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Comparison of Instream Methods for Measuring Hydraulic Conductivity in Sandy Streambeds

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Abstract

Streambed hydraulic conductivity (K) values were determined at seven stream transects in the Platte River Basin in Nebraska using different instream measurement techniques. Values were compared to determine the most appropriate technique(s) for use in sandy streambeds. Values of K determined from field falling- and constant-head permeameter tests analyzed using the Darcy equation decreased as permeameter diameter increased. Seepage meters coupled with hydraulic gradient measurements failed to yield K values in 40% of the trials. Consequently, Darcy permeameter and seepage meter tests were not preferred approaches. In the upper 0.25 m of the streambed, field falling- and constant-head permeameter tests analyzed with the Hvorslev solution generally had similar K values that were significantly greater than those determined using the Hazen grain-size, Bouwer and Rice slug test for anisotropic and isotropic conditions, and Alyamani and Sen grain-size methods; median differences between these tests and the Hvorslev falling-head 60 cm diameter permeameter were about 8, 9, 17, and 35 m/day, respectively. The Hvorslev falling-head permeameter test is considered the most robust method for measuring K of the upper 0.25 m of the streambed because of the inherent limitations of the empirical grain-size methods and less sediment disturbance for permeameter than slug tests. However, lateral variability in K along transects on the Platte, North Platte, and Wood Rivers was greater than variability in K between valid permeameter, grain-size, or slug tests, indicating that the method used may matter less than making enough measurements to characterize spatial variability adequately. At the Platte River tributary sites, the upper 0.3 m of the streambed typically had greater K than sediment located 0.3 to 2.5 m below the streambed surface, indicating that deposits below the streambed may limit ground water/surface water fluxes. The Hvorslev permeameter tests are not a practical measurement approach for these greater depths. Thus, selection of a method for measuring streambed K needs to consider the vertical location of the sediments that are most likely to limit the rate of ground water/surface water interaction.

Introduction

Streambed hydraulic conductivity (K) is an important parameter to estimate in order to quantify the magnitude and spatial distribution of ground water/surface water interactions. Because silt, clay, and organic materials often are deposited in streams, the streambed can have lower K than the aquifer, thereby restricting ground water/surface water fluxes (Rosenshein 1988; Larkin and Sharp 1992; Conrad and Beljin 1996). Such restriction can occur even in predominantly sandy streambeds if K is lower than that of the surrounding aquifer. Determination of streambed K can be important for studies designed to determine base flow (Petersen et al. 1995; Cey et al. 1998); to quantify the impacts of pumping wells on streamflow (Sophocleous et al. 1995; Chen and Yin 1999; Hunt 1999); to simulate regional ground water flow balances (McDonald and Harbaugh 1988; Luckey and Becker 1999; Yu and Schwartz 1999); and to quantify solute transport, retention, and exchange between ground water and surface water (Harvey and Bencala 1993; McMahon et al. 1995; Hart et al. 1999).

Streambed K has been estimated using a variety of approaches including numerical modeling (Yager 1993; Sophocleous et al.

1995) and analytical solutions for pumping-aquifer tests conducted near streams (Hantush 1965; Hunt 1999), analytical solutions for analysis of bank storage effects (Barlow and Moench 1998; Zlotnik and Huang 1999), chemical tracer experiments (Harvey and Bencala 1993; Hart et al. 1999), and physical instream methods. For regional studies, it is often beyond the resources of investigations to install monitoring wells, conduct pumping-aquifer tests, and evaluate streambed properties using analytical or numerical modeling or to conduct laborious and expensive chemical tracer tests considering the number of stream reaches that need to be characterized. In contrast, physical instream methods are relatively quick and inexpensive and measurements can be made at many locations using portable equipment. Consequently, a comparative study of instream methods was performed as a pilot investigation to guide subsequent efforts to generate streambed K data for input into regional ground-water-flow models of the Platte River in Nebraska (COHYST 2000) being developed to quantify river gains and losses from interaction with ground water (Figure 1).

Instream methods of determining K include slug tests (Lee and Cherry 1978; Duwelius 1996; Cey et al. 1998; Springer et al. 1999), in situ permeameter tests (McMahon et al. 1995; Duwelius 1996; Lindgren and Landon 2000; Rosenberry 2000), and seepage flux measurements with seepage meters coupled with measurement of hydraulic gradient through the streambed (Lee and Cherry 1978; Wolf et al. 1991b). In addition, streambed samples can be collected for grain-size analysis and K can be estimated from grain-size distribution (Vukovic and Soro 1992). Although field permeameter and coupled seepage meter/hydraulic gradient measurements measure vertical K (K_v), slug tests measure horizontal K (K_h), and

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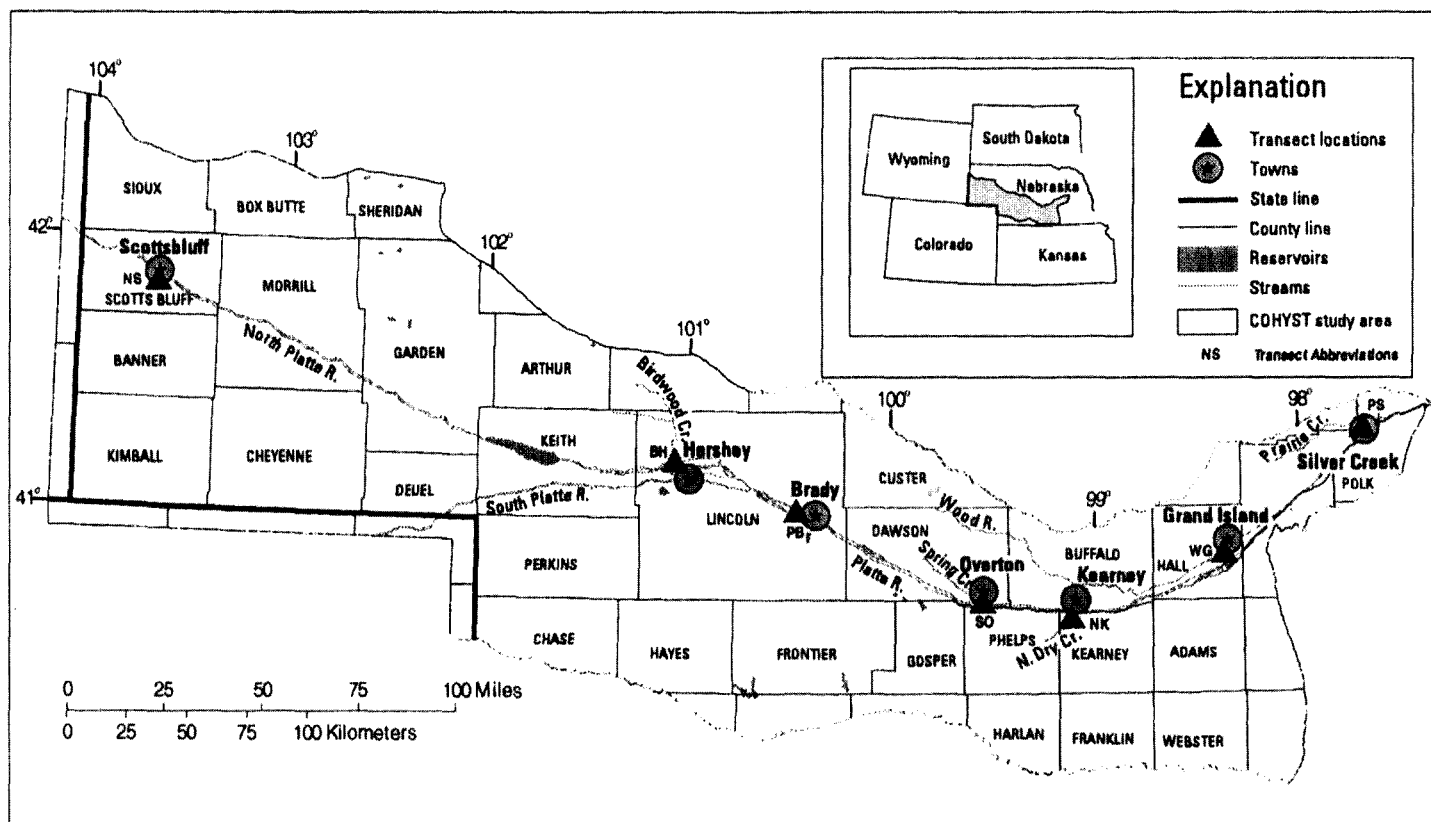Received January 2001, accepted June 2001.

Figure 1. Map showing location of study area and transects at which streambed hydraulic conductivity was measured.

Table 1
Site Characteristics

Site Name	Site Code	Channel Width (m)	Max. Depth[1] (m)	Min. Depth[1] (m)	Stream Flow (m³/sec)	Mean Velocity (m/sec)	Stream Slope[2] (m/km)	Median Grain-Size (mm)	Bed Description
Main-Stem Sites									
North Platte River at Scottsbluff, Nebraska	NS	60.5	0.79	0.11	12.5	0.56	1.17	1.21	Coarse to very coarse sand with some sand and gravel
Platte River near Brady, Nebraska	PB	144	[3].61	[3].20	[4,5]26.3	[5,6].62	1.27	1.20	Sand and gravel
Wood River Site									
Wood River near Grand Island, Nebraska	WG	8.8	.66	.20	1.7	.59	1.14	.87	Medium to coarse sand overlying fine and medium sand
Tributary Sites									
Birdwood Creek near Hershey, Nebraska	BH	25.3	.56	.12	[4]3.9	[6].69	1.23	.33	Fine sand
Spring Creek near Overton, Nebraska	SO	8.5	.35	.08	.50	.38	1.35	.59	Sand and gravel overlying fine sand and silt
North Dry Creek near Kearney, Nebraska	NK	10.4	.44	.05	[4].15	.27	1.08	.49	Fine sand with coarse sand overlying fine sand and silt
Praire Creek near Silver Creek, Nebraska	PS	10.7	.21	.04	[3].24	.24	.81	.42	Fine sand

[1]Determined from surveying across streambed transect unless otherwise noted.
[2]Taken from Bentall (1991) and from U.S. Geological Survey topographic quadrangle maps, 7.5-minute series.
[3]Based on water depths recorded for slug tests at the measuring points.
[4]Mean streamflow for a day of the test period based on stream-gauge records of the United States Geological Survey and the Nebraska Department of Water Resources (NDWR).
[5]Based on NDWR gauge on the North Channel Platte River approximately 8 km below the study site.
[6]Based on discharge measurement notes from the gauge at a similar discharge.

K values from grain-size methods are nondirectional (isotropic), these different K values are directly compared in this study for the purpose of characterizing streambed K values. Commonly used sim- ulation models such as MODFLOW (McDonald and Harbaugh 1988) treat ground water/surface water fluxes through a streambed as being vertical. In reality, both horizontal and vertical fluxes can

occur and the directions are a complex function of many hydrogeologic variables (Harvey and Bencala 1993; Woessner 2000). Particularly in broad, braided streams like the Platte River that partially penetrate a relatively permeable alluvial aquifer and may have many flow-through or parallel-flow reaches (Woessner 2000), ground water/surface water fluxes are expected to have both horizontal and vertical components and the distribution of these directional fluxes will be highly complex. In addition, the anisotropy ratio (K_H/K_v) is expected to be small for relatively small-scale K tests (Freeze and Cherry 1979; Butler 1998) considering that the streambed sediments of the Platte River and tributaries are generally sandy and well rounded (Kircher 1983; Kinzel et al. 1999).

This study was conducted because well-constrained values of streambed K are critical for estimating ground water/surface water fluxes, and the performance of instream methods for determining K in sandy streambed environments has not been evaluated. Previous studies have indicated that substantial differences between slug tests and grain size can occur in sandy aquifers (Wolf et al. 1991a; Millham and Howes 1995). However, field permeameters and coupled seepage meter/hydraulic gradient measurements can be used only to determine K at or near the sediment surface. While the instream methods listed have been used in lake studies (Lee and Cherry 1978; Wolf et al. 1991b), we are unaware of a study that has compared K values determined with these different methods in lakes. Moreover, sandy streambed environments will have greater water velocity and sediment mobility than typical lake environments, which could affect the performance of some of the methods. For example, it was expected that the Platte River and its tributaries would have flow velocities (Table 1) greater than environments in which seepage meters are used—typically less than 0.2 m/sec (Lee and Cherry 1978). Moreover, the bedload deposition and scour that occurs in active sandy stream channels has the potential to bury or unearth, respectively, devices such as seepage meters and field permeameters that are placed into the streambed to measure streambed K.

All techniques of determining K have uncertainties. The magnitude of the uncertainty is highly dependent upon the conditions under which the tests are conducted (Butler 1998). To isolate the effect of method imprecision from other sources of variability in K values, duplicate tests were performed for all methods at each location and the differences between duplicates were analyzed statistically. Differences in K values determined using different methods are often interpreted to result from differences in measurement scale (Wolf et al. 1991a; Millham and Howes 1995; Rovey and Cherkauer 1995), although the relationship between measurement scale and K has been questioned in some studies (Butler and Healy 1998). Over a range of scales, it has been documented that spatial variations in K can range over several orders of magnitude (Freeze and Cherry 1979; Eggleston and Rojstaczer 1998). This variability is a major source of uncertainty in measured K values and in comparing values determined using different methods. Because all instream measurements disturb the streambed, tests using different methods cannot be conducted at exactly the same location on the streambed. Thus, spatial uncertainty in K values has the potential to have a substantial effect on the results of comparative studies of field methods for determining K. To address the expected problem of spatial variability in K on the results, many measurements were made and the results of side-by-side tests using the same methods and different methods were analyzed statistically to evaluate the significance of differences in values due to different methods and local scale spatial variability.

This study compares streambed K determined using different instream measurement techniques, including field falling- and constant-head permeameter tests of different sizes analyzed using Hvorslev (1951) and Darcy solutions, seepage meters of different sizes coupled with hydraulic gradient measurements, slug tests, and grain-size data used in two empirical formulas. The purpose of the study is to determine which technique(s) are most appropriate for measuring K in sandy streambeds considering the reproducibility and sensitivity to design of each technique, differences between techniques, and spatial variability. Statistical tests are applied to evaluate the importance of these factors to variability in K values.

Description of Study Area

Most of the flow in the North Platte, South Platte, and Platte Rivers (collectively hereafter referred to as the main-stem rivers) is derived from spring snowmelt in the Rocky Mountains in Colorado and Wyoming (Eschner et al. 1983), whereas flow in the tributaries of the main-stem rivers is derived from local precipitation and ground water discharge. Precipitation on the Great Plains ranges from 330 to 650 mm annually in the study area. Streams in the study area are hydraulically connected to ground water in Pleistocene alluvial deposits and the Tertiary Ogallala Formation and White River Group of the High Plains aquifer. The main-stem rivers are predominantly braided and the bed material generally comprises sand and gravel with local deposits of silt- and clay-sized particles in low energy environments. The tributaries generally have well-defined channels and sandy bed materials with some silt- and clay-sized particles.

Methods

Design of Data Collection

Determinations of K were made along transects across streams at seven locations from August through October 1999 (Figure 1). Measurements were made at one site on the North Platte River at Scottsbluff (NS), one site on the main stem of the Platte River near Brady (PB), and five tributary sites including Wood River near Grand Island (WG), Birdwood Creek near Hershey (BH), Spring Creek near Overton (SO), North Dry Creek near Kearney (NK), and Prairie Creek near Silver Creek (PS) (Table 1). Although the WG site was on the tributary Wood River, a north channel of the Platte River used to join the Wood River about 7.1 km above the measurement location before being cut off several years ago (Woodward 2000). Because this lower reach of the Wood River once was impacted by water and sediment transport in the Platte River, the WG site has different sediments than other Platte River tributaries. For the purposes of discussing the results at similar sites, the sites were classified into main stem (NS and PB), Wood River (WG), and tributary (BH, SO, NK, and PS) sites.

At the NS and PB transects, measurements were made with each method at four clusters. At the much narrower tributaries (Table 1), measurements were made at two clusters along transects. At the WG site, measurements were made along two transects, each with two clusters. The clusters were about equally spaced across the stream at all transects.

Because all of the methods disturb the streambed, equipment for the different testing methods could not be placed in exactly the same location. Instead, the equipment for the different tests was placed into the streambed along lines perpendicular to the transect but in close proximity to each other.

Table 2
Method Descriptions and Testing Volumes

Method Abbreviation	Method	Meter Diameter (cm)	Equation Used to Solve (Figure 2)	Vertical Length of Sediment Tested (m)	Volume of Sediment Tested[1] (m³)
CHP14D	Constant-head permeameter	14	Darcy	0.25	0.004
CHP28D	Constant-head permeameter	28	Darcy	.25	.015
CHP60D	Constant-head permeameter	60	Darcy	.25	.071
CHP90D	Constant-head permeameter	90	Darcy	.25	.159
CHP14H	Constant-head permeameter	14	Hvorslev	.25	.004
CHP28H	Constant-head permeameter	28	Hvorslev	.25	.015
CHP60H	Constant-head permeameter	60	Hvorslev	.25	.071
CHP90H	Constant-head permeameter	90	Hvorslev	.25	.159
FHP14D	Falling-head permeameter	14	Darcy	.25	.004
FHP28D	Falling-head permeameter	28	Darcy	.25	.015
FHP60D	Falling-head permeameter	60	Darcy	.25	.071
FHP90D	Falling-head permeameter	90	Darcy	.25	.159
FHP14H	Falling-head permeameter	14	Hvorslev	.25	.004
FHP28H	Falling-head permeameter	28	Hvorslev	.25	.015
FHP60H	Falling-head permeameter	60	Hvorslev	.25	.071
FHP90H	Falling-head permeameter	90	Hvorslev	.25	.159
SEM28	Seepage meter	28	Darcy	.18	.011
SEM61	Seepage meter	61	Darcy	.18	.053
SEM91	Seepage meter	91	Darcy	.18	.117
GSH	Grain-size distribution	NA	Hazen	.20	.00023
GSA	Grain-size distribution	NA	Alyamani and Sen	.20	.00023
SLUGI	Slug test	NA	Bouwer and Rice, Isotropic	.47	.011
SLUGA	Slug test	NA	Bouwer and Rice, Anisotropic	.47	.011

The method abbreviations consist of a two-or-three letter abbreviation for the method. a two-digit diameter in centimeters (for permeameter and seepage meters), and a one-letter abbreviation for the equation used to analyze the test (for all but seepage meters).

[1]The volume of sediment tested for field permeameter and seepage meter tests was calculated as the vertical length of sediment inside the device multiplied by the cross-sectional area of the device. For the grain-size samples, the volume was calculated as the vertical length of sediment collected inside the bed-sediment sampler multiplied by the cross-sectional area of the sampler. For slug tests, the length of the screen was multiplied by the cross-sectional area of a circle with radius equal to the average calculated effective radius over which head loss is dissipated (R_e, Figure 2), which was equal to 17.4 cm.

For all methods, two measurements were made at each test location in the streambed to evaluate the inherent variability in the results associated with each test (hereafter referred to as duplicates). Thus, duplicate measurements were made in each permeameter, seepage meter, and slug-test screen location, and duplicate laboratory analyses of grain-size samples were performed. In each of the instrument clusters, data also were collected for each method from two stations usually located 1 to 3 m away (hereafter referred to as side-by-side tests).

Values of K were determined using varying diameters of permeameters (14, 28, 60, and 90 cm) and seepage meters (28, 61, and 91 cm). The volume of sediment inside the largest diameter permeameter was about 42 times larger than in the smallest diameter permeameter (Table 2). The difficulty involved in moving and installing large devices efficiently made it impractical to use permeameters and seepage meters greater than 91 cm in diameter. The measurements with different sizes of devices were used to evaluate whether different testing volumes and boundary effects would result in significant differences in K.

Field Permeameter Measurements

Each field permeameter consisted of a 61 or 122 cm long pipe that was pushed partially into the streambed before adding water to impose a hydraulic head on the sediments inside the pipe. The 14 and 28 cm permeameters were composed of smooth wall, schedule-80, polyvinyl chloride (PVC) pipe, with beveled outside ends to make installation easier and minimize disturbance of the sed-

iments inside the meter. The 60 and 90 cm permeameters were composed of corrugated metal pipe.

The permeameters were installed with minimal disturbance of the streambed to a consistent measurement depth of 0.25 ± 0.05 m. Once installed, two falling-head tests were performed. The displacement, or imposed head above the initial water level, was varied between the two tests. Water was added, while minimizing disturbance of the bed, until the head reached a target displacement, H_0. The water level then was allowed to fall while the displacement, H_1 (Figure 2a), was recorded four to eight times during each test. Thereafter, two constant-head tests with variable displacements were conducted by adding water until the head reached a target displacement, H, which then was maintained over a given time period by adding a known volume of water (Figure 2b). This water volume was computed by measuring the change in mass in four preweighed 2 L water containers. The tests were conducted over a three-minute period, or until all four containers had been emptied, whichever came first.

Vertical K (K_v) values were computed using Darcy solutions for falling-head (Figure 2a, Equation 1) and constant-head tests (Figure 2b, Equation 3). Equation 1 represents the application of Darcy's equation to analysis of a falling-head permeameter problem, as described by Todd (1980, p. 74), and is referred to as the Darcy solution for the falling-head permeameter test in this paper. The constant-head permeameter tests used the normal form of the Darcy equation (Figure 2b, Equation 3). Values of K_v were computed using Hvorslev solutions for the condition of uniform sediment within and below the
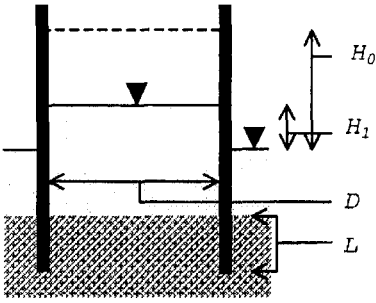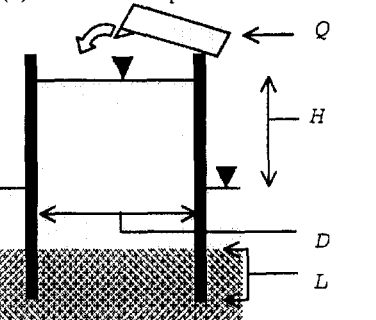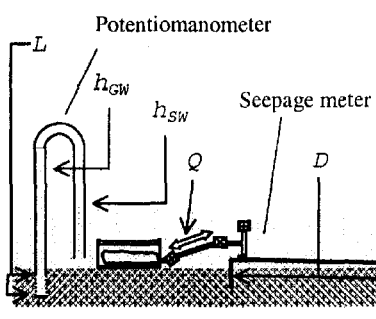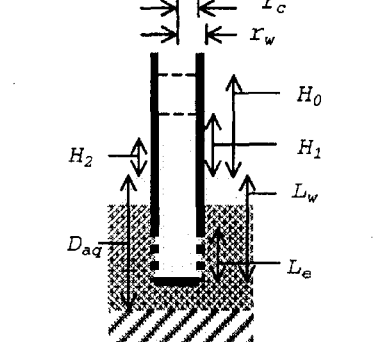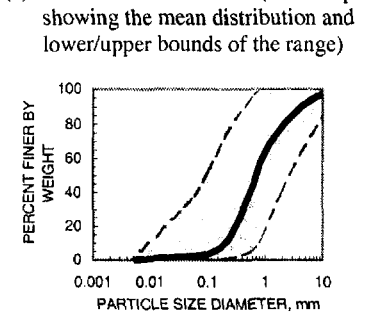
Diagrams	Equations	Explanation of Variables
(a) Falling-head permeameter 	(1) Darcy equation, $K_v = \dfrac{L}{t_1 - t_0} \ln \dfrac{H_0}{H_1}$ (2) Hvorslev (1951) equation, $K_v = \dfrac{\dfrac{\pi}{11}\dfrac{D}{m} + L}{t_1 - t_0} \ln \dfrac{H_0}{H_1}$	A_{xs} = Cross-sectional area of device, m^2 A, B = Bouwer-Rice dimensionless parameters calculated as a function of L_e/r_w (Bouwer 1989) A_H = Hazen dimension coefficient (equals 1.0 for m/d) C = Hazen empirical coefficient (equals 860 (Vukovic and Soro 1992)) D = Diameter of device, m D_{aq} = Saturated thickness of the aquifer, m d_{10} = Grain-size diameter of which 10% of the distribution is finer, mm d_{50} = Median grain size, mm H = Displacement (difference of imposed and ambient water levels), m H_0 = Displacement at time 0, m H_1 = Displacement at time 1, m H_2 = Displacement at time 2, m H_a = Ambient ground-water minus surface-water head difference, m h_{GW} = Hydraulic head of ground water, m h_{SW} = Hydraulic head of surface water, m I_0 = X-intercept from straight line between d_{50} and d_{10}, mm K = Isotropic hydraulic conductivity, m/d K_h = Horizontal hydraulic conductivity, m/d K_v = Vertical hydraulic conductivity, m/d L = Sediment interval being tested, m L_e = Length of the well screen, m L_w = Initial height of water above the bottom of the screen, m m = Isotropic transformation ratio, or $\sqrt{K_h/K_v}$ Q = Flow of water, m^3/d R_e = Effective radius of well over which head loss is dissipated, m r_c = Inside radius of casing, m r_w = Radial distance between undisturbed aquifer and well center, m r_w^* = r_w modified for anisotropy t = time of test, d T = Hazen temperature correction factor, equals 1.0 at 10° C t_1-t_0 = time elapsed between times 0 and 1, d t_2-t_1 = time elapsed between times 1 and 2, d y_1 = Normalized displacement at time 1, or H_1/H_0 y_2 = Normalized displacement at time 2, or H_2/H_0 Note: Use of empirical coefficients or numerical values in empirical equations 7 and 8 results in consistent units on both sides of the equations.
(b) Constant-head permeameter 	(3) Darcy equation, $K_v = \dfrac{Q}{A_{xs}}\dfrac{L}{H}$ Where $A_{xs} = \dfrac{\pi D^2}{4}$ (4) Hvorslev (1951) equation, $K_v = \dfrac{4Q\left(\dfrac{\pi}{11}\dfrac{D}{m} + L\right)}{\pi D^2 H}$	
(c) Seepage meter/potentiomanometer 	(5) Darcy equation, $K_v = \dfrac{Q}{A_{xs}}\dfrac{L}{H_a}$ Where $H_a = h_{GW} - h_{SW}$	
(d) Slug tests 	(6) Modified Bouwer and Rice (1976) equation, $K_h = \dfrac{r_c^2 \ln\left(\dfrac{R_e}{r_w}\right)}{2L_e}\dfrac{1}{t_2 - t_1}\ln\left(\dfrac{y_1}{y_2}\right)$ $\ln\left(\dfrac{R_e}{r_w}\right) = \left(\dfrac{1.1}{\ln\left(\dfrac{L_w}{r_w}\right)} + \dfrac{A + B \ln\left[\dfrac{\left(D_{aq} - L_w\right)}{r_w}\right]}{L_e/r_w}\right)^{-1}$ (7) $r_w^* = \dfrac{r_w}{m}$ From Zlotnik (1994)	
(e) Grain Size Distributions (112 samples showing the mean distribution and lower/upper bounds of the range) 	(8) Hazen (1893) empirical K-grain size relation: $K = A_H C T d_{10}^2$ (9) Alyamani and Sen (1993) empirical K-grain size distribution relation: $K = 1300\left[I_0 + 0.025\left(d_{50} - d_{10}\right)\right]^2$	

Figure 2. Diagrams of instrument design, equations, and explanation of variables for instream methods used to determine streambed hydraulic conductivity for (a) falling-head permeameters, (b) constant-head permeameters, (c) seepage meter/potentiomanometers, (d) slug tests, and (e) empirical grain-size methods.

permeameter (Hvorslev 1951, p. 31, case 6) for falling-head tests (Figure 2a, Equation 2) and constant-head tests (Figure 2b, Equation 4). The Hvorslev equations required the isotropic transformation ratio (m; Equations 2 and 4) be estimated. For a sandy streambed with rounded particles, isotropic conditions were assumed for the upper 0.3 m.

Average K_v for each cluster was calculated using duplicate measurements made at each station with the 60 cm falling-head permeameters. These average K_v values and the distances between clusters were used to calculate a width-weighted average K_v for each transect for this method.

Seepage Meter/Hydraulic Gradient Measurements

Each seepage meter consisted of a covered cylinder about 0.2 m long connected to a sheltered bag (Figure 2c). The 28 cm device was made of schedule 80 PVC covered on one end with sheet metal (sealed with silicone caulk) and beveled on the outside of the open end. The 61 cm device was made of a 208 L steel drum cut in half. The 91 cm device was made of a circular livestock-watering tank. The measurement bags were gusseted, had a maximum volume of 4.4 L, and were made of 1 mm thick polyethylene. Bag type has not been found to affect the results of seepage meter tests significantly (Erickson 1981; Isiorho and Meyer 1999). The bags were connected to the seepage meters with 1.1 cm inside diameter (I.D.) reinforced plastic tubing and a valve system for controlling the measurement period. Fellows and Brezonik (1980) found that seepage-meter-flow resistance was negligible for connector tube diameters greater than about 0.5 cm and seepage meter flow rates of less than about 50 cm³/min. The relatively low seepage meter flow rates (maximum of 20.4 cm³/min) and the larger diameter tubing used in this study indicate that resistance caused by the tubing was negligible.

To reduce the effect of stream velocity on the measurement bag, a shelter for the bag was constructed that consisted of a semicircular piece of Schedule-80 PVC with sheet metal attached to the bottom and ends. Holes were drilled in the shelter to allow pressure equilibration with the stream. One end-piece was removed for inserting the bag and had an access hole to allow tubing attached to the bag to exit the shelter.

During installation, the covered cylinders were placed at a slight angle to the streambed to allow venting of air bubbles out of the meter prior to measurement. The cylinders generally were pushed into the streambed about 0.17 to 0.19 m. A measured volume of water (0.5 to 1.0 L) was added to the measurement bags so that downward seepage fluxes, should they occur, could be measured and because use of dry bags has been shown to reduce inflow in response to deformation and relaxation of the submerged bags (Erickson 1981; Shaw and Prepas 1990; Belanger and Montgomery 1992). Once installed, the cylinders sat for 10 to 15 minutes before any tests were conducted. It was expected that this was a sufficient time for the predominantly sandy sediments to equilibrate following meter installation.

The seepage flux was measured as the change in volume in the measurement bag after two to four hours. Two seepage measurements were conducted in each device at each location. At several times during the seepage measurements, the ambient hydraulic gradient between the ground water and surface water was recorded using a hydraulic potentiomanometer after the design of Winter et al. (1988) (Figure 2c). The average hydraulic gradient during the seepage measurements was calculated using the data from the potentiomanometer. The Darcy equation (Figure 2c, Equation 5) was used to calculate K_v.

Slug Tests

Shallow wells with 2.5 cm outside diameter (O.D). and a 1.3 cm I.D. alloy-steel casing were driven into the streambed. The screen had 2.5 cm O.D. and 1.9 cm I.D. with fifteen 5.1 cm long by 0.5 mm wide vertical slots over a 47 cm interval. Slug tests were conducted at three depths at each station with the screen at depth intervals of about 0.07 to 0.54, 0.98 to 1.45, and 1.90 to 2.37 m below the streambed. About 3.8 to 8.3 casing volumes of water were withdrawn to develop the well.

Pneumatic slug tests were conducted by attaching a gas-tight manifold to the top of the casing and applying a vacuum to draw the water level into a clear piece of PVC pipe in the manifold, so that the initial displacement could be measured. The vacuum then was released and the response was recorded using a Druck® PDCR 35/D 10-pounds-per-square-inch submersible pressure transducer attached to a Campbell® CR10 data logger. At least two replicate tests with the same displacement were done at each screen depth.

Slug tests with similar displacements to those used in the field were performed in a large water-filled tank. These tests indicated that the time for the water level to recover to the initial level was substantially shorter (about one second) than for any of the field tests, indicating that sediments limited the rate of water flow out of the well during the field tests, not the well casing and screen.

Slug-test results were analyzed using the method of Bouwer and Rice (1976) and Bouwer (1989) (Figure 2d, Equation 6) to calculate horizontal K (K_h). The Bouwer and Rice (1976) method assumes isotropic conditions, but an extension of the Bouwer and Rice method by Zlotnik (1994) that considers the effect of anisotropic sediments on the calculated K_h also was used. Using this method, the anisotropy ratio (K_h/K_v) is determined externally or assumed and inserted into Equation 7 (Figure 2d, subsequently r_w^* is substituted for r_w in Equation 6). Based on typical K_h/K_v values of 1 to 10 for relatively small-scale tests (Freeze and Cherry 1979; Butler 1998), a K_h/K_v of 10 was assumed for all slug-test K_h values corrected for anisotropy to bound the expected effects of anisotropy on K_h values.

Grain-Size Analyses

Shallow streambed samples were collected from the upper 0.2 m using a BMH-53 piston-style sampler (Edwards and Glysson 1988). At the NS and WG sites, deeper core samples were collected to depths of about 2.5 m using a 122 cm long 3.8 cm I.D. piston-core barrel. In the saturated sands sampled, core recoveries were about 50% to 60%, so lithologic records were incomplete. Loss of equipment prevented collection of cores to 2.5 m at the PB, BH, SO, PS, and NK sites. At these sites, cores to about 0.6 m were collected using hand-driven 3.8 cm I.D. polycarbonate tubes. Core samples were subsampled by lithologic layer and depth interval.

Grain-size distributions (Figure 2e) were determined by sieve analysis at the University of Nebraska-Lincoln Soils Laboratory. Field samples were split into two fractions in the laboratory and both subsamples were analyzed for making comparisons of the reproducibility of grain-size distributions.

Values of K (isotropic) were estimated from the diameter at which 10% of the grain-size distribution is finer (d_{10}) using the widely applied, empirical formula of Hazen (1893; Figure 2e, Equation 8). The Hazen formula includes a temperature correction

(equal to 1.0 at a temperature of 10°C, the approximate mean annual air temperature along the Platte River in Nebraska), an empirical coefficient (for sand, a value of 860 was used; Vukovic and Soro 1992, p. 12), and a dimension coefficient (1.0 for K values in m/day). Values of K also were estimated using the method of Alyamani and Sen (1993), which incorporates the slope and intercept of the grain-size distribution curve between d_{10} and d_{50} (Figure 2e, Equation 9), rather than relying on a single representative grain-size parameter, such as the d_{10} used in the Hazen method.

Cores of the upper 0.2 m sometimes were split into multiple samples that were analyzed for grain-size distribution. In these cases, the harmonic mean K (Freeze and Cherry 1979, p. 34) for the upper 0.2 m was calculated from the K values of individual samples in that interval to obtain K values that were comparable directly to those determined for the permeameters and seepage meters.

Statistical Analyses

Sign tests (Helsel and Hirsch 1992) were used to determine if differences in K between paired duplicate tests, side-by-side tests, and different methods were statistically significant. The entire set of paired data for each comparison was analyzed. For example, for a comparison of K values determined using the Hazen (GSH) and Alyamani and Sen (GSA) grain-size methods, the GSH K value was paired with the GSA K value at the same station, and the entire data set, consisting of paired values from each individual station, was analyzed to determine if there were significant differences between the GSH and GSA K values. The sign test is fully nonparametric (no assumptions about the distribution of the differences between the groups are required) and determines if one group tends to produce different values from the other group. If the attained significance level (p-value) was less than a predetermined significance level ($\alpha = 0.05$), the differences in K between paired groups were considered significant. The median difference between paired data sets is the most robust estimator of the magnitude of the differences between data sets (Helsel and Hirsch 1992) and was computed for all comparisons. All statistics were determined using S-Plus 2000 software, professional release version 1 (Mathsoft 1999).

Results and Discussion

Sources of Variability and Comparison of Hydraulic Conductivity Values

Variations in K could be caused by (1) imprecision and size dependence of each measurement method, (2) spatial variability in sediment characteristics, and (3) differences between measurement methods. The results of measurements designed to identify variations in K related to each of these factors are presented in the following sections.

Reproducibility and Size Dependence of Measurements

Measurement precision was a minor-to-negligible source of variation in K. For 17 of the 23 K calculation methods evaluated, there were no significant differences between duplicate tests. Significant differences between duplicate tests occurred for the CHP14D, CHP28D, CHP14H, CHP28H, GSH, and GSA (abbreviations defined in Table 2) methods (Table 3), although the median differences of each of these methods were less than 2 m/day. These differences between duplicate tests are a small imprecision relative to the general range of K values measured at the sites of 20 to 200

Table 3
Differences in Hydraulic Conductivity Values Determined for Duplicate Tests and Side-by-Side Tests for Each Method Evaluated

Method	Comparison of Duplicate Tests			Comparison of Side-by-Side Tests		
	Number of Tests	Attained Significance (p-value)	Median Difference (m/day)	Number of Tests	Attained Significance (p-value)	Median Difference (m/day)
CHP14D	37	**0.01**	1.3	34	0.12	2.8
CHP28D	38	**0.01**	1.4	36	0.62	−2.4
CHP60D	37	1.00	−0.1	34	1.00	0.0
CHP90D	38	0.87	0.2	36	0.87	−3.9
CHP14H	38	**0.01**	1.3	36	0.24	2.0
CHP28H	38	**0.01**	1.8	36	1.00	−1.8
CHP60H	37	1.00	0.0	35	1.00	0.8
CHP90H	38	0.87	0.4	36	0.87	−5.5
FHP14D	38	0.42	0.9	36	0.07	2.6
FHP28D	38	0.42	0.3	36	0.87	1.8
FHP60D	38	0.26	0.4	36	0.62	0.3
FHP90D	38	0.32	−0.3	36	0.24	1.2
FHP14H	38	0.26	1.1	36	**0.03**	2.0
FHP28H	38	0.42	0.5	36	0.62	2.4
FHP60H	38	0.26	0.9	36	0.62	2.9
FHP90H	37	0.19	−1.2	36	0.62	2.7
SEM28	14	0.79	1.3	11	1.00	0.4
SEM61	12	0.15	0.3	12	0.77	0.3
SEM91	8	1.00	0.0	6	1.00	0.4
GSH	112	**0.00**	0.9	34	0.39	2.0
GSA	112	**0.00**	0.8	34	0.23	−2.0
SLUGI	41	0.53	0.0	14	1.00	0.0
SLUGA	44	0.17	−0.2	14	1.00	0.2

Significant differences, at a significance level of 0.05, are shown in bold.

m/day considering typical uncertainties in K of an order of magnitude or more due to heterogeneity and scale (Freeze and Cherry 1979; Eggleston and Rojstaczer 1998). Sources of measurement imprecision for each technique are discussed next.

Field Permeameters

The differences between duplicate tests for the 14 and 28 cm constant-head permeameters reflect primarily the sensitivity of these tests to the height of displacement. However, even for those constant-head tests that showed significant dependence on displacement, median differences between duplicate tests at different displacements were less than 4 m/day. Thus, the practical importance of the dependence of the constant-head test results on displacement may be minimal.

For falling-head tests, there were similar differences in displacement between duplicate tests for different sizes of permeameter, and reproducible results were obtained for all sizes. The effects of different displacements are likely to be less for the falling-head than the constant-head tests because the displacement adjusts dynamically throughout a falling-head test rather than being fixed as in the constant-head test.

Factors that could contribute to measurement uncertainty associated with field permeameter tests include (1) scouring of sediment around permeameters, (2) development of micro-erosional preferential pathways resulting from excessive head gradients (Sillanpää 1956), (3) disturbance of soil structure (Fadl 1979), and (4) boundary flow or side leakage at the sediment permeameter interface (Fadl 1979; Hill and King 1982). These factors generally did not result in significant differences between duplicate tests.

Number of off-scale values	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
Maximum, m/d	170	220	110	120	200	290	200	380	180	130	140	94	210	200	230	210	180	39	8.7
n	74	76	75	77	76	76	75	77	77	77	76	77	77	77	76	77	35	34	23

EXPLANATION
+ VALUE GREATER THAN Q_{75} + 1.5 × IR
  MAXIMUM VALUE LESS THAN Q_{75} + 1.5 × IR
  75th PERCENTILE (Q_{75})
INTERQUARTILE
RANGE (IR)   MEDIAN
  25th PERCENTILE (Q_{25})
  MINIMUM VALUE GREATER THAN Q_{25} - 1.5 × IR
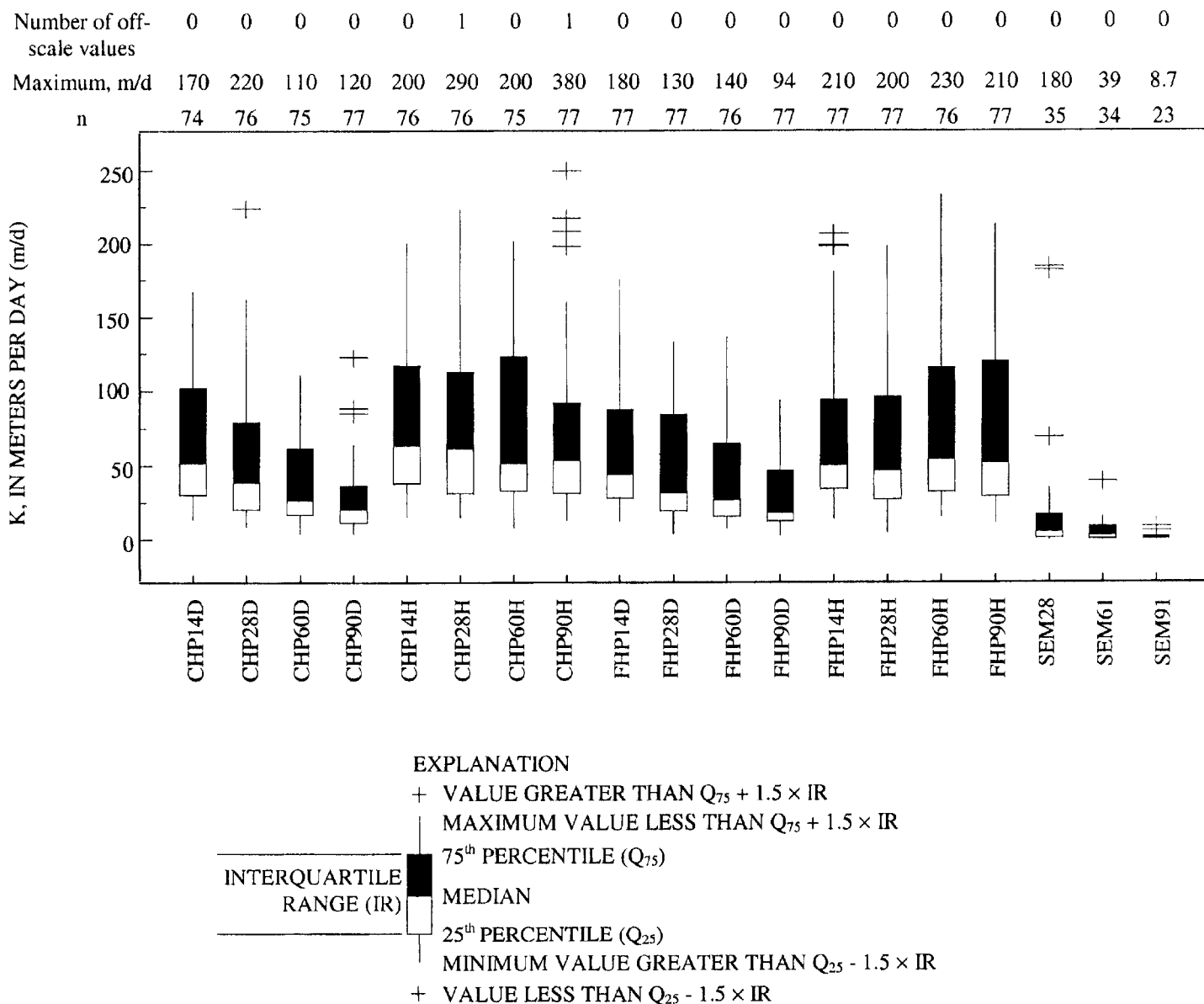+ VALUE LESS THAN Q_{25} - 1.5 × IR

Figure 3. Box plots showing hydraulic conductivity values determined using different diameters of field permeameters and seepage meters. The number of hydraulic conductivity values determined (n) using each method also is shown. Method abbreviations are defined in Table 2.

Significant differences were detected between all diameters of the field permeameter tests (both constant- and falling-head) when analyzed with the Darcy equation (Figure 3, Table 4). In contrast, most of the field permeameter tests of different diameters analyzed with the Hvorslev equations were not significantly different. The exception to this observation was for the 28 cm permeameters, which had significantly different K_v values (when analyzed with the Hvorslev equation) from other diameters for five of the six comparisons (Table 4). The reasons for the anomalous results obtained with the 28 cm permeameters could not be determined.

Values of K_v decreased as diameter increased for field permeameter tests analyzed using the Darcy equation. Because the same tests did not show this size dependence when analyzed with the Hvorslev equations, the results indicate that there are errors associated with the use of the Darcy equation to analyze the field permeameter tests. This result is not unexpected given that the application of the Darcy equation to the field permeameter problem assumes that all head loss occurs across the sediment inside the permeameter and disregards radial head loss from the bottom of the permeameter. For an equal displacement, flow out of the meter (Figure 2a) increases

as diameter increases, and this increase in flow causes more radial head loss. Thus, the assumptions of the Darcy equation deviate further from reality for the field permeameter test as diameter and displacement increase. These limitations to applying the Darcy solution to field permeameter tests were known in advance, but because this method has been used for measuring K_v in shallow saturated sands, it was used for comparison with more sophisticated approaches. It is likely that K_v calculated with the Hvorslev equation for different sizes of permeameters were not significantly different because this method considers both head losses inside the permeameter and radial head losses outside the permeameter through the incorporation of a shape factor (Hvorslev 1951).

Seepage Meter/Hydraulic Gradient Measurements

Values of K_v determined with all three sizes of seepage meters coupled with hydraulic gradient measurements were not significantly different where duplicate K_v values were determined. However, when considering those cases in which K_v values could not be determined from one or both duplicate measurements, this approach was not reproducible for estimating K_v. The SEM28, SEM61, and

a.

Number of off-scale values	0	0	1	0	0	0	0	0	0	0
Maximum	200	200	380	210	230	210	290	200	240	160
n	44	43	45	45	44	44	44	46	42	42

b.

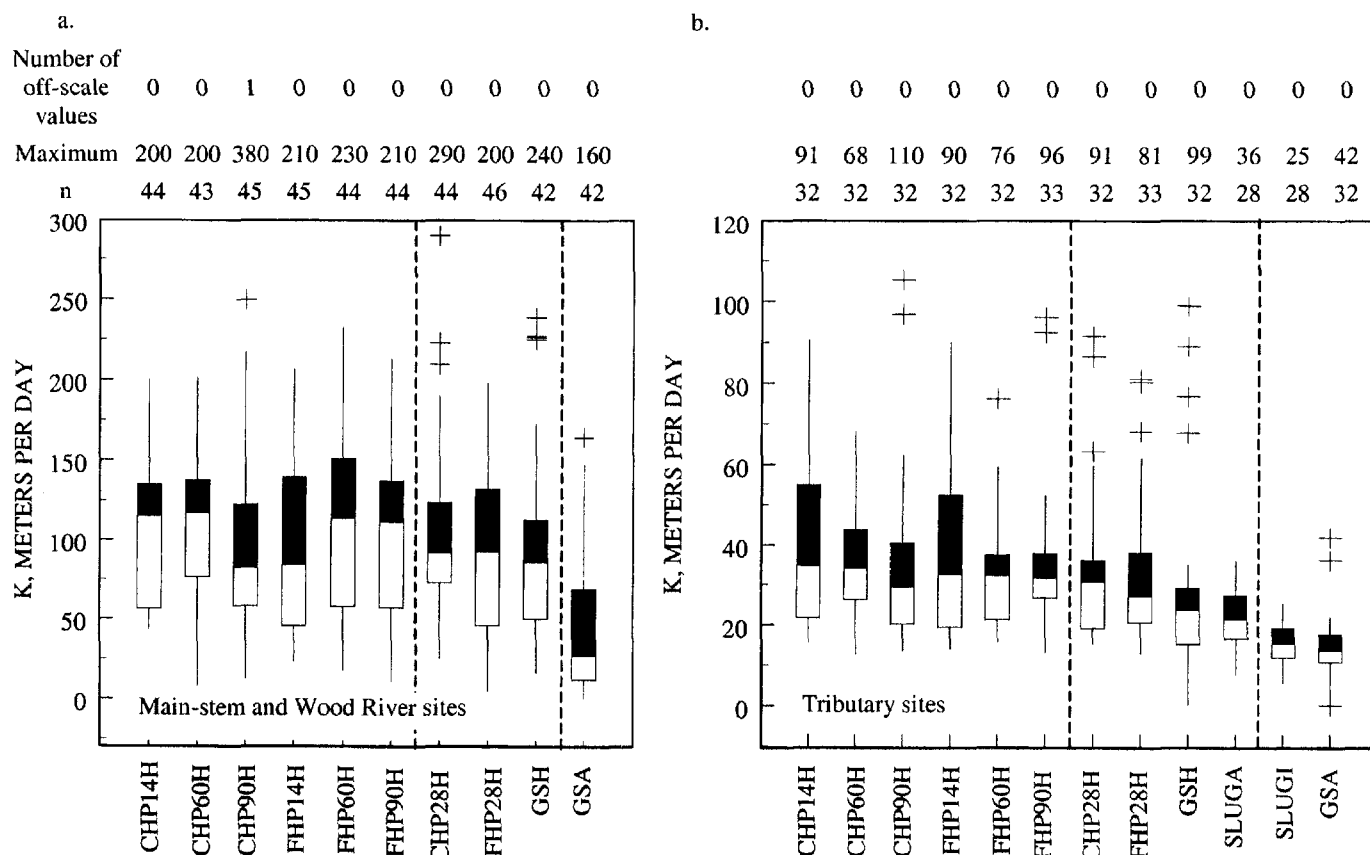|											
0	0	0	0	0	0	0	0	0	0	0	0
91	68	110	90	76	96	91	81	99	36	25	42
32	32	32	32	32	33	32	33	32	28	28	32

Figure 4. Box plots showing hydraulic conductivity values determined using field permeameter tests analyzed using Hvorslev (1951) solutions, empirical grain-size formulas, and slug tests from (a) main-stem and Wood River and (b) tributary sites. The number of tests using each method (n) also is shown. The vertical dashed lines separate groups of tests that generally had significantly different values. Method abbreviations are defined in Table 2.

SEM91 methods failed to yield duplicate K_v values for 50%, 57%, and 62%, respectively, of the attempted duplicate measurements. Because of time constraints, it was generally not possible to attempt more than two measurements with each seepage meter. Individual seepage-meter tests coupled with hydraulic gradient measurements were unsuccessful for determining K_v values about 40% of the time. Values of K_v determined with different diameters of seepage meter were not significantly different (Figure 3, Table 4).

Several factors contributed to the relatively high rate of failure to obtain K_v values. Of the failed measurements, 58% were caused by ground water/surface water gradients measured with the potentiomanometer being opposite the flux direction indicated by gains or losses from the seepage bag. This result could have multiple causes related to the seepage-meter measurements, including flow-field deflection caused by frictional resistance of the meter (Erickson 1981; Belanger and Montgomery 1992), stream velocity effects on the bag resulting in deformation or relaxation of the submerged bags (Erickson 1981; Shaw and Prepas 1990; Belanger and Montgomery 1992), leakage between the seepage meters and surface water related to setting and sealing meters into the bottom (Welch et al. 1989; Belanger and Montgomery 1992), or combinations of these variables. At the only site (PS) where head gradients consistently indicated the stream was losing water, measured seepage-meter fluxes were consistently in the opposite direction of the measured gradient. This result suggests that the seepage-meter measurements were not successful under conditions with downward head gradients. Although potentiomanometer measurements are simpler and have fewer sources of error than seepage meters, head gradients were often spatially variable across the stream

and temporally variable in response to stream fluctuations, including some cases of reversals during the seepage-meter measurements. Thus, uncertainty in the head gradients contributed, to a lesser extent than the seepage meter measurements, to problems calculating K_v values from the coupled measurements.

Holes in seepage meter bags caused 18% of the failures. Bedload deposition on top of the collection bag, thereby preventing the bag from changing volume freely, caused 11% of the failures in spite of the shelters installed to protect the measurement bags. The sediment entered the shelter through holes in the top and ends of the shelter. Holes in other parts of the seepage meter and procedural errors caused 10% of the failures. Scouring of the bed away from the side of the seepage meter such that the seal of the meter into the bed was broken caused 3% of the failures, a source of error also discussed by Welch et al. (1989).

Slug Tests

Duplicate slug tests with the same displacement were not significantly different, indicating the slug-test results were reproducible under the imposed test conditions (Table 3). However, there are several substantial sources of uncertainty in the slug-test K_h values.

The semilog data plots for many of the tests showed an approximately linear segment relatively early in the test followed by a second, longer linear segment with a greater slope. This concave-downward response curve with a break in the slope near the beginning of the test could reflect several factors. Such a response is consistent with the occurrence of a low-K "skin" near the well screen (Butler 1998) caused by mobilized or concentrated fine-particles that modify formation char-

Table 4
Results of Sign Tests to Determine Significance of Differences in Hydraulic Conductivity Values Between Different Methods and Median Differences

	CHP14D	CHP28D	CHP60D	CHP90D	CHP14H	CHP28H	CHP60H	CHP90H	FHP14D	FHP28D	FHP60D	FHP90D	FHP14H	FHP28H	FHP60H	FHP90H	SEM28	SEM61	SEM91	GSH	GSA	SLUGI	SLUGA
CHP14D		74	73	74	74	74	73	73	74	74	74	74	74	74	73	74	35	34	23	72	72	28	28
CHP28D	0.00		75	76	76	76	75	76	76	76	76	76	76	76	76	76	35	34	23	74	74	28	28
CHP60D	0.00	0.00		75	75	75	75	75	75	75	75	75	75	75	75	74	35	34	23	73	73	28	28
CHP90D	0.00	0.00	0.00		76	76	75	77	75	76	76	76	76	76	76	76	35	34	23	74	74	28	28
CHP14H	0.00	0.00	0.00	0.00		76	75	76	76	76	76	76	76	76	76	76	35	34	23	74	74	28	28
CHP28H	0.05	0.00	0.00	0.00	0.01		75	76	76	76	76	76	76	76	76	76	35	34	23	74	74	28	28
CHP60H	0.00	0.00	0.00	0.00	0.36	0.04		75	75	75	75	75	75	75	75	75	35	34	23	73	73	28	28
CHP90H	0.03	0.00	0.00	0.00	0.42	0.42	0.11		76	76	76	76	76	76	76	76	35	34	23	74	74	28	28
FHP14D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		77	76	76	77	77	76	76	35	34	23	74	74	28	28
FHP28D	0.00	0.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00		76	77	77	79	76	77	35	34	23	74	74	28	28
FHP60D	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00		76	76	76	76	76	35	34	23	74	74	28	28
FHP90D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		76	77	76	77	35	34	23	74	74	28	28
FHP14H	0.00	0.00	0.00	0.00	0.00	1.00	0.17	0.30	0.00	0.00	0.00	0.00		77	76	76	35	34	23	73	74	28	28
FHP28H	0.73	0.00	0.00	0.00	0.00	0.14	0.01	0.08	0.25	0.00	0.00	0.00	0.01		76	77	35	34	23	74	74	28	28
FHP60H	0.02	0.00	0.00	0.00	0.57	0.05	0.25	1.00	0.00	0.00	0.00	0.00	0.08	0.00		76	35	34	23	74	74	28	28
FHP90H	0.01	0.00	0.00	0.00	0.42	0.00	0.25	0.02	0.00	0.00	0.00	0.00	0.08	0.00	0.08		35	34	23	74	74	28	28
SEM28	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00		24	13	34	34	16	16
SEM61	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31		17	32	32	20	20
SEM91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.58	0.14		21	21	8	8
GSH	0.91	0.00	0.00	0.00	0.00	0.42	0.00	0.03	0.56	0.00	0.00	0.00	0.03	0.73	0.00	0.00	0.00	0.00	0.00		74	28	28
GSA	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.20	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00		28	28
SLUGI	0.00	0.01	1.00	0.01	0.00	0.00	0.00	0.00	0.00	0.34	0.57	0.04	0.00	0.00	0.00	0.00	0.08	0.00	0.01	0.00	0.04		28
SLUGA	0.00	0.85	0.01	0.00	0.00	0.04	0.00	0.09	0.09	0.18	0.04	0.00	0.00	0.34	0.00	0.00	0.00	0.00	0.01	0.85	0.00	0.00	

Significance level (p-value) for two-sided sign tests (lower left) and number of observations (upper right) are shown. Significance criteria: $p < 0.05$.

Median Differences (in m/day) (K_s of Test on X-axis – K_s of Test on y-axis)

p-values	CHP14D	CHP28D	CHP60D	CHP90D	CHP14H	CHP28H	CHP60H	CHP90H	FHP14D	FHP28D	FHP60D	FHP90D	FHP14H	FHP28H	FHP60H	FHP90H	SEM28	SEM61	SEM91	GSH	GSA	SLUGI
CHP28D	8.5																					
CHP60D	20	3.9																				
CHP90D	26	16	8																			
CHP14H	-11	-17	-29	-33																		
CHP28H	-2.4	-20	-19	-36	3.5																	
CHP60H	-6.9	-17	-28	-33	1.9	-4.7																
CHP90H	-4.7	-16	-20	-34	1.8	-1.6	2.3															
FHP14D	2.4	-4.5	-11	-22	10	3.6	7.8	8.1														
FHP28D	11	0.43	-4.8	-13	20	17	18	16	8.5													
FHP60D	19	4.7	0.82	-6.4	25	21	26	18	13	3.7												
FHP90D	26	15	5.8	-1.7	34	32	31	28	19	13	4.4											
FHP14H	-2.9	-8.6	-18	-27	3	0.16	3	3.2	-5.9	-14	-18	-24										
FHP28H	-0.41	-10	-16	-26	6.6	1.7	6.9	4.3	-2.4	-10	-14	-24	4.1									
FHP60H	-4.1	-17	-22	-32	2	-2.4	1.3	-0.26	-6.3	-16	-25	-32	-2.2	-5.2								
FHP90H	-8	-22	-29	-33	-1.9	-4.1	-2.6	-3.5	-11	-21	-22	-34	-5.5	-7.3	-2.4							
SEM28	46	24	20	12	54	37	40	46	37	21	16	12	38	29	42	37						
SEM61	51	32	20	14	67	52	47	48	46	30	18	15	62	42	46	45	3.6					
SEM91	74	63	52	26	110	91	100	76	52	63	46	31	66	87	94	110	2.1	0.26				
GSH	0.14	-6.8	-11	-20	12	1.1	8.7	3.9	-1.2	-7.4	-11	-17	5.6	1.2	8.3	11	-32	-30	-87			
GSA	28	13	7.1	-2.7	40	32	37	22	22	8.6	4.6	-1.4	25	16	36	27	-11	-15	-33	23		
SLUGI	13	6.2	0.82	-3.2	20	16	18	16	11	2.4	-1.3	-2.7	18	11	17	20	-9.9	-13	-10	7.1	-1.2	
SLUGA	6.3	-0.3	-5.9	-9.9	13	8.5	11	9.9	4.3	-3.6	-7.7	-7.8	10	2.9	9.3	13	-16	-18	-15	1.5	-6.6	-6.1

Bold values indicate statistically significant differences.

acteristics in the vicinity of the well screen. The slope break also may reflect that the relatively small casing diameter or open area of the screen restricted the early-time response during the displacements (which were relatively large considering the shallow well depths) and high velocities at the beginning of the tests, resulting in frictional head losses in the well. The presence of a low-K skin or frictional losses with the well creates substantial uncertainty in estimated K_h values using the Bouwer and Rice method (Butler 1998). A straight line was fit to the middle or second linear segment to estimate K_h, an approach that should yield reasonable estimates of K_h for virtually all values of storativity (Butler 1998). This linear segment suggests that the theoretical conditions of the Bouwer and Rice method were met once the effects of the large early displacements passed. However, the exact effects of a low-K skin or test-design limitations on the K_h values determined using late-time response data with relatively low displacements are not fully known.

Slug-test data collected at the NS, PB, and WG sites generally could not be analyzed successfully because the response data were oscillatory and exhibited poor fits to theoretical solutions using a modified Springer-Gelhar solution of Zlotnik and McGuire (1998a, 1998b) and a Kipp solution discussed by Weight and Wittman (1999). The poor fit of these tests to theoretical solutions likely resulted from the combination of relatively high displacements, small well diameter, small screen open area, and high K sediments (Butler 1998).

At the tributary sites, the nonoscillatory slug-test response data, and relatively good fits to the theoretical Bouwer and Rice model likely occurred because these sites had relatively lower K
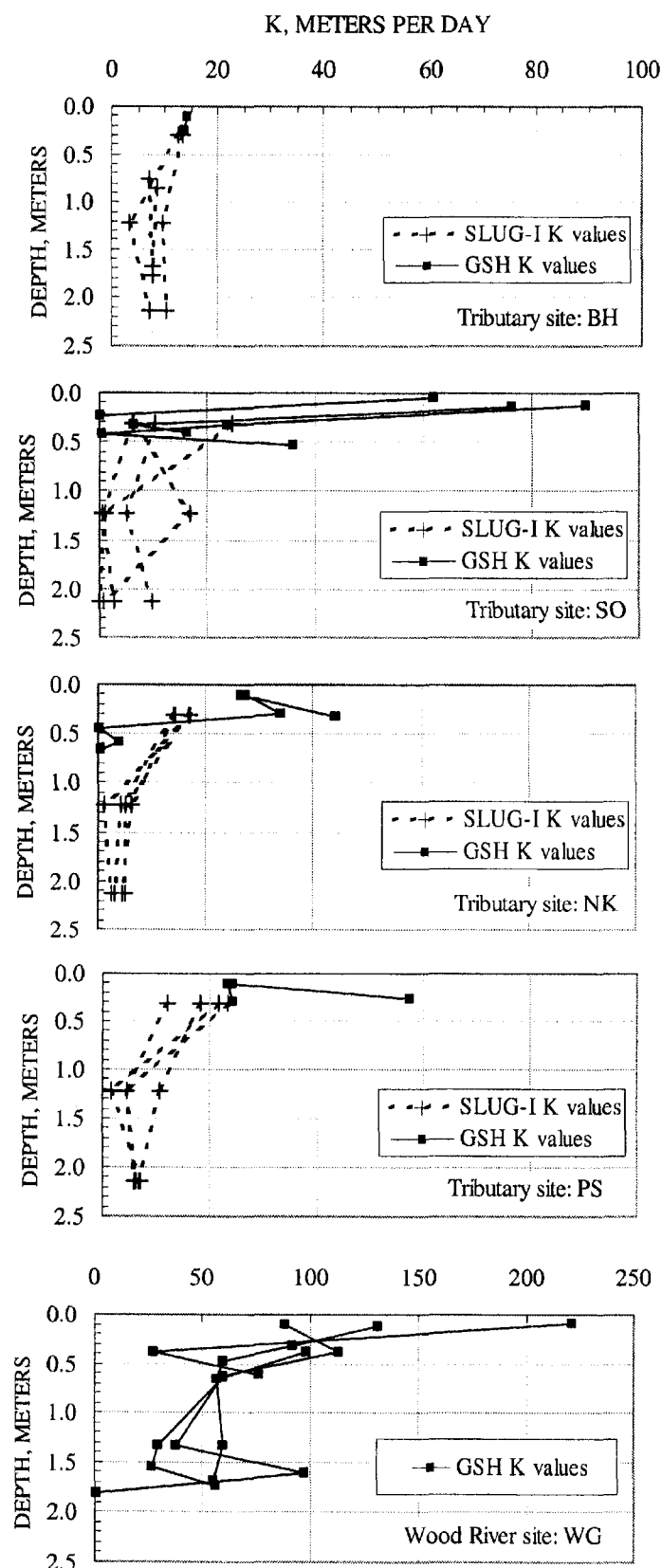
K, METERS PER DAY

Figure 5. Graphs showing changes in hydraulic conductivity values with depth below the stream bottom at selected locations. Note the change in scale for the WG site. Site abbreviations are defined in Table 1, and method abbreviations are defined in Table 2.

(indicated by slower response times) than the main-stem and Wood River sites. Although reproducible at the displacements used, K_h values estimated using the Bouwer and Rice slug tests have substan-

tial uncertainty and are included mainly for comparative purposes to other tests.

Grain-Size Analyses

Although the differences between duplicate tests for the GSH and GSA methods were statistically significant, the median differences between duplicates were less than 1 m/day, and of little practical importance.

Local Spatial Variability of Sediment Properties

Local scale spatial variability in streambed properties over distances of less than 3 m did not have a substantial impact on K values determined in this study (Table 3). This result was somewhat unexpected given that previous studies using seepage meters to measure ground water/surface water fluxes had found that spatial variability over distances less than 2 m was a major cause of variability in seepage meter measurements in lakes (Shaw and Prepas 1990) and laboratory tank experiments with fine-to-medium sand (Belanger and Montgomery 1992). These spatial variations were interpreted primarily to be the result of spatial variations in hydraulic conductivity caused by sedimentary heterogeneity. In this study, median differences between side-by-side tests for all sizes of seepage meters were less than 0.4 m/day, although measurement failure resulted in the number of comparisons ranging from only 6 to 12 (Table 3). Only one method, FHP14H, had significant differences in K_v values for side-by-side tests. The reason for this result is unclear.

Different Measurement Methods

Because the results of field permeameter tests analyzed with the Darcy equation were dependent upon diameter and coupled seepage meter/hydraulic gradient measurements had a relatively high incidence of failure, neither was a preferred approach for determining K under the conditions encountered in this study. The remaining methods, including field permeameter tests analyzed with the Hvorslev solutions, empirical grain-size methods, and slug tests, are compared in this section for determining K in the upper 0.2 to 0.3 m of the streambed. At depths greater than about 0.3 m, field permeameter and seepage meter tests could not be used to measure K; therefore, K values estimated from grain-size and slug tests at greater depths are excluded from the comparisons discussed in this section.

The remaining methods were grouped such that most of the comparisons between methods in each group indicated that the results were statistically similar. Falling- and constant-head tests with the 14, 60, and 90 cm diameter field permeameters analyzed with the Hvorslev solutions generally had similar K values (Figure 4, Table 4). Comparisons between these tests indicated that they were not significantly different with the exception of comparisons between the CHP90H and FHP90H and the CHP14H and FHP14H tests. These Hvorslev field permeameter tests generally had significantly higher K than grain-size and slug-test analyses (Figure 4, Table 4). Values of K determined with CHP28H, FHP28H, GSH, and SLUG-A tests were not significantly different, with the exception of comparisons between the FHP28H and SLUG-A tests. Values for these tests were intermediate between values from most Hvorslev permeameter tests, which were greater, and values determined from SLUG-I and GSA tests, which were less.

The Hvorslev permeameter tests should be a more rigorous approach to determine K compared to grain-size tests because
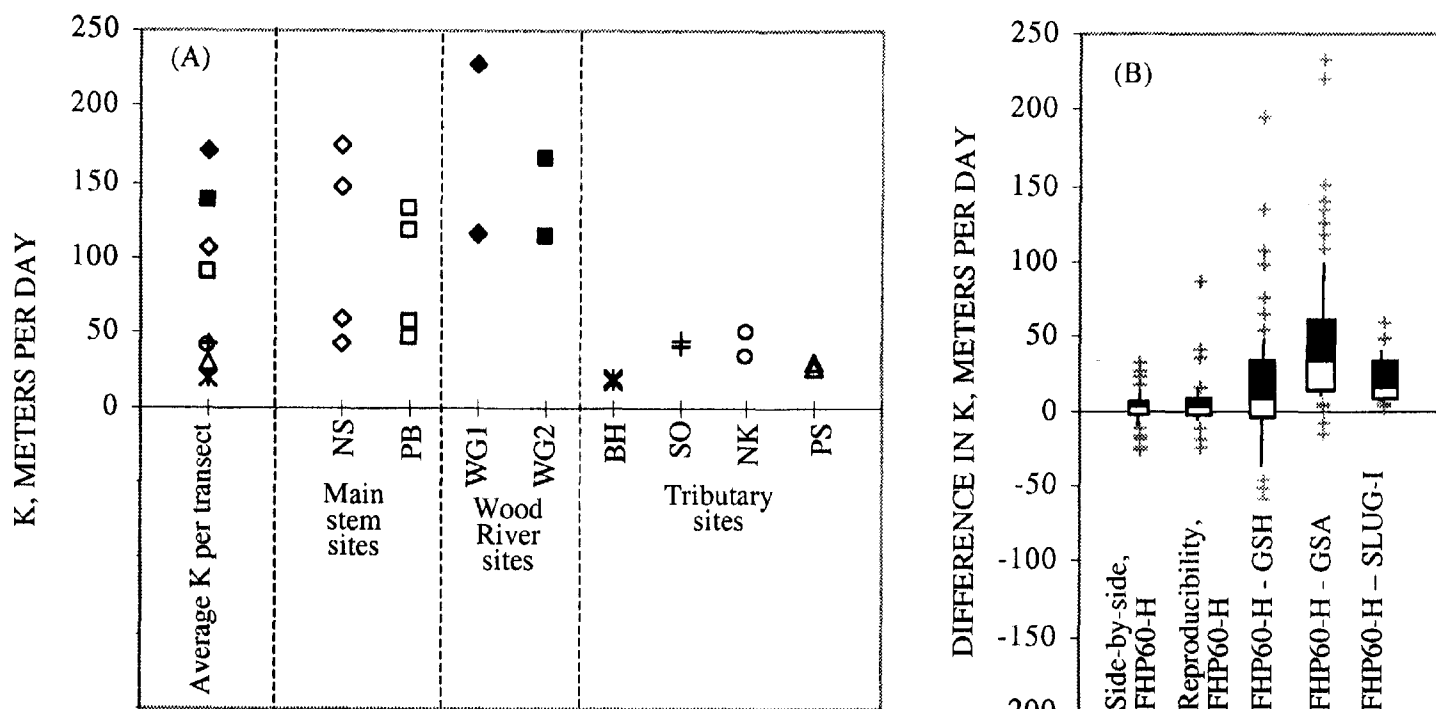
Figure 6. Graphs comparing (a) spatial variability of hydraulic conductivity values of the upper 0.25 m measured using the 60 cm falling-head permeameter test analyzed using the Hvorslev equation (FHP60H); (b) variability caused by local scale spatial variability (side-by-side tests for the FHP60H method), measurement imprecision (reproducibility tests for the FHP60H method), and different methods of measurement (differences between the FHP60H and Hazen grain size (GSH), Alyamani and Sen grain size (GSA), and slug test (assuming isotropic conditions, SLUG-I) methods). The FHP60H is used as the standard test for comparison because it is the preferred method for use in the upper 0.25 m identified in this study (see Implications for Additional Data Collection). Site abbreviations are defined in Table 1 and method abbreviations are defined in Table 2.

they are field hydraulic analyses rather than empirical relations of grain-size to K. The results of this investigation are consistent with those of previous studies in sandy aquifers (Wolf et al. 1991a; Millham and Howes 1995; Rovey and Cherkauer 1995) indicating that K values estimated from empirical grain-size formulas are generally less than those determined from field hydraulic testing. These previous studies principally attributed the differences to the larger measurement scale of the field tests. However, K values calculated using the grain-size methods may be smaller because K is a complex function of packing, sediment structure, heterogeneity, and other factors not accounted for in the empirical grain-size methods (Taylor et al. 1990).

Values of K determined from slug tests were likely lower than those computed using Hvorslev permeameter tests because the screened interval of 0.07 to 0.54 m of the slug test intersected lower K sediments than the permeameter tests of the upper 0.25 m, and possibly because of greater well-skin effects on the slug-test results. At the tributary sites, K generally decreased with depth (Figure 5). At four locations where grain-size depth profiles with multiple samples over the slug test screened interval were available, K values were calculated for the upper 0.25 m and the 0.07 to 0.54 m depth using the harmonic means of GSH K values. For these four cases, vertically averaged K in the upper 0.25 m (K_{0-25}) was 1.5 to 12 times greater than over the 0.07 to 0.54 m interval (K_{7-54}). These vertical changes in K were similar to the median ratio of FHP60H to slug-test values of 2.2 for the slug-test results analyzed assuming isotropic conditions and 1.6 for anisotropic conditions ($K_h/K_z = 10$). The similarity of the ratios of K_{0-25}/K_{7-54} and K_{FHP60H}/K_{slug} indicates that much of the difference between permeameter and slug-test values could be explained by the inherent variation in K with depth.

Well-skin and test-design effects may be less of a concern for

permeameter tests than slug tests. Butler (1998) recommends that the results of slug tests be viewed as lower bounds of the estimated K because of the prevalence of low-K well skin effects. For slug tests in screened wells driven into the sediment, the entire length of the well screen is in contact with sediment potentially disturbed during the driving process. Although driving wells minimizes formation disturbance relative to other drilling methods (Morin et al. 1988), disturbance can still occur because of smearing of fine particles along the casing, compaction of sediments in the vicinity of the driven pipe, and penetration of soil structure. Alternatively, slug-test values may have been reduced because of the combination of the small diameter of the wells and the relatively large displacements used for the slug testing. Head losses in the narrow diameter wells may have been sufficient to decrease the calculated K, especially in relatively high-K sediments (Butler 1998, pp. 168-169). Slope breaks in the slug-test response curves that may indicate either well-skin or test-design effects were sometimes observed. In contrast, permeameters do not have a well screen through which flow will be restricted by fine materials. In addition, disturbance of sediment during installation generally will be less for the permeameters than the slug tests, especially for larger diameters, because sediment disturbance will occur only along the walls of the permeameter. The volume of undisturbed sediment in the middle of the permeameter will be relatively large in comparison with the volume of disturbed sediment along the permeameter walls.

It is unlikely that the differences between the Hvorslev permeameter and Bouwer and Rice slug tests can be attributed only to the fact that the former measures K_v whereas the latter measures K_h. Anisotropy ratios (K_h/K_v) calculated by dividing slug-test values by Hvorslev permeameter values ranged from about 0.1 to 1.3 with an average of 0.6. Anisotropy ratios of less than one are contrary to typ-

ical literature values from one to 100 (Freeze and Cherry 1979; Butler 1998; Chen and Yin 1999). Rather than indicating that the anisotropy ratio in the upper 0.25 m of the streambed was actually less than 1.0, it is more likely that these differences reflected differences in testing intervals, sedimentary disturbance, or test design between the Hvorslev permeameter and Bouwer and Rice slug tests.

The actual anisotropy ratios of the streambed sediments were uncertain. Chen and Yin (1999) determined that aquifer anisotropy ratios have a substantial effect upon modeled streamflow depletion. The streambed sediments in the upper 0.25 m generally comprise more than 99% sand and gravel-sized particles that were well rounded. In such sediments, local anisotropy is expected to be minimal. Therefore, for the Hvorslev permeameter calculations, isotropic conditions ($K_h/K_v = 1$) were assumed in the upper 0.25 m. However, the Wood River and tributary sites had vertical variations in grain size (Table 1) and this sedimentary layering could result in anisotropic conditions below the upper 0.3 m. The screened interval of the slug tests spanned some of these lithologic layers. Thus, it is likely that anisotropy affected the slug-test responses. Slug-test K values were calculated assuming K_h/K_v values of one for the Bouwer and Rice (1976) method and 10 for the Zlotnik (1994) extension of the Bouwer and Rice method. These values of K_h/K_v represent the typical range for relatively small-scale tests (Freeze and Cherry 1979; Butler 1998) and were selected to bound the expected effects of anisotropy on K_h values. Values of K_h were an average of 40% higher when K_h/K_v was assumed to be 10 than when a value of one was assumed. These variations in slug-test K_h values due to the assumed anisotropy ratio were not large enough to change the conclusions drawn with respect to the comparison of slug tests to other tests (Figure 4). While the anisotropy ratio cannot be determined from the data collected, the presence of lithologic layering makes it likely that the most reasonable slug-test K_h values were between the values determined for K_h/K_v of one and 10.

Values of K estimated using the GSH method were closer than the GSA estimates to values determined using the Hvorslev permeameter tests, which likely represented the best estimate of K in the upper 0.25 m. Similarly, Sperry and Peirce (1995) determined that K values estimated with the Hazen method compared more closely to those measured in laboratory column experiments than values estimated using the Alyamani and Sen (1993) method. Calculation of K values using the Hazen method for grain-size data reported in Alyamani and Sen (1993, Table 1) indicates that the Hazen K values are consistently greater than Alyamani and Sen values by a median factor of about 1.5.

Values of K determined with coupled seepage meter/hydraulic-gradient measurements were significantly lower than other methods. Apart from the lack of reliability of these measurements because of high failure rates, lower K may reflect flow-field deflection caused by frictional resistance in the meter (Erickson 1981; Belanger and Montgomery 1992).

Spatial Variability of Streambed Hydraulic Conductivity

The main-stem transects have substantial spatial variability in K of the upper 0.25 m across the stream (Figure 6). Large spatial variations in streambed properties across a braided river were expected given the complex sedimentary processes occurring (Karlinger et al. 1983; Walker and Cant 1984). While the highest K values sometimes were found in the deeper channels, the depositional patterns of the Platte River are complex enough that the locations of relatively high K deposits will not always be predictable.

The Wood River (WG) site also shows a relatively large amount of spatial variation in K of the upper 0.25 m across the stream in spite of the relative uniformity of the channel. At the four tributary sites, K varied little across the stream transects, which may reflect that the channels are only 6% to 18% as wide as the PB transect, and that sedimentary processes are more uniform across the channel on the tributaries than on the braided main stem.

The magnitude of spatial variability in K along the NS, PB, and WG transects is similar to the differences between transects in width-weighted mean K (Figure 6). Regional variations in streambed characteristics were expected based on regional variations in stream slope, discharge, and sediment load (Kircher 1983; Kinzel et al. 1999). For the tributary sites, spatial variation in K values along transects were generally less than variations in mean values between transects.

At the four tributary sites and the Wood River site, K values determined from grain-size analyses and slug tests were generally greater at or near the streambed interface than at depth (Figure 5). At the SO, NK, and WG sites, grain-size samples collected through the upper 0.6 m indicated that K decreased from the upper 0.25 m to greater depths. Grain-size data was not collected to a sufficient depth to confirm similar decreases below the upper 0.3 m at the BH and PS sites. However, K between the shallowest slug test (with the middle of the screen at about 0.3 m) and the next greatest depth (with the middle of the screen at about 1.2 m) decreased at all four tributary sites (SO, NK, BH, and PS) (Figure 5). At the NS site (North Platte River), GSH K was highly variable with depth, and no consistent relation was apparent.

Implications for Additional Data Collection

Using Darcy's equation, calculated ground water/surface water fluxes will be directly proportional to values of streambed K. Thus, it is desirable to have estimates of streambed K that are as well constrained as possible. More than 50% of the Hvorslev permeameter, slug test, and grain-size determinations indicated K values of 50 to 150 m/day at the main-stem and Wood River sites and 15 to 55 m/day at the tributary sites (Figure 4). These values represent substantially better constrained estimates of K than values based upon textural descriptions (Table 1, Freeze and Cherry 1979, p. 29), which range over two orders of magnitude from about 8 to 900 m/day for the main-stem and Wood River sites and 0.8 to 90 m/day for tributary sites. Thus, field measurements of streambed K are useful for constraining initial parameter estimates for ground water/surface water flux calculations.

Field permeameter tests analyzed using Hvorslev solutions have advantages compared to seepage meters, empirical grain-size formulas, and slug tests for determining streambed K at the streambed interface (approximately the upper 0.3 m). Field permeameter tests are easier to conduct, and more consistently successful at determining streambed K than coupled seepage meter and hydraulic gradient measurements. Because Hvorslev permeameter tests are field hydraulic tests that inherently consider factors such as packing, grain shape, and sedimentary heterogeneity that affect K, these tests are superior to empirical grain-size formulas. Compared to slug tests, Hvorslev permeameter tests are less likely to be influenced by well-skin and test-design effects, and determine K_v through the streambed rather than K_h some depth below the streambed.

The problems encountered in this study with determining K_v with coupled seepage-meter and hydraulic-gradient measurements were related principally to the relatively high-energy environment

in which the measurements were attempted and the fact that two independent measurements had to be made to calculate K_v. Although the shelters installed to protect the measurement bags offered greater protection than leaving the bags in open water, the shelters did not entirely prevent water velocity or sediment deposition effects on the measurement bags. Uncertainties in seepage meter and ground water/surface water gradient measurements were compounded in trying to estimate K_v. Seepage meters have been used widely for measuring ground water/surface water fluxes in low energy settings such as lakes and are a very useful method in these settings (Lee 1977; Fellows and Brezonik 1980; Erickson 1981; Cherkauer and McBride 1988; Welch et al. 1989; Shaw and Prepas 1990; Belanger and Montgomery 1992). This study suggests that there may be limited applicability for seepage meters to measure seepage flux and coupled seepage-meter and hydraulic-gradient measurements to determine K_v in relatively high-energy flowing streams with mobile beds.

While the Hvorslev falling-head permeameter test may be an advantageous test for determining K at the streambed interface, slug tests and empirical grain-size methods should not be discredited as approaches for determination of streambed K. Although statistically different, median differences in K values between the FHP60H method and the GSH, SLUGA, SLUGI, and GSA methods were about 8, 9, 17, and 35 m/day, respectively (Table 4). These differences in K values were not particularly large considering typical uncertainties in K values of an order of magnitude or more due to heterogeneity and scale (Freeze and Cherry 1979; Eggleston and Rojstaczer 1998). While it is desirable to have estimates of streambed K that are as well constrained as possible, spatial variations in K over a variety of hydrogeologic scales may make variability in K caused by the method of measurement a comparatively minor source of uncertainty in K values. Selecting a method that can feasibly be applied to generate consistently determined data and identify relative variations in streambed K across the study area is probably of greater importance than method selection between valid field permeameter, grain-size, and slug tests.

Spatial variability of K across streams and with depth also needs to be considered in selecting an instream method of measuring K. Spatial variability along and between transects was generally greater than variability in K because of measurement uncertainty for each method (particularly for the preferred permeameter methods), or local scale (side-by-side) variability of streambed sediments (Figure 6). Spatial variability in K was also generally greater than variability between methods (Figure 6). This result implies that choice of method between valid permeameter, grain-size, or slug-test analyses may not be as significant as making multiple measurements to characterize the variability across transects.

The streambed interface was not a low K layer relative to underlying deposits, as has commonly been found (Conrad and Beljin 1996), on any of the streams measured. At the Wood River and tributary sites, the streambed interface typically had greater K than the sediments below. It is probable that deposits deeper than about 0.3 m below the streambed interface limit the rate of ground water/surface water interaction. However, the Hvorslev permeameter tests are not a practical approach for determining K at these depths because the permeameters cannot be driven to or retrieved from these depths easily. The K of these buried streambed deposits could be determined by conducting slug tests or analyzing core samples for grain-size distribution.

The main advantages of instream methods of measuring K are that the measurements are relatively quick and inexpensive, and can be used to make many measurements to characterize variations in K across a regional study area. However, there are logistical limitations for instream methods, chiefly, access to the stream. It was practically impossible to make measurements in streams with water depth greater than about 1 m, or with water velocities greater than about 0.8 m/sec. Relatively high flows in the South Platte and Platte Rivers from August through October 1999 resulted in water depths and velocities greater than these practical thresholds, and prevented additional instream measurements from being made on these rivers. These constraints may limit the utility of instream measurements in some cases, and may require alternative methods such as analysis of pump tests or bank-storage effects near streams.

Conclusions

Estimates of streambed K are needed to quantify the magnitude and spatial distribution of ground water/surface water interactions. Physical instream methods offer a practical approach for characterizing K over regional study areas because the measurements are relatively quick and inexpensive and numerous measurements can be made at many locations using portable equipment. Comparisons of K values determined in sandy streambeds at seven stream transects in the Platte River Basin in Nebraska using different instream measurement techniques indicate the following conclusions.

1. Field permeameter tests analyzed using the Darcy equation and coupled seepage meter/hydraulic-gradient measurements were not preferred techniques based upon test design and logistical concerns; seepage meters often fail in relatively high-energy flowing streams with mobile beds.

2. The Hvorslev analysis of field permeameter tests has advantages compared with other methods for determining K in the upper 0.25 m of the streambed.

3. Measurement precision and local spatial variability over distances of less than 3 m were very minor to negligible sources of variation in K.

4. Spatial variability along and between transects on the Platte, North Platte, and Wood Rivers was greater than variability in K values between methods. Thus, selection of a method between valid permeameter, grain-size, or slug-test analyses may matter less than making multiple measurements to characterize the variability across transects adequately.

5. When selecting a method for measuring streambed K, the vertical location of the low-permeability sediments needs to be considered. The streambed was not a low K layer on any of the streams investigated. On tributary streams, the deposits deeper than about 0.3 m below the streambed probably limited ground water/surface water fluxes. The Hvorslev permeameter tests are not a practical measurement approach below 0.3 m because the permeameters cannot be driven to and retrieved from these depths easily. Slug tests or collection of core samples represent more practical instream approaches for determining the K of these buried deposits.

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