Measurement of streambed hydraulic conductivity and its anisotropy

Xunhong Chen

Abstract A method is described for the measurement of streambed hydraulic conductivity. Unlike permeameter methods, this method applies straight and L-shaped standpipes directly to streambeds for measurements of in-situ hydraulic conductivity in the vertical (K_v) and horizontal (K_h) directions, as well as in other oblique directions (K_s). This method has advantages in determination of K_v values over grain-size analysis, permeameter tests, or slug test methods. Also unique to this method is that it provides K_s values of a streambed. The measured results can be used to construct a hydraulic conductivity ellipse and to evaluate the anisotropy of streambed sediments. Field examples from the Republican River, Nebraska, demonstrated the usefulness of this method in the determination of streambed hydraulic conductivity and anisotropy along or across a river channel. Results indicate that the K_h is about three to four times larger than K_v, whereas K_s values are larger than K_v but smaller than K_h.

Key words Anisotropy · Hydraulic conductivity · Streambed

Introduction

The hydraulic relationship between streams and adjacent aquifers is an important issue for water resource management where streamflow depletion is concerned or for wellhead protection in alluvial aquifers when water quality is concerned. The hydraulic conductivity of the streambed is a necessary variable in determining the hydraulic connection between a stream and adjoining aquifers. This parameter has effects on stream infiltration to the aquifer or on the discharge of groundwater to the stream (Sophocelous and others 1995; Conrad and Beljin 1996). A careful measurement of the streambed hydraulic conductivity is the first step in the analysis of the hydraulic relationship between streams and aquifers. For example, measurement of the vertical (K_v) and horizontal (K_h) hydraulic conductivity of a streambed is important for analysis of streamflow depletion caused by groundwater extractions (Chen and Yin 1999).

Grain-size analysis of streambed sediments can provide empirical values of streambed hydraulic conductivity. However, such derived values do not represent the true hydraulic feature of the streambed because they are not the in-situ properties. The original sediment structures of the streambed have been destroyed during the sediment sampling. Grain-size analysis methods provide neither the horizontal (K_h) nor vertical (K_v) hydraulic conductivities, and they preclude any evaluation of anisotropy and/or differences in directional hydraulic conductivity.

While pumping tests measure in-situ hydraulic conductivity of aquifers, it is difficult to apply them to the investigation of the streambed because of the complexity of boundary conditions, as well as logistical concerns. A pumping test is expensive and requires a great number of wells to quantify the effects of anisotropy caused by scattered heterogeneities, i.e., highly dispersed sediment lenses. Therefore, alternative methods are highly desirable for the measurement of hydraulic conductivities of streambeds in river channels.

Various tests have shown that porous aquifers are anisotropic; the K_h is usually larger than the K_v in one or two orders of magnitude. Depositional processes, for example, the laminations and bedding formed by clay minerals in sediments, usually result in larger horizontal hydraulic conductivities. Studies on aquifer anisotropy have been valuable to researchers. For streams partially penetrating the aquifer, there exist vertical and horizontal flow components around the streambed. The vertical and horizontal hydraulic conductivities of the streambed play important roles in surface water and groundwater exchanges. Therefore, determination of the streambed anisotropy is of importance in the analysis of stream-aquifer interactions.

This paper describes a standpipe method to measure streambed hydraulic conductivities directly in river channels. Straight and L-shaped standpipes are used. This

Received: 6 March 2000 · Accepted: 18 April 2000

X. Chen
Conservation and Survey Division, 113 Nebraska Hall,
University of Nebraska-Lincoln, Lincoln, NE 68588-0517, USA
e-mail: xchen2@unl.edu
Tel.: +402-472-0772
Fax: +402-472-4608

method can provide hydraulic conductivity of the streambed along the vertical and horizontal directions, as well as along other directions. Field examples will be used to demonstrate the usefulness of this method. The hydraulic conductivities determined using the standpipe method will be compared with those from grain-size analysis.

Method

The principle of this standpipe method is similar to that of the permeameter method, which was described by Hvorslev (1951) and several textbooks (Freeze and Cherry 1979; Todd 1980; Domenico and Schwartz 1998). However, this method has advantages over the permeameter method. Permeameter measurement in the laboratory offers no opportunity to obtain in-situ hydraulic conductivity of the streambed and hardly provides its anisotropy because sampling is a disruptive process. In contrast, the standpipe method can be easily performed directly in stream channels and is flexible enough to measure in-situ aquifer anisotropy. The method is described as follows. Figure 1a shows a vertical standpipe in the stream channel, where the lower part of the pipe has been pressed into the streambed and is filled with the unconsolidated sediment. Disturbance of the sedimentary structures of the streambed materials in the pipe is assumed to be nominal. Water is poured into the pipe to fill the rest of the pipe. The hydraulic head at the bottom of the sediment column is approximately equal to the water level in the stream. Because of the difference of hydraulic heads at the two ends of the sediment column in the pipe, water flows through the sediment column and the water table in the pipe falls. This method measures the vertical hydraulic conductivity K_v of the sediment column, which can be calculated using

$$K_v = L_v/(t_2 - t_1)\ \ln(h_1/h_2) \tag{1}$$

where K_v = vertical hydraulic conductivity of the streambed, L_v = thickness of the measured streambed in the pipe, h_1 = the hydraulic head in the pipe measured at time t_1, and h_2 = the hydraulic head in the pipe measured at time t_2. It is assumed that the water level of the stream is constant during the test. The thickness of the streambed to be measured depends on the purpose of the investigation. The K_v value can be calculated using two head readings from the pipe. If more than two readings were collected, any two of them should provide a similar K_v value. However, because of possible errors introduced to the head readings in the test, a minor difference between K_v values is expected from one calculation to another.

Hvorslev (1951) provided a formula to calculate the vertical hydraulic conductivity for a standpipe test in saturated soils such that

$$K_v = (\pi D/11m + L_v)/(t_2 - t_1)\ln(h_1/h_2) \tag{2}$$

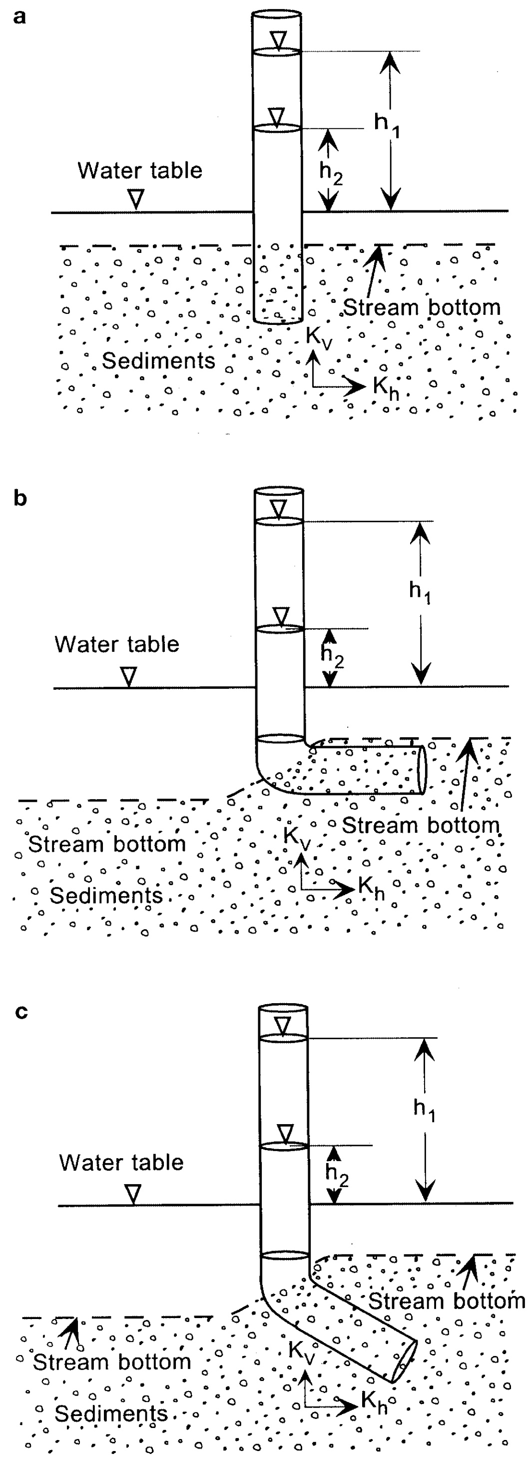

Fig. 1
Schematic diagrams showing the measurement of streambed hydraulic conductivity along **a** the vertical direction, **b** the horizontal direction, and **c** an oblique direction. The hydraulic head in the standpipe is based on the datum of the stream water table; that is, the hydraulic head of the stream water table = 0 for all time

where D = diameter of the pipe, and $m = (K_h/K_v)^{0.5}$. Because the two unknown variables K_h and K_v occur in Eq. (2), calculation of K_v from two head measurements h_1 and h_2 is not possible. However, Eq. (2) can be approximated using Eq. (1) when the length of sediment column in the pipe (L) is several times larger than the diameter of the pipe. For example, if $L_v/D = 4$ and $K_h/K_v = 4$, Eq. (1) will underestimate the K_v value by only ~3.4%. For a stronger anisotropic streambed, the underestimated error using Eq. (1) is even smaller. The error is ~2.9% when $L_v/D = 3$ and $K_h/K_v = 10$.

Figure 1b shows an L-shaped pipe for the measurement of the streambed hydraulic conductivity in the horizontal direction. The angle between the two pipes is 90°. The horizontal segment is pressed into the streambed and is filled with the channel sediments. Water is poured into the vertical pipe. Because K_h is usually larger than K_v, the rate of water table decline in this test is expected to be faster for a same length of sediment column. The same equation can be used to calculate the horizontal hydraulic conductivity K_h.

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

where L_h = length of streambed column in the horizontal pipe. One may use this L-shaped standpipe to obtain K_h values along a direction parallel to stream channels, a direction perpendicular to channels, or any other directions on a horizontal plane.

Hvorslev (1951) developed a method for estimation of K_h values of anisotropic soils using a standpipe with a perforated extension at the bottom end. The extension, however, is not filled with sediment. Again, the calculation of a K_h value from two head measurements is not possible using an equation he developed because two unknown variables, K_h and K_v, occur in the same equation.

For hydraulic conductivity along a direction between horizontal and vertical, an L-shaped pipe with an angle greater than 90° can be designed (Fig. 1c). K_s is used to designate the hydraulic conductivity along these oblique directions. The same equation can be used to calculate the oblique hydraulic conductivity K_s.

$$K_s = L_s/(t_2 - t_1)\ln(h_1/h_2) \qquad (4)$$

where L_s = length of streambed column in the pipe.

In a later section of this paper, descriptions will be provided for two tests with the angles of 135 and 157.5° respectively.

Field examples

Field tests were conducted at two locations in the Republican River, Nebraska, one near McCook, and the other near Bloomington (Fig. 2), about 136 km apart. The Republican River in the area flows from west to east and is ~30 m wide. Water depth is often <30 cm. The sediments in the river channel consist mainly of fine- and medium-grained sand.

McCook site

Two tests were conducted at this site, one for K_v and the other for K_h. A PVC standpipe, 100.5 cm long and 7.6 cm in the inside diameter, was pressed vertically into the streambed. Sediment filled the lower part of the pipe as the pipe was pressed into the streambed materials. A column of unconsolidated channel sediments 25.5 cm high was formed inside the pipe. Water was poured to fill the rest of the pipe above the sediment column. Then, head losses in the pipe were measured. Figure 3a shows the curve of hydraulic head versus time for the K_v test. Any two water level readings can be used to calculate the hydraulic conductivity of the sand column in the pipe. A series of calculations was performed using Eq. (1). Here, the hydraulic head at $t = 0$ was used as h_1 for all the calculations, and all the five hydraulic head readings for

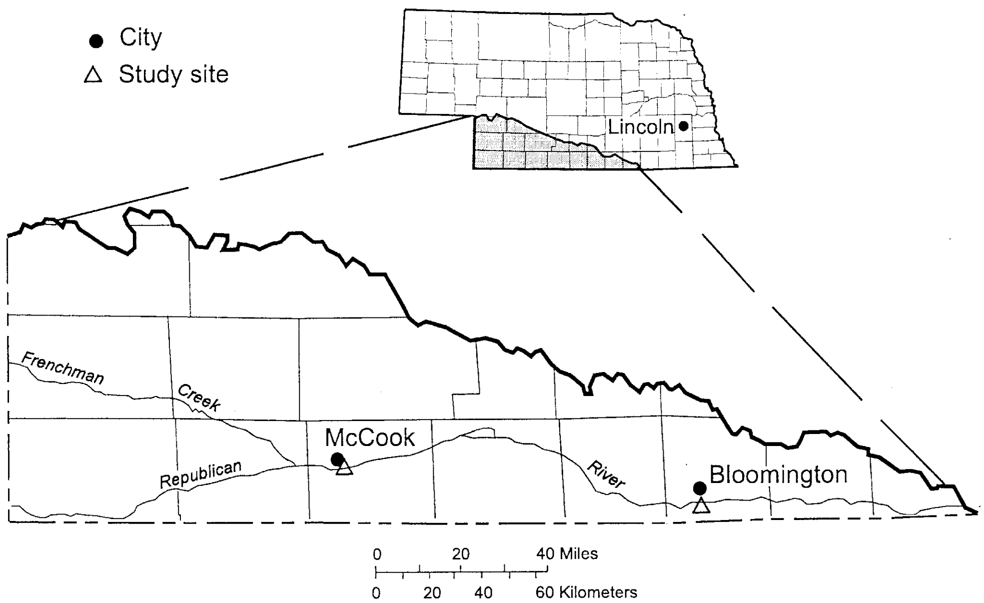

Fig. 2
Location map showing the two test sites in the Republican River, Nebraska, USA

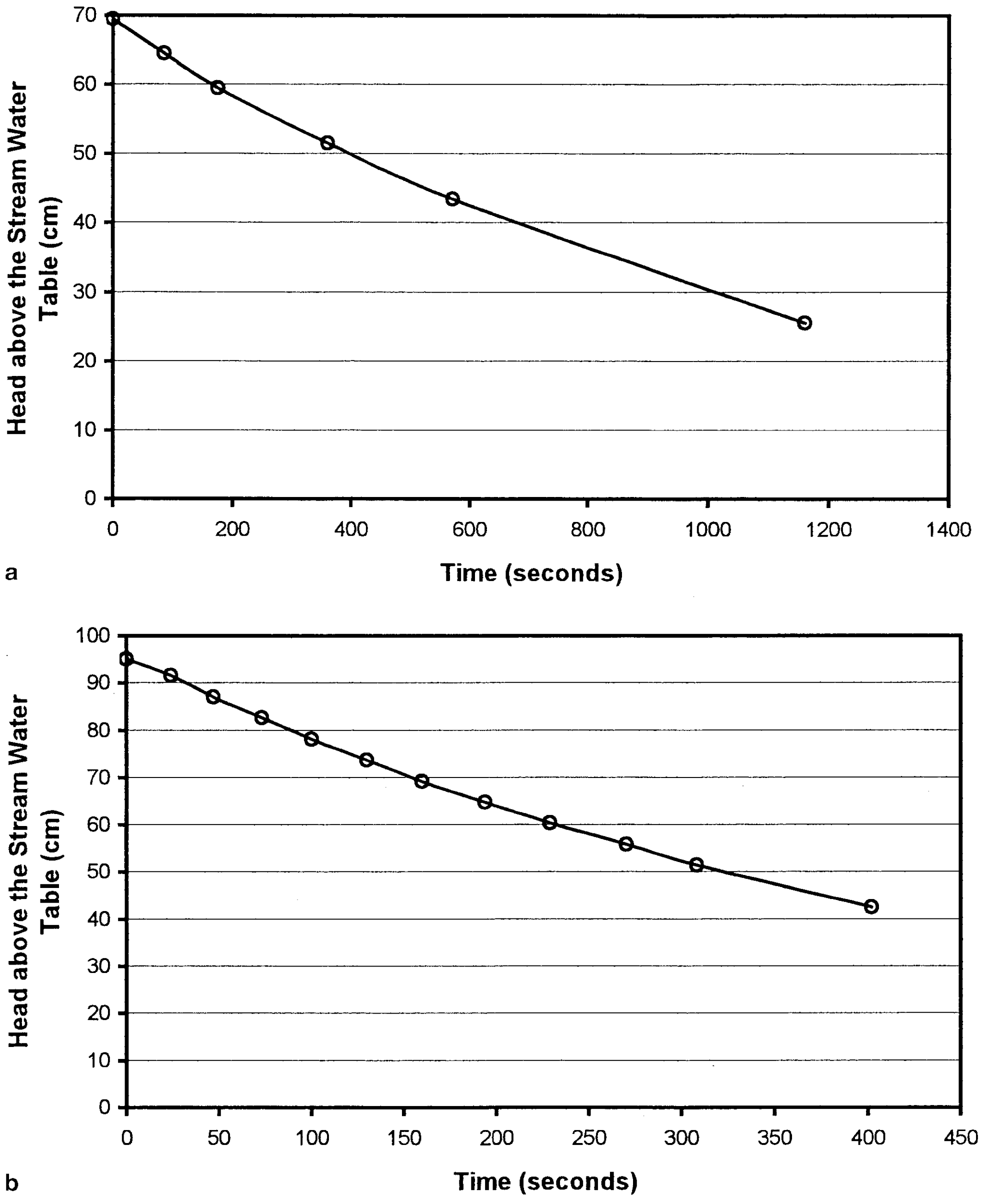

Fig. 3
Water level in the standpipe versus time from the McCook site. **a** The test for the vertical direction and **b** the test for the horizontal direction

$t>0$ were used as h_2 respectively, in each calculation. All the calculations provide similar K_v results, which are summarized in Table 1. The averaged K_v is ~ 18.8 m/day. For a comparison, calculations were also conducted for a pair of head readings collected in two consecutive measurements. The results are also listed in Table 1. The averaged K_v value is 18.7 m/day. Although the average K_v values for both calculations are close to each other, the standard deviation for the former calculation is smaller. To measure the horizontal hydraulic conductivity K_h, two pieces of PVC pipes were connected to a 90° joint to form an L-shaped instrument (see Fig. 1b). The length of the pipe along the horizontal direction was ~ 52 cm, and 100.5 cm in the vertical direction. The shorter pipe was pushed horizontally into the sediment below the stream bottom and was filled with the channel sediment as the pipe moved into the streambed (see Fig. 1b). The length of the sediment core in the pipe was about 52 cm long. The horizontal pipe was approximately parallel to the channel transect. After the vertical pipe was filled with water, 12 water level readings were collected. Figure 3b shows the curve of water level versus time. K_h was calculated using Eq. (3). Similarly, K_h was calculated using each head reading for $t>0$, and the head at $t=0$ was used as h_1 for each of the 11 calculations. The calculated K_h values are listed in Table 1. The K_h values for these calculations are very close to each other. They are averaged to be 91.24 m/day, and the standard deviation is $\sim$ 0.9 m/day. Again, calculations of K_h values were conducted using a pair of head readings collected in two consecutive measurements. The results are also summarized in Table 1. The averaged K_h value for these calculations is 91.2 m/day; the standard deviation is 3 m/day, which is larger than that from the former calculations.

Table 1
The K_v and K_h values calculated for the standpipe tests in Republican River near McCook, Nebraska

	K_v (m/day) Calc. 1[a]	K_v (m/day) Calc. 2[b]	K_h (m/day) Calc. 1[a]	K_h (m/day) Calc. 2[b]
	19.1	19.1	88.98	88.98
	19.5	19.8	93.14	97.48
	18.3	17.3	92.29	90.76
	18.1	17.5	92.28	92.24
	19.0	20.0	91.26	87.89
			91.66	93.37
			90.99	87.86
			91.06	91.43
			89.99	84.04
			91.01	98.21
			90.99	90.91
Mean	18.8	18.7	91.24	91.20
SD	0.48	1.1	0.8	3.0

[a] Calculation 1 uses a pair of head readings h_1 and h_2, h_1 and h_3, h_1 and h_4, etc.
[b] Calculation 2 uses a pair of head readings h_1 and h_2, h_2 and h_3, h_3 and h_4, etc.

The ratio of K_h/K_v is about 4.9. Because the approximate equations must be used in the calculation of K_v and K_h, the resulting errors are 3.7 and 1.8% respectively.

Bloomington site

Four tests were conducted at the Bloomington site. The test procedures to measure K_v and K_h are the same as those for the McCook site. Figure 4a,b shows the water level curves for the two tests. The lengths of the streambed sediments in the pipe were $L_v=32$ cm, and $L_h=52$ cm. The computational procedures for K_h and K_v values are the same as those for the McCook test. The results are summarized in Table 2. The head reading at $t=0$ was used as h_1 for each calculation. The averaged K_v value is 43 m/day, the K_h value is ~ 142 m/day, and the ratio of K_h/K_v is 3.3. Both K_h and K_v are larger than those for the McCook site. The errors in K_v and K_h from the approximate computations are ~ 3.6 and 2.2% respectively.
Another two tests were conducted along the directions 45 and 67.5° below the horizontal direction ($\theta=45$, and $\theta=67.5$). The angle between the two pipes in the L-shaped instrument is 135 and 157.5° (see Fig. 1c for an oblique direction). Figure 5a,b shows the water level curves for the two tests. The length of sediment filled in the oblique pipe was 43 cm for each of the two tests. K_s is designated to represent the hydraulic conductivity along a direction between the horizontal and vertical directions in the channel sediments. Again, a series of calculations was performed for each set of the water level readings where the head reading at $t=0$ was used as h_1 for each calculation. The averaged K_s value for the angle of 45° [$K_s(\theta=45)$] is 64.8 m/day and $K_s(\theta=67.5)$ is 57 m/day. Both are greater than K_v but smaller than K_h. It is expected that $K_s(\theta=45)>K_s(\theta=67.5)$ because the latter test is closer to the vertical direction. The results are summarized in Table 2.

Table 2
Hydraulic conductivities along vertical, horizontal, and oblique directions in the streambed of the Republican River near Bloomington, Nebraska

	K_v (m/day)	K_h (m/day)	K_s ($\theta=45°$) (m/day)	K_s ($\theta=67.5°$) (m/day)
	35.4	143.4	61.9	45.5
	41.0	151.8	61.7	53.2
	42.5	152.0	65.9	54.7
	43.1	147.8	65.6	56.3
	44.3	145.3	66.4	57.8
	45.3	145.8	67.0	57.9
	44.9	143.6	68.6	58.7
	45.9	143.6	67.0	58.9
	45.4	146.1	66.8	59.0
	44.9	144.3	65.8	58.9
	44.6	141.5	65.8	59.1
	44.5	142.2	66.2	59.0
	44.1	139.5	65.4	59.1
	43.6	136.9	64.9	58.7
	43.6	134.8	64.0	58.4
	43.1	135.6	63.5	58.4
	42.6	134.8	62.3	
	42.2	134.9	61.4	
	42.0	135.1	60.7	
	41.2	136.2		
	39.0	145.7		
Mean	43.0	141.9	64.8	57.1

Results of grain-size analysis

Sediment samples were collected across the river channel near both locations and were analyzed to characterize the grain-size distribution. Hydraulic conductivities (K) were calculated using the Hazen method (Vukovic and Soro 1992). The K values for two samples collected near the Bloomington test site are 36.8 and 32.7 m/day respectively. The K values for three samples near the McCook site are 20.3, 14.8 and 17.8 m/day. These K values are smaller than the vertical and horizontal hydraulic conductivity determined using the standpipe method for each site. Note that these K values from grain-size analyses do not represent the hydraulic conductivity of the streambed along any particular direction and they are not in-situ hydraulic properties. According to Rovey and Cherkauer (1995), hydraulic conductivities determined using the grain-size composition are always lower than those determined using other methods because of scale dependence.

Anisotropy

According to Freeze and Cherry (1979), the distribution of the hydraulic conductivity over a vertical profile of porous media follows the hydraulic conductivity ellipse. The K_s values are dependent on the K_h and K_v values.

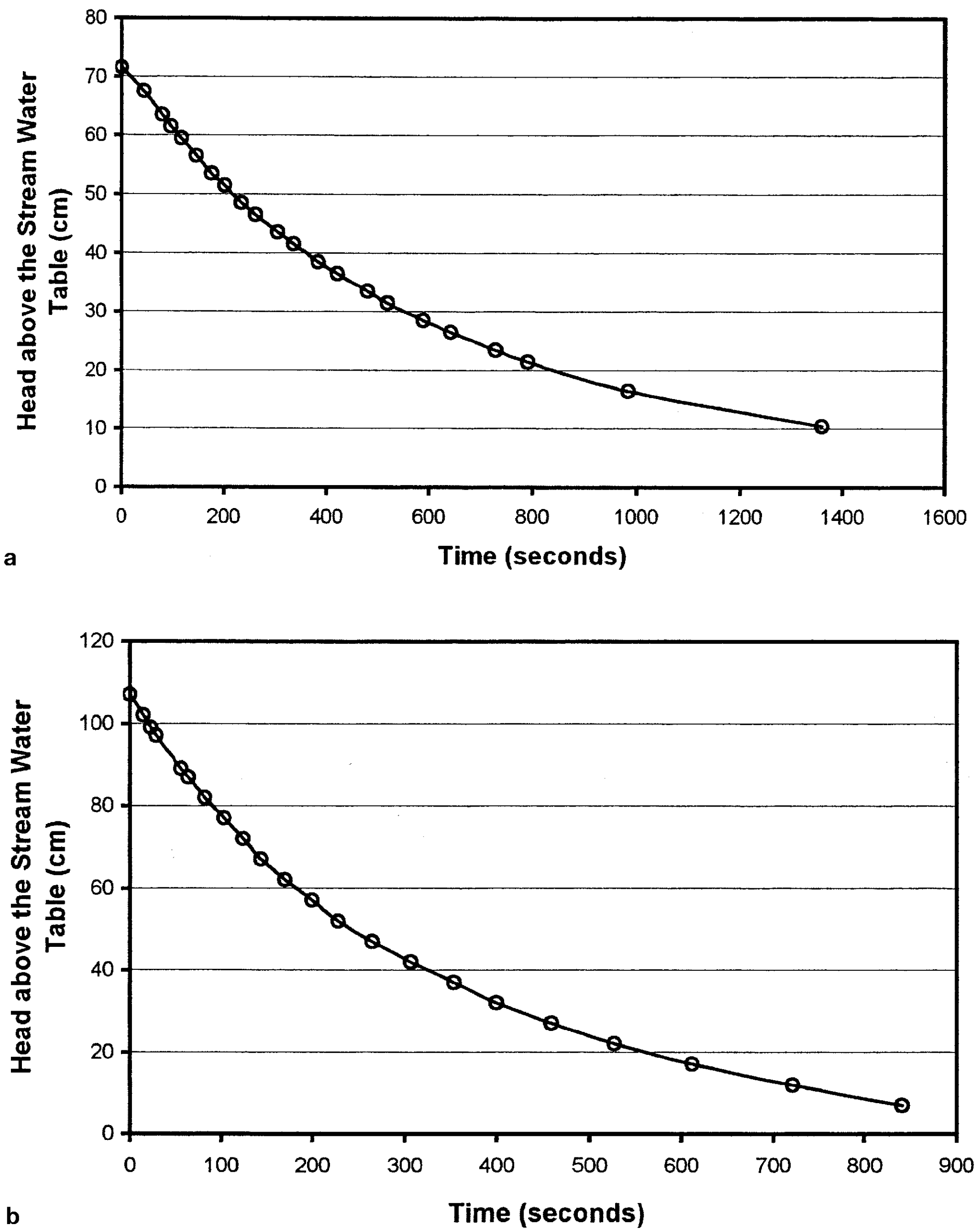

Fig. 4
Water level in the standpipe versus time from the Bloomington site. **a** The test for the vertical direction and **b** the test for the horizontal direction

Assuming the measured K_v and K_h values along the vertical and horizontal directions correspond to the principal directions, their relation to the $K_s(\theta)$ values along other directions is

$$\frac{1}{K_s} = \frac{\cos^2\theta}{K_h} + \frac{\sin^2\theta}{K_v} \tag{5}$$

where θ is the angle from the horizontal direction, and K_s is the hydraulic conductivity along the direction with the angle θ. Accordingly, any one of the three hydraulic conductivity values can be determined from Eq. (5), as long as other two hydraulic conductivity values are known. Because the K_v, K_h, and K_s values for the streambed in the Republican River had been determined using the standpipe method, Eq. (5) was used to evaluate the validity of these measurements. By taking $K_v = 43$ m/day, $K_h = 142$ m/day, and $\theta = 45°$, the calculated K_s using Eq. (5) is 65.9 m/day, which is close to the measured K_s value at the Bloomington site (64.8 m/day). The calculated K_s value for $\theta = 67.5°$ is ~48 m/day, which is smaller than the measured one (57 m/day).

Discussion

Pumping tests were conducted in the alluvial aquifers adjacent to the two sites (Chen and others 1999). The reported K_h and K_v values for the alluvial aquifer near Bloomington are 104 and 1.5 m/day, and the ratio of K_h/K_v is about 69. The test in an alluvial aquifer near the

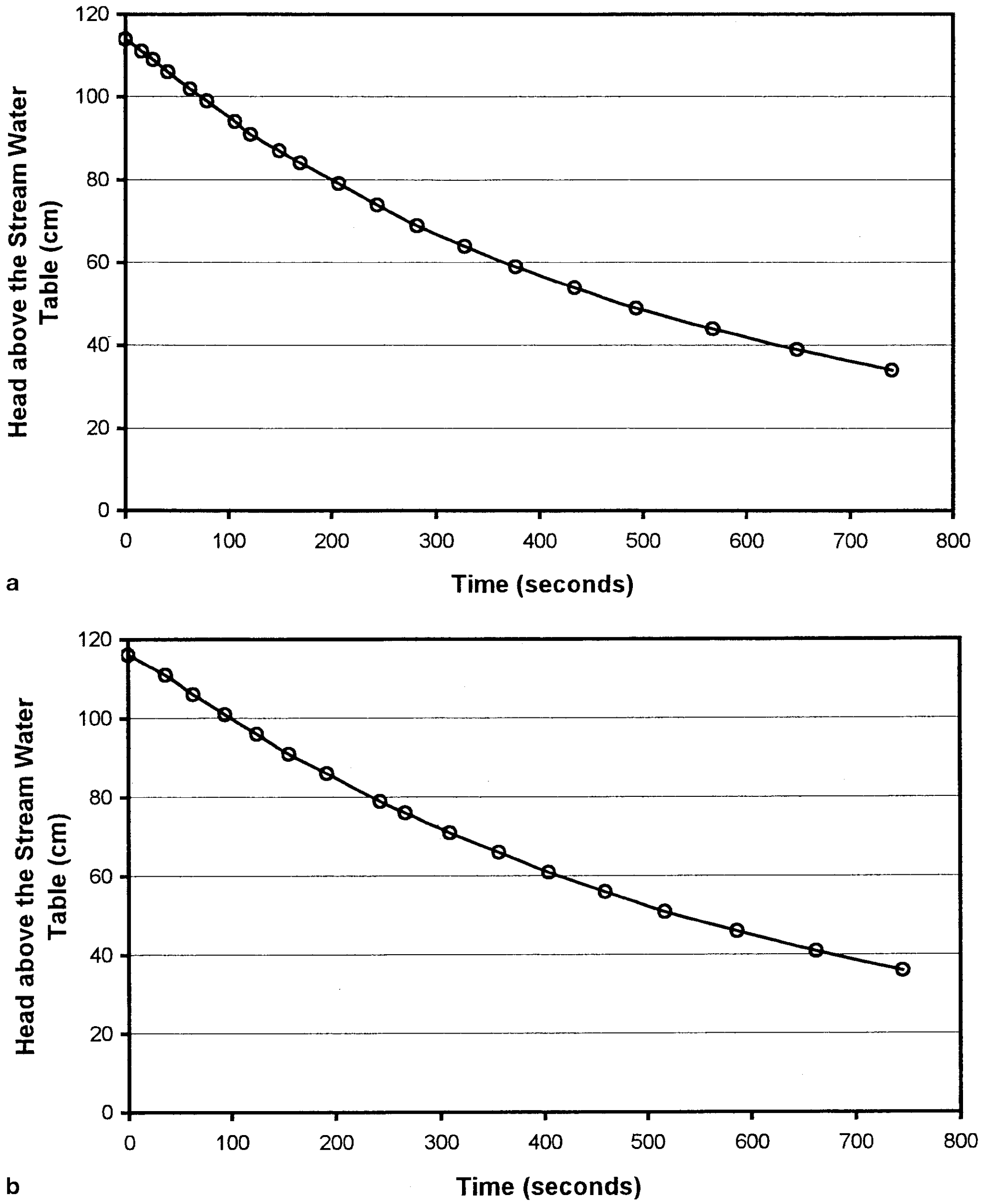

Fig. 5
Water level in the standpipe versus time from the Bloomington site. **a** The test for $\theta = 45°$ below the horizontal direction and **b** for $\theta = 67.5°$ below the horizontal direction

McCook site gives $K_h = 82$ m/day, $K_v = 3.6$ m/day, and the ratio of K_h/K_v is about 23. Both pumping tests show a much stronger anisotropy. First, compaction of the aquifer material may reduce the vertical hydraulic conductivity. Second, as explained by Freeze and Cherry (1979), interbedded sediment layers of varied hydraulic conductivity results in a very large anisotropy. For example, a two-layer aquifer, where $K_{v1} = K_{h1} = 10$ m/day for layer 1, $K_{v2} = K_{h2} = 300$ m/day for layer 2, and each unit = 10 m thick, will lead to $K_h/K_v = 8$ for the aquifer. Typically, alluvial aquifers contain thin, layered clay/silt beds, which are interbedded with sand and gravel layers. The hydraulic conductivity for sand/gravel and silt/clay layers can be very different. The saturated thickness of the alluvial aquifer is 10.4 m for the Bloomington test site and 20.4 m for the McCook test site. The pumping tests have impacted a much larger volume of sediment materials in which interbedded sediment layers exist. Freeze and Cherry (1979) pointed out that it is not uncommon for layered heterogeneity to lead to regional anisotropy values of the order of 100:1 or even larger. In contrast, the standpipe method measures the hydraulic conductivity for a limited thickness of sediment, which has a weaker anisotropy. Results of this study clearly demonstrate that anisotropy exists even in a relatively small thickness of the streambed. The smaller ratios of K_h/K_v from the standpipe method are acceptable because the thicknesses of the measured sediments were much smaller than the aquifer thickness measured in the pumping tests. Pumping tests can be used to determine the K_v and K_h. However, observation wells must be close to the pumping well because the effects of K_v disappear at the locations farther from the pumping well (Chen 1998). Strictly speaking, the K_h value determined from pumping tests represent the hydraulic conductivity in the radial direction. Furthermore, pumping tests do not provide K_s values along any oblique directions over a vertical profile. Commonly used slug test methods often use a perforated casing at the bottom of a well. The data from these tests can provide the radial hydraulic conductivities for the sediment around the well. These methods do not provide K_v and K_s values.

Unlike traditional permeameter methods, the standpipe method approximately measures the in-situ hydraulic conductivities of the streambed. The advantage of using this method over grain-size analysis is also obvious because it provides hydraulic conductivities along a number of directions.

Like all other methods, this method has its limitations. For example, some disturbances in the sediment column may occur when the pipe is pressed through the streambed.

Conclusions

The method measures not only vertical and horizontal hydraulic conductivity of streambeds, but also the hydraulic conductivities along oblique directions. Therefore, the anisotropic features of the streambed can be determined by constructing the hydraulic conductivity ellipses. The results are very important for the study of groundwater flow, stream leakage, and contaminant transport in streambeds.

The standpipe method provides researchers with a useful tool to measure the hydraulic conductivity of a streambed directly in river channels. The measured values represent approximately the in-situ hydraulic properties of sediment in the stream channel. It has advantages over other methods such as grain-size analysis, permeameter tests, and slug tests in the determination of streambed hydraulic conductivity and anisotropy. This method can be used to effectively characterize the hydraulic heterogeneity of various sediment bodies in river channels, for example, longitudinal bars, side bars, etc. Field examples suggest that the vertical hydraulic conductivity of the streambed is several times smaller than the horizontal hydraulic conductivity. The hydraulic conductivity along an oblique direction is between the two extremes.

Acknowledgements The research was supported in part by US Geological Survey and Conservation and Survey Division, University of Nebraska-Lincoln. The author benefited from discussions about slug test methods with J. Butler, Jr. and V. Zlotnik. Jerry Leach participated in the fieldwork at the Republican River and Ann Mack drafted several figures. Nebraska Department of Water Resources collected sediment samples. Charlie Flowerday provided editorial reviews.

References

Chen XH (1998) Assessment of hydraulic parameters from an alluvial aquifer near Grand Island, Nebraska. J Am Water Resour Assoc 34(3):603–616

Chen XH, Yin Y (1999) Evaluation of streamflow depletion for vertical anisotropic aquifers. J Environ Syst 27(1):55–69

Chen XH, Goeke J, Summerside S (1999) Hydraulic properties and uncertainty analysis for an unconfined alluvial aquifer. Ground Water 37(6):845–854

Conrad LP, Beljin MS (1996) Evaluation of an induced infiltration model as applied to glacial aquifer systems. Water Resour Bull 32(6):1209–1220

Domenico PA, Schwartz FW (1998) Physical and chemical hydrogeology, 2nd edn. Wiley, New York

Freeze RA, Cherry JA (1979) Groundwater. Prentice-Hall, Englewood Cliffs

Hvorslev MJ (1951) Time lag and soil permeability in groundwater observations. Waterways Experiment Station, Corps of Engineers, US Army Bull 36, Vicksburg, Mississippi

Rovey CW II, Cherkauer DS (1995) Scale dependency of hydraulic conductivity measurements. Ground Water 33(5):769–780

Sophocleous M, Koussis A, Martin JL, Perkins SP (1995) Evaluation of simplified stream-aquifer depletion models for water rights administration. Ground Water 33(4):579–588

Todd DK (1980) Groundwater hydrology, 2nd edn. Wiley, New York

Vukovic M, Soro A (1992) Determination of hydraulic conductivity of porous media from grain-size composition. Water Resources Publications, Littleton, Colorado