Environ Geol (2005) 48: 693–701
DOI 10.1007/s00254-005-0007-1

ORIGINAL ARTICLE

Xunhong Chen

Statistical and geostatistical features of streambed hydraulic conductivities in the Platte River, Nebraska

Received: 15 January 2005
Accepted: 24 April 2005
Published online: 27 July 2005

X. Chen
School of Natural Resources,
University of Nebraska-Lincoln,
LincolnNE 68588-0517,
E-mail: xchen2@unl.edu
Tel.: +402-472-0772
Fax: +402-472-4608

Abstract This paper presents streambed hydraulic conductivities of the Platte River from south-central to eastern Nebraska. The hydraulic conductivities were determined from river channels using permeameter tests. The vertical hydraulic conductivities (K_v) from seven test sites along this river in south-central Nebraska belong to one statistical population. Its mean value is 40.2 m/d. However, the vertical hydraulic conductivities along four transects of the Ashland test site in eastern Nebraska have lower mean values, are statistically different from the K_v values in south-central Nebraska, and belong to two different populations with mean values of 20.7 and 9.1 m/d, respectively. Finer sediments carried from the Loup River and Elkhorn River watersheds to the eastern reach of the Platte River lowers the vertical hydraulic conductivity of the streambed. Correlation coefficients between water depth and K_v values along a test transect indicates a positive correlation – a larger K_v usually occurs in the part of channel with deeper water. Experimental variograms derived from the vertical hydraulic conductivities for several transects across the channels of the Platte River show periodicity of spatial correlation, which likely result from periodic variation of water depth across the channels. The sandy to gravelly streambed contains very local silt and clay layers; spatially continuous low-permeability streambed was not observed in the river channels. The horizontal hydraulic conductivities were larger than the vertical hydraulic conductivities for the same test locations.

Keywords Streambed · Permeameter test · Hydraulic conductivity · Variogram models · Platte River

Introduction

In the Platte River valley of Nebraska, well fields for water supply for most cities are located near the river. Preventing the migration of potential contaminants from the river to nearby well fields requires a better understanding of the stream-aquifer connectedness. In addition, thousands of irrigation wells withdraw groundwater from the High Plains aquifer in this river valley, raising concerns about streamflow depletion. The Platte River segment between Kearney and Columbus (Fig. 1) dried up in the summers of 2002 to 2004. The drying river in this area meant river habitats significantly deteriorated for several federal endangered species. The Platte River was named as one of the nation's most endangered rivers of 2003 by the conservation group American Rivers, which cited concerns that growing water demands will undermine a tri-state (Nebraska, Colorado, and Wyoming) agreement to protect the river. The Platte River was No. 7 on the annual list.

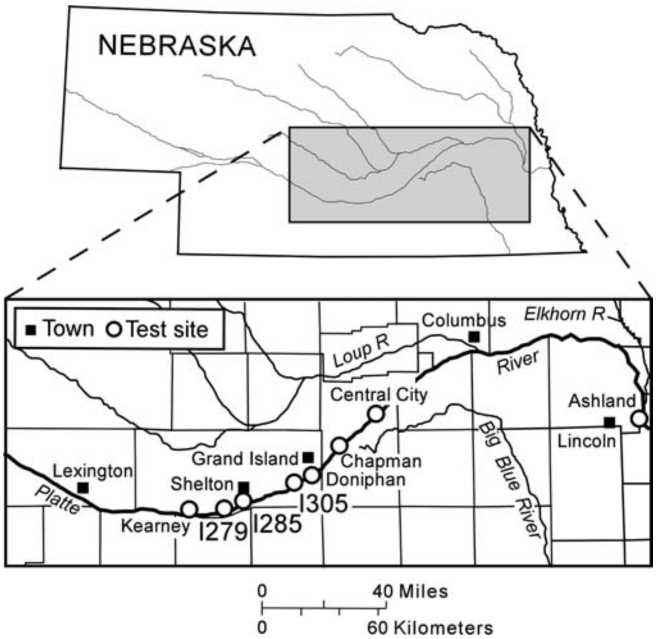

Fig. 1 Map showing permeameter test sites along the Platte River in south-central and eastern Nebraska

The vertical hydraulic conductivity (K_v) of a streambed is a key parameter in the determination of stream-aquifer hydrologic connections. Permeameter tests for measuring streambed hydraulic conductivity in the Platte River have been conducted by several investigators. Nguyen and Gilliland (1985) conducted permeameter tests in the Platte River channels near the Grand Island well field. They used a 5-cm diameter tube and pushed it vertically into a streambed to a depth of about 15 cm. The value of K_v from 24 tests range from 27.7 to 159.6 m/d, with an average of 78.2 m/d. According to Chen (2000), a short penetration of tube into a streambed can introduce errors to the derived K_v values. Landon et al. (2001) conducted permeameter tests on the Platte River near Brady, about 80 miles west to Kearney, and on several tributaries of this river, and provided results of K_v values with some uncertainties due to a shallow penetration of the streambed (25 cm). The derived K_v values show a trend with a change in tube diameters, and were seemingly overestimated by assuming an isotropic feature of the streambed (horizontal and vertical hydraulic conductivity was equal to 1) in the calculation of the K_v values. Chen (2004) reported the K_v values of the streambed along five transects at three sites on the Platte River in south-central Nebraska. In these permeameter tests, a 10-cm diameter tube was pushed into a streambed about 40 cm deep. A larger depth of streambed penetration can reduce errors in the calculation of K_v values. Chen (2004) reported the values of K_v fluctuate largely across the river channels. Rus et al. (2001) performed slug tests in the channels of the Platte River to measure the horizontal hydraulic conductivity (K_h). The mean values for four test sites (near North Platte, Brady, Lexington, and Grand Island) are 293, 140, 186, and 213 m/d, respectively, assuming the ratio of horizontal to vertical hydraulic conductivity to be 10. Slug tests, however, do not provide values of vertical hydraulic conductivity of the streambed.

To better understand the spatial variation of streambed hydraulic conductivity across the channels and from upstream to downstream along the river, more permeameter tests were conducted along the Platte River from south-central to eastern Nebraska (Fig. 1). Results of streambed hydraulic conductivities from these test sites were evaluated to determine statistical and geostatistical behaviors and analyze their relation to streamflow conditions. Experimental variograms are presented to show the spatial variations of K_v across the channels of the Platte River.

River Hydrology of the Study Area

The Platte River, originating from the Rocky Mountains, is about 450 miles long within Nebraska, and joins the Missouri River at the state's eastern border. The river is braided in south-central Nebraska, and sand/gravel bars divide the river into multiple channels. There are no large tributaries contributing flow to the Platte River in south-central Nebraska, but the Loup River and the Elkhorn River merge with the Platte River in eastern Nebraska (Fig. 1). The Loup River drains water from the Sand Hills area, which is covered mostly by sand dunes. The Elkhorn River drains an area of about 17,900 km^2 in northeastern Nebraska, the eastern part of which is covered by glacial till of silty clay and loamy loess (Bentall 1971).

According to U. S. Geological Survey's streamflow records (http://water.usgs.gov/waterwatch/), the annual streamflow rate was 44 m^3 /s between 1935 and 2002 at the gauging station near Grand Island, 50 m^3 /s between 1929 and 2002 at the Duncan gauge about 11 km southwest of Columbus, and increased to 159 m^3 /s at the Ashland gauge between 1929 and 1959 and between 1989–2002. A streamflow record was not available between 1960 and 1988 for the Ashland gauging station. The higher flow rate of the Platte River near Ashland is basically the contribution of water from the Loup River and the Elkhorn River. According to Bentall (1971), the Elkhorn and Loup rivers together contributed 63.7 percent of the flow of the Platte at its mouth during the 1959–68 decade. That so large a percentage of total flow was derived from about a quarter of the Platte's total drainage basin is due mostly to greater precipitation in the eastern part of the basin (Bentall 1971) and the constant baseflow discharging to the rivers in the Sand Hills.

The width of Platte River channels varies from one test site to another. The width of the main channel (south channel) in south-central Nebraska can be as wide as 250 m. The river is not braided at the Ashland test sites, and its width is about 400 m. The Platte River is characterized by its shallow water depth. During the permeameter tests, the water depth across most of the river was shallower than 60 cm.

Nebraska, after California and Texas, ranks third nationally in groundwater use per state. According to Hutson and others (2004), total groundwater withdrawals in Nebraska were 7,860 million gallons per day in 2000, the largest groundwater use per person in the nation. There are nearly 100,000 registered wells, most for gravity or center-pivot irrigation, in Nebraska. In the central Platte valley of Nebraska, high capacity irrigation wells occur densely. In some counties, the average number of irrigation wells is more than 3.4 per square kilometers . Irrigation wells constructed in the alluvial aquifer often have a high-yield capacity, ranging from 500 to 1,500 gallons per minute. The streambed sediments consist mainly of sand and gravel, which provide a good connection between the river and the surrounding alluvial aquifers. The combination of shallow water depth and coarse streambed sediments potentially makes the streamflow of the Platte River vulnerable to depletion due to groundwater withdrawals in the nearby alluvial aquifer. A small decline of the water table in the aquifer can potentially deplete a significant amount of streamflow or even dry up the river.

Methods

Permeameter tests

Figure 2 is a schematic diagram showing a permeameter test in a streambed. The tube is vertically pushed into the top part of the streambed and a sediment column is formed at the lower part of the tube. Water is added to fill the rest of the tube. The hydraulic head inside the tube begins to fall as soon as pouring water stops. The rate of falling head inside the tube depends on the hydraulic conductivity of the sediment column in the tube and the head difference between the streambed and the tube. During a permeameter test, hydraulic heads at a given time were recorded for the derivation of K_v values.

Figure 1 shows the sites of permeameter tests conducted on the channels of the Platte River from Kearney in south-central Nebraska to Ashland in eastern Nebraska. The hydraulic heads were measured manually for the test sites near Kearney, I279, I285, and I305, and were measured using pressure transducers for the sites near Doniphan, Chapman, Central City, and Ashland. The number of head readings for manual measurements ranges from 6 to 15, and often exceeds 80 using pressure transducers. Figure 3 shows the decline of hydraulic head with time for one test at the Doniphan site on the south channel of the Platte River and another test at the Ashland site in eastern Nebraska. The diameter of the tube for the permeameter test was 10 cm. The length of sediment column for each test was about 40 cm, and test duration varied from about 10 to 20 minutes for a sand and gravel streambed. The tests for I279, I285, and I305 were conducted in October 2001, and the results of streambed hydraulic conductivity were presented in Chen (2004). The permeameter tests for the Kearney site were conducted in October 2004. The tests for the other sites were performed in 2002. There were 48 tests along four transects at the Ashland site. During the permeameter tests, the water depth at each test location was measured to determine its relationship to streambed hydraulic conductivities.

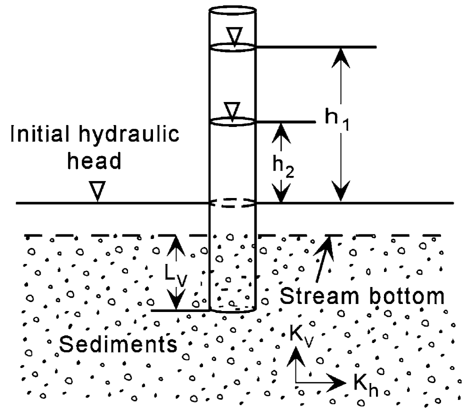

Fig. 2 Schematic showing a permeameter test for measuring streambed hydraulic conductivity in river channels

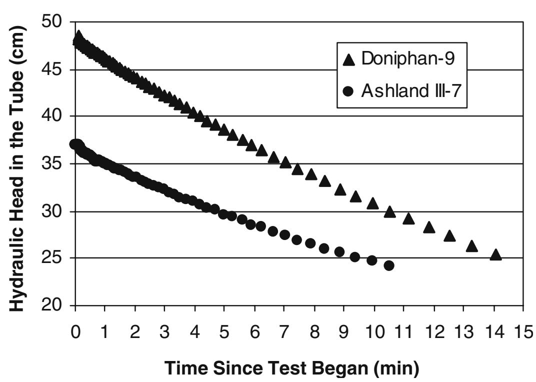

Fig. 3 Curves showing decline of hydraulic head in the tube of permeameter tests in the Platte River

Estimation of streambed hydraulic conductivities

Hvorslev (1951) provided a formula to calculate the K_v of the sediment column in the pipe such that

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

where L_v [L] is the length of the sediment column in the pipe, D [L] is the inner diameter of the pipe, h_1 [L] and h_2 [L] are the hydraulic heads measured inside the pipe at time t_1 and t_2 since a permeameter test began, and $m = \sqrt{K_h/K_v}$, which is often unknown at the time of computation. Assuming an isotropic streambed ($m = 1$) will simplify Eq. (1). This simplification leads to an overestimation of the K_v value for anisotropic stream sediments with $K_h > K_v$.

Chen (2000) used a simplified version of Eq. (1) by neglecting the term $\pi D/11m$ such that

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

This simplification implies a very strong anisotropic streambed where $K_h \gg K_v$. Chen (2000) noticed that this application can, however, underestimate the K_v value for stream sediments of smaller anisotropy, for example, $1 < m < 5$.

Any pair of head readings at given times can be used to calculate a value of K_v. The values of K_v, however, may vary slightly from one calculation to another for the same test. This inconsistency comes mainly from measurement noise. In order to eliminate it, the least squares method was used in this study to take into account all the head readings simultaneously and inversely calculate K_v values.

Equation (1) can be rewritten such that

$$h = \frac{K_v \tau}{B} \quad (3)$$

where $h = ln\ (h_1/h_2)$ (scaled hydraulic head), $\tau = (t_2 - t_1)$, and $B = (\pi D/11m + L_v)$. The inverse method minimizes the squared differences between the observed and calculated h

$$E = \sum_{i=1}^{N} (h_{oi} - h_i^*)^2 \quad (4)$$

where h_{oi} and h_i^* are the observed and calculated scaled hydraulic heads, respectively, at scaled time τ_i (i = 1, 2, 3, ..., N). N is the number of paired head readings used in the computation. The value of K_v is determined by iterations such that

$$K_v^{j+1} = K_v^j + \Delta K_v \quad (5)$$

where $\Delta K_v = \frac{B\sum_{i=1}^{N}(h_{oi}-h_i^*)(\tau_1,\tau_2,...,\tau_N)^T}{\sum_{i=1}^{N}(\tau_i)^2}$ with $(\tau_1, \tau_2, ..., \tau_N)^T$ = a column vector, and $K^j{}_v$ is the value calculated from previous iteration. The initial value $K^0{}_v$ was given prior to the first iteration.

The approach was also implemented using Eq. (2) to calculate the K_v values. For each permeameter test, a value of K_v was calculated based on Eqs. 1 and 2, respectively.

Statistical and geostatistical analysis of the streambed hydraulic conductivities

Kruskal-Wallis test was used to determine the similarity of the K_v values of the streambed between each test site. The hypotheses tested by the Kruskal-Wallis test include: H_0: all of the n population distribution functions are identical; H_1: at least one of the populations tends to yield larger observations than at least one of the other populations (Conover 1980; Gilbert 1987).

At each test location, water depth was measured. The correlation coefficients between K_v and water depth were computed for individual transects to evaluate their relationship.

Experimental variograms were computed for the Doniphan and Ashland test sites. Because the measurements of K_v along each transect at the two sites were at regular sampling intervals, one-dimensional variograms (or semi-variograms) were calculated using (Webster and Oliver, 2000)

$$\gamma(p) = \frac{1}{2(M-p)} \sum_{i=1}^{M-p} (K_i - K_{i+p})^2 \quad (6)$$

where i = 1, 2, 3, ..., M denote the locations of permeameter tests, and p is the number of lags. Variogram models were derived by fitting the experimental variograms.

Results and Discussions

Variation of K values across the river channels

Most permeameter tests were conducted to measure K_v of the streambed, and a few tests were for K_h. At the Ashland site (Fig. 1), permeameter tests were conducted along four transects (Fig. 4) on the west half of the Platte River, three transects approximately perpendicular to the river and one parallel to it. The average K_v values for transects I through IV were 9.1, 19.4, 21.8, and 22.3 m/d, respectively. The values of K_v show a spatial variation across each transect (Fig. 5). The values of K_v from transect I are the smallest among the four

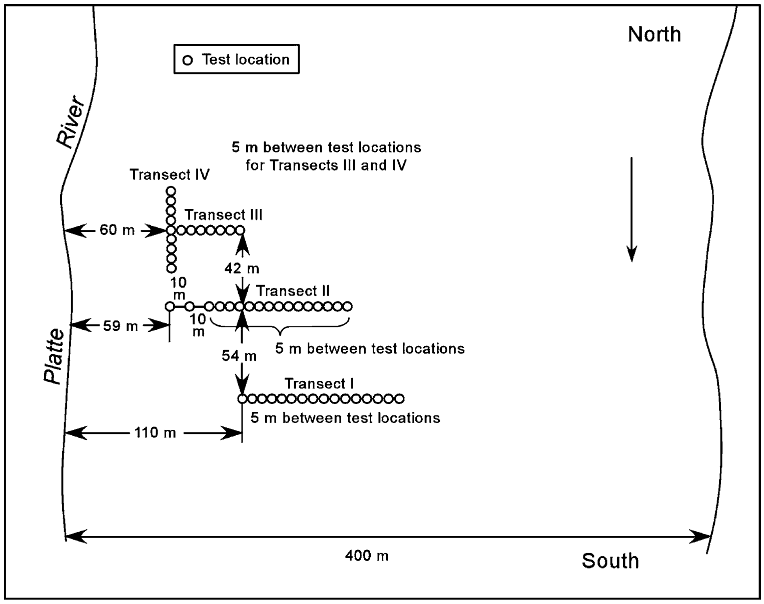

Fig. 4 Locations of permeameter tests along four transects in the Platte River, the Ashland test site, eastern Nebraska

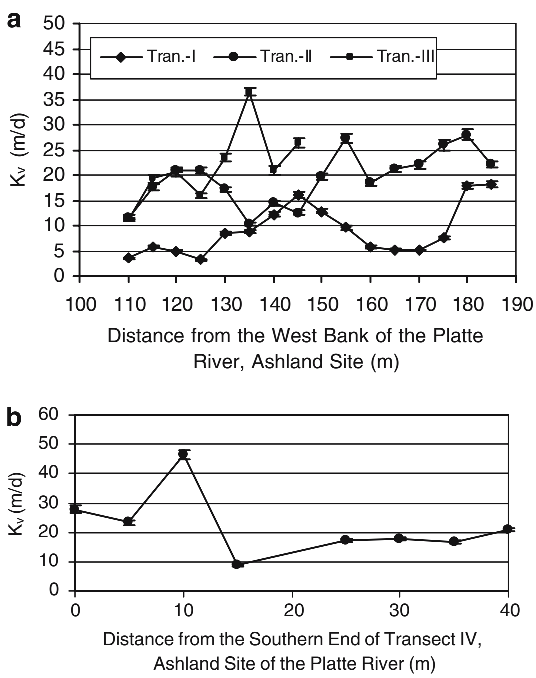

Fig. 5 Variation of K_v values along transects I, II, and III (**a**) and transect IV (**b**) at the Ashland site

transects. The K_v values from transects I, II, and III (Fig. 5a) have an increased tendency toward locations farther from the river bank. These permeameter tests were conducted on June 19 and 20, 2002, and during that time, the daily streamflow rate was 121 and 147 m^3/s at the Ashland gauging station (http://water.usgs.gov/waterwatch/). The averaged water depth of the test locations along transects I, II, III, and IV was 8.9, 14.2, 23.1, and 7.8 cm, respectively.

One permeameter test was conducted to measure K_h, and it was 58.5 m/d. Another test was conducted to measure the hydraulic conductivity along a 45-degree angle from the streambed, and the value was 24.8 m/d. The two tests were conducted near the middle of transect IV. Chen (2000) described the methods of measuring the K values along arbitrary directions in streambeds.

A total of 10 permeameter tests were conducted across the main channel of the Platte River near Central City (Fig. 1). Figure 6a shows the variation of eight K_v values, from 19 to 64.3 m/d, across the Platte River channel, about 236 m wide at the test site. The average K_v values along this transect were 43.7 m/d. A pair of tests was conducted 15 m north of the transect and about 75 m from the north bank of the river. One test was for K_h (60.3 m/d) and the other was for the K_v (53 m/d). The value of K_h is slightly larger than the value of K_v. These tests were conducted on September 18, 2002, and the daily streamflow at the Grand Island gauge was 14.3 m^3/s. The averaged water depth of the test locations was 16.3 cm.

Four permeameter tests 10 m apart were conducted in the south channel of the Platte River near Chapman (Fig. 1). The K_v values were 61.9, 41.2, 41.5, and 42.4 m/d, respectively. The channel was 80 m wide. These tests were conducted on September 18, 2002.

Twenty-one permeameter tests were conducted in the south channel of the Platte River at the Doniphan test site (Fig. 1). The channel was 156 m wide and divided by a sand bar of 62 m into a south and north part. Eighteen tests were conducted in the north part at 3 m intervals. Figure 6b shows the K_v values varying along the transect

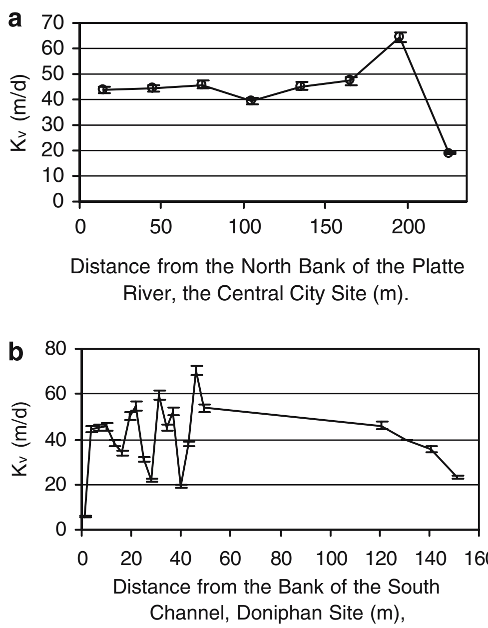

Fig. 6 Variation of K_v values across the Platte River at the Central City test site (**a**) and at the Doniphan test site (**b**)

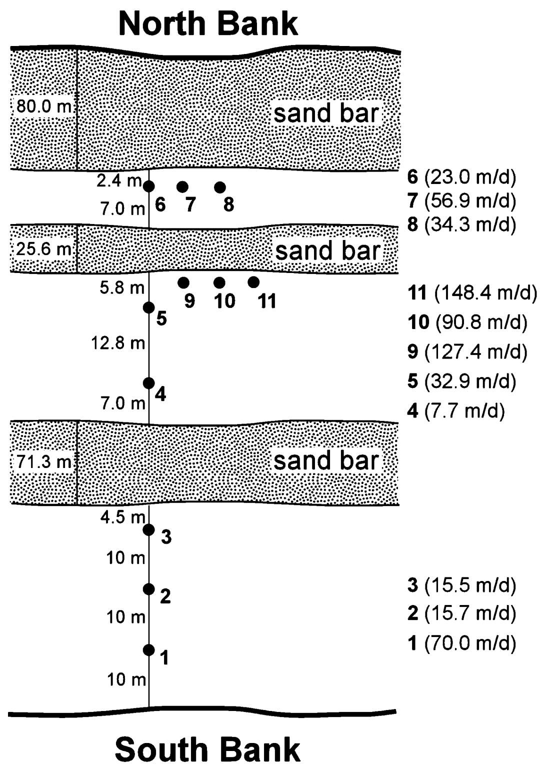

Fig. 7 The vertical and horizontal streambed hydraulic conductivities at the Kearney test site on the Platte River

ranging from 5.8 to 68.4 m/d, with an average value of 42.4 m/d. These tests were conducted on September 17, 2002; the average water depth of the 21 test locations in the south channel was 13.8 cm.

Figure 7 shows locations of 11 permeameter tests in the Platte River near Kearney. The tests were conducted on October 15, 2004, and the streamflow, recorded in the nearby gauging station, was about 6 m^3 /s, 1/6 of the averaged rate of this day between 1982 and 2002. As shown in this figure, large sand bars appeared in the river channel and occupied a large width of this channel. Among the 11 tests, eight (tests 1 through 8, see Fig. 7) were conducted to measure the vertical hydraulic conductivity and three (tests 9, 10, and 11) for horizontal hydraulic conductivity. The hydraulic conductivity values are shown in Figure 7. The vertical hydraulic conductivity also varies largely in space with an average value of 32.5 m/d. The horizontal hydraulic conductivity varies from 98.8 to 148.4 m/d. These few tests for K_h are not sufficient to characterize the spatial variation of K_h. These K_h values are smaller than those determined by slug tests (Rus et al. 2001) for other parts of the Platte River channel and those determined by a pumping test in an island on the Platte River (Chen and Chen 2003).

Figure 8 shows the histogram of the K_v values from all the test sites in Figure 1, with the exclusion of three K_v values for clay/silt at test site I305, the values of which range from 0.8 to 2.8 m/d (Chen 2004). The mean of K_v from 124 measurements is 31.2 m/d and the standard deviation is 17.1 m/d. The skewness is 0.445.

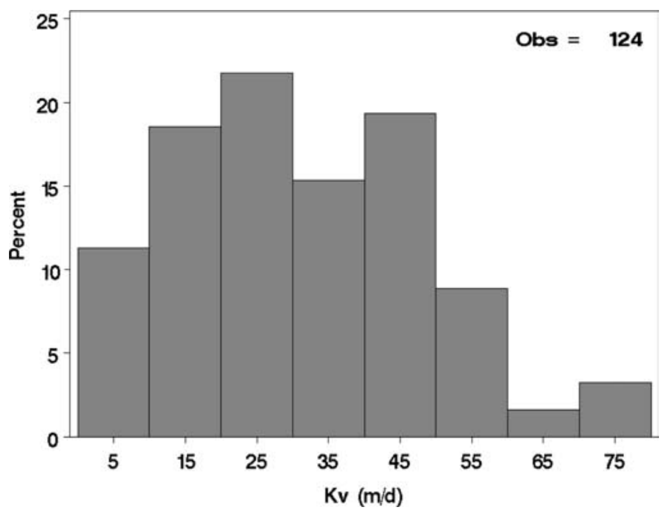

Fig. 8 Histogram showing the distribution of the K_v values from all the test sites

The Shapiro-Wilk test indicates that these K_v values are not normally distributed but its distribution is close to normal.

Kruskal-Wallis test

The Kruskal-Wallis test was used to determine the similarities of the K_v values from these test sites presented in Figure 1. The K_v values from 13 transects of the eight test sites, including five transects of three sites from Chen (2004), were treated as individual groups. The number of samples in these transects varies from four to twenty one. For meaningful results using the Kruskal-Wallis test, a total of three groups of data and three samples in each group are needed. The K_v data meets this requirement. The results of the Kruskal-Wallis test at the $\alpha = 0.05$ level indicate that

1. The K_v values from the sites between Central City and Kearney, located in south-central Nebraska, have the same mean or statistically belong to the same population;
2. The mean of the K_v values from each of the four transects at the Ashland site differs from the mean of the K_v values from the sites above Central City;
3. At the Ashland site, the four groups have different means; K_v values from transects II, III, and IV come from the same population, but the K_v values of transect I belong to another population.

After exclusion of the 48 K_v values from the Ashland site, the K_v values of the Platte River in south-central Nebraska show a normal distribution (Fig. 9). The mean is 40.2 m/d, standard deviation is 14.8 m/d, and skewness is 0.16. Mean K_v values for transects I, II, III, and IV at the Ashland site are only 9.1, 19.4, 21.8, and 22.8 m/d, which are about half or less than half of the mean K_v in the other test sites. The lower streambed hydraulic conductivity at the Ashland site and its different statistical behavior are likely due to a supply of fine grains of sediments in the surrounding and adjacent watersheds, which were deposited in this shallow and wide reach of the Platte River.

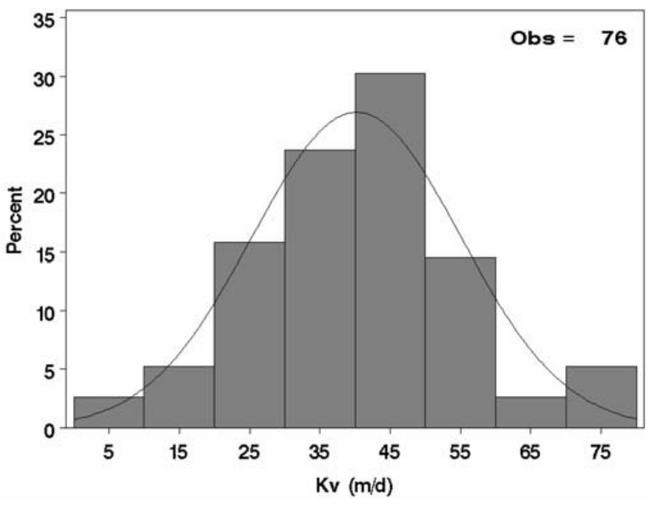

Fig. 9 Histogram showing a normal distribution of the 76 K_v values from the Platte River in south-central Nebraska

Correlation between water depth and K_v values

Correlation coefficients between water depth and the vertical hydraulic conductivity were calculated for several transects. The correlation coefficients for transects I, II, III, and IV at the Ashland site were 0.61, 0.38, 0.6, and 0.23, respectively. The correlation coefficient was 0.43 for the Central City test site, and 0.79 for the Kearney test site. The correlation coefficient for the Doniphan test site was 0.43, excluding the K_v from the test location closest to the northern bank, but became 0.16 including this value. This extreme value generates an erratic result compared to other correlation coefficients, and it is probably an outlier (Kitanidis 1997). All the correlation coefficients were positive. A larger K_v value often occurred in the part of the channel with deeper water where the flow velocity is usually larger. The area of the channel where the water is deeper will likely have larger flow velocity, which can wash finer-grained particles off and carry them to areas of lower flow velocities.

Water depth in river channels represented only the present flow conditions during permeameter tests, but the sediment column tested for streambed hydraulic conductivity was deposited over a prolonged period, during which the flow conditions may have fluctuated. The correlation between the two variables may not be perfect. Nevertheless, these positive correlation coefficients suggest the influence of flow condition on the distribution of streambed hydraulic conductivities in the Platte River.

Spatial variation of K_v across the channels

Spatial correlation of a geological variable often decreases with the increase in distance between two measurements. Variograms describe the spatial correlation of a geologic variable and increase with the lag distances of two tests. Variogram models such as spherical, exponential and Gaussian models have been commonly used to describe monotonic features of spatial correlation as the lag distance increases (Kitanidis 1997). Some variables, however, seem to fluctuate more or less periodically. A sine hole effect variogram model describes the damped oscillation around the sill (Olea 1999). Webster (1977) indicated periodic behaviors of some soil survey data.

Experimental variograms of K_v were calculated for the Doniphan and Ashland test sites. For the Doniphan site, only the K_v values north of the sand bar were used in the computation. A normality test indicates that these

K_v values are normally distributed. However, the analysis of correlation between K_v and water depth suggested that the K_v value from the location nearest to the north bank was an outlier and was excluded for the calculation of the experimental variogram. Figure 10a shows the curves of the experimental variogram and the fitted variogram model. A periodicity of spatial variation can be observed from this variogram. The fitted variogram model is written as follows:

$$\gamma(h) = 66.35 + 107.7[1 - \sin(\frac{2\pi h}{13.45} + 1.72)]. \quad (7)$$

The variogram was fitted using the least squares methods in SAS (SAS Institute 2001). The nugget effect of this variogram is 66.35; the amplitude and length of wave are 107.7 and 13.45, respectively; the phase shift is 1.72. The length of wave indicates the horizontal distance beyond which the level of spatial correlation repeats. This experimental variogram shows three periodicities in about a 40-m lag distance.

An experimental variogram was also calculated using the K_v values measured along Transect I at the Ashland test site. Figure 10b shows the curves of the experimental variogram and the fitted model. Periodicity also appears in this variogram. The fitted variogram model is

$$\gamma(h) = 8.65 + 13.19\left[1 - \sin\left(\frac{2\pi h}{38.66}\right) + 1.05\right]. \quad (8)$$

The nugget effect of this variogram is 8.65; the amplitude and length of wave are 13.19 and 38.66, respectively; the phase shift is 1.05. The length of wave for this variogram is about three times wider than that for the Doniphan site. This can probably be attributed to the wider channel at the Ashland test site. The channel width was about 400 m at the Ashland site but only 156 m at the Doniphan site in which a sand bar of 62 m existed.

The water depth, measured during permeameter tests, also fluctuated across the channels at both test sites. Figure 11a shows the water depth in the south channel of the Platte River at the Doniphan test site. As can be seen from this figure, the stream stage was relatively shallow ($<$ 30 cm). This curve of water depth does show some periodicity, which may indicate its moderate impact on the periodicity occurring in the K_v values. An experimental variogram was thus calculated to determine its possible periodicity. Figure 11b shows the experimental variogram of the water depth for the Doniphan site. It clearly displays the periodicity of the wave length, which is similar to that in the experimental variogram of K_v.

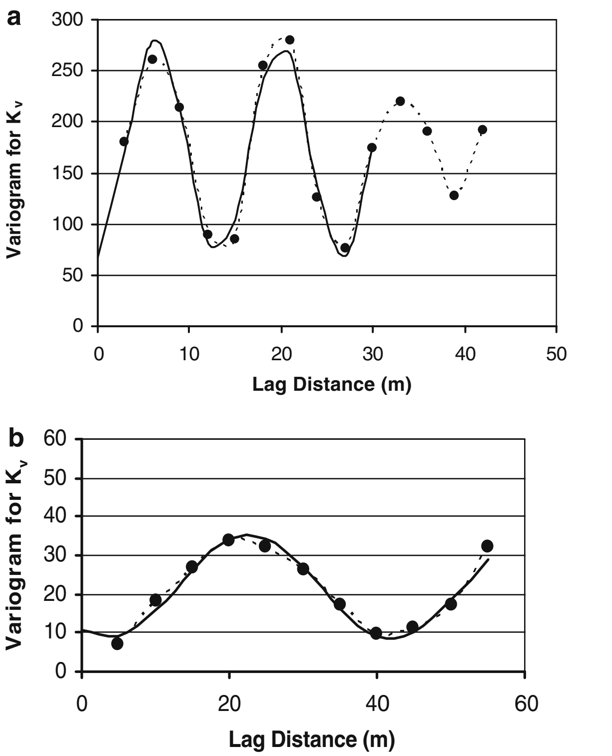

Fig. 10 Experimental varigram and fitted variogram (*solid line*) models for the K_v values at the Doniphan test site (**a**) and for the transect I of the Ashland test site (**b**)

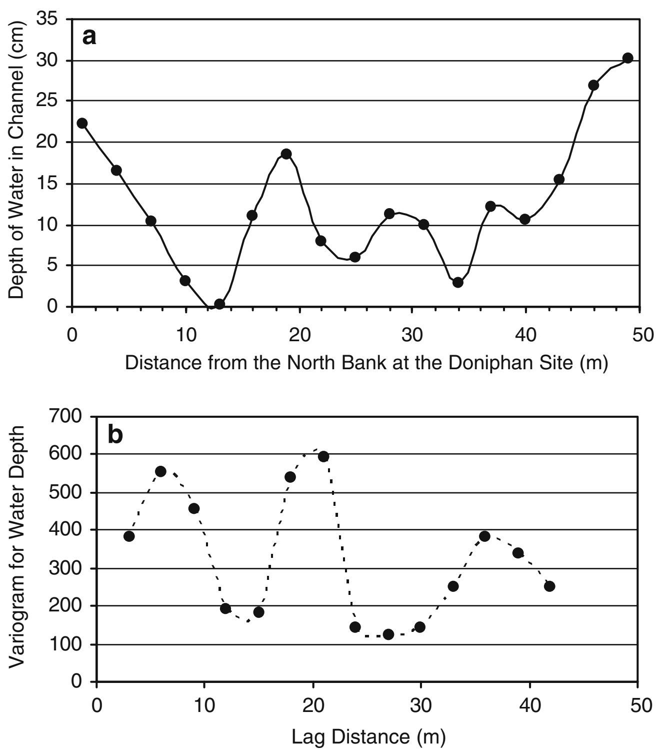

Fig. 11 Variation of water depth (**a**) across the south channel of the Platte River at the Doniphan test site and the experimental variogram of the water depth (**b**)

Summary

The vertical hydraulic conductivity of a sandy streambed in the Platte River has a wide range, varying from about 3 to 65 m/d. The variation can occur in short distances, for example, 3 m apart, and is observed along transects across or parallel to channels of this river.

Statistically, the K_v values from all the test sites between Kearney and Central City, south-central Nebraska, are the same but differ from the K_v values from the Ashland site. This difference is mainly attributed to the addition of finer sediments in the Platte River in eastern Nebraska. The fine sediments carried by the Loup River and the Elkhorn River, as well as from other small creeks to the Platte River, result in a lower vertical K_v value of the streambed for the Ashland site. At the Ashland site, the K_v values belong to two populations. The K_v values from Transect I are statistically different from K_v values from the other three transects.

There is a positive correlation between K_v and the water depth, ranging from 0.23 to 0.79 for the test sites. Larger K_v often occurs in the part of channels with greater water depth. Periodic features of K_v values across the channel were observed. This periodicity is probably produced by the variation of water depth across the channel, which controls the flow velocity.

Several permeameter tests conducted to measure the horizontal hydraulic conductivities of the streambed suggest that the horizontal hydraulic conductivity of streambed was larger than the vertical hydraulic conductivity at the same test locations. The streambed of the Platte River at the study sites consists mainly of sand and gravels; silt and clay layers occur only sporadically. No spatially continuous low-permeability layer was observed at the study sites.

Acknowledgments This work was partially supported by a U. S. Geological Survey grant (104b) through the Water Center of the University of Nebraska-Lincoln. Jerry Leach, Yanfeng Yin, and Fujiang Wen assisted permeameter tests on the Platte River. Dee Ebbeka and Ann Mack drafted several figures. Charlie Flowerday provided editorial reviews. This paper is assigned Journal Series Number 14922, Agricultural Research Division, University of Nebraska-Lincoln.

References

Bentall R (1971) Water supplies and the land – the Elkhorn River basin of Nebraska, Conservation and Survey Division Resource Atlas No. 1, University of Nebraska-Lincoln, 51 p

Conover WJ (1980) Practical Nonparametric Statistics, 2nd edn. John Wiley& Sons, New York, p 493

Chen XH (2000) Measurement of streambed hydraulic conductivity and its anisotropy. Environmental Geology 39(12): 1317–1324

Chen XH, Chen X (2003) Sensitivity analysis and determination of streambed leakance and aquifer hydraulic properties. Journal of Hydrology (284): 270–284

Chen XH (2004) Streambed hydraulic conductivity for rivers in south-central Nebraska. Journal of the American Water Resource Association 40(3): 561–574

Gilbert RO (1987) Statistical Methods for Environmental Pollution Monitoring, Van Nostrand Reinhold, New York, p 320

Hutson SS, Barber NL, Kenny JF, Linsey KS, Lumia DS, Maupin MA (2004) Estimated Use of Water in the United States in 2000. U. S. Geological Survey Circular 1268, 46 p

Hvorslev MJ (1951) Time lag and soil permeability in ground water observations. Waterways Experiment Station, Corps of Engineers, U. S. Army Bulletin 36, Vicksburg, Mississippi, p 50

Kitanidis PK (1997) Introduction to Geostatistics, Applications in Hydrogeology, Cambridge University Press, p 249

Landon MK, Rus DL, Harvey FE (2001) Comparison of instream methods for measuring hydraulic conductivity in sandy streambeds. Ground Water 39(6): 870–885

Nguyen QM, Gilliland MW (1985) Soil, surface water, and groundwater characteristics of the Platte River and its aquifer in the vicinity of Grand Island's Platte River well field. Report prepared by Department of Civil Engineering, University of Nebraska-Lincoln Omaha Campus

Olea RA (1999) Geostatistics for Engineers and Earth Scientists. Kluwer Academic Publishers, Boston

Rus DL, McGuire VL, Zurbuchen BR, Zlotnik V (2001) Vertical profiles of streambed hydraulic conductivity determined using slug tests in central and western Nebraska. U. S. Geological Survey Water-resources Investigation Report 01–4212, 32 p

SAS Institute (2001) SAS/STAT, Version 8, 1999–2001, SAS Institute Inc., Cary, NC, USA

Webster R (1977) Spectral analysis of gilgai soil. Australian Journal of Soil Research 15, 191–204

Webster R, Oliver M (2000) Geostatistics for Environmental Scientists, John Wiley& Sons, LTD, New York, 271 p