

# 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

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## 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

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.

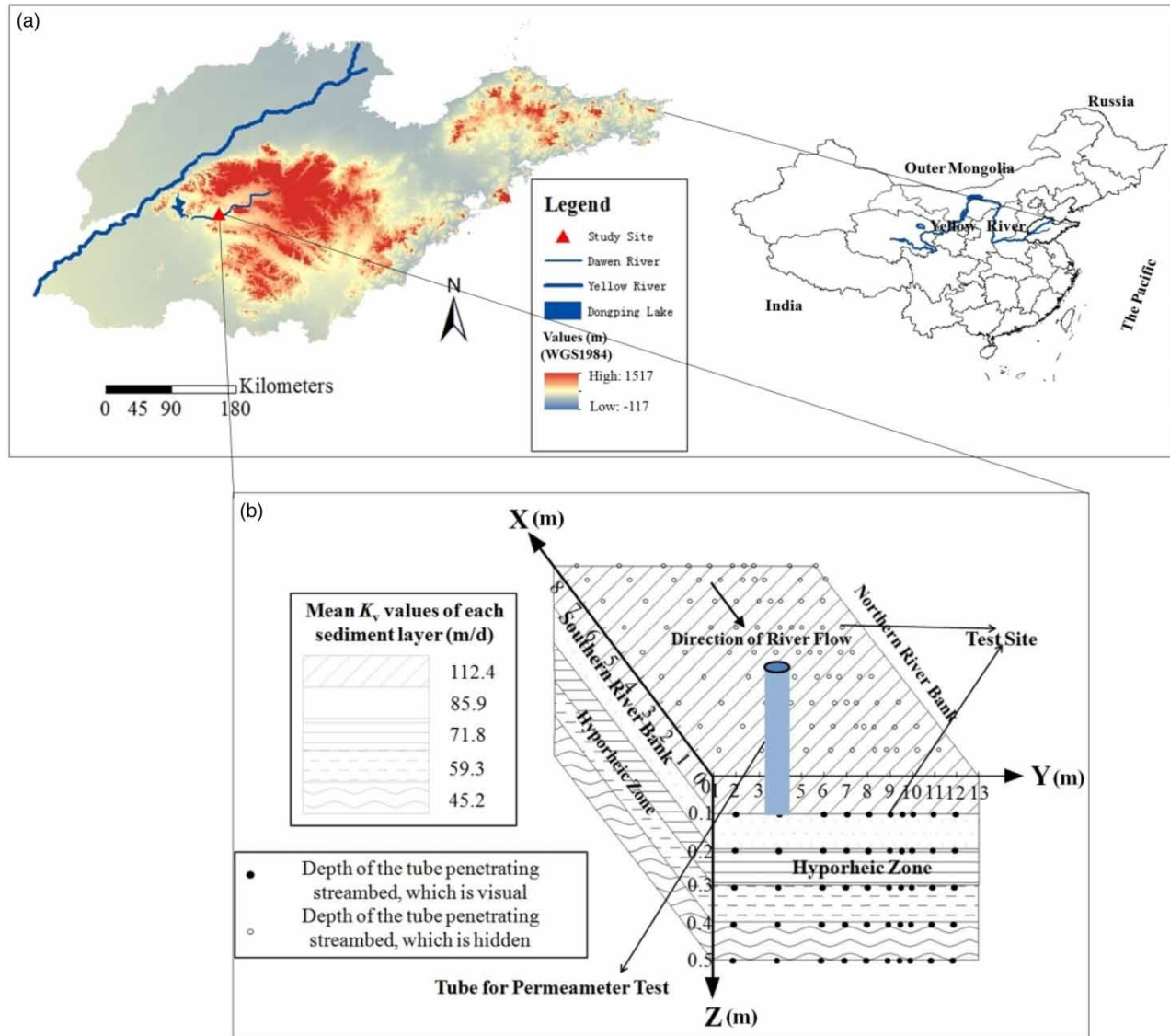
Field tests were performed in a reach with a straight longitudinal plan-form. The field investigation was conducted on

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)

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

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 ( $K_1 \dots K_5$ ) (Figure 2), the vertical hydraulic conductivity of the whole layer ( $K_n$ ) and individual sediment layer ( $K_1, \dots K_5$ ) should have a relationship expressed by the following equation (Todd & Mays 2005):

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

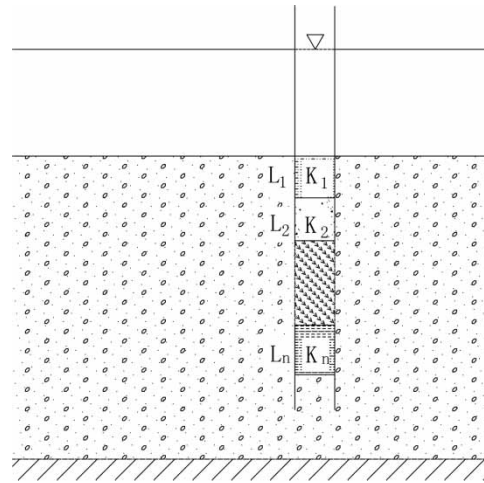


Figure 2 | Profile of the permeameter test at varied depths of the streambed sediments.

where the parameters  $L_i$  ( $i = 1, \dots, 5$ ) 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  $L_1 + \dots + L_n$  and the parameters  $K_i$  ( $i = 1, \dots, 5$ ) 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.

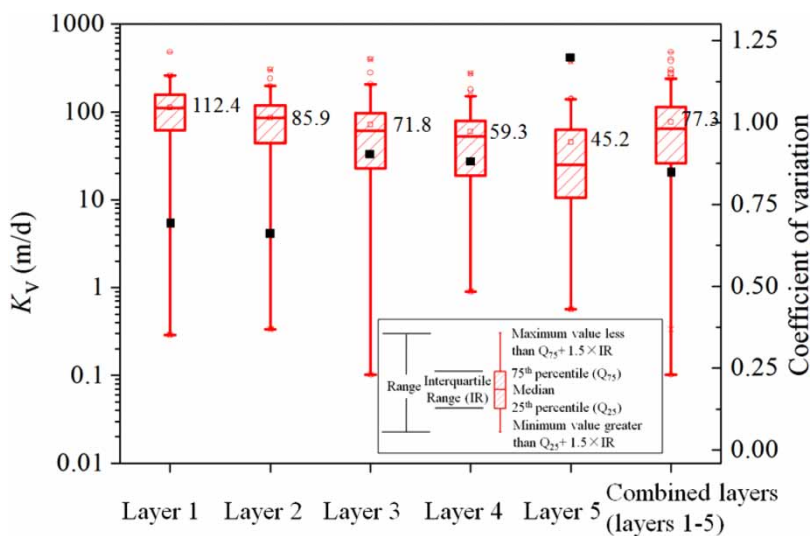
During permeameter tests, water depth at each test location was measured to determine the correlation with streambed  $K_v$ . Correlation coefficient produced using SPSS v18.0 was considered as a representative factor to reflect how closely streambed  $K_v$  was associated with water depth, implicitly 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. Nevertheless, 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.  $\square$  indicates the mean,  $-$  the 1st or 99th percentile,  $\times$  the minimum or maximum, and  $\circ$  the outliers. Note that  $\blacksquare$  stands for coefficient of variation of each sediment depth interval.

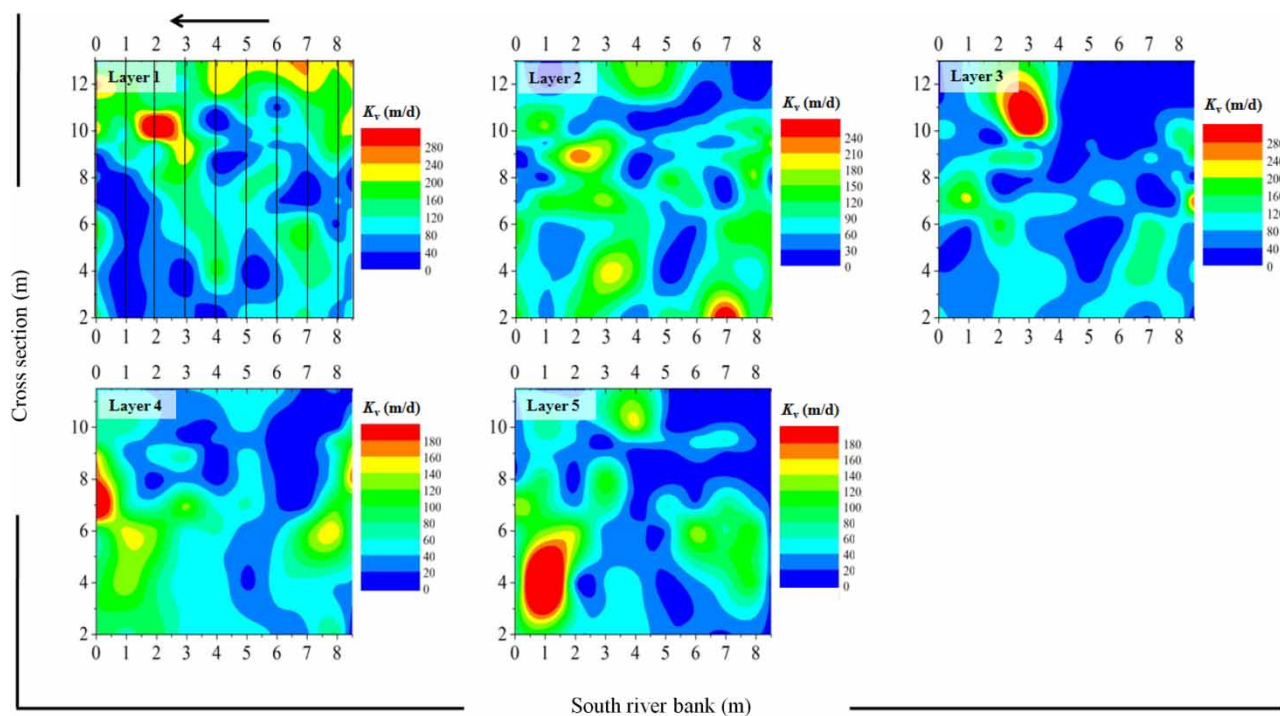


### Spatial variability of $K_v$ in horizontal dimension

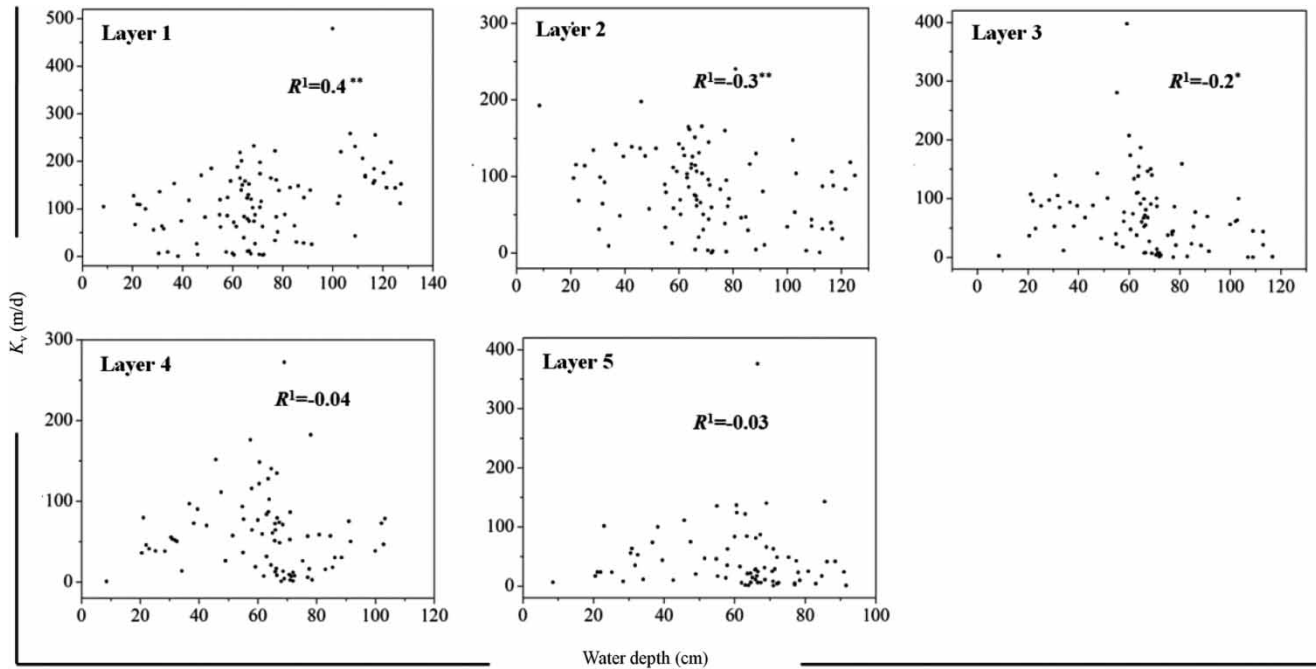
Contour plots of  $K_v$  for each sediment layer were generated by origin 8.0 using kriging interpolation method (Figure 4), showing the distributions of  $K_v$  at different depth intervals. It can be detected from Figure 4 that  $K_v$  values varied greatly in space. The remarkable contrast of  $K_v$  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

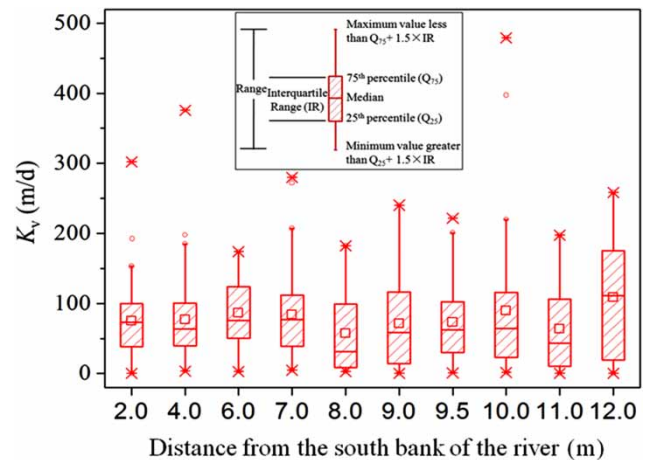


**Figure 4** | Interpolated map of  $K_v$  values from individual layers (layers 1–5). The arrow points downstream. The black lines in layer 1 are grid lines along the cross section.



**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.

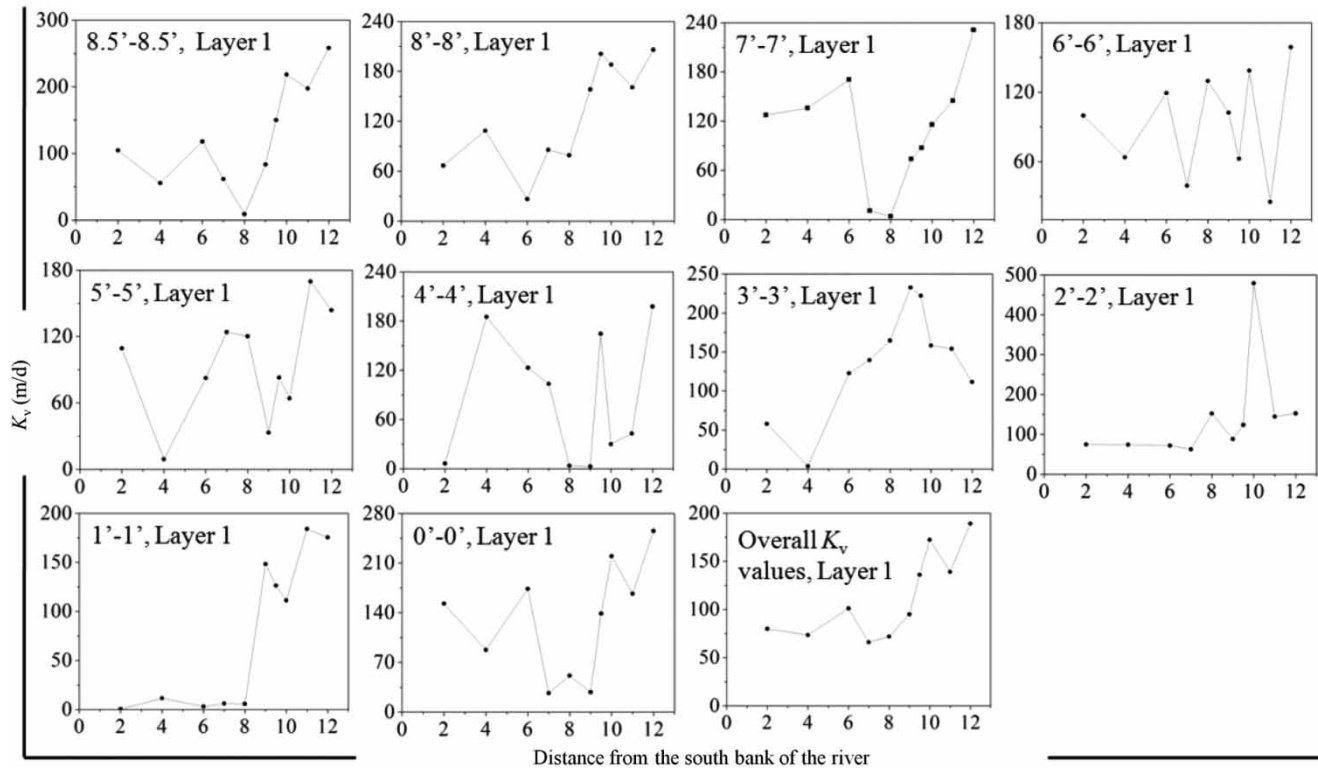
correlations for layers 2–5 (Figure 5). It can be found from Figure 4 that the larger  $K_v$  values for layer 1 more likely appeared in the midstream and the smaller  $K_v$  values at the sides of the channel, whereas the large  $K_v$  values for layers 2–5 possibly occurred at either the banks or the 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.

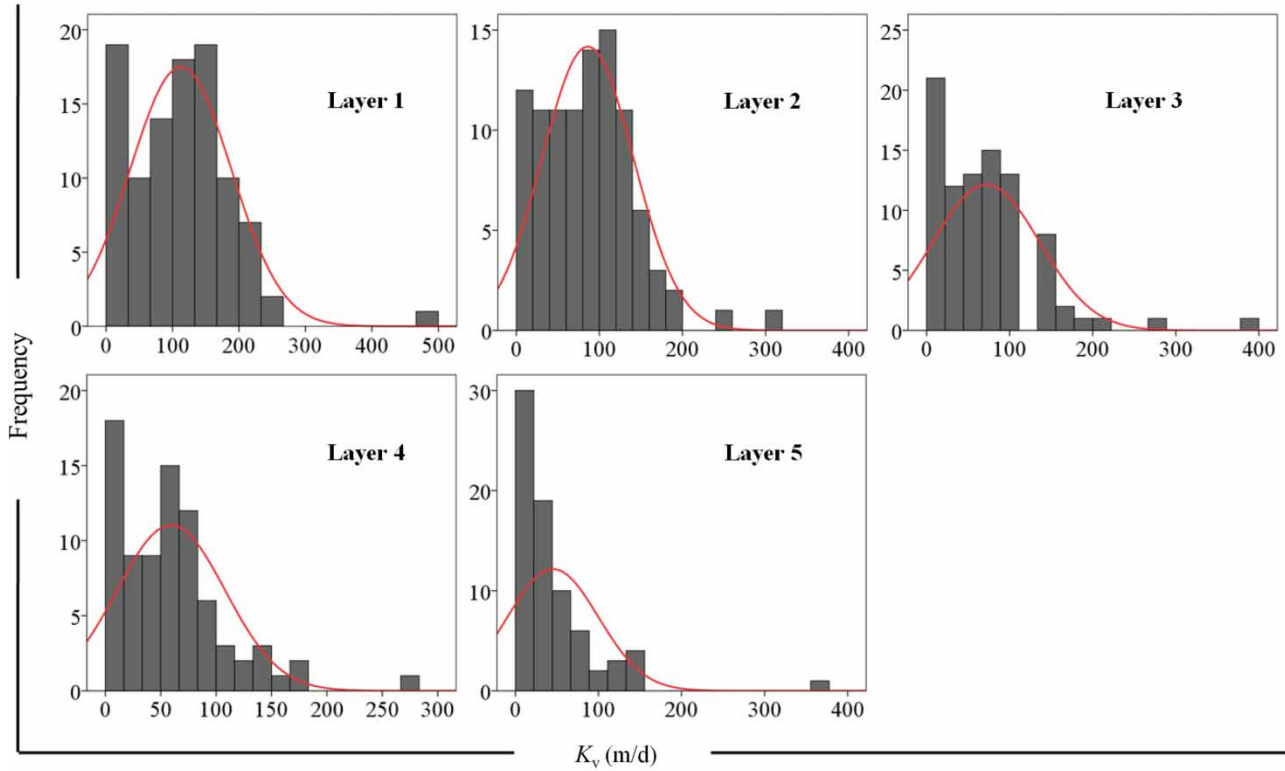
the Platte River Valley of Nebraska was the most permeable. The mean  $K_v$  value of layer 1 was two to three times greater than that of layer 5; the difference even reached four to five times for the median  $K_v$  values (Figure 3). Thus, the  $K_v$  values decreased with depth greatly even in the 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

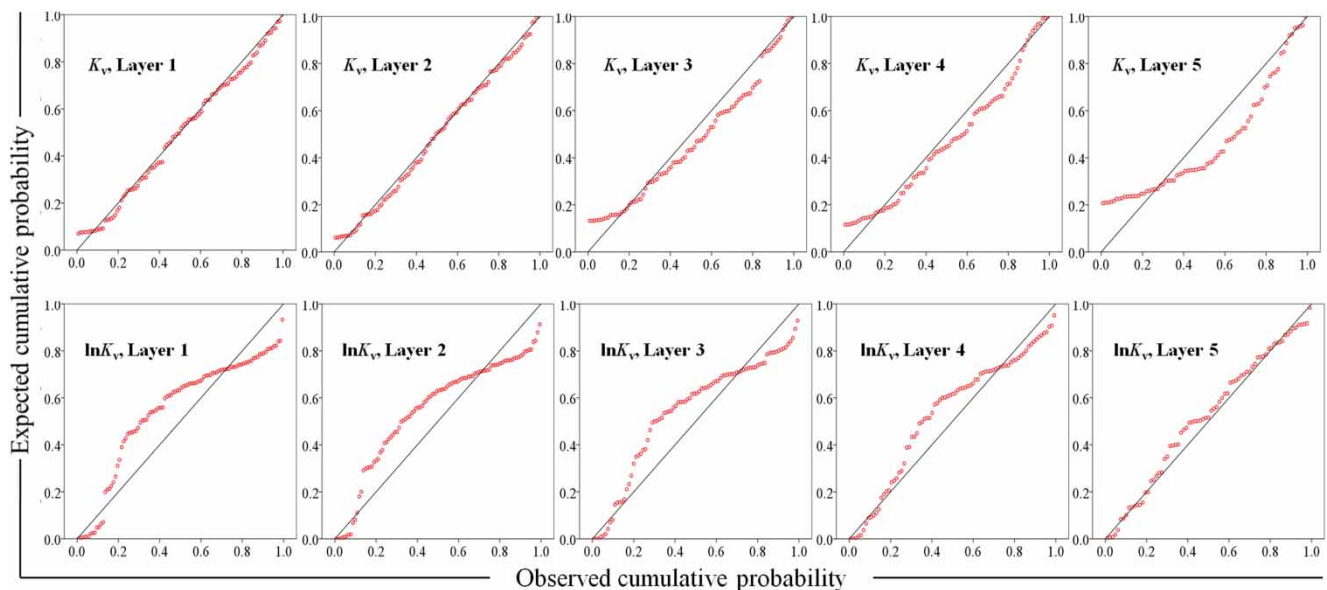




**Figure 8** | Histograms of  $K_v$  values from individual layers (layers 1–5).

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



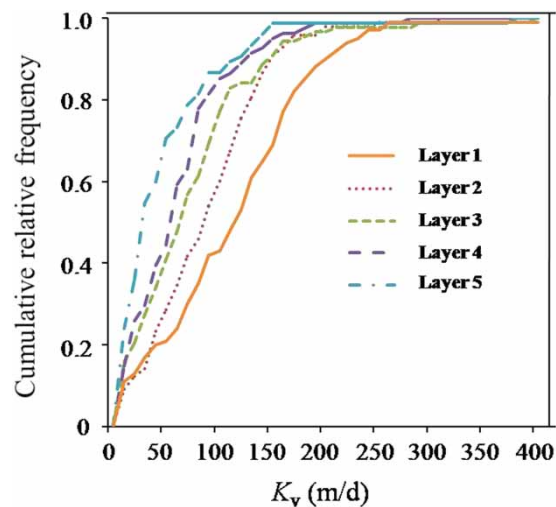
**Figure 9** | Probability plots of  $K_v$  and  $\ln K_v$  from individual layers (layers 1–5).

**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

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

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 five 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.

## 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  $\times$  10 rows  $\times$  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
<i>P</i> -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  $i$  ( $i = 1, \dots, 5$ ) 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.

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