fig. 5; Table 3), whereas the erosional side likely has greater grain size contrast because of depositional conditions. Such are the reasons for hydraulic conductivity variability and the spatial distribution patterns.

Table 2 Statistics for K_v values from permeameter tests. *SD* standard deviation

Test site	Range (m/d)	Mean of L/C/R (R_1/R_2) (m/d)	Mean (m/d)	Median (m/d)	SD	Standard error mean	Coefficient of variation
MB1	0.03–10.67	10.67/2.58/(0.12/0.08)	3.36	0.11	4.27	1.29	1.27
AC	0.08–26.92	3.01/11.11/17.31	10.48	8.94	8.62	1.88	0.82
SC	0.01–15.62	4.18/9.49/0.15	4.60	1.33	5.59	1.61	1.21
MB2	0.07–13.48	1.43/4.81/7.81	4.68	2.04	4.32	1.12	0.92

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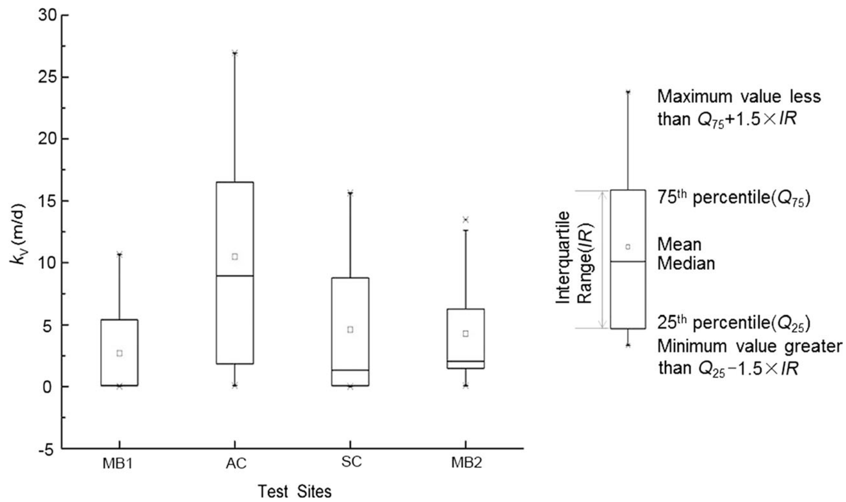

Fig. 4 Box plots of streambed K_v for each test site along the Beiluo River

Correlation between K_v and water depth

Statistical analyses of K_v values (Table 2; Fig. 2) and the mean of water depth (Table 1) calculated from the mean of L/C/R (R_1/R_2) positions generally suggest that deeper water depth corresponds to higher K_v values. Spearman Bivariate Correlation analysis was used to verify whether two non-normally distributed variables are significantly correlated at the 95 % confidence level. However, when all the data from correlation coefficients between water depth and the vertical hydraulic conductivity are taken into account for each test site, the correlation coefficients for sites MB1, AC, SC, and MB2 were 0.55, 0.44, −0.24 and 0.15, respectively. The results for MB1, SC, and MB2 revealed that the correlation is not significant at the 95 % confidence level. Although the relationship between K_v and water depth was not as significant as expected and the correlation coefficient was negative in SC, a lower K_v value at these study sites often occurred in the part of the channel with the shallower bank. This is consistent with what was reported in the publication by Min et al. (2013).

In general, where there is more rapid flow, there is deeper water and greater flow strength, both of which could result in coarser sediments (Min et al. 2013). However, these results show that there is insignificant correlation between K_v and water depth. It must be taken into account, however, that the time interval spent at the test sites spanned only 10 days. Time and active channel reworking of sediment have great influence on the distribution of K_v. In dynamic streams where sediments are constantly reworked, the hydraulic conductivity changes with time as the sediments are reworked and as the weight of overlying sediments increases or decreases the shear stress. Also, when making the measurements at the MB1 site, the water rose about 5 cm in the afternoon. There was also pumping taking place on the right bank downstream of SC and MB2. These may be the reasons for temporary changes of the water depth. The measurements of water depth represent the water flow conditions only at the time of testing. However, the sediments in the channel that were used to test streambed hydraulic conductivity were deposited over a long period of time (Chen 2005). Therefore, the hydraulic conductivity is not evidenced by a snapshot in time of the current water depth.

Grain size analysis

Erosional areas mainly occur in the central channel towards the right at site SC; the erosional bank is located on the right side of the channel at the AC site. The highest average median grain size of d_{50} and lowest average value of cumulative percentage in weight of silt and clay was in the central part at SC and the right side at AC, respectively. It has been demonstrated that erosion and deposition near a meander bend would result in different grain size distributions of streambed sediments at sites MB1 and MB2. For streambed sediments (Fig. 5) from each test site along the Beiluo River, the average value of cumulative percentage in weight for particle size diameter <0.075 mm (silt and clay) increases from the erosional to

Table 3 Sediment grain size distributions for the 59 samples collected

Particle size		Test sites												
		MB1				AC			SC			MB2		
		L	C	R1	R2	L	C	R	L	C	R	L	C	R
%	<2 mm	97.6	98.6	97.5	98.3	85.3	82.1	76.4	95.4	92.9	97.5	99.1	99.2	92.0
Average value of cumulative percentage in weight	<0.075 mm (silt+clay)	2.7	9.7	33.1	32.3	3.5	9.9	2.1	4.8	2.3	19.2	32.9	6.3	3.4
Average median grain size	d_{50} (mm)	0.25	0.18	0.12	0.09	0.20	0.28	0.64	0.24	0.57	0.16	0.08	0.12	0.28

depositional side at the MB1 (L/C/R_1/R_2) and MB2 (L/C/R) sites. Conversely, the average median grain size decreases from the erosional to depositional side at the MB1 and MB2 sites (Table 3). This evidence supports the previous view of the Beiluo River: stream morphology, bedform pattern, and contrasting erosional and depositional conditions are the driving factors impacting the distribution of riverbed sediments. This difference in sediment distribution can lead to spatial variability of K_v for each test site. In particular, the grain size distribution at MB1 is significantly different from the other sites and indicates more sediment mixing, and, consequently, higher variability coefficients for K_v.

Grain size is a main controlling factor for streambed hydraulic conductivity (Song et al. 2010). The average grain size distributions of streambed sediments have significant differences at each position of the channel at all tested sites (Fig. 5). Comparing the statistics and distributions of K_v values (Table 2; Fig. 2) collected from permeameter tests at each position L/C/R (R_1/R_2) at all test sites, it is evident that a higher average median grain size of d_{50}, and a lower average value of cumulative percentage in weight of silt and clay (<0.075 mm) correlate with higher hydraulic conductivity. The vertical hydraulic conductivity of channel sediments has a wide range of distribution; a difference of five orders of magnitude in K_v exists between silt-clay and sand-gravel sediments (Chen et al. 2008). Roque and Didier (2006) have studied the relationship between hydraulic conductivity and the weight of clay and silt contained in sediments under three different conditions. Their results show that there is a negative exponential relationship for both clay and silt. However, for site AC, the average value of cumulative percentage in weight with silt and clay at the left side was less than that at the central part, but that side had lower hydraulic conductivity. Therefore, in the Beiluo River streambed, the distribution of streambed K_v is not just controlled by the change of grain size. Sedimentary structures (Leek et al. 2009), clogging sediment (Song et al. 2010), and hyporheic processes between stream water and groundwater (Nowinski et al. 2011) may also influence hydraulic conductivity there.

Generally, where the porosity is larger, the grain size is larger, the water flow channel is relatively smooth, and the hydraulic conductivity is larger. In fact, Song et al. (2009) have developed an empirical formula relating the hydraulic conductivity and grain size. For example, grain size data have been used to deduce K_v values based on the Shepherd equation ($K_v = Cd_{50}^{1.65}$ where C is a dimensionless coefficient, Shepherd 1989). This equation focuses on particle diameter at 50 % of cumulative weight of sediment, which shows that there is a positive relationship

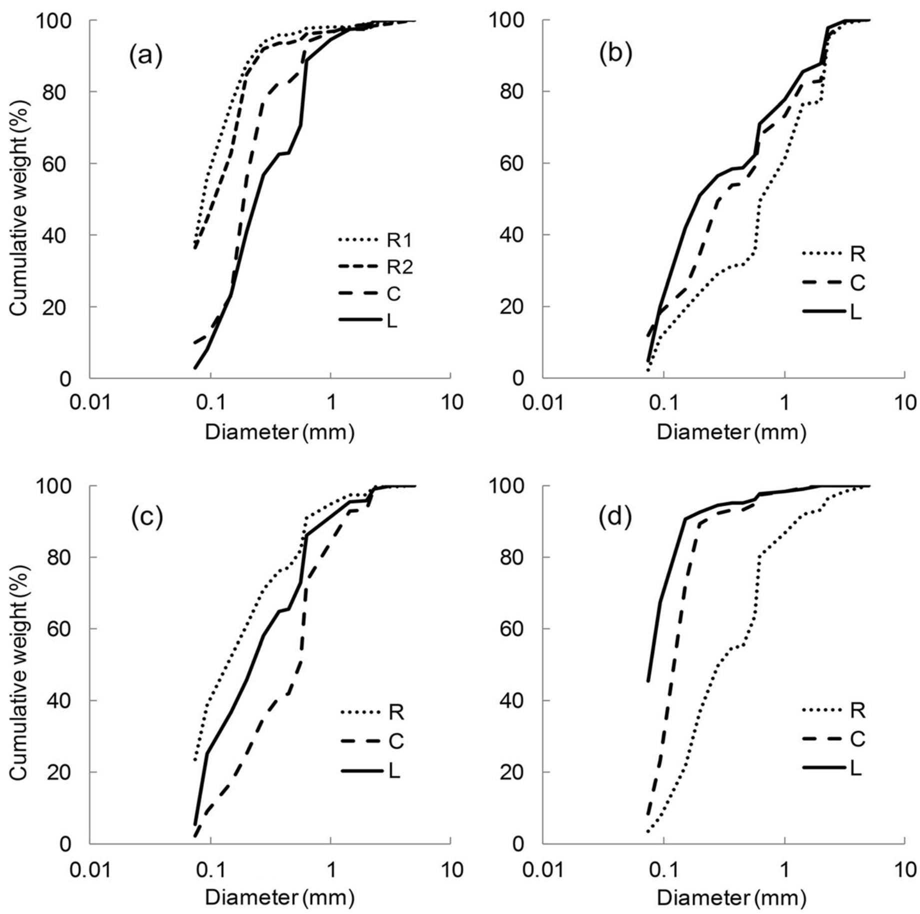

Fig. 5 Average grain size distributions of streambed sediments from each test site along the Beiluo River. **a** Meander bend 1, **b** Anabranching channel, **c** Straight channel, and **d** Meander bend 2

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between grain size and hydraulic conductivity (Song et al. 2009). The results generated by this formula provide corroboration for the present study.

Conclusions

In this report, an in-situ permeameter test method was applied to determine the spatial variability in streambed K_v in an 18.5 km stream reach in the Beiluo River. Collectively, the data from 59 measurements at 4 test sites were analyzed. There were three different stream morphologies: straight channel, anabranching channels, and two distinctive meander bends. Each test site had great spatial variability in K_v and different K_v distributions.

The K_v distribution at four test sites could be divided into three patterns—at the two sites near meander bends, the K_v values are generally highest on the erosional bank and the smallest K_v values occur near the depositional bank; the K_v distributions in the straight channel show that the K_v values are greater in the center of the river. In the anabranching channels, the K_v values are generally highest on the branch with more alluvial channel features.

Distributions of riverbed morphologies from each test site along the Beiluo River showed that the stream morphology is a significant factor influencing erosional and depositional conditions and bedforms. The erosional and depositional stream hydrologic processes winnowed the sediments and mobilized the sand and other particles contained in the streambed to form deposits of different grain size. Streambed hydraulic conductivity could be directly related to the grain size. Grain size analysis results indicate that the average grain size distributions of streambed sediments have significant differences in each part L/C/R (R_1/R_2) of the channel at all test sites. A higher average median grain size of d_{50} is found on the erosional bank and there is a generally a lower average value of cumulative percentage in weight for silt and clay.

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