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This manuscript will appear in Journal of the American Water Resources Association. The data in this paper may be useful in the analysis of stream-aquifer connectivity.

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Streambed Hydraulic Conductivity for Rivers in South-central Nebraska

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Abstract

This paper presents hydraulic conductivities of streambeds measured in three rivers in south-central Nebraska: the Platte, Republican, and Little Blue rivers. Unlike traditional permeameter tests in streams that determine only the vertical hydraulic conductivity (K_v), the extended permeameter methods used in this study can measure K in both vertical and horizontal as well as oblique directions. As a result, the anisotropy of channel sediments can be determined from streambed tests of similar sediment volumes. Sandy streambeds with occasional silt/clay layers exist in the Republican and Platte rivers. The average K_v values range from about 15 to 47 m/day for the sandy streambed and about 1.6 m/day for the silt/clay layers. Statistical analyses indicated that the K_v values of sand and gravel in the Platte and Republican rivers essentially have the same mean; but, the K_v values from the Little Blue River have a statistically different mean. K_v is about 4 times smaller than the horizontal hydraulic conductivity (K_h) for the top 40-cm of sandy streambed. Measured K_h values of the sandy streambed are in the same magnitude as the K_h of the alluvial aquifer determined using pumping tests. The smaller K_v value in the whole aquifer is the result of interbedded layers of silt and clay within the sand and gravel sediments.

Key Words: Streambed sediments, hydraulic conductivity, permeameter test, stream-aquifer interactions.

Introduction

Streambed hydraulic conductivity is a key parameter in the analysis of stream-aquifer interactions. Calver (2001) summarized the hydraulic conductivities (K) of streambeds from various reports and showed a variation of over eight orders of magnitude with a common range of 0.0086 to 86.4 m/d. Variability within a site can also be over several orders of magnitude. Hydrauilc conductivity of the streambed varies also in time (Kaleris 1988; Kaleris 1998). It is difficult to select a representative K value for a given stream because each stream has a unique depositional environment. Therefore, for a given study site, field investigations conducted directly in the stream channels are a necessary aspect of the analysis of stream-aquifer interactions.

Evaluation of K in stream channels has been reported by numerous researchers (de Lima 1991; Duwelius 1996; Chen 2000; Landon et al. 2001; Rus et al. 2001). Common methods include the use of permeameters (de Lima 1991; Duwelius 1996; Landon et al. 2001; Chen 2000) and slug tests (Rus et al. 2001). Numerical modeling techniques were also used for estimation of K by calibration of hydraulic head (Yager 1986; 1993). Slug tests have been used to measure the horizontal hydraulic conductivity (K_h) of sediment around a perforated stand pipe, and permeameters have been used to measure the vertical hydraulic conductivity (K_v) of streambed sediments inside a pipe that is not perforated (Duwelius 1996; Landon et al. 2001). Such a practice can lead to the ratio of the measured K_h to K_v (anisotropy ratio) being less than one for the streambed materials. For example, Duwelius (1996) reported the anisotropy ratio at one transect in the east branch of the Grand Calumet River in Indiana as 1:8.5. Similarly, Landon et al. (2001) reported that the average anisotropy ratio of the streambed in the Platte River, Nebraska, is about 1:1.7. Landon et al. (2001) suspected that one of the reasons for this value being contrary to typical values for K_h to K_v ratios, which range from one to 100 for alluvial sediments, is the difference of design between the slug test and permeameter test. In contrast, Chen (2000) extended the permeameter method for measuring K_v and K_h of streambeds and reported that the anisotropy ratio (K_h/K_v) was between 3 and 4 for the top layer of the streambed in the Republican River, Nebraska. In the analysis of the permeameter test data, two formulae have been used in the estimation of K values. One results in an overestimation; the other gives underestimated K values. Chen (2000) discussed the associated errors of underestimation. The possible errors of overestimation of K values need, however, to be discussed.

Most streams in the High Plains region of the United States are believed to be hydraulically connected to the nearby alluvial aquifers. Thickness of channel sediments can easily exceed 10 m. In some streams of Nebraska, the sediments are often the same as the materials of the nearby alluvial aquifers (Swinehart et al. 1994). While permeameters test a small volume of streambed sediment, a pumping test affects a much larger volume of aquifer sediments. A number of pumping tests conducted in the Platte and Republican river valleys, Nebraska, have given estimates for the K values of the alluvial aquifers. The results of the pumping tests, combined with the results of instream methods, provide a picture of K values for the stream-aquifer systems.

In this study, streambed tests using permeameters were conducted in three rivers of south-central Nebraska (Figure 1): the Platte, Republican, and Little Blue rivers. Most tests were conducted to determine K_v of streambeds. The K values in the horizontal and oblique directions were also determined at several locations. This paper will first describe a method for determination of K by instream methods. It will then present K values of streambed sediments across channels, between up- and downstream segments of the same stream, and between different streams in south-central Nebraska. Finally, a discussion of the anisotropy of streambeds and alluvial aquifers is provided.

Method

Figure 2 is a schematic diagram showing a permeameter test in a streambed, which determines K_v [L/T] of a sediment column inside a standpipe. Hvorslev (1951) provided a formula to calculate the K_v of the sediment column in the pipe such that

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

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 inside the pipe corresponding to 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 Equation (1). This simplification results in an overestimation of the K_v value for anisotropic stream sediments with $K_h > K_v$. Figure 3 shows the deviation between the values resulting from Equation (1) for m = 1 and the values for m > 1. This deviation (negative values in Figure 3) is the overestimation of K_v values, and its magnitude is dependent on the ratio of L_v to D. A small ratio can lead to a very significant error. For a given D, a longer L_v can reduce the overestimation errors. An overestimated value of K_v may lead to the ratio of K_h (from a slug test) to the K_v value smaller than 1, as reported by Landon et al. (2001).

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

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

This simplification implies a very strong anisotropic streambed where $K_h >> K_v$. Chen (2000) noticed that this application can, however, underestimate the K_v value for stream sediments of smaller anisotropy, for example, $1 < m < 5$. Figure 3 shows the deviation (the positive values) between the value resulting from Equation (2) and the values from Equation (1) for $1 \leq m \leq 5$. This deviation indicates the underestimated error. For stream sediments with $m > 3$, utilization of Equation (2) gives the K_v value in which an underestimated error is smaller than the amount of overestimation resulting from Equation (1) with $m = 1$. Equation (2) has been presented in several textbooks (Todd 1980; Domenico and Schwartz 1990), and it has been used to estimate K_v values of streambeds (de Lima 1991; Landon et al. 2001). Figure 3 shows that the underestimated errors in K_v can be reduced by increasing the ratio of L_v/D. When $L_v/D > 5$, the error will be less than 5% for any anisotropic sediments (or any m values).

Presumably, both K_v and K_h values may be simultaneously determined from Equation (1) using regression methods (Beck and Arnold, 1977; Chen 1998). If that can be done, the above-mentioned estimation errors can possibly be avoided because the value of m is no longer assumed. The analysis of sensitivity (McElwee 1987) of the hydraulic head h with respect to K_v and K_h indicates that h is often more sensitive to K_v by two orders of magnitude. Figure 4 shows the normalized sensitivities of h to K_v and K_h, that is, $K_v(\partial h/\partial K_v)$ and $K_h(\partial h/\partial K_h)$. Low values of $K_h(\partial h/\partial K_h)$ are obtained for streambed tests with a large L_v but a small D. This is because the role of K_h near the bottom of the pipe becomes insignificant. As shown in Figure 4, the sensitivity (its absolute value) increases as a permeameter test progresses, but it decreases as the test time approaches a certain value (about 20 minutes in this case). After this time, continuation of the permeameter test is no longer necessary. The parameters used for the calculation of the sensitivities in Figure 4 include $K_v = 30$ m/day, $K_h/K_v = 3$, $L_v = 40$ cm, and D = 10 cm.

A nonlinear regression method (Chen 1998) was applied to determine both K_v and K_h values simultaneously from field test data and hypothetical time-head data. In that, the squared difference between measured hydraulic head and calculated head was minimized. However, the analyses all failed to converge. The low sensitivity of K_h to h is believed to be the main reason for this nonconvergence. The high correlation between the two sensitivities is also an important factor. Readers are referred to Beck and Arnold (1977) and McElwee et al. (1995) for a detailed discussion of nonconvergence of the fitting process.

Chen (2000) proposed to directly measure the horizontal hydraulic conductivity (K_h) of streambed using an L-shaped standpipe (Figure 5a). The angle between the two segments of PVC pipe is 90°. The horizontal segment is inserted into the streambed and is filled with channel sediments. Tests can be conducted after pouring water into the vertical pipe. The values of K_h can be calculated using

$$K_h = \frac{L_h}{(t_2 - t_1)} \ln(h_1 / h_2) \qquad (3)$$

where L_h is the length of the sediment column in the horizontal pipe. Here, the anisotropic feature of the sediment surrounding the end of the horizontal segment may have some effect on the analysis of the falling head tests. However, such an effect can be minimized using a slightly longer sediment column in the horizontal pipe.

Similar techniques can be utilized to determine the hydraulic conductivity of the streambed along a direction between the horizontal and vertical (Figure 5b), or the oblique direction. The angle between the two pipes is greater than 90°. During the test, one pipe is driven into the streambed and the other stands vertically. The angle between the pipe in the sediment and the stream bottom is denoted as θ; the hydraulic conductivity for the sediment column is $K_s(\theta)$ along the direction of θ and is calculated using

$$K_s(\theta) = \frac{L_s}{(t_2 - t_1)} \ln(h_1 / h_2) \tag{4}$$

where L_s is the length of sediment column in the oblique pipe. The K values of a streambed for vertical, horizontal, and a number of oblique directions can be used to construct a hydraulic conductivity ellipse.

Study Areas and Test Sites

The study areas are located in south-central Nebraska where the Platte and Republican rivers flow from west to east (Figure 1). Lateral migration of both rivers during the Pleistocene deposited alluvial sediments in the river valleys where the yield of irrigation wells often ranges from 2,700 to 5,400 cubic meters per day. Three test sites were selected along the Platte and Republican rivers, respectively, and one test site was selected in the Little Blue River. A number of pumping tests have been conducted in the nearby alluvial aquifers in the Republican and Platte River valleys and the hydraulic conductivities have been reported by Wenzel (1942), McGuire and Kilpatrick (1994), Ayers et al. (1998), Chen (1998), Chen et al. (1999), and Chen et al. (2003).

Table 1 summaries the characteristics of the channels at the test sites. The streambed in the Republican River consists predominantly of sand. Local silt and clay sediment layers covered some small sand bars. Figure 6 shows the average grain size distribution curves of 30 sediment samples collected from the river in Franklin County and 26 sediment samples from Red Willow County. The width of the river is from 20 to 50 m, and the water depths were 20 to 30 cm during streambed tests that occurred in September 1999, November 2000, and August 2001. Streambed tests were conducted in the river near Orleans, Bloomington and Red Cloud (Figure 1). Tests were conducted along three transects across the river at the Orleans site and two transects at the Red Cloud site (Figure 7); these tests were conducted to determine K_v. While most tests at these two sites were conducted in sandy sediment, a few involved silt and clay layers. The tests at the Bloomington site were near the middle of the river for determination of K_v, K_h, and K_s. In addition to sand and gravel, the stream sediments at this site contain scattered fragments of Cretaceous shale, ranging from 1.5 to 2.5 cm in diameter.

The Platte River in the study area is braided and consists of several channels. The width of the channels varied from 50 to 250 m. The water depth was about 25 cm during the streambed tests in early October 2001. The streambed consists mainly of sand and gravel. Local silt and clay layers covered some sand bars, which were above stream water levels. The Platte River in the study area is approximately parallel to US Highway I-80. The three exits of I-80, Exits 305, 285 and 279, are used to designate the test sites: PR-I305, PR-I285, and PR-I279. Streambed tests were conducted in two channels at PR-I305, two parts of the same channel at PR-I285, and in one channel at PR-I279 (see Figure 1 for test site locations).

The Little Blue River, originating in southeastern Nebraska, flows from northwest to southeast. The river is 60 m wide at the study site, and water depth was about 10 cm during the tests in August 2001. The sediment at the study site consists mainly of sand and gravels. The channel sediments are about 5.6 m thick in the study area, and the bedrock is the Cretaceous Dakota Formation. Streambed tests were conducted to measure K_v along two transects.

Results

1. *Directional Hydraulic Conductivities*

Streambed tests for K_v, K_h, and K_s were conducted at the Bloomington site. PVC pipes of an inside diameter of 10, 7.5 and 5 cm, respectively, were used to make the test instruments, as illustrated in figures 2 and 5. Two angles, $\theta = 22.5$ and 45°, were considered in the investigation of the K_s values. The test locations between the three pipes were one meter apart. In order to use all the head readings simultaneously in a single computation, a nonlinear regression method (Beck and Arnold 1977; Chen 1998) was used to inversely calculate the values of K_v, K_h, and K_s. K_v was calculated using equations (1) and (2), respectively; the two K_v values were then averaged to represent the vertical hydraulic conductivity of the streambed sediment. The calculation of K_h and K_s was based on equations (3) and (4), respectively. Table 2 summarizes the values of streambed hydraulic conductivities. According to the averaged K_h and K_v values, the ratio of K_h/K_v is about 7.6. Chen (2000) conducted streambed tests near the riverbank at this site where the sandy sediment did not contain shale fragments and reported 141 and 43 m/day for K_h and K_v, respectively.

A nonparametric statistical test, the Kruskal-Wallis test (Conover 1980), was performed to determine the statistical difference of the K values estimated from the permeameter tests of the three diameters of pipes. A total of 15 K values for the Bloomington test site, five from each group, were used in the statistical analysis. The values for $K_s(\theta=22.5^\circ)$ were not used because permeameter tests were not conducted for $D = 5$ cm along the angle $\theta = 22.5^\circ$. The results of the Kruskal-Wallis test indicate that the K values from the three pipe diameters have the same population distribution functions. Thus, the variation in the pipe diameter did not result in a statistical difference of these K values shown in Table 2.

Directional tests were also conducted at site PR-I279 in the Platte River (see Figure 1 for the site location). The tests were conducted using the 10-cm pipe only. The calculated values of K_h, K_v, $K_s(22.5^o)$, and $K_s(45^o)$ are 101.2, 24.3, 66, and 29 m/d, respectively. The ratio of K_h/K_v is 4.2.

2. *Vertical Hydraulic Conductivities*

Tests of stream sediment at the other sites were conducted to measure only the vertical hydraulic conductivities. Only PVC pipe of an inside diameter of 10 cm was used for these tests.

Figure 7 shows the locations of the tests at the Orleans site. The distance between two tests was mostly 3 m. Deeper water near either the south or north bank prevented any streambed test at some locations. Table 3 summaries the range of the vertical sediment columns formed in the pipe and the length of the tests.

For each test, the value of K_v was calculated using equations (1) and (2), respectively. K_h/K_v was assumed to be 1 in the utilization of Equation (1). As mentioned earlier, the use of Equation (2) implies that K_h is significantly larger than K_v. The calculated results are plotted in Figure 8(a) against the test locations. For each test, an error bar is used to show the two values of K_v derived from the two equations; the smaller one is computed using Equation (2) and the larger one is from Equation (1) with $m = 1$. As shown in this figure, the underestimated and overestimated K_v values are very close to each other. The true K_v value is believed to be between them but is not the average of the two. The linear line connecting the neighboring pairs is only for the purpose of graphing and is not an indication of a linear interpolation of K_v between any two test locations. The tests along transects 2 and 3 were on sandy streambed, and their K_v values vary from about 20 to 64 m/day. Tests along transect 1 occurred in sandy streambed, as well as in silt and clay deposits. The calculated K_v values are from 0.6 to 2.5 m/day for this low-permeability bed, and the average is 1.54 m/day. As shown by Figure 8(a), the K_v values along a transect or between the transects can vary significantly.

At the Red Cloud site, streambed tests were conducted along two transects 37 m apart (Figure 7). The average vertical sediment column in the pipes was 42.6 cm for 16 tests (Table 3). Figure 8(b) shows the K_v values of the streambed. Again, two K_v values were calculated for each test, and both are plotted in this figure. Most K_v values are around 30 m/day, but it can be as low as 6.5 m/day and as high as 58 m/day. The K_v values at this site seem to be more uniform than those from the Orleans site.

The test site in the Little Blue River is to the west of the city of Fairbury. About one third of the streambed was above the stream stage at the time of testing, so on this part of the streambed tests was unable to be conducted. Sixteen streambed tests were conducted along two transects in the sediments that were under water; the two transects were 63 m apart. The average length of the sediment column in the pipe was 45.1 cm for these tests. The calculated K_v values are plotted in Figure 8(c), and they vary from 23.6 to 80.7 m/day.

Streambed tests at site PR-I279 (Figure 1) were conducted in the south channel of the Platte River. The length of the vertical sediment columns in the PVC pipes ranges from 37 to 40.5 cm, with an average of 38.1 cm for 10 tests. The calculated K_v values using equations (1) and (2) are shown in Figure 8(d). The K_v values of the streambed in the middle and northern parts of the channel are relatively constant and are around 30 m/day. The K_v values for the streambed in the southern part of the channel show more variation, and they vary from about 20.7 to 54.4 m/day. The average K_v value at this site is 31.3 m/day.

Test site PR-I285 is about 6 miles downstream from the previous test site. Streambed tests were conducted in the middle channel of the Plate River. A larger island, about 90 m wide, divides the middle channel into north and south parts. Five tests were conducted in the south part of the channel. The K_v values are plotted in Figure 8(e); they vary from 26.3 to 54.2 m/day. Four tests were conducted in the northern part. The calculated K_v values are plotted in Figure 8(f); they range from 24.9 to 36.1 m/day and are lower than those in the south channel.

Streambed tests were conducted in two separate channels, the middle and south channels of the Platte River at the site PR-I305. The middle channel is 86 m wide, and the south channel is 228 m wide. This site is about 20 miles east of PR-I285. A total of 14 tests were conducted in the middle channel; among them, three were conducted in a silt/clay sediment. The other tests were in sand and gravel materials. The calculated K_v values are plotted in Figure 8(g). The K_v value for the sandy streambed varies from 26.1 to 77.8 m/day, and its average is 46.7 m/day; the K_v value for the silt and clay bed is from 0.8 to 2.8 m/d, and the average is 1.82 m/day. This value is close to the average K_v value of the silt and clay streambed at the Orleans site in the Republican River. A total of 10 tests were conducted in the south channel. The streambed is mainly sand and gravel. The calculated K_v values are plotted in Figure 8(h). They vary from 25.8 to 75.2 m/day, and the average is 46.8 m/day.

The averaged K_v values and the standard deviations for all the test sites in the three rivers are summarized in Table 4. The averaged K_v value for the sandy streambed is the highest for the Little Blue River and for the Platte River at PR-I305, and it is the lowest for the Republican River at the Bloomington site. The coefficients of variation (CV), the ratio of standard deviation to average K_v, are also summarized in Table 4. The CV values are larger for the silt/clay sediments than for sand and gravels. The CV values for the sand and gravel sediments range from 19.3 to 30.9% for the Republican River, and from 26.8 to 28.1% for the Platte River. The CV value for the Little Blue River is the largest (36.8%).

The Kruskal-Wallis test (Conover 1980) was used to determine the significance of the difference of the K_v values between two test sites of the same river and between the test sites of two rivers. There is no significant statistical difference in the K_v values between the Orleans and Red Cloud sites in the Republican River; the same result is found among the three test sites in the Platte River. The test indicated a significant statistical difference of the K_v values between the Little Blue and Republican rivers and between the Little Blue and Platte rivers, but there is no significant statistical difference of the K_v values between the Republican and Platte rivers for these test sites. The K_v values for silt/clay layers were excluded for the Kruskal-Wallis tests.

Discussion of Anisotropy

The average depth of the tested streambed sediments in the three rivers is about 40 cm. Field observation indicated that there are two distinct streambed materials in the rivers: sand and gravel vs. silt and clay sediments; the latter type is much more limited in its distribution. For the sand and gravel streambed materials, anisotropy is characteristic of the top part of the streambed shown from our results, with the K_h value being larger. The ratio of K_h/K_v is 4.1 for the sand and gravel at the test site PR-I279. An earlier study by Chen (2000) in the Republican River near McCook and Bloomington indicated the ratio of K_h/K_v to be from 3.3 to 4.9. A higher ratio of $K_h/K_v = 7.6$ was determined for sand and gravel that contains shale fragments in the middle of the Republican River at the Bloomington site.

Rus et al. (2001) conducted streambed slug tests at a number of locations in the Platte River and its tributaries. Among them, two locations are close to our test sites in the Platte River; one is near Grand Island, and the other is near Lexington. Their K_h values at a depth of 49 cm were 149 m/day near Lexington and 67 m/day near Grand Island, compared to the K_h value of 97.2 m/day determined by the test at PR-I279. All these K_h values are greater than the average K_v values of this study. They suggest the existence of anisotropy in the top part of streambed materials.

Borehole logs of the streambed materials from the construction of bridges over the rivers indicate that the sand and gravel streambed is interbedded with low-permeability silt and clay layers in the Platte River. According to the borehole logs and cross-sections for the channel sediment near the test site PR-I285 (the Nebraska Department of Roads), the streambed sediments above the Ogallala Group consist of three layers: two sand and gravel layers that are separated by a silt/clay layer in the middle. In one case, a silt/clay layer of 3.5 m separates an upper sand/gravel layer of 6.6 m from a lower sand/gravel layer of 5.6 m; in the other case, the middle layer of silt/clay is 1.4 m thick and the upper and lower sand/gravel layers are 4.7 and 5.9 m, respectively. Freeze and Cherry (1979) and Todd (1980) demonstrated that a strong anisotropy of a sediment profile can result from several interbedded layers, in which individual layers are less anisotropic.

A number of pumping tests were conducted in the vicinity of the Republican and Platte rivers. Table 5 summarizes the K_h and K_v values of the alluvial aquifers. Aquifer test results are not available in the vicinity of the Little Blue River. Wenzel (1942) conducted a pumping test in the alluvial aquifer about 4 miles east of Grand Island. Ground water level readings were collected from 83 observation wells during the pumping test that lasted about 48 hours (Figure 1). Analysis of the pumping test data by Chen (1998) indicated that $K_h = 108.1$ m/day with $K_h/K_v = 59.7$.

McGuire and Kilpatrick (1998) conducted two pumping tests in the alluvial aquifer at the Nebraska Management Systems Evaluation Area Site (MSEA), about 2 miles southwest of Shelton (Figure 1), and about 6 miles from the streambed test site PR-I285. The ground water pumping lasted 53 hours for the first test and 50 hours for the second test. The determined K_h values are 103.1 and 118.9 m/d, respectively, and the K_h/K_v ratios are 9.1 and 20, respectively, for tests 1 and 2.

Another pumping test in the alluvial aquifer conducted by Ayers et al. (1998), about 1 mile east of the MESA site (McGuire and Kilpatrick, 1998), also suggested a strong anisotropy of the alluvium. The determined average K_h is 210.2 m/day and $K_h/K_v = 51.3$. Chen et al. (2003) reported that the values of K_h and K_v are 104 and 9.5 m/d, respectively, from a pumping test conducted in the alluvial aquifer near Wood River. This pumping test site is about 2,500 m from the middle channel of the Platte River.

One pumping test was conducted in alluvium about 600 m from the Bloomington streambed test site in the Republican River valley (Chen et al. 1999). Pumping of ground water lasted about 24 hours. The derived K_h and K_v values are 104.3 and 1.5 m/day, respectively, and the ratio of K_h/K_v is 69.5. The K_h and K_v values determined from the streambed test at the Bloomington site are 115.4 and 14.5 m/day. Another aquifer test conducted in the alluvium near McCook (Figure 1) indicated that K_h and K_v values are 82 and 3.6 m/day with $K_h/K_v = 22.8$ (Chen et al. 1999). The unconsolidated alluvium at both sites is believed to be deposited by the Republican River during the Pleistocene.

A comparison of all the foregoing data indicates a similarity in the K_h values between the streambeds and the alluvial aquifers. A smaller K_v values for the alluvial aquifer is most likely due to the fact that the pumping tests in the aquifers sampled a larger volume of sediments and therefore more vertical heterogeneity. The impacted thickness of aquifer sediments by these pumping tests ranges from 10.4 to 30.5 m (Table 5), in which silt and clay layers are contained in the predominant sand and gravel. On the other hand, the permeameter tests sampled a sediment column that is only about 40 cm thick. This depth can hardly penetrate any interbedded sand and silt/clay layers.

Summary and Conclusions

Sandy streambeds commonly occur in the Little Blue River, the Republican River, and the Platte River in south-central Nebraska. Low-permeability silt and clay layers locally cover the river channels. The K_v for the top 40-cm sediment of sandy streambeds is usually greater than 20 m/day, and the most common range is from 30 to 40 m/day, but can reach as high as 80 m/day. In contrast, the average K_v for the silt and mud layer is about 1.6 m/day. Statistical analyses indicated that the K_v values of sand and gravel in the Platte and Republican rivers have about the same mean but the mean K_v value from the Little Blue River is somewhat different.

The sediment of the top 40-cm sand and gravel layers seems to be relatively uniform by field observation, and it can be regarded as a single layer. Nevertheless, anisotropy of the streambed conductivity can still be measured. The ratio of the horizontal to vertical hydraulic conductivity is about 4 for sandy sediments; this ratio is as large as 7.6 for sand and gravel that contains small shale fragments. These thin and flat fragments have apparently reduced the vertical hydraulic conductivity of the streambed.

The K_h values of the alluvial aquifers in the Republican and Platte river valleys determined using pumping tests are similar to the K_h values of the sandy streambed measured with permeameter tests. However, the K_v values of the alluvial aquifers are much lower than those of the top portion of the sandy streambed. This difference is due to layers of silt and clay in the entire alluvial thickness, which leads to a stronger vertical heterogeneity than for the upper layer of stream sediments. The K_v values of the sandy and silty streambeds determined using the method described here provide essential information in the analysis of the anisotropy of interbedded sediment layers.

Calculation of K_v values using Equation (1) for $m = 1$ and Equation (2) can possibly result in errors. These errors, however, can be minimized during instream tests by simply increasing the length of L_v (the length of sediment column) for a given D (the diameter of pipe).

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Figure Captions

Figure 1. Location map showing the streambed tests and aquifer pumping tests in south-central Nebraska.

Figure 2. Schematic diagram showing a permeameter test for measuring vertical hydraulic conductivities in a streambed.

Figure 3. Overestimated and underestimated errors by using equations (1) (with $m = 1$) and (2). Increase in the ratio of L_v/D will reduce the error.

Figure 4. Variation of normalized sensitivities, $K_v(\partial h/\partial K_v)$ and $K_h(\partial h/\partial K_h)$, with test time. Hydraulic head h is much more sensitive to K_v. Both sensitivity curves were calculated based on Equation (1).

Figure 5. Schematic diagrams showing permeameter tests in a streambed for measuring the K in the horizontal (a) and oblique (b) directions.

Figure 6. Grain size distribution of streambed sediments from the Republican River.

Figure 7. Streambed tests along three transects at the Orleans site and along two transects at the Red Cloud site, Republican River (diagram not scaled).

Figure 8. Variation of the K_v of stream sediments at the test sites in the Republican, Little Blue, and Platte rivers. The error bar indicates the difference of K_v values calculated using equations (1) and (2), respectively.

Table 1. Channel Characteristics at Streambed Test Sites

Test Sites	Channel Width	Sediment Thickness above Bedrock (m)	Bedrock	Sediments of Top Layer
Republican River:				
Orleans	Main Stem, 35.5 m	6.1	Pierre Shale	Sand, Silt/Clay
Red Cloud	Main Stem, 50.5 m	4.9	Niobrara Shale	Coarse Sand
Bloomington	Main Stem, 37.8 m	11.7	Niobrara Shale	Sand/Gravel and Shale Fragment
Platte River:				
I-305	Middle Channel, 86 m	13.2	Ogallala Fm.	Sand/Gravel, Silt/Clay
	South Channel, 228 m	16.4	Ogallala Fm.	Sand/Gravel
I-285	N. Middle Channel, 107 m	17.1	Ogallala Fm.	Sand/Gravel
	S. Middle Channel, 101 m	17.1	Ogallala Fm.	Sand/Gravel
I-279	South Channel, 249.5 m	19.6	Ogallala Fm.	Sand/Gravel
Little Blue River:				
Fairbury, LBR	Main Stem, 63 m	5.6	Dakota Fm.	Sand/Gravel

Table 2. Summary of Directional Hydraulic Conductivities of Streambed at Bloomington and PR-I279 Test Sites

River	Sediment Column		K_v values (m/day) D = 10 cm	 D = 7.5 cm	 D = 5 cm
Republican	Vertical	K_v	17.4	16.6	13.2
	Perpend. to Stream	K_h	120.7	167.5	83.4
	Parallel to Stream	K_h	97.0	119.9	132.7
	Perpend. to Stream	$K_s(\theta=45^o)$	40.1	48.9	73.4
	Parallel to Stream	$K_s(\theta=45^o)$	53.7	73.9	14.4
	Perpend. to Stream	$K_s(\theta=22.5^o)$	44.8	77.6	
	Parallel to Stream	$K_s(\theta=22.5^o)$	101.6	83.4	
Platte	Vertical	K_v	24.3		
	Perpend. to Stream	K_h	101.2		
	Perpend. to Stream	$K_s(\theta=45^o)$	29		
	Perpend. to Stream	$K_s(\theta=22.5^o)$	66		

Table 3. Range of the Lengths of Vertical Sediment Columns and Testing Time for Permeameter Tests.

Rivers	Test Sites	L_v, Sediment Column (cm)		Test Time (sec.)	Reference to Figure
		Range	Average		
Republican	Orleans	35 - 45.5	39.1	913 - 5771	Fig. 8a
	Red Cloud	38 - 45.5	42.6	780 - 1200	Fig. 8b
Platte	PR-I305				
	Middle Channel	34 - 53.3	41.4	524 - 1242	Fig. 8g
	South Channel	38 - 47.5	43.3	545 - 711	Fig. 8h
	PR-I285	35 - 41.5	38.2	622 - 1319	Fig. 8e, 8f
	PR-I279	37 - 40.5	38.1	690 - 1030	Fig. 8d
Little Blue	Fairbury, LBR	36.6 - 58.5	45.1	553 - 1039	Fig. 8c

Table 4. Average K_v Values of Streambed for Test Sites

Rivers	Test Sites	Sediment	# of Tests	K_v Values			Reference
				Mean	St. Deviation	C.V. (%)	
Republican	Orleans	Sand	16	35.3	7.2	20.4	(Fig. 8a)
		Silt/clay	4	1.5	0.7	46.7	(Fig. 8a)
	Bloomington	Sand/gravel and shale fragments	3	14.5	2.8	19.3	(Table 2)
	Red Cloud	Sand	16	32.4	10	30.9	(Fig. 8b)
Platte	PR-I305	Sand/gravel	21	46.8	13	27.8	(Fig. 8g, 8h)
		Silt/clay	3	1.8	0.8	44.4	(Fig. 8g)
	PR-I285	Sand/gravel	9	38.1	10.2	26.8	(Fig. 8e, 8f)
	PR-I279	Sand/gravel	10	32.7	9.2	28.1	(Fig. 8d)
Little Blue	Fairbury, LBR	Sand/gravel	16	46.2	16.6	35.9	(Fig. 8c)

Table 5. K_v and K_h of the Alluvium in the Vicinity of the Republican and Platter River Valleys Determined from Aquifer Tests

Location	Aquifer	Sat. Thick (m)	Depth to Water	K_h (m/d)	K_v (m/d)	K_h/K_v	References
Wood River	Unconfined	23.5	2.4	104.2	9.5	11	Chen et al. (2003)
Grand Island	Unconfined	30.5	1.5	108.1	1.8	59.7	Chen (1998)
Shelton	Unconfined	13.1	5.2	210.2	4.1	51.3	Ayers et al. (1998)
MSEA (test 1)	Unconfined	13	4.9	103.1	11.3	9.1	McGuire and Kilpatrick (1998)
MSEA (test 2)*		13	5.5	118.9	5.9	20	McGuire and Kilpatrick (1998)
Bloomington	Unconfined	10.4	3.4	104.3	1.5	69.5	Chen et al. (1999)
McCook	Unconfined	20.4	2.4	82	3.6	22.8	Chen et al. (1999)

*the pumping wells for the two tests are about 275 m apart.

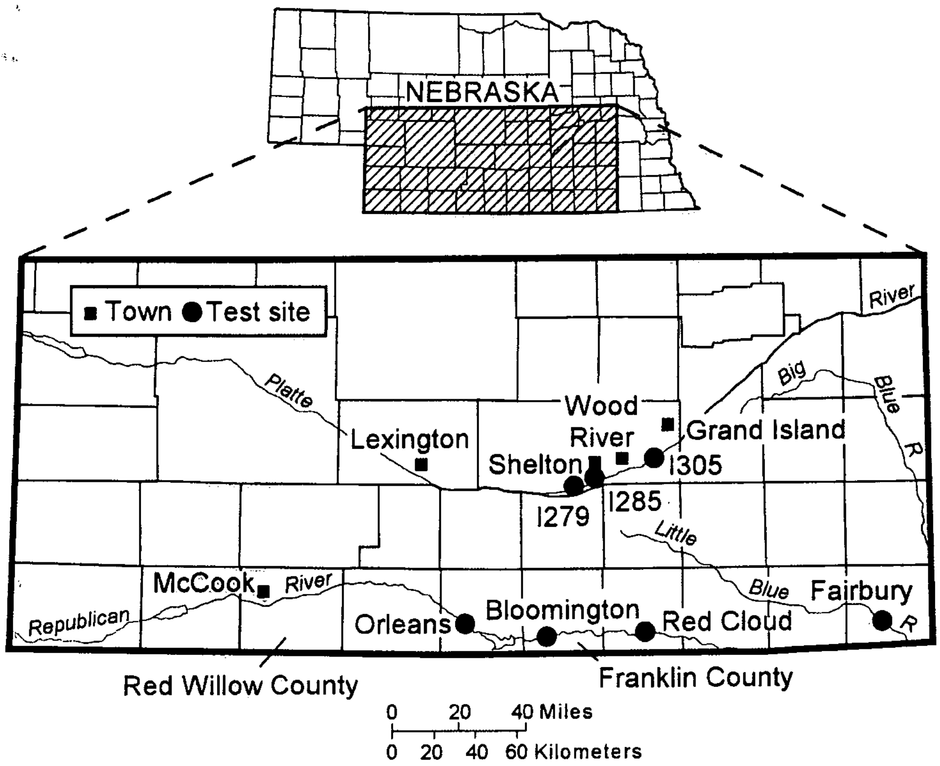

NEBRASKA
■ Town ● Test site
Platte
Lexington
Wood River
Grand Island
Shelton
1305
1279
1285
River
Big
Blue
R
Little
Blue
Fairbury
R
McCook
River
Republican
Orleans
Bloomington
Red Cloud
Red Willow County
Franklin County
0 20 40 Miles
0 20 40 60 Kilometers

Figure 1

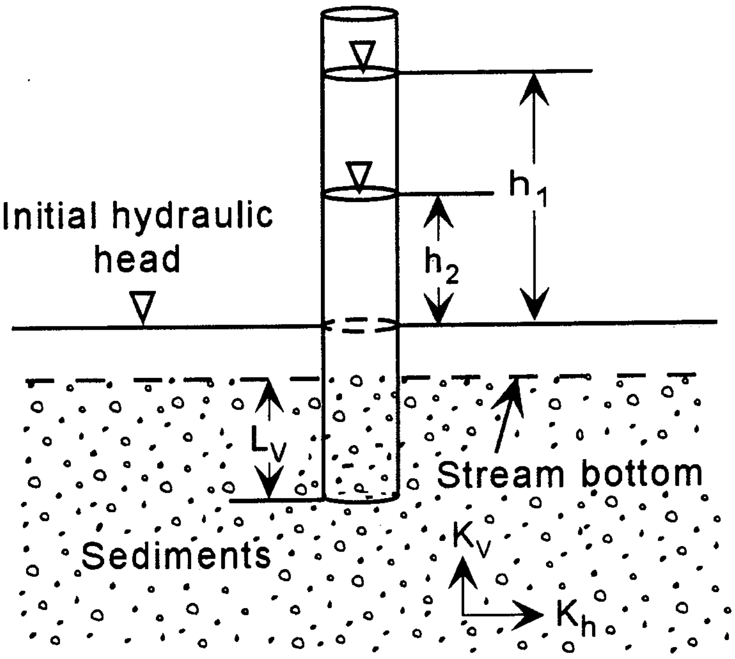


Figure 2

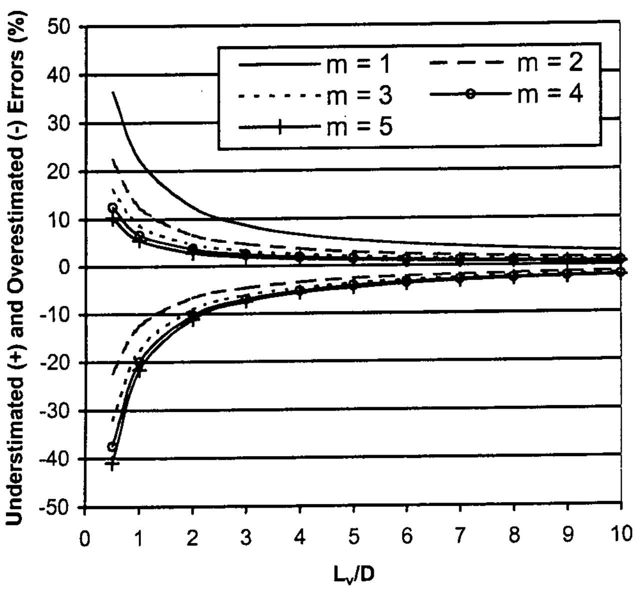
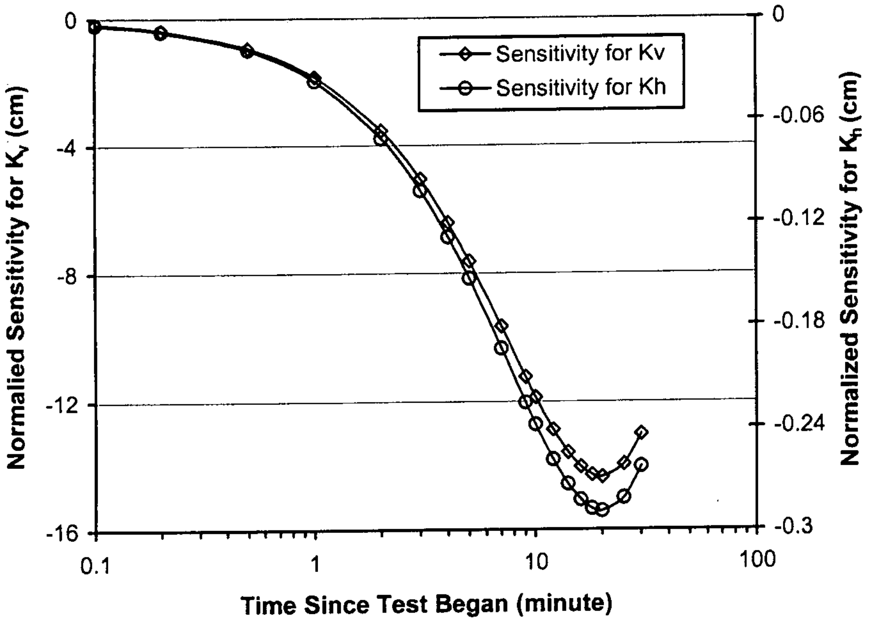


Figure 3



Sensitivity for Kv
Sensitivity for Kh
Normalied Sensitivity for K_v (cm)
Normalized Sensitivity for K_h (cm)
Time Since Test Began (minute)
0
-4
-8
-12
-16
0
-0.06
-0.12
-0.18
-0.24
-0.3
0.1
1
10
100

Figure 4

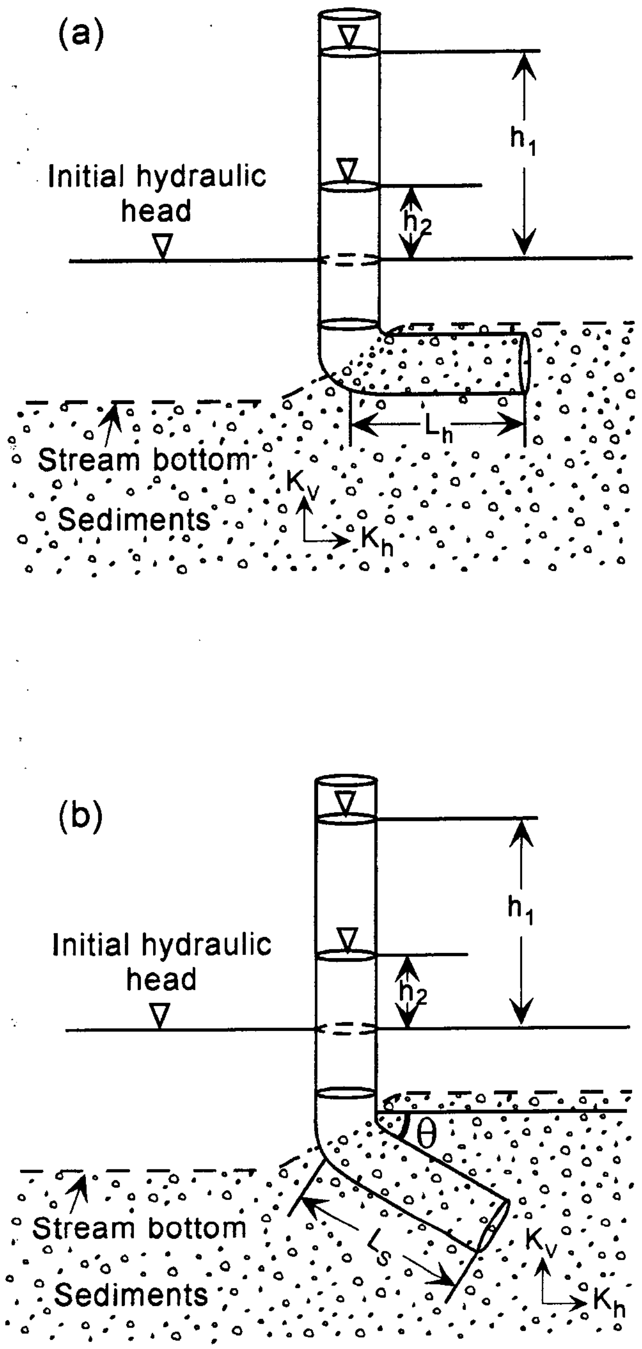

(a)
h1
Initial hydraulic head
h2
Stream bottom
Sediments
Kv
Kh
Lh
(b)
h1
Initial hydraulic head
h2
θ
Stream bottom
Sediments
Ls
Kv
Kh

Figure 5

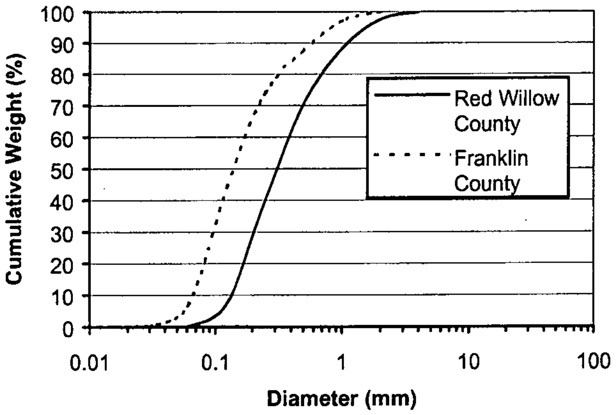
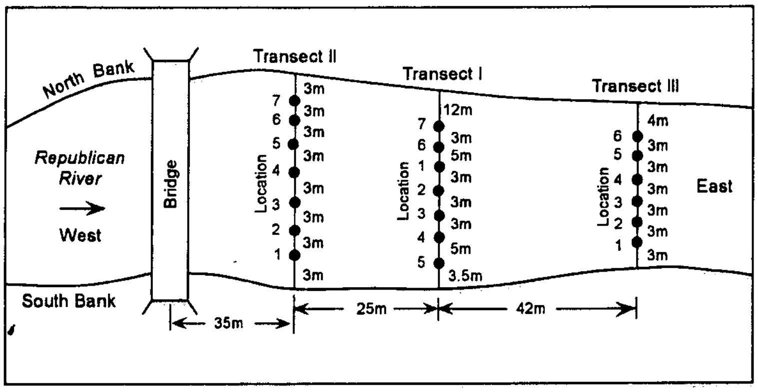

100
90
80
70
60
50
40
30
20
10
0
Cumulative Weight (%)
0.01
0.1
1
10
100
Diameter (mm)
Red Willow County
Franklin County

Figure 6

Orleans Site



Red Cloud Site

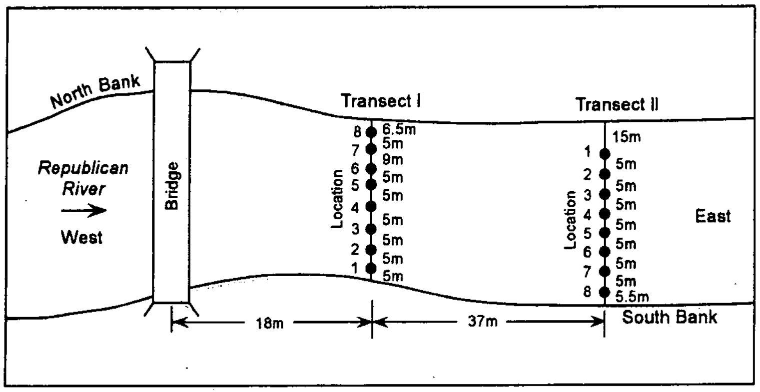


Figure 7

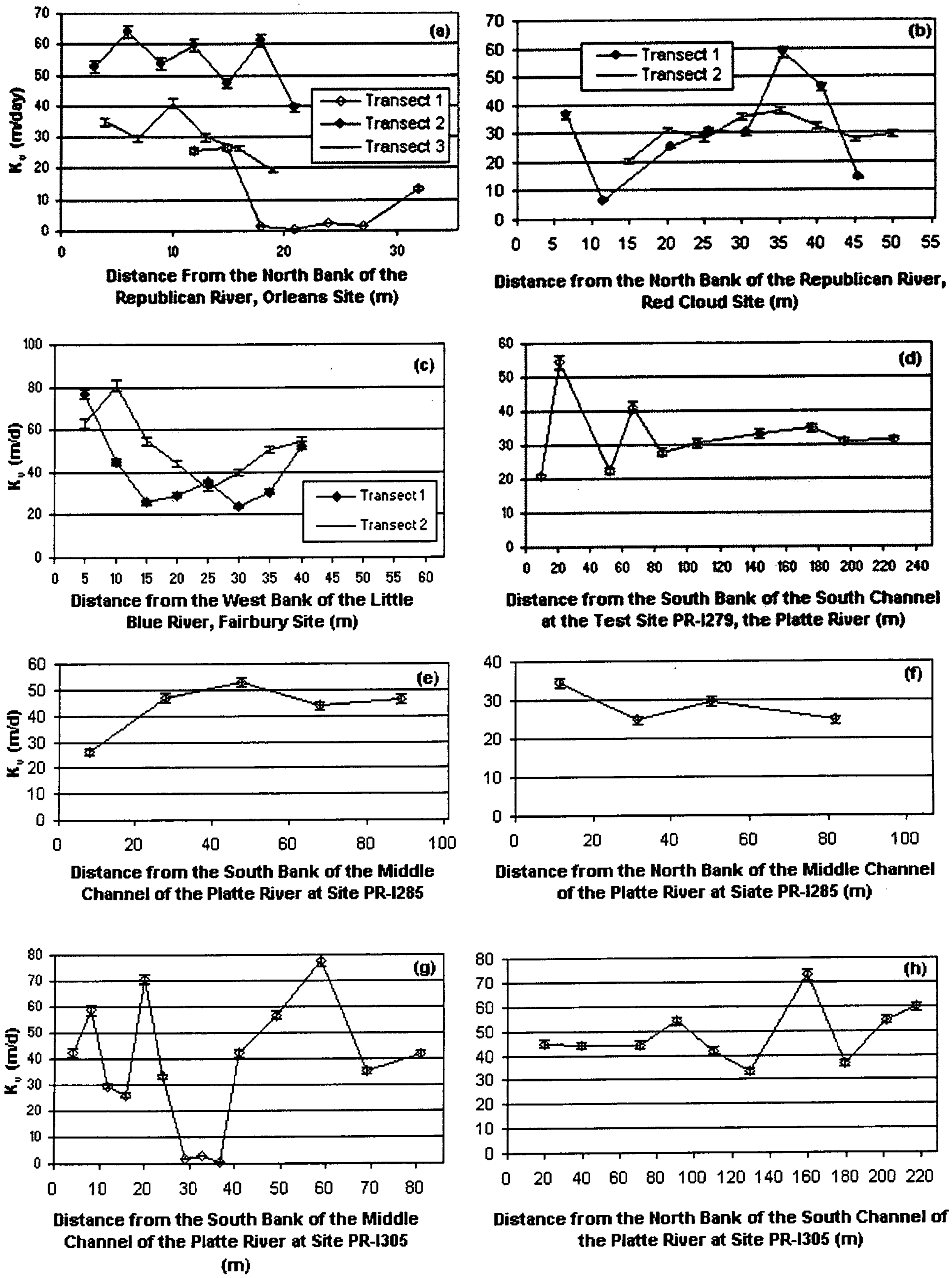
(a)
Kᵥ (m/day)
Transect 1
Transect 2
Transect 3
0
10
20
30
40
50
60
70
Distance From the North Bank of the Republican River, Orleans Site (m)
(b)
Transect 1
Transect 2
0
5
10
15
20
25
30
35
40
45
50
55
Distance from the North Bank of the Republican River, Red Cloud Site (m)
(c)
Kᵥ (m/d)
Transect 1
Transect 2
0
20
40
60
80
100
Distance from the West Bank of the Little Blue River, Fairbury Site (m)
(d)
0
20
40
60
80
100
120
140
160
180
200
220
240
Distance from the South Bank of the South Channel at the Test Site PR-I279, the Platte River (m)
(e)
Kᵥ (m/d)
Distance from the South Bank of the Middle Channel of the Platte River at Site PR-I285
(f)
Distance from the North Bank of the Middle Channel of the Platte River at Siate PR-I285 (m)
(g)
Kᵥ (m/d)
Distance from the South Bank of the Middle Channel of the Platte River at Site PR-I305 (m)
(h)
Distance from the North Bank of the South Channel of the Platte River at Site PR-I305 (m)

Figure 8