Hydraulic Conductivity of the Streambed, East Branch Grand Calumet River, Northern Lake County, Indiana

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
foot (ft)	0.3048	meter
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
foot per second (ft/sec)	0.3048	meter per second
foot per minute (ft/min)	0.3048	meter per minute
[1]foot per day (ft/day)	0.0003528	centimeter per second
foot per mile (ft/mi)	0.1894	meter per kilometer
cubic foot per second (ft^3/sec)	0.02832	cubic meter per second
gallon (gal)	3.785	liter

[1]Foot per day is the mathematically reduced term of cubic foot per day per square foot of cross sectional area, the unit of measure for hydraulic conductivity.

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Abstract

Horizontal and vertical hydraulic conductivity of the streambed were estimated from results of hydraulic tests along four transects across the east branch Grand Calumet River in northern Lake County, Indiana. Tests were done in two types of temporary wells installed in the streambed—2-inch-diameter wells that had a 1- or 2-foot length of wire-wrapped screen and 3-inch-diameter wells that were open at the ends. When possible, the hydraulic tests included monitoring both falling- and rising-water levels. A total of 47 tests for horizontal hydraulic conductivity and 20 tests for vertical hydraulic conductivity were done. Data collected during the tests were analyzed by use of methods developed by earlier investigators.

Horizontal hydraulic conductivity of the streambed was varied and ranged from 1.0×10^{-2} to $1.2 \times 10^{+3}$ feet per day. Compared to the previously reported range of horizontal hydraulic conductivity for the Calumet aquifer, 6.5×10^{-1} to $3.6 \times 10^{+2}$ feet per day, results of 24 hydraulic tests in the streambed of the east branch Grand Calumet River were within the reported range, 18 were less than the lowest reported value, and 5 were greater than the highest reported value.

Vertical hydraulic conductivity of the streambed was less varied than horizontal hydraulic conductivity and ranged from 3.0×10^{-1} to $7.3 \times 10^{+1}$ feet per day. The ratio between horizontal and vertical hydraulic conductivity calculated for each transect ranged from 1:0.09 to 1:8.5.

The hydraulic conductivity of the streambed generally was dependant on the type of sediments in the part of the streambed that was tested. Although most of the streambed contained soft, fine-grained sediments, parts of the streambed also contained fill materials including coal, cinders, and concrete and asphalt rubble. The highest values of horizontal hydraulic conductivity generally were calculated from data collected at locations where the streambed contained fill materials, particularly concrete and asphalt rubble. Horizontal hydraulic conductivities determined for 11 hydraulic tests in predominantly fill materials ranged from $1.2 \times 10^{+1}$ to $1.2 \times 10^{+3}$ feet per day and averaged $5.6 \times 10^{+2}$ feet per day. The lowest values of horizontal hydraulic conductivity were calculated from data collected at locations where the streambed contained fine-grained sediments. Horizontal hydraulic conductivities determined for 36 hydraulic tests in predominantly fine-grained sediments ranged from 1.0×10^{-2} to $2.4 \times 10^{+2}$ feet per day and averaged $1.5 \times 10^{+1}$ feet per day.

INTRODUCTION

The east branch Grand Calumet River flows through a large urban and industrial region along Lake Michigan's southern shoreline in northern Lake County, Ind. The river flows westward approximately 10 mi from its source at the Grand Calumet Lagoons to its confluence with the Indiana Harbor Canal and the west branch Grand Calumet River (fig. 1). A previous study indicated that more than 90 percent of the flow in the river is from municipal and industrial discharges; the remaining 10 percent or less is attributed to ground-water seepage to the river (Crawford and Wangsness, 1987, p. 32). That study was done during dry weather when surface-water flow to the river was negligible.

The depth of the river ranges from about 2 ft near its source to about 10 ft near the junction with the Indiana Harbor Canal. On the basis of water-level measurements by Kay and others (1996, p. 42), the average gradient for the east branch Grand Calumet River is 0.7 ft/mi; however, gradients are highest in the upper reaches and lowest in the lower reaches of the river. The average velocity of flow is about 1 ft/sec (Crawford and Wangsness, 1987, p. 3). During normal flow conditions, most of the flow from the east branch Grand Calumet River is discharged to Lake Michigan through the Indiana Harbor Canal. A rise in the stage of Lake Michigan can cause backwater conditions and reverse flow directions in parts of the river.

The U.S. Geological Survey (USGS) operates a streamflow-gaging station on the east branch Grand Calumet River at U.S. Highway 12 (station number 04092677) and another on the Indiana Harbor Canal at East Chicago (station number 04092750) (fig. 1). Gage-height data from 1991 to the present (1996) are available for these stations; however, because of problems with gaging equipment, discharge data are intermittent for the Indiana Harbor Canal until 1994. Discharge data are not available for the Grand Calumet River until 1994, when an ultrasonic velocity meter was installed at that gage. From October 1994 to September 1995, discharge averaged about 460 ft^3/sec for the east branch Grand Calumet River and about 660 ft^3/sec for the Indiana Harbor Canal (Stewart and others, 1996, p. 182 and 184).

For more than 100 years, municipal and industrial wastes have been disposed of in the Grand Calumet River. Discharge of wastes to the river was largely unregulated during most of this time. With regulations, initiated primarily during the 1970's, water quality of the east branch Grand Calumet River has improved (Crawford and Wangsness, 1987, p. 2); however, a layer of soft, fine-grained sediments has been deposited in the streambed. Chemical analyses of samples of these sediments indicate they may contain toxic materials such as oil and grease, organic compounds, and polychlorinated biphenyls (Roger Koelpin, Indiana Department of Environmental Management, oral commun., 1995).

The Grand Calumet River is underlain by a silty-sand aquifer known as the Calumet aquifer (Hartke and others, 1975, p. 25). The aquifer is relatively thin (less than 65 ft thick) but is areally extensive in northern Lake County (Watson and others, 1989, p. 1). Water in the Calumet aquifer is unconfined. Although not utilized extensively as a source of water supply, the quality of water in the Calumet aquifer is of concern to Federal, State, and local environmental agencies because of the potential for contamination from human sources and the subsequent discharge of those contaminants to Lake Michigan.

Although numerous hydrologic investigations have been done in the drainage basin of the Grand Calumet River, little is known about the hydraulic connection between the river and the Calumet aquifer. Maps of ground-water levels from previous investigations indicate that ground water is discharged to the river, although periods of flow reversals between the river and the aquifer related to rises in the stage of Lake Michigan are common (Fenelon and Watson, 1993; Greeman, 1995; Kay and others, 1996). Simulations of ground-water flow by Fenelon and Watson (1993, p. 37) suggested values between 0.1 and 1.0 ft/day for vertical hydraulic conductivity of the streambed in the Grand Calumet River; however, the flow model could not be calibrated because of the lack

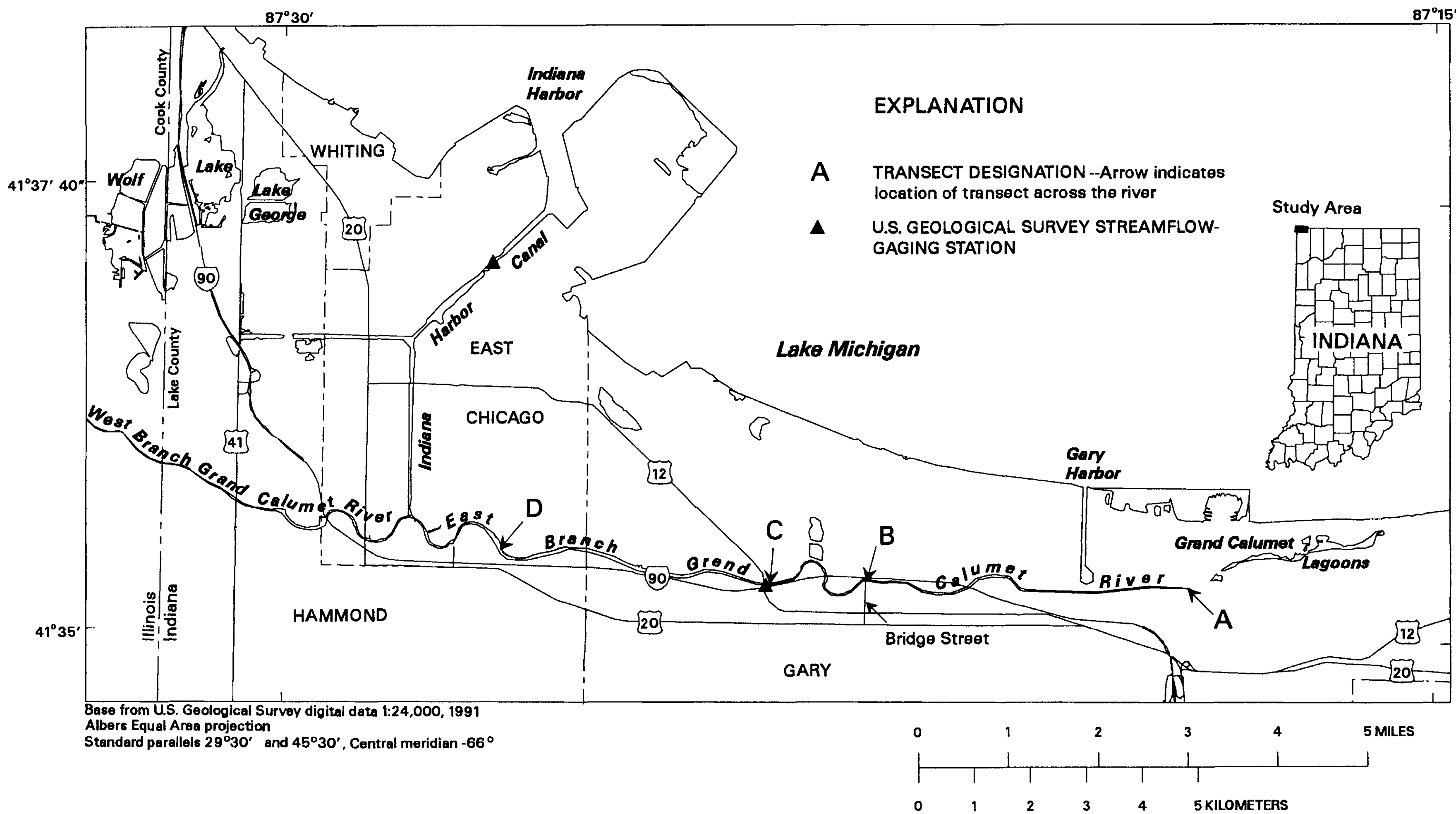


Figure 1. Location of study area and transects across the east branch Grand Calumet River, northern Lake County, Indiana.

of data from which hydraulic properties could be estimated.

Measurements of hydraulic conductivity of the streambed of the east branch Grand Calumet River are necessary to understand ground-water-flow paths and assess the hydraulic connection between the river and the Calumet aquifer. Therefore, the USGS, in cooperation with the Indiana Department of Environmental Management, completed hydraulic tests in the streambed sediments along four transects across the east branch Grand Calumet River during August 1995. Results of the tests can be used to assess the flow of water between the river and the Calumet aquifer. This information is needed by environmental agencies, private companies, and others who are involved in identifying and cleaning up contamination in this region.

Purpose and Scope

This report describes the results of hydraulic tests along four transects across the east branch Grand Calumet River. The hydraulic tests were done to provide information that would increase understanding of the interaction between the river and the Calumet aquifer. Data collected at each transect and input variables used to calculate hydraulic conductivity are reported. Calculated values of horizontal and vertical hydraulic conductivity of the streambed are presented and discussed. Results of this study are compared to the range of hydraulic conductivity of the Calumet aquifer reported for previous studies.

Acknowledgments

The author gratefully acknowledges DuPont Chemicals in East Chicago and U. S. Steel, Gary Works in Gary, for allowing access to their properties for data collection; Roger Koelpin of the Indiana Department of Environmental Management for assisting in the reconnaissance and selection of transects; and Shaun Austad, a summer employee of the U.S. Geological Survey, for participating in the data collection.

METHODS OF INVESTIGATION

Hydraulic tests of a type commonly called "slug tests," in which the static water level in a well is displaced upwards or downwards, were done along four transects across the east branch Grand Calumet River. Slug tests were selected to assess the hydraulic connection between the river and the Calumet aquifer because sediments in the streambed previously had been determined to contain toxic materials. Other methods, such as the use of seepage meters, would require working in direct contact with the sediments.

For this study, the transects were assigned an alphabetical designation, A through D (fig. 1). The transects were selected to include a variety of streambed-sediment types. Results of sediment particle-size analyses from a previous investigation indicated the streambed was primarily sand at transect A, sandy clay at transects B and D, and clay at transect C (Roger Koelpin, Indiana Department of Environmental Management, written commun, 1995). In addition, access to the river was an important consideration in selecting the transects. A floating platform from which the work could be accomplished was designed and built. Components of the platform were carried to the streambank and assembled at each transect.

A rope was stretched across the river at each transect and the width of the river was measured by use of a steel tape. A qualitative determination of the nature of the streambed sediments at each test location was made by probing with a 3/4-in.-diameter steel pipe. The pipe was pushed into the streambed by hand until resistance was felt. The depth of penetration was recorded and used to estimate the thickness of soft, fine-grained sediments in the streambed.

Two types of test wells were utilized to estimate horizontal and vertical conductivity of the streambed. Test wells for horizontal hydraulic conductivity consisted of 2-in. inside-diameter steel pipe and a 1- or 2-ft length of wire-wrapped well screen. Test wells for vertical hydraulic conductivity consisted of 3-in. inside-diameter aluminum pipe that was open at the ends. At least five locations for horizontal hydraulic conductivity and three locations for vertical hydraulic conductivity were tested at each transect.

Test wells were installed temporarily in the streambed according to the conceptual model shown on figure 2. Test wells for determination of horizontal hydraulic conductivity were placed at two locations near each streambank and at one location at the center of the stream. This was done on the basis of an assumption that ground-water flow is mostly horizontal near the streambank. Test wells for determination of vertical hydraulic conductivity were placed at and on either side of the center of the stream where mostly vertical flow is assumed. These assumptions apply regardless of whether the stream is gaining or losing water with respect to ground water.

Test locations for horizontal hydraulic conductivity are designated by the transect designation followed by an "H" and the test-location number; test locations for vertical hydraulic conductivity are designated by the transect designation followed by a "V" and the test-location number. Test locations are numbered sequentially, starting with one, from the southern streambank toward the north. Additional tests at or near the same test location are designated by a suffix composed of a hyphen followed by a number corresponding to the number of the test at that location. For example, test BH3-2 is the second test at test-site BH3.

Test wells were installed by pushing or pounding them into the streambed. The depth of the river, the top of the well casing above the surface-water level, the water level in the well, and the total depth of the well were measured by use of either a steel tape or a 6-ft folding ruler. The measured total depth of the well was compared to the length of well casing and screen that were installed to determine if any sediments entered the well screen during installation.

For most of the tests, a weighted cylinder (slug) was rapidly lowered into the water column in the well to displace the water, thereby raising the water level in the well. The decline in water level with time (falling-head test) was recorded. If the water level in the well recovered sufficiently during the test, the slug was rapidly removed from the well to lower the water level, and the rate of rise in water level (rising-head test) was recorded. Where the depth of water in the test well was not sufficient to allow use of the cylindrical slug, falling-head tests were accomplished by adding 1 gal of water to the well. Changes in water levels with time were recorded by use of a submersible pressure transducer and data logger.

Data from tests for horizontal hydraulic conductivity were analyzed by use of one or more of three methods. The method of Bouwer and Rice (1976) was the principal method of analysis and was used to analyze data from 44 of 47 slug tests for horizontal hydraulic conductivity. The basic time-lag method of Hvorslev (1951) was used to analyze data from 37 tests. The method of van der Kamp (1976) was used to analyze data from three tests during which water levels recovered rapidly and produced data that did not conform to the mathematical models of the other two methods. These methods are described briefly in this report; for additional explanation, the referenced material can be reviewed.

The method of Bouwer and Rice (1976) is based on the Thiem equation for steady-state flow to a well and was designed to determine horizontal hydraulic conductivity for unconfined aquifers (Bouwer, 1989, p. 304). The method used for this study is for the case of partially penetrating wells where the well is open to only a portion of the permeable sediments. For this method, the change in water level with time is plotted on a semi-logarithmic graph as shown on figure 3. A straight line is fit to a selected part of the data. Typically, water levels recover faster near the start of the test and slower as the water level approaches its static level. The early data, near the start of the test, were selected for analysis to best represent horizontal hydraulic conductivity near the screened interval of the test well. The method uses two equations (fig. 3). First, a value of $\ln (R_e/r_w)$ is determined from the geometric variables of the test and coefficients obtained from Bouwer and Rice (1976, p. 426). Second, horizontal hydraulic conductivity is calculated from test data and the value of $\ln (R_e/r_w)$ obtained from the first equation.

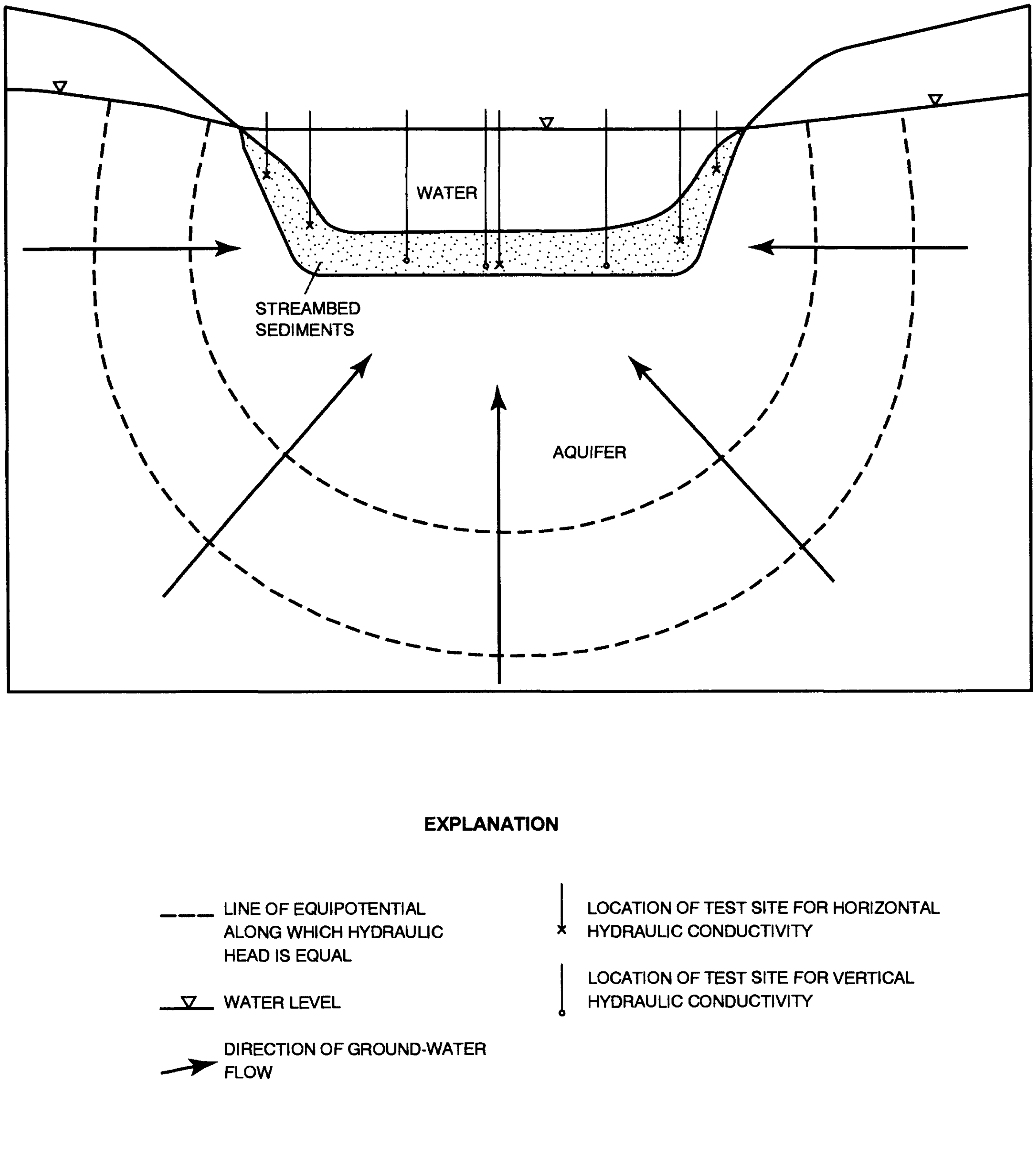
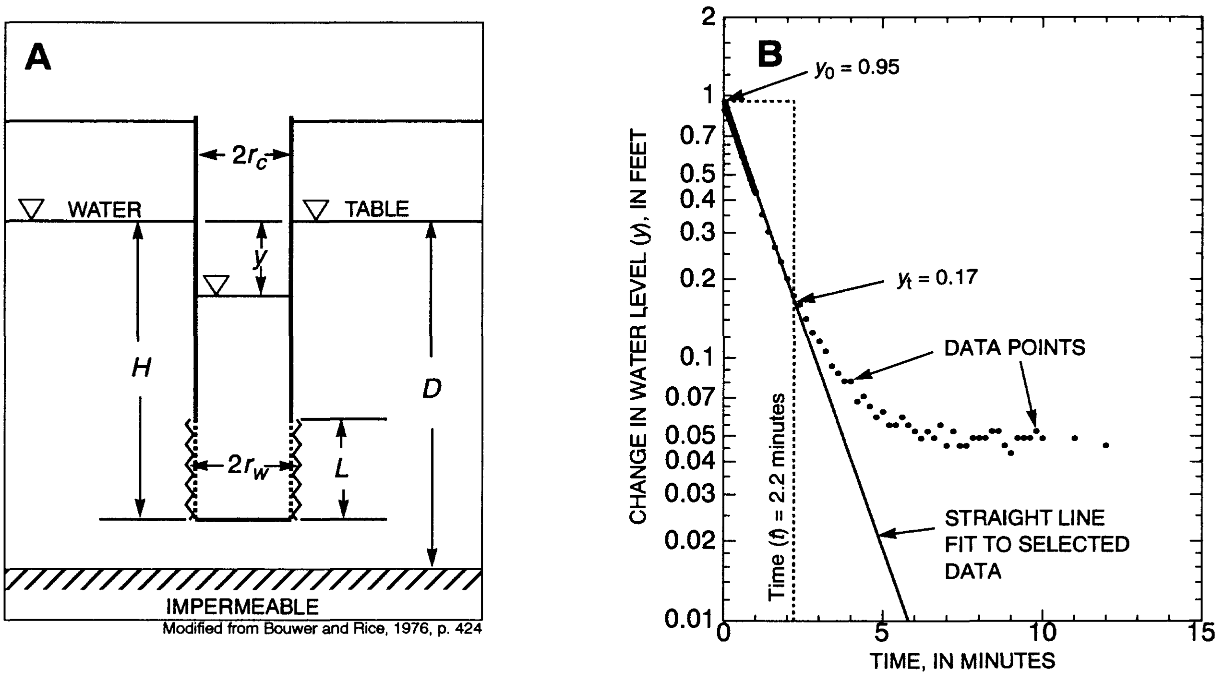


Figure 2. Hypothetical section across a gaining stream showing location of streambed sediments and test sites and typical directions of ground-water flow.



C

CALCULATIONS

1. $$\ln\frac{R_e}{r_w} = \left[\frac{1.1}{\ln\left(\frac{H}{r_w}\right)} + \frac{A + B\left(\ln\left[\frac{(D-H)}{r_w}\right]\right)}{\frac{L}{r_w}}\right]^{-1} = 1.61$$

note:
When $\ln[(D-H)/r_w] > 6.0$,
then $\ln[(D-H)/r_w] = 6.0$

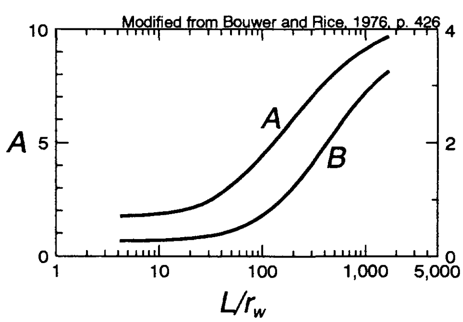
2. $$K = \frac{r_c^2 \ln\left(\frac{R_e}{r_w}\right)}{2L}\frac{1}{t}\ln\frac{y_0}{y_t}$$ = 5.4x10^{-3} feet per minute *x* 1440 minutes per day = 7.8 feet per day

EXPLANATION

R_e = effective radius of the aquifer

r_w = effective radius of well screen = 0.083 feet

A = aquifer coefficient (related to L/r_w) = 1.8



B = aquifer coefficient (related to L/r_w) = 0.26

D = saturated thickness of aquifer = 40 feet

H = height of static water level above bottom of well = 4.7 feet

L = effective length of well screen = 0.8 feet

K = hydraulic conductivity

r_c = radius inside of well casing = 0.083 feet

t = time since start of test interval = 2.2 minutes

y_0 = water level at start of test interval = 0.95 feet

y_t = water level at time t = 0.17 feet

Figure 3. Diagram showing (A) geometry, (B) plot of data, and (C) calculations to determine horizontal hydraulic conductivity for the rising-head test at test-site AH3 by use of the method of Bouwer and Rice (1976).

This method requires knowledge of the saturated thickness of the aquifer, which was estimated from a map showing saturated thickness of the Calumet aquifer (Watson and others, 1989, p. 24) and a map showing thickness of the sand deposits that comprise the Calumet aquifer (Kay and others, 1996, p. 22).

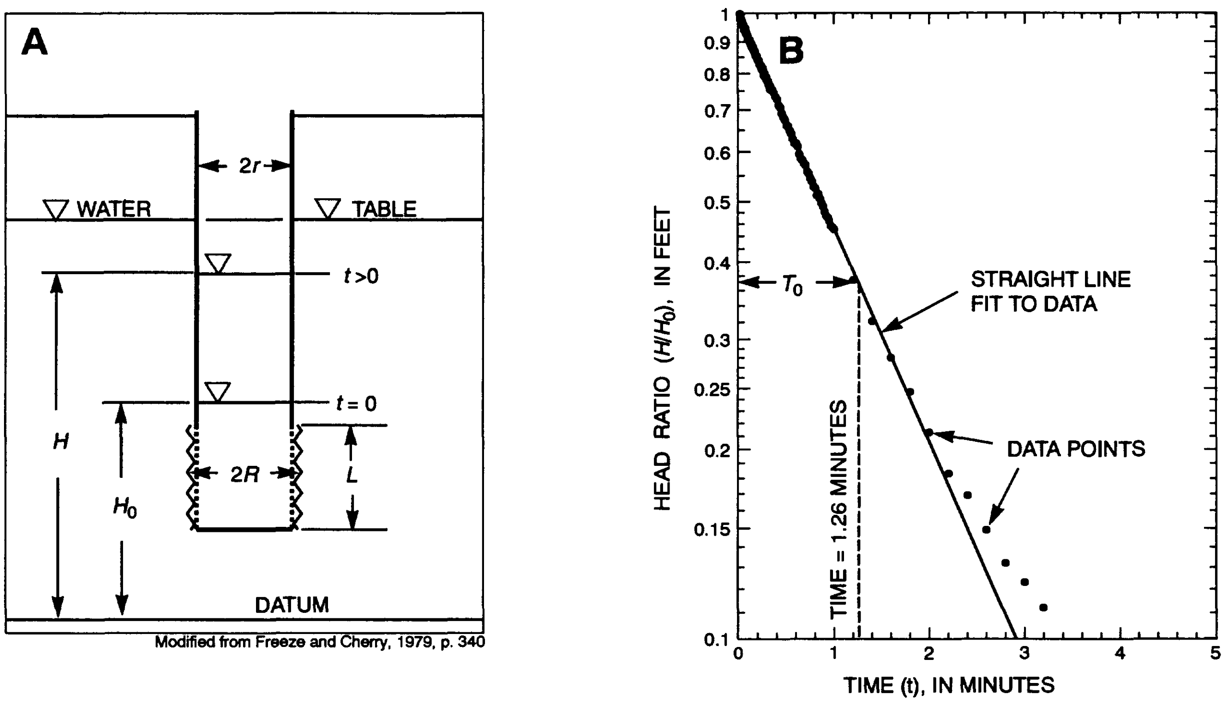
The method of Hvorslev (1951) assumes an infinite aquifer that is homogeneous and isotropic and that the rate of flow into or out of the test well is related to the horizontal hydraulic conductivity of the aquifer, a shape factor that describes the geometry of the openings in the test well, and a basic time lag. The ratio of water levels recorded during the test divided by the maximum change in water level at the start of the test (H/H_0) is plotted against time on a semilogarithmic graph as shown on figure 4. The basic time lag is obtained from the graph by determining the time when the water level in the well falls or rises to 37 percent of the initial change ($H/H_0 = 0.37$). Hvorslev (1951) evaluated various shape factors for the open interval of the well that determine the equation used to calculate hydraulic conductivity. The equation on figure 4 is applicable to the screened test wells used for this study when the length of the screen is more than eight times the diameter of the screen (Freeze and Cherry, 1979, p. 341).

The method of van der Kamp (1976) is applicable to slug tests in aquifers having very high hydraulic conductivity when recovery of the water level is so fast that its inertia results in oscillation of the water level in the test well (fig. 5). A series of equations is solved using values obtained from the test data, the test-well geometry, and an assumed value for the aquifer storage coefficient. Transmissivity, T, is calculated by use of an iterative procedure because T is on both sides of the equation. Horizontal hydraulic conductivity is obtained by dividing T by the length of the screened interval of the test well because the screened interval is approximately equal to the effective thickness of the sediments that were tested.

The test wells were open to unconfined streambed sediments. According to Lohman and others (1972, p. 13), the storage coefficient of an unconfined aquifer is virtually equal to the specific yield. The streambed at the test locations that produced results analyzed by the method of van der Kamp (1976) consisted of mixed fill materials, including concrete and asphalt rubble. It is assumed that the fill contains numerous and interconnected voids. Values of specific yield for coarse gravel, given by Morris and Johnson (1967, p. D20), range from about 0.13 to 0.44; therefore, a value of 0.2, near the middle of the range, was selected to represent the storage coefficient of the fill materials.

Data from tests for vertical hydraulic conductivity were analyzed exclusively by use of the method of Hvorslev (1951). For this method, the change in water level with time is plotted on a semilogarithmic graph as shown on figure 6, and a straight line is fit to a selected part of the data. The equation utilized to calculated vertical hydraulic conductivity was determined by Hvorlsev (1951) to account for the shape factor of an open-end casing with a sediment core (fig. 6). Additionally, the equation used for this analysis is for the case of variable head, and the basic time lag was not determined.

The methods of slug-test analysis utilized for this study provide estimates of hydraulic conductivity for a small volume of the streambed sediments around the open section of the test well. These estimates may or may not apply to other areas of the streambed. In addition, installation of a well disturbs the sediments into which the well is placed. Compaction is the most likely result of the well installation methods used for this study. Compaction of sediments near the open section of a well generally would lower the value of hydraulic conductivity obtained from a slug test. Therefore, the values of hydraulic conductivity from analysis of the slug tests are probably conservative estimates of the actual value.



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CALCULATIONS

$$K = \frac{r^2 \ln (L/R)}{2\,L\,T_0} = 7.7\text{x}10^{-3} \text{ feet per minute } x \text{ 1440 minutes per day} = 1.1\text{x}10^{+1} \text{ feet per day}$$

EXPLANATION

K = hydraulic conductivity

r = radius inside of the well casing = 0.083 feet

L = effective length of the well screen = 0.8 feet

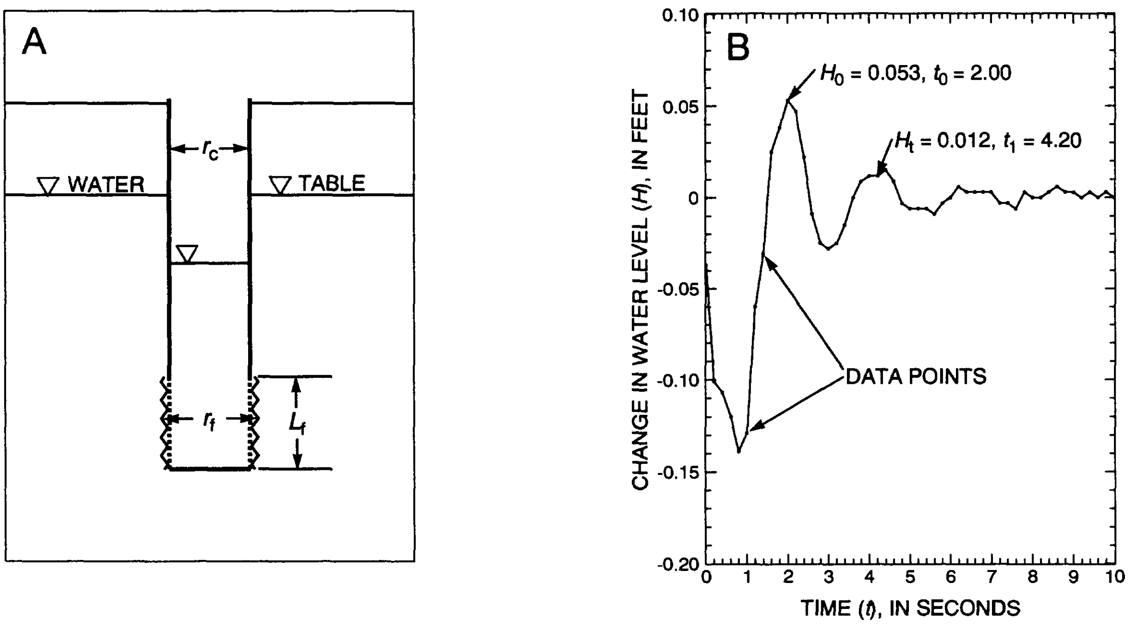
R = effective radius of well screen = 0.083 feet

T_0 = basic time lag (H/H_0), time it takes for the water level to fall or rise to 37 percent of the initial change = 1.26 minutes

H = water level during test, recorded at various time intervals, in feet

H_0 = maximum change in water level at the start of the test, in feet

Figure 4. Diagram showing (A) geometry, (B) plot of data, and (C) calculations to determine horizontal hydraulic conductivity for the rising-head test at test-site AH3 by use of the basic time-lag method of Hvorslev (1951).



C

CALCULATIONS

1. $\omega = 2\pi \dfrac{1}{t_1 - t_0} = 2.86$

2. $\gamma = \dfrac{\ln(H_0/H_t)}{t_1 - t_0} = 0.675$

Note: Equations 1 and 2 are taken from Kruseman and others (1991, p. 242).

3. $L = \dfrac{g}{\omega^2 + \gamma^2} = 3.73$

4. $d = \dfrac{\gamma}{(g/L)^{1/2}} = 0.230$

5. $a = \dfrac{r_c^{\,2}(g/L)^{1/2}}{8d} = 0.011$

6. $b = -a \ln\left[0.79 r_f^{\,2} S (g/L)^{1/2}\right] = 0.063$

7. $T = b + a \ln T$ Equation 7 is solved iteratively for T

T = 0.019 square feet per second x 86,400 seconds per day = 1,676 square feet per day

8. $K = \dfrac{T}{L_f}$ = 838 feet per day

EXPLANATION

ω = angular frequency, in seconds^{-1}

t_1 = time when water level = H_t, in seconds

t_0 = time when water level = H_0, in seconds

γ = damping constant, in seconds^{-1}

H_t = later water level at time t_1, in feet

H_0 = initial water level at time t_0, in feet

L = effective length of water column, in feet

g = gravitational constant = 32.2 feet per second ^{2}

d = parameter defined by equation 4

a = parameter defined by equation 5

r_c = radius of well casing = 0.083 feet

b = parameter defined by equation 6

r_f = radius of well screen = 0.083 feet

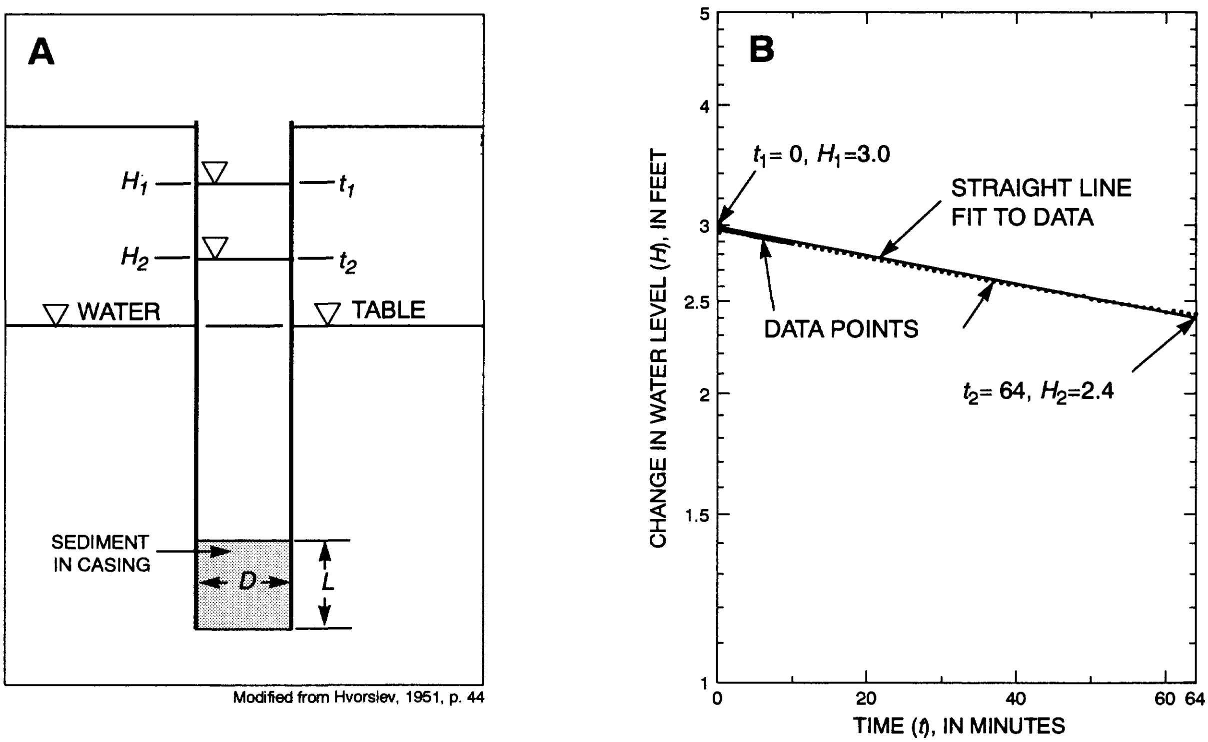
S = aquifer storage coefficient, estimated from literature = 0.2

T = transmissivity

K = hydraulic conductivity

L_f = length of screen = 2 feet

Figure 5. Diagram showing (A) geometry, (B) plot of data, and (C) calculations to determine horizontal hydraulic conductivity for the rising-head test at test-site BH1-1 by use of the method of van der Kamp (1976).



C

CALCULATIONS

$$K_v = \frac{\frac{\pi}{11} \cdot \frac{D}{m} + L}{t_2 - t_1} \cdot \ln \frac{H_1}{H_2}$$

The equation is solved iteratively by substituting values for K_v

$K_v = 2.3 \times 10^{-3}$ feet per minute x 1440 minutes per day = 3.3 feet per day, when $m = 1.27$

EXPLANATION

K_v = vertical hydraulic conductivity

D = diameter of well casing = 0.25 feet

$m = \sqrt{K_h / K_v}$, where K_h = horizontal hydraulic conductivity = 5.3 feet per day

L = length of sediment core = 0.6 feet

t_1 = time at start of test = 0 minutes

t_2 = time at end of test = 64 minutes

H_1 = head at start of test = 3.0 feet

H_2 = head at end of test = 2.4 feet

Figure 6. Diagram showing (A) geometry, (B) plot of data, and (C) calculations to determine vertical hydraulic conductivity for the falling-head test at test-site AV2 by use of the variable-head method of Hvorslev (1951).

HYDRAULIC CONDUCTIVITY OF THE STREAMBED

Hydraulic conductivity of the streambed is presented and discussed according to the four transects where data were collected. The geometry of the river channel at each transect is described. Data collected at the transects are listed in table 1 at the back of the report. Summaries of results are included in tables within the text, and complete listings of the input variables used for the analyses are provided in tables 2 through 5 at the back of the report. Values of hydraulic conductivity are discussed in units of ft/day; for readers who prefer units of centimeters/second, these units are included in tables 2 through 5 at the back of the report.

Transect A

Transect A, 55 ft downstream from a culvert that drains the Grand Calumet Lagoons (fig. 1), was the most upstream transect for this study and was upstream of any municipal or industrial discharge to the river. The culvert was apparently plugged because no flow was observed from this structure. A small amount of flow was observed south of the culvert, an indication that water was flowing through the sand along the outside of the culvert. A delta of sand, about 8 ft in width, had been deposited where this flow enters the river. At transect A, the river is entrenched and straightened as a result of past dredging and construction of a steel mill north of the river.

The river was 38-ft wide at transect A (fig. 7). The maximum depth of water measured along the transect was 2.1 ft, near the center of the river. The maximum thickness of soft sediments in the streambed determined by probing was 5 ft, also at the center of the river (table 1, at back of report). The southern streambank was sandy; the northern streambank primarily consisted of loose coal—presumably from coking operations at the steel mill. Adjacent to the northern streambank, the

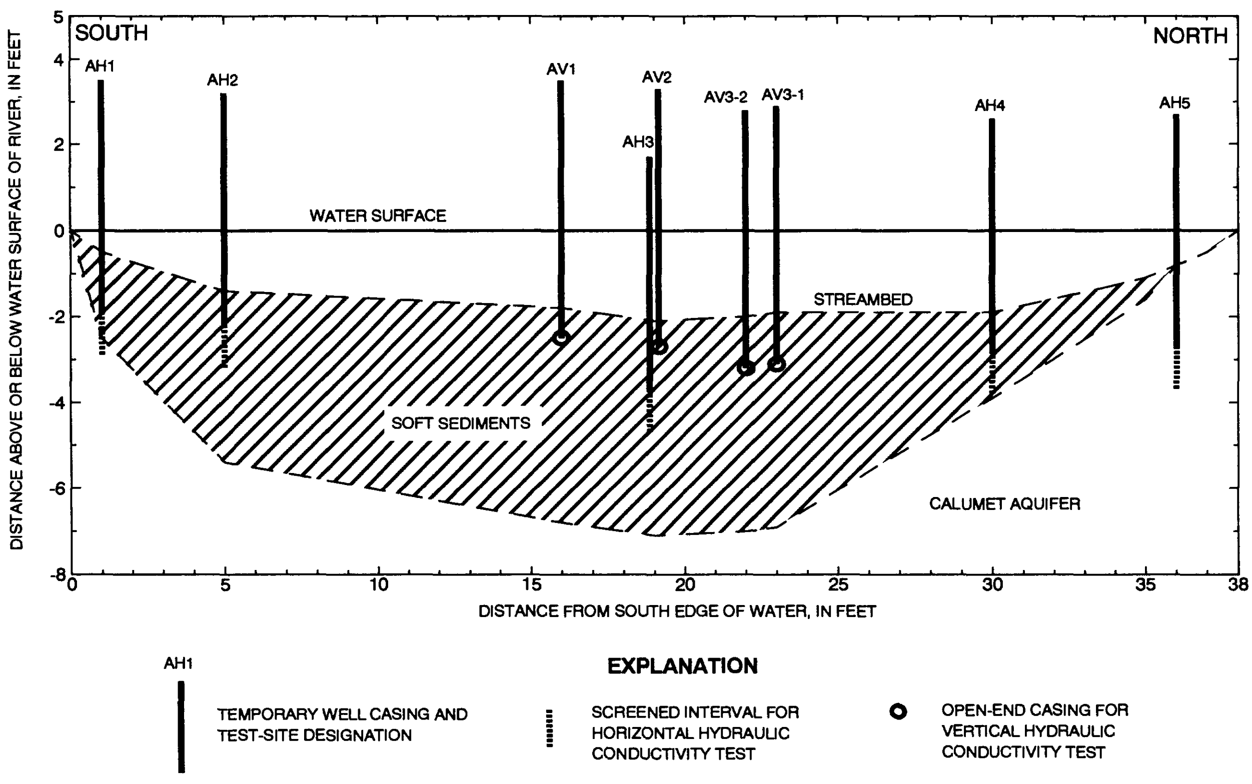


Figure 7. Cross section of streambed and locations of test sites at transect A, east branch Grand Calumet River, northern Lake County, Indiana.

streambed was firm. Probing indicated no soft sediments at a distance of 2 ft south from the northern streambank.

Wells at test-sites AH1 and AH5 were installed by pounding in order to achieve sufficient depth beneath the streambed. Wells at sites AH3 and AH4 were pushed by hand. At test-site AH2, the well was installed by a combination of pushing and pounding. All wells for horizontal hydraulic conductivity at transect A were equipped with 1-ft screens. Measurements of total depth in wells at test-sites AH1, AH2, and AH3 indicated that the well-screen intervals were partially filled with sediments (table 1, at back of report). The effective screen length (0.3 ft) at test-sites AH1 and AH2 was too short to allow use of the Hvorslev (1951) method for calculating horizontal hydraulic conductivity. The depth of water at test-sites AH1 and AH5 was not sufficient to allow use of the cylindrical slug; therefore, falling-head tests were accomplished by adding 1 gal of water to wells at these sites. Rising-head tests were not done at sites AH1 and AH5; although two falling-head tests were done at site AH5.

Horizontal hydraulic conductivity was varied (table 6) as a result of the various materials in the streambed at transect A. The lowest value of horizontal hydraulic conductivity, $6.2x10^{-2}$ ft/day, was calculated by use of the method of Bouwer and Rice (1976) from data for the falling-head test at site AH1, 1 ft from the southern streambank. Horizontal hydraulic conductivity generally increased northward along transect A and the highest value, $2.6x10^{+2}$ ft/day, was calculated by use of the method of Hvorslev (1951) from data for the falling-head test at site AH5-1, 2 ft from the northern streambank. For test-sites AH2, AH3, and AH4, calculated values of horizontal hydraulic conductivity ranged from $5.1x10^{-1}$ to $1.9x10^{+1}$ ft/day (table 6). The average of falling-head and rising-head tests was 7.3 ft/day for test-site AH2, 5.3 ft/day for test-site AH3, and 8.8 ft/day for test-site AH4. Values of horizontal hydraulic conductivity calculated by use of the method of Hvorslev (1951) were similar to, although consistently higher than, values calculated by use of the method of Bouwer and Rice (1976). Except for falling-head tests at sites AH1 and AH2, the calculated values of horizontal hydraulic conductivity at transect A are within the range of horizontal hydraulic conductivity, $6.5x10^{-1}$ to $3.6x10^{+2}$ ft/day, reported for the Calumet aquifer by Kay and others (1996).

Table 6. Summary of horizontal hydraulic conductivity for transect A, east branch Grand Calumet River, northern Lake County, Indiana

[Location of test sites shown on figure 7; F, falling-head test; --, not applicable; R, rising-head test]

Test-site name	Type of test	Horizontal hydraulic conductivity calculated by the method of Bouwer and Rice[1] (feet per day)	Horizontal hydraulic conductivity calculated by the method of Hvorslev[2] (feet per day)	Horizontal hydraulic conductivity, average of both methods (feet per day)
AH1	F	$6.2x10^{-2}$	--	--
AH2	F	$5.1x10^{-1}$	--	--
AH2	R	$1.4x10^{+1}$	--	--
AH3	F	$1.0x10^{0}$	$1.4x10^{0}$	$1.20x10^{0}$
AH3	R	$7.8x10^{0}$	$1.1x10^{+1}$	$9.40x10^{0}$
AH4	F	$1.4x10^{+1}$	$1.9x10^{+1}$	$1.65x10^{+1}$
AH4	R	$8.0x10^{-1}$	$1.2x10^{0}$	$1.05x10^{0}$
AH5-1	F	$1.7x10^{+2}$	$2.6x10^{+2}$	$2.15x10^{+2}$
AH5-2	F	$1.7x10^{+2}$	$2.5x10^{+2}$	$2.10x10^{+2}$

[1]Bouwer and Rice, 1976.
[2]Hvorslev, 1951.

Calculated values of horizontal hydraulic conductivity varied not only among tests at different test sites but also between falling-head and rising-head tests at the same site for test-sites AH2 and AH4. At test-site AH2, the value of horizontal hydraulic conductivity obtained by use of data from the falling-head test was two orders of magnitude lower than that obtained by use of data from the rising-head test. At test-site AH4, the data from the falling-head test produced a value of horizontal hydraulic conductivity that was two orders of magnitude higher than the value calculated by use of data from the rising-head test. The reasons for these differences are not known; however, the differences indicate that hydraulic conditions in or around the well screen were changing during the tests.

Some of the difference may be explained by the distribution of sediment-grain size in the streambed sediments. For example, streambed sediments at both test sites include a percentage of soft, fine-grained sediments (silt, clay, and organic material) mixed with sand. These sediments are mixed with comparatively large pieces of coal at test-site AH4. The coal may have functioned as a gravel pack around the well screen and did not allow the fine-grained materials to enter the screen. The measured depth of the well indicated that no sediment had entered the screen during installation. During the falling-head test, water was able to flow out of the screen through the coal gravel pack. During the rising-head test, water flowing toward the well screen may have forced the fine-grained materials into the coal gravel pack or screen slots and blocked flowpaths that previously had been open. At test-site AH2, sediments entered the well screen during installation. During the falling-head test, water could flow out of the well only through the part of the screen that was not blocked by the sediments. During the rising-head test, the sediments may have been suspended by water flowing into the well screen, which would increase the effective length of the screen.

All well casings for the vertical hydraulic conductivity tests at transect A were installed by pushing them into the streambed. No rising-head tests for vertical hydraulic conductivity were done at transect A; however, two falling-head tests were done at test-site AV3 (table 7). During installation of the test wells, the streambed sediments felt gritty—an indication of sand mixed with the soft sediments. Comparison of measured depths to the streambed inside and outside the well casing indicated compaction of the sediments inside some well casings (table 1, at back of report). No compaction was measured at test-site AV2; however, compaction was about 27 percent at test-site AV1, 33 percent at test-site AV3-1, and 17 percent at test-site AV3-2.

Table 7. Summary of vertical hydraulic conductivity for transect A, east branch Grand Calumet River, northern Lake County, Indiana

[Location of test sites shown on figure 7]

Test-site name	Vertical hydraulic conductivity calculated from falling-head data (feet per day)
AV1	5.9×10^{0}
AV2	3.3×10^{0}
AV3-1	6.1×10^{0}
AV3-2	3.5×10^{0}

Calculated values of vertical hydraulic conductivity generally were consistent across transect A and ranged from 3.3 ft/day for test-site AV2 to 6.1 ft/day for test-site AV3-1 (table 7). The average value of vertical hydraulic conductivity for all test sites at transect A was 4.7 ft/day. Values of vertical hydraulic conductivity were similar to the average value of horizontal hydraulic conductivity, 5.3 ft/day, calculated from data for test-site AH3. Compared to AH3, the average ratio of horizontal to vertical hydraulic conductivity at transect A was about 1:0.89.

Transect B

Transect B was 80 ft upstream from an iron bridge where Bridge Street crosses the river and approximately 3.7 river miles downstream from transect A (fig. 1). The river channel was straight at the transect location but turned sharply to the southwest downstream from the bridge. Flow in the river was steady but sluggish. The northern streambank was steeper and higher than the southern streambank. The land south of the river was a topographically low, swampy area that appeared to have been filled at least partially.

The river was 98 ft wide at transect B (fig. 8). The maximum depth of water measured along the transect was 7.3 ft at test-site BV2, at the center of the river, and test-site BV1, 4.5 ft south from the center of the river. The maximum thickness of soft sediments in the streambed determined by probing was 5 ft near the northern streambank (table 1, at back of report). The total thickness of soft sediments near the center of the stream is not known because the 10-ft long pipe used for probing at transect B did not reach the bottom of the soft sediments. Adjacent to the southern streambank, the streambed was firm and consisted of fill materials including concrete and asphalt rubble. Probing did not indicate soft sediments at a distance of 4 ft from the southern streambank. At a distance of 6.5 ft from the southern streambank, 1 ft of soft sediments was determined by probing.

Wells at test-sites BH1 and BH2 were pounded to achieve sufficient depth beneath the streambed. Wells at the remaining test sites were pushed into the streambed by hand. Wells at test-sites BH1, BH2, and BH3 were equipped with 2-ft screens; wells at test-sites BH4 and BH5 were equipped with 1-ft screens. Falling-head and rising-head tests for all test sites were analyzed for horizontal hydraulic conductivity, except test-site BH4 where the rising-head test produced data that could not be analyzed by the available methods. A plot of the water level with time for BH4 indicated that the submersible transducer was plugged

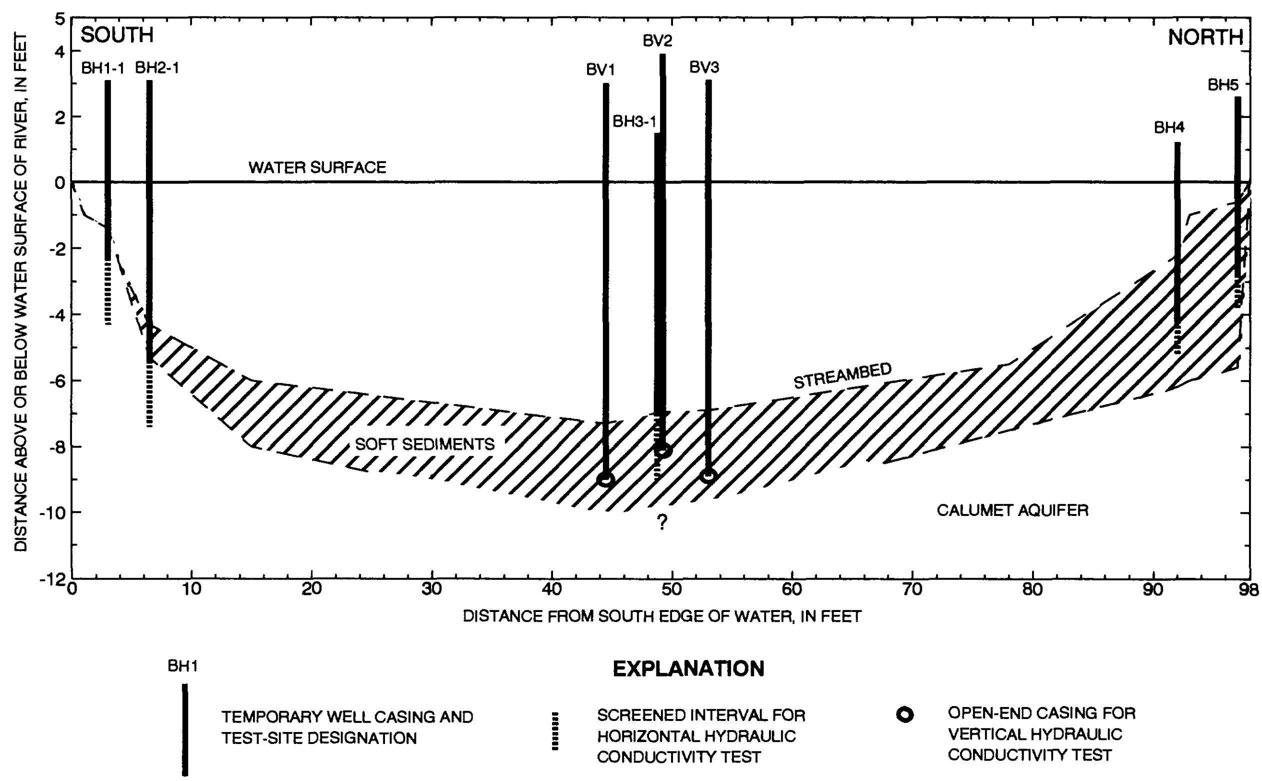


Figure 8. Cross section of streambed and locations of selected test sites at transect B, east branch Grand Calumet River, northern Lake County, Indiana.

intermittently with sediment entering the well screen during the rising-head test; the resulting recovery curve did not fit the mathematical models used by the available methods. Additional tests were done at sites BH1, BH2, and BH3 after moving the well 3 ft upstream from the original test site at BH1 and BH2 and moving the well 2.5 ft upstream at test-site BH3.

Horizontal hydraulic conductivity generally decreased from south to north along transect B (table 8). The highest value of horizontal hydraulic conductivity, $1.2x10^{+3}$ ft/day, was calculated by use of the method of van der Kamp (1976) for test-site BH1, 3 ft north from the southern streambank. The lowest value of horizontal hydraulic conductivity, $7.8x10^{-2}$ ft/day, was calculated by use of the method of Bouwer and Rice (1976) for test-site BH4, 6 ft south from the northern streambank. For test-sites BH2, BH3, and BH5, calculated values of horizontal hydraulic conductivity ranged from $3.2x10^{-1}$ ft/day for data from the falling-head test at test-site BH5 to $7.5x10^{+2}$ ft/day for data from two tests at test-site BH2. The average of all falling-head and rising-head tests for each test site was $9.2x10^{+2}$ ft/day for test-site BH1, $4.1x10^{+2}$ ft/day for test-site BH2, $8.3x10^{+1}$ ft/day for test-site BH3, $9.4x10^{-2}$ ft/day for test-site BH4, and $4.5x10^{-1}$ ft/day for test-site BH5.

Values of horizontal hydraulic conductivity calculated by use of the method of Hvorslev (1951) were similar to, although slightly higher than, values calculated from the same test data by use of the method of Bouwer and Rice (1976). Although not used with data from the same tests, the method of van der Kamp (1976) produced values that were larger than the values calculated for other tests at the same site by use of the other two methods.

Table 8. Summary of horizontal hydraulic conductivity for transect B, east branch Grand Calumet River, northern Lake County, Indiana

[Location of test sites shown on figure 8; F, falling-head test; --, not applicable; R, rising-head test]

Test-site name	Type of test	Horizontal hydraulic conductivity calculated by the method of Bouwer and Rice[1] (feet per day)	Horizontal hydraulic conductivity calculated by the method of Hvorslev[2] (feet per day)	Horizontal hydraulic conductivity calculated by the method of van der Kamp[3] (feet per day)	Horizontal hydraulic conductivity, average of all methods (feet per day)
BH1-1	F	$6.1x10^{+2}$	$8.5x10^{+2}$	--	$7.30x10^{+2}$
BH1-1	R	--	--	$8.4x10^{+2}$	--
BH1-2	R	--	--	$1.2x10^{+3}$	--
BH2-1	F	$4.9x10^{+2}$	$7.5x10^{+2}$	--	$6.20x10^{+2}$
BH2-1	R	$1.2x10^{+1}$	$1.6x10^{+1}$	--	$1.40x10^{+1}$
BH2-2	F	$1.9x10^{+2}$	$3.2x10^{+2}$	--	$2.55x10^{+2}$
BH2-2	R	--	--	$7.5x10^{+2}$	--
BH3-1	F	$2.3x10^{+2}$	$2.4x10^{+2}$	--	$2.35x10^{+2}$
BH3-1	R	$3.5x10^{0}$	$4.6x10^{0}$	--	$4.05x10^{0}$
BH3-2	F	$7.0x10^{+1}$	$9.9x10^{+1}$	--	$8.45x10^{+1}$
BH3-2	R	$5.6x10^{0}$	$7.4x10^{0}$	--	$6.50x10^{0}$
BH4	F	$7.8x10^{-2}$	$1.1x10^{-1}$	--	$9.40x10^{-2}$
BH5	F	$3.2x10^{-1}$	$4.8x10^{-1}$	--	$4.00x10^{-1}$
BH5	R	$4.2x10^{-1}$	$5.6x10^{-1}$	--	$4.90x10^{-1}$

[1]Bouwer and Rice, 1976.
[2]Hvorslev, 1951.
[3]van der Kamp, 1976.

Except for test-sites BH2 and BH3, the average values of horizontal hydraulic conductivity are outside of the range of horizontal hydraulic conductivity reported for the Calumet aquifer (Kay and others, 1996). The average horizontal hydraulic conductivity at test-site BH1 is greater than the highest reported value, $3.6 \times 10^{+2}$ ft/day; the average horizontal hydraulic conductivities at test-sites BH4 and BH5 are less than the lowest reported value, 6.5×10^{-1} ft/day.

Calculated values of horizontal hydraulic conductivity differed for falling-head and rising-head tests at some test sites. Values obtained from data for rising-head tests were one order of magnitude lower than the values obtained from data for falling-head tests at test-sites BH2-1 and BH3-2 and two orders of magnitude lower at test-site BH3-1. These results are consistent with those discussed for slug tests at AH4 where the streambed contained fill materials.

All well casings for the vertical hydraulic conductivity tests at transect B were installed by pushing them into the streambed. Comparison of measured depths to the streambed inside and outside of the well casing (table 1, at back of report) showed that compaction of the sediment core inside the casings was about 6 percent at test-site BV1, 12.5 percent at test-site BV2, and 10 percent at test-site BV3. Falling-head and rising-head tests were done at test-sites BV1 and BV2; one falling-head test was done at test-site BV3 (table 9).

Vertical hydraulic conductivity was more varied at transect B than at the other transects. Calculated values of vertical hydraulic conductivity at transect B ranged from 3.0×10^{-1} ft/day for data from the falling-head test at test-site BV3 to $7.3 \times 10^{+1}$ ft/day for data from the rising-head test at BV1 (table 9). The average of falling-head and rising-head tests was $3.7 \times 10^{+1}$ ft/day for test-site BV1 and 2.2 ft/day for test-site BV2. The average of all tests was $1.6 \times 10^{+1}$ ft/day. Compared to the average horizontal hydraulic conductivity of all tests at test-site BH3, $8.3 \times 10^{+1}$ ft/day, the average ratio of horizontal to vertical hydraulic conductivity at transect B was 1:0.19.

Table 9. Summary of vertical hydraulic conductivity for transect B, east branch Grand Calumet River, northern Lake County, Indiana

[Location of test sites shown on figure 8; -- no data]

Test-site name	Vertical hydraulic conductivity calculated from falling-head data (feet per day)	Vertical hydraulic conductivity calculated from rising-head data (feet per day)	Vertical hydraulic conductivity, average of falling- and rising-head data (feet per day)
BV1	7.0×10^{-1}	$7.3 \times 10^{+1}$	$3.68 \times 10^{+1}$
BV2	1.8×10^{0}	2.6×10^{0}	2.20×10^{0}
BV3	3.0×10^{-1}	--	--

Transect C

Transect C was 60 ft upstream from the U.S. Highway 12 bridge and approximately 1.6 river miles downstream from transect B (fig. 1). The river channel was fairly straight at the transect location. The transect was downstream from treated sewage discharge from the City of Gary, and flow at the transect was steady. The southern streambank was steep and contained fill materials similar to those at transect B mixed with sand. The northern streambank was low lying, swampy, and thickly vegetated.

The river was 108-ft wide at transect C (fig. 9). The maximum depth of water was 4.1 ft, at the center of the river. The maximum thickness of soft sediments in the streambed was 13 ft, also near the center of the river (table 1, at back of report). Soft sediments were not found in the streambed adjacent to the southern streambank; instead the streambed was firm and contained fill materials, including concrete and asphalt rubble. About 1 ft of soft sediments was determined by probing 6 ft from the southern streambank. Probing indicated about 10 ft of soft sediments at the northern streambank.

The well at test-site CH1 was pounded into the streambed. The well at test-site CH2 was pushed and pounded. All other test wells were installed by pushing them into the streambed. Falling-head and rising-head tests were done at all test sites for horizontal hydraulic conductivity, except CH5 where two falling-head tests were done (table 10). Two additional falling-head tests were done at test-site CH3—for one of these tests, a 2-ft screen was used. All other test wells for horizontal hydraulic conductivity were equipped with 1-ft screens. Measurement of total depth in the test well at CH2 indicated that fine-grained sediments partially had filled the well screen (table 1, at back of report). The effective screen length (0.4 ft) was not sufficient to allow use of the

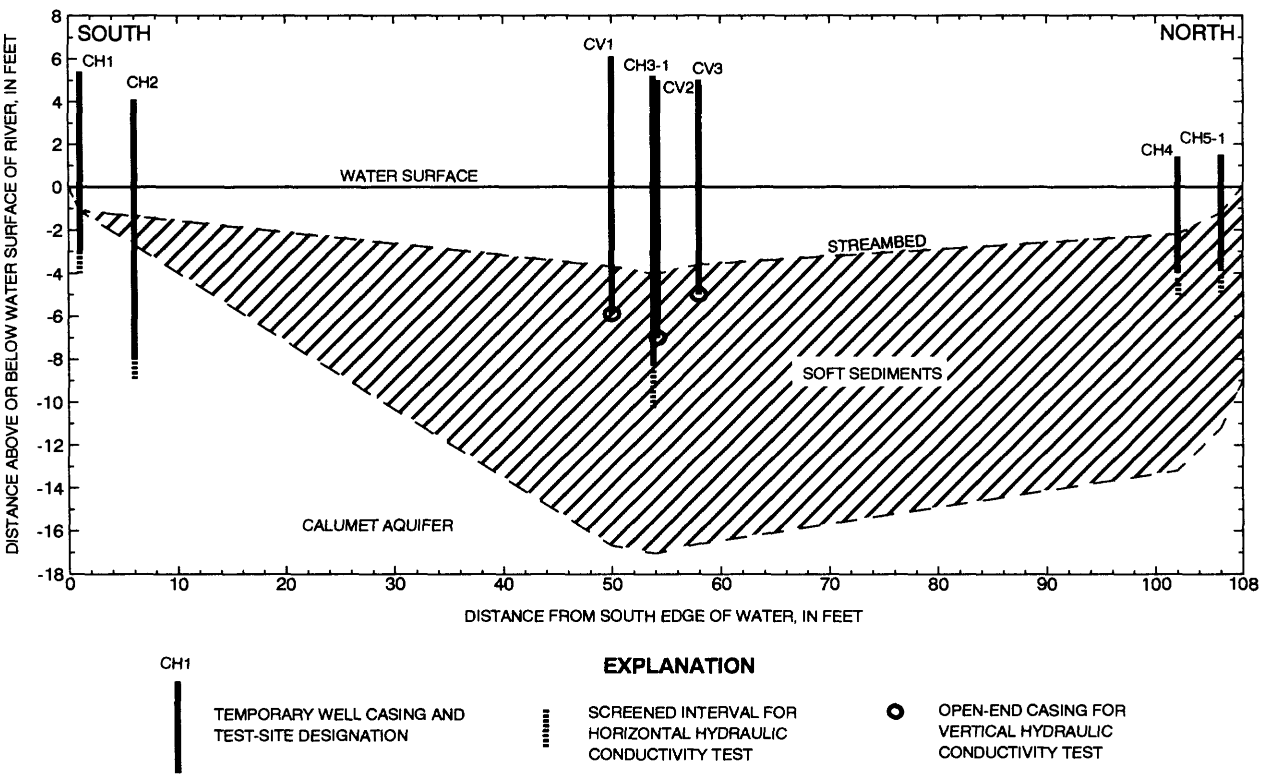


Figure 9. Cross section of streambed and locations of selected test sites at transect C, east branch Grand Calumet River, northern Lake County, Indiana.

Table 10. Summary of horizontal hydraulic conductivity for transect C, east branch Grand Calumet River, northern Lake County, Indiana

[Location of test sites shown on figure 9; F, falling-head test; --, not applicable; R, rising-head test]

Test-site name	Type of test	Horizontal hydraulic conductivity calculated by the method of Bouwer and Rice[1] (feet per day)	Horizontal hydraulic conductivity calculated by the method of Hvorslev[2] (feet per day)	Horizontal hydraulic conductivity, average of both methods (feet per day)
CH1	F	$1.6x10^{+2}$	$2.5x10^{+2}$	$2.05x10^{+2}$
CH1	R	$8.7x10^{+1}$	$1.1x10^{+2}$	$9.85x10^{+1}$
CH2	F	$5.3x10^{0}$	--	--
CH2	R	$1.4x10^{+1}$	--	--
CH3-1	F	$7.2x10^{-1}$	$8.6x10^{-1}$	$7.90x10^{-1}$
CH3-2	F	$5.9x10^{+1}$	$8.2x10^{+1}$	$7.05x10^{+1}$
CH3-2	R	$2.7x10^{-1}$	$3.8x10^{-1}$	$3.25x10^{-1}$
CH3-3	F	$2.6x10^{+1}$	$2.5x10^{+1}$	$2.55x10^{+1}$
CH4	F	$5.2x10^{-2}$	$5.3x10^{-2}$	$5.25x10^{-2}$
CH4	R	$1.4x10^{-1}$	$2.5x10^{-1}$	$1.95x10^{-1}$
CH5-1	F	$2.5x10^{-2}$	$2.3x10^{-2}$	$2.40x10^{-2}$
CH5-2	F	$1.4x10^{-2}$	$1.0x10^{-2}$	$1.20x10^{-2}$

[1]Bouwer and Rice, 1976.

Hvorslev (1951) method for calculating horizontal hydraulic conductivity.

Horizontal hydraulic conductivity generally decreased from south to north in relation to the type of material in the streambed along transect C. The highest value of horizontal hydraulic conductivity, $2.5x10^{+2}$ ft/day, was calculated by use of the method of Hvorslev (1951) for test-site CH1, 1 ft north from the southern streambank. The lowest value of horizontal hydraulic conductivity, $1.0x10^{-2}$ ft/day, was calculated by use of the method of Hvorslev (1951) for test CH5-2, 2 ft south from the northern streambank (table 10). Calculated values of horizontal hydraulic conductivity ranged from $5.2x10^{-2}$ to $8.2x10^{+1}$ft/day for test-sites CH2, CH3, and CH4. The average of all falling-head and rising-head tests for each test site was $1.5x10^{+2}$ for test-site CH1, 9.6 ft/day for test-site CH2, $2.4x10^{+1}$ ft/day for test-site CH3, $1.3x10^{-1}$ ft/day for test-site CH4, and $1.8x10^{-2}$ ft/day for test-site CH5. Comparable values of horizontal hydraulic conductivity were calculated by use of either the Bouwer and Rice (1976) or Hvorslev (1951) method. Values of horizontal hydraulic conductivity for tests at CH1, CH2, CH3-1, CH3-3, and the falling-head test at CH3-2 were within the range of values for horizontal hydraulic conductivity, $6.5x10^{-1}$ to $3.6x10^{+2}$ ft/day, reported by Kay and others (1996) for the Calumet aquifer. Values of horizontal hydraulic conductivity for tests at CH4, CH5, and the rising-head test at CH3-2 were lower than the reported range.

Comparison of falling-head and rising-head-test results (table 10) shows differences for several test sites. The differences are not large except for tests at sites CH3-2 and CH4. Data from falling-head tests produced values of horizontal hydraulic conductivity that were two orders of magnitude higher than values from rising-head data for test-site CH3-2. For test-site CH4, the value of horizontal hydraulic conductivity obtained by use of falling-head data was one order of magnitude lower than that obtained by use of rising-head data.

Results from test-site CH3 indicate a decrease in horizontal hydraulic conductivity with increasing depth. The average horizontal hydraulic conductivity was $3.5 \times 10^{+1}$ ft/day for all tests at site CH3-2 where the well was screened from 1.5 to 2.5 ft beneath the streambed and $2.6 \times 10^{+1}$ ft/day for test CH3-3 where the well was screened from 2.6 to 3.6 ft beneath the streambed (table 1, at back of report). For test CH3-1, where the well was screened 4.3 to 6.3 ft beneath the streambed, the average horizontal hydraulic conductivity was 7.9×10^{-1} ft/day. A decrease in horizontal hydraulic conductivity may be caused by compaction of the sediments or related to differences in the grain size or other properties of the sediments with depth.

Well casings for the vertical hydraulic conductivity tests at transect C were installed by pushing them into the streambed. The wells at CV1 and CV2 were pushed slightly deeper than wells for vertical hydraulic conductivity tests at the other transects (table 1, at back of report). Surface-water-flow velocities were faster at transect C than at the other transects, and the flow would push the well over during the test if it was not pushed far enough into the streambed. Comparison of measured depths to the streambed inside and outside of the casing showed no compaction of the sediment core inside the well casings at test-sites CV1 and CV2 and about 14 percent compaction at test-site CV3. Falling-head and rising-head tests were done at test-sites CV1 and CV3; a falling-head test was done at test-site CV2 (table 11).

Calculated values of vertical hydraulic conductivity ranged from 7.9×10^{-1} ft/day for data from the falling-head test at test-site CV3 to 4.0 ft/day for data from the falling-head test at test-site CV2 (table 11). The average value of vertical hydraulic conductivity of all tests was 2.9 ft/day. This value is one order of magnitude lower than the average value of horizontal hydraulic conductivity, $3.2 \times 10^{+1}$ ft/day, for tests at sites CH3-2 and CH3-3. Results of the horizontal hydraulic conductivity tests at site CH3-1 were not used to calculate vertical hydraulic conductivity at transect C because the test well at site CH3-1 was much deeper than the wells for vertical hydraulic conductivity. The average ratio of horizontal to vertical hydraulic conductivity at transect C was 1:0.09.

Table 11. Summary of vertical hydraulic conductivity for transect C, east branch Grand Calumet River, northern Lake County, Indiana

[Location of test sites shown on figure 9; -- no data]

Test-site name	Vertical hydraulic conductivity calculated from falling-head data (feet per day)	Vertical hydraulic conductivity calculated from rising-head data (feet per day)	Vertical hydraulic conductivity, average of falling- and rising-head data (feet per day)
CV1	3.8×10^{0}	3.0×10^{0}	3.4×10^{0}
CV2	4.0×10^{0}	--	--
CV3	7.9×10^{-1}	3.0×10^{0}	1.9×10^{0}

Transect D

Transect D, approximately 3.2 river miles downstream from transect C and 1.5 river miles upstream from the confluence with the Indiana Harbor Canal, was the most downstream transect for this study (fig. 1). The river channel near and downstream from transect D forms several meanders that are bordered by wetlands generally along the inside curves of the meanders. Along this reach, the river has some of the characteristics of an estuary, including small and fluctuating gradients that cause rising and falling stage and reversals of flow in the river.

The river was 110 ft wide at transect D (fig. 10). The maximum depth of water was 7.2 ft, 5 ft north from the center of the river. The maximum thickness of soft sediments in the streambed was 10 ft near the center of the river (table 1, at back of report). The southern streambank was a mudflat bordered by cattail marsh; the northern streambank was steep and primarily consisted of cinders mixed with medium- and fine-grained sediments. The streambed was soft across the entire transect.

All of the test wells for horizontal hydraulic conductivity tests at transect D had 1-ft screens. Except for the well test DH3 that was pushed and pounded, all test wells were installed by pushing them into the streambed. The well screen at test-site DH3 was filled partially with fine-grained sediments (table 1, at back of report). For the first of two tests at DH3, the effective screen length (0.9 ft) was sufficient to allow use of both the Bouwer and Rice (1976) and Hvorslev (1951) methods; however, for the second test for which the well was pounded an additional 1.5 ft, the effective screen length (0.5 ft) was too short to

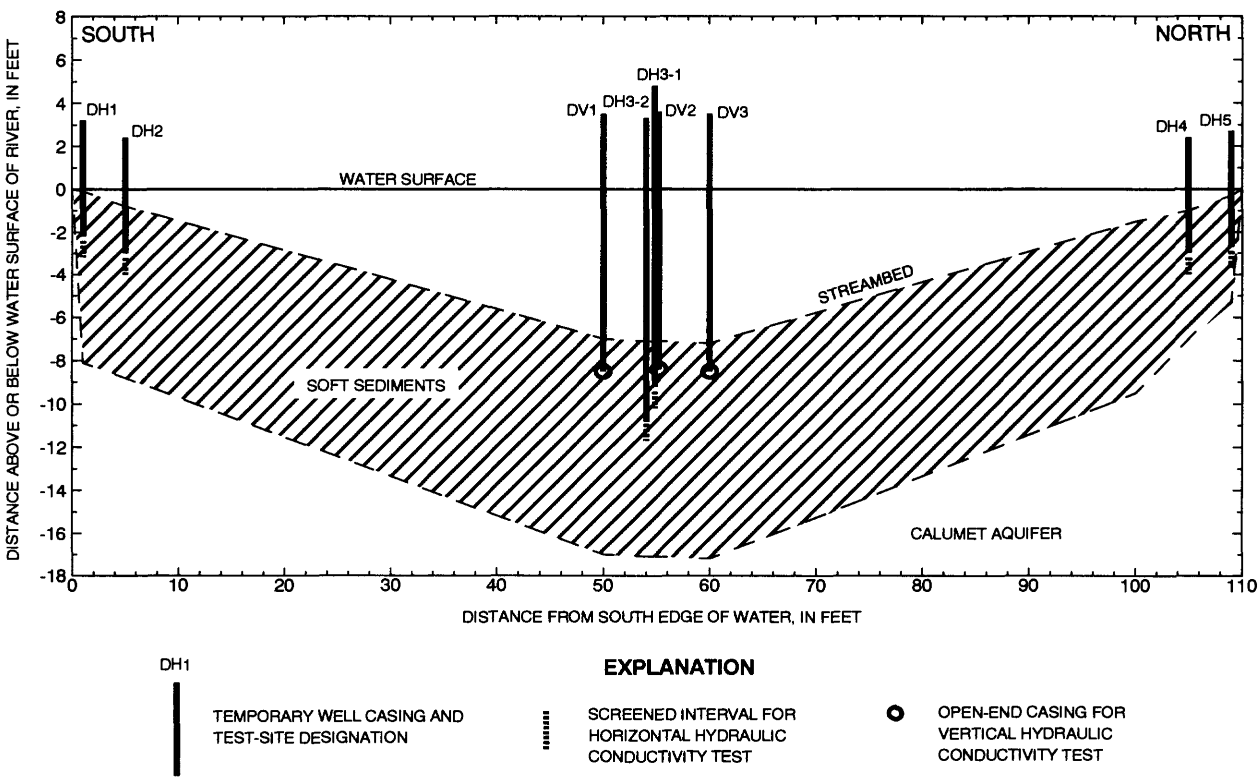


Figure 10. Cross section of streambed and locations of test sites at transect D, east branch Grand Calumet River, northern Lake County, Indiana.

allow use of the Hvorslev (1951) method for calculating horizontal hydraulic conductivity. Falling-head and rising-head tests were done in all test wells.

Horizontal hydraulic conductivity at transect D (table 12) was less varied than at the other three transects. Values of horizontal hydraulic conductivity were similar near both streambanks and were about one order of magnitude higher at the center of the river. The similarity of hydraulic conductivity indicates that the streambed sediments are distributed uniformly across the channel with more coarse-grained sediments in the deepest part of the channel where the greatest volume and velocity of flow is expected. The lowest value of horizontal hydraulic conductivity, 8.8×10^{-2} ft/day, was calculated by use of the method of Bouwer and Rice (1976) from data for the rising-head test at test-site DH4, 5 ft south from the northern streambank. The highest values of horizontal hydraulic conductivity were calculated from data from test-site DH3 at the center of the river where results from four tests ranged from 1.2 to 3.4 ft/ day. The average of all falling-head and rising-head tests for each test site was 3.3×10^{-1} ft/day for test-site DH1, 2.9×10^{-1} ft/day for test-site DH2, 2.0 ft/day for test-site DH3, 1.9×10^{-1} for test-site DH4, and 3.4×10^{-1} ft/day for test-site DH5.

Data from falling-head and rising-head tests produced similar results for individual test sites, although values of horizontal hydraulic conductivity calculated using data from rising-head tests were slightly lower than values calculated using data from falling-head tests for most of the tests. Values of horizontal hydraulic conductivity calculated by use of the method of Hvorslev (1951) were similar to, although

Table 12. Summary of horizontal hydraulic conductivity for transect D, east branch Grand Calumet River, northern Lake County, Indiana

[Location of test sites shown on figure 10; F, falling-head test; --, not applicable; R, rising-head test]

Test-site name	Type of test	Horizontal hydraulic conductivity calculated by the method of Bouwer and Rice[1] (feet per day)	Horizontal hydraulic conductivity calculated by the method of Hvorslev[2] (feet per day)	Horizontal hydraulic conductivity, average of both methods (feet per day)
DH1	F	3.3×10^{-1}	5.0×10^{-1}	4.15×10^{-1}
DH1	R	2.0×10^{-1}	3.0×10^{-1}	2.50×10^{-1}
DH2	F	2.4×10^{-1}	3.4×10^{-1}	2.90×10^{-1}
DH2	R	2.4×10^{-1}	3.4×10^{-1}	2.90×10^{-1}
DH3-1	F	2.5×10^{0}	3.4×10^{0}	2.95×10^{0}
DH3-1	R	1.7×10^{0}	2.2×10^{0}	1.95×10^{0}
DH3-2	F	1.8×10^{0}	--	--
DH3-2	R	1.2×10^{0}	--	--
DH4	F	2.2×10^{-1}	3.3×10^{-1}	2.75×10^{-1}
DH4	R	8.8×10^{-2}	1.3×10^{-1}	1.09×10^{-1}
DH5	F	2.9×10^{-1}	4.2×10^{-1}	3.55×10^{-1}
DH5	R	2.5×10^{-1}	3.8×10^{-1}	3.15×10^{-1}

consistently higher than, values calculated by use of the method of Bouwer and Rice (1976). Values of horizontal hydraulic conductivity for test-site DH3 are within the range of horizontal hydraulic conductivity, $6.5x10^{-1}$ to $3.6x10^{+2}$ ft/day, reported for the Calumet aquifer (Kay and others, 1996); however, values for the remaining test sites are slightly lower than the reported range.

All well casings for the vertical hydraulic conductivity tests at transect D were installed by pushing them into the streambed. As at transect A, the streambed materials at transect D felt gritty—indicating sand or possibly cinders mixed with the soft sediments. Comparison of measured depths to the streambed inside and outside of the well casing (table 1, at back of report) showed about 13–15 percent compaction of the sediments inside the well casings. Falling-head and rising-head tests were done at all test sites (table 13).

Calculated values of vertical hydraulic conductivity were consistent among all test sites and ranged from $1.1x10^{+1}$ ft/day for the falling-head test at test-site DV2 to $2.2x10^{+1}$ ft/day for the rising-head test at that same site. The average of falling-head and rising-head tests was nearly identical among all sites (table 13). The average vertical hydraulic conductivity of all tests at transect D was $1.7x10^{+1}$ ft/day. Values of vertical hydraulic conductivity were about one order of magnitude higher than the average value of horizontal hydraulic conductivity, 2.0 ft/day, calculated for all tests at site DH3. The average ratio of horizontal to vertical conductivity at transect D was approximately 1:8.5.

Table 13. Summary of vertical hydraulic conductivity for transect D, east branch Grand Calumet River, northern Lake County, Indiana

[Location of test sites shown on figure 10]

Test-site name	Vertical hydraulic conductivity calculated from falling-head data (feet per day)	Vertical hydraulic conductivity calculated from rising-head data (feet per day)	Vertical hydraulic conductivity, average of falling- and rising-head data (feet per day)
DV1	$1.9x10^{+1}$	$1.6x10^{+1}$	$1.75x10^{+1}$
DV2	$1.1x10^{+1}$	$2.2x10^{+1}$	$1.70x10^{+1}$
DV3	$1.2x10^{+1}$	$2.0x10^{+1}$	$1.65x10^{+1}$

SUMMARY AND CONCLUSIONS

Horizontal and vertical hydraulic conductivity of the streambed in the east branch Grand Calumet River were estimated from results of slug tests at four transects across the river. The slug tests were accomplished by monitoring the water-level response to displacement by a cylindrical weight (slug) or by addition of 1 gal of water in temporary wells installed in the streambed. Slug tests for horizontal hydraulic conductivity were done at five locations on each transect in 2-in.-diameter wells that had 1- or 2-ft-long wire-wrapped screens. Slug tests for vertical hydraulic conductivity were done at three locations near the midpoint of each transect in 3-in.-diameter wells that were open at the ends. A total of 47 slug tests for horizontal hydraulic conductivity and 20 slug tests for vertical hydraulic conductivity were analyzed. When possible, both falling-head and rising-head tests were done in the wells. A total of 27 falling-head tests and 20 rising-head tests were analyzed for horizontal hydraulic conductivity by applicable methods of Bouwer and Rice (1976), Hvorslev (1951), and van der Kamp (1976). A total of 13 falling-head tests and 7 rising-head tests were analyzed for vertical hydraulic conductivity by use of the variable-head method of Hvorslev (1951).

The width of the river ranged from 38 to 110 ft among the four transects. The maximum depth of water ranged from 2.1 ft at transect A to 7.3 ft at transect B. The thickness of soft sediments determined by pushing a 3/4-in.-diameter pipe into the streambed ranged from 0 ft, where the soft sediments were absent, to 13 ft. The maximum measured thickness of soft sediments was 5 ft at transects A and B, 13 ft at transect C, and 10 ft at transect D. Although much of the streambed contained soft sediments, the streambed also contained fill materials at each of the four transects. At transect A, the streambed near the northern streambank contained pieces of coal from an adjacent steel-mill operation. Urban rubble, containing pieces of concrete and asphalt, was found in the streambed near the southern streambank at transects B and C. The streambed near the northern streambank at transect D contained cinders.

Horizontal hydraulic conductivity of the streambed was varied at each transect. Calculated values of horizontal hydraulic conductivity ranged from 6.2×10^{-2} to $2.6 \times 10^{+2}$ ft/day for transect A, 7.8×10^{-2} to $1.2 \times 10^{+3}$ ft/day for transect B, 1.0×10^{-2} to $2.5 \times 10^{+2}$ ft/day for transect C, and 8.8×10^{-2} to 3.4 ft/day for transect D. Compared to the range of horizontal hydraulic conductivity, 6.5×10^{-1} to $3.6 \times 10^{+2}$ ft/day, for the Calumet aquifer (Kay and others, 1996), results for 24 slug tests in the streambed of the east branch Grand Calumet River were within the reported range, 18 were less than the reported range, and 5 were greater than the reported range.

The hydraulic conductivity of the streambed was dependant on the type of sediments in the part of the streambed that was tested. The largest values of horizontal hydraulic conductivity were calculated from data collected at locations where the streambed contained fill materials, particularly concrete and asphalt rubble. Horizontal hydraulic conductivity calculated using data from 11 slug tests at test sites in predominantly fill materials at AH5, BH1, BH2, and CH1 ranged from $1.2 \times 10^{+1}$ to $1.2 \times 10^{+3}$ ft/day and averaged $5.6 \times 10^{+2}$ ft/day. The smallest values of horizontal hydraulic conductivity were calculated for data at locations where the streambed contained fine-grained sediments. Horizontal hydraulic conductivity for 36 test at sites in predominantly fine-grained sediments ranged from 1.0×10^{-2} to $2.4 \times 10^{+2}$ ft/day and averaged $1.5 \times 10^{+1}$ ft/day.

Results from slug tests at CH3 indicate a decrease in horizontal hydraulic conductivity with increasing depth. The average horizontal hydraulic conductivity was $3.5 \times 10^{+1}$ ft/day for test CH3-2, screened from 1.5 to 2.5 ft beneath the streambed; $2.6 \times 10^{+1}$ ft/day for test CH3-3, screened from 2.6 to 3.6 ft beneath the streambed; and 7.9×10^{-1} ft/day for test CH3-1, screened from 4.3 to 6.3 ft beneath the streambed. The decrease in horizontal hydraulic conductivity with depth may be related to compaction of the sediment or to differences in the grain size or other properties of the sediment with depth.

Vertical hydraulic conductivity of the streambed was less varied than horizontal hydraulic conductivity and ranged from 3.3 to 6.1 ft/day at transect A, 3.0×10^{-1} to $7.3 \times 10^{+1}$ ft/day at transect B, 7.9×10^{-1} to 4.0 ft/day at transect C, and $1.1 \times 10^{+1}$ to $2.2 \times 10^{+1}$ ft/day at transect D. The ratio between horizontal and vertical hydraulic conductivity ranged from 1:0.09 at transect C to 1:8.5 at transect D.

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– PAGE 27 FOLLOWS –

SUPPLEMENTAL DATA

Table 1. Data collected at transects across the east branch Grand Calumet River, northern Lake County, Indiana, August 1995

[probe, indicates location where thickness of soft sediments was determined by pushing a 3/4-inch-diameter pipe to refusal; >, greater than; --, no data]

Transect A, Latitude 41°36′30″ Longitude 87°18′06″, Universal Transverse Mercator coordinates 474835.46, 4606085.52

Test-site name	Date, 1995	Distance from south edge of water (feet)	Depth of surface water (feet)	Thickness of soft sediments (feet)	Length of well casing (feet)	Length of well screen (feet)	Slot size of well screen (inches)	Measured depth of test well from top of casing (feet)	Effective length of well screen (feet)	Top of well casing above surface water (feet)	Depth to water in well from top of well casing (feet)	Screened interval below surface-water level (feet)	Screened interval below streambed (feet)
AH1	8/2	1	0.5	2	5.4	1	0.03	5.7	0.3	3.5	3.39	1.9-2.2	1.4-1.7
AH2	8/2	5	1.4	>4	5.4	1	.03	5.7	.3	3.0	2.71	2.4-2.7	1.0-1.3
AH3	8/2	19	2.1	5	5.4	1	.03	6.2	.8	1.5	1.41	3.9-4.7	1.8-2.6
AH4	8/2	30	1.9	2	5.4	1	.03	6.4	1	2.4	2.74	3.0-4.0	1.1-2.1
probe	8/2	35	1.1	.5	--	--	--	--	--	--	--	--	--
AH5	8/7	36	.8	0	5.4	1	.03	6.4	1	2.7	2.69	2.7-3.7	1.9-2.9
probe	8/2	37	.5	0	--	--	--	--	--	--	--	--	--

Test-site name	Date, 1995	Distance from south edge of water (feet)	Depth of surface water (feet)	Thickness of soft sediments (feet)	Length of well casing (feet)	Measured depth of test well from top of casing (feet)	Top of well casing above surface water (feet)	Depth to water in well from top of casing (feet)	Depth of well casing below surface-water level (feet)	Depth of well casing below stream-bed (feet)	Length of sediment core (feet)
AV1	8/3	16	1.8	5	6.0	5.2	3.1	3.18	2.9	1.1	0.8
AV2	8/3	19	2.0	5	6.0	5.4	3.3	3.32	2.7	.6	.6
AV3-1	8/7	23	1.9	5	6.0	5.3	2.9	3.05	3.1	1.2	.8
AV3-2	8/7	22	2.0	5	6.0	5.0	2.8	2.96	3.2	1.2	1.0

Table 1. Data collected at transects across the east branch Grand Calumet River, northern Lake County, Indiana, August 1995—Continued

Transect B, Latitude 41°36′32″ Longitude 87°22′17″, Universal Transverse Mercator coordinates 469086.42, 4606218.96

Test-site name	Date, 1995	Distance from south edge of water (feet)	Depth of surface water (feet)	Thickness of soft sediments (feet)	Length of well casing (feet)	Length of well screen (feet)	Slot size of well screen (inches)	Measured depth of test well from top of casing (feet)	Effective length of well screen (feet)	Top of well casing above surface water (feet)	Depth to water in well from top of well casing (feet)	Screened interval below surface-water level (feet)	Screened interval below streambed (feet)
probe	8/8	1	1.0	0	--	--	--	--	--	--	--	--	--
BH1-1,2	8/8	3	1.4	0	5.4	2	0.03	6.4	1.0	3.1	3.09	2.3-4.3	0.9-2.9
probe	8/8	4	2.5	0	--	--	--	--	--	--	--	--	--
BH2-1	8/8	6.5	4.3	1	8.5	2	.02	10.5	2.0	3.1	3.17	5.4-7.4	1.1-3.1
BH2-2	8/8	6.5	3.7	1	8.5	2	.02	10.5	2.0	3.7	3.70	4.8-6.8	1.1-3.1
probe	8/8	15	6.0	2	--	--	--	--	--	--	--	--	--
BH3-1	8/8	49	6.6	>3	8.5	2	.02	10.5	2.0	1.5	1.44	7.0-9.0	.4-2.4
BH3-2	8/8	49	6.3	>3	8.5	2	.02	10.5	2.0	1.6	1.58	6.9-8.9	.6-2.6
probe	8/8	78	5.5	2	--	--	--	--	--	--	--	--	--
BH4	8/9	92	2.2	4	5.4	1	.02	6.4	1.0	1.2	1.25	4.2-5.2	2.0-3.0
probe	8/8	93	1.0	5	--	--	--	--	--	--	--	--	--
BH5	8/9	97	.6	5	5.4	1	.02	6.4	1.0	2.6	2.56	2.8-3.8	2.2-3.2

Test-site name	Date, 1995	Distance from south edge of water (feet)	Depth of surface water (feet)	Thickness of soft sediments (feet)	Length of well casing (feet)	Measured depth of test well from top of casing (feet)	Top of well casing above surface water (feet)	Depth to water in well from top of casing (feet)	Depth of well casing below surface-water level (feet)	Depth of well casing below stream-bed (feet)	Length of sediment core (feet)
BV1	8/8	44.5	7.3	>3	12.0	10.4	3.0	3.33	9.0	1.7	1.6
BV2	8/8	49	7.3	>3	12.0	11.3	3.9	3.75	8.1	.8	.7
BV3	8/9	53	6.9	>3	12.0	10.2	3.1	3.57	8.9	2.0	1.8

Table 1. Data collected at transects across the east branch Grand Calumet River, northern Lake County, Indiana, August 1995—Continued

Transect C, Latitude 41°36′29″ Longitude 87°23′37″, Universal Transverse Mercator coordinates 467169.43, 4606116.43

Test-site name	Date, 1995	Distance from south edge of water (feet)	Depth of surface water (feet)	Thickness of soft sediments (feet)	Length of well casing (feet)	Length of well screen (feet)	Slot size of well screen (inches)	Measured depth of test well from top of casing (feet)	Effective length of well screen (feet)	Top of well casing above surface water (feet)	Depth to water in well from top of well casing (feet)	Screened interval below surface-water level (feet)	Screened interval below streambed (feet)
CH1	8/1	1	1.1	0	8.4	1	0.03	9.4	1.0	5.4	5.54	3.0- 4.0	1.9-2.9
CH2	8/1	6	1.8	1	12.0	1	.03	12.4	.4	4.1	4.09	7.9- 8.3	6.1-6.5
CH3-1	8/1	54	4.0	13	13.5	2	.02	15.5	2.0	5.2	5.44	8.3-10.3	4.3-6.3
CH3-2	8/10	54	3.8	13	8.4	1	.02	9.4	1.0	3.1	3.12	5.3- 6.3	1.5-2.5
CH3-3	8/10	54	3.8	13	8.4	1	.02	9.4	1.0	2.0	2.06	6.4- 7.4	2.6-3.6
CH4	8/10	102	2.2	11	5.4	1	.02	6.4	1.0	1.4	1.69	4.0- 5.0	1.8-2.8
CH5-1	8/10	106	1.2	10	5.4	1	.02	6.4	1.0	1.5	1.46	3.9- 4.9	2.7-3.7
CH5-2	8/10	106	1.2	10	5.4	1	.02	6.4	1.0	1.4	1.27	4.0- 5.0	2.8-3.8
probe	8/10	108	0	>9	--	--	--	--	--	--	--	--	--

Test-site name	Date, 1995	Distance from south edge of water (feet)	Depth of surface water (feet)	Thickness of soft sediments (feet)	Length of well casing (feet)	Measured depth of test well from top of casing (feet)	Top of well casing above surface water (feet)	Depth to water in well from top of casing (feet)	Depth of well casing below surface-water level (feet)	Depth of well casing below stream-bed (feet)	Length of sediment core (feet)
CV1	8/1	50	3.7	13	12.0	9.8	6.1	6.21	5.9	2.2	2.2
CV2	8/1	54	4.1	13	12.0	9.1	5.0	5.13	7.0	2.9	2.9
CV3	8/10	58	3.6	13	10.0	8.8	5.0	5.05	5.0	1.4	1.2

Table 1. Data collected at transects across the east branch Grand Calumet River, northern Lake County, Indiana, August 1995—Continued

Transect D, Latitude 41°36′46″ Longitude 87°27′05″, Universal Transverse Mercator coordinates 462422.72, 4606694.79

Test-site name	Date, 1995	Distance from south edge of water (feet)	Depth of surface water (feet)	Thickness of soft sediments (feet)	Length of well casing (feet)	Length of well screen (feet)	Slot size of well screen (inches)	Measured depth of test well from top of casing (feet)	Effective length of well screen (feet)	Top of well casing above surface water (feet)	Depth to water in well from top of well casing (feet)	Screened interval below surface-water level (feet)	Screened interval below streambed (feet)
DH1	8/15	1	0.1	>8	5.4	1	0.02	6.4	1.0	3.2	3.15	2.2- 3.2	2.1-3.1
DH2	8/15	5	.8	8	5.4	1	.02	6.4	1.0	2.4	2.56	3.0- 4.0	2.2-3.2
DH3-1	8/16	55	7.1	10	14.0	1	.02	14.9	.9	4.8	4.84	9.2-10.2	2.1-3.0
DH3-2	8/16	54	7.1	10	14.0	1	.02	14.5	.5	3.3	3.33	10.7-11.2	3.6-4.1
probe	8/15	100	1.5	8	--	--	--	--	--	--	--	--	--
DH4	8/15	105	1.0	6	5.4	1	.02	6.4	1.0	2.4	2.25	3.0- 4.0	2.0-3.0
DH5	8/15	109	.3	5	5.4	1	.02	6.4	1.0	2.7	2.92	2.7- 3.7	2.4-3.4

Test-site name	Date, 1995	Distance from south edge of water (feet)	Depth of surface water (feet)	Thickness of soft sediments (feet)	Length of well casing (feet)	Measured depth of test well from top of casing (feet)	Top of well casing above surface water (feet)	Depth to water in well from top of casing (feet)	Depth of well casing below surface-water level (feet)	Depth of well casing below stream-bed (feet)	Length of sediment core (feet)
DV1	8/16	50	7.0	10	12.0	10.7	3.5	3.56	8.5	1.5	1.3
DV2	8/16	55	7.1	10	12.0	10.8	3.6	3.83	8.4	1.4	1.2
DV3	8/16	60	7.2	10	12.0	10.9	3.5	3.67	8.5	1.3	1.1

Table 2. Values of input variables and results of the method of Bouwer and Rice (1976) for calculating horizontal hydraulic conductivity for slug-test data collected along transects across the east branch Grand Calumet River, northern Lake County, Indiana

[F, falling-head test; R, rising-head test]

Test-site name	Type of test	Effective radius of well screen, r_w (feet)	Height of static water level above bottom of well, H (feet)	Aquifer coefficient, A	Aquifer coefficient, B	Saturated thickness of aquifer, D (feet)	Effective length of well screen, L (feet)	Inside radius of well casing, r_c (feet)	Time since start of test, t (minutes)	Water level at start of test, y_0 (feet)	Water level at time t, y_t (feet)	Horizontal hydraulic conductivity, K (feet per day)	Horizontal hydraulic conductivity, K (centimeters per second)
AH1	F	0.083	2.2	1.70	0.25	40	0.3	0.083	29	3.04	2.66	6.2×10^{-2}	2.2×10^{-5}
AH2	F	.083	2.7	1.70	.25	40	.3	.083	18	.89	.46	5.1×10^{-1}	1.8×10^{-4}
AH2	R	.083	2.7	1.70	.25	40	.3	.083	2.0	.75	.10	$1.4 \times 10^{+1}$	4.9×10^{-3}
AH3	F	.083	4.7	1.80	.26	40	.8	.083	7.0	1.00	.49	1.0×10^{0}	3.5×10^{-4}
AH3	R	.083	4.7	1.80	.26	40	.8	.083	2.2	.95	.17	7.8×10^{0}	2.8×10^{-3}
AH4	F	.083	4.0	1.89	.27	40	1	.083	1.0	.85	.17	$1.4 \times 10^{+1}$	4.9×10^{-3}
AH4	R	.083	4.0	1.89	.27	40	1	.083	19	.88	.15	8.0×10^{-1}	2.8×10^{-4}
AH5-1	F	.083	3.7	1.89	.27	40	1	.083	.12	1.00	.09	$1.7 \times 10^{+2}$	6.0×10^{-2}
AH5-2	F	.083	3.7	1.89	.27	40	1	.083	.11	.84	.10	$1.7 \times 10^{+2}$	6.0×10^{-2}
BH1-1	F	.083	4.3	2.23	.30	35	2	.083	.02	.11	.012	$6.1 \times 10^{+2}$	2.2×10^{-1}
BH2-1	F	.083	7.4	2.23	.30	35	2	.083	.02	.65	.13	$4.9 \times 10^{+2}$	1.7×10^{-1}
BH2-1	R	.083	7.4	2.23	.30	35	2	.083	1.4	.495	.035	$1.2 \times 10^{+1}$	4.2×10^{-3}
BH2-2	F	.083	6.8	2.23	.30	35	2	.083	.06	.147	.022	$1.9 \times 10^{+2}$	6.7×10^{-2}
BH3-1	F	.083	9.0	2.23	.30	35	2	.083	.018	1.40	.072	$2.3 \times 10^{+2}$	8.1×10^{-2}
BH3-1	R	.083	9.0	2.23	.30	35	2	.083	5.8	2.05	.08	3.5×10^{0}	1.2×10^{-3}
BH3-2	F	.083	8.9	2.23	.30	35	2	.083	.03	.63	.45	$7.0 \times 10^{+1}$	2.5×10^{-2}
BH3-2	R	.083	8.9	2.23	.30	35	2	.083	1.5	1.82	.47	5.6×10^{0}	2.0×10^{-3}
BH4	F	.083	5.2	1.89	.27	35	1	.083	58	.625	.376	7.8×10^{-2}	2.8×10^{-5}
BH5	F	.083	3.8	1.89	.27	35	1	.083	10	1.05	.72	3.2×10^{-1}	1.1×10^{-4}
BH5	R	.083	3.8	1.89	.27	35	1	.083	10	.78	.48	4.2×10^{-1}	1.5×10^{-4}

Table 2. Values of input variables and results of the method of Bouwer and Rice (1976) for calculating horizontal hydraulic conductivity for slug-test data collected along transects across the east branch Grand Calumet River, northern Lake County, Indiana—Continued

Test-site name	Type of test	Effective radius of well screen, r_w (feet)	Height of static water level above bottom of well, H (feet)	Aquifer coefficient, A	Aquifer coefficient, B	Saturated thickness of aquifer, D (feet)	Effective length of well screen, L (feet)	Inside radius of well casing, r_c (feet)	Time since start of test, t (minutes)	Water level at start of test, y_0 (feet)	Water level at time t, y_t (feet)	Horizontal hydraulic conductivity, K (feet per day)	Horizontal hydraulic conductivity, K (centimeters per second)
CH1	F	0.083	4.0	1.89	0.27	35	1	0.083	0.1	0.12	0.02	$1.6x10^{+2}$	$5.6x10^{-2}$
CH1	R	.083	4.0	1.89	.27	35	1	.083	.1	.09	.04	$8.7x10^{+1}$	$3.1x10^{-2}$
CH2	F	.083	8.3	1.73	.25	35	.4	.083	5	2.1	.31	$5.3x10^{0}$	$1.9x10^{-3}$
CH2	R	.083	8.3	1.73	.25	35	.4	.083	2	2.0	.25	$1.4x10^{+1}$	$4.9x10^{-3}$
CH3-1	F	.083	10.3	2.23	.30	35	2	.083	5	1.59	.90	$7.2x10^{-1}$	$2.5x10^{-4}$
CH3-2	F	.083	6.3	1.89	.27	35	1	.083	.5	1.25	.05	$5.9x10^{+1}$	$2.1x10^{-2}$
CH3-2	R	.083	6.3	1.89	.27	35	1	.083	10	1.08	.80	$2.7x10^{-1}$	$9.5x10^{-5}$
CH3-3	F	.083	7.4	1.89	.27	35	1	.083	1	1.60	.10	$2.6x10^{+1}$	$9.2x10^{-3}$
CH4	F	.083	5.0	1.89	.27	35	1	.083	10	1.06	1.00	$5.2x10^{-2}$	$1.8x10^{-5}$
CH4	R	.083	5.0	1.89	.27	35	1	.083	10	.28	.24	$1.4x10^{-1}$	$4.9x10^{-5}$
CH5-1	F	.083	4.9	1.89	.27	35	1	.083	10	1.10	1.07	$2.5x10^{-2}$	$8.8x10^{-6}$
CH5-2	F	.083	5.0	1.89	.27	35	1	.083	10	.99	.98	$1.4x10^{-2}$	$4.9x10^{-6}$
DH1	F	.083	3.2	1.89	.27	35	1	.083	10	1.05	.71	$3.3x10^{-1}$	$1.2x10^{-4}$
DH1	R	.083	3.2	1.89	.27	35	1	.083	10	.88	.69	$2.0x10^{-1}$	$7.1x10^{-5}$
DH2	F	.083	4.0	1.89	.27	35	1	.083	10	1.08	.82	$2.4x10^{-1}$	$8.5x10^{-5}$
DH2	R	.083	4.0	1.89	.27	35	1	.083	15	.78	.52	$2.4x10^{-1}$	$8.5x10^{-5}$
DH3-1	F	.083	10.1	1.84	.26	35	.9	.083	1	2.05	1.61	$2.5x10^{0}$	$8.8x10^{-4}$
DH3-1	R	.083	10.1	1.84	.26	35	.9	.083	10	2.00	.38	$1.7x10^{0}$	$6.0x10^{-4}$
DH3-2	F	.083	11.2	1.75	.26	35	.5	.083	4	2.10	1.23	$1.8x10^{0}$	$6.4x10^{-4}$
DH3-2	R	.083	11.2	1.75	.26	35	.5	.083	10	2.15	.85	$1.2x10^{0}$	$4.2x10^{-4}$
DH4	F	.083	4.0	1.89	.27	35	1	.083	20	1.02	.61	$2.2x10^{-1}$	$7.8x10^{-5}$
DH4	R	.083	4.0	1.89	.27	35	1	.083	20	.87	.71	$8.8x10^{-2}$	$3.1x10^{-5}$
DH5	F	.083	3.7	1.89	.27	35	1	.083	15	1.05	.63	$2.9x10^{-1}$	$1.0x10^{-4}$
DH5	R	.083	3.7	1.89	.27	35	1	.083	19	.75	.43	$2.5x10^{-1}$	$8.8x10^{-5}$

Table 3. Values of input variables and results of the basic time-lag method of Hvorslev (1951) for calculating horizontal hydraulic conductivity for slug-test data collected along transects across the east branch Grand Calumet River, northern Lake County, Indiana
[NA, not applicable when L/R is less than 8]

Test-site name	Type of test	Radius of well casing, r (feet)	Radius of well screen, R (feet)	Effective length of well screen, L (feet)	Time it takes for water level to fall or rise to 37 percent of the initial change, T_0 (minutes)	Horizontal hydraulic conductivity, K (feet per day)	Horizontal hydraulic conductivity, K (centimeters per second)
AH1	Falling-head	0.083	0.083	0.3	NA	NA	NA
AH2	Falling-head	.083	.083	.3	NA	NA	NA
AH2	Rising-head	.083	.083	.3	NA	NA	NA
AH3	Falling-head	.083	.083	.8	9.9	1.4×10^{0}	4.9×10^{-4}
AH3	Rising-head	.083	.083	.8	1.26	$1.1 \times 10^{+1}$	3.9×10^{-3}
AH4	Falling-head	.083	.083	1	.65	$1.9 \times 10^{+1}$	6.7×10^{-3}
AH4	Rising-head	.083	.083	1	10.6	1.2×10^{0}	4.2×10^{-4}
AH5-1	Falling-head	.083	.083	1	.048	$2.6 \times 10^{+2}$	9.2×10^{-2}
AH5-2	Falling-head	.083	.083	1	.049	$2.5 \times 10^{+2}$	8.8×10^{-2}
BH1-1	Falling-head	.083	.083	2	.009	$8.5 \times 10^{+2}$	3.0×10^{-1}
BH2-1	Falling-head	.083	.083	2	.011	$7.5 \times 10^{+2}$	2.6×10^{-1}
BH2-1	Rising-head	.083	.083	2	.48	$1.6 \times 10^{+1}$	5.6×10^{-3}
BH2-2	Falling-head	.083	.083	2	.025	$3.2 \times 10^{+2}$	1.1×10^{-1}
BH3-1	Falling-head	.083	.083	2	.033	$2.4 \times 10^{+2}$	8.5×10^{-2}
BH3-1	Rising-head	.083	.083	2	1.70	4.6×10^{0}	1.6×10^{-3}
BH3-2	Falling-head	.083	.083	2	.080	$9.9 \times 10^{+1}$	3.5×10^{-2}
BH3-2	Rising-head	.083	.083	2	1.07	7.4×10^{0}	2.6×10^{-3}
BH4	Falling-head	.083	.083	1	114	1.1×10^{-1}	3.9×10^{-5}
BH5	Falling-head	.083	.083	1	25.9	4.8×10^{-1}	1.7×10^{-4}
BH5	Rising-head	.083	.083	1	22.0	5.6×10^{-1}	2.0×10^{-4}
CH1	Falling-head	.083	.083	1	.05	$2.5 \times 10^{+2}$	8.8×10^{-2}
CH1	Rising-head	.083	.083	1	.108	$1.1 \times 10^{+2}$	3.9×10^{-2}

Table 3. Values of input variables and results of the basic time-lag method of Hvorslev (1951) for calculating horizontal hydraulic conductivity for slug-test data collected along transects across the east branch Grand Calumet River, northern Lake County, Indiana—Continued

Test-site name	Type of test	Radius of well casing, r (feet)	Radius of well screen, R (feet)	Effective length of well screen, L (feet)	Time it takes for water level to fall or rise to 37 percent of the initial change, T_0 (minutes)	Horizontal hydraulic conductivity, K (feet per day)	Horizontal hydraulic conductivity, K (centimeters per second)
CH2	Falling-head	.083	.083	.4	NA	NA	NA
CH2	Rising-head	.083	.083	.4	NA	NA	NA
CH3-1	Falling-head	.083	.083	2	9.15	8.6×10^{-1}	3.0×10^{-4}
CH3-2	Falling-head	.083	.083	1	.15	$8.2\times10^{+1}$	2.9×10^{-2}
CH3-2	Rising-head	.083	.083	1	32.5	3.8×10^{-1}	1.3×10^{-4}
CH3-3	Falling-head	.083	.083	1	.50	$2.5\times10^{+1}$	8.8×10^{-3}
CH4	Falling-head	.083	.083	1	235	5.3×10^{-2}	1.9×10^{-5}
CH4	Rising-head	.083	.083	1	50	2.5×10^{-1}	8.8×10^{-5}
CH5-1	Falling-head	.083	.083	1	535	2.3×10^{-2}	8.1×10^{-6}
CH5-2	Rising-head	.083	.083	1	1,230	1.0×10^{-2}	3.5×10^{-6}
DH1	Falling-head	.083	.083	1	24.8	5.0×10^{-1}	1.8×10^{-4}
DH1	Rising-head	.083	.083	1	41.0	3.0×10^{-1}	1.1×10^{-4}
DH2	Falling-head	.083	.083	1	36.0	3.4×10^{-1}	1.2×10^{-4}
DH2	Rising-head	.083	.083	1	36.0	3.4×10^{-1}	1.2×10^{-4}
DH3-1	Falling-head	.083	.083	.9	3.87	3.4×10^{0}	1.2×10^{-3}
DH3-1	Rising-head	.083	.083	.9	6.0	2.2×10^{0}	7.8×10^{-4}
DH3-2	Falling-head	.083	.083	.5	NA	NA	NA
DH3-2	Rising-head	.083	.083	.5	NA	NA	NA
DH4	Falling-head	.083	.083	1	37.0	3.3×10^{-1}	1.2×10^{-4}
DH4	Rising-head	.083	.083	1	96.0	1.3×10^{-1}	4.6×10^{-5}
DH5	Falling-head	.083	.083	1	29.2	4.2×10^{-1}	1.5×10^{-4}
DH5	Rising-head	.083	.083	1	32.5	3.8×10^{-1}	1.3×10^{-4}

Table 4. Values of input variables and results of the method of van der Kamp (1976) for calculating horizontal hydraulic conductivity for slug-test data collected along transects across the east branch Grand Calumet River, northern Lake County, Indiana

[R, rising-head test]

Test-site name	Type of test	Initial water level, H_0 (feet)	Time of initial water level, t_0 (seconds)	Later water level, H_t (feet)	Time of later water level t_1 (seconds)	Radius of well casing, r_c (feet)	Radius of well screen, r_f (feet)	Assumed specific yield, S (dimensionless)	Length of well screen, L_f (feet)	Horizontal hydraulic conductivity, K (feet per day)	Horizontal hydraulic conductivity, K (centimeters per second)
BH1-1	R	0.053	2.00	0.012	4.2	0.083	0.083	0.2	2	$8.4 \times 10^{+2}$	3.0×10^{-1}
BH1-2	R	.054	1.60	.016	3.8	.083	.083	.2	2	$1.2 \times 10^{+3}$	4.2×10^{-1}
BH2-2	R	.052	1.60	.013	7.8	.083	.083	.2	2	$7.5 \times 10^{+2}$	2.6×10^{-1}

Table 5. Values of input variables and results of the variable-head method of Hvorslev (1951) for calculating vertical hydraulic conductivity for slug-test data collected along transects across the east branch Grand Calumet River, northern Lake County, Indiana
[F, falling-head test; R, rising-head test]

Test-site name	Type of test	Inside diameter of well casing, D (feet)	Length of sediment core, L (feet)	Elapsed time of test, t_2-t_1 (minutes)	Water level at start of test, H_1 (feet)	Water level at end of test H_2 (feet)	Horizontal hydraulic conductivity, K_h (feet per day)	$\sqrt{K_h/K_v}$ m	Vertical hydraulic conductivity, K_v (feet per day)	Vertical Hydraulic conductivity, K_v (centimeters per second)
AV1	F	0.25	0.8	62	3.20	2.40	$5.3x10^{0}$	0.948	$5.9x10^{0}$	$2.1x10^{-3}$
AV2	F	.25	.6	64	3.00	2.40	$5.3x10^{0}$	1.27	$3.3x10^{0}$	$1.2x10^{-3}$
AV3-1	F	.25	.8	32	2.80	2.40	$5.3x10^{0}$	.932	$6.1x10^{0}$	$2.2x10^{-3}$
AV3-2	F	.25	1.0	71	2.65	2.25	$5.3x10^{0}$	1.23	$3.5x10^{0}$	$1.2x10^{-3}$
BV1	F	.25	1.6	46	1.44	1.42	$8.3x10^{+1}$	10.9	$7.0x10^{-1}$	$2.5x10^{-4}$
BV1	R	.25	1.6	10	.088	.065	$8.3x10^{+1}$	1.07	$7.3x10^{+1}$	$2.6x10^{-2}$
BV2	F	.25	.7	30	1.39	1.32	$8.3x10^{+1}$	6.79	$1.8x10^{0}$	$6.4x10^{-4}$
BV2	R	.25	.7	10	.081	.079	$8.3x10^{+1}$	5.65	$2.6x10^{0}$	$9.2x10^{-4}$
BV3	F	.25	1.8	60	1.44	1.43	$8.3x10^{+1}$	16.6	$3.0x10^{-1}$	$1.1x10^{-4}$
CV1	F	.25	2.2	12	3.55	3.50	$3.2x10^{+1}$	2.90	$3.8x10^{0}$	$1.3x10^{-3}$
CV1	R	.25	2.2	10	2.15	2.13	$3.2x10^{+1}$	3.27	$3.0x10^{0}$	$1.1x10^{-3}$
CV2	F	.25	2.9	12	1.77	1.75	$3.2x10^{+1}$	2.83	$4.0x10^{0}$	$1.4x10^{-3}$
CV3	F	.25	1.2	64	1.40	1.36	$3.2x10^{+1}$	6.36	$7.9x10^{-1}$	$2.8x10^{-4}$
CV3	R	.25	1.2	29	.042	.040	$3.2x10^{+1}$	3.27	$3.0x10^{0}$	$1.1x10^{-3}$
DV1	F	.25	1.3	60	1.41	.83	$2.0x10^{0}$	.324	$1.9x10^{+1}$	$6.7x10^{-3}$
DV1	R	.25	1.3	62	.60	.38	$2.0x10^{0}$	.354	$1.6x10^{+1}$	$5.6x10^{-3}$
DV2	F	.25	1.2	62	1.40	.98	$2.0x10^{0}$	.426	$1.1x10^{+1}$	$3.9x10^{-3}$
DV2	R	.25	1.2	62	.47	.24	$2.0x10^{0}$	.302	$2.2x10^{+1}$	$7.8x10^{-3}$
DV3	F	.25	1.1	62	1.40	.93	$2.0x10^{0}$	.408	$1.2x10^{+1}$	$4.2x10^{-3}$
DV3	R	.25	1.1	60	.50	.27	$2.0x10^{0}$	.316	$2.0x10^{+1}$	$7.1x10^{-3}$