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Statistical Distribution of Streambed Vertical Hydraulic Conductivity along the Platte River, Nebraska

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Abstract
Streambed vertical hydraulic conductivity (K_v) plays an important role in understanding and quantifying the stream–aquifer interactions. While several researchers have discussed the spatial variability of streambed horizontal hydraulic conductivity or K_v at one or several close-located sites in a river, they did not develop any statistical distribution analysis of streambed K_v at distant sites along a large river. In this paper, the statistical distribution and spatial variation of streambed K_v at 18 test sites in a 300-km reach of the Platte River in Nebraska are presented. Insitu permeameter tests using the falling-head method were carried out to calculate the streambed K_v values. Fine-grained sediments transported by two tributaries, the Loup River and the Elkhorn River, to the Platte River appear to result in lower streambed K_v values downstream of the confluences between the Platte River and the tributaries. The streambed K_v values were found to be normally distributed at nearly each test site. When the correlated K_v values were eliminated from the grid sampling plots, the remaining independent sub-datasets of streambed K_v values were still in normal distribution at each test site. Furthermore, the combined streambed K_v values upstream of the first confluence between the Platte River and the Loup River was normally distributed, which may be due to the lack of tributaries in-between and thus streambed sediments were well distributed in this reach and belonged to a single population of hydraulic conductivity values. In contrast, the combined dataset of all measurements conducted downstream of this confluence was no longer in normal distribution, presumably as a result of the mixing of different sediment sources.

Keywords: streambed vertical hydraulic conductivity, permeameter test, normal distribution, Platte River

1 Introduction

Streambed vertical hydraulic conductivity (K_v) plays an important role in understanding and quantifying the stream-aquifer interactions and stream ecosystems (Goswami et al. 2010). Chen and Shu (2002) reported that a higher streambed K_v induces a higher rate of stream depletion due to groundwater withdrawal. Sun and Zhan (2007) noted that one of the most important factors controlling the interaction of an aquifer with two parallel streams is the hydraulic conductivity ratio of the two streambeds, especially when a low-*K* streambed exists. Heterogeneity of streambed *K* could affect hyporheic zone fluxes and groundwater discharge (Salehin et al. 2004; Kalbus et al. 2009; Kennedy et al. 2009). Also, hyporheic exchange at channel surface affects the distribution of streambed K_v such that streambed K_v in the upper sediment layer is higher than that in the lower sediment layer (Song et al. 2007). Therefore, knowledge of streambed K_v is essential to characterize hydrologic connections between a stream and its adjacent aquifers, and streambed K_v is also a necessary parameter in numerical modeling of stream-aquifer interactions (Sophocleous et al. 1995).

A number of researchers discussed the methods for the determination of streambed *K*, which include the permeameter test (Hvorslev 1951; Chen 2000, 2004, 2005; Landon et al. 2001; Genereux et al. 2008; Kennedy et al. 2009), slug and bail tests (Springer et al. 1999; Landon et al. 2001; Ryan and Boufadel 2007; Leek et al. 2009), grain-size analysis (Chen 2000; Landon et al. 2001), and pumping test (Kelly and Murdoch 2003). Generally slug and bail tests can only provide streambed horizontal hydraulic conductivity (K_h) values, while grain-size analysis cannot evaluate the anisotropy of *K* values because the sediment structure is destroyed during sampling (Chen 2000; Kalbus et al. 2006; Cheng and Chen 2007). In contrast, permeameter tests can provide streambed K_v values which are more accurate than grain-size analysis and less expensive than those determined using pumping tests. The spatial and temporal variations of streambed K_h and K_v have been analyzed and discussed by many researchers. Springer et al. (1999) suggested a bimodal distribution for the K_h of the sediments within several reattachment bars in the Colorado River of Grand Canyon. They also noted that K_h is lower after a flood due to the increased effective stress of the newly deposited sediments. Cardenas and Zlotnik (2003) used multilevel constant-head injection tests to collect streambed K_h values in the Prairie Creek of Nebraska, and their results indicated that streambed K_h is normally distributed based on 456 measurements. Chen (2005) performed 124 *in situ* permeameter tests at eight sites along the Platte River in south-central and eastern Nebraska. He found that streambed K_v values of the Platte River show a normal distribution when 48 K_v values from one test site in eastern Nebraska were excluded. Ryan and Boufadel (2007) conducted slug tests using a portable fallinghead permeameter to estimate streambed K_h values at two different depths in the Indian Creek in Philadelphia, Pennsylvania. They noted that K_h is log-normally distributed within each sediment layer but not for the combined dataset of two sediment layers. Additionally, their results indicated that streambed K_h decreases with depth while horizontal heterogeneity increases with depth. Genereux et al. (2008) carried out *in situ* permeameter tests to obtain 487 measurements of streambed K_v over the course of a year in the West Bear

Creek in North Carolina. They found that streambed K_v values are neither normally nor log-normally distributed, but are found to have a bimodal distribution. Moreover, their results indicated that streambed K_v varies spatially in a river, and the highest K_v appears in the center of the channel which may be due to the differences of streambed sediment grain size between the center and the sides of the channel. They also pointed out that erosion and deposition may contribute to the observed temporal variation of streambed K_v.

The hydraulic conductivity of aquifer materials has most often been found to be log-normally distributed (Freeze 1975; Bjerg et al. 1992; Hess et al. 1992; Sudicky 1986; Woodbury and Sudicky 1991; Rehfeldt et al. 1992). Chen et al. (2008) used Geoprobe direct-push techniques to generate the electrical conductivity (EC) logs and collect cores of channel sediments at nine sites from Kearney to Columbus in the Platte River. Their results indicated that the streambed near the channel surface at these sites consists mostly of sand and gravel. For the area studied, there was no apparent boundary between channel sediments and the underlain alluvial aquifer; thus, streambed sediments in this reach of the Platte River may be considered part of the aquifer material (Chen et al. 2008). Above all, the K_v value of streambed near the channel surface is a crucial factor in controlling the interactions between surface water and groundwater, and it is beneficial to better understand its statistical distribution and spatial variability at different sites in a large river.

Over the past 10 years, numerous *in situ* and laboratory permeameter tests have been conducted in determining streambed K_v in the Platte River of Nebraska (Landon et al. 2001; Chen 2004, 2005; Song et al. 2007; Chen et al. 2008). Landon et al. (2001) performed *in situ* permeameter tests to investigate the streambed K_v in the Platte River near Brady. They concluded that streambed K_v is usually greater than 50 m/day; however, their results were based on the top 25-cm streambed. Chen (2004) presented the streambed K_v values in three rivers (the Platte, Republican, and Little Blue Rivers) in south-central Nebraska. The average K_v ranges from 15 to 47 m/day with an L_v (length of sediments in the tube) of 40 cm for sandy streambed. The average streambed K_v is 40.2 m/day at seven test sites between Kearney and Central City in the Platte River (Chen 2005). Song et al. (2007) reported that the average streambed K_v is about 34.4 and 48.2 m/day for sites F and G (see Figure 1 for site locations) in the Platte River.

Most of the previous research papers discussed the spatial variability of streambed K_h or K_v at one or several adjacent sites in small creeks (Cardenas and Zlotnik 2003; Ryan and Boufadel 2007; Genereux et al. 2008); however, they did not develop a statistical distribution analysis of streambed K_v at distant sites along a large river. Although Chen (2005) analyzed the streambed K_v values at eight sites in the Platte River, he did not provide site-by-site statistical distribution analysis of streambed K_v values in the Platte River in Nebraska, and the test sites in his study were mainly located in the reach without tributaries to the Platte River. Furthermore, additional streambed K_v measurements were conducted at two other sites in the Platte River (Song et al. 2007) and at eight new test sites in this study. The objective of this paper is to determine the statistical distribution and spatial variation of streambed K_v values at 18 test sites between Kearney and Ashland, about 300 km apart, in the Platte

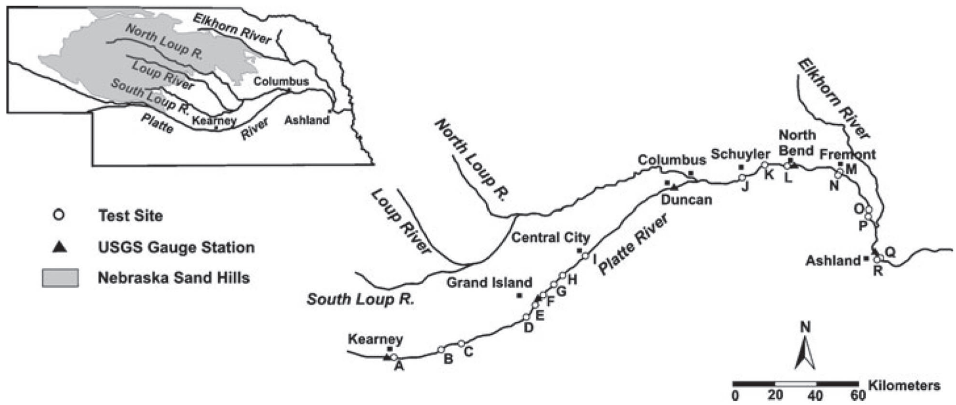


Figure 1. Map showing the study sites. *In situ* permeameter tests were performed at 18 test sites (from sites **a** to **q**) between Kearney and Ashland, *square dots* indicating the nearby city or town names.

River from south-central to eastern Nebraska (Figure 1). This study can provide a detailed picture of site-by-site statistical distribution of streambed K_v along a 300-km segment of the Platte River, and present the possible influences of tributary in controlling streambed permeability at a large scale.

2 Study Area and Test Sites

The study sites are located in the Platte River from south-central to eastern Nebraska (Figure 1). The Platte River originates from the Rocky Mountains and flows through Nebraska from west to east. Within Nebraska, the Platte River is braided at some locations and the Loup River and the Elkhorn River merge with the Platte River in eastern Nebraska. The primary land uses in the basin consist of dry cropland, irrigated cropland, pastureland, and rangeland. Dense vegetation including trees, shrubs and grasses occur in the riparian zone, and cottonwood is the dominant tree. Data from a climate station near Fremont showed the average annual precipitation was about 755 mm between 1950 and 2004. The monthly precipitation shows that most of the precipitation occurs from April to September, which accounts for 75% of the total annual amount. The Platte River is usually wider than 200 m, becomes wider toward downstream and can be as wide as 400 m at Ashland. However, the Platte River is generally shallow and the water depth is less than 1 m (Chen et al. 2008). The Platte River is an important habitat for a number of endangered river species. In recent years, stream depletion in the Platte River due to extensive use of groundwater has become an important issue because it may threaten river habitats (Chen and Shu 2002; Chen 2007).

Five USGS (U.S. Geological Survey) gauge stations recorded the stream stage and streamflow rate in the Platte River within the study area. The stations are USGS 06770200 near Kearney, USGS 06770500 near Grand Island, USGS 06774000 near Duncan, USGS 06796000 near North Bend, and USGS 06801000 near Ashland, respectively (Figure 1). The average stream level and stream discharge for the five stations are shown in Table 1. Thus, the Platte River may bring fine-grained sediments from up-

Table 1. Average stream level and stream discharge of the Platte River at five USGS gauge stations

Station location	USGS code	Mean stream level (m)	Stream level date range	Mean stream discharge (m^3/s)	Discharge date range
Kearney	06770200	651	1987 to 2008	38	1985 to 2008
Grand Island	06770500	559	1986 to 2008	44	1942 to 2008
Duncan	06774000	451	1997 to 2008	50	1941 to 2008
North Bend	06796000	386	1989 to 2008	128	1949 to 2008
Ashland	06801000	322	1992 to 2008	185	1988 to 2008

stream stations to downstream stations and result in a downstream fining trend. Furthermore, the higher streamflow discharge rate at the North Bend and Ashland stations is a result of the contribution of streamflow from the Loup River and the Elkhorn River.

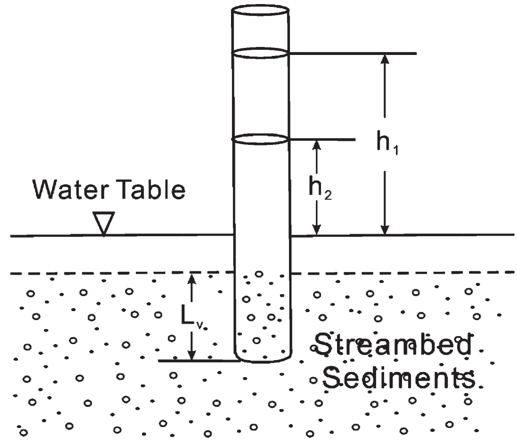
Streambed K_v values at 10 of the 18 sites between Kearney and Ashland in the Platte River were presented by Chen (2004, 2005), and Song et al. (2007). Eight new test sites between Schuyler and Ashland (Figure 1), about 100 km apart along the Platte River in eastern Nebraska, were selected to perform permeameter tests in June and July 2008. The total eighteen sites were designated as sites A to R between Kearney and Ashland in the Platte River (Figure 1). At each site, tens to hundreds of measurements of *in situ* permeameter tests were made to characterize the streambed variability. Near the City of Fremont, two test sites were selected. One was site M where the permeameter tests were conducted close to the north bank of the Platte River, and the other one was site N where the permeameter tests were conducted near the south bank of the Platte River. Similarly, near the City of Ashland, the tests conducted at site Q in this study were located in the eastern half of the Platte River, while the tests at site R conducted by Chen (2005) were located in the western half of the river. Most of the permeameter tests were conducted in sandy streambed sediments and were over 50 m away from the river bank. However, at site M, the nearest measurements were only 3.0 m from the river bank.

3 Methods

3.1 *In situ* Permeameter Test

An *in situ* permeameter test using the falling head method usually involves inserting a standpipe into channel sediments (Figure 2). In this case, transparent polycarbonate tubes were used for all the tests. The tube is 147 cm in length and 5.1 cm in diameter, and is pressed vertically into the channel sediments. The wall of the tube is about 1 mm thick, thus its effects of disturbance on streambed sediments would be expected to be negligible. After the tube was pressed into a desired depth, the tube remained in the channel for an appropriate length of time to allow the hydraulic head inside the tube to reach equilibrium due to the slight compaction of the streambed sediments inside the tube (Chen et al. 2009). After the head inside the tube equilibrated, the surface water-level at the streambed surface was considered as the initial hydraulic head at the measurement point. Water was then added from the top of the tube. The hydraulic head in the tube began to fall and the head was recorded in

Figure 2. Schematic diagram showing *in situ* permeameter test to determine streambed *Kv* (Chen 2000).



different time steps. In the study, water levels were recorded more than 10 times for each permeameter test. Any pair of measurements from the *in situ* permeameter tests can be used to calculate the K_v value using the equation of Hvorslev (1951):

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

where L_v is the length of sediment in the tube; h_1 and h_2 are hydraulic head inside the tube measured at times t_1 and t_2, respectively, D is the interior diameter of the tube, and $m = \sqrt{K_h/K_v} \cdot K_h$ is the horizontal hydraulic conductivity of the channel sediment around the base of the sediment core.

A nonlinear regression method was used to determine the streambed K_v (Chen 2005). This method could enhance the estimation of K_v by taking into account all the water level records simultaneously. In the computation of K_v, m must be arbitrarily chosen. Chen (2004) noted that increasing L_v could reduce the overestimation of K_v. He found that the estimation error of K_v is less than 5% by arbitrarily choosing a value of m when the ratio of L_v to D is greater than 5. All tubes were 5.1 cm in diameter in this study. The L_v for each measurement of *in situ* permeameter tests ranged from 42 to 58.4 cm. Therefore, the ratios of L_v to D are all greater than 5 for the *in situ* permeameter tests at all sites.

The number of permeameter tests, the grid spacing between test points, the average L_v, and the average water depth are summarized for each of the eight new test sites (sites J to Q) between Schuyler and Ashland in the Platte River, which are shown in Table 2.

3.2 Normality Test and *t*-Test

Normality tests are used to determine whether a set of measurements comes from a normal distribution population. In this study, Jarque–Bera (J–B), Kolmogorov–Smirnov (K–S), Lilliefors, and Shapiro–Wilk (S–W) tests (Sprent 2001) were applied at the 0.05 significance level. The K–S and S–W tests are commonly used, and the Lil-

Table 2. Average streambed K_v values, average L_v, average water depth, and grid spacing at the eight test sites (sites J to Q) from Schuyler to Ashland in the Platte River in eastern Nebraska

Test site	Test date	Number of tests	Grid spacing: # of rows, distance between each test point	Grid spacing: # of columns, distance between each test point	Average *Lv*(cm)	Average *Kv* (m/day)	Standard deviation of *Kv*	Average water depth (cm)
J	June 19, 2008	64	8, 3.0 m	8, 3.0 m	42.0	31.4	5.0	46.8
K	June 26, 2008	20	4, 30 m	5, 10 m	51.9	32.4	4.8	35.8
L	July 3, 2008	48	8, 1.5 m	6, 1.5 m	50.8	33.3	7.1	34.4
M	July 11, 2008	200	4, 1.5 m	50, 1.5 m	50.8	17.7	4.7	44.8
N	July 10, 2008	49	7, 1.5 m	7, 1.5 m	50.8	29.8	6.2	21.5
O	July 21, 2008	49	7, 1.5 m	7, 1.5 m	50.8	37.8	4.7	24.4
P	July 9, 2008	64	8, 1.5 m	8, 1.5 m	50.8	45.2	7.7	34.3
Q	July 17, 2008	40	4, 1.5 m	10, 1.5 m	50.8	23.4	9.7	16.0

liefors test is an adaption of the K–S test. The S–W test has requirements for the sample size N ($7 \le N \le 2{,}000$), while the K–S and Lilliefors tests are preferable to apply for a large sample size N ($N \ge 2{,}000$). The J–B test is not good at distributions with short tails, and the K–S and Lilliefors tests are also less powerful than the S–W test. These tests were used to determine whether streambed K_v at each test site is normally distributed. Furthermore, a *t*-test with unequal variance is used to compare the K_v values at two test sites, and this test can determine whether streambed K_v differ significantly between different test sites.

3.3 Determination of Independent Samples Using an Exponential Model

Rehfeldt et al. (1992) noted that a population of samples can be reduced to independent samples by taking out the spatially correlated samples, and they introduced a reduction factor to identify both the horizontal and vertical correlation. In this study, we used an exponential model to fit the experimental semi-variogram along the flow direction at each test site. The fitted model provided the correlation scale (Hess et al. 1992; Genereux et al. 2008; Zhao et al. 2010). If the correlation scale is smaller than the sampling spacing, then the measurements of streambed K_v were regarded as independent; otherwise, the measurements within the correlation scale were eliminated from the sample and thus the remaining streambed K_v values were considered to be independent. Furthermore, the streambed K_v values across the flow direction were regarded as independent in this study. The exponential model used in this study did not include a nugget effect, and is written as

$$\gamma = C\left(1 - \exp\left(\frac{-h}{\lambda}\right)\right) \tag{2}$$

where γ is the semi-variogram statistic, C is the variogram sill value, h is the lag distance, and λ is the correlation scale. Note that this correlation scale is related to the range of influence but not the range of influence as defined in some geostatistical text books (Goovaerts 1997). The four normality tests were also used to testify the independent sub-datasets of streambed K_v values.

4 Results

4.1 Streambed K_v Values Between Schuyler and Ashland in the Platte River

Previous studies showed that the vertical hydraulic gradient (VHG) may vary spatially across the streambed at nearby locations (Chen et al. 2009; Leek et al. 2009). Chen et al. (2009) noted that the positive and negative VHG values could occur between two locations only several meters apart for the streambed sediments in the Elkhorn River of Nebraska, which indicates the significant presence of downward and upward flux at water-streambed interface. Similar findings were reported by Leek et al. (2009). In this study, the VHG values at the test sites in the Platte River are very small (all less than 0.02), thus using the surface water-level at the streambed surface as the initial hydraulic head at the measurement point may not greatly affect the accuracy of the estimation of streambed K_v values.

The average streambed K_v values and standard deviation of K_v at each of the eight new test sites are shown in Table 2. The average L_v from sites J to Q in this study is about 49.8 cm, which is slightly larger than that from sites A to I and site R (40.7 cm) from previous studies (Chen 2004, 2005; Song et al. 2007). At sites J, K, and L, the average streambed K_v values were similar. The different average streambed K_v values at sites M and N indicated that K_v values can vary significantly in space, even though the two sites are adjacent. Furthermore, the average streambed K_v values at the two sites were lower than those values at sites J, K, and L; while the average streambed K_v values at sites O and P were higher than those values at other test sites.

The test site near Ashland (site Q) in this study was different from the Ashland site (site R) of Chen (2005). He performed *in situ* permeameter tests along four transects on the west half of the Platte River, while the permeameter tests in this study were conducted on the east half of the Platte River, about 200 m apart from the test locations of Chen (2005). The streambed K_v values ranged from 2.9 to 41.9 m/day with an average K_v of 23.4 m/day, while Chen (2005) reported that the average streambed K_v is 16.8 m/day at 40 test points. Nevertheless, the standard deviation of streambed K_v of the two sites is similar. The average K_v value at site Q was lower than those values at other new test sites in this study except for site M.

Out of the eight new test sites, the K_v values at site Q had the largest standard deviation, while the K_v values at siteMhad the smallest standard deviation (Table 2; Figure 5). Large standard deviation of K_v indicates that the streambed K_v values can vary significantly within the same site, especially at sites J, P, and Q (Table 2). On the whole, the standard deviations of K_v values at the eight sites were slightly different, and they were smaller than those from sites A to I between Kearney and Central City in the Platte River (Chen 2004, 2005; Song et al. 2007; Table 3). This difference is probably because (1) a larger number of permeameter tests were conducted at the eight new sites in this study and (2) the tests for these eight new sites were conducted in regularly spaced but closely located points compared to the tests along the acrosschannel transect for the sites A to I between Kearney and Central City (Chen 2004, 2005; Song et al. 2007). It can be anticipated that larger heterogeneity in streambeds exists along a transect across the channel and less heterogeneity in streambeds of smaller scale plots.

4.2 Statistical Distribution of Streambed K_v Values along the Platte River

The histograms of the streambed K_v values and the cumulative distributions on normal probability plots at the eight new sites (sites J to Q) from Schuyler to Ashland in the Platte River are shown in Figure 3(a–h). The J–B and S–W tests indicated that the streambed K_v values are in normal distribution at the eight test sites at the 0.05 significance level except for site N (Table 3), while the Lilliefors and K–S tests implied nonnormal distribution of streambed K_v at sites J and Q as well as site N. At site N, all four tests suggested that the streambed K_v values are not in normal distribution at the 0.05 significance level, since the p-values are all smaller than 0.05. However, if the two

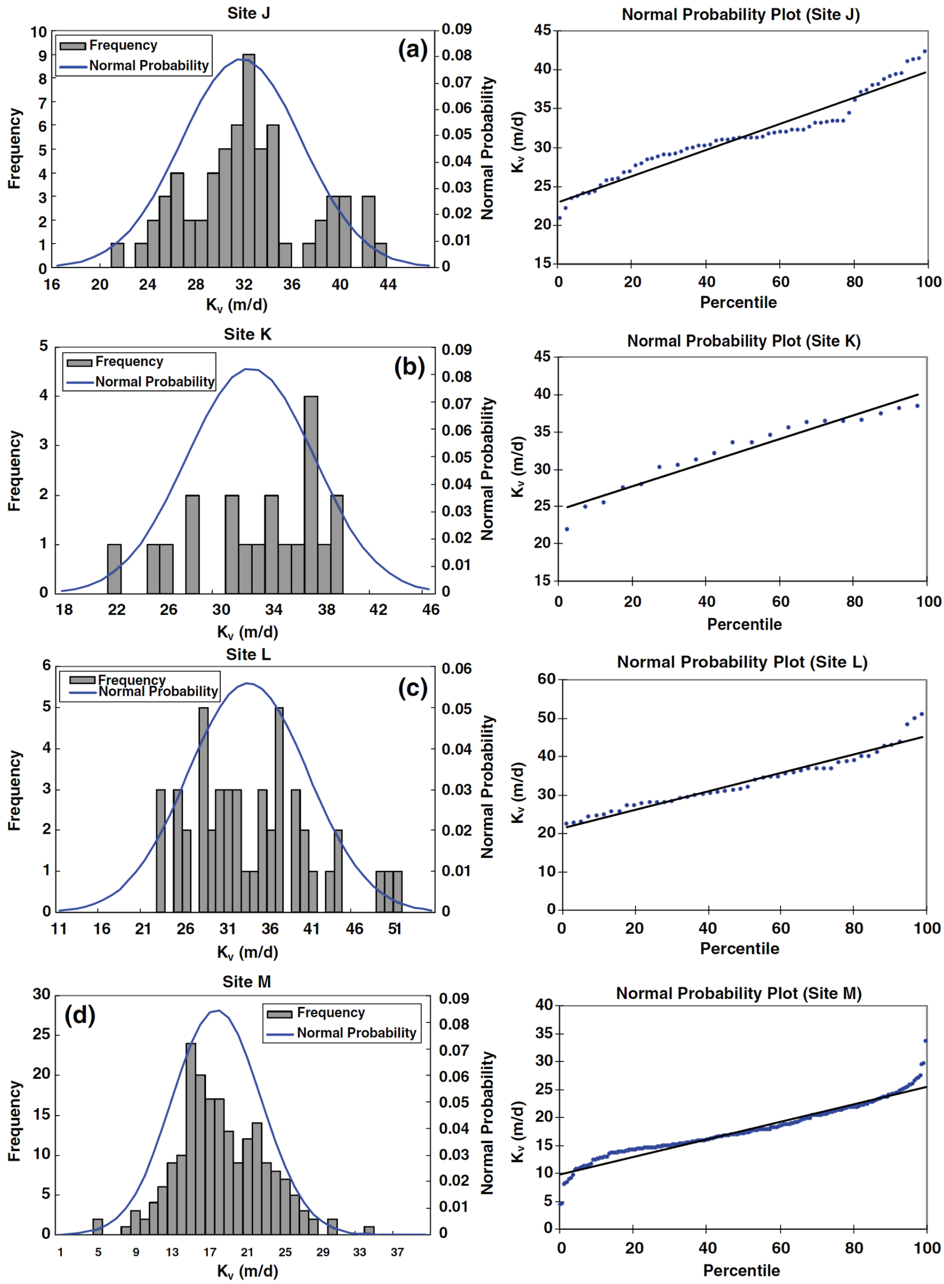


Figure 3. Histograms and normal probability plots of streambed *Kv* from sites J to Q between Schuyler and Ashland in the Platte River **a** site J; **b** site K; **c** site L; **d** site M; **e** site N; **f** site O; **g** site P; **h** site Q.

largest K_v values were considered as outliers and eliminated from the sample, the remaining 47 K_v values at site N were normally distributed from all four normality tests. Furthermore, the 48 streambed K_v values at site R determined by Chen (2005) were normally distributed according to the Lilliefors and K–S tests. When the streambed K_v val-

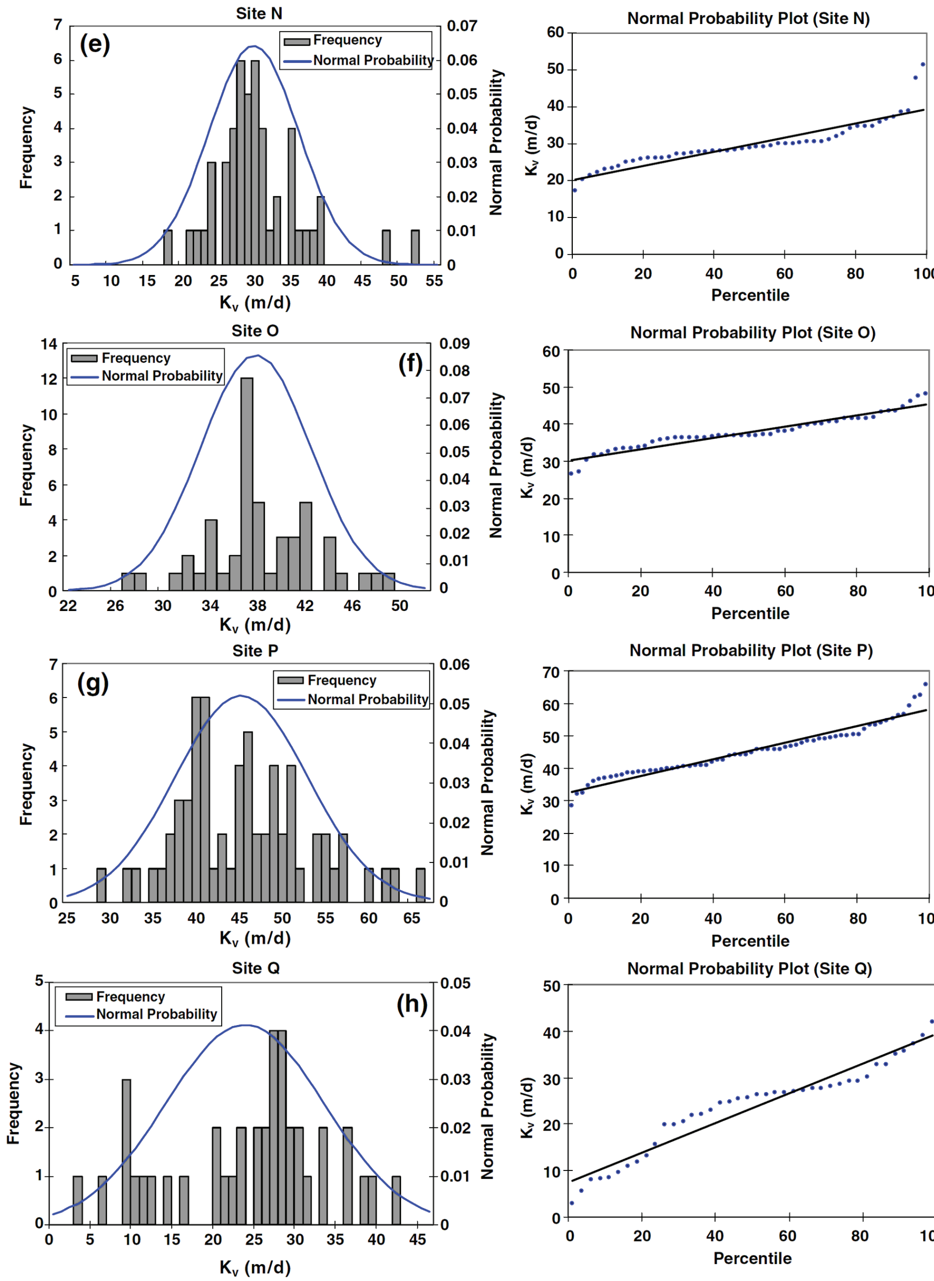


Figure 3. (continued)

ues at both sites Q and R near Ashland were combined as a single dataset, the 88 K_v values were normally distributed according to all four normality tests (Table 3).

Chen (2005) noted that streambed K_v values are normally distributed for the combined dataset at sites A, B, C, D, E, H, and I between Kearney and Central City in the Platte River (Figure 1). In this study, all four normality tests were performed for

Table 3. Average streambed K_v values and length of tested streambed sediment at the 18 test sites (Chen 2004, 2005; Song et al. 2007).

Test site	Number of tests	Average K_v(m/d)	Average L_v(cm)	Standard deviation of K_v	Normal distribution by J–B test	Normal distribution by K–S test	Normal distribution by Lilliefors test	Normal distribution by S–W test
A	8	32.5	40.0	23.1	Yes	Yes	Yes	Yes
B	10	32.7	38.1	9.6	Yes	Yes	Yes	Yes
C	9	38.1	38.2	10.7	Yes	Yes	Yes	Yes
D	16	45.9	42.4	14.9	Yes	Yes	Yes	Yes
E	21	40.7	40.0	14.9	Yes	Yes	Yes	Yes
F	15	34.4	48.0	16.7	Yes	Yes	Yes	Yes
G	16	48.2	50.3	20.5	Yes	Yes	Yes	Yes
H	4	46.8	40.0	10.1	NA	NA	NA	NA
I	8	46.7	40.0	10.1	Yes	Yes	Yes	Yes
A to I	107	41.0	42.7	16.6	Yes	Yes	Yes	Yes
J	64	31.4	42.0	5.0	Yes	No	No	Yes
K	20	32.4	51.9	4.8	Yes	Yes	Yes	Yes
L	48	33.3	50.8	7.1	Yes	Yes	Yes	Yes
M	200	17.7	50.8	4.7	Yes	Yes	Yes	Yes
N	49	29.8	50.8	6.2	No	No	No	No
N excluding two outliers	47	29.0	50.8	4.7	Yes	Yes	Yes	Yes
O	49	37.8	50.8	4.7	Yes	Yes	Yes	Yes
P	64	45.2	50.8	7.7	Yes	Yes	Yes	Yes
J to P	494	28.3	49.7	11.3	No	No	No	No
Q	40	23.4	50.8	9.7	Yes	No	No	Yes
R	48	16.8	40.0	8.7	No	Yes	Yes	No
Q and R	88	19.8	44.9	9.7	Yes	Yes	Yes	Yes
All test sites	689	29.2	48.0	13.4	No	No	No	No

Normality tests by the Jarque-Bera (J–B), Kolmogorov-Smirnov (K–S), Lilliefors, and Shapiro-Wilk (S–W) tests indicate whether streambed K_v values at these sites are in normal distribution

Yes= streambed K_v is normally distributed, *No* = K_v is not normally distributed, *NA* = not available streambed K_v values at each of the eight test sites (sites A to I) except for site H, which had only four measurements (Chen 2004, 2005; Song et al. 2007). The results indicated that streambed K_v is normally distributed at these individual sites (Table 3). Song et al. (2007) reported the streambed K_v values at sites F and G, but they did not perform a statistical distribution analysis of K_v values. All four normality tests illustrated that streambed K_v values are in normal distribution at sites F and G as well (Table 3). When the K_v values obtained from sites F and G were combined with those values reported by Chen (2005), the new dataset of streambed K_v values from sitesAto I (Chen 2004, 2005; Song et al. 2007; Figure 1) was in normal distribution, which may be attributed to the fact that the Platte River has no tributaries between Kearney and Central City (Figure 1) and thus the streambed sediments within this river reach were well distributed and belonged to a single population of hydraulic conductivity values.K_v

When all the K_v values from sites J to P were combined, the normality tests indicated that the data are not in normal distribution (Table 3), which may be a result of different hydrogeological processes, including geological conditions, geomorphic history, and physical transport processes (Hoey and Bluck 1999; Rice and Church 1998), controlling the structure of channel sediments at individual sites. Streambed K_v was also not normally distributed for the combined data of all the 689 measurements in the Platte River from sites A to R between Kearney and Ashland which was concluded by the four normality tests (Table 3).

The experimental semi-variograms of K_v and fitting exponential models along the flow direction at the eight new test sites (sites J to Q) in the Platte River are shown in Figure 4. At site L, the measured semi-variograms of K_v increased with the lag distance gradually and the fitted exponential model showed that the values of λ (correlation scale) and C (variogram sill value) cannot be determined uniquely when all the semi-variogram values were used. Thus, we chose the first three measured semivariograms of K_v to fit an exponential model, and the fitted values of C and λ were about 45.2 and 2.1 m, respectively (Figure 4c). At sites K, O, P, and Q, the correlation scale was less than 1.5 m which corresponds to the distance between the test points. As a result, the streambed K_v values along the flow direction at these sites in the Platte River were considered to be independent samples as well as the K_v values across the flow direction. However, the correlation scale was larger than the sampling spacing at each of sites J, L, M, and N. The K_v values within the correlation scales were taken out and normality tests were performed on the remaining independent sets of streambed K_v values. At sites J, L, and M, the correlation scales were less than twice the sample spacing at each site, two independent sets of K_v values can be generated after the correlated samples were removed; while at site N, three independent sets of K_v values were generated. All the datasets of independent streambed K_v values were in normal distribution except for one dataset at site J which was identified by the K–S and Lilliefors tests and one dataset at site N which was identified by the J–B and S–W tests (Table 4). However, when the largest K_v value in this dataset at site N was regarded as an outlier and taken out, the remaining 13 values are normally distributed determined by all four normality tests. Therefore, the streambed K_v values at each of the eight test sites (sites J to Q) between Schuyler and Ashland in the Platte River can be regarded as normally distributed, which indicated that the streambed K_v values

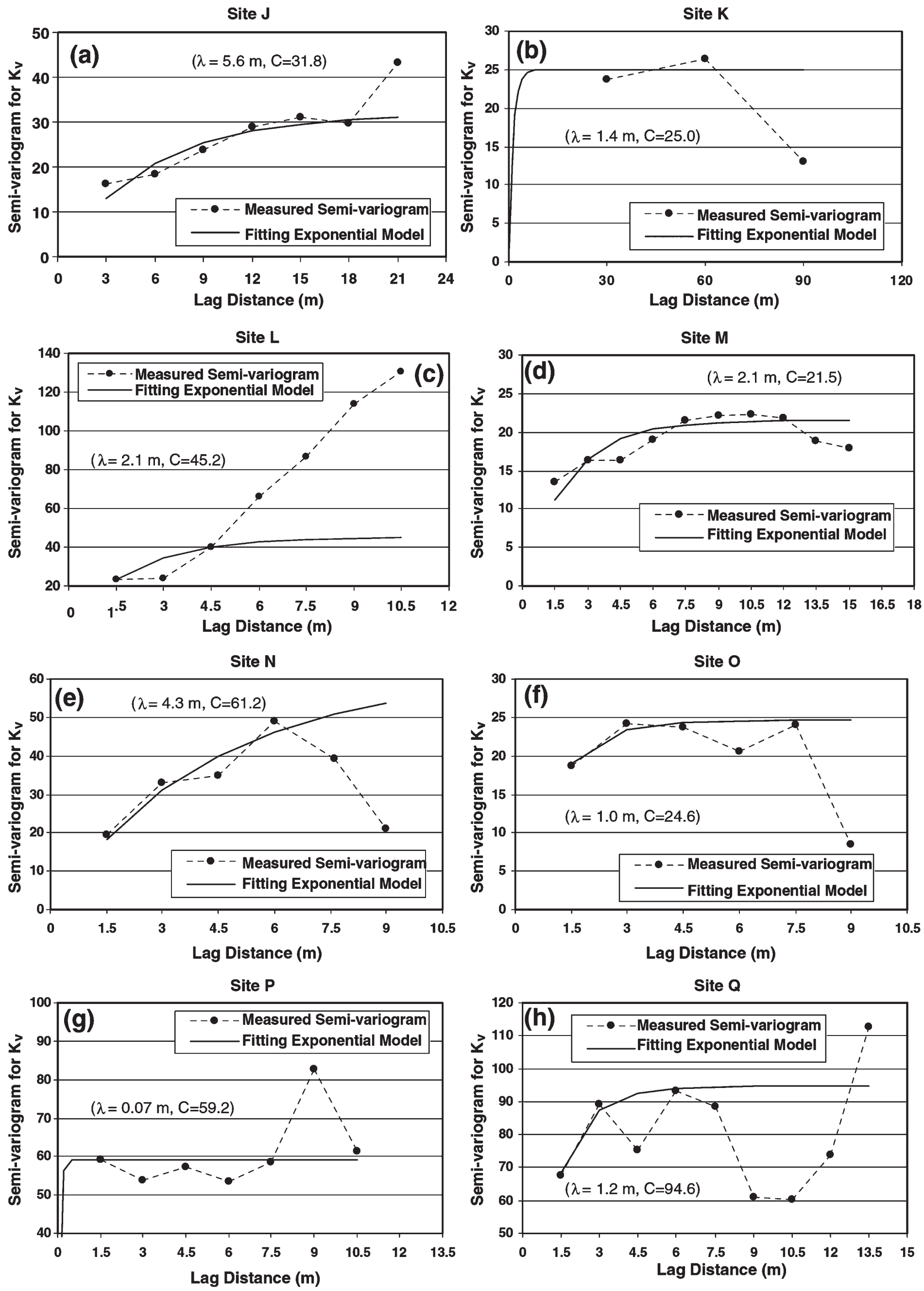


Figure 4. Semi-variogram of K_v along the flow direction from sites J to Q between Schuyler and Ashland in the Platte River. **a** site J; **b** site K; **c** site L; **d** site M; **e** site N; **f** site O; **g** site P; **h** site Q.

cluster around the average K_v value and using the average K_v value obtained from a large number of measurements to represent the streambed K_v characteristics was appropriate at these sites in the Platte River.

Table 4. Average streambed K_v values of the independent datasets at sites J, L, M, and N

Test site and set of independent samples	Number of samples	Average K_v (m/day)	Normal distribution by J–B Test	Normal distribution by K–S Test	Normal distribution by Lilliefors Test	Normal distribution by S–W Test
Sub-dataset 1 at site J	32	32.3	Yes	No	No	Yes
Sub-dataset 2 at site J	32	30.4	Yes	Yes	Yes	Yes
Sub-dataset 1 at site L	24	32.3	Yes	Yes	Yes	Yes
Sub-dataset 2 at site L	24	34.3	Yes	Yes	Yes	Yes
Sub-dataset 1 at site M	100	17.8	Yes	Yes	Yes	Yes
Sub-dataset 2 at site M	100	17.6	Yes	Yes	Yes	Yes
Sub-dataset 1 at site N	21	28.3	Yes	Yes	Yes	Yes
Sub-dataset 2 at site N	14	30.9	No	Yes	Yes	No
Sub-dataset 2 at site N (excluding the largest value)	13	29.4	Yes	Yes	Yes	Yes
Sub-dataset 3 at site N	14	31.0	Yes	Yes	Yes	Yes

Normality tests by the Jarque-Bera (J–B), Kolmogorov-Smirnov (K–S), Lilliefors, and Shapiro-Wilk (S–W) tests indicate whether streambed K_v values at these sites are in normal distribution

Yes = streambed K_v is normally distributed, *No* = K_v is not normally distributed, *NA* = not available

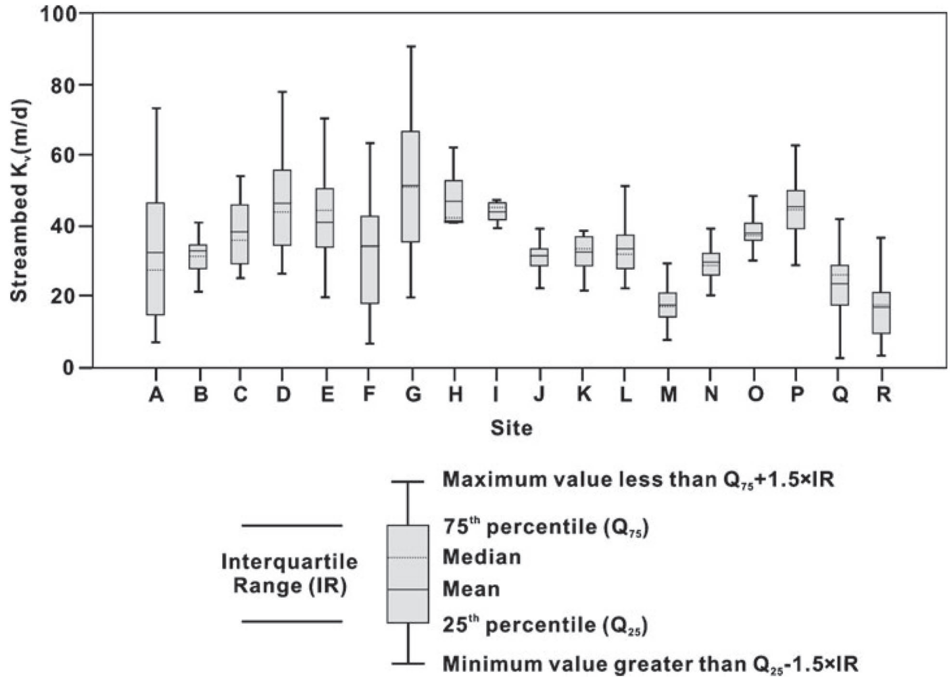


Figure 5. Boxplot of streambed K_v values at the 18 test sites (from sites A to R) between Kearney and Ashland in the Platte River in Nebraska (Chen 2004, 2005; Song et al. 2007). *Box* indicates the upper and lower quartile, the *dash horizontal line* indicates the median value, and the *solid horizontal line* indicates the mean value.

5 Discussion

5.1 Spatial Variation of Streambed K_v Values along the Platte River

At the eight new test sites in this study, the *t*-test suggested that the K_v values are similar between sites J, K, and L with that all the *p*-values were larger than 0.05. Site N also had similar K_v values with sites J and K but not site L. The K_v values at sites M and Q were significantly lower than those at all other sites ($p < 0.0001$). Site M had the lowest average streambed K_v value, while the average streambed K_v value at site P was the highest among the eight test sites.

Compared to the average streambed K_v values from sites A to I between Kearney and Central City (Figure 1) in the Platte River (Chen 2004, 2005; Song et al. 2007), larger average streambed K_v values occurred at sites D, E, G, H, I, and P, which were all greater than 40 m/day (Figure 5). The average streambed K_v values at the eight new test sites (sites J to Q) between Schuyler and Ashland in the Platte River were all lower than those between Kearney and Central City, except for sites O and P, which may be attributed to localized coarse streambed sediments where the permeameter tests were conducted. Nevertheless, the average streambed K_v value from sites J to Q in the Platte River was 27.1 m/day, which was lower than that from sites A to I in the Platte River (41.0 m/day; Chen 2004, 2005; Song et al. 2007).

5.2 Effects of Tributaries on Streambed K_v Variability

Usually the grain size of streambed sediments declines with the distance downstream due to abrasion and sorting, and selective transport (Surian 2002; Frings 2008) and a downstream gravel–sand transition occurs (Singer 2008). Additionally, sediment sources of the tributaries play a significant role in controlling the grain-size pattern change for river bed sediments (Rice 1998). In this study, two other major rivers merge with the Platte River, which can induce additional effects on the distribution of streambed K_v values. The Loup River merges with the Platte River near Columbus, which is upstream of site J, while the Elkhorn River merges with the Platte River at where it is only 10 km upstream of sites Q and R near Ashland. The Loup River originates from the Nebraska Sand Hills, which has about 49,695 km_2 in drainage. Previous studies hypothesized that the Nebraska Sand Hills is an important factor for the distribution of loess deposits downwind of the Sand Hills. The Sand Hills either serves as a sediment transport pathway and allows loess deposits to be carried away (Mason 2001), or generates silt sized sediments by abrasion and ballistic impacts under strong winds (Muhs 2004). The Loup River thus can carry these fine-grained sediments, which can mix with the sediments moving downstream in the Platte River and result in lower streambed K_v values at the eight test sites. At site Q near Ashland, the streambed K_v values were lower than those values at other sites in this study and similar results were reported by Chen (2005). Previous research suggests that the Elkhorn River has also lower streambed K_v values than the Platte River. First, Huntzinger and Ellis (1993) noted that low-permeability glacialtill deposits occur in the subsurface of the Elkhorn River; and second, Song et al. (2009) found that streambed K_v values at the West Point site in the Elkhorn River (about 67 km upstream of the confluence with the Platte River) were on average 20.7 m/day. These relatively fine sediments may be carried from the Elkhorn River downstream, and deposited in the Platte River thus resulting in additional damped effects on streambed K_v values as well as the Loup River at sites Q and R near Ashland.

5.3 Streambed K_v Variability across the Channel

Streambed K_v values can vary laterally across the river channel. At site R, Chen (2005) conducted permeameter tests along four transects on the west half of the Platte River, and he found that the K_v values tend to increase towards locations that are further from the river bank. Genereux et al. (2008) also reported that the K_v value at the center of the channel is usually higher than the values close to the river bank. In this study, streambed K_v values at site M were much lower than those at site N, given that both sites were located at different sides of the Platte River. However, the nearest measurements were only 3.0 m to the river bank at site M and flow velocity was very small here, while site N was over 50 m away from the river bank. The center of the river usually has higher flow velocity than the sides of the channel. A larger K_v value may occur in the channel sediments where the flow velocity is generally higher, since fine-grained sediments can be washed away by higher flows and they may deposit again in the area with lower flow velocity (Chen 2005). Furthermore, the lowest streambed K_v values at site M may suggest that the streambed sediments at this site are dominated by the sediments transported from the Loup River; however, a mixture of sediments from the Loup River and Platte River might occur between sites J and N, while the upstream Platte River sediments can be dominant at sites O and P.

6 Summary and Conclusions

In situ permeameter tests were conducted at eighteen test sites between Kearney and Ashland in the Platte River from south-central to eastern Nebraska. The streambed K_v values at the eighteen sites (sites A to R) may be categorized into three groups in terms of downstream fining and tributary inputs. The first group was the streambed K_v values from site A to I between Kearney and Central City in the Platte River (Chen 2004, 2005; Song et al. 2007). Within this area, the Platte River has no tributaries and the average streambed K_v value was 41.0 m/day. The second group was the streambed K_v values from site J to P in the Platte River, and the average streambed K_v value was 28.3 m/day within this area. The Loup River merges with the Platte River near Columbus, which is upstream of site J. The Loup River originates from the Nebraska Sand Hills and can carry the fine-grained sediments generated by the Sand Hills to the Platte River. The mixing of the fine-grained sediments from the Loup River and sediments from the downstream Platte River could explain the lower-*K* streambed sediments that occur downstream of the confluence. The third and final group was the streambed K_v at sites Q and R (Chen 2005) near Ashland in the Platte River. Another large river, the Elkhorn River, merges with the Platte River at where it is only 10 km upstream of both the Ashland sites. Low-permeability glacial-till deposits occur in the subsurface of the Elkhorn River (Huntzinger and Ellis 1993), and permeameter tests suggest a lower K_v value for streambed sediments in the Elkhorn River (Song et al. 2009), which may contribute additional fine-grained sediments to the Platte River and these lower-*K* sediments were deposited in the downstream Platte River. The average streambed K_v value was 19.8 m/day for sites Q and R (Chen 2005), which was much lower than those values at other sites, except for site M. Moreover, the streambed sediments at site M might be dominated by the sediments from the Loup River, which resulted in the second-lowest average streambed K_v value out of the eighteen test sites. A mixture of sediments from the Loup River and Platte River may occur between sites J and N; however, the streambed sediments at sites O and P can be dominated by the upstream Platte River sediments. At sites Q and R (Chen 2005) near Ashland, a mixture of sediments from the Loup and Elkhorn Rivers and the upstream Platte River can lead to an even lower streambed K_v value.

Streambed K_v values were normally distributed at nearly each test site in the Platte River from south-central to eastern Nebraska, except for site N. However, when the two largest K_v values were regarded as outliers and eliminated from the sample, the remaining streambed K_v was in normal distribution at site N. Additionally, when the correlated K_v values were removed from the datasets collected from gridded sampling plots, the remaining independent sub-datasets of streambed K_v values were still in normal distribution at each of the eight new test sites. The characteristic of normal distribution of streambed K_v in the Platte River was different from the distribution of K_v reported in the West Bear Creek in North Carolina (neither normal nor log-normal) (Genereux et al. 2008), from the log-normal distribution of streambed K_v in the Indian Creek in Philadelphia, Pennsylvania reported by Ryan and Boufadel (2007), from the bimodal distribution of streambed K_h in the Colorado River (Springer et al. 1999), and from the log-normal distribution for aquifer materials (Freeze 1975). Moreover, the combined dataset of streambed K_v values from site A to I between Kearney and Central City, about 200 km apart along the Platte River, were normally distributed, which may be due to the fact that the Platte River has no tributaries in-between and thus the streambed sediments were well distributed in the Platte River in this reach and belonged to a single population of hydraulic conductivity values. On the other hand, the combined dataset of streambed K_v values from site J to R (Chen 2005) between Schuyler and Ashland, about 100 km apart along the Platte River, were not in normal distribution. Within this lower reach, the mixture of three sediment sources from the upstream Platte River, the Loup River, and Elkhorn River leads to a wide range of variations in streambed vertical hydraulic conductivity.

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