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Estimating Streambed Seepage Using Heat as a Tracer on the Lower Boise River, Canyon County, Idaho

Scientific Investigations Report 2005–5215

U.S. Department of the Interior
U.S. Geological Survey

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Gale A. Norton, Secretary

U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2006

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Suggested citation:
Skinner, K.D., 2006, Estimating streambed seepage using heat as a tracer on the lower Boise River, Canyon County, Idaho: U.S. Geological Survey Scientific Investigations Report 2005–5215, 16 p.

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Conversion Factors and Datums

Inch/Pound to SI

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per mile [(ft^3/s)/mi]	0.0176	cubic meter per second per kilometer
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
mile (mi)	1.609	kilometer
pound per day (lb/d)	0.4536	kilogram per day
pound per square inch (lb/in^2)	6.895	kilopascal

SI to Inch/Pound

Multiply	By	To obtain
meter (m)	3.281	foot
foot (ft)	0.3048	meter
meter per second	3.281	foot per second

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8.$$

Vertical coordinate information is referenced to the insert datum name (and abbreviation) here for instance, “North American Vertical Datum of 1988 (NAVD 88).”

Horizontal coordinate information is referenced to the insert datum name (and abbreviation) here for instance, “North American Datum of 1983 (NAD 83).”

Altitude, as used in this report, refers to distance above the vertical datum.

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Estimating Streambed Seepage Using Heat as a Tracer on the Lower Boise River, Canyon County, Idaho

By Kenneth D. Skinner

Abstract

A total maximum daily load (TMDL) management plan was developed for the lower Boise River after it was listed as water-quality limited in 1992, in accordance with Section 303(d) of the Clean Water Act. The management plan includes TMDLs for nutrients, suspended sediment, bacteria, elevated water temperature, and low dissolved-oxygen concentrations. A 2001 synoptic study estimated that as much as 150 pounds per day of the nutrient, dissolved phosphorus, from ground-water seepage was entering a 3 river-mile reach of the lower Boise River. Better estimates of ground-water seepage into the lower Boise River are required if further nutrient transport studies are to be done. This study was designed to determine ground-water seepage estimates for the lower Boise River using the USGS model VS2DI and the parameter estimation code PEST. These seepage estimates potentially can be used to help determine the approximate amount of nutrients being transported to or from the stream.

To obtain seepage rates, a two-dimensional heat and water transport simulation model was created for each of four transects distributed over 3 river miles on the lower Boise River and representing conditions from April to August 2003. As many as seven piezometers were installed at each transect to obtain monthly stage and ground-water head values, continuous temperature, and saturated hydraulic conductivity from slug tests.

Analysis of model results indicated that three of the four transects gained water, with seepage rate estimates ranging from 6 to 73 cubic feet per second per mile [$(ft^3/s)/mi$]. The fourth transect showed seepage from the Boise River to ground water, with rates ranging from 2 to 18 $(ft^3/s)/mi$. One benefit of this seepage estimation method is the ability to model how seepage changes over time. The trend of seepage to the river increased for most of the 5-month study period in the three transects that gained water. Likewise, the transect that lost water showed a decreasing trend of seepage from the river. Seepage estimates for this study were higher than those of previous studies using different methodologies. Seepage values for this study are representative of a unit meter stream length as opposed to long stream reaches. Comparison of seepage estimates for all transects also aids in identifying the seepage variability within a river reach.

Introduction

Water quality in the lower Boise River has changed over time due to anthropogenic activities such as land-use changes, increased urbanization, and an altered flow regime in the Boise River (MacCoy, 2004). The lower Boise River was listed as water-quality limited in 1992 in accordance with Section 303(d) of the Clean Water Act (Idaho Department of Environmental Quality, 1999). This listing required the development of a total maximum daily load (TMDL) management plan for the lower Boise River. The management plan includes TMDLs for nutrients, suspended sediment, bacteria, elevated water temperature, and low dissolved-oxygen concentrations.

The Lower Boise River Water Quality Plan, Inc. (LBRWQP) was formed in 1992 with membership composed of public and private agencies, groups, and individuals. The LBRWQP's mission is to identify water-quality problems, to initiate voluntary water-quality management practices, and to monitor the long-term effectiveness of these practices on the water quality and biotic integrity of the lower Boise River. In 1994, in cooperation with the LBRWQP and the Idaho Department of Environmental Quality (IDEQ), the U.S. Geological Survey (USGS) began a comprehensive, 8-year study to assess water quality and biotic integrity of the lower Boise River using a combination of reconnaissance, synoptic, and interval water-quality sampling, in addition to annual biological sampling.

A 2001 synoptic study estimated that as much as 150 lb/d of dissolved phosphorus and 215 lb/d of total nitrogen, likely from ground-water seepage, was entering the Boise River approximately between river miles (RM) 2 and 4 (MacCoy, 2004). Results of the synoptic study indicated (1) the potential for significant seepage of nutrients into the lower Boise River from ground water, and (2) the need for a more focused study of ground-water and surface-water interaction. In 2003, the present study was designed and implemented to identify and estimate seepage between ground water and the lower Boise River. Seepage estimates might be used to help determine the approximate amount of nutrients being transported between ground water and the lower Boise River.

Interconnections Between Surface Water and Ground Water

Historically, surface water and ground water were evaluated as distinct, independent resources to be utilized and managed separately. Over time, the interconnection of these two resources became clearer; surface water and ground water are, in fact, part of a single, interconnected water resource (Winter and others, 1998). For example, when one component of the water resource increases or decreases, the other component responds similarly, thereby complicating efforts to manage the two water components separately. Therefore, an understanding of the interconnections between surface water and ground water is essential to effectively managing water resources.

One indicator of these interconnections is temperature. Water exchange between surface water and ground water affects temperatures not only in the two water components, but also in the sediments near them. Therefore, analyses of subsurface temperature patterns provide information about surface-water and ground-water interaction. Modeling the transport of heat can thus improve understanding of the magnitudes and mechanisms of water exchange between the two resources (Stonestrom and Constantz, 2003).

Heat has long been identified as a potential tracer of water exchange between streams and ground-water systems (Rorabaugh, 1954; Lapham, 1989). Continuing improvements in data-acquisition and computation have enabled the economical and routine application of heat as a hydrologic tracer. The USGS model VS2DI (Hsieh and others, 2000) has been used to simulate the transport of heat between surface water and ground water in different environments from ephemeral to perennial streams (Silliman and Booth, 1993; Bartolino and Niswonger, 1999; Su and others, 2004).

Purpose and Scope

The objective of this study is to estimate the flux between ground water and surface water within a 3 river-mile reach of the lower Boise River using heat as a tracer. Two-dimensional models of four transects along the 3-river mile reach were created using the USGS model, VS2DI. The two-dimensional models represent temperature and flow conditions in the four transects from April to August 2003.

Acknowledgments

The author wishes to extend thanks to the Boise Field Office for the arduous task of piezometer installation, and to the following individuals for assistance with the VS2DI modeling: Jim Constantz, Hedeff Essaid, and Stephanie Moore of the USGS; and Christine Hatch at the University of California, Santa Cruz.

Description of Study Area

The study area is located between RM 2 and 5 of the Boise River near Parma, Idaho (fig. 1). This reach of river is in the downstream portion of the 1,290-mi^2 lower Boise River basin. Approximately 432,000 people (about 33 percent of Idaho's total population) live within the basin (U.S. Census Bureau, 2002), which is a 46 percent increase over the 1990 population for this area.

In 1994, land use in the lower Boise River basin was approximately split between agriculture and rangeland with less than 5 percent of the land being used for urban or residential purposes. Crops grown in the basin included alfalfa hay and seed, corn and corn seed, wheat, potatoes, onions, sugar beets, barley, spearmint and peppermint, and dry edible beans (Koberg and Griswold, 2001). Since 1994, land use in the basin has shifted from farmland to residential areas, and residential areas in and near cities are being converted to businesses, parking lots, and right of ways resulting in an increase in the amount of impervious surface in the basin.

The basin is semiarid, with the majority of the surface water originating in the upper Boise River basin (fig. 1). The upper Boise River basin contains three reservoirs that assist in the control of flow in the Boise River. Lucky Peak Lake lies farthest downstream, and it separates the upper Boise River basin from the lower Boise River basin. Other factors influencing the flow in the Boise River are inputs from major tributary streams, irrigation withdrawals and return flows, and seepage of shallow ground water (Thomas and Dion, 1974).

Aquifer Description

The sediments that comprise the modeling study area along the lower Boise River are Quaternary Alluvium composed of sandy pebble gravels (Othberg and Stanford, 1992). The ground water is recharged primarily from the surface as precipitation, irrigation seepage, or stream channel losses (Petrich and Urban, 2004). Slug tests conducted for this study on shallow piezometers indicated hydraulic conductivity values ranging from less than 1 to 360 ft/d. The wide range of hydraulic conductivity values indicates a large heterogeneity in subsurface sediments and the presence of silt or clay lenses in the subsurface.

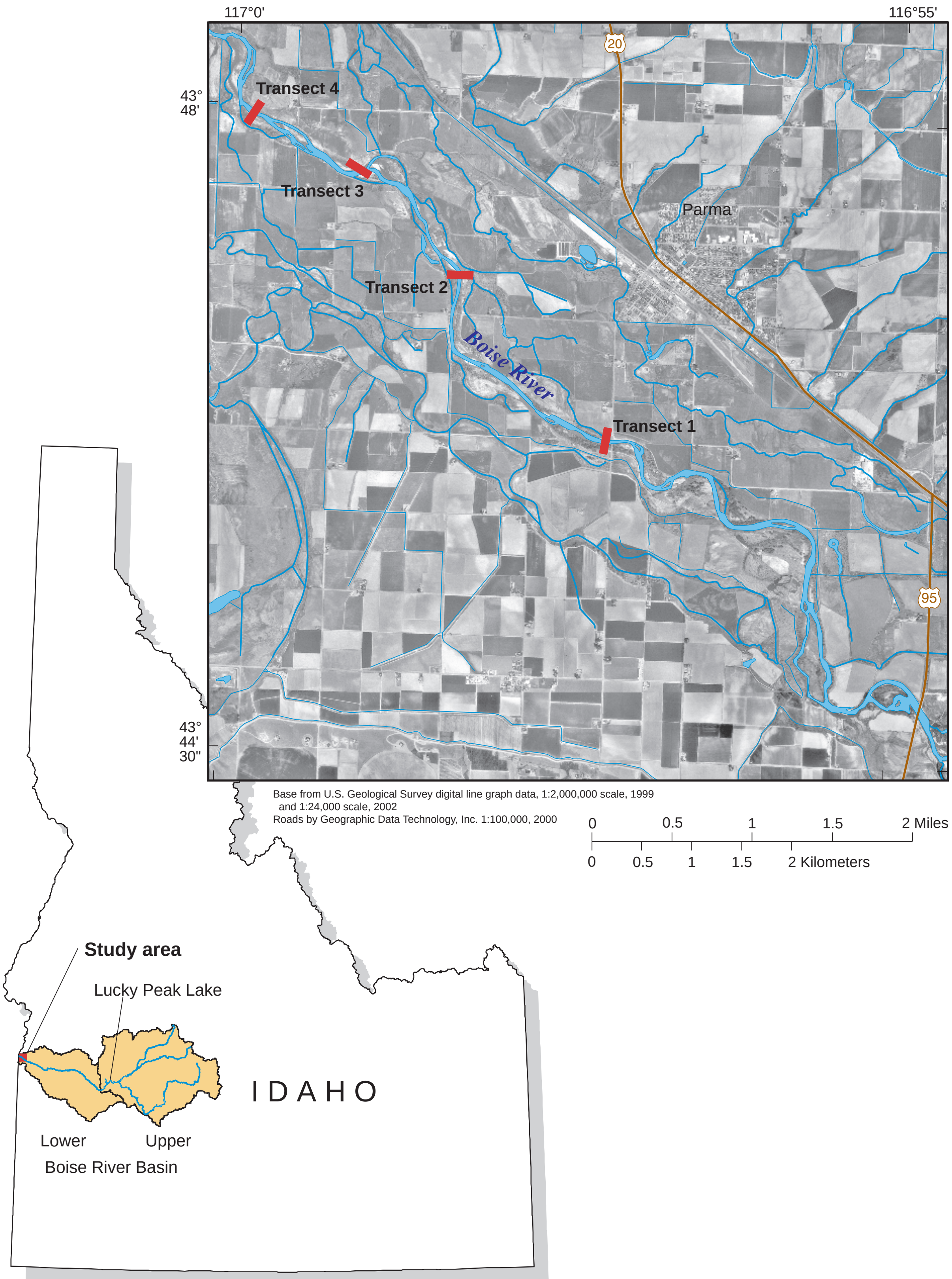


Figure 1. Location of study area in the Lower Boise River, Canyon County, Idaho.

Modeling Procedure and Data

Four transects were modeled to estimate seepage along the 3 river-mile reach of the Boise River (fig. 1). Each transect was represented by a two-dimensional VS2DI model. Due to data input limitations with VS2DI, five similar versions of the model were created for each transect, one for each month of the modeling period: April through August 2003. The ending conditions for the first model were copied into the following month's model as initial conditions. The transfer of a model's ending conditions to the following model's initial conditions continued for the remaining model periods (modeling procedure is explained in detail under specific sections below).

Field Data Collection

Three categories of field data were collected for input into the modeling software to estimate ground- and stream-water seepage: (1) hydraulic conductivity of the subsurface sediments via slug tests, (2) monthly ground-water head and stream stage values, and (3) temperature measured at various depths and locations throughout the transect. These data were measured in various piezometers installed at each of the four transects.

As many as seven piezometers were installed at each of the four transects along the lower Boise River near Parma. One piezometer was installed in the center of the stream, one near each bank in the stream, one on each bank, and another installed a short distance from each bank of the stream (fig. 2). The piezometers were installed to a depth of 5.5 ft below the deepest part of the stream within each transect, and they were then surveyed to verify installation to the correct depth. Piezometers range in length from 8 to 16 ft, with buried lengths from 6 to 15 ft. The near bank and bank piezometers labeled B, C, E, and F in figure 2 were constructed of 1.25 inch diameter steel pipe with the bottom of the pipe pinched off to form a drive point. Above the drive point, the steel pipe was punched with holes on four opposite sides along a 6-inch length to allow water flow in and out of the piezometer. The other three piezometers labeled A, D, and G in figure 2 were created similarly, but from 0.75-inch diameter steel pipe. Each piezometer was developed after installation by pumping several bore volumes of water out of the piezometer.

It was possible to install all seven piezometers only at transect two; however, piezometer D in transect 2 was destroyed by high water flows early in the study period. Several attempts were made to install piezometer G at transect 1, but these attempts failed because of pipe breakage from a possible old roadbed in the subsurface. Piezometer D in transect 1 was destroyed in August. The river at transect 3 was too deep to install a center stream piezometer (D), and lack of access at transect 4 prevented the installation of piezometer G in that transect. Data loss because of the missing piezometers was limited to water-level measurements; compensations were made in the seepage modeling.

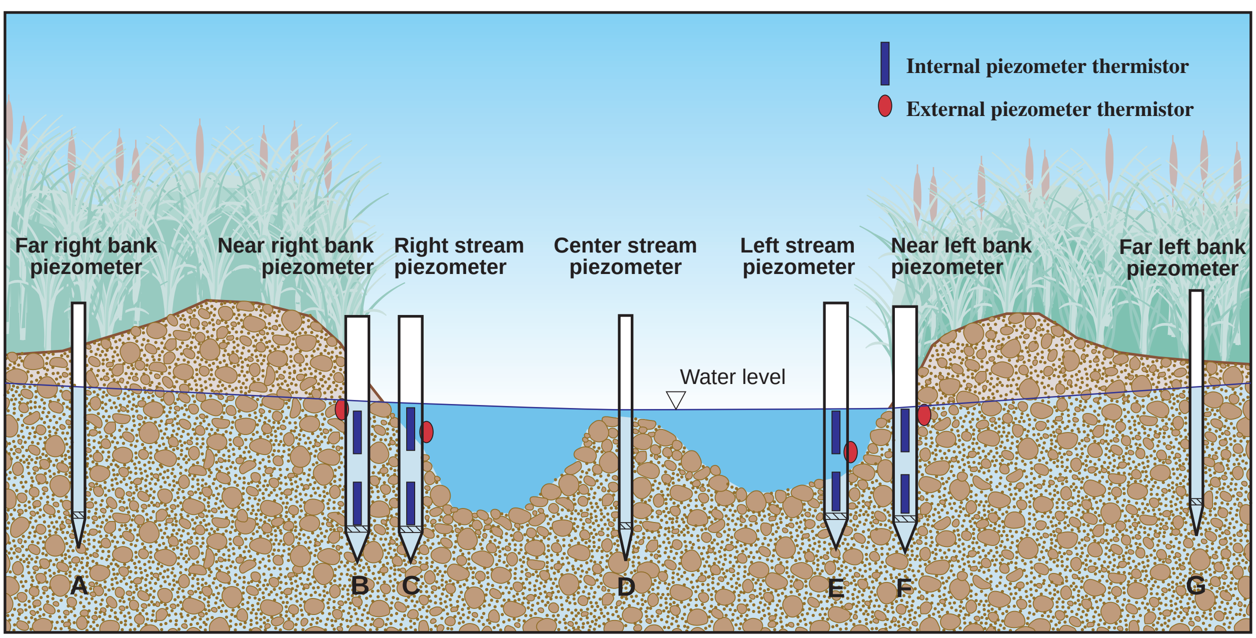


Figure 2. Schematic of piezometer installation, viewing the stream cross-section upstream.

Slug Tests

Slug tests were conducted in the near-bank piezometers (piezometers B, C, E, and F) to estimate saturated hydraulic conductivity of the near-surface fluvial sediments. The slug test estimate of saturated hydraulic conductivity actually represents a small volumetric area around the perforated section of the piezometer The same method was used to perform all of the slug tests. Water levels for each slug test were measured with an In-situ mini-troll pressure transducer placed just above the perforated section of the piezometer. The pressure transducer has a 30-lb/in^2 (equivalent to a 69-foot change in water level) range with an accuracy of ±0.02 percent full scale. The water level in the piezometer was measured with a calibrated electric tape, and was then programmed into the mini-troll. During the slug test, water levels were measured by the mini-troll every 0.50 second and were downloaded to a computer for analysis following the slug test.

To simulate an instantaneous injection of water, a bucket of water was used to fill the piezometer. Average time to fill the piezometer with water was approximately 1–3 seconds. The computer software AQTESOLV (Duffield, 2000) was used to analyze the slug tests. AQTESOLV provides three different slug-test solutions for unconfined aquifers: the Hvorslev (1951), Bouwer-Rice (1976), and KGS (Hyder and others, 1994). All three tests were used to analyze the slug-test data. Manual adjustments were made after automatic curve fits by AQTESOLV. The KGS model is more appropriate for sediments with high hydraulic conductivities similar to those found in most of the study area. Multiple tests were conducted on each piezometer to narrow variability with the slug-test analysis. The slug-test results are listed in table 1, with the piezometer name denoted by the transect number and piezometer letter. For example, piezometer E of transect 3 is labeled T3E. Slug-test estimates of saturated hydraulic conductivity ranged from less than 1 to 360 ft/d.

Table 1. Results of slug tests performed in near-bank piezometers in four transects of the lower Boise River, Canyon County, Idaho, 2003.

[Method of analyses: Bouwer-Rice (1976); Hvorslev (1951); KGS, Hyder and others (1994). Abbreviations: ft/d, foot per day]

Piezometer	Test No.	Saturated hydraulic conductivity (ft/d)	Method of analysis
T1B	1	121	Bouwer-Rice
	2	68	Bouwer-Rice
	3	70	Bouwer-Rice
	1	124	Hvorslev
	2	77	Hvorslev
	3	79	Hvorslev
	1	63	KGS
	2	70	KGS
	3	68	KGS
T1C	1	70	Bouwer-Rice
	2	66	Bouwer-Rice
	3	70	Bouwer-Rice
	1	80	Hvorslev
	2	76	Hvorslev
	3	81	Hvorslev
	1	72	KGS
	2	71	KGS
	3	81	KGS
T1E	1	139	Bouwer-Rice
	2	128	Bouwer-Rice
	3	134	Bouwer-Rice
	4	134	Bouwer-Rice
	5	130	Bouwer-Rice
	1	159	Hvorslev
	2	152	Hvorslev
	3	159	Hvorslev
	4	159	Hvorslev
	5	154	Hvorslev
	1	142	KGS
	2	130	KGS
	3	145	KGS
	4	142	KGS
	5	146	KGS
T1F	1	4	Bouwer-Rice
	2	1	Bouwer-Rice
	1	4	Hvorslev
	2	1	Hvorslev
	1	4	KGS
	2	2	KGS
T2B	1	128	Bouwer-Rice
	2	142	Bouwer-Rice
	3	148	Bouwer-Rice
	4	124	Bouwer-Rice
	1	146	Hvorslev
	2	171	Hvorslev
	3	169	Hvorslev
	4	150	Hvorslev
	1	117	KGS
	2	113	KGS
	3	114	KGS
	4	111	KGS
T2C	1	95	Bouwer-Rice
	2	97	Bouwer-Rice
	3	95	Bouwer-Rice
	4	93	Bouwer-Rice
	1	120	Hvorslev
	2	118	Hvorslev
	3	114	Hvorslev
	4	112	Hvorslev
	1	93	KGS
	2	93	KGS
	3	95	KGS
	4	95	KGS

Table 1. Results of slug tests performed in near-bank piezometers in four transects of the lower Boise River, Canyon County, Idaho, 2003—Continued.

[Method of analyses: Bouwer-Rice (1976); Hvorslev (1951); KGS, Hyder and others (1994). Abbreviations: ft/d, foot per day]

Piezometer	Test No.	Saturated hydraulic conductivity (ft/d)	Method of analysis
T2E	1	42	Bouwer-Rice
	2	44	Bouwer-Rice
	3	46	Bouwer-Rice
	4	48	Bouwer-Rice
	1	50	Hvorslev
	2	53	Hvorslev
	3	54	Hvorslev
	4	55	Hvorslev
	1	45	KGS
	2	48	KGS
	3	48	KGS
	4	51	KGS
T2F	1	293	Bouwer-Rice
	2	295	Bouwer-Rice
	3	310	Bouwer-Rice
	4	285	Bouwer-Rice
	1	342	Hvorslev
	2	343	Hvorslev
	3	362	Hvorslev
	4	332	Hvorslev
	1	238	KGS
	2	237	KGS
	3	251	KGS
	4	228	KGS
T3B	1	61	Bouwer-Rice
	2	66	Bouwer-Rice
	1	71	Hvorslev
	2	78	Hvorslev
	1	60	KGS
	2	66	KGS
T3C	1	46	Bouwer-Rice
	2	45	Bouwer-Rice
	3	44	Bouwer-Rice
	4	44	Bouwer-Rice
	1	54	Hvorslev
	2	52	Hvorslev
	3	52	Hvorslev
	4	51	Hvorslev
	1	48	KGS
	2	46	KGS
	3	47	KGS
	4	45	KGS
T3E	1	185	Bouwer-Rice
	2	197	Bouwer-Rice
	3	195	Bouwer-Rice
	4	193	Bouwer-Rice
	1	225	Hvorslev
	2	219	Hvorslev
	3	226	Hvorslev
	4	225	Hvorslev
	1	175	KGS
	2	151	KGS
	3	148	KGS
	4	159	KGS

Piezometer	Test No.	Saturated hydraulic conductivity (ft/d)	Method of analysis
T3F	1	222	Bouwer-Rice
	2	235	Bouwer-Rice
	3	231	Bouwer-Rice
	4	229	Bouwer-Rice
	1	248	Hvorslev
	2	275	Hvorslev
	3	259	Hvorslev
	4	257	Hvorslev
	1	164	KGS
	2	155	KGS
	3	146	KGS
	4	168	KGS
T4B	1	8	Bouwer-Rice
	2	3	Bouwer-Rice
	3	5	Bouwer-Rice
	1	10	Hvorslev
	2	3	Hvorslev
	3	5	Hvorslev
	1	9	KGS
	2	4	KGS
	3	4	KGS
T4C	1	0	Bouwer-Rice
	2	0	Bouwer-Rice
	1	1	Hvorslev
	2	0	Hvorslev
	1	1	KGS
	2	0	KGS
T4E	1	167	Bouwer-Rice
	2	179	Bouwer-Rice
	3	177	Bouwer-Rice
	4	172	Bouwer-Rice
	5	178	Bouwer-Rice
	1	192	Hvorslev
	2	207	Hvorslev
	3	204	Hvorslev
	4	198	Hvorslev
	5	206	Hvorslev
	1	149	KGS
	2	128	KGS
	3	158	KGS
	4	145	KGS
T4F	1	46	Bouwer-Rice
	2	54	Bouwer-Rice
	3	62	Bouwer-Rice
	4	64	Bouwer-Rice
	1	53	Hvorslev
	2	63	Hvorslev
	3	72	Hvorslev
	4	73	Hvorslev
	1	47	KGS
	2	53	KGS
	3	61	KGS
	4	63	KGS

Ground-Water Head and Stream-Stage Measurements

Monthly ground-water head measurements were conducted in all piezometers at each transect during the study period. Stream stage was measured at the same time as the ground-water head measurements by using a stilling well near a piezometer at each transect. Because each transect is located below a straight stretch of the river, stage mounding was not a concern. With the piezometers at each transect installed to the same depth, ground-water head measurements provide information on the horizontal hydraulic gradient. Comparisons between the ground-water head measurements and stream stage determines the relation between the two (gaining or losing stream) because the river and aquifer are in direct communication.

Elevations of the piezometers at transects 1, 3, and 4 were established using an arbitrary datum because only relative differences between the head and stage measurements were required. A known elevation datum was located near transect 2 so the head and stage values are based on actual elevations.

The ground water and river are hydraulically connected in this area throughout the season as indicated in figures *3A-D*. Head measurements in piezometers in the stream are very close to the stream stage, whereas head values in distant piezometers have a greater range than the stream stage. Transects 1, 3, and 4 were gaining streams, with varying vertical hydraulic gradients throughout the study period (figs. *3A*, *3C*, and *3D*). Transect 2 was a losing stream during April, and then became a flow-through reach for the remainder of the study period. Transect 2 showed a hydraulic gradient from the east to the west, or from piezometer A to G (fig. *3C*). Transect 4 also has an increasing horizontal gradient from the south to the north, or from piezometer F to A (fig. *3D*).

Temperature Data

The near-bank piezometers (B, C, E, and F) were each equipped with two continuous recording temperature thermistors installed at 1 and 5 ft from the bottom of the piezometers (fig. 2). One additional thermistor was either attached to the outside of the piezometer at the bottom of the stream for the instream piezometers, or was buried several inches below the bank surface for the piezometers installed on the banks. The external piezometer thermistor (StowAway TidbiT Temp Logger) and the internal piezometer thermistor (Optic StowAway Temp) are both made by the Onset Computer Corporation, Pocasset, Massachusetts. They measure temperature to within ± 0.4°C and record temperature within a range of -0.5° to 37°C. The thermistors were set to record temperature at hourly intervals from March 19, 2003 until retrieved on October 31, 2003. The temperature data for the upper interior thermistor in piezometer E of transect 1 could not be retrieved due to a malfunctioning thermistor. The temperature data were used primarily for the VS2DI modeling.

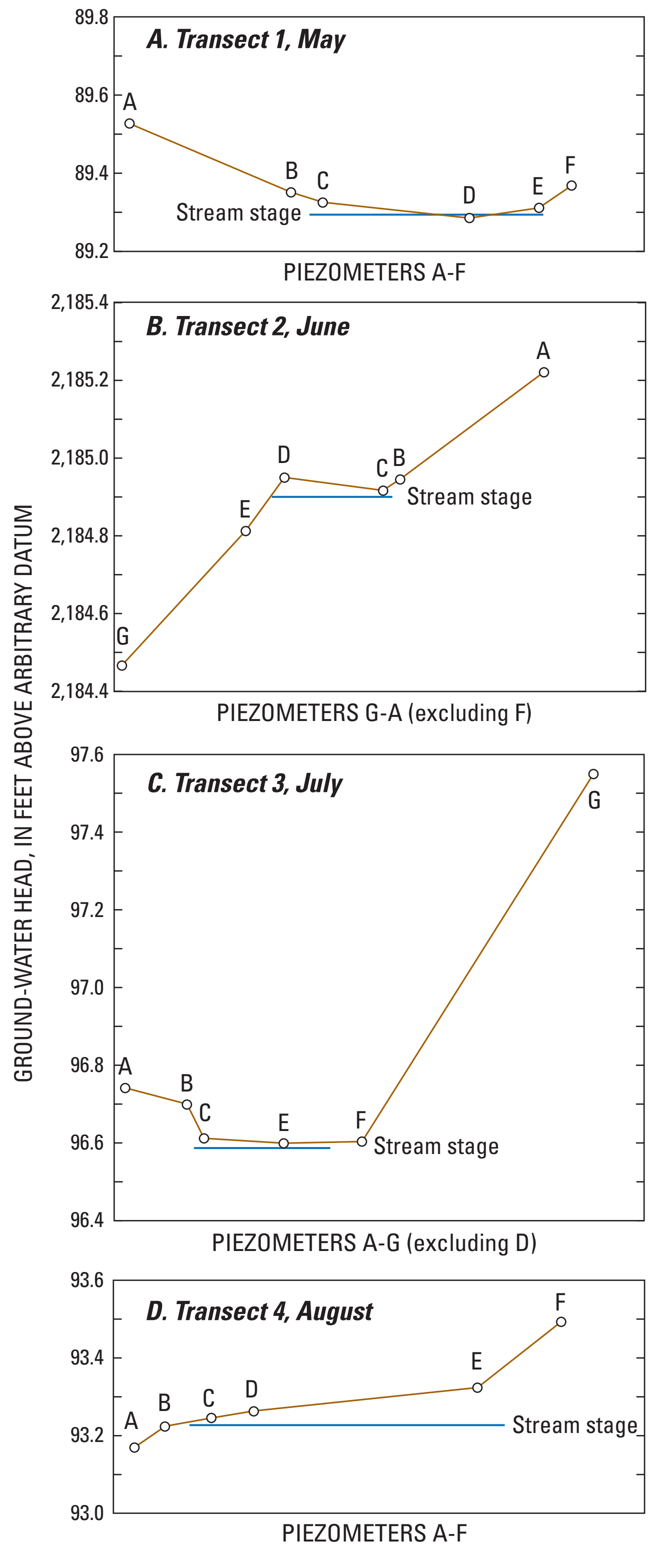


Figure 3. Stream stage and ground-water head measured in transects 1-4, Lower Boise River, Canyon County, Idaho, May to August 2003.

Seepage Modeling (VS2DI)

VS2DI (Hsieh and others, 2000) is a graphical software package for modeling flow and transport in a variably saturated porous media. VS2DI contains a preprocessor that enables easy input of data into the software, a postprocessor (VS2POST) that enables viewing of previous simulation runs, and the numerical model VS2DH (Healy and Ronan, 1996). VS2DH is a two-dimensional, variably saturated, ground-water flow model that has been modified to simulate heat transport by advection and conduction; it uses the advective-dispersion equation to model energy transport (Healy, 1990).

Model Setup

Setting up the two-dimensional VS2DI model involves defining model options, textural classes, initial conditions, and boundary conditions for each recharge period. VS2DI defines a recharge period as a period of time during which model conditions and stresses do not change. Once the model is set up, it can be run either by using the VS2DI postprocessor for a graphical display of the model run, or by running the VS2DH model directly from the command line. A thorough explanation of VS2DI model setup and usage is available in Hsieh and others (2000) and Stonestrom and Constantz (2003).

VS2DI model options include settings to specify the flow and transport processes, computational algorithm, and model output. All models were set up with the same options; for example, the use of metric units, hydraulic characteristic functions defined by the van Genuchten model, and numerical model solver options.

Textural Classes

Textural classes must be defined for the entire area of the VS2DI models. Textural classes define the hydraulic and transport properties of the medium such as, porosity, saturated hydraulic conductivity, and the vertical to horizontal ratio of saturated hydraulic conductivity (hence referred to as the anisotropy ratio). A textural class was defined for the region around the piezometers at which slug tests were performed (piezometers B, C, E, and F). Saturated hydraulic conductivity values were then assigned to the textural class according to the slug-test results. For adjacent piezometers with similar saturated hydraulic conductivity values, one textural class was defined for that region instead of two. The textural classes encompassed an area approximately 6 ft below the piezometers, and the upper area of the model was divided between the slug-test defined textural classes. The lower and outer areas of the VS2DI model were assigned a general, predefined textural class (representative of medium sand) that was provided with the VS2DI modeling software.

Boundary Conditions

Boundary conditions are required for each recharge period of the model. All models used a recharge period of 1 hour. Surface boundaries representing the stream-subsurface interface were assigned a specified total head flow boundary condition of the measured head value from the stream-stage measurement. Other surface boundaries were assigned a no-flow boundary condition. The vertical or side-flow boundary conditions were set to the head measurement from the nearest piezometer, and the lower boundary was set to the difference between the two side boundary conditions. VS2DI also allows for flux or seepage-face flow boundary conditions, but these conditions were not applicable to this modeling study. Surface-transport boundary conditions were set using the upper or external temperature from the nearest measured piezometer, while the vertical or side-transport boundary conditions were interpolated from the deepest temperature measurements in the piezometers. The transport boundary condition for the lower boundary was set at a temperature of 14.5°C, which represents the average ground-water temperature in the study area at a depth of 50 ft.

A linear trend for ground-water head and stage values was used to interpolate the actual measurements because continuous measurements were not available. A linear regression comparing the stage measurements at each of the four transects and stage data for the USGS gaging station on the Boise River near Parma (13213000) resulted in good correlations for two of the transects. Stage values derived from the regression analysis were tested in modeling transect three, which had the best R^2 value. However, modeling results were not substantially improved; therefore, the linear interpolated values were used for all models to maintain consistency between the models.

Model Discretization

The VS2DH grids have a 1.5-meter horizontal spacing and a 0.5-meter vertical spacing. Each model represents a two-dimensional cross section of the stream oriented vertically. The vertical grid spacing was decreased to 0.25 m for the 3-meter model area below the stream bottom. The total grid depth was 15 m and the total width was 150 m.

Initial Settings

The VS2DH models require initial conditions for the hydraulic condition and temperature of the model area. The initial hydraulic condition was set to the model option of ‘initial equilibrium profile’, which is defined as the pressure head equaling the negative elevation head above the water table. This value was determined by taking the mean water level of the seven piezometers at a transect. The total difference in head between the seven piezometers was typically about 3–4 in.

The initial temperature for the model is input by drawing temperature contours. The contours were interpolated from the temperature measurements. The first model of each transect was simulated for an extra initial 10 days (240 recharge periods) to allow the models to stabilize with the boundary conditions. After the first model of each transect was completed, the ending temperature data were then entered into the following month's model run as the initial temperature.

PEST

Slug tests estimate the saturated hydraulic conductivity for a small volumetric area around the perforated section of a piezometer. However, the slug-test area represents a very small portion of the textural classes in VS2DI models. The slug tests provide a starting point for estimating saturated hydraulic conductivities, but additional estimation is necessary to represent the full area of each textural class in the VS2DI models.

The Parameter ESTimation code, or PEST (Doherty, 2004), was used to refine the slug-test estimate for the saturated hydraulic conductivity and to estimate the anisotropy ratio for the textural classes in the VS2DI models. PEST exists independently of the VS2DI software and adjusts the two parameters using the Gauss-Marquardt-Levenberg optimization algorithm (Doherty, 2004). PEST automatically reruns the VS2DH models until the objective function is minimized in a weighted least-squares sense using the measured and simulated temperatures. The initial value of the anisotropy ratio was set to 0.5, and the saturated hydraulic conductivity initial value came from the slug-test estimates. PEST allows the user to set the range within which the parameters can be altered. The saturated horizontal hydraulic conductivity was allowed to adjust within the range of 1×10^{-6} to 1×10^{-2} m/s and the saturated vertical to horizontal anisotropy ratio had a range of 0.1 to 1.

Modeling Results

PEST Results

Each monthly VS2DH model's saturated hydraulic conductivity and anisotropy ratio was optimized with PEST based on simulated and measured subsurface temperatures. The results varied greatly between a single transect's monthly model runs for saturated hydraulic conductivity and the anisotropy ratio. Saturated hydraulic conductivity values varied from month to month at one transect as much as three orders of magnitude from the slug-test estimate, and some anisotropy ratio estimates varied the entire allowed range from 0.1 to 1.

Based on PEST results and visual interpretations of the simulated and measured temperature comparisons, saturated hydraulic conductivity was adjusted within an order of magnitude of the slug-test estimate. A single value of saturated hydraulic conductivity was chosen for each textural class for the entire modeling period. Anisotropy values were chosen following the same methodology within the range of acceptable values for the area (0.1–1).

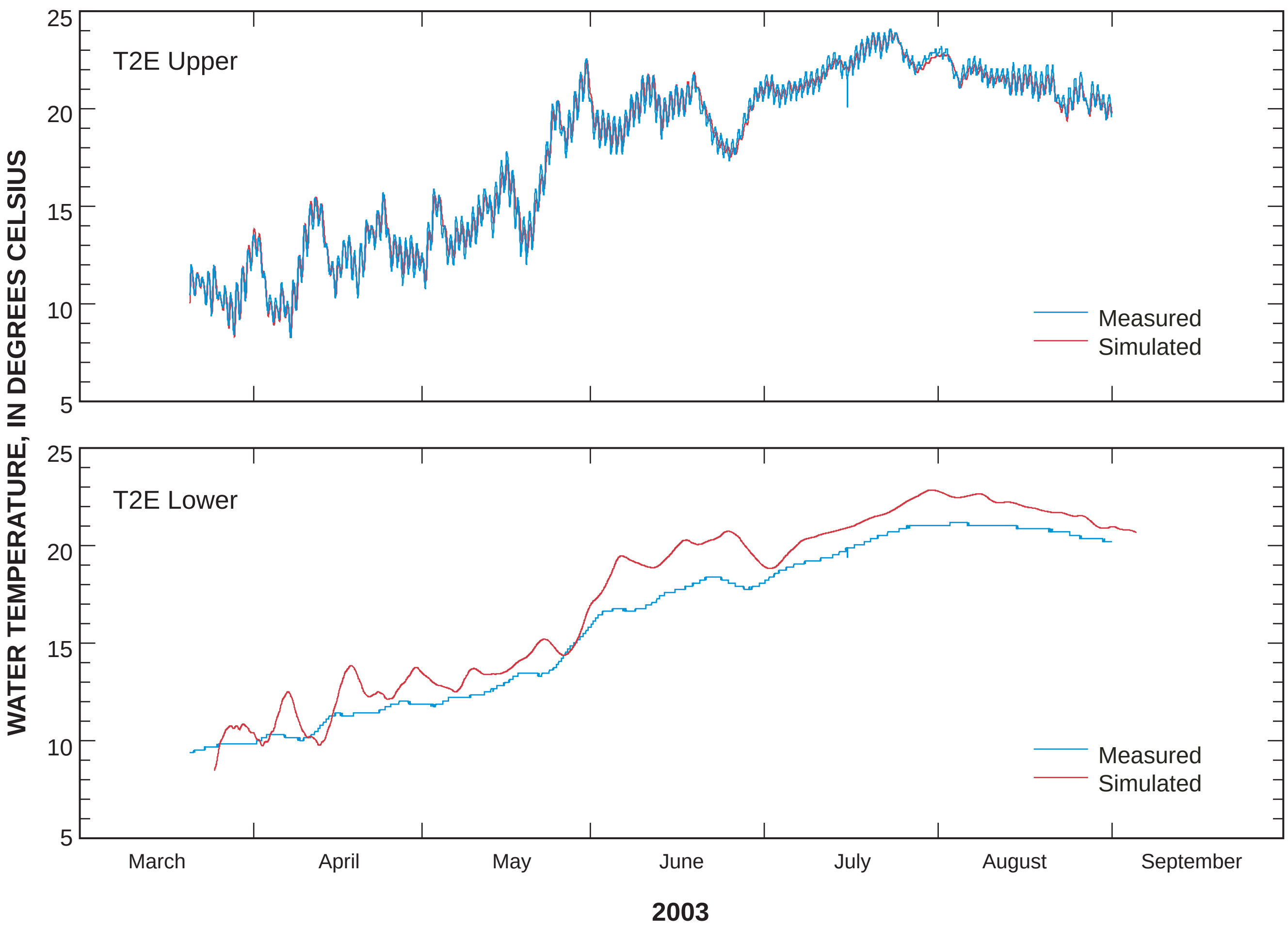
VS2DI Modeling Results

Because VS2DI models heat transport, comparisons between measured and simulated subsurface temperatures are the primary indication of model accuracy. Differences between the temperature comparisons are typically less than 2°C, with a range of 0–5°C (figs. 4*A-B*). As noted earlier, the PEST modeling results were used to update saturated hydraulic conductivity and the anisotropy ratio. Using simulated and measured temperature differences, additional modifications in the saturated hydraulic conductivity and anisotropy ratio were made. For example, an increase in the saturated hydraulic conductivity increases the amplitude of the simulated temperature to match the measured temperature variation, while decreasing the anisotropy ratio prevents the increased temperature amplitude from propagating to the simulated subsurface temperature.

Another evaluation of model performance is to compare measured and simulated head values. Simulated ground-water head information was exported along with the temperature data at piezometers B, C, E, and F. The field measured head values were then subtracted from the simulated head values with corresponding dates and times (table 2) to determine

Table 2. Measured minus simulated ground-water head measurements in near-bank piezometers in four transects of the lower Boise River, Canyon County, Idaho, 2003.

Transect	Piezometer	Month				
		April	May	June	July	August
1	B	0.59	0.51	0.47	0.40	0.51
1	C	.61	.44	.41	.33	.46
1	E	.80	.57	.58	.79	.60
1	F	.75	.59	.74	.83	.73
2	B	.24	.02	-.03	.08	.02
2	C	.60	.04	.00	.09	.06
2	E	.13	-.00	-.04	.03	.03
2	F	.39	.15	.21	.17	.25
3	B	.05	.47	.17	.13	.25
3	C	.13	.40	.21	.18	.25
3	E	.18	.35	.20	.21	.22
3	F	.33	.78	.46	.47	.59
4	B	1.43	1.47	1.44	1.47	2.24
4	C	1.01	.98	.98	1.02	1.72
4	E	.76	.79	.81	.79	1.56
4	F	.83	.74	.81	.73	1.72



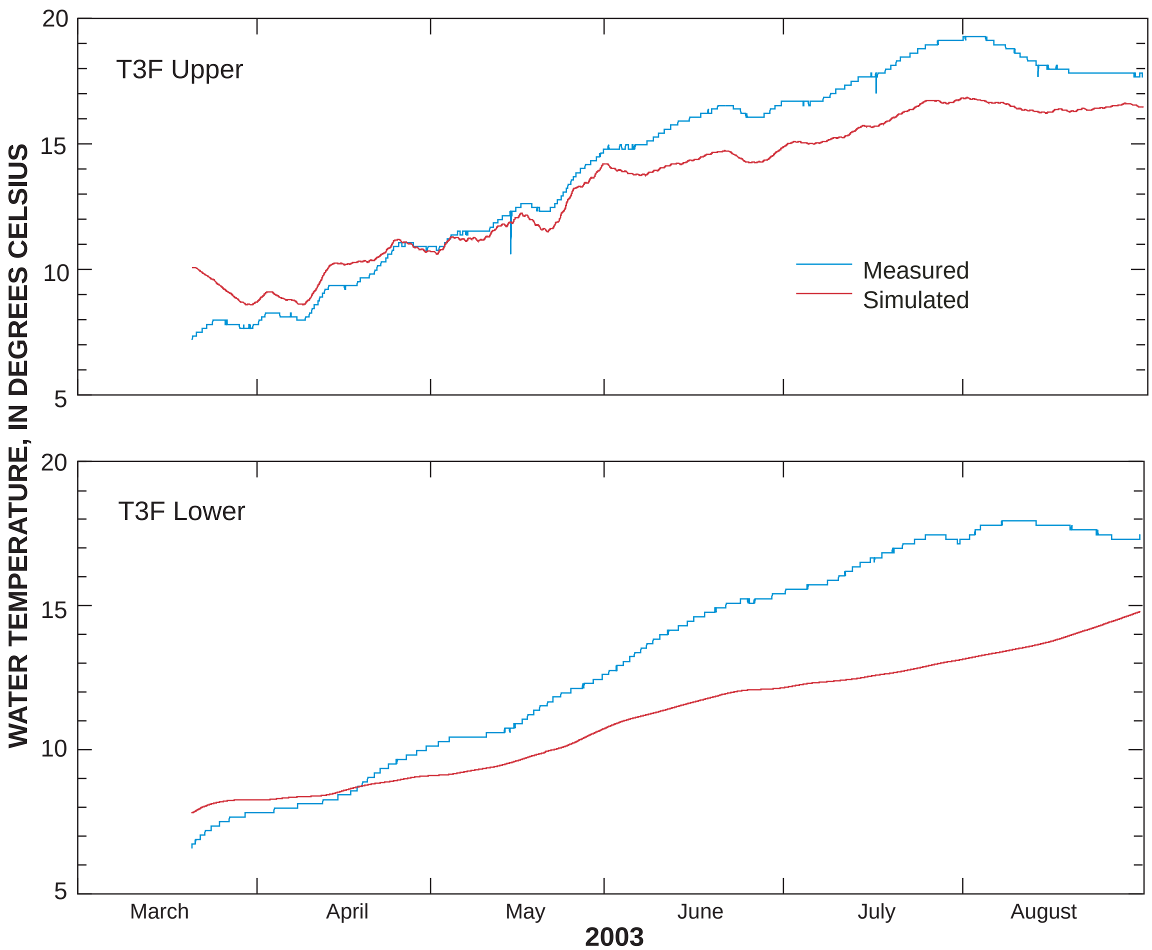
A. Piezometer E (Instream), Transect 2.

Figure 4 Upper and lower measured and simulated water temperatures for piezometer E (Instream),transect 2 and piezometer F (far bank),transect 3, lower Boise River, Canyon County, Idaho, April – August 2003.

simulated head errors. The simulated heads were greater than the measured heads except for a couple of instances for the model of transect 2. Transect 2 had the smallest head differences at less than 0.25 ft, followed by transect 3 at about 0.25 ft. Transects 2 and 3 have the best estimates of seepage according to their low simulated and measured head differences. Transect 3's head differences were about 0.5 ft, and transect 4 was the worst at about 1 ft head difference between the simulated and measured.

Seepage Estimates

The objective of the modeling is to estimate the flux between ground water and surface water within a 3 river-mile reach of the lower Boise River. The VS2DI software estimates the total seepage (or flux) of water through the model for every hourly recharge period and the total seepage for the entire model run. However, the VS2DI models estimate seepage for the entire model area, not just within specific boundaries (i.e., only the streambed boundary). As



B. Piezometer F (far bank), transect 3.

Figure 4.—Continued.

head measurements indicate, there is a horizontal gradient of ground water through each transect. The horizontal gradient precludes using the seepage estimates provided by VS2DI because they would include ground water flowing in from one side of the model and out the other.

An alternative method for determining seepage using the Darcy equation was identified by using the ground-water velocities for each model grid cell along the streambed. VS2DH can export horizontal and vertical ground-water velocities for each grid cell and recharge period. The vertical ground-water velocities at each grid cell along the streambed of the model were multiplied by the grid cell's cross-sectional area to determine a volume flux per time (cubic feet per second [ft^3/s]) through the unit width (1 meter) modeled streambed. The volumes were then summed to get a total flux per time for the portion of the transect that interacts with the streambed. The resultant flux estimate is expressed in units of (ft^3/s)/m, which were then converted to (ft^3/s)/mi for comparison with previous studies.

The seepage-rate estimates (fig. 5) are primarily controlled by the relation between the ground-water head and stream stage. A linear change in the simulated seepage occurs between the times the ground-water head and stream stage values were measured. Breaks in the seepage estimates, most visible in transect 2, indicate the transition from one month's model to the next (fig. 5). Even though all the ending conditions from one month's model are copied into the beginning conditions of the next month's model, a short transition period still occurs.

Transect 2 was the only transect indicating a losing stream condition (that is, seepage from the stream into the ground water). However, due to the large simulated head errors in transect 4, seepage estimates for this transect are high. Therefore, an equilibrium or slightly losing stream condition could be within the error range. The seepage rates shown in figure 5 vary greatly from transect to transect. Seepage rate estimates range from 8 to 16 (ft^3/s)/mi for transect 1, gradually increasing throughout the modeling period. Transect 4 was similar to transect 1, with a seepage rate increasing from 6 to 14 (ft^3/s)/mi throughout the simulation period. Transect 2 was a losing reach with seepage from the river at a decreasing rate of 18 to 2 (ft^3/s)/mi. Transect 3 had the highest seepage rates to the river at 73 (ft^3/s)/mi. They all indicate a rising water table and/or a falling stream stage during the summer months.

One previous estimate of seepage in the lower Boise River was conducted during the non-irrigation season in November 1971 by comparison of discharge measurements throughout the river reach. Thomas and Dion (1974) estimated the seepage of ground water to the Boise River between the gaging stations at Notus (13212500) and Parma (13213000) to be an average of 3 ft^3/s. This estimate is for seepage due to seeps and very short drains, all of which come from ground water, Thomas and Dion (1974) conducted this study during a 3-day period when no water was being released from Lucky Peak Dam. The difference between discharge measurements at the U.S. Highway 95 crossing of the Boise River and the gaging station at Parma was a gain of 43 ft^3/s from tributaries, diversions, and drains. This figure converts to an average gain of 10 (ft^3/s)/mi. A 1999 seepage study by Berenbrock (1999) in canals near this project's study area during June-July and again in September 1996 yielded seepage ranges of -10.3 to 3.52 (ft^3/s)/mi (negative values indicate a seepage from the river to ground water) with the late summer seepage values being less than those for early summer except for one location. Berenbrock (1999) also conducted seepage measurements during November 1996 in the Boise River near this project's study area with seepage rates of -3.9 to -3.1 (ft^3/s)/mi (fig. 6).

The previous estimates for seepage in the study area are based on seepage run estimates, which result in a seepage rate representative of an extended reach of a stream or canal. Seepage run estimates are determined by measuring all of the inflow and outflow surface-water discharges for a reach of stream. The difference between inflow and outflow is either seepage into the stream from ground water or out of the stream to ground water. The seepage rate estimates from VS2DI are

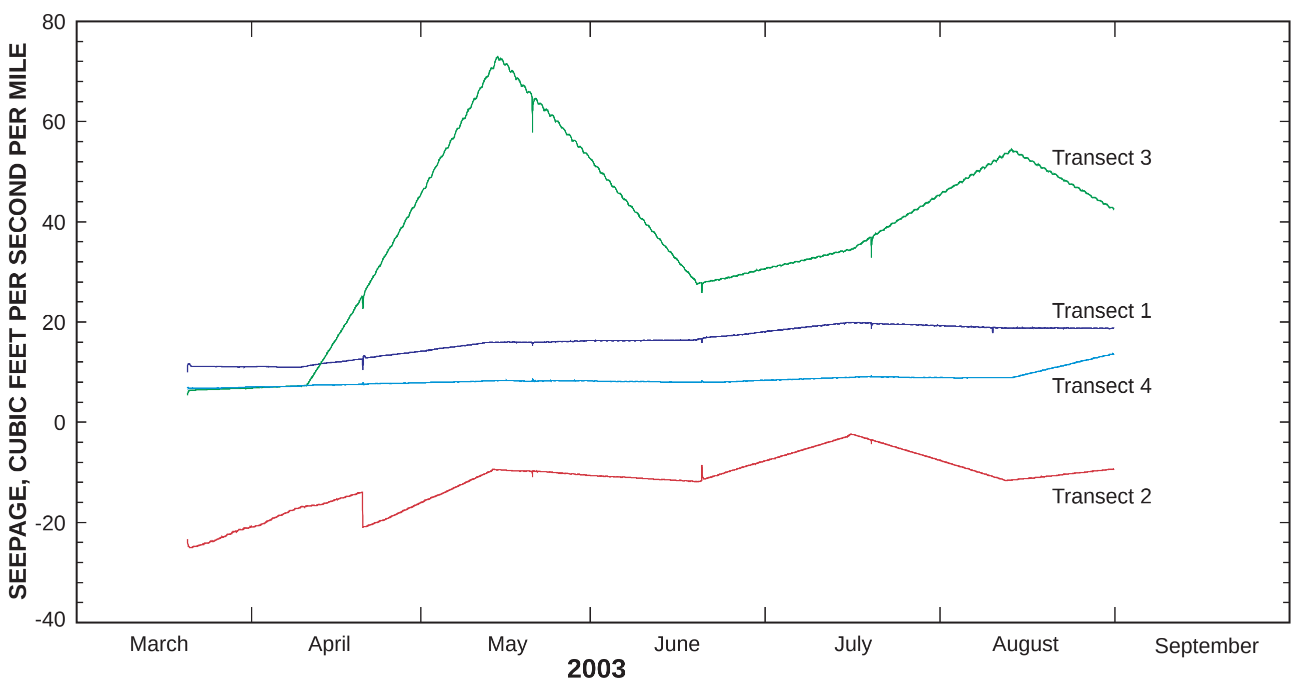


Figure 5. Seepage rate estimates for each of the four modeling transects, lower Boise River, Canyon County, Idaho, April – August 2003.

for transect locations on the stream with a unit width of one meter, and they are indicative of that short river reach only. Multiple VS2DI seepage estimates indicate the variability of seepage that occurs within an extended stream reach and how it varies over time. While the VS2DI seepage estimates show the variability of seepage throughout a stream reach, the variability makes it difficult to determine the total amount of seepage occurring in the entire stream reach. Although this variability creates uncertainty with respect to the extent to which measurements for one transect may be extrapolated over a stream reach, figure 6 shows all the reported seepage values for this and previous reports providing a comparative survey of reported seepage fluxes for this section of the lower Boise River.

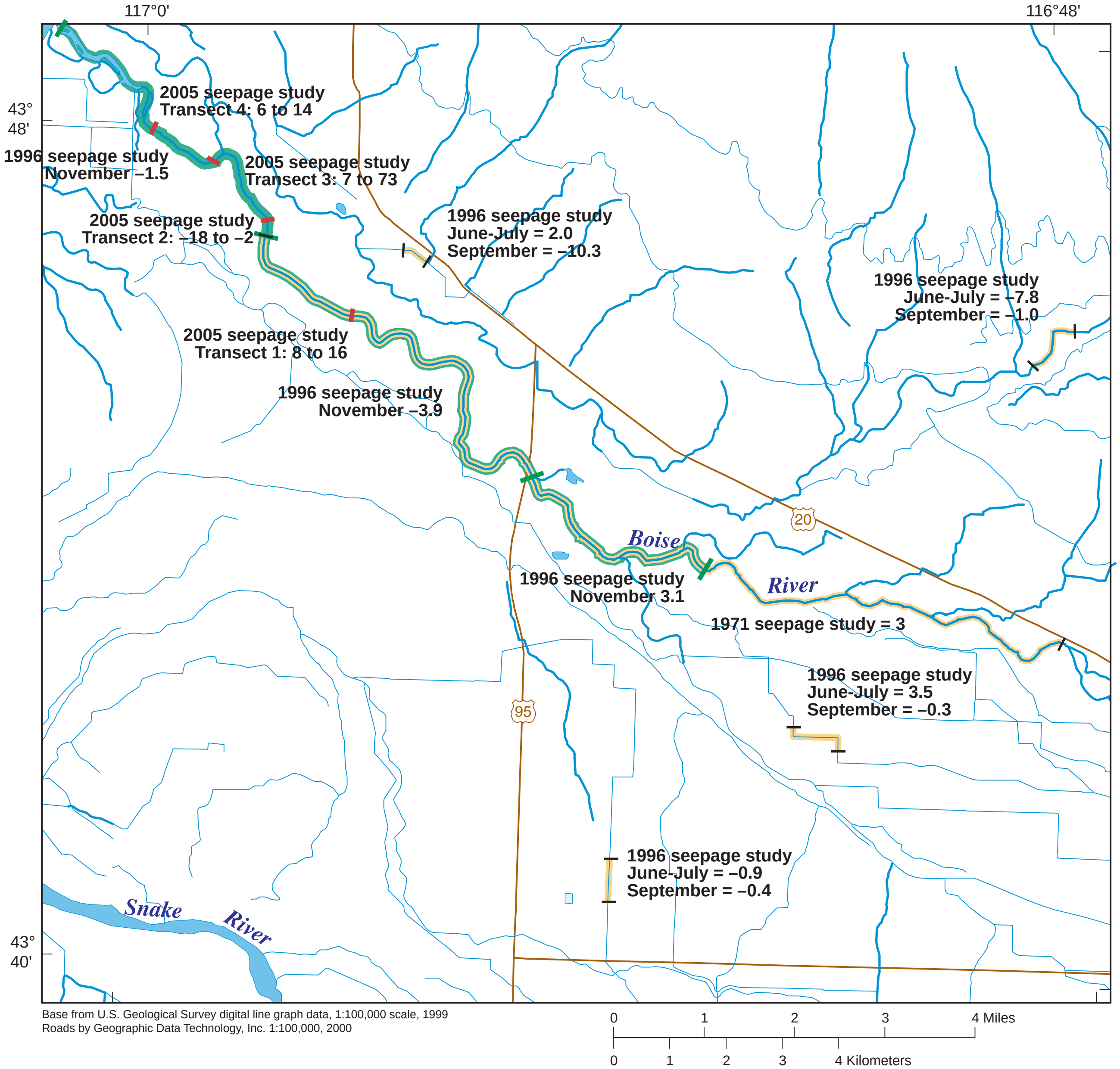


Figure 6. Location of three studies conducted on the lower Boise River with seepage estimates in cubic foot per second per mile for each study, Canyon County, Idaho.

Summary

Water quality in the lower Boise River has changed over time due to anthropogenic activities such as land-use changes, increased urbanization, and an altered flow regime in the Boise River. The lower Boise River was listed as water-quality limited in 1992 in accordance with Section 303(d) of the Clean Water Act. This listing required the development of a total maximum daily load (TMDL) management plan for the lower Boise River. The management plan includes TMDLs for nutrients, suspended sediment, bacteria, elevated water temperature, and low dissolved-oxygen concentrations.

A 2001 synoptic study estimated that as much as 150 pounds per day of the nutrient, dissolved phosphorus, from ground-water seepage was entering a 3-mile reach of the Boise River.

Results of the synoptic study indicated (1) the potential of significant seepage of nutrients to the lower Boise River from ground water, and (2) the need for a more focused study of ground-water and surface-water interaction. In 2003, this study was designed and implemented to identify and estimate seepage between ground water and the lower Boise River. Seepage estimates can potentially be used to help determine the approximate amount of nutrients being transported to or from the stream.

Water exchange between surface water and ground water affects temperatures not only in the two water resources, but also in the sediments near them. Therefore, analyses of subsurface temperature patterns provide information about surface-water and ground-water interaction. The USGS model VS2DI is a two-dimensional, variably-saturated, ground-water flow model that has been modified to simulate heat transport by advection and conduction. It was used to estimate seepage between ground water and surface water within a 3 river-mile reach of the lower Boise River. Two-dimensional models of four transects along this reach were modeled representing temperature and flow conditions from April to August 2003.

As many as seven piezometers were installed to the same depth at each of four transects along the lower Boise River near Parma. Hydraulic conductivity of the subsurface sediments was estimated using slug tests in the piezometers, monthly ground-water head and stream stage values, and continuous temperature was measured at various depths and locations in piezometers throughout the transect. The parameter estimation code, PEST, was used to refine two VS2DI model parameters: (1) saturated hydraulic conductivity, and (2) the horizontal to vertical saturated conductivity anisotropy ratio. Comparisons between simulated and measured temperatures and ground-water head measurements were used to evaluate the VS2DI models.

The VS2DI modeling resulted in a large variability of seepage estimates among the four transects. Models of three of the four transects resulted in seepage gains to the Boise River, with rates ranging from 6 to 73 ft^3/s. The model for the other transect resulted in losing stream conditions, or seepage from the river at rates of 2–18 ft^3/s. One of the benefits of VS2DI modeling is the ability to see how the seepage rates change over time. All models that resulted in gaining stream conditions showed an increasing trend of seepage to the river from April to August 2003. In the case of the losing stream transect, the seepage from the river decreased during the modeling period.

Previous estimates of seepage in the lower Boise River were conducted with a different technique using seepage runs. A seepage estimate during the non-irrigation season in November 1971 that included the upper one-half of the study area for this study estimated an average seepage of ground water to the Boise River of 3 $(ft^3/s)/mi$. A 1996 seepage study in canals near this project's study area during the pre- and post-irrigation season yielded seepage ranges of -10 to 4 $(ft^3/s)/mi$ (negative values indicate seepage from the river), with the late summer seepage values being less than those for early summer. Although these previous studies gave lower estimates of seepage to the Boise River than this study did, it should be noted that they were conducted over long stream or canal reaches. The seepage estimates from this study are focused at transects with a unit meter width, and they indicate the variability of seepage throughout the 3-mile river reach.

Future Considerations for Seepage Modeling

The VS2DH modeling could be improved by using continuous head recorders for both the piezometers and stream stage. At least one additional piezometer installed at depth would help to identify the vertical hydraulic gradient of the subsurface. Although VS2DH is not currently available in a three-dimensional format, three-dimensional modeling would improve seepage estimates for river reaches, thereby providing additional information beyond that available from two-dimensional transect models. SUTRA (Voss and Provost, 2002), a heat and ground-water transport model with three-dimensional capabilities, has been successfully applied using three-dimensional temperature and head data to examine surface-water/ground-water exchanges (Burow and others, 2005). However, three-dimensional modeling requires considerably more field data than two-dimensional modeling, which could affect the economic feasibility for this type of seepage modeling over a large river reach.

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Manuscript approved for publication, September 29, 2005
Prepared by the U.S. Geological Survey Publishing Staff

Publishing Service Center, Salt Lake City, Utah
Joe Gardner

Publishing Service Center, Tacoma, Washington
Linda Rogers
Sharon Wahlstrom

For more information concerning the research in this report, contact the
Idaho Water Science Center Director,
U.S. Geological Survey, 230 Collins Road
Boise, Idaho 83702-4520
http://id.water.usgs.gov

USGS Skinner **Estimating Streambed Seepage Using Heat as a Tracer on the Lower Boise River, Canyon County, Idaho** SIR 2005–5215