The heterogeneity of 3-D vertical hydraulic conductivity in a streambed

Guangdong Wu, Longcang Shu, Chengpeng Lu and Xunhong Chen

ABSTRACT

The heterogeneity of vertical hydraulic conductivity (K_v) is a key attribute of streambed for researchers investigating surface water–groundwater interaction. However, few three-dimensional (3-D) K_v models with high spatial resolutions have been achieved. In this study, *in-situ* permeameter tests were conducted to obtain K_v values. A 3-D model with 443 K_v values was built comprising 10 lines, 10 rows, and five layers. Statistical analysis was done to reveal the spatial characteristics of K_v. The influence of bedform on K_v values was restricted to the near-surface streambed. K_v increased with the increasing distance from the south river bank for the upmost layer, but it was not the case for other layers and the combined K_v values of five layers; the spatial pattern at transects across the channel did not differ significantly. The K_v values of each layer pertained to different populations; the sediments of individual layers were formed under different sedimentation environments. The coupling of erosion/deposition process and transport of fine materials primarily contributed to a reduction of the mean and median of K_v values and an increase of heterogeneity of K_v values with depth. Thus, a collection of K_v values obtained from different layers should be considered when characterizing the heterogeneity of streambed.

Key words | groundwater–surface-water relations, heterogeneity, hydraulic conductivity, permeameter test

Guangdong Wu
Longcang Shu
Chengpeng Lu (corresponding author)
State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering,
Hohai University,
Nanjing 210098,
China
E-mail: *luchengpeng@hhu.edu.cn*

Xunhong Chen
School of Natural Resources,
University of Nebraska-Lincoln,
Lincoln,
NE 68583-0996,
USA

INTRODUCTION

The heterogeneity of streambed vertical hydraulic conductivity (K_v) is a major controlling factor in water and solute fluxes through the streambed–aquifer interface (Cardenas & Zlotnik 2003; Salehin *et al.* 2004; Ryan & Boufadel 2007). Overexploitation of groundwater in northern China, especially high-K_v areas, resulted in base-flow reduction and stream infiltration, and the degradation of stream ecosystem (Chen & Shu 2002). Therefore, the concern about induced stream depletion urgently requires a more detailed picture illustrating the heterogeneity of streambed. Especially, the spatial variability of vertical hydraulic conductivity and bedform is an important aspect of streambed heterogeneity.

Spatial heterogeneity of streambed hydraulic conductivity has been widely studied by many researchers. Chen (2005) and Genereux *et al.* (2008) reported the significant spatial variation of streambed K_v in their individual study reaches. The spatial variability of hydraulic conductivity under different topographic features has also been frequently surveyed (Genereux *et al.* 2008; Sebok *et al.* 2015). To quantitatively characterize the heterogeneity of streambed, the probability distribution was applied to describe the spatial variability of streambed hydraulic conductivity (Chen 2005; Genereux *et al.* 2008; Cheng *et al.* 2011). As is well known, the influence of multiple layered sediments on hyporheic exchange is significant (Landon *et al.* 2001). However, studies about the variability of streambed hydraulic conductivity with depth have only been mentioned by a limited number of researchers (Ryan & Boufadel 2007). Song *et al.* (2007) investigated the variations of streambed K_v with two connected depths in three rivers of Nebraska. Chen (2011) even produced K_v vertical profiles of the channel sediments to a depth of 15 m below. However, those two studies only

doi: 10.2166/nh.2015.224

dealt with the one-dimensional issue regarding spatial variability of streambed K_v. Leek *et al.* (2009) compared the spatial patterns of horizontal hydraulic conductivity (K_h) at 0.3–0.45, 0.6–0.75, 0.9–1.05, and 1.2–1.35 m depth intervals in two selected sites in Touchet River. Ryan & Boufadel (2007) introduced the probability distribution of K_h values of two depth intervals of 7.5–10 cm and 10–12.5 cm in an 80 m reach of Indian Creek in Philadelphia. However, the variability of spatial pattern in streambed K with varied depths was beyond a full understanding.

Uncertainties have existed in K_v estimation, which are partially derived from the layout of measurement locations. Leek *et al.* (2009) and Chen *et al.* (2014) underlined the huge influence of the distribution of test locations on probability distribution of K_v. Kennedy *et al.* (2008) and Genereux *et al.* (2008) also emphasized the role of sampling density in estimation of streambed attributes. Landon *et al.* (2001) even found that the method used may matter less than making sufficient measurements to characterize spatial variability adequately. To diminish the uncertainties in estimation of the K_v as much as possible, more three-dimensional (3-D) measurements carried out in a streambed are essential. The objectives of this study are to build a 3-D K_v model and to reveal the spatial characteristics within and between individual layers. The K_v values of stream channel were obtained from permeameter tests. To achieve high-resolution characterization of K_v, a total of 443 measurements in a cubic space of 8.5 m in length, 11 m in width, 0.5 m in depth were logged. Statistical analysis was used to reveal the spatial heterogeneity of streambed K_v.

STUDY AREA AND TEST SITE

The study was conducted in the Dawen River, the only tributary of the Yellow River in Shandong Province, China (Figure 1(a)). The Dawen River flows from east to west into the Dongping Lake merging with the Yellow River. The local climate is semi-humid with an average annual temperature of 12.9 °C. The monthly precipitation shows that most of the precipitation occurs from June to September, accounting for almost 80% of the total annual amount of 694.0 mm.

Field tests were performed in a reach with a straight longitudinal plan-form. The field investigation was conducted on 5–7 June 2012. Stream discharge and water level were relatively constant in the previous several months. Spatially continuous silt/clay layers were not observed in the shallow streambed. Grain-size analysis shows that channel sediments tested consisted largely of sand and gravel, with a very small amount of silt and clay. The silt and clay (particle diameter <0.075 mm) accounted only for about 2.6% of the sediments by weight. More than 70% of the weight percentages of the sediment fell into the category of sand with particle diameter between 0.075 and 2 mm. During the investigation period, the averaged width of the submerged channel was 21 m and the averaged water depth measured at test sites was 0.71 m. Amounts of invertebrates and small bubbles produced by microbes were observed in sediments of streambed. Water temperature was measured using temperature sensors when field tests were being performed and ranged from 19.87 to 28.50 °C with an average temperature of 25.23 °C. Although temperature may have effects on the estimation of K_v values, the influence of diurnal oscillation of water temperature was neglected in this paper. The groundwater was dominantly fed by stream water within the tested channel during the period of field testing (Zhu *et al.* 2013). A total of 100 test locations comprising 10 columns and 10 rows at a horizontal grid coordinate were determined covering the half part of the channel. In terms of spatial correlation range in K_v (just under 0.5 m) and complicated bed form, the grid spacing was determined to be 0.5 or 1 m along the longitudinal channel and reached a maximum of 2 m except for 0.5 or 1 m along the traverse section. In consideration of the small thickness (just under 1 m) of this hyporheic zone (Zhu *et al.* 2013), at each grid point, permeameter tests were carried out at five depths: 0.1, 0.2, 0.3, 0.4, and 0.5 m below the streambed. Consequently, a 3-D K_v model consisting of a total of 443 values was built up (Figure 1(b)).

METHODS

In-situ permeameter test

To estimate K_v of the streambed, *in-situ* permeameter test using the falling head method was used in this study. This method has many advantages, such as plug and play, low cost, short duration, and determination of hydraulic

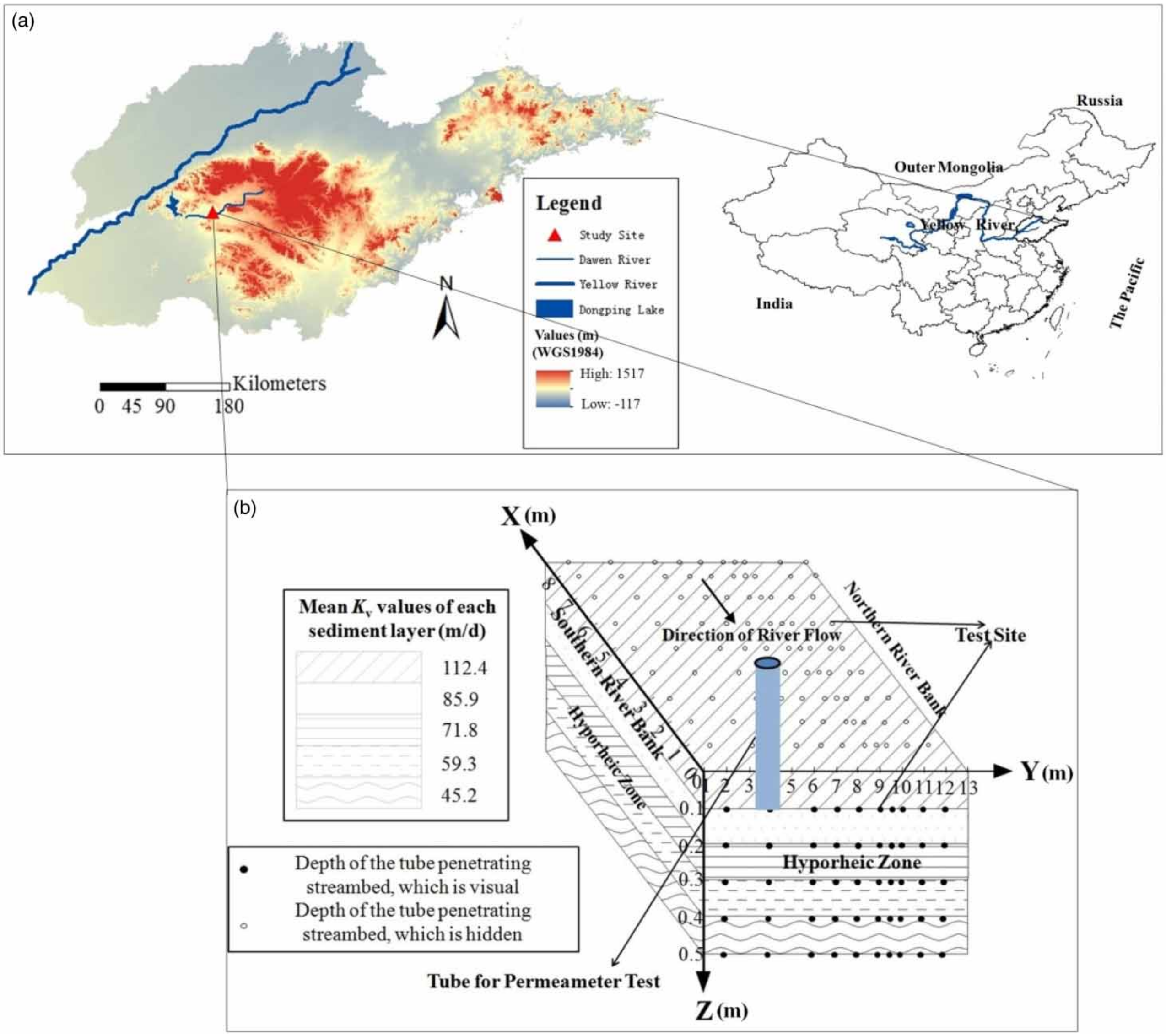

Figure 1 | Map showing the study area (a) and schematic of the layered streambed where permeameter tests were conducted (b). The term 'hyporheic zone' is used to refer to the zone beneath and adjacent to a river or stream in which groundwater and surface water mix (Environment Agency 2005).

conductivity along any direction compared to other methods, such as grain-size analysis (Landon *et al.* 2001), slug and bail tests (Leek *et al.* 2009), and pumping test (Kelly & Murdoch 2003). The principle of the permeameter test has been introduced by a number of papers (Chen 2000, 2005; Genereux *et al.* 2008; Cheng *et al.* 2011). The main procedure includes three steps: step one, inserting a standpipe into the unconsolidated sediments; step two, pouring river water to fill the pipe; step three, timing the elapsed decline of hydraulic head using a stopwatch as soon as water inside the pipe falls because of hydraulic head differences. Note that it is assumed that hydraulic head at the bottom of the sediment column is approximately equal to ambient water level that is considered to be constant during testing. The tube of permeameter is 150 cm in length and 4.5 cm in inner diameter. The wall of the tube is about 3.5 mm thick. Thus, the disturbance of the tube on surrounding sediments can be neglected when the tube is being pressed into the streambed. Water heads during each permeameter testing were recorded at least six times and the test was relatively quick (<20 min). K_v can be calculated using any pair of water head readings at a given time interval. To achieve K_v values of streambed at different depths, permeameter tests were conducted at the depth intervals of 0–10 cm, 0–20 cm, 0–30 cm, 0–40 cm, and 0–50 cm, respectively. After the permeameter testing at the depth interval of 0–10 cm was done, the tube was then pressed vertically into the sediments to a depth of 20 cm. The permeameter test was again conducted at the depth interval of 0–20 cm. The same procedure was repeated for the other three depth intervals of 0–30, 0–40, and 0–50 cm.

K_v values can be calculated using the following formula as mentioned by Hvorslev (1951)

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

where D is the inner diameter of the permeameter; m is the square root of the ratio of K_h to K_v (i.e., $m = \sqrt{K_h/K_v}$), K_h is horizontal hydraulic conductivity of the channel sediment around the base of the sediment core; L_v is the length of measured sediment column; h_1 and h_2 are hydraulic head inside the tube measured at time t_1 and t_2, respectively, since the permeameter test began.

On the basis of sedimentary structure and composition of the sediment columns tested, 1.2 can relatively be an appropriate value for m in the study area (Mutiti & Levy 2010; Lu *et al.* 2012). A non-linear regression method was applied to eliminate measurement noise and enhance the precision in the computation of K_v by taking into account all the head readings simultaneously (Chen 2005).

Calculation of K_v for five sediment layers

To capture spatial variability of K_v with depth explicitly, K_v values obtained from five sediment layers are essential. If one horizontal sediment layer with a vertical hydraulic conductivity value of K_n, consists of five parallel horizontal layers with different vertical hydraulic conductivity values ($K_1 \ldots K_5$) (Figure 2), the vertical hydraulic conductivity of the whole layer (K_n) and individual sediment layer ($K_1, \ldots K_5$) should have a relationship expressed by the following equation (Todd & Mays 2005):

$$K_n = \frac{\sum_{i=1}^{n} L_i}{\sum_{i=1}^{n} \frac{L_i}{K_i}}, (n = 2, \cdots, 5) \tag{2}$$

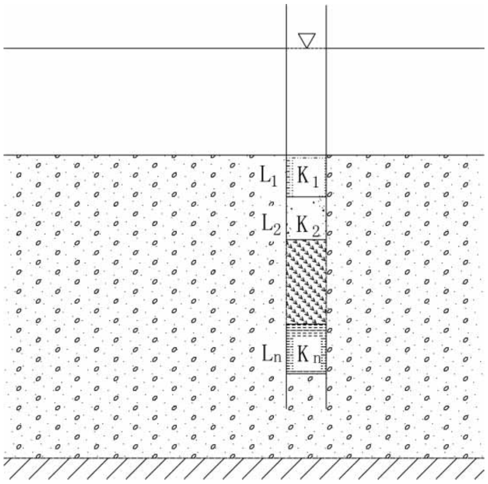

Figure 2 | Profile of the permeameter test at varied depths of the streambed sediments.

where the parameters $L_i (i = 1, \ldots, 5)$ represent the thickness of each sediment layer from the top downwards, the parameter K_n represents vertical hydraulic conductivity of the sediment layer with a thickness of $L_1 + \ldots + L_n$ and the parameters $K_i (i = 1, \ldots, 5)$ represent vertical hydraulic conductivity of each sediment layer from the top downwards. Thus, in this study, K_v values for individual depth intervals of 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, and 40–50 cm (we named them layer 1, layer 2, layer 3, layer 4, and layer 5, respectively) were calculated.

Statistical analysis

One-sample Kolmogorov–Smirnov (K-S) test was used to determine whether K_v values of each sediment layer were distributed normally or lognormally. The analysis was performed using SPSS v18.0 that returned a p value. If $p <$ 0.05, it rejects the null hypothesis that the K_v values did not belong to the normal or lognormal distribution. If $p >$ 0.05, it accepts the null hypothesis that K_v values belonged to the normal or lognormal distribution.

The non-parametric Kruskal–Wallis test and Wilcoxon rank-sum test were conducted at a significance level of 0.05. Kruskal–Wallis test is used to compare two independent samples that may have different sample sizes and to determine whether they originate from the same population; whereas Wilcoxon rank-sum test is applied to the determination of the similarity for matched pairs that are relevant. They have the same hypothesis. The null hypothesis is that the K_v values for the two layers are drawn from the same population. The hypothesis will be rejected if $p < 0.05$, or else if $p > 0.05$, the null hypothesis will be accepted.

During permeameter tests, water depth at each test location was measured to determine the correlation with streambed K_v. Correlation coefficient produced using SPSS v18.0 was considered as a representative factor to reflect how closely streambed K_v was associated with water depth, implicitly showing the influence of bedform on K_v of streambed.

RESULTS AND DISCUSSION

Statistics of K_v

The distributions of streambed K_v for the individual layers and combined layers are presented in Figure 3. The mean value was 77.3 m/d and compatible with that for similar streambed materials in other studies. Lu *et al.* (2012) reported a mean value of 84.5 m/d for the four tributaries of the Platter River Basin. Genereux *et al.* (2008) showed that the mean of a sandy reach of a North Carolina stream was 16 m/d. However, these data collected from the tributary channel were significantly different from the K_v values consistently less than 1.0 m/d for main-stem channel of the lower reaches of the Yellow River (Shu *et al.* 2007). The Dongping Lake occurs at the confluence of the main stream of the Yellow River and the Dawen River, reducing the amount of coarse-grained sediments transported to the Yellow River, which partially lowers streambed K_v values of lower reaches of the Yellow River. A wide variation range of hydraulic conductivity values was frequently observed in the streambed. Values from the Platter River reported by Chen (2005) were predominantly in the range of 3–65 m/d. Cardenas & Zlotnik (2003) reported values in the range of 0.15–74.5 m/d for Prairie Creek, a sand bed stream in central Nebraska. Neverthless, compared to other streams, this study channel had a greater variation range of 0.1–479 m/d, reflecting the greater heterogeneity of streambed. The mean for the first sediment layer was 112.4 m/d, which indirectly indicated the absence of a thin, continual fine-grained deposition layer commonly occurring on the surface of streambed (Min *et al.* 2013). Song *et al.* (2007) and Chen (2011) also did not find the colmation phenomenon in their individual study sites.

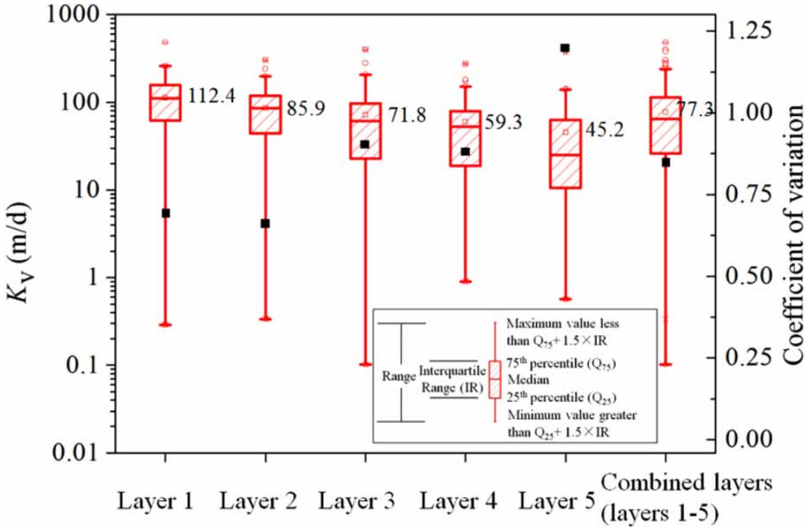

Figure 3 | Box plots of K_V values from individual layers (layers 1–5) and combined layers (layers 1–5) during the investigation period. □ indicates the mean, - the 1st or 99th percentile, × the minimum or maximum, and ○ the outliers. Note that ■ stands for coefficient of variation of each sediment depth interval.

Spatial variability of K_v in horizontal dimension

Contour plots of K_v for each sediment layer were generated by origin 8.0 using kriging interpolation method (Figure 4), showing the distributions of K_v at different depth intervals. It can be detected from Figure 4 that K_v values varied greatly in space. The remarkable contrast of K_v at the NW (north west) corner for layers 1 and 2 in Figure 4 revealed that the K_v values varied substantially within a vertical distance of 10 cm.

Spatial variability of K_v is closely related to bedform. Many papers (Chen 2005; Genereux *et al.* 2008) reported that the K_v values at the center of the channel are usually higher than the values close to the river bank. There is higher flow velocity in the middle of the channel than in the areas close to the river bank. A larger K_v value more probably occurs in high-flow condition of the midstream, since fine-grained sediments can be washed away, then deposit in low-flow condition of the river bank (Chen 2005). Lu *et al.* (2012) and Min *et al.* (2013) also reported the positive correlation between K_v values and bedform, although the correlation between them was not very significant. In this study, correlation analysis for water depth and K_v values of different layers was made, which returned correlation coefficients determining how great the influence of bed forms was on streambed K_v. The correlation coefficient for the 0–10 cm depth interval (layer 1) was 0.385 at the significance level of 0.01. Chen (2005) reported similar correlation coefficients for the 0–40 cm depth interval, which varied from one place to another. However, the correlations between water depth and the K_v values for layers 4 and 5 were considerably weak, even significantly negative for layers 2 and 3. This unique phenomenon was probably caused by the complicated flow condition, special geographical features, or occurrence of outliers for the K_v values, as Chen (2005) said that the correlation between the two variables may not be perfect. Figure 4 shows that the spatial pattern in K_v for layer 1 had the greatest difference from other layers. The sediments of layers 2–5 likely deposited in the previous flow conditions leading to a poor correlation, although stream discharge and water table remained relatively unchanged in the preceding months. A scatter diagram is used to illustrate the significantly positive correlation for layer 1 and poor

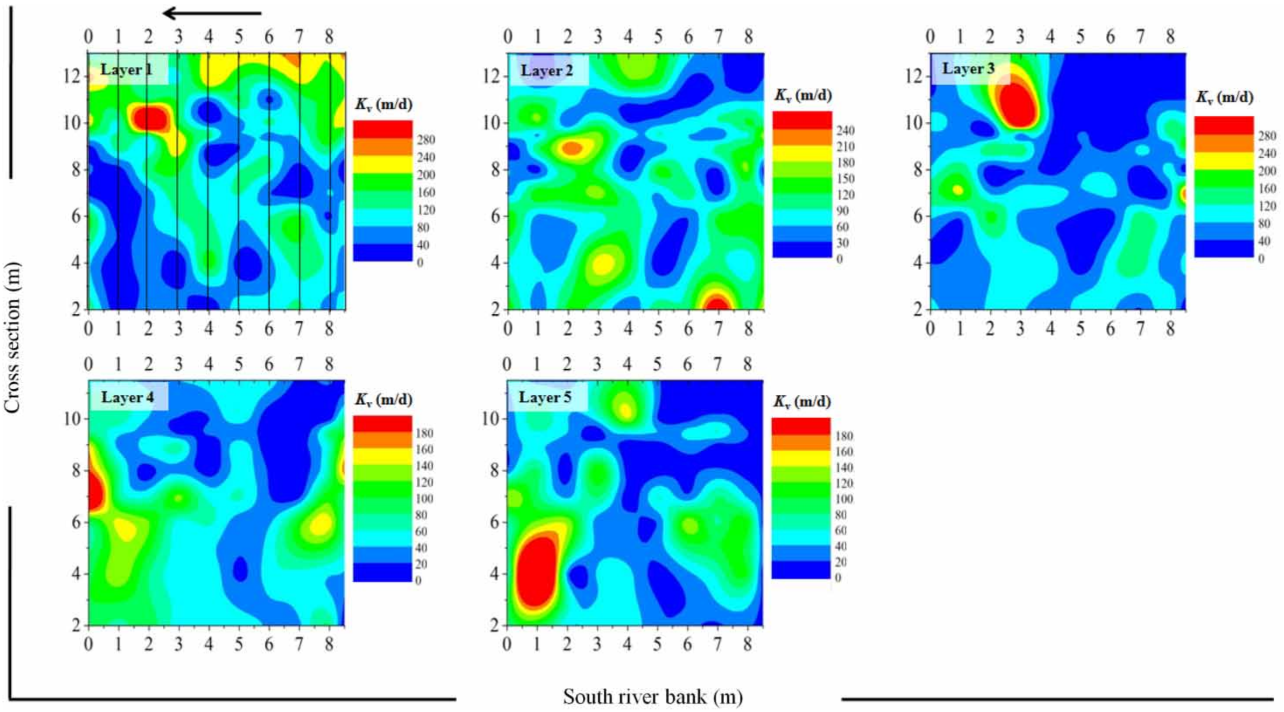

Figure 4 | Interpolated map of K_v values from individual layers (layers 1–5). The arrow points downstream. The black lines in layer 1 are grid lines along the cross section.

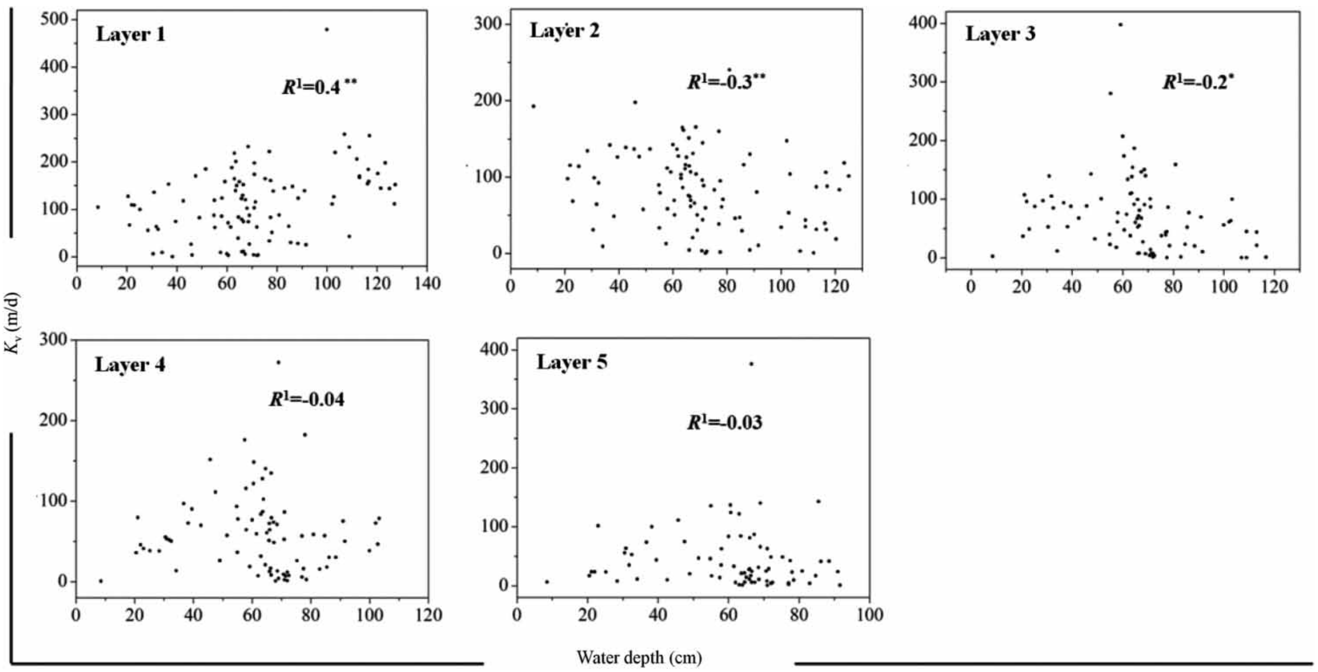

Figure 5 | Bivariate plots showing the relationship between water depth and K_v values from individual layers (layers 1–5). *R* indicates the coefficient of correlation and ^{1} Pearson correlation coefficient; ** and * represent the significance level of 0.01 and 0.05, respectively.

correlations for layers 2–5 (Figure 5). It can be found from Figure 4 that the larger K_v values for layer 1 more likely appeared in the midstream and the smaller K_v values at the sides of the channel, whereas the large K_v values for layers 2–5 possibly occurred at either the banks or the midstream, as did the low K_v values. In addition, although the variation showed an increasing trend from the south bank, no apparent pattern of variation in mean and median K_v values across the stream channel was found for combined K_v values of layers 1–5 (Figure 6). Therefore, bedform was sensitive to streambed K_v values in the vertical dimension and the correlation of K_v values with water depth was restrained near the streambed surface (approximately 10 cm below the streambed surface). Min *et al.* (2013) found that the patterns of variability in K_v differed greatly between transects a dozen kilometers apart; the difference was probably because the sediments tested at these sites experienced completely different hydraulic dynamic processes. However, in this study, spatial patterns in K_v at transects across the channel were almost in accord with each other (Figure 7). It can be concluded that the spatial variability of K_v across the stream nearly stayed consistent within a distance of 10 m along this study reach.

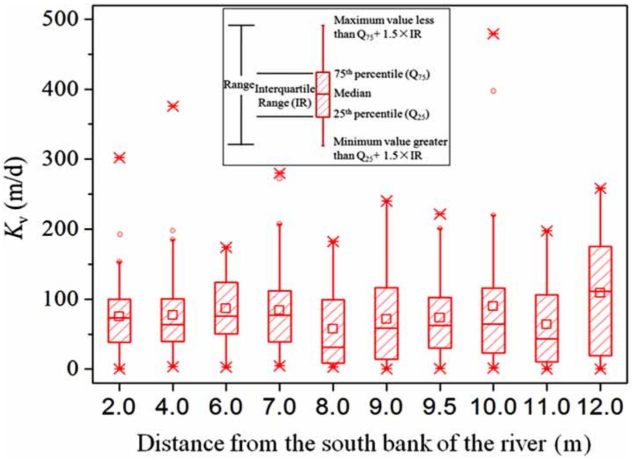

Figure 6 | Boxplots of combined K_v values of layers 1–5 with the distance from the south bank.

Spatial variability of K_v in vertical dimension

A gradual decreased trend of the mean and median K_v values from the top to the bottom is presented in Figure 3. The pattern in K_v with depth in this study agreed well with the results from Song *et al.* (2007) and Ryan & Boufadel (2007). Chen (2011) even thought that the channel surface of

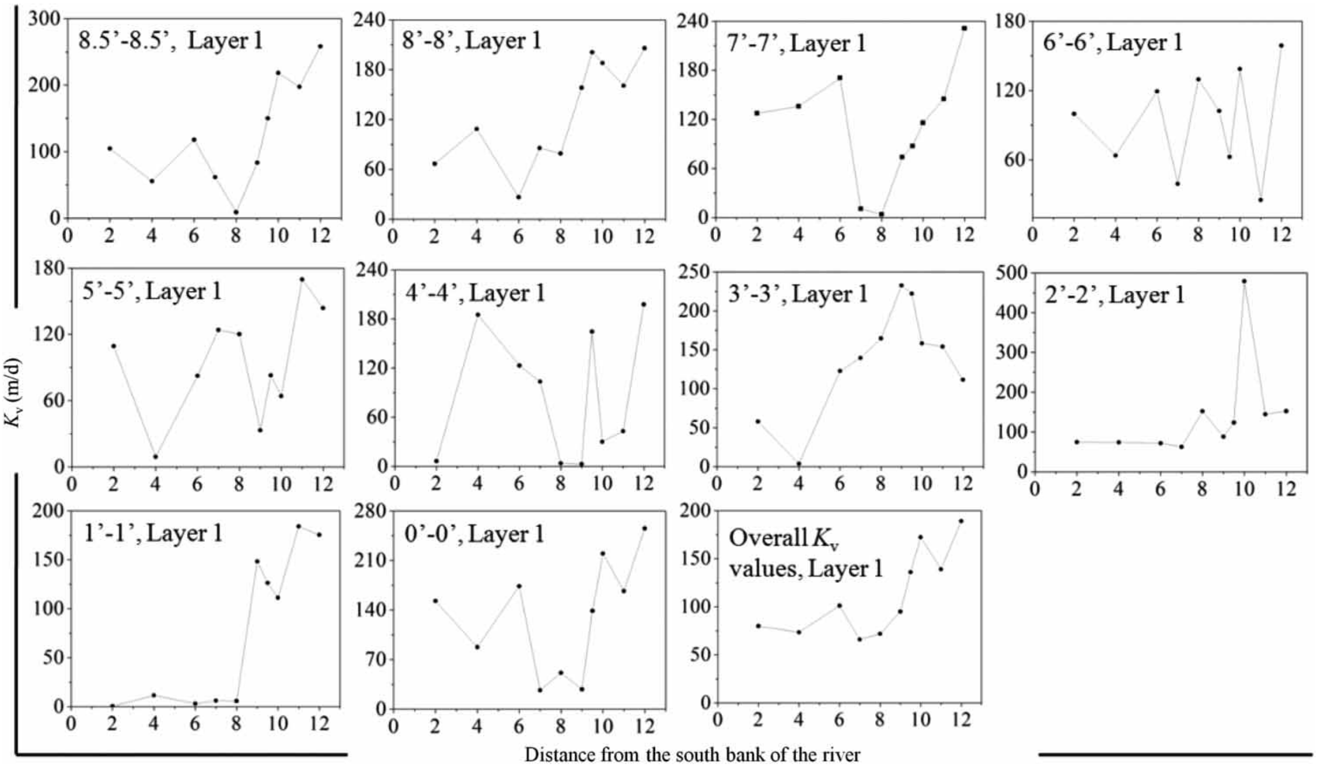

Figure 7 | Broken line chart of K_v values for individual lines from the upstream (8.5′–8.5′) to the downstream (0′–0′) (as shown in Figure 4) across the channel for the first layer.

the Platte River Valley of Nebraska was the most permeable. The mean K_v value of layer 1 was two to three times greater than that of layer 5; the difference even reached four to five times for the median K_v values (Figure 3). Thus, the K_v values decreased with depth greatly even in the 0–50 cm depth interval of streambed. The smaller K_v values in the lower layer were partially attributed to the compression due to overlying burying. In addition, invertebrate activities, water exchange, and the upward movement of gas contributed to the higher K_v in the upper layers (Song *et al.* 2007; Chen 2011). Nowinski *et al.* (2011) investigated the evolution of hydraulic conductivity in the floodplain of a meandering river using particle tracking and found an impact of hyporheic transport of fine materials on the distribution of hydraulic conductivity. Chen (2011) proposed that fine-grained sediments carried by hyporheic water could arrive at a deeper part, of several meters, altering K_v distribution. Suspended sediments deposited in streambeds from the bottom upward (Brunke 1999) and the relatively small-sized particles in shallower streambeds were more readily suspended again and flushed away as well. The histograms reflected that the dominance of small values less than 20 m/d almost increased with depth (Figure 8). Therefore, the content of fine-grained particles tended to increase with depth; these fine materials filled the voids in coarse sediments, consequently lowering the K_v in the lower part of streambeds.

Coefficients of variation were given to determine the variability of K_v for each depth interval (Figure 3). The mean values for layers 1 and 2 were almost equal to the median values, but those for layers 3–5 exceeded the corresponding median values; the mean for layer 5 approached near the 75th percentile indicating large variability in K_v and the statistical effect of the few largest values. There was an increasing trend in heterogeneity of K_v with depth (Figure 3). Ryan & Boufadel (2007) investigated the heterogeneity of K_h from two layers and also found the increasing trend with depth.

In this study, probability–probability (P-P) plots were used to determine whether the distribution of the sediment K_v values matched the normal distribution or the lognormal distribution which has been widely documented in many

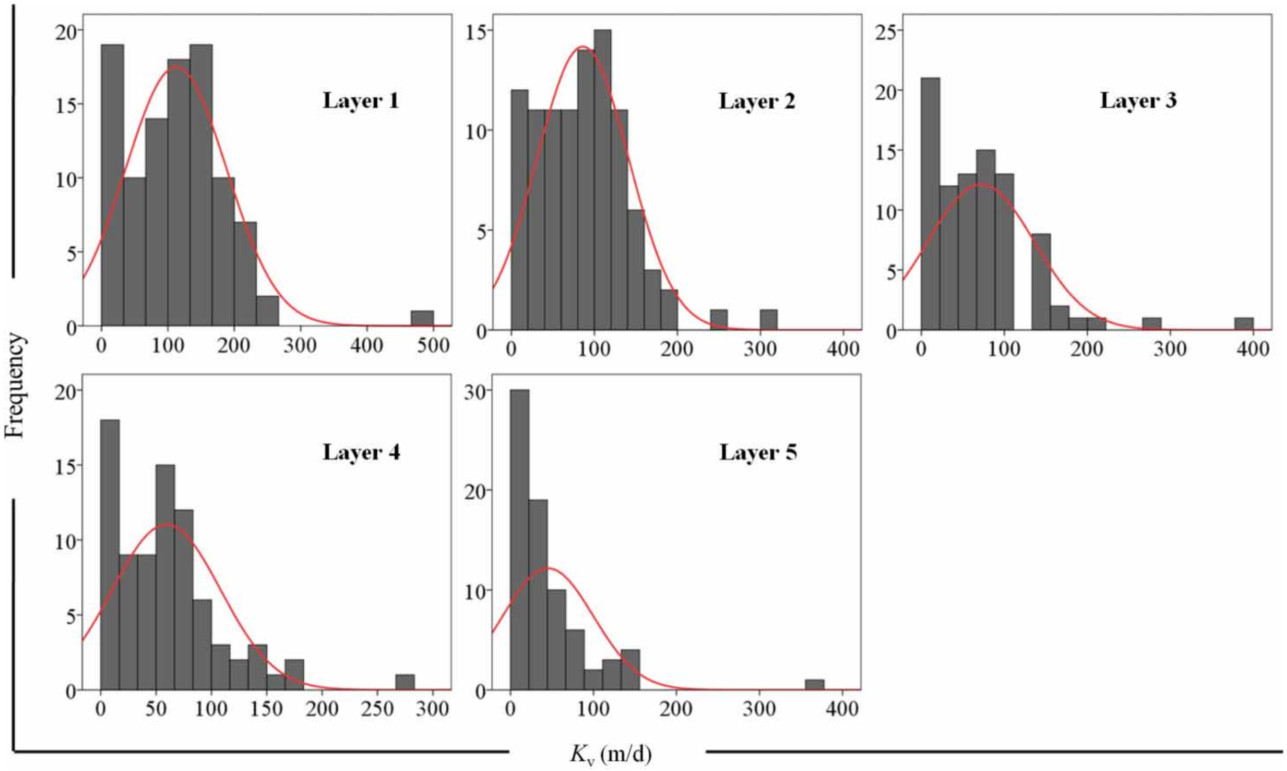

Figure 8 | Histograms of K_v values from individual layers (layers 1–5).

studies (Cheng *et al.* 2011; Chen *et al.* 2014). If the points cluster around a straight line in P-P plots, the sediment K_v values follow the corresponding distribution. One sample K-S test was also applied to the determination of normality of K_v values. P-P tests and K-S tests (Figure 9 and Table 1) all suggest that K_v values of each layer belonged to the

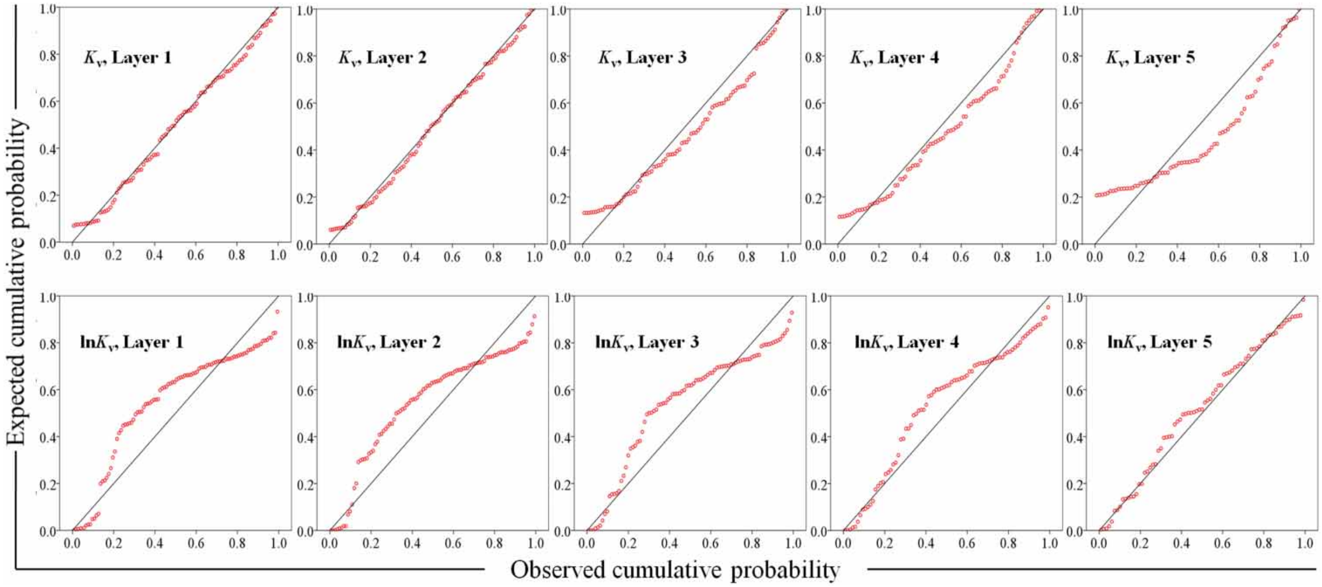

Figure 9 | Probability plots of K_v and lnK_v from individual layers (layers 1–5).

Table 1 | *P* values from one-sample Kolmogorov–Smirnov test of K_v and $\ln K_v$ from individual layers (layers 1–5)

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
K_v	0.7*	0.9*	0.1*	0.2*	0.003
$\ln K_v$	0	0.003	0.001	0.025	0.5*

*For the significance level of 0.05.

normal distribution for layers 1–4 (*P* for K_v ranging from 0.1 to 0.9 and *P* for $\ln K_v$ ranging from 0.001 to 0.025) whereas they were in the lognormal distribution for layer 5 (*P* for $K_v = 0.003$ and *P* for $\ln K_v = 0.5$). The histogram (Figure 8) shows that K_v values of each layer for layers 1–4 approached near the normal distribution. Ryan & Boufadel (2007) and Chen *et al.* (2014) gave a similar probability distribution between layers. However, our results differed from theirs. Layer 5 had a different probability distribution from layers 1 to 4; the difference was probably attributed to intrusion of fine materials, leading to larger heterogeneity of streambed K_v for layer 5. However, when the streambed K_v values of each layer for the upper four layers were combined as a single data set, the K_v values were distributed neither normally nor lognormally. This implicitly suggested that the K_v values of individual layers for layers 1–4 did not come from the same population. If the K_v values less than 1.0 m/d were eliminated from the sample, the combined K_v values of layers 1–4 belonged to the normal distribution. It can be inferred that fine sediments played an important role in the determination of probability distribution of streambed K_v. The box plots (Figure 3) and the cumulative frequency distribution plots (Figure 10) consistently show that the K_v values for layers 1–5 were statistically different in terms of their cumulative frequency distribution, and both the mean and median of K_v for the upper layer were higher. Kruskal–Wallis test (*P* ranging from <0.001 to 0.02 except for $P = 0.2$) suggests that there were significant differences in K_v between individual layers except for layers 3 and 4; there was a relatively closer relationship in cumulative frequency distribution between layer 3 and 4 (Figure 8 and Table 2). As well, Wilcoxon rank-sum test (*P* ranging from <0.001 to 0.006) shows that great differences in K_v occurred in mean for any pair of layers. Leek *et al.* (2009) noticed that K_h for the 0.3–0.45 m depth interval differed statistically from those at other depth intervals, but other than that no significant difference existed between individual depth intervals. Figure 10 illustrates that the difference probably became greater when the distance between two layers was larger. The contour plots (Figure 4) further indicated that spatial pattern in K_v varied among different layers. Leek *et al.* (2009) alike found the variation of spatial pattern with depth. Therefore, it can be assumed that the sediments of the five layers have been formed under different flow conditions. In addition, the fine materials carried by hyporheic water deposited in sediments disproportionately altered the streambed K_v. This post-sedimentation process also contributed to a reduction of K_v values and an increase of heterogeneity. Consequently, the fiver layers should be treated as separate entities. It is noted that, to obtain a better characterization of streambed, a collection of K_v values from different layers is essential.

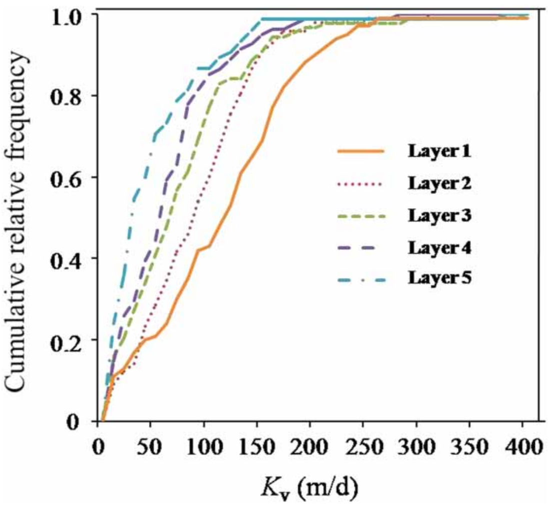

Figure 10 | Empirical cumulative distribution of K_v values from individual layers (layers 1–5).

SUMMARY AND CONCLUSIONS

The study site was located in a reach of the Dawen River, China. *In-situ* falling head standpipe tests were carried out in channel for the achievement of 3-D K_v model comprising 10 lines × 10 rows × 5 layers. The correlation analysis of K_v values for individual layers with water depth was performed. The statistical analysis of K_v values obtained was made to

Table 2 | *P* values from the Kruskal–Wallis test and Wilcoxon rank-sum test of K_v values between any pair of layers

		1 vs. 2	1 vs. 3	1 vs. 4	1 vs. 5	2 vs. 3	2 vs. 4	2 vs. 5	3 vs. 4	3 vs. 5	4 vs. 5
P-value	Kruskal–Wallis	0.01	<0.001	<0.001	<0.001	0.02	<0.001	<0.001	0.2*	0.001	0.01
	Wilcoxon rank-sum	0.004	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	0.006	<0.001	0.002

*The similarity is statistically significant ($P > 0.05$). The number *i* ($i = 1,\ldots,5$) represents the *i*th layer.

reveal the spatial distribution of streambed K_v under horizontal and vertical dimensions, simultaneously. The following conclusions were drawn:

1. The sediments primarily consisted of sand/gravel, with a small amount of silt/clay. No colmation occurred at the surface of the streambed. As a tributary of the Yellow River, the Dawen River has distinctly different streambed sediment K_v values up to two orders of magnitude greater than the lower reach of the Yellow River. This study reach had a high degree of spatial variability.
2. The correlation between K_v values and water depth was significantly positive for layer 1 whereas that was not the case for layers 2–5. Thus, the influence of bedform on K_v values was restricted to the near-surface streambed (0–10 cm depth interval) although stream discharge and water level remained smooth in the last few months. For layer 1, spatial patterns in K_v at transects across the channel remained almost unchanged within a distance of about 10 m along the channel; K_v had an increasing trend with the distance from the river bank. As well, the variation of K_v was larger at the midstream than the bank sides.
3. Mean and median K_v values decreased with depth in the shallow streambed; on the contrary, heterogeneity of K_v tended to increase with depth. The intrusion of fine materials contributed to larger heterogeneity in K_v for the lower layer. The histograms, P-P plots, and K-S test all suggest that the K_v values of each layer belonged to the normal distribution for layers 1–4 and those for layer 5 tended to be distributed lognormally. When the K_v values of layers 1–4 were combined as a single data set, the assembled data set did not belong to the normal/lognormal distribution. However, the combined data set from which the values less than 1.0 m/d were removed belonged to the normal distribution. Therefore, fine-grained materials carried by hyporheic exchange strongly affected the spatial distribution of K_v with depth. In addition, similarity analysis suggests that the K_v values of individual layers came from different populations; the sediments of each layer were formed under different sedimentation environments. This phenomenon was primarily attributed to the coupling of erosion/deposition process and transport of fine materials. It is noted that, to better capture spatial heterogeneity of streambeds and hyporheic exchange, a collection of K_v values should depend on measurement points at different depths.

ACKNOWLEDGEMENTS

This research was supported by the National Natural Science Foundation of China (41201029), Specialized Research Fund for the Doctoral Program of Higher Education of China (20120094120019), Fundamental Research Funds for the Central Universities of China (2012B00314), and China Postdoctoral Science Foundation (2013M540410).

REFERENCES

Brunke, M. 1999 Colmation and depth filtration within streambeds: retention of particles in hyporheic interstices. *Int. Rev. Hydrobiol.* **84**, 99–117.

Cardenas, M. B. & Zlotnik, V. A. 2003 Three-dimensional model of modern channel bend deposits. *Water Resour. Res.* **39**, 1141, doi:10.1029/2002WR001383.

Chen, X. H. 2000 Measurement of streambed hydraulic conductivity and its anisotropy. *Environ. Geol.* **39**, 1317–1324.

Chen, X. H. 2005 Statistical and geostatistical features of streambed hydraulic conductivity in the Platte River, Nebraska. *Environ. Geol.* **48**, 693–701.

Chen, X. H. 2011 Depth-dependent hydraulic conductivity distribution patterns of a streambed. *Hydrol. Process.* **25**, 278–287.

Chen, X. H. & Shu, L. C. 2002 Stream-aquifer interactions: evaluation of depletion volume and residual effects from ground water pumping. *Ground Water* **40**, 284–290.

Chen, X. H., Mi, H. C., He, H. M., Liu, R. C., Gao, M., Huo, A. D. & Cheng, D. H. 2014 Hydraulic conductivity variation within and between layers of a high floodplain profile. *J. Hydrol.* **515**, 147–155.

Cheng, C., Song, J. X., Chen, X. H. & Wang, D. M. 2011 Statistical distribution of streambed vertical hydraulic conductivity along the Platte River, Nebraska. *Water Resour. Res.* **25**, 265–285.

Environment Agency. 2005 *Groundwater-surface water interactions in the hyporheic zone*. Environment Agency, Bristol. www.environment-agency.gov.uk.

Genereux, D. P., Leahy, S., Mitasova, H. & Kennedy, C. D. 2008 Spatial and temporal variability of streambed hydraulic conductivity in West Bear Creek, North Carolina, USA. *J. Hydrol.* **358**, 332–353.

Hvorslev, M. J. 1951 Time lag and soil permeability in groundwater investigation. *US Army Corps Eng. Water. Exp. Station Bull.* **36**, 1–50.

Kelly, S. E. & Murdoch, L. C. 2003 Measuring the hydraulic conductivity of shallow submerged sediments. *Ground Water* **41**, 431–439.

Kennedy, C. D., Genereux, D. P., Mitasova, H., Corbett, D. R. & Leahy, S. 2008 Effect of sampling density and design on estimation of streambed attributes. *J. Hydrol.* **355**, 164–168.

Landon, M. K., Rus, D. L. & Harvey, F. E. 2001 Comparison of instream methods for measuring hydraulic conductivity in sandy streambeds. *Ground Water* **39**, 870–885.

Leek, R., Wu, J. Q., Wang, L. & Hanrahan, T. P. 2009 Heterogeneous characteristics of streambed saturated hydraulic conductivity of the Touchet River, south eastern Washington, USA. *Hydrol. Process.* **23**, 1236–1246.

Lu, C. P., Shu, L. C. & Chen, X. H. 2012 Numerical analysis of the impacts of bedform on hyporheic exchange. *Adv. Water Sci.* **23**, 789–795 (in Chinese).

Min, L. L., Yu, J. J., Liu, C. M., Zhu, J. T. & Wang, P. 2013 The spatial variability of streambed vertical hydraulic conductivity in an intermittent river, northwestern China. *Environ. Earth Sci.* **69**, 873–883.

Mutiti, S. & Levy, J. 2010 Using temperature modeling to investigate the temporal variability of riverbed hydraulic conductivity during storm events. *J. Hydrol.* **388**, 321–333.

Nowinski, J. D., Cardenas, M. B. & Lightbody, A. F. 2011 Evolution of hydraulic conductivity in the floodplain of a meandering river due to hyporheic transport of fine materials. *Geophys. Res. Lett.* **38**, L01401.

Ryan, R. J. & Boufadel, M. C. 2007 Evaluation of streambed hydraulic conductivity heterogeneity in an urban watershed. *Stoch. Environ. Res. Risk Assess.* **21**, 309–316.

Salehin, M., Packman, A. & Paradis, M. 2004 Hyporheic exchange with heterogeneous streambeds: laboratory experiments and modeling. *Water Resour. Res.* **40**, W11504, doi:10.1029/2003WR002567.

Sebok, E., Duque, C., Engesgaard, P. & Boegh, E. 2015 Spatial variability in streambed hydraulic conductivity of contrasting stream morphologies: channel bend and straight channel. *Hydrol. Proc.* **29**, 458–472.

Shu, L. C., Wang, Z. H., Basil, I. O., Wang, L., Hao, Z. C., Wang, Y. M., Wang, M. M., Liu, B. & Li, W. 2007 Determination methods for streambed hydraulic conductivity in the lower reach of the Yellow River. *Int. Symp. Methodol. Hydrol.* **311**, 594–599.

Song, J. X., Chen, X. H., Cheng, C., Summerside, S. & Wen, F. J. 2007 Effects of hyporheic processes on streambed vertical hydraulic conductivity in three rivers of Nebraska. *Geophys. Res. Lett.* **34**, L07409.

Todd, D. K. & Mays, L. W. 2005 *Groundwater Hydrology*, 3rd edn. John Wiley and Sons, New York.

Zhu, J. S., Shu, L. C. & Lu, C. P. 2013 Study of heterogeneity characteristics of vertical hyporheic flux using a heat tracing method. *J. Hydraul. Eng.* **44**, 818–825 (in Chinese).

First received 11 December 2014; accepted in revised form 13 March 2015. Available online 15 April 2015