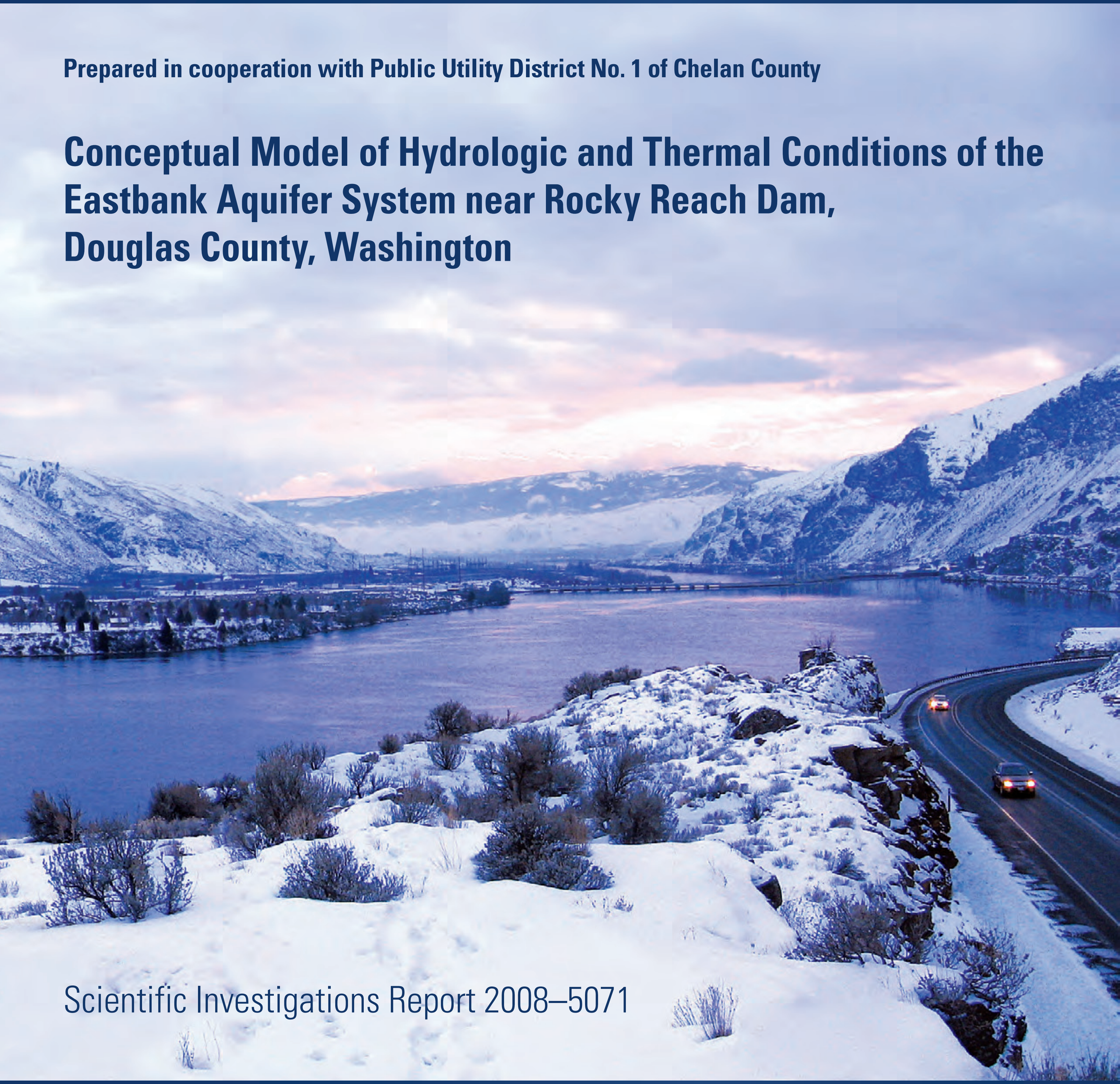
Prepared in cooperation with Public Utility District No. 1 of Chelan County

Conceptual Model of Hydrologic and Thermal Conditions of the Eastbank Aquifer System near Rocky Reach Dam, Douglas County, Washington



Scientific Investigations Report 2008–5071

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

Cover: Downstream view of Columbia River upstream of Rocky Reach Dam near Wenatchee, Washington. The Eastbank Aquifer system is located in the river-terrace deposit in the center-left of the picture on the front cover. Photograph by Marijke van Heeswijk, U.S. Geological Survey, January 27, 2008.

Conceptual Model of Hydrologic and Thermal Conditions of the Eastbank Aquifer System near Rocky Reach Dam, Douglas County, Washington

By Marijke van Heeswijk, Stephen E. Cox, Raegan L. Huffman, and Christopher A. Curran

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Suggested citation:
van Heeswijk, Marijke, Cox, S.E., Huffman, R.L., and Curran, C.A, 2008, Conceptual model of hydrologic and thermal conditions of the Eastbank Aquifer System near Rocky Reach Dam, Douglas County, Washington: U.S. Geological Survey Scientific Investigations Report 2008–5071, 66 p.

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Conversion Factors and Datums

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
section (640 acres or 1 square mile)	259.0	square hectometer (hm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

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

$$°F=(1.8\times°C)+32.$$

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Datums

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29), unless otherwise noted.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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

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Conceptual Model of Hydrologic and Thermal Conditions of the Eastbank Aquifer System near Rocky Reach Dam, Douglas County, Washington

By Marijke van Heeswijk, Stephen E. Cox, Raegan L. Huffman, and Christopher A. Curran

Abstract

The Lower and Combined Aquifers of the Eastbank Aquifer system, located in a river-terrace deposit along the Columbia River near Rocky Reach Dam, Washington, are primarily recharged by the Columbia River and provide water to the Eastbank Hatchery and the regional water system servicing the cities of Wenatchee, East Wenatchee, and parts of unincorporated Chelan and Douglas Counties. In 2006, mean annual pumpage from the aquifers by the hatchery and regional water system was about 43 and 16 cubic feet per second, respectively. Reportedly, temperatures of ground water pumped by the hatchery have been increasing, thereby making water potentially too warm for salmonid fish production. An evaluation of hourly ground-water and river temperatures from January 1991 through August 2007 indicates increasing interannual trends in temperatures in most of the Lower and Combined Aquifers from 1999 through 2006 that correspond to increasing trends in the annual mean and annual maximum river temperatures during the same period of 0.07 and 0.17°C per year, respectively. There were no trends in the annual minimum river temperatures from 1999 through 2006, and there were no trends in the annual minimum, mean, and maximum river temperatures from 1991 through 1998 and from 1991 through 2007. Increases in river temperatures from 1999 through 2006 are within the natural variability of the river temperatures.

Most of the Lower and Combined Aquifers reached thermal equilibrium—defined by constant time lags between changes in river temperatures and subsequent changes in ground-water temperatures—during 1991–98. The only exceptions are the Combined Aquifer north of the well field of the regional water system, which had not reached thermal equilibrium by 2006, and the Lower Aquifer west of the well fields of the hatchery and the regional water system, which reached thermal equilibrium prior to 1991. Because most of the Lower and Combined Aquifers were in thermal equilibrium from 1999 through 2006 and seasonal pumpage patterns were relatively stable, reported trends of increasing temperatures of water pumped by the hatchery well field are most likely explained by increasing trends in river temperatures. Most of the water pumped by the hatchery well field recharges in an area west to southwest of the well field about 2 months prior to the time it is pumped from the aquifer. The northern extent of the hatchery well field may pump some colder water from a bedrock depression to the north and west of the well field. The conceptual model of hydrologic and thermal conditions is supported by analyses of historical water temperatures, water-level data collected on July 18, 2007, and dissolved-constituent and bacterial concentrations in samples collected on August 20–22, 2007.

Introduction

The Eastbank Aquifer system is located in sedimentary deposits east of and adjacent to Rocky Reach Dam, which is a run-of-the-river hydroelectric dam on the Columbia River north of Wenatchee and East Wenatchee, Washington (fig. 1). Construction of the dam began in 1956 and the dam is owned and operated by Public Utility District No. 1 of Chelan County (PUD). By the time the dam was put into commercial operation in 1961, the water level of the Columbia River was raised from a natural low water level of about 610 ft (Stone and Webster Engineering Corporation, 1959) to a full-pool level of 707 ft. This rise formed a lake called Lake Entiat, which extends from Rocky Reach Dam upstream to Wells Dam (fig. 1). The water-level rise of the Columbia River similarly increased the saturated thickness of the Eastbank Aquifer system. As part of dam construction, a subsurface cutoff wall was constructed in the aquifer system (fig. 2) to minimize seepage around the eastern extent of Rocky Reach Dam and prevent destabilization of the east bank. This cutoff wall in effect acts as a “subsurface dam” and helps maintain elevated ground-water levels in the Eastbank Aquifer system to the north of the cutoff wall. The result is that the drop in ground-water levels from north to south of the cutoff wall is similar to the drop in river water levels from upstream to downstream of Rocky Reach Dam.

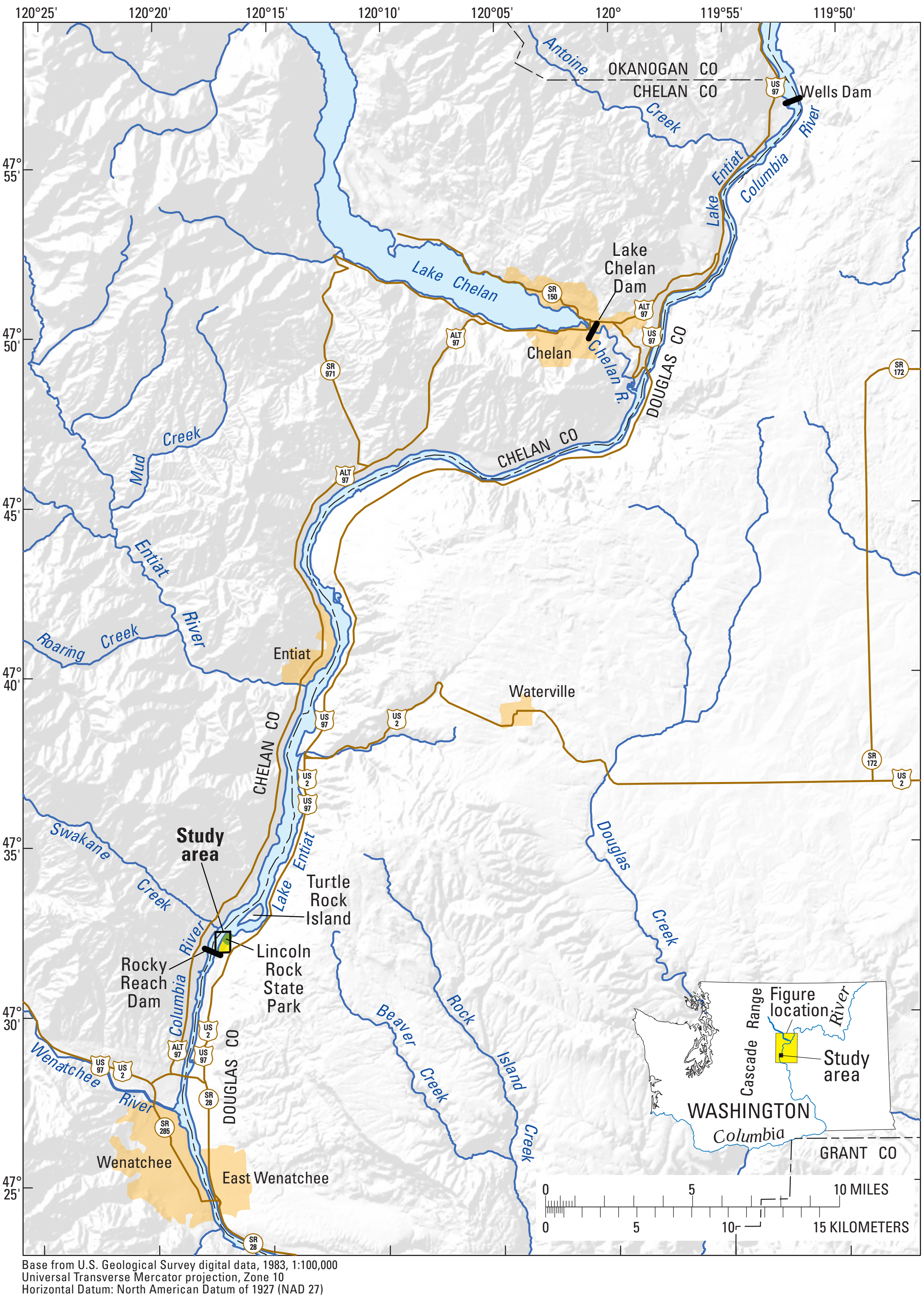
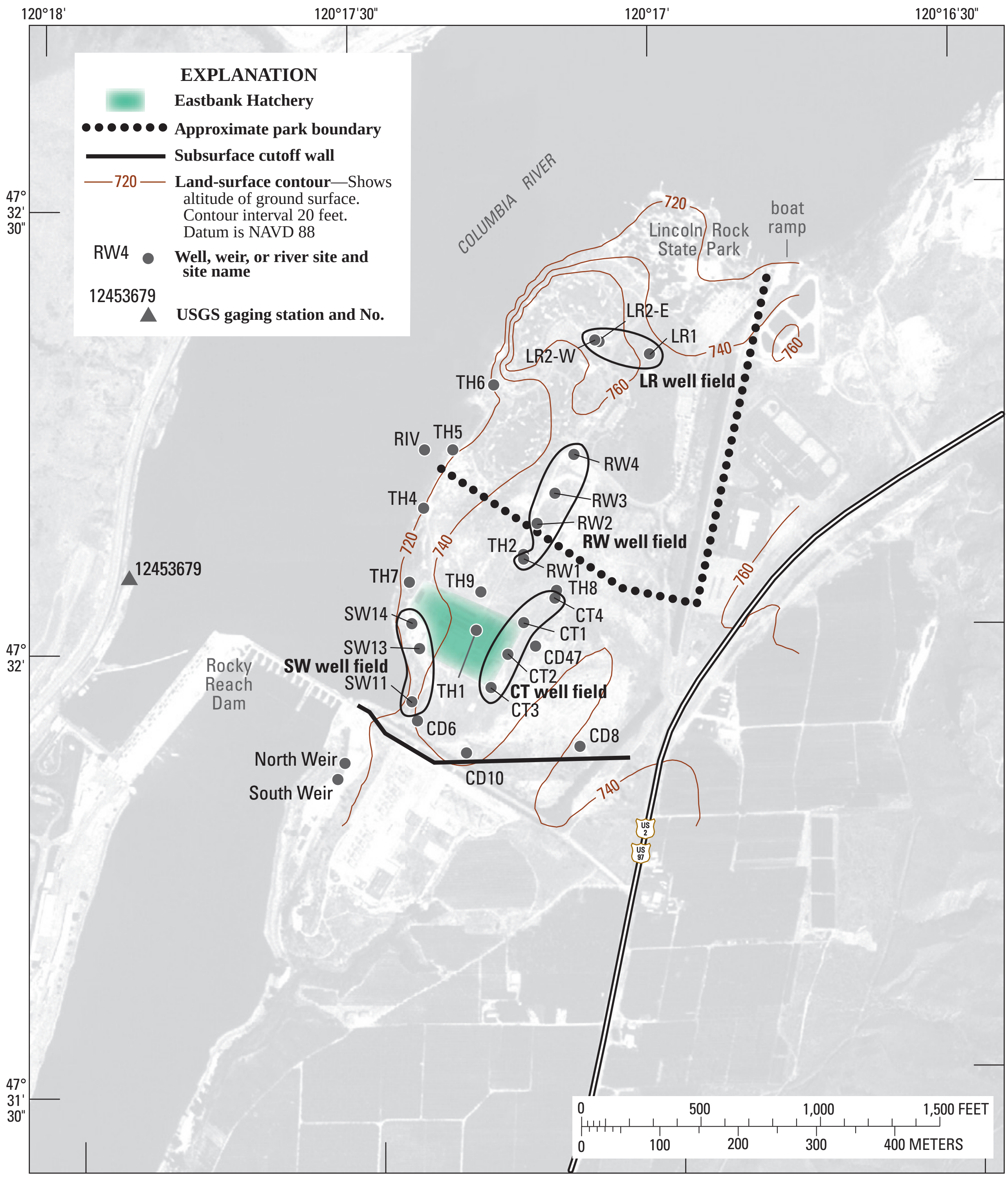


Figure 1. Location of Eastbank Aquifer system and vicinity, Douglas County, Washington.



U.S. Forest Service orthophoto, Rocky Reach Dam quad, August 2, 1998
Universal Transverse Mercator projection, Zone 10
Horizontal datum: North American Datum of 1927 (NAD 27)

Figure 2. Locations of the Eastbank Hatchery, subsurface cutoff wall, wells, weirs, river-monitoring site, and U.S. Geological Survey gaging station, Douglas County, Washington.

The primary use of the Eastbank Aquifer system is to supply water for an on-site fish hatchery called the Eastbank Hatchery (fig. 2), and the regional water system serving the cities of Wenatchee, East Wenatchee, and parts of unincorporated Chelan and Douglas Counties. In 2006, mean annual pumpage from the regional water system was about 16 ft^3/s and mean annual pumpage from the Eastbank Hatchery was about 43 ft^3/s. The regional water system pumps water from the RW well field—wells RW1, RW2, RW3, and RW4 (fig. 2) and serves more than 65,000 people through about 26,000 connections (M. Cockrum, City of Wenatchee, written commun., 2008). As the population of the service area continues to grow, the regional water system may need to pump more water in the future to serve additional customers. The hatchery pumps water from the CT well field—wells CT1, CT2, CT3, and CT4 (fig. 2). The secondary use of the Eastbank Aquifer system is to supply irrigation water for Lincoln Rock State Park (LR well field—wells LR1, LR2-E, and LR2-W; fig. 2), a small quantity of industrial water to lubricate turbines of the Rocky Reach Hydroelectric Project (wells SW13 and SW14 of the SW well field; fig. 2), and a small quantity of irrigation water for miscellaneous sites outside Lincoln Rock State Park (well SW11 of the SW well field; fig. 2).

The Eastbank Hatchery is owned by the PUD and operated by the Washington Department of Fish and Wildlife. The hatchery forms part of the Anadromous Fish Agreement and Habitat Conservation Plans that allow the PUD to operate the Rocky Reach and Rock Island Hydroelectric Projects under license agreements with the U.S. Federal Energy Regulatory Commission (FERC). The hatchery helps compensate for losses of sockeye, spring and summer Chinook salmon, and summer steelhead (Public Utility District No. 1 of Chelan County, 2007a). Successful operation of the hatchery relies on access to relatively cool ground water, preferably not exceeding 13°C (Ian Adams, Public Utility District No. 1 of Chelan County, written commun., 2008). Ground-water temperatures are reported to have increased in recent years. If these increases continue, the PUD would either need a different approach for supplying appropriate water to the hatchery or alternative solutions for meeting its hatchery obligations.

To help understand why the ground-water temperatures may have been increasing and to determine the data needs for possible future evaluations of aquifer-system management alternatives that maintain sufficiently cool ground water for the successful production of fish in the Eastbank Hatchery, the PUD requested that the U.S. Geological Survey (USGS) conduct a study of the Eastbank Aquifer system. The objective of this study is to improve the understanding of the hydrologic and thermal conditions of the Eastbank Aquifer system and the processes that affect those conditions. The objective was met by evaluating available hydrologic, water-temperature, and related information, identifying data gaps, collecting new data, and developing an updated data-collection program.

Purpose and Scope

This report documents the development of a conceptual model of hydrologic and thermal conditions of the Eastbank Aquifer system near Rocky Reach Dam, Douglas County, Washington, and the need for additional data and analyses to improve the understanding of the Eastbank Aquifer system. Information used to develop the conceptual model includes reports that document the design and construction of the subsurface cutoff wall east of Rocky Reach Dam (Stone and Webster Engineering Corporation, 1959), analyses of the hydrology and hydrogeology of the Eastbank Aquifer system (CH2M Hill, 1977 and 1988; Water & Environmental Systems Technology, Inc., 1990), vertical temperature profiles of the ground-water system (Water & Environmental Systems Technology, Inc., 1990), and numerical models of the Eastbank Aquifer system that simulate hydrologic and thermal conditions starting in 1989–90 (Water & Environmental Systems Technology, Inc., 1990 and 1998). Additional information evaluated include hourly river and aquifer water levels and water temperatures collected by the PUD in a monitoring network since 1990, miscellaneous data from PUD files, historical ground-water pumpage from wells supplying the regional water system and Eastbank Hatchery, and water-level, water-temperature, and other water-quality data collected during 2007–08 as part of this study.

Description of Study Area

The study area is located in Douglas County, Washington, in a river-terrace deposit along the east side of the Columbia River about 8 mi north of Wenatchee (fig. 1). The study area, which covers about 150 acres, includes Lincoln Rock State Park and the area to the south, including a subsurface cutoff wall constructed as part of Rocky Reach Dam. The dam is located at river mile (RM) 473.7 and creates Lake Entiat (fig. 1), which ranges in altitude from a normal low pool of 703 ft to a normal full pool of 707 ft (Public Utility District No. 1 of Chelan County, 2007b). The Columbia River drainage area upstream of Rocky Reach Dam is about 88,000 mi^2 and drains parts of Washington, Idaho, and Montana; and British Columbia, Canada. Mean discharge at Rocky Reach Dam for the period of record (October 1961 through September 2006) is 113,900 ft^3/s with a maximum discharge of about 535,000 ft^3/s on June 10, 1961, and a minimum daily discharge of 25,100 ft^3/s on November 11, 1973 (U.S. Geological Survey, 2007).

The subsurface of the study area consists of coarse- and fine-grained sediments deposited along the east side of the Columbia River Valley on top of metamorphic bedrock. This bedrock forms the base beneath Rocky Reach Dam and crops out along the west bank of the river. East of the study area, metamorphic bedrock is overlain by Columbia River flood basalts that form the Columbia Plateau. The topography of the study area has low relief, with an average altitude of about

740 ft (fig. 2). Bedrock on the west and east sides of the river steeply rises to altitudes exceeding 2,400 and 2,000 ft, respectively, within 1 mi of the study area.

The climate of the study area exhibits characteristics of both maritime and continental climates (National Oceanic and Atmospheric Administration Western Regional Climate Center, 2007a). The prevailing wind direction is from the southwest or west, which brings in the remnants of humid air masses generated over the Pacific Ocean after their flow has been impeded by the Cascade Range. Extreme summer and winter temperatures occur when the wind direction shifts to the north and east and continental air flows into the area (National Oceanic and Atmospheric Administration Western Regional Climate Center, 2007a). Generally, summers in the study area are warm and dry and winters are cold and also relatively dry. During the most recent climate-normal period (1971–2000) at the National Weather Service climate station in nearby Wenatchee (site 459074), the mean monthly precipitation ranged from 0.3 in. in July to 1.5 in. in December and the mean monthly minimum and maximum air temperatures ranged from -4.9 and 1.7°C in January, respectively, to 16.1 and 31.0°C in July, respectively (National Oceanic and Atmospheric Administration Western Regional Climate Center, 2007b; fig. 3). Mean annual precipitation was 9.1 in. and mean annual minimum and maximum air temperatures were 5.4 and 16.9°C, respectively.

Except for irrigated lawns, shrubs, and trees in Lincoln Rock State Park and limited additional sites, the study area is sparsely vegetated with primarily grasses and shrubs that have adapted to local conditions.

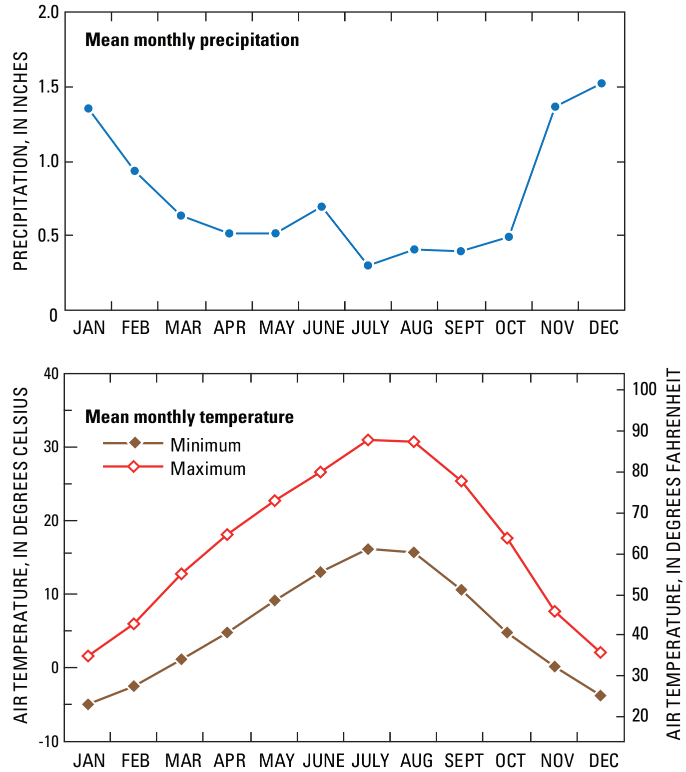


Figure 3. Mean monthly precipitation and mean monthly minimum and maximum air temperatures for the Wenatchee climate station (site 459074), Chelan County, Washington, 1971–2000.

Previous Investigations

As part of the design process for Rocky Reach Dam in the 1950s, geotechnical engineering surveys and hydrologic assessments were conducted in and near the study area. Results of this work near the subsurface cutoff wall (fig. 2) were summarized by Stone and Webster Engineering Corporation (1959) when they described the design and construction of the subsurface cutoff wall. The feasibility of using the Eastbank Aquifer system as a public water supply for the Wenatchee urban area was investigated by R.W. Beck and Associates (1973) and included an aquifer assessment by Robinson and Noble, Inc. Subsequently, Robinson and Noble, Inc. conducted a more detailed aquifer assessment that was reported by CH2M Hill (1977) as part of a predesign study of the regional water system. The study included descriptions of the installation and testing of well RW1, the first well of the regional water system. CH2M Hill documented the installation and testing of wells RW2, RW3, and RW4 (1979; as reported by Water & Environmental Systems Technology, Inc., 1990) and wells CT1, CT2, CT3, and CT4 (1988). CH2M Hill (1988) also presented results of seismic-refraction and electrical-resistivity surveys of the Eastbank aquifer system and parts of a draft report dated 1987 that included detailed hydrogeologic cross sections of the system (appendix 1).

Water & Environmental Systems Technology, Inc. (1990) analyzed the feasibility of using the Eastbank Aquifer system as a source of water for the Eastbank Hatchery over the long term by considering both the availability and temperature of ground water. As part of this analysis, they developed numerical ground-water models to help evaluate the hydrologic and thermal conditions of the ground-water system in 1989–90 and possible future conditions. The first of these models was a finite-difference ground-water flow model, MODFLOW (McDonald and Harbaugh, 1988), that was used to verify the conceptual model of the flow system and refine aquifer properties. The second model was a finite-element model, CFEST (Gupta and others, 1987), that was used to assess hydrologic and thermal conditions in 1989–90 and evaluate possible future conditions for different combinations of river temperature and seasonal pumping. Water & Environmental Systems Technology, Inc. (1990) also designed a network for monitoring river and aquifer water levels and water temperatures. Data from this network collected by the PUD since 1990 were used by Water & Environmental

Systems Technology, Inc. to verify the previously developed CFEST model (Water & Environmental Systems Technology, Inc., 1998). The model was subsequently used to assess possible impacts on the hydrologic and thermal conditions of the Eastbank Aquifer system, assuming increased pumping by the regional water system to accommodate a possible expansion of the system's service area to include East Wenatchee (Water & Environmental Systems Technology, Inc., 1998). The expansion of the service area and the increase in pumping took place in 2001.

Well-Numbering System

In Washington, the USGS assigns wells identifiers that describe their locations with respect to township, range, section, and tract. For example, number 24N/20E-35G01 (fig. 4) indicates that the well is in township 24 North (N) and Range 20 East (E) of the Willamette base line and meridian. The number immediately following the hyphen indicates the section (35) within the township; the letter following the section gives the tract within the section, as shown in figure 4. The two-digit sequence number (01) following the letter indicates that the well was the first inventoried by USGS personnel in that tract. The nominal size of a section is 1 mi^2 and the nominal size of a tract is 40 acres. In the study area, sections and tracts may deviate from their nominal sizes because they do not have standard rectangular shapes.

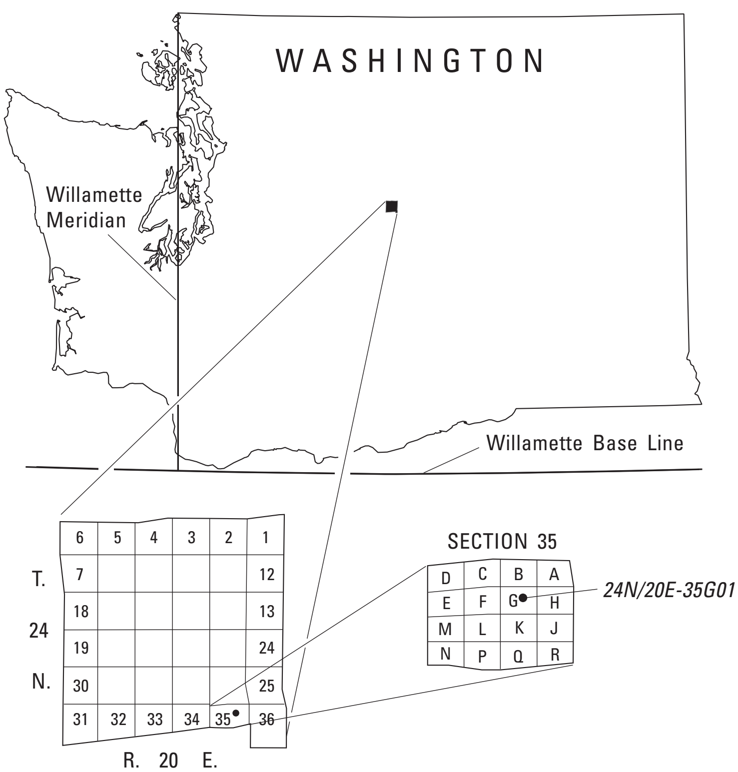


Figure 4. Well-numbering system used in Washington.

Methods of Investigation

All available monitoring and pumping wells in the study area were inventoried by the USGS and their locations were determined using a hand-held GPS unit. Altitudes of wells were based on a survey conducted by Horton Dennis & Associates, Inc. in 1998 (S. Dilly, written commun., 2007) and spot-checked and expanded on by PUD surveyors. Surveyed altitudes were reported to the nearest 0.01 ft and, for the purpose of this study, were considered accurate to ±0.05 ft. Water levels were measured using an electrical or steel tape that was read to the nearest 0.01 ft. Water levels were considered accurate to ±0.1 ft. Vertical temperature profiles in wells were measured using a recently verified electrical tape and water temperatures were read to the nearest 0.1°C. The time of all measurements was recorded in local time, which is either Pacific Standard Time or Pacific Daylight Time, depending on the time of year. Continuous water levels measured during several hours on July 18, 2007, were made using electrical and steel tapes that had been verified to give the same results. The times of the continuous water-level measurements were read from cellular phones that were verified to match the times recorded by the continuous monitoring network run by the PUD within 1 minute.

Water-Quality Sampling Procedures

All ground-water samples, with the exception of the sample collected from well TH4, were collected following protocols described by Wilde (1999) in order to ensure representative samples of ground water. Clean-sampling protocols, as described by Wilde and others (2002), were used to process the samples. Sampling equipment consisted of polyethylene tubing with Teflon® or stainless-steel fittings that were attached to a faucet at the well head. The tubing was then connected directly to a flow chamber to monitor physical properties (water temperature, pH, specific conductance, and concentrations of dissolved oxygen) and through a splitter to provide either raw or filtered water samples. Existing pumps were active in all wells that were sampled except for well TH4. An equivalent volume of purge water had already been pumped during the previous 24 hours, therefore, the sampling equipment was flushed with ground water and samples were collected after ensuring that physical properties measured in the flow chamber had stabilized. All lines and processing equipment that came in contact with the sample water after the point of attachment to the well discharge structure were composed of Teflon®, polyethylene, or stainless steel. Ground-water samples were pumped directly through a line or a filtration cartridge into sample bottles and samples were preserved or stored on ice and shipped for analysis to the USGS National Water Quality Laboratory (NWQL) in Denver, Colorado and Pacific Analytical Laboratory in Corvallis, Oregon. Because there was no pump in well TH4, a 2-L Kemmerer© sampler was lowered into the well to obtain a grab sample of water from the upper 10 ft of the perforated interval. The sampler was retrieved from the well and water was then pumped from the Kemmerer© sampler with a peristaltic pump and processed like all other samples. The Columbia River sample was collected with the Kemmerer© bottle near the location labeled RIV in figure 2. The sampler was lowered through the water column to about 3 ft above the riverbed before the sampling mechanism was triggered. Water from the Kemmerer© bottle was withdrawn from the sampler using a peristaltic pump and processed like the ground-water samples. Aseptic techniques were used in the collection of samples for bacterial enumeration.

Laboratory Analytical Procedures

Laboratory analyses were performed for common ions and bacteria enumeration. Water samples for the analysis of nitrate plus nitrite were received at the NWQL and stored at less than 4°C prior to analysis. Samples were analyzed for nitrate plus nitrite using a cadmium reduction-diazotization colorimetric method described by Fishman (1993). Samples were analyzed for chloride and sulfate using ion chromatography (Fishman and Friedman, 1989); calcium, magnesium, sodium, and iron were analyzed using inductively coupled plasma (Fishman, 1993); and potassium was analyzed using flame atomic absorption (Fishman and Friedman, 1989). Manganese was analyzed using inductively coupled plasma detected with a mass spectrometer (ICP/MS) (Faires, 1993). Variability in reported concentrations due to variability in laboratory analytical processes was expected to be less than 2 percent.

Bacterial enumerations were done using fluorescent counting techniques (Hurst and others, 1997). Bacterial-enumeration samples were sent to Pacific Analytical Laboratory in Corvallis, Oregon, where enumerations were conducted using Moleculer Probes BacLight viability and counting stains with a fluorescent microscope. The 95-percent confidence interval for enumerations provided by the laboratory was about 10 percent.

Hydrogeology

The subsurface of the study area consists of unconsolidated sedimentary layers with a wide range of hydraulic conductivities. These layers are deposited on top of bedrock to form two aquifers separated by a confining unit, which is absent in the northwestern part of the study area. An aquifer is a hydrogeologic unit that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs, and a confining unit is a hydrogeologic unit of distinctly less permeable material bounding one or more aquifers. The lower aquifer, which is in direct contact with the Columbia River, is the source of water for the regional water system, the Eastbank Hatchery, and irrigation and industrial uses.

Geologic Setting

Rocky Reach Dam and the Eastbank Aquifer system are located in a canyon incised into Late Cretaceous metamorphic bedrock of biotite gneiss (Tabor and others, 1987). The canyon has been eroded by the ancestral Columbia River and multiple catastrophic outburst floods from glacial Lake Missoula during the Pleistocene age. Estimates of the discharge of those floods are on the order of 600 million ft^3/s (O'Connor and Baker, 1992). Large gravel deposits have formed inside the Columbia River valley from the accumulation of up to boulder-sized sediments deposited by the catastrophic floods at locations of channel widening or downstream of bedrock promontories, such as Turtle Rock Island located about 1 mi northeast of the study area (fig. 1). In the Columbia River valley south of Wenatchee, catastrophic-flood discharges from Moses Coulee deposited sufficient sediment to create temporary flood backwater and a lake that deposited fine-grained, lacustrine sediments. Cycles of catastrophic flooding and lake formation deposited the glacio-fluvial gravels and varved clays that make up the aquifers and confining unit, respectively, of the Eastbank Aquifer system.

Hydrogeologic Units

Previous studies (Stone and Webster Engineering Corporation, 1959; CH2M Hill, 1977 and 1988; and Water & Environmental Systems Technology, Inc., 1990) determined that at river levels following the completion of Rocky Reach Dam, the Eastbank Aquifer system consists of two highly permeable, sand-and-gravel aquifers separated by a confining unit. A schematic hydrogeologic cross section through the south-central part of the Eastbank Aquifer system is shown in figure 5. In this study, the lower confined aquifer is referred to as the Lower Aquifer and the upper unconfined aquifer is referred to as the Upper Aquifer. Previous studies have used different names and terminology for the hydrogeologic units (table 1). The confining unit, which consists of varved clays and is referred to as the Clay Confining Unit in this study, generally thins towards the north, west, and east and is absent in the northwestern part of the study area (fig. 6; Water & Environmental Systems Technology, Inc., 1990). Where the Clay Confining Unit is absent, the Lower and Upper Aquifers merge to form the Combined Aquifer, which is unconfined.

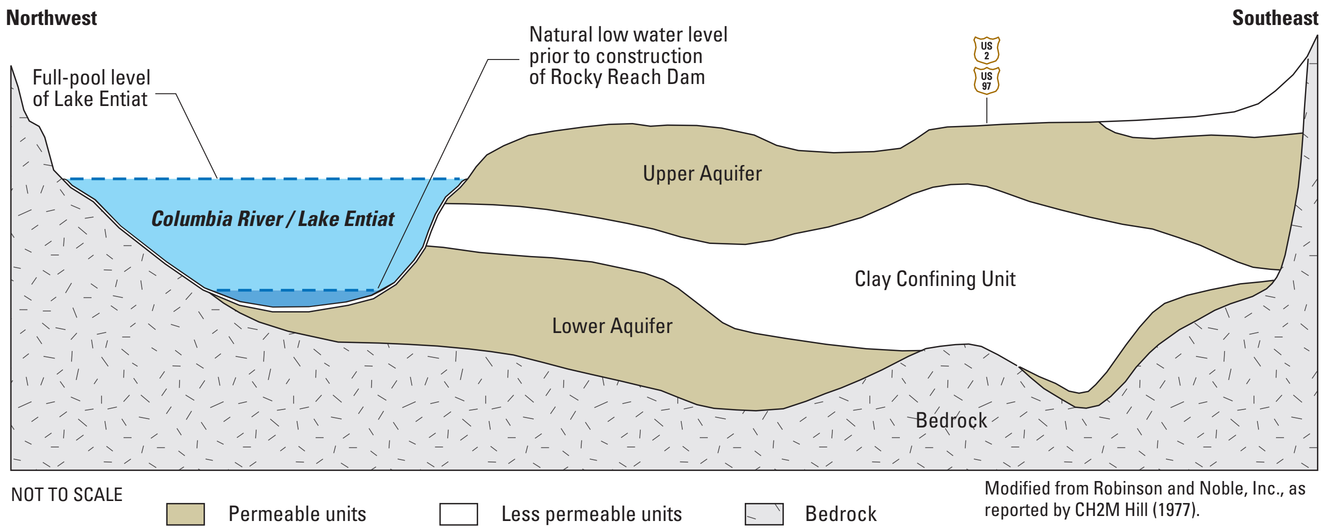


Figure 5. Schematic hydrogeologic cross section through the south-central part of the Eastbank Aquifer system, Douglas County, Washington.

Table 1. Hydrogeologic-unit names and terminology used in this study and previous studies, Eastbank Aquifer system, Douglas County, Washington.

[–, not named]

Hydrogeologic unit				Source
Lower Aquifer	Upper Aquifer	Combined Aquifer	Clay Confining Unit	This study
Eastbank Aquifer	–	Eastbank Aquifer	–	Water & Environmental Systems Technology, Inc. (1990)
deep aquifer	shallow aquifer	combined aquifer	aquitard	CH2M Hill (1988)

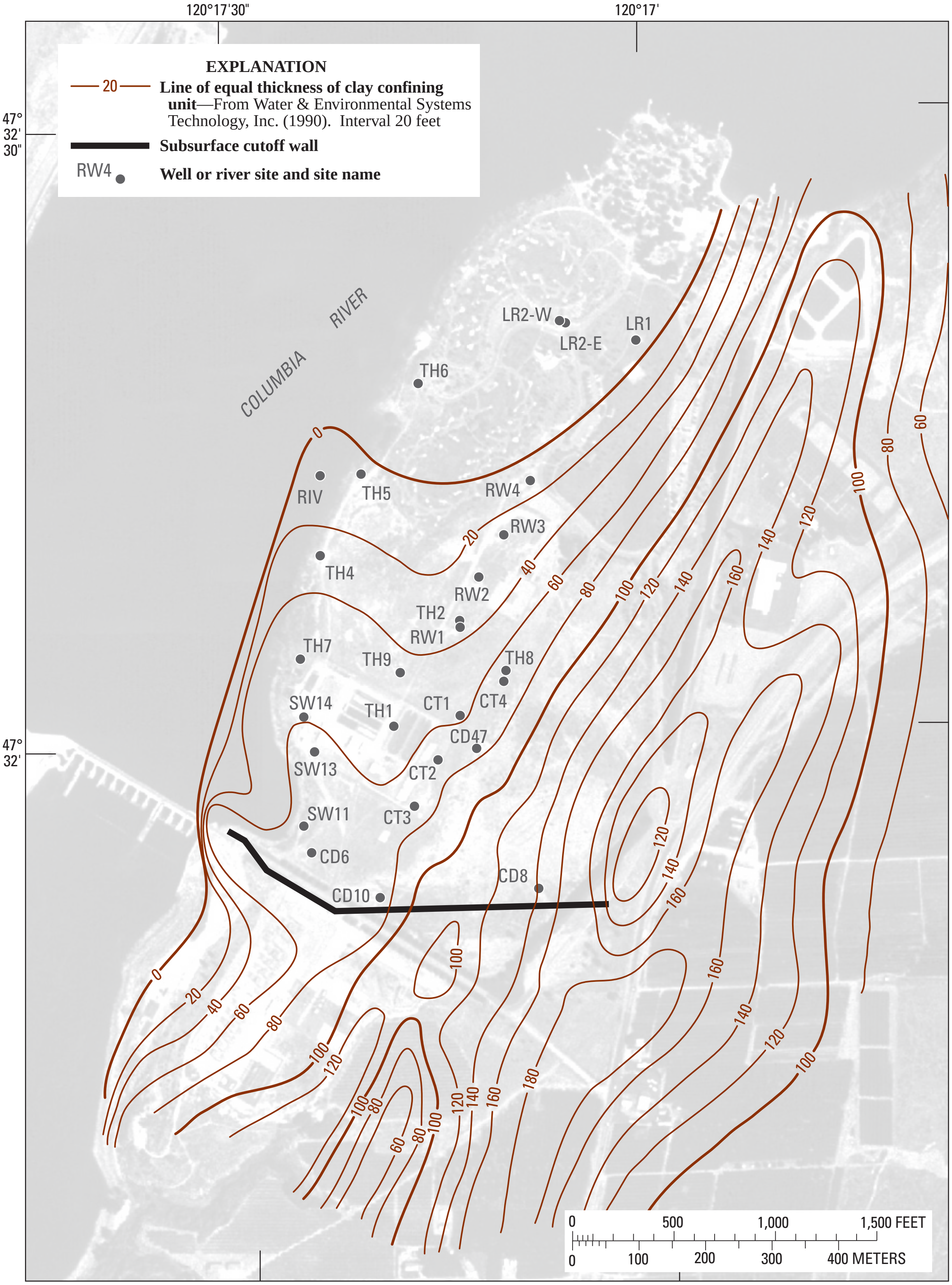
The Eastbank Aquifer system lies on top of crystalline bedrock, which has an undulating surface as shown in figure 7 (Water & Environmental Systems Technology, Inc., 1990). Near the RW wells near the center of the study area, the altitude of the top of the bedrock is less than 340 ft. This is lower than approximated on the hydrogeologic cross sections by CH2M Hill (1988; appendix 1) but is based on interpretations of seismic-refraction data reported by CH2M Hill (1988). Water & Environmental Systems Technology, Inc. (1990) relied on indirect methods to estimate the altitude of the top of bedrock near the center of the study area because none of the RW wells was drilled to bedrock. It is estimated that there may be up to about 200 ft of sedimentary material about which little is known between the bottom of the RW wells and the top of bedrock (appendix 1). In the eastern part of the study area bedrock is shallower and truncates the Lower Aquifer. Water & Environmental Systems Technology, Inc. (1990) cautions, however, that well coverage in the eastern part of the study area is sparse and thus the interpretation of the subsurface is less certain. The resulting thickness of the Lower Aquifer in the study area, including the Combined Aquifer, ranges from 0 ft to more than 300 ft (fig. 8; Water & Environmental Systems Technology, Inc., 1990). It is not known how far north the Lower Aquifer extends beyond the study area.

During construction of Rocky Reach Dam, Stone and Webster Engineering Corporation (1959) determined on the basis of a dye-tracer study that the hydraulic conductivities of the Lower Aquifer near the subsurface cutoff wall are on the order of 14,000 to 22,000 ft/d. Hydraulic conductivity is a measure of the ease with which water can move through a material. The horizontal hydraulic conductivity of an aquifer is related to the transmissivity of an aquifer according to

$$T = K_h b \,, \qquad (1)$$

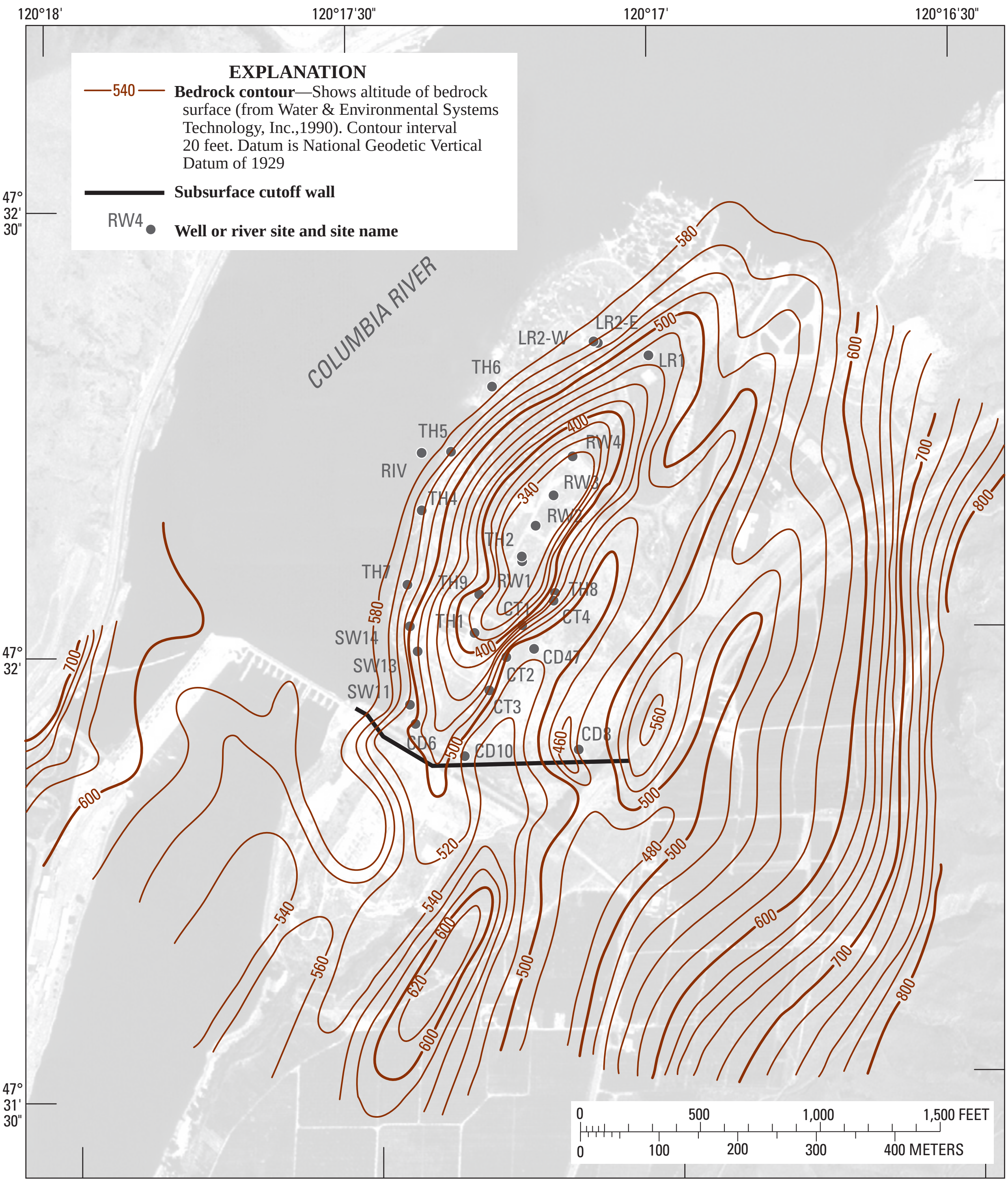
where

T is transmissivity, in feet squared per day,
K_h is horizontal hydraulic conductivity, in feet per day, and
b is thickness of the aquifer, in feet.



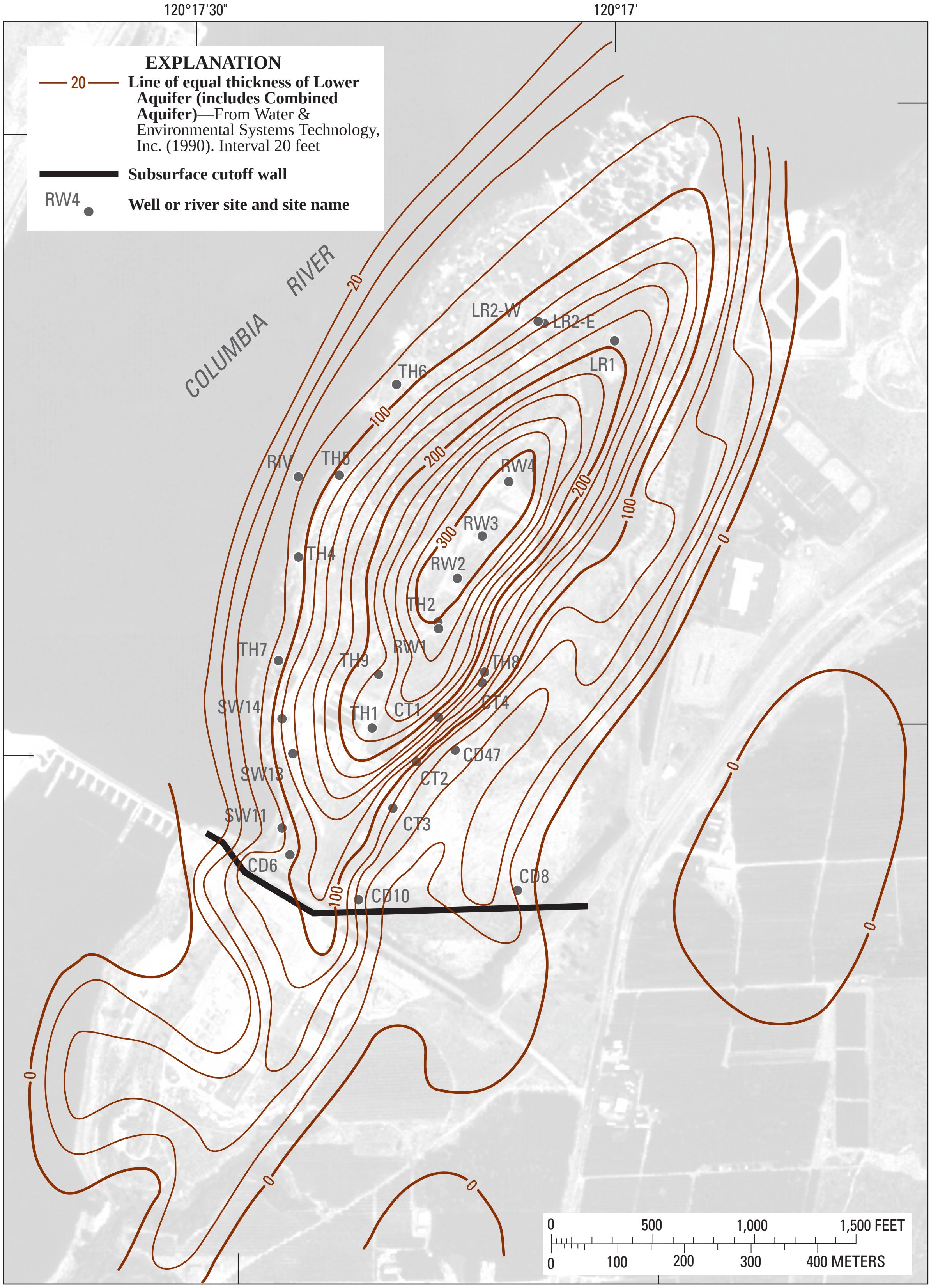
U.S. Forest Service orthophoto, Rocky Reach Dam quad, August 2, 1998
Universal Transverse Mercator projection, Zone 10
Horizontal datum: North American Datum of 1927 (NAD 27)

Figure 6. Thickness of the Clay Confining Unit, Eastbank Aquifer system, Douglas County, Washington.



U.S. Forest Service orthophoto, Rocky Reach Dam quad, August 2, 1998
Universal Transverse Mercator projection, Zone 10
Horizontal datum: North American Datum of 1927 (NAD 27)

Figure 7. Altitude of the top of bedrock, Eastbank Aquifer system, Douglas County, Washington.



U.S. Forest Service orthophoto, Rocky Reach Dam quad, August 2, 1998
Universal Transverse Mercator projection, Zone 10
Horizontal datum: North American Datum of 1927 (NAD 27)

Figure 8. Thickness of the Lower Aquifer, Eastbank Aquifer system, Douglas County, Washington.

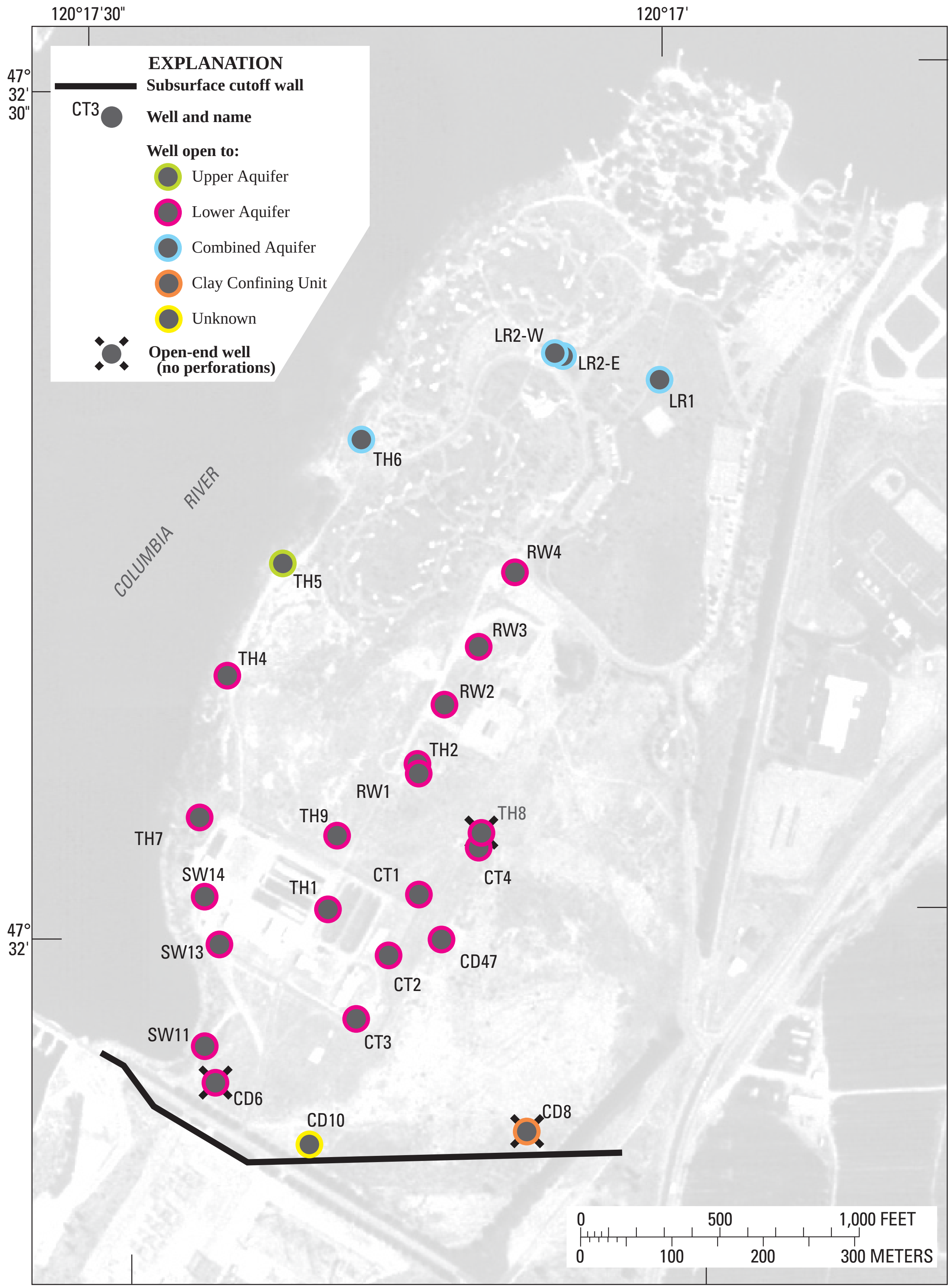
Transmissivity is defined as the volume of water per unit time that will flow through a unit width of an aquifer perpendicular to the flow direction in response to a unit hydraulic head gradient. Another important aquifer parameter, the storativity, is defined as the volume of water an aquifer releases from, or takes into, storage per unit area of aquifer per unit change in head. Transmissivities and storativities of the Lower Aquifer calculated from aquifer tests performed between 1973 and 1990 in different parts of the study area ranged from 37,000 to 1.7 million ft^2/d and from 0.0021 to 0.12, respectively (table 2). Results from aquifer tests of the CT well field (wells CT1, CT2, CT3, and CT4) described by CH2M Hill (1988) are not included in table 2 because they were reported as apparent transmissivities and storativities due to interference of the aquifer tests by intermittent pumping by the regional water system and other complications. The transmissivities and storativities of the Lower Aquifer indicate that it is a highly permeable, leaky confined aquifer with recharge entering the aquifer primarily from the Columbia River (Water & Environmental Systems Technology, Inc., 1990). In a numerical model of the Eastbank Aquifer system, Water & Environmental Systems Technology, Inc. (1990) achieved the best results by simulating hydraulic conductivities in the Lower and Upper Aquifers of 9,500 and 6,700 ft/d, respectively.

The interpretation of the hydrogeologic framework of the Eastbank Aquifer system in previous studies is based primarily on lithologic and geophysical logs of wells and borings. Although many well logs were available for use in this study, a significant number were not available and either no information was known about certain wells or only limited information was known from descriptions by previous studies. To learn more about these wells and also to ascertain the condition of all accessible wells currently (2008) in the study area, downhole-camera surveys and natural-gamma logs were made of selected wells in December 2007. A description of the downhole-camera surveys is included in appendix 2 and the natural-gamma logs are included in appendix 3. Several wells that existed when previous studies were conducted have since been abandoned or destroyed and were not available in this study. Wells that are currently (2008) in the study area and the hydrogeologic units the wells are open to are shown in figure 9; known information for these wells is summarized in table 3.

Table 2. Transmissivities and storativities of the Lower Aquifer, Eastbank Aquifer system, Douglas County, Washington.

[Locations of wells are shown in figure 2. **Abbreviations:** ft^2/d, foot squared per day; –, not available]

General area	Transmissivity (ft^2/d)		Storativity (dimensionless)		Source
	Range	Final estimate	Range	Final estimate	
South of well CD47 and north of subsurface grout wall	470,000–1,200,000	670,000	–	–	Robinson and Noble, Inc. (as reported by R.W. Beck and Associates, 1973)
North of well CD47	500,000–1,700,000	630,000	0.0021–0.0054	0.0032	Robinson and Noble, Inc. (as reported by CH2M Hill, 1977)
RW well field (wells RW1, RW2, RW3, and RW4)	250,000–380,000	320,000	0.021–0.12	0.06	CH2M Hill (1979; ranges as reported by Water & Environmental Systems Technology, Inc., 1990; final estimates as reported by CH2M Hill, 1988)
Entire study area north of subsurface grout wall	37,000–650,000	–	0.007–0.095	–	Water & Environmental Systems Technology, Inc. (1990)



U.S. Forest Service orthophoto, Rocky Reach Dam quad, August 2, 1998
Universal Transverse Mercator projection, Zone 10
Horizontal datum: North American Datum of 1927 (NAD 27)

Figure 9. Wells that are currently (2008) completed in the Eastbank Aquifer system and hydrogeologic units to which they are open, Douglas County, Washington.

Table 3. Summary information for wells completed in the Eastbank Aquifer system, Douglas County, Washington.

[Locations of wells are shown in figure 2. **USGS well No.:** See figure 4 for explanation of well-numbering system. Latitudes and longitudes of the wells are on file with the U.S. Geological Survey. **Completion date of well:** Source of information is well log or first mention in previous studies. **Altitude of land surface:** Datum is National Geodetic Vertical Datum (NGVD 29). **Depth of well:** Source of information is well log unless otherwise noted. **Type of log available in this study:** C, down-hole camera; D, driller's; G1, natural gamma from previous studies; G2, natural gamma from this study; L, lithology. **Abbreviations:** USGS, U.S. Geological Survey; –, not available]

Local well name	USGS well No.	Completion date of well	Hydrogeologic unit to which well is open	Altitude of land surface (feet)	Depth of well (feet)	Primary use of water since completion of Rocky Reach Dam	Type of log available in this study	Remarks
CD6	24N/20E-35Q06	1972 or earlier; probably 1957 or earlier	Lower Aquifer	744.7	216	Monitoring	C, G2, L	Open-end well (no perforations).
CD8	24N/20E-35R01	1957 or earlier	Clay Confining Unit	724.0	231	Monitoring	L	Open-end well (no perforations). Well may be open to a sand lens connected to the Lower Aquifer based on cross section *A-A'* by Stone and Webster Engineering Corporation (1959); the water-level response to the 2-hour shutdown of pumping on July 18, 2007; and the fact that this well is used to monitor the integrity of the subsurface cutoff wall.
CD10	24N/20E-35Q01	1959 or earlier; probably 1957 or earlier	—	733.6	230	Monitoring	L	Well may be open to the Lower Aquifer based on cross section *A-A'* by Stone and Webster Engineering Corporation (1959); the water-level response to the 2-hour shutdown of pumping on July 18, 2007; and the fact that this well is used to monitor the integrity of the subsurface cutoff wall.
CD47	24N/20E-35Q02	1959 or earlier; probably 1957 or earlier	Lower Aquifer	746.6	245	Monitoring	C, G2, L	
CT well field								
CT1	24N/20E-35K10	November 1987	Lower Aquifer	747.7	206	Hatchery	D	
CT2	24N/20E-35Q04	November 1987	Lower Aquifer	748.1	204	Hatchery	D	
CT3	24N/20E-35Q03	December 1987	Lower Aquifer	749.9	213	Hatchery	D	
CT4	24N/20E-35K11	January 1988	Lower Aquifer	747.9	203	Hatchery	D	
LR well field								
LR1	24N/20E-35H04	after 1977 and before 1988	Combined Aquifer	750	–	Irrigation	–	Altitude of land surface is ±10 ft.
LR2-E	24N/20E-35H01	after 1977 and before 1988	Combined Aquifer	770	157	Irrigation	–	Altitude of land surface is ±10 ft. Depth of well estimated from hydrogeologic cross section by CH2M Hill (1988).
LR2-W	24N/20E-35H02	after 1977 and before 1988	Combined Aquifer	770	–	Irrigation	–	Altitude of land surface is ±10 ft; Chelan County PUD notes indicate this well is 140 ft deep.
RW well field								
RW1	24N/20E-35K07	July 1977	Lower Aquifer	742.7	219	Public Supply	D	
RW2	24N/20E-35K08	July 1979	Lower Aquifer	747.6	226	Public Supply	D	
RW3	24N/20E-35K09	June 1979	Lower Aquifer	746.8	230	Public Supply	D	
RW4	24N/20E-35H03	June 1979	Lower Aquifer	737.8	179	Public Supply	D	

Table 3. Summary information for wells of the Eastbank Aquifer system, Douglas County, Washington.—Continued

[Locations of wells are shown in figure 2. **USGS well No.:** See figure 4 for explanation of well-numbering system. Latitudes and longitudes of the wells are on file with the U.S. Geological Survey. **Completion date of well:** Source of information is well log or first mention in previous studies. **Altitude of land surface:** Datum is National Geodetic Vertical Datum (NGVD 29). **Depth of well:** Source of information is well log unless otherwise noted. **Type of log available in this study:** C, down-hole camera; D, driller's; G1, natural gamma from previous studies; G2, natural gamma from this study; L, lithology. **Abbreviations:** USGS, U.S. Geological Survey; –, not available]

Local well name	USGS well No.	Completion date of well	Hydrogeologic unit to which well is open	Altitude of land surface (feet)	Depth of well (feet)	Primary use of water since completion of Rocky Reach Dam	Type of log available in this study	Remarks
SW well field								
SW11	24N/20E-35Q05	1959 or earlier	Lower Aquifer	726.9	–	Irrigation	–	
SW13	24N/20E-35K12	1959 or earlier	Lower Aquifer	740.3	176	Irrigation/Dam	–	
SW14	24N/20E-35K13	1959 or earlier	Lower Aquifer	737.8	–	Irrigation/Dam	–	
TH1	24N/20E-35K05	1977	Lower Aquifer	748.1	190	Monitoring	D, G1	
TH2	24N/20E-35K06	1977	Lower Aquifer	741.4	225	Monitoring	C, D, G1, G2	
TH4	24N/20E-35K02	1977	Lower Aquifer	723.8	170	Monitoring	C, D, G1	
TH5	24N/20E-35G01	July 1987	Upper Aquifer	713.1	47	Monitoring	C, D	
TH6	24N/20E-35G02	July 1987	Combined Aquifer	727.6	134	Monitoring	C, D, G2	
TH7	24N/20E-35K01	July 1987	Lower Aquifer	723.8	176	Monitoring	C, D	
TH8	24N/20E-35K04	November 1987	Lower Aquifer	747.8	255	Monitoring	C, D	Open-end well (no perforations).
TH9	24N/20E-35K03	October 1987	Lower Aquifer	743.2	211	Monitoring	C, D	

Hydrology

The Lower Aquifer of the Eastbank Aquifer system has been used as a water source for the Eastbank Hatchery and the regional water system since the 1980s. Historical water-level and water-temperature data and water-quality data collected in 2007 were analyzed to evaluate how pumping of the Lower Aquifer has affected its hydrologic and thermal conditions. The source of the historical data is a monitoring network operated by the PUD (fig. 10) that has measured hourly water levels and temperatures in 12 wells and 1 river site from 1990 to the present (2008). The network was designed by Water & Environmental Systems Technology, Inc. (1990) as part of a long-term aquifer test that was completed in 1990. The continuous records from January 1991 through August 2007 were used in this study.

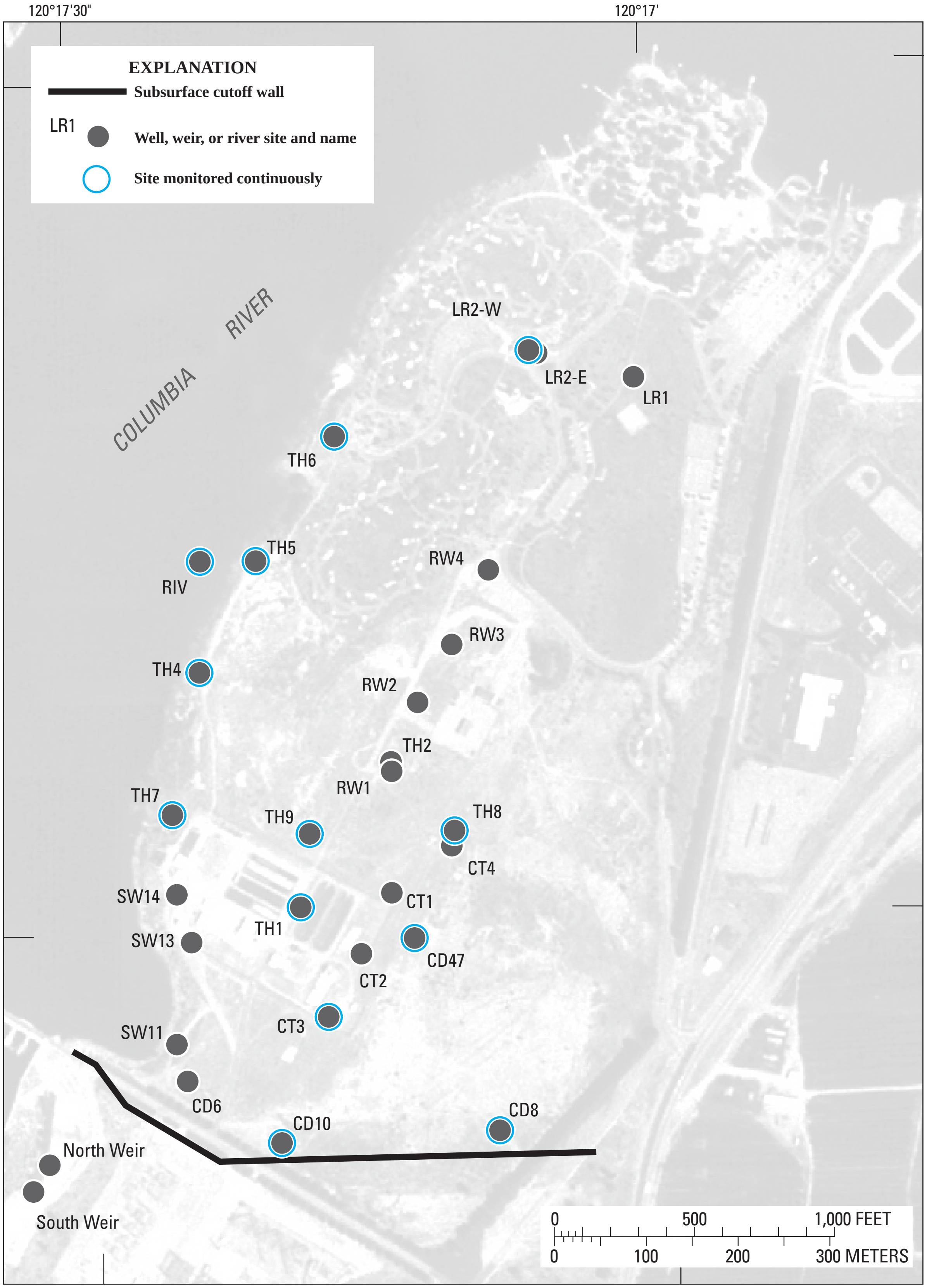
Aquifer Conditions Before and After Construction of Rocky Reach Dam

Prior to the construction of Rocky Reach Dam, when the Columbia River was a free-flowing river in the study area, the natural low water level of the river was 610 ft (Stone and Webster Engineering Corporation, 1959). The water level in the Lower Aquifer was likely similar to the river level, so the Lower Aquifer was probably largely unconfined and only partially saturated (fig. 5). The Upper Aquifer is presumed to have been unsaturated entirely, except for a possible seasonal, perched unconfined aquifer above the Clay Confining Unit. Once construction of Rocky Reach Dam was completed and the hydroelectric project became operational in 1961, the natural water level was raised by almost 100 ft to normal pool levels ranging from 703 to 707 ft (Public Utility District No. 1 of Chelan County, 2007b). This raised the water level in the Eastbank Aquifer system such that the Lower Aquifer became confined and the Upper Aquifer became partially saturated to form an unconfined aquifer (fig. 5). Water levels are maintained in the Upper and Lower Aquifers by the subsurface cutoff wall that extends to bedrock. This wall consists of a clay curtain across the Upper Aquifer and a grout curtain across the Lower Aquifer. Ground water that seeps through the subsurface cutoff wall from the Lower and Upper Aquifers is captured by drains and flows through the North and South Weirs (fig. 2). Seepage around and through the subsurface cutoff wall likely is not all captured by the drains (G. Yow, Public Utility District No. 1 of Chelan County, written commun., 2008).

Potentiometric-surface maps of the Lower Aquifer prior to the construction of Rocky Reach Dam, which show the altitude at which water levels would have stood in tightly cased wells, were not available for this study. However, in July 1977, prior to pumping of the Eastbank Aquifer system by the regional water system and the Eastbank Hatchery, and years following the decline of ground-water levels to facilitate dam construction, Robinson and Noble, Inc. (as reported by CH2M Hill, 1977) prepared a potentiometric-surface map of the Lower and Combined Aquifers (fig. 11). This map demonstrates that prior to extensive pumping of the aquifer system, water levels in the Lower and Combined Aquifers were lower than the water level in the river, and the primary ground-water flow direction generally was parallel to the river from northeast to southwest (fig. 11). The sparse water-level data also support an alternative interpretation of a more dominant ground-water flow component from the west-northwest along the western extent of the Lower and Combined Aquifers than shown in figure 11. The interpretation shown in figure 11 is reasonable, however. The potentiometric surface shown in figure 11 can be considered a map of post-dam, pre-development water levels, as it represents static water levels prior to the start of extensive, approximately continuous pumping of the Eastbank Aquifer system since 1983.

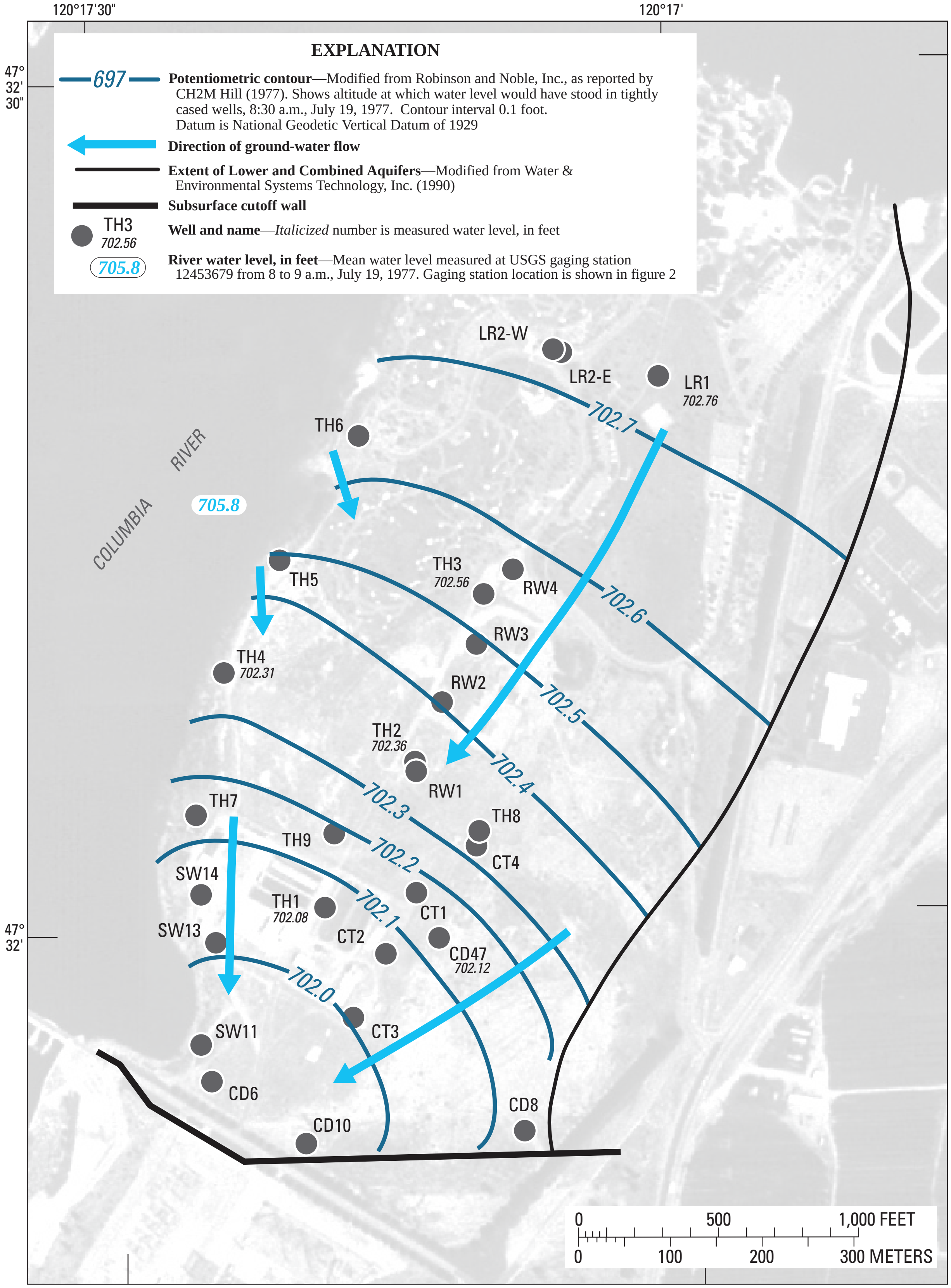
Sources of Ground-Water Recharge and Discharge

The sources of ground-water recharge to the Eastbank Aquifer system are flow from the Columbia River, recharge from precipitation, and recharge from irrigation. The mean annual recharge from precipitation is small, because the mean annual precipitation is only 9.1 in. and potential evapotranspiration is large (the mean annual reference evapotranspiration is 44.5 in. at AgriMet weather station MASW in Manson, Washington, located about 25 mi north-northeast of the study area [Bureau of Reclamation, 2008]). In a ground-water recharge study of the Yakima River basin, about 75 mi south of the study area, Vaccaro and Olsen (2007) estimated mean annual ground-water recharge rates of less than 0.5 in. in parts of the lower basin with similar mean annual precipitation and temperatures as the study area and with similarly short vegetation. A regression equation developed by Bauer and Vaccaro (1990) for estimating recharge to the Columbia Plateau regional aquifer system, which is located just to the east of the study area, was used to estimate a mean annual recharge of 0.65 in. to the Eastbank Aquifer system. However, because the study area has thin to no soils and because the surficial geology consists of very coarse gravels, mean annual recharge may be larger. In the northern part of the U.S. Department of Energy Hanford Site, about 80 mi south-southeast of the study area, Bauer and Vaccaro (1990) simulated mean annual recharge from 23 to 39 percent of precipitation with a median of 35 percent of precipitation in areas with coarse sediments and no vegetation (J. Vaccaro, U.S. Geological Survey, written commun., 2008).



U.S. Forest Service orthophoto, Rocky Reach Dam quad, August 2, 1998
Universal Transverse Mercator projection, Zone 10
Horizontal datum: North American Datum of 1927 (NAD 27)

Figure 10. Water-level and temperature monitoring network, Eastbank Aquifer system, Douglas County, Washington.



U.S. Forest Service orthophoto, Rocky Reach Dam quad, August 2, 1998
Universal Transverse Mercator projection, Zone 10
Horizontal datum: North American Datum of 1927 (NAD 27)

Figure 11. Potentiometric surface of the Lower and Combined Aquifers for post-dam, predevelopment conditions, Eastbank Aquifer system, Douglas County, Washington, 8:30 a.m., July 19, 1977. Well LR1 was called well CD46 in 1977.

The median percentage applied to the study area results in a mean annual recharge of 3.2 in. However, because there is vegetation in the study area, actual recharge from precipitation is likely less than 3.2 in. Irrigation is limited to lawn, shrub, and tree irrigation in small parts of the study area and is considered a negligible source of recharge. Thus, the only significant source of recharge to the Eastbank Aquifer system is the Columbia River.

Current (2008) sources of ground-water discharge from the Eastbank Aquifer system are ground-water pumping from the Lower Aquifer and ground-water seepage around and through the subsurface cutoff wall. Although ground-water discharge from the Lower Aquifer to the Columbia River may have been significant prior to the construction of Rocky Reach Dam, it is presumed to be currently (2008) non-existent.

Historical Ground-Water Discharge

After the completion of Rocky Reach Dam in 1961 and the complete and partial saturation of the Lower and Upper Aquifers, respectively, the Eastbank Aquifer system was not used as a significant resource until 1983, when the regional water system came on-line. This was followed by use of the aquifer system by the Eastbank Hatchery, which started in 1989. (Lincoln Rock State Park, which uses the Eastbank Aquifer system for limited irrigation, started pumping ground water sometime after an agreement was signed with the PUD in April 1980.) In addition to ground-water pumping, ground water also has been removed from the aquifer system by seepage around and through the subsurface cutoff wall.

A history of ground-water pumping was reconstructed using daily flow-meter records for the RW wells provided by the City of Wenatchee (M. Cockrum, written commun., 2007) and seasonal records for the CT and LR wells provided by the Eastbank Hatchery and PUD, respectively (S. Dilly, Public Utility District No. 1 of Chelan County, written commun., 2007). Mostly semi-annual records of discharge through the North and South Weirs, representing seepage through the subsurface cutoff wall, were provided by the PUD (I. Adams, written commun., 2007).

Ground-Water Pumpage

The annual mean pumpage from the RW well field was computed from 1990 through 2006 based on records provided by the City of Wenatchee (M. Cockrum, written commun., 2007; fig. 12*A*) for years with at least 11 months of data. From 1990 through 2000, annual mean pumpage was relatively constant, with a mean annual pumpage of 10.7 ft^3/s. In 2001, the service area of the regional water system was expanded to include the City of East Wenatchee and pumpage increased about 40 percent to a mean annual pumpage of 15.0 ft^3/s from 2002 through 2006, excluding 2003. A breakdown of pumpage into quarterly mean pumpage by the RW well field shows that regional water system pumpage is largest in the summer (July–September) and generally smallest in the winter (January–March; fig. 12*B*). Quarterly pumpage is only shown for quarters with 3 months of data.

The annual mean pumpage from the CT well field was computed from 1991 through 2006 using data provided by the Eastbank Hatchery, including seasonal estimates of pumpage and run-time information for the wells (S. Dilly, Public Utility District No. 1 of Chelan County, written commun., 2007; fig. 12*A*). Data conflicted for part of 1998. Data available initially indicated an annual pumpage of 42.0 ft^3/s and data available later indicated an annual pumpage of 43.2 ft^3/s. The initial data were used in this study and are shown in figure 12. Over the years, the hatchery used different methods to estimate pumpage from the CT well field. Prior to 1999, pumpage estimates were based on the run time and nominal pumping rate of each CT well, which is 12.5 ft^3/s. From 1999 until November 10, 2001, pumpage estimates were based on flow measurements over damboards at the end of hatchery ponds, and from November 10, 2001 through 2005, pumpage was measured by a flow meter. Based on the available data, it appears that by 2006, pumpage was again estimated based on the run time and nominal pumping rate of each CT well. The mean annual pumpage from 1999 through 2001, which was almost entirely based on damboard measurements, was 36 percent less than the mean annual pumpage during the 10-year period including 1994 through 1998 and 2002 through 2006 (26.7 ft^3/s versus 41.4 ft^3/s, respectively). Because there was no known change in operations of the hatchery between 1999 and 2001 (S. Dilly, Public Utility District No. 1 of Chelan County, oral commun., 2007), the pumpage estimates based on damboard measurements were assumed to be in error. Instead, new pumpage estimates were computed based on the run time and nominal pumping rate of each CT well. This increased the estimate of mean annual pumpage from 1999 through 2001 by 41 percent to 37.6 ft^3/s (fig. 12).

The information provided by the Eastbank Hatchery notes that around the time the flowmeter was installed in late 2001, wells of the CT well field received maintenance that increased the peak capacity of the well field by about 5 ft^3/s and restored the well field to close to its nominal capacity of 50 ft^3/s. The maximum pumpage from the CT well field prior to well maintenance was reported to be 43 ft^3/s, but it is not known how long the wells had been pumping at reduced capacity. The maximum pumpage from the CT well field measured by the flow meter was 48.5 ft^3/s in 2003 and 47 ft^3/s from 2004 through 2005. This information indicates that pumpage estimates for the CT well field based on the run time and nominal pumping rate of individual wells may be too high by as much as about 15 percent prior to 2002 and by as much as about 6 percent in 2006. The percentage of overestimation of pumpage prior to 2002 would depend on how long the CT wells had been pumping at reduced capacity.

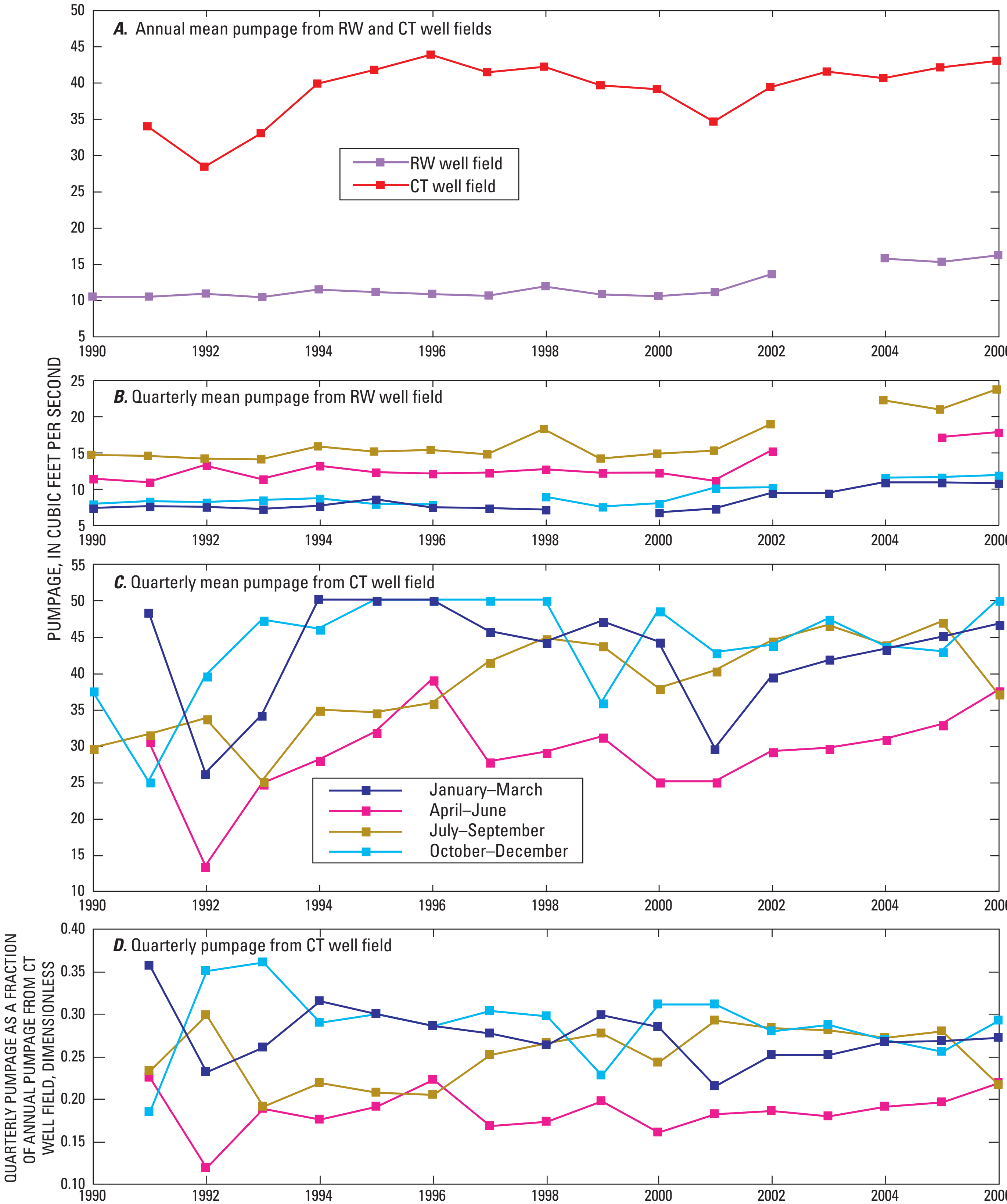


Figure 12. Annual mean and quarterly mean pumpage from the RW and CT well fields, Eastbank Aquifer System, Douglas County, Washington, 1990–2006.

A breakdown of pumpage from the CT well field into quarterly mean pumpage (fig. 12*C*) and quarterly pumpage as a fraction of annual pumpage (fig. 12*D*) shows that the seasonal pumpage pattern has changed over time. Since 1994, summer (July–September) pumpage generally has increased, although the annual mean pumpage has remained relatively constant and increases expressed as a fraction of annual pumpage (fig. 12*D*) generally occurred prior to 1999. Winter (January–March) pumpage generally decreased from 1994 until about 2002. Starting in 2001, summer pumpage exceeded winter pumpage, except in 2006. From 1999 through 2006, the overall seasonal pumpage patterns were relatively stable. The seasonal pumpage patterns of the CT well field differ from the RW well field because pumpage from the CT well field is determined by fish-production needs of the Eastbank Hatchery and pumpage from the RW well field is determined by public-supply needs. In 2006, the mean annual pumpage from the CT and RW well fields was about 43 and 16 ft^3/s, respectively.

Other well fields in the study area are the SW and LR well fields, and pumpage from these well fields is negligible compared to pumpage from the RW and CT well fields. The original purpose of the SW well field was to lower ground-water levels during construction of Rocky Reach Dam. Since completion of the dam, two wells of the SW well field (SW13 and SW14) have continued to be pumped at a combined rate of about 80 gal/min or about 0.2 ft^3/s to lubricate turbines at Rocky Reach Dam and one well, SW11, has been used seasonally to irrigate small parts of the study area. Pumpage from the SW11 well is unknown but it is assumed to be negligible. The LR well field provides water for irrigation of Lincoln Rock State Park. The well field has been in operation since about 1980 and the wells are pumped several hours per day for about 6 months per year. Pumpage data for 2004 through 2006 (S. Dilly, Public Utility District No. 1 of Chelan County, written commun., 2007) show that the mean annual pumpage from the LR well field is about 0.14 ft^3/s. It is assumed that mean annual pumpage has remained relatively constant from the LR well field since the start of its operation and from the SW well field since the start of its use for irrigation and turbine lubrication.

Ground-Water Seepage Through the Subsurface Cutoff Wall

Ground-water seepage through the subsurface cutoff wall that was captured by drains has been measured in the North and South Weirs since July 1, 1977 (I. Adams, Public Utility District No. 1 of Chelan County, written commun., 2007; fig. 13). Weir stage is recorded by a strip-chart recorder and converted to discharge using the stage-discharge rating curve for the weir. Prior to 1989, weir discharge was recorded monthly and starting in 1989, weir discharge was mostly recorded semi-annually. Other than a note indicating that the weirs were recalibrated sometime between late 2001 and late 2002, the only other historical calibration information available to this study was from K. deRubertis and others (written commun., 2007) stating that measurements made on February 24, 2006, correlated with the recorded values. At 8:43 a.m. on July 17, 2007, measured stage of the water in the box of the North Weir was 0.36 ft and recorded stage was 0.335 ft. These values are close (within 7 percent of each other) and so both the North and South Weirs were assumed to be accurately recording weir stage. A more detailed analysis of the weir recordings was beyond the scope of this study.

Seepage from the Lower Aquifer is assumed to flow through the North Weir and seepage from the Upper Aquifer is assumed to flow through the South Weir. This assumption is based on the significant decrease in discharge that occurred in the North Weir after October 1987 (fig. 13) that coincided with the installation of the CT well field. No other information is available to support this assumption and it is possible each weir captured a combination of seepage from the Lower and Upper Aquifers.

Mean discharges in the North Weir were 5.4 ft^3/s from July 1977 through October 1987 and 3.1 ft^3/s from November 1987 through December 1998. This means that the long-term mean seepage from the Lower Aquifer through the subsurface cutoff wall decreased by 2.3 ft^3/s or 43 percent. In contrast, discharge in the South Weir, and thus seepage from the Upper Aquifer through the subsurface cutoff wall, was relatively constant during the same time period, showing an increase of 0.7 ft^3/s or about 13 percent, from 5.4 to 6.1 ft^3/s.

The first wells of the CT well field were completed in November 1987, followed by CT3 in December 1987 and CT4 in January 1988 (table 3). Even though the Eastbank Hatchery did not become operational until July 1989 and expanded to full operations by about November 1989 (I. Adams, Public Utility District No. 1 of Chelan County, written commun., 2008), it is postulated that the CT well field started pumping as soon as wells were installed and that this explains the decrease in seepage from the Lower Aquifer.

From 2004 through 2006, the mean total discharge through the North and South Weirs was 8.4 ft^3/s. This indicates that from 2004 through 2006, the mean annual ground-water pumpage from the Eastbank Aquifer system was about seven times the measured portion of the mean annual ground-water seepage through the subsurface cutoff wall.

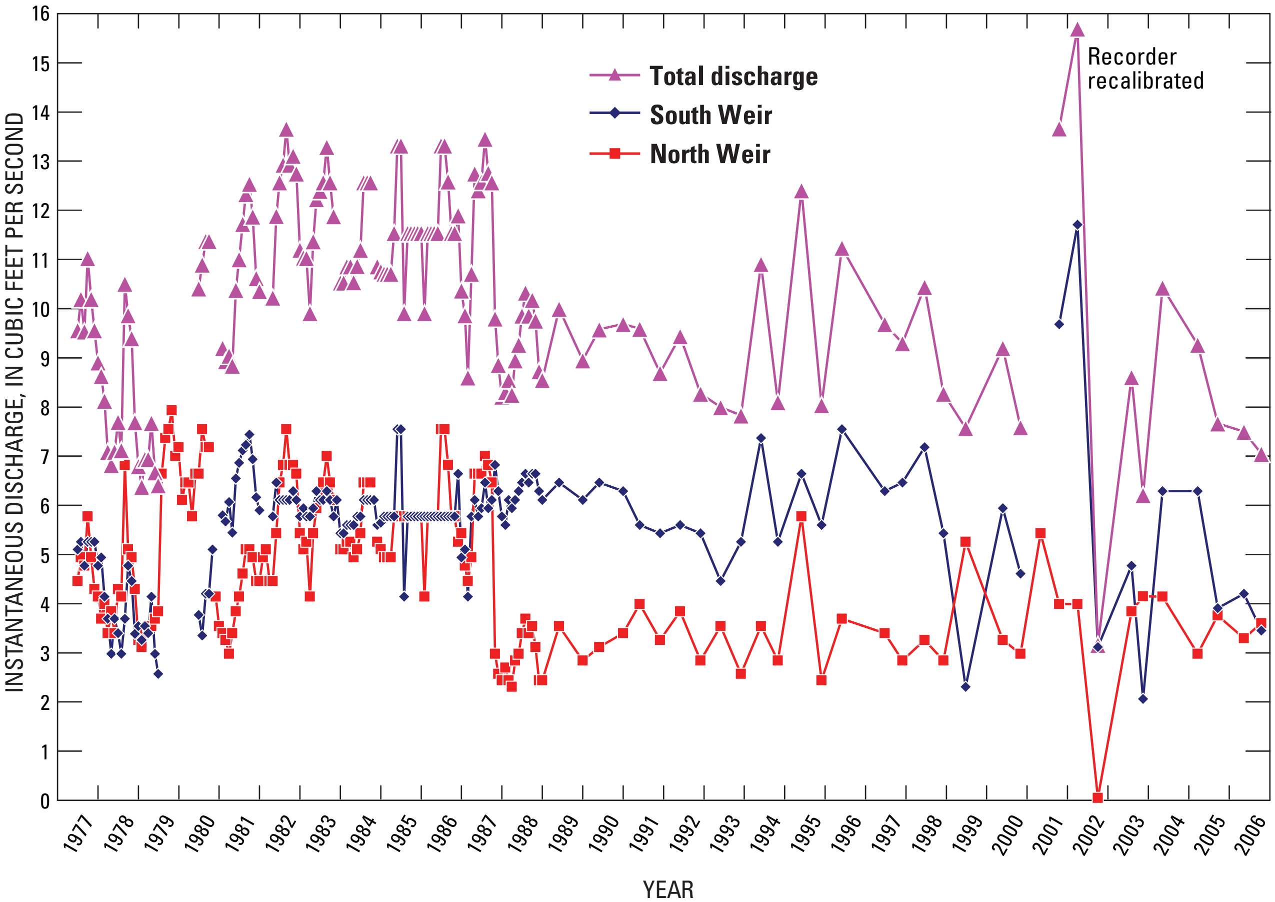


Figure 13. Instantaneous discharge through the North and South Weirs and total instantaneous discharge, Eastbank Aquifer System, Douglas County, Washington, 1977–2006.

Historical Ground- and Surface-Water Levels

Water levels have been measured hourly in 12 wells and 1 river site by the PUD since 1990 (fig. 10) for the purpose of monitoring hydrologic conditions of the Eastbank Aquifer system. Daily means of the hourly water levels for January 1, 1991 through September 30, 2006, are shown in figure 14. In addition to the continuous, hourly measurements, occasional manual water-level measurements have been made to verify the continuous measurements.

Reliability of Historical Water-Level Measurements

The historical hourly water levels have been measured using sealed probes that measure both water levels and water temperature (see Water & Environmental Systems Technology, Inc., 1990, for a detailed description of the instrumentation). Because the probes are not vented to the atmosphere, changes in atmospheric pressure are recorded as apparent changes in water levels, even if the actual water levels did not change in response to changes in atmospheric pressure. Without corrections for atmospheric effects, errors between actual and recorded water levels by non-vented probes may be on the order of inches to feet (Wardwell, 2007). Other sources of error in the recorded water-level data are instrument drift, possible incomplete information about the timing of probe replacements, and noise that resulted from spliced transmission cables that had to be repaired. Probes were replaced in case of obvious instrument failure (D. Davies, Public Utility District No. 1 of Chelan County, oral commun., 2007).

To be able to correct for instrument drift and other possible sources of error, manual water-level verification measurements are needed at regular intervals throughout the year for comparison to recorded water levels. The first water-level verification measurements since the start of the monitoring network in 1990 known to this study were made in July 1998, when the monitoring network was recalibrated.

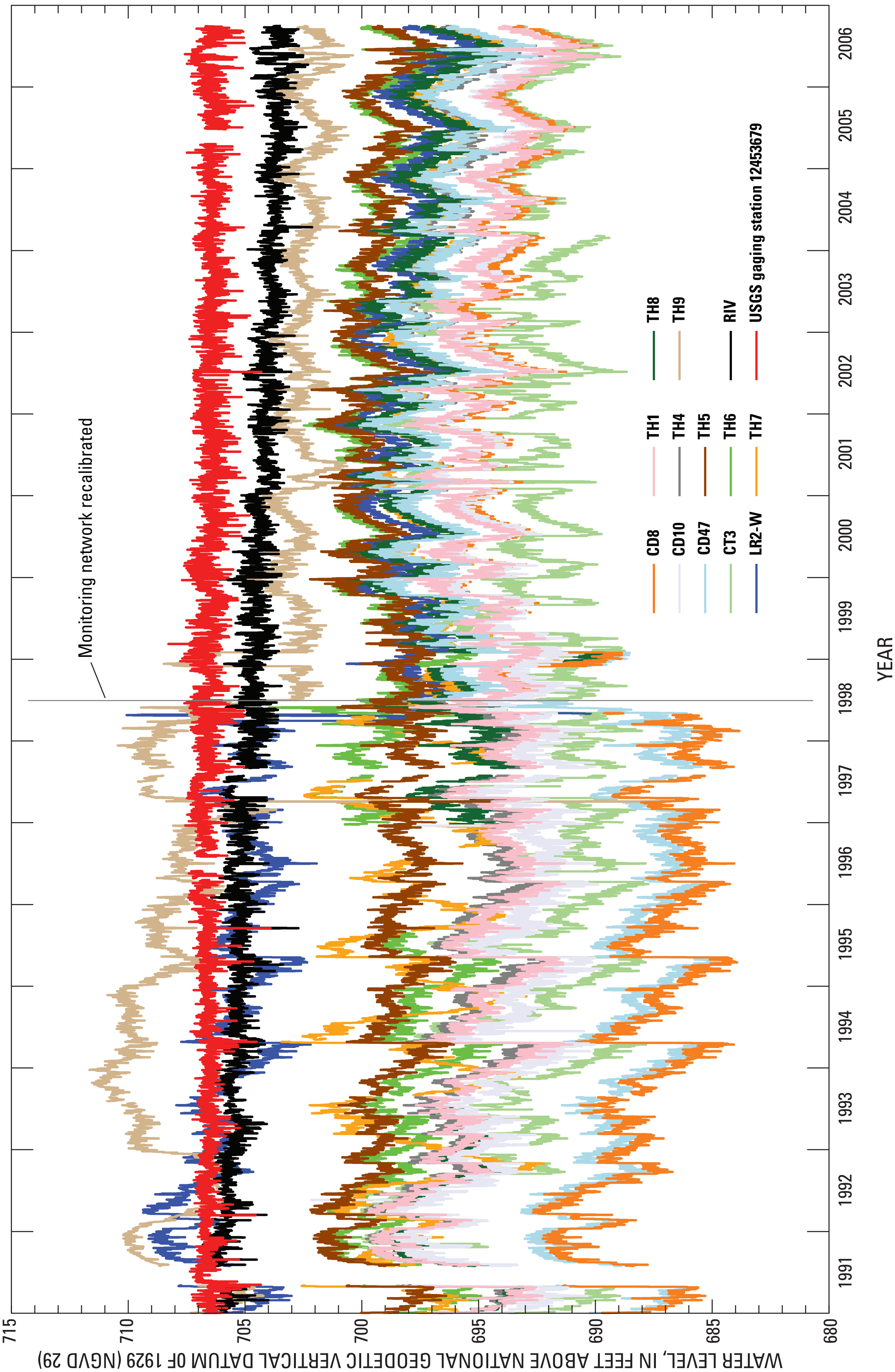


Figure 14. Daily mean water levels recorded by the monitoring network of the Eastbank Aquifer system, Douglas County, Washington, and daily water levels recorded at midnight by USGS gaging station 12453679, Chelan County, Washington, January 1991 – September 2006.

This recalibration resulted in significant shifts in some recorded water levels at that time (fig. 14). (Sudden rises in water levels during the spring of the mid-1990s correspond to seasonal reductions in pumping by the CT wells.) The next known verification measurements were made in February, 2006 (K. deRubertis and others, written commun., 2007) followed by periodic measurements made by this study from July 2007 through January 2008. Differences between water levels measured manually in February 2006 (K. deRubertis and others, written commun., 2007) and July 2007 and those recorded by the monitoring network are summarized in table 4. Other than the outlier of 9.51 ft, the differences in the measurements range from -2.39 to 3.39 ft. Because few verification measurements have been made over the period of record of the monitoring network, there is significant uncertainty in the historical continuous water-level data.

To evaluate the accuracy of the long-term record of the river probe (RIV in fig. 14), river water levels measured by the monitoring network were compared to river water levels recorded by USGS gaging station 12453679 (period of record July 25, 1975 to the present [2008]). The gaging station is located along the west bank of the river at the forebay of Rocky Reach Dam (fig. 2). The gaging station measures hourly water levels but only measurements at midnight are reported by the USGS (fig. 14). Recorded water levels are verified at regular intervals with manual measurements and the water-level record is adjusted accordingly. A comparison of the water-level record of the USGS station and the probe labeled RIV shows that probe RIV has been subject to a steady downward instrument drift of about 3 ft since 1990. Probes in wells of the monitoring network are of the same type and it is likely that they have drifted also, but the magnitude and direction of their drifts over the life of the monitoring network cannot be determined due to a lack of manual water-level measurements.

The pre-development potentiometric surface measured in the Eastbank Aquifer system in 1977 (fig. 11) shows that potentiometric gradients in the study area are small and thus accurate water-level measurements are required to be able to use the historical continuous water-level data for analyses of long-term changes in the aquifer system. The uncertainty of the historical continuous water-level data is too large for this purpose and so these data were not further analyzed in this study.

Table 4. Differences between water levels measured manually and those recorded by the monitoring network, Eastbank Aquifer system, Douglas County, Washington, February 2006 and July 2007.

[Locations of wells are shown in figure 2. **USGS well no.:** See figure 4 for explanation of well-numbering system. Latitudes and longitudes of the wells are on file with the U.S. Geological Survey. **Difference between manually measured and recorded water levels:** negative values indicate that manually measured water levels are lower than recorded water levels, and positive values indicate that they are higher. **February 6-8, 2006:** Values computed from data provided by K. deRubertis and others (written commun., 2007). **July 18, 2007:** Values are medians of differences computed from multiple measurements between 11:00 a.m. and 3:30 p.m., Pacific Daylight Time. **Abbreviations:** USGS, U.S. Geological Survey; –, not available]

Local well name	USGS well No.	Difference between manually measured and recorded water levels (feet)	
		February 6–8, 2006	July 18, 2007
CD8	24N/20E-35R01	0.01	2.57
CD10	24N/20E-35Q01	-2.39	3.39
CD47	24N/20E-35Q02	.4	1.22
CT3	24N/20E-35Q03	.72	.79
LR2-W	24N/20E-35H02	.53	–
TH1	24N/20E-35K05	–	–
TH4	24N/20E-35K02	9.51	1.96
TH5	24N/20E-35G01	.7	1.30
TH6	24N/20E-35G02	-.08	-.29
TH7	24N/20E-35K01	.66	1.07
TH8	24N/20E-35K04	-.36	.42
TH9	24N/20E-35K03	.23	1.08

Ground-Water Levels on July 18, 2007

To make equipment repairs at the Eastbank Hatchery, the PUD scheduled a shutdown of the CT well field from 1 to 3 p.m. on July 18, 2007. Because a complete shutdown of all CT wells is rare, the opportunity was used to schedule a shutdown of all significant pumping wells in the study area and to measure water levels before and after the shutdown. Arrangements were made with the City of Wenatchee and Lincoln Rock State Park to simultaneously shut down the RW and LR well fields. In addition, the PUD shut down wells SW13 and SW14, and only continued to pump about 20 gal/min from well SW11. From about 9 a.m. until about 5 p.m. on July 18, 2007, the recording frequency of the monitoring network was increased from once per hour to once per minute and a team of PUD and USGS personnel made multiple manual water-level measurements from about 10 a.m. until shortly after 3 p.m. River water levels measured at USGS gaging station 12453679 were nearly stable between 10 a.m. and 3 p.m., ranging from 704.33 ft at 10 a.m. to 704.59 ft at 1 p.m. Water levels were not measured in the LR and SW wells because they were not accessible, and water levels were not measured in well CD6 because it had not been located at the time. In addition, before pumping ceased, water levels were not measured in pumping wells except for one measurement in well RW4. The water-level data were used to document the ground-water flow pattern of the Lower and Combined Aquifers before and after the shutdown of pumping.

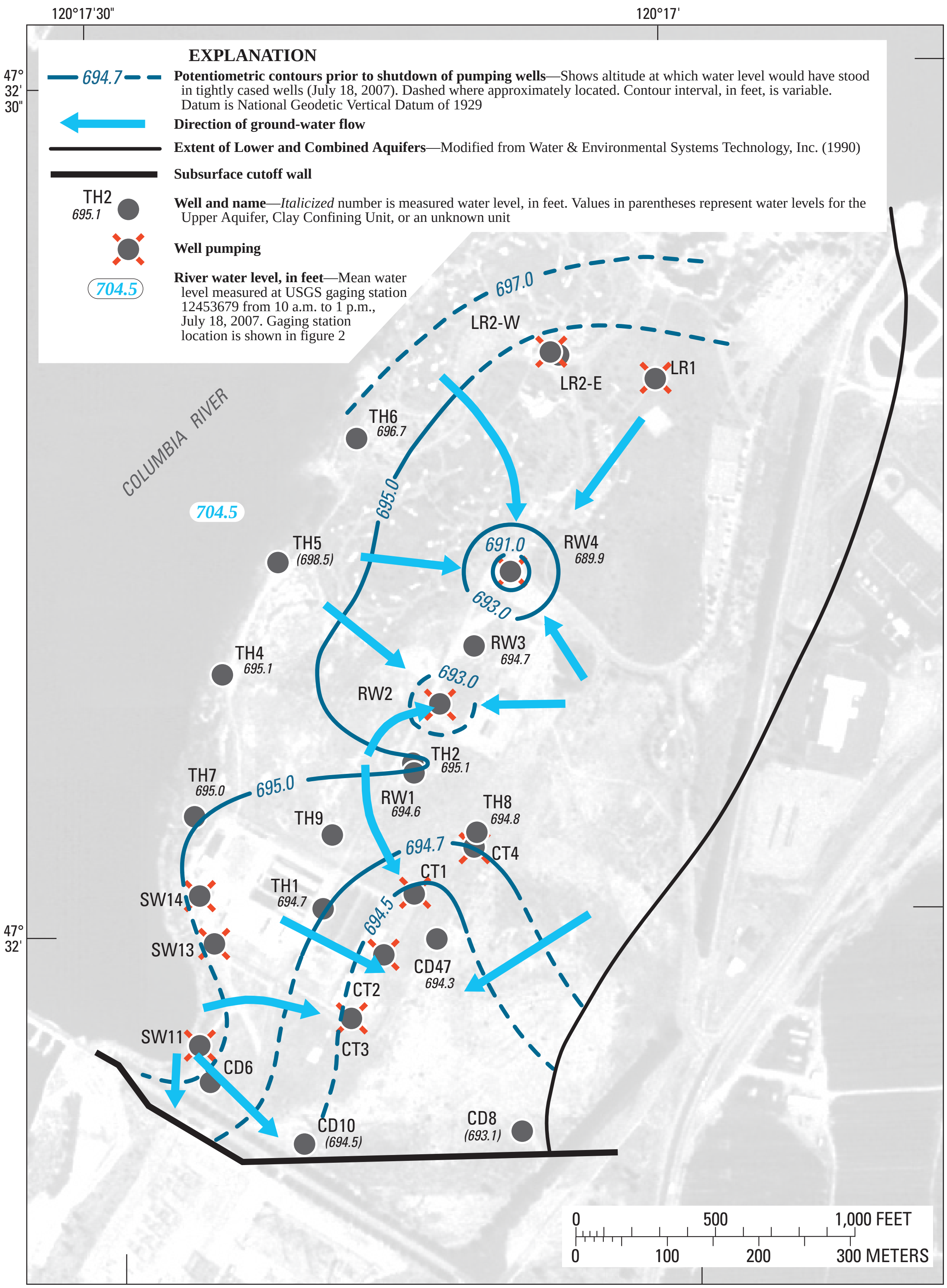
During the shutdown, the water-level probe in well TH1 was not working properly and the water level in well TH9 did not respond to the shutdown of pumping. The lack of response in well TH9 is considered anomalous and remains unexplained. A slug test was performed in well TH9 to determine if the well was isolated from the aquifer due to clogging of its perforations. However, changes in water levels induced by the slug test dissipated quickly and thus the well perforations were not clogged. A subsequent down-hole camera survey of well TH9 revealed that it contained a 1-inch inner-diameter PVC pipe at depth attached to a heavy object that was presumed to be a pump. An attempt to remove the pipe and pump was unsuccessful (see appendix 2 for additional detail).

Prior to Cessation of Ground-Water Pumping

Multiple water levels measured manually prior to the shutdown of pumping wells were averaged, plotted, and contoured to create a potentiometric-surface map of the Lower and Combined Aquifers (fig. 15). At the time, wells CT1, CT2, CT3, CT4, RW2, RW4, LR1, LR2-W, SW11, SW13, and SW14 were pumping. The nominal pumping rate of each CT well was 12.5 ft^3/s, and wells RW2 and RW4 were pumped at rates of 18.5 and 22.3 ft^3/s, respectively. The combined pumping rates of the LR and SW wells were estimated to be 0.3 and 0.2 ft^3/s, respectively. Figure 15 shows that with four CT and two RW wells pumping, a cone of depression surrounds the RW field and another cone of depression surrounds the CT well field. The cone of depression of the CT well field widens towards the south because some ground water drains through the subsurface cutoff wall. The cones of depression of the RW and CT well fields intersect and create a ground-water divide along an approximately east-west line going through the general area between wells RW1 and TH8. Based on the potentiometric contours, the horizontal ground-water flow direction is approximately radial towards the pumping wells with source water originating along the aquifer boundary with the Columbia River (fig. 15). A steep potentiometric gradient exists between the river and the western extent of the Lower and Combined Aquifers, indicating that the bottom of the Columbia River is blanketed with materials of lower permeability than the sediments of the Lower and Combined Aquifers. An aquatic habitat study of Lake Entiat confirmed the presence of fine-grained sediments at the bottom of the Columbia River near the study area (Duke Engineering & Services, Inc., 2001). The layer of fine-grained sediments impedes ground-water recharge from the Columbia River but it does not prevent it, as demonstrated by the potentiometric-surface maps (figs. 11 and 15). In addition to the approximately radial horizontal ground-water flow toward the pumping wells, ground water also flows towards the subsurface cutoff wall. The majority of flow to the CT well field may come from the small embayment northeast of and adjacent to Rocky Reach Dam (fig. 15). The aquatic habitat study mapped large cobble and gravel at the bottom of the embayment (Duke Engineering & Services, Inc., 2001), which is riprap that was put at the bottom of the embayment after it was excavated as part of the construction of Rocky Reach Dam.

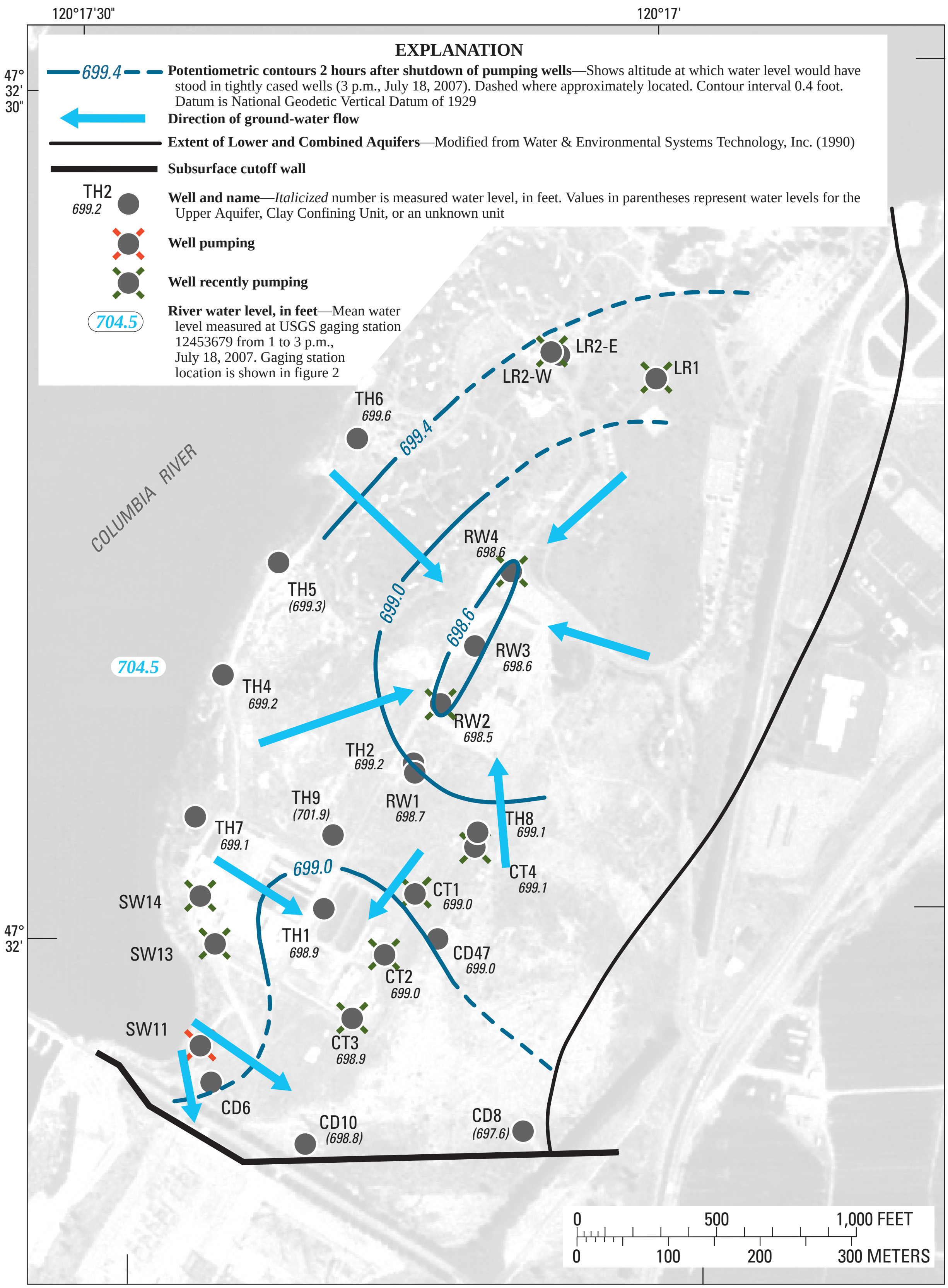
Two Hours after Cessation of Ground-Water Pumping

Following the shutdown of the pumping wells at 1 p.m., multiple water levels were measured manually in monitoring wells and wells that were previously pumping. The manual measurements continued until shortly after 3 p.m., when the pumping wells that were shut down at 1 p.m. were turned back on. The last set of manual water-level measurements that were made from 3 to 26 minutes before 3 p.m. were extrapolated to 3 p.m. to obtain a set of estimated water levels that represented the potentiometric surface 2 hours after the start of water-level recovery. For wells that are part of the monitoring network, extrapolations of manual water-level measurements were based on the water-level recovery pattern recorded every minute by the monitoring network; for wells that are not part of the monitoring network, extrapolations were made visually based on trends in multiple manual water-level measurements. Water-level adjustments ranged from -0.1 to 0.5 ft with a median adjustment of 0.1 ft. Figure 16 shows that after 2 hours of water-level recovery, the cones of depression surrounding the RW and CT well fields remain, although the potentiometric gradients are less steep. Excluding water-level recoveries of 0 ft in well TH9 and 8.7 ft in well RW4, the water levels recovered from 0.8 ft in well TH5 to 4.7 ft in well CD47, with a median recovery of 4.1 ft. The water levels recorded every minute by the monitoring network indicated that although recovery had slowed down after 2 hours, complete recovery was not achieved. Complete recovery would be expected to return the potentiometric surface to the predevelopment conditions measured on July 19, 1977 (fig. 11). Based on the pattern of the water-level contours, the horizontal ground-water flow directions after 2 hours of recovery were still similar to the flow directions prior to the shutdown of the pumping wells.



U.S. Forest Service orthophoto, Rocky Reach Dam quad, August 2, 1998
Universal Transverse Mercator projection, Zone 10
Horizontal datum: North American Datum of 1927 (NAD 27)

Figure 15. Potentiometric surface of the Lower and Combined Aquifers prior to the shutdown of pumping wells, Eastbank Aquifer system, Douglas County, Washington, July 18, 2007.



U.S. Forest Service orthophoto, Rocky Reach Dam quad, August 2, 1998
Universal Transverse Mercator projection, Zone 10
Horizontal datum: North American Datum of 1927 (NAD 27)

Figure 16. Potentiometric surface of the Lower and Combined Aquifers 2 hours after shutdown of pumping wells, Eastbank Aquifer system, Douglas County, Washington, 3 p.m., July 18, 2007.

Historical Ground- and Surface-Water Temperatures

Water temperatures have been measured hourly in 12 wells and 1 river site by the PUD since 1990 for the purpose of monitoring thermal conditions of the Eastbank Aquifer system. The river probe (RIV in fig. 10), which also measures the water level of the river, is in a PVC pipe draped along the bottom of the river, about 200 ft offshore. Hourly water temperatures measured in the monitoring-network wells represent temperatures at particular depths and do not provide vertical temperature profiles. Daily median temperatures were computed from hourly temperatures for 2006 (fig. 17), which is an example of a typical 1-year period. The temperature records indicated that different wells have different annual temperature ranges and different time lags between changes in river temperatures and subsequent changes in well temperatures (fig. 17).

Water & Environmental Systems Technology, Inc. (1990) measured vertical temperature profiles in wells CD6, CD47, TH1, TH4, TH5, TH6, TH7, TH8, and TH9 at selected times between July 1989 and April 1990. These profiles indicated that there were significant vertical temperature gradients in the Eastbank Aquifer system that changed seasonally. In July 1987, CH2M Hill (1988) measured vertical temperature profiles in wells TH4, TH5, and TH6 but these data were not available to this study. In February 2006, K. deRubertis and others (written commun., 2007) measured vertical temperature profiles in the same wells as CH2M Hill and also wells CD8, CD10, CD47, LR2-W and TH7. This study measured vertical temperature profiles in wells CD10, TH1, TH4, TH6, TH7, and TH9 between August and September 2007 and started a network of monthly measurements of vertical temperature profiles in 12 wells (CD6, CD8, CD10, CD47, TH1, TH2, TH4, TH5, TH6, TH7, TH8, and TH9) in December 2007 that is now maintained by the PUD.

On August 20, 2007, 32 vertical temperature profiles were measured using CTD (conductivity-temperature-depth) casts in the Columbia River near the study area to determine if the river was thermally stratified in the area of likely ground-water recharge. Profiles were located in an approximately 500-ft-wide band extending from the north shore near the boat ramp (fig. 2) to the shore along the embayment adjacent to Rocky Reach Dam. One profile was measured in the center of the river. Excluding two anomalous temperature profiles located near the outfall from the Eastbank Hatchery, negligible

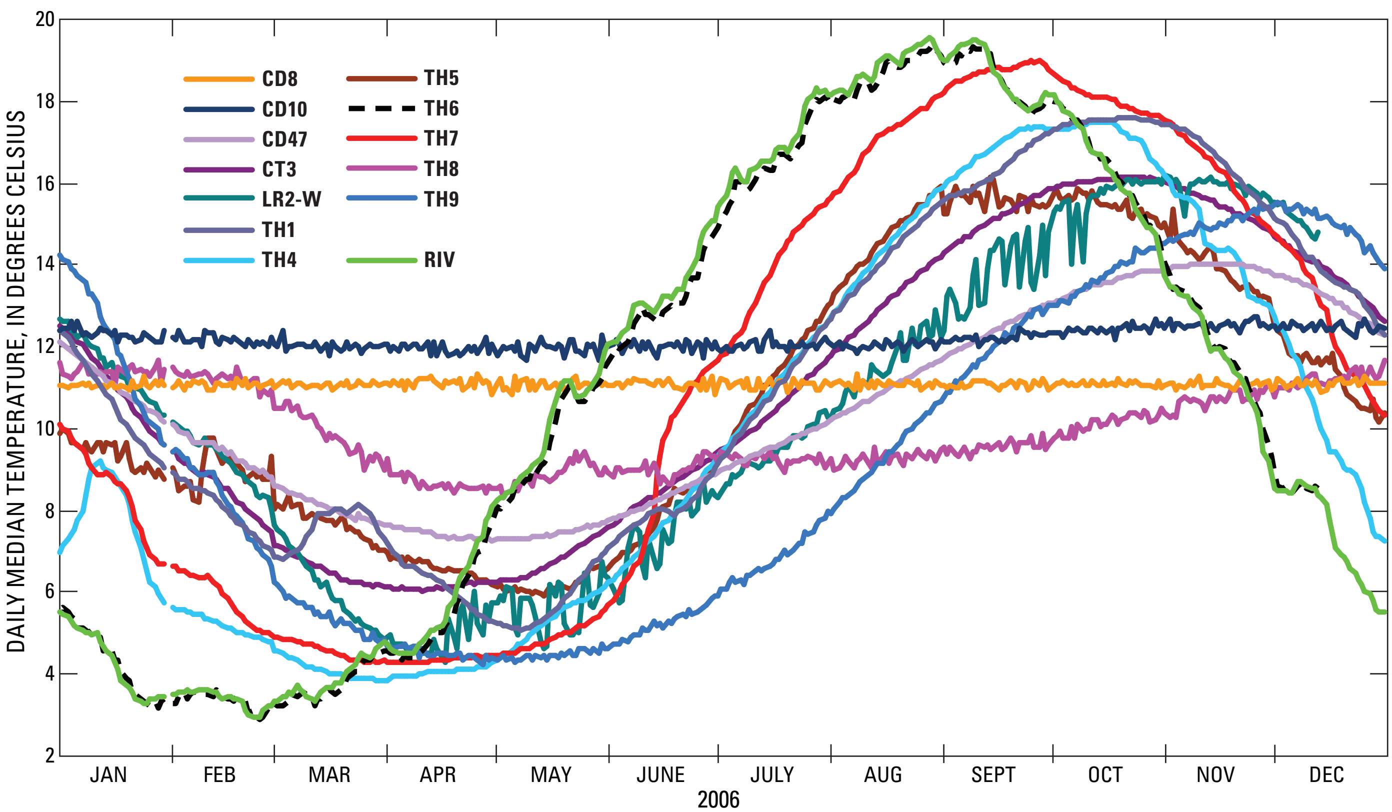


Figure 17. Daily median water temperatures recorded by the monitoring network of the Eastbank Aquifer system, Douglas County, Washington, 2006.

temperature variation was measured. Water temperatures ranged from 19.0 to 19.5°C, with a median of 19.3°C and a standard deviation of 0.1°C. Previous temperature studies also showed a lack of both vertical and lateral stratification of the river near the study area. For example, in a series of approximately monthly vertical temperature-profile measurements from October 1999 through September 2000 located in the center of the river approximately due west of well TH6, Parametrix, Inc. and Rensel Associates Aquatic Science Consultants (2001) measured a maximum temperature range of 0.32°C on July 14, 2000. Parametrix, Inc. and Thomas R. Payne & Associates (2002) recorded nearly constant temperatures in a temperature transect of the river adjacent to the study area in the morning and afternoon of September 2, 2001, except for a slight warming of the surface layer in the afternoon ranging from 0 to 1.3°C. Based on these data, thermal stratification of the Columbia River near the study area was insignificant and water temperatures measured at any nearby river location were representative of the temperature of water that recharged the Eastbank Aquifer system within about ±0.5°C.

Reliability of Historical Water-Temperature Measurements

The historical hourly water temperatures were measured with the same sealed instruments used to measure water levels. Similar to the lack of manual measurements to verify water levels recorded by the monitoring network, there also was a lack of manual measurements to verify water temperatures recorded by the network. Temperature probes also are subject to failure, instrument drift, possible incomplete information about the timing of probe replacements, and the addition of noise due to transmission-cable repairs. However, water-temperature probes generally are more robust than water-level probes and their measurements are not affected by day to day changes in atmospheric pressure.

To evaluate the accuracy of the river probe (probe RIV), hourly river temperatures measured by the monitoring network were compared with hourly river temperatures measured at the forebay of Rocky Reach Dam (S. Hayes, Public Utility District No. 1 of Chelan County, written commun., 2007) for the time period of concurrent data, March 25, 2003 through August 15, 2007. River temperatures are measured at the forebay for the purpose of monitoring fish habitat and the time series used in this study consisted of merged records of four separate temperature probes (S. Hayes, Public Utility District No. 1 of Chelan County, written commun., 2007). Figure 18 shows that except for some scatter at the low-temperature range that represents several days in January 2007, there is a close match between the temperatures measured at midnight at the forebay and by probe RIV. Statistics based on all hourly data for the concurrent period show that the differences in temperature range from -0.7 to 2.1°C, with a median difference of 0.3°C and a standard deviation of 0.2°C. These results indicate that the temperature measurements of probe RIV since March 2003 have been accurate within a comparable margin of error (generally less than 1°C) as may result from assuming that water temperatures measured at any nearby river location are representative of the temperature of water that recharges the Eastbank Aquifer system. In addition, because probe RIV has not been replaced since its installation in 1990, it is reasonable to assume that temperature measurements by probe RIV have been reliable since 1990.

Similar temperature data were not available to verify the accuracy of temperature measurements by probes in wells of the monitoring network. Instead, probes were pulled from three wells (TH4, TH6, and TH7) and submerged in a water bath with two thermometers to obtain a representative comparison of temperature readings by the monitoring network (table 5). One thermometer was a Cole-Parmer® reference thermometer calibrated against a National Institute of Standards and Technology (NIST) standard thermometer (INNOCAL test no. 22144) and the other thermometer was a 300-ft-long TLC (temperature-level-conductivity) probe made by Solinst®. The accuracy of the TLC thermometer was confirmed using a 4-point verification in the USGS laboratory in Tacoma, Washington, on July 31, 2007. The temperature probe of a fourth well (CD10) was checked in place by submerging the TLC thermometer into the well to the reported depth of the probe. The probe was not pulled from well CD10 because it was stuck. Side-by-side thermometer and monitoring-network probe comparisons in a water bath are considered more reliable because the method leaves no question that all instruments are measuring the same water and that the measurements are made simultaneously. The results of the temperature comparisons indicate that the monitoring-network probes for wells TH4, TH6, and TH7 measured temperatures within 0.3°C of the reference thermometer (table 5). The monitoring-network probe for well CD10 measured temperature within 0.1°C of the TLC thermometer. Based on verifications of the subset of monitoring-network probes, bias and variability in temperature measurements for all monitoring-network probes were assumed to be less than 0.5°C.

In February 2006, K. deRubertis and others (written commun., 2007) made in-place comparisons of temperatures recorded by all probes of the monitoring network, except the probe in well CD47, at reported probe depths. They found that temperatures matched within 0.5°C, except for probes in wells LR2-W and TH8 for which differences exceeded 1.5°C. Water temperatures recorded once per minute on July 18, 2007, indicated that several temperature probes of the monitoring network had noisy recordings (defined as large variability over short periods of time), including the temperature probes of wells LR2-W and TH8. The large temperature discrepancies reported by K. deRubertis and others (written commun., 2007) for the probes in wells LR2-W and TH8 may therefore have resulted from small differences between the times the verification temperatures were read and the times the probe temperatures were recorded by the monitoring network.

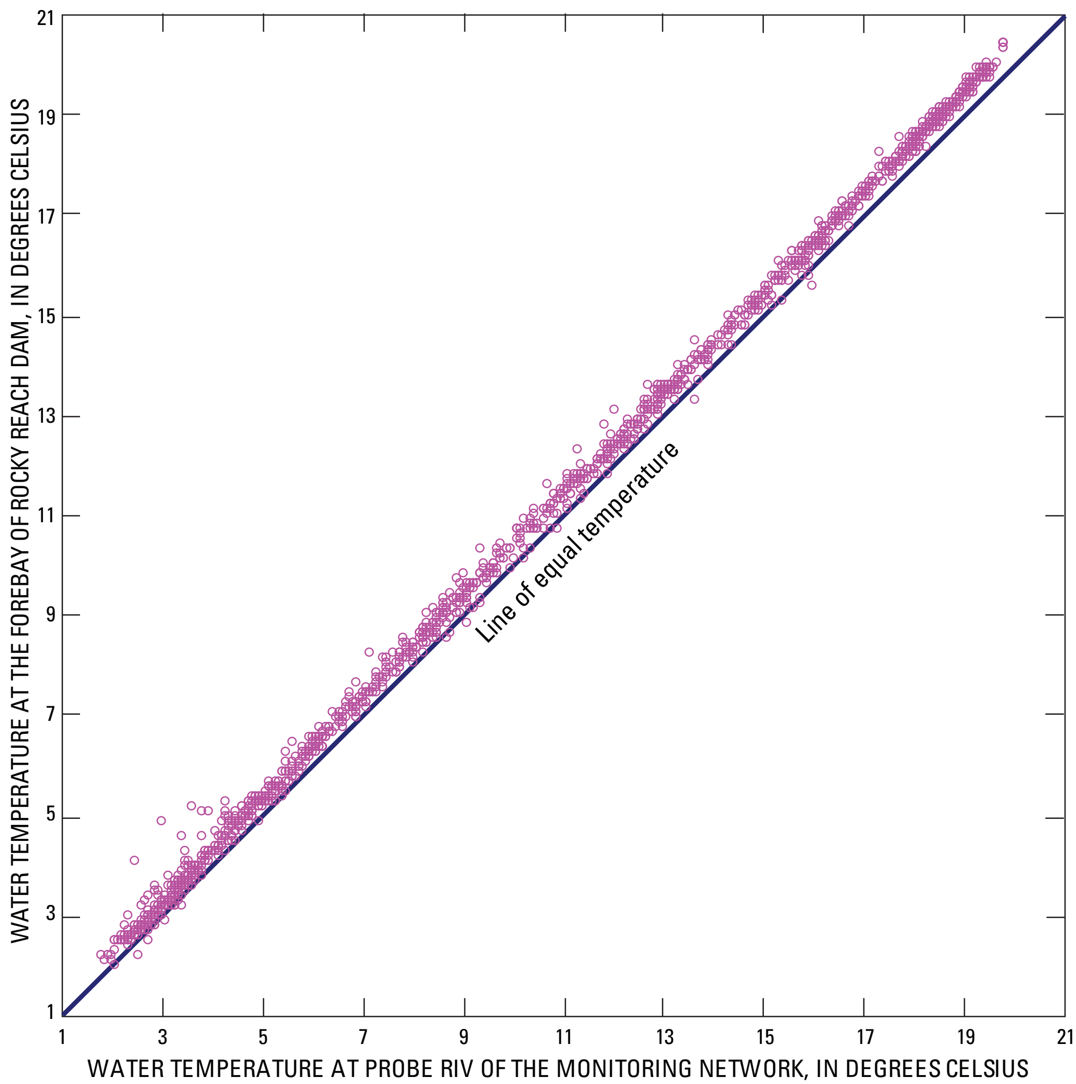


Figure 18. Daily river water temperatures recorded at midnight at the forebay of Rocky Reach Dam and at probe RIV of the monitoring network of the Eastbank Aquifer system, Douglas County, Washington, March 25, 2003 – August 15, 2007.

The limited verification data available for the temperature probes of the monitoring network indicate that many of the temperature probes may be making reliable temperature measurements and presumably have done so since they were installed or last replaced. Even if water temperatures recorded by the monitoring network cannot be relied on with great certainty due to limited verification data, the relative pattern of the historical temperature record is reliable and the recorded times of the annual minimum and maximum water temperatures are likely accurate within 1 day.

Trends in Water Temperatures

Ground-water recharge transports heat from the Columbia River to the Eastbank Aquifer system, and each location in the aquifer system has an annual temperature record that mimics the annual temperature record of the river. Generally, with increasing distance from the river, the time lag between a change in river temperature and a subsequent change in well temperature increases and the annual temperature range decreases. The spatial and temporal patterns of ground-water temperatures may change as thermal and hydraulic conditions change in the river and/or aquifer system. Water temperatures measured by the monitoring network were analyzed to determine if and how patterns of ground-water temperatures in the Eastbank Aquifer system have changed.

Table 5. Comparison of temperature measurements by probes in selected wells of the monitoring network of the Eastbank Aquifer system and two thermometers, Douglas County, Washington, September 12, 2007.

[Locations of wells are shown in figure 2. **USGS well No.:** See figure 4 for explanation of well-numbering system. Latitudes and longitudes of the wells are on file with the U.S. Geological Survey. **Monitoring-network probe**: Geokon probe. **Reference thermometer**: Cole-Parmer reference thermometer calibrated against a National Institute of Standards and Technology standard thermometer. **TLC**: Solinst temperature-level-conductivity (TLC) meter probe, 300 feet long. **Abbreviations:** USGS, U.S. Geological Survey; –, not available]

Local well name	USGS well No.	Water temperature (degrees Celsius)			Measurement type
		Monitoring-network probe	Reference thermometer	TLC	
CD10	24N/20E-35Q01	12.3	–	12.4	in place
TH4	24N/20E-35K02	13.2	13.5	13.6	water bath
		21.3	21.0	21.0	
TH6	24N/20E-35G02	20.5	20.3	–	water bath
TH7	24N/20E-35K01	24.2	24.3	24.6	water bath

Hourly water temperatures measured by the monitoring network from January 1, 1991 through August 31, 2007, were simplified to time series of daily median temperatures. The entire record of daily values was analyzed to determine if there were trends in the time lags between changes in river and well temperatures. The part of the record starting in 1999 was analyzed to determine if there were trends in the annual minimum and maximum well temperatures and in the annual temperature ranges of wells with respect to the river. The well-temperature record prior to 1999 was not analyzed for trends in annual extreme temperatures and annual temperature ranges due to uncertainty in the data. An analysis of temperature trends in the Eastbank Aquifer system must consider both horizontal and vertical variability of ground-water temperatures. A limited number of vertical temperature profiles were available to illustrate the three-dimensionality of ground-water temperatures, but too few profiles were available to determine interannual trends in vertical temperature profiles.

Analyses of trends in time lags and annual temperature ranges help determine if the ground-water flow system is in thermal equilibrium. In this study, the ground-water flow system is defined to be in thermal equilibrium at a given location if the time lags between changes in river temperatures and subsequent changes in ground-water temperatures are constant at that location. The equilibrium is a dynamic equilibrium because temperatures vary throughout the year. When the ground-water flow system is in thermal equilibrium, the ratios of annual temperature ranges in the wells to annual temperature ranges in the river also should be constant at a given location. Because transport of heat is primarily by advection (flow of water) within aquifers and by conduction within confining units, and because transport by advection is faster than by conduction (Miller and Delin, 2002), decreasing trends in time lags and increasing trends in ratios are likely explained by increasing transport of heat by advection. This transport increases as ground-water fluxes increase due to increases in pumping and/or increases in hydraulic conductivities as fine sediments in the aquifers are removed or rearranged as a result of pumping and preferential flowpaths form.

Because the only significant source of recharge to the Eastbank Aquifer system is the Columbia River, it is important to know whether there have been trends in river temperature during the periods of analysis. Annual minimum, maximum, and mean river temperature measured by probe RIV (fig. 10) from 1991 through August 2007 is shown in figure 19. Straight-line linear regressions of each time series for the entire time period show that there are no statistically significant trends in the annual minimum, maximum, and mean river temperature at a confidence level of 95 percent. However, straight-line linear regressions of each time series starting in 1999 show that there are statistically significant trends in the annual mean and maximum river temperature at a confidence level of 95 percent, indicating a mean annual increase in the annual mean and maximum river temperature from 1999 through 2006 of 0.07 and 0.17°C, respectively (fig. 19). There are no statistically significant trends in the annual minimum river temperature since 1999 at a confidence level of 95 percent, nor are there statistically significant trends in the annual minimum, maximum, and mean river temperature from 1991 through 1998 at a confidence level of 95 percent.

The analysis of well-temperature records was based on the assumption that the water temperature measured at a given depth in a monitoring well was representative of the water temperature at the same depth in the ground-water flow system outside the well. This assumption is justified because convective flow, and thus temperature-controlled density stratification of the water column, is unlikely to occur in the monitoring wells analyzed in this study due to their small diameters (3 to 8 in.; Diment, 1967; Gillespie, 1995). Well CT3, which is a hatchery well with a temperature probe located about 85 ft above the top of the open interval, has a casing diameter of 26 in. for most of its depth. Due to its large diameter, density stratification may occur in well CT3 when it is not pumping. When the well is pumping, the temperature probe measures water temperatures that are likely affected both by the ambient temperature of the ground-water flow system outside the well and the temperature of pumped water moving through a pipe inside the well casing. Well CT3 was

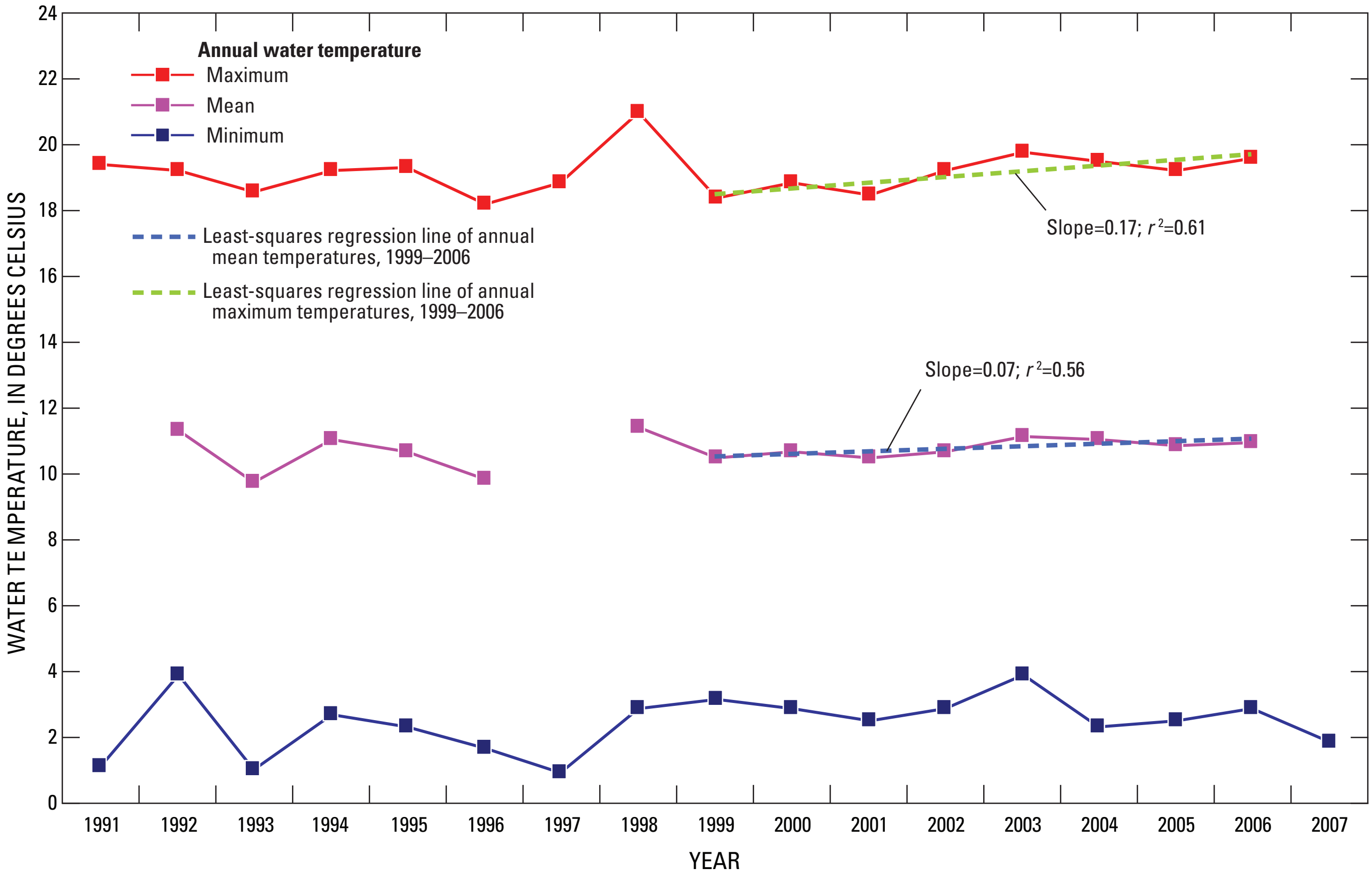


Figure 19. Annual minimum, maximum, and mean temperature of the Columbia River near the Eastbank Aquifer system, Douglas County, Washington, 1991–2007.

pumping the majority of the time, except during 1991 and 1992. Annual temperature extremes measured in well CT3 and that were used in the trend analyses were all measured when well CT3 was pumping, except for the annual maximum temperature in 1991 and the annual minimum temperatures in 1992, 1998, 2005, and 2006. Due to the poorly known variables that affect the temperature record of well CT3, there is greater uncertainty in the interpretation of the temperature records of well CT3 than the records of the monitoring wells.

Vertical Temperature Profiles

Figure 20 shows selected historical vertical temperature profiles in three wells, CD6, CD47, and TH8, measured in 1989–90 by Water & Environmental Systems Technology, Inc. (1990), in 2006 by K. deRubertis and others (written commun., 2007), and in 2007–08 by this study. Profiles were selected to illustrate the maximum temperature range that may occur in each hydrogeologic unit in each well. Although wells CD6 and TH8 had multiple temperature-profile measurements throughout 1989–90, none of the wells had a sufficient number of measurements to be sure that the annual temperature extremes had been measured.

The Upper Aquifer at well CD6 (fig. 20*A*), which is located near the shoreline and subsurface cutoff wall (fig. 15), has a temperature range that is almost identical to the temperature range of the river (fig. 19). In addition, the annual extreme temperatures in the river and Upper Aquifer at well CD6 occur at about the same time of year; usually the annual minimum and maximum river temperatures occur in February and August or September, respectively. Temperatures in the Upper Aquifer at the location of well CD6 track the river temperatures closely, because sediments of the Upper Aquifer near the well were highly disturbed during construction of Rocky Reach Dam and probably consist primarily of high-permeability backfill. The annual temperature range in the Lower Aquifer at well CD6 is smaller than that in the Upper Aquifer and the dates of annual high and low temperatures are different between the aquifers, with the Clay Confining Unit showing transitional patterns.

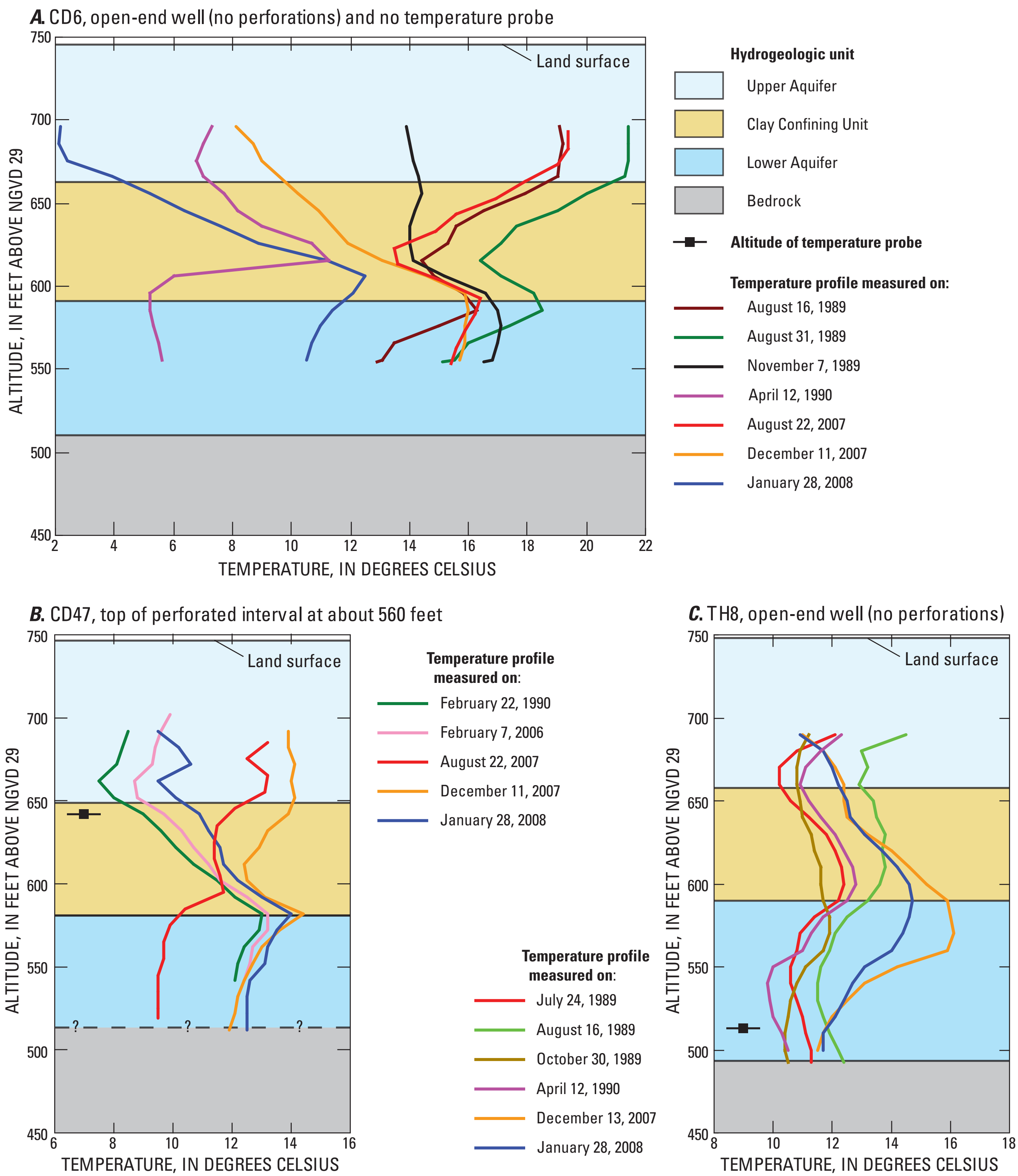


Figure 20. Selected vertical temperature profiles in wells CD6, CD47, and TH8 of the Eastbank Aquifer system, Douglas County, Washington, 1989–2008. Data for 1989–90 are from Water & Environmental Systems Technology, Inc. (1990) and data for 2006 are from K. deRubertis and others (written commun., 2007).

Wells CD47 and TH8 (figs. 20*B* and 20*C*) show complex vertical temperature profiles that are different from each other and well CD6, indicating that each location in the Eastbank Aquifer system has a set of unique, time-varying vertical temperature profiles. The temperature profile at each location at a given time is a function of the temperature and water level of the river; the proximity to the river, pumping wells, and subsurface cutoff wall; the rate and schedule of pumping; the horizontal and vertical hydraulic conductivities and thicknesses of the hydrogeologic units; and the thermal properties of the sediments of and the bedrock beneath the Eastbank Aquifer system. Even though the vertical temperature profiles of wells CD6, CD47, and TH8 differ, temperature changes across the confining units at each of these wells indicate that the flow systems of the Upper and Lower Aquifers are not tightly connected although there is a stronger connection at well TH8.

A comparison of the vertical temperature profiles of the Lower Aquifer of wells CD47 and TH8 shows that generally, the vertical temperature gradients are slightly larger in well TH8 than in well CD47 indicating slightly more flow in the upper part of the Lower Aquifer near well TH8. Well TH8 has no perforated interval, so water inside its casing has likely equilibrated to the temperature of the surrounding aquifer by conduction. One possible explanation for the increased flow in the upper part of the Lower Aquifer is that it has a relatively larger horizontal hydraulic conductivity, although the driller's log for well TH8 did not indicate a significant change in lithology from the upper to the lower parts of the Lower Aquifer. An alternative explanation for the increased flow in the upper part of the Lower Aquifer near well TH8 is that the well is very near the CT well field, and in particular near well CT4 (fig. 15). Well CT4 is open to the Lower Aquifer from an altitude of 549 to 575 ft and the open intervals for all wells of the CT well field range from 540 to 576 ft.

The smaller vertical temperature gradients in the lower part (below the altitude of the CT well field open intervals) of the Lower Aquifer of well TH8 during much of the year represent colder and thus denser water that probably is pumped by the CT well field at a lower rate than water in the upper part (within the altitude range of the CT well field open intervals) of the Lower Aquifer. The source of some of this colder water may be colder and denser water that settled locally in the bedrock depression north and west of well TH8 (fig. 7) and is captured by well CT4. The smaller vertical temperature gradients in the Lower Aquifer of well CD47 may result from mixing of water at and near the open interval because well CD47 is perforated below an altitude of about 560 ft. The mixing would result in more uniform water temperatures in the well that represent the average ambient ground-water temperatures near the perforated interval. Alternatively, mixing in well CD47 is minimal and the vertical temperature profile measured in the well reflects the vertical temperature profile of the ambient water temperatures. Vertical temperature profiles not shown for other monitoring wells with perforated intervals (for example, wells TH1, TH4, and TH7) include significant vertical temperature gradients (up to about 0.1°C/ft) adjacent to open intervals and so it is assumed that generally, vertical temperature profiles measured in monitoring wells with perforated intervals are representative of vertical temperature profiles of ambient temperatures.

The vertical temperature profiles in figure 20 also indicate that the depth at which a temperature probe is located substantially influences the ground-water temperature measurements. For example, a probe located in the upper part of the Lower Aquifer of well TH8 (fig. 20*C*) would measure a different temperature record than a probe located in the lower part of the aquifer, where the probe in well TH8 has been located since the start of the monitoring network. Trend analyses of the temperature record of a probe that has remained at a constant depth through time can provide useful insights into the dynamics of the aquifer system.

Spatial Patterns

Temporal trends in time lags between changes in river and ground-water temperatures; annual ranges in ground-water temperatures with respect to annual ranges in river temperatures; and annual extreme ground-water temperatures were analyzed spatially.

Time Lags

Time series of daily median water temperatures were used to estimate the time lag between a change in river temperature and the subsequent change in ground-water temperature at a given well. Particular focus was on the time lag between annual minimum and maximum temperatures. The time lags were estimated as the difference between the date of an annual extreme temperature in the river and the date of the subsequent annual extreme temperature in individual wells. Time lags did not exceed 1 year. The resulting annual time series of time lags of annual minimum and maximum temperatures are shown in figure 21. Time lags of wells in which the subsequent annual extreme occurred in the following year are plotted according to the year of the annual extreme in the river. Data are missing for years when well-temperature records had gaps or when the record was unclear when the annual minimum or maximum occurred.

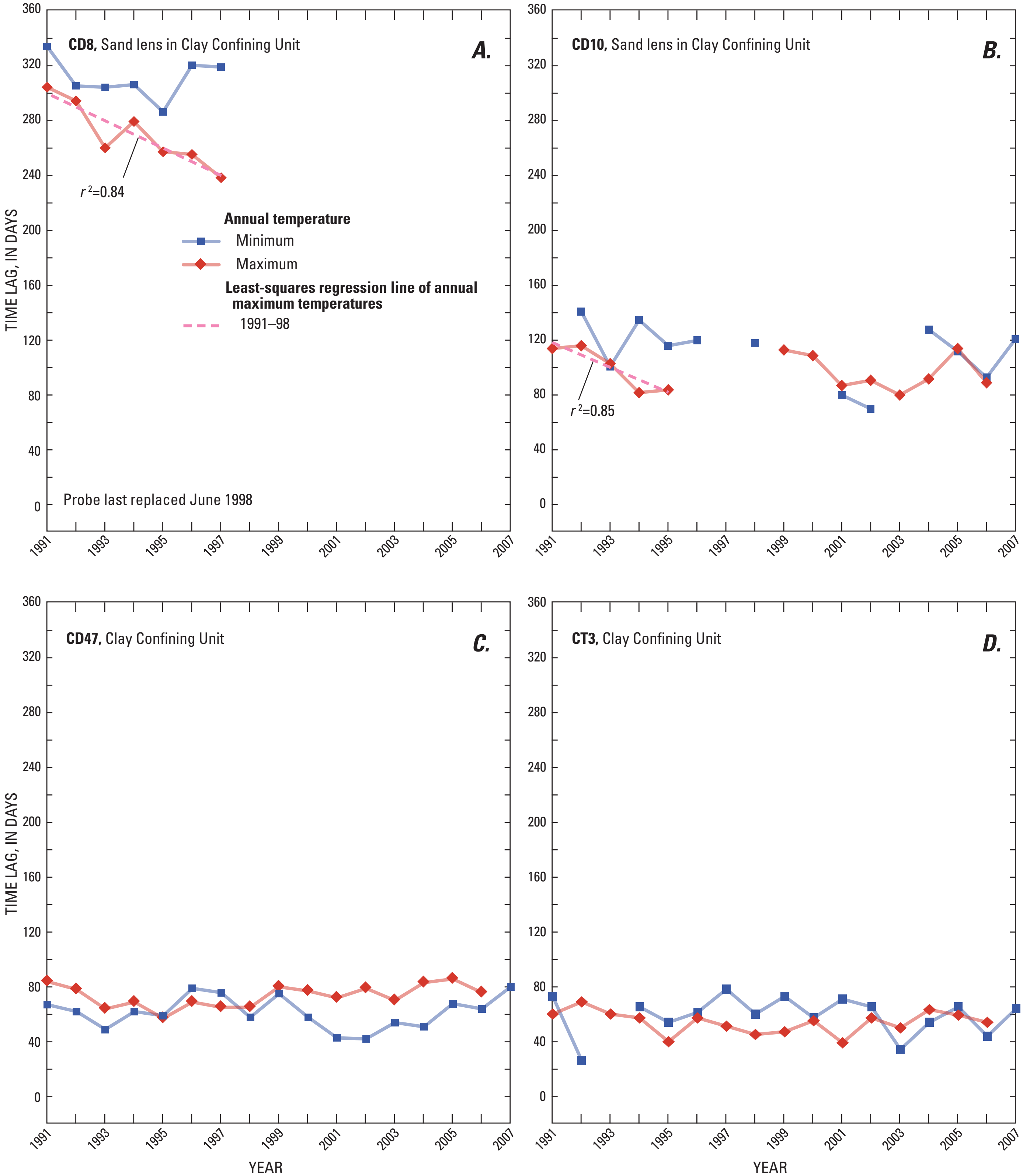


Figure 21. Time lag between annual minimum and maximum temperatures in the Columbia River at probe RIV and in wells of the monitoring network of the Eastbank Aquifer system, Douglas County, Washington, 1991–2007.

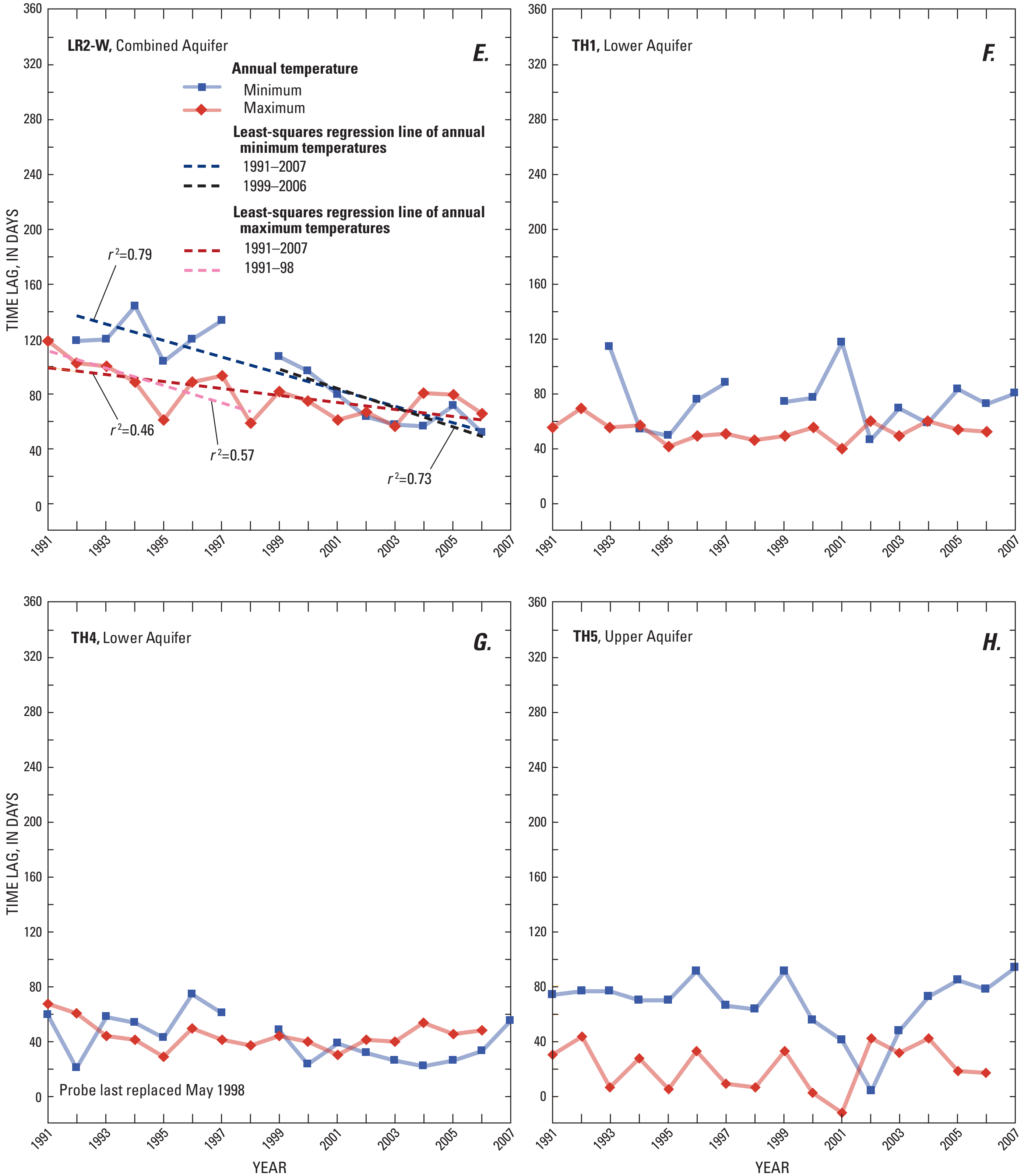


Figure 21.—Continued.

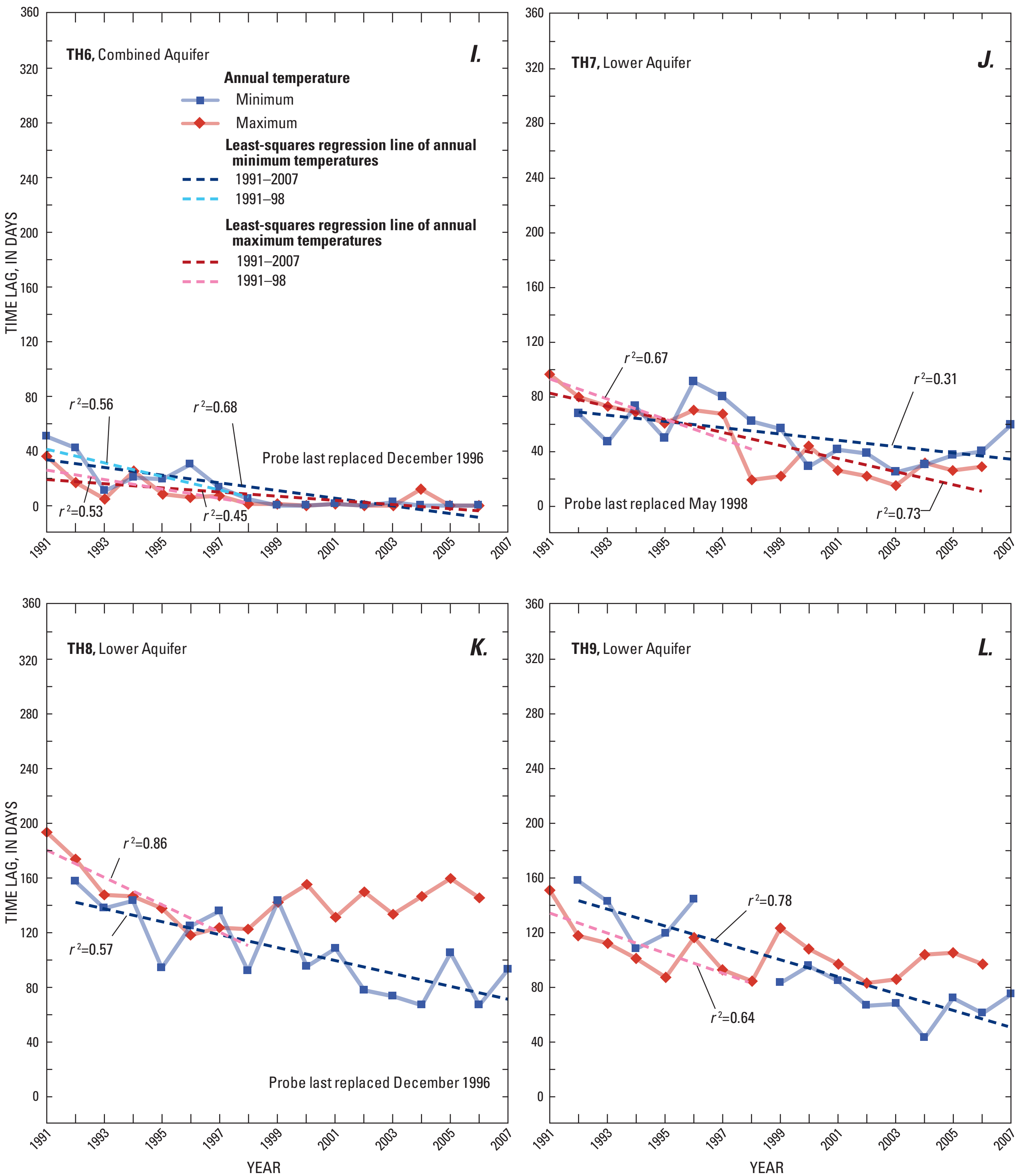


Figure 21.—Continued.

Trends in the time series of time lags from 1991 through 2007 were evaluated using straight-line linear regressions with each of the time series shown in figure 21. The results of the trend analyses are summarized in table 6, and trends of decreasing time lags that are statistically significant at a confidence level of 95 percent are shown in figure 21. A decreasing trend in time lags is indicated (table 6) if the trend is observed in the time lag for either the annual maximum or the annual minimum temperature. The results indicate that there were no decreasing trends in time lags in the Upper Aquifer and Clay Confining Unit. However, with the exception of wells TH1 and TH4, there were decreasing trends in time lags in the Lower and Combined Aquifers. The lack of decreasing trends in Lower Aquifer wells TH1 and TH4 indicates that the thermal conditions of the Lower Aquifer near wells TH1 and TH4 have been in equilibrium for the pumping and aquifer conditions that have existed since 1991. Any decreases in time lags near wells TH1 and TH4 presumably would have occurred following activation of the CT and RW well fields, respectively, and prior to 1991.

Trends in the time series of time lags also were evaluated from 1991 through 1998 and from 1999 through 2006. The selected time periods were arbitrary, except that the period 1999-2006 coincides with the period of analysis of annual well-temperature ranges described in section "Annual Temperature Ranges." From 1991 through 1998, there were statistically significant decreasing trends at a confidence level of 95 percent in either the annual minimum or maximum temperatures in wells CD8 and CD10 in the Clay Confining Unit and all wells in the Lower and Combined Aquifers except wells TH1 and TH4 (table 6; fig. 21). (The temperature probes in wells CD8 and CD10 are adjacent to sand lenses near the

Table 6. Summary of temperature trends in the Eastbank Aquifer system, Douglas County, Washington, 1991–2007.

[Locations of wells are shown in figure 2. **USGS well No.**: See figure 4 for explanation of well-numbering system. Latitudes and longitudes of the wells are on file with the U.S. Geological Survey. **Abbreviations:** USGS, U.S. Geological Survey; X, not analyzed because too few or no data points; na, not applicable; –, not available]

Local well name	USGS well No.	Hydrogeologic unit at depth of temperature probe	Is indicated trend statistically significant at a confidence level of 95 percent? Decreasing time lag between annual minimum and/or maximum river and well temperatures 1991–2007	1991–98	1999–2006	Increasing ratio of annual temperature range of well divided by annual temperature range of river, 1999–2006	Increasing annual maximum well temperature, 1999–2006	Mean annual increase of annual maximum temperature, 1999–2006 (degrees Celsius)	Hydrogeologic unit to which well is open	Primary use of water since completion of Rocky Reach Dam
Temperature probe in Upper Aquifer or Clay Confining Unit										
CD8	24N/20E-35R01	Sand lens in Clay Confining Unit	X	Yes	X	X	X	X	Clay Confining Unit	Monitoring
CD10	24N/20E-35Q01	Sand lens in Clay Confining Unit	No	Yes	No	X	No	na	–	Monitoring
CD47	24N/20E-35Q02	Clay Confining Unit	No	No	No	Yes	Yes	0.12	Lower Aquifer	Monitoring
CT3	24N/20E-35Q03	Clay Confining Unit	No	No	No	X	Yes	.14	Lower Aquifer	Hatchery
TH5	24N/20E-35G01	Upper Aquifer	No	No	No	No	No	na	Upper Aquifer	Monitoring
Temperature probe in Lower Aquifer or Combined Aquifer										
LR2-W	24N/20E-35H02	Combined Aquifer	Yes	Yes	Yes	Yes	Yes	0.23	Combined Aquifer	Irrigation
TH1	24N/20E-35K05	Lower Aquifer	No	No	No	No	Yes	.26	Lower Aquifer	Monitoring
TH4	24N/20E-35K02	Lower Aquifer	No	No	No	Yes	Yes	.22	Lower Aquifer	Monitoring
TH6	24N/20E-35G02	Combined Aquifer	Yes	Yes	No	Yes	Yes	.19	Combined Aquifer	Monitoring
TH7	24N/20E-35K01	Lower Aquifer	Yes	Yes	No	No	Yes	.18	Lower Aquifer	Monitoring
TH8	24N/20E-35K04	Lower Aquifer	Yes	Yes	No	No	No	na	Lower Aquifer	Monitoring
TH9	24N/20E-35K03	Lower Aquifer	Yes	Yes	No	Yes	Yes	.19	Lower Aquifer	Monitoring

base of the Clay Confining Unit that may be connected to the Lower Aquifer.) From 1999 through 2006, there were no statistically significant trends in time lags, except for well LR2-W (table 6; fig. 21). These results indicate that during 1999-2006, the Lower and Combined Aquifers were in thermal equilibrium except for the Combined Aquifer near well LR2-W. The thermal equilibrium was reached prior to 1991 in the Lower Aquifer near wells TH1 and TH4, and during 1991-98 in the remainder of the Lower and Combined Aquifers except for the Combined Aquifer near well LR2-W.

The spatial distribution of decreasing trends in time lags of wells in the Lower and Combined Aquifers during 1991–98 and the time lags of the annual maximum temperatures in 1991, 1999, and 2006 are shown in figure 22. The distribution of time lags shows that as early as 1991, the time lag in well TH1 was significantly shorter than in wells TH7, TH8, and TH9, which is likely the result of a large ground-water flux from the Columbia River west-to-southwest of well TH1 to the CT well field. The short time lag in well TH1 as early as 1991 is consistent with the lack of decreasing trends in time lags at the well during 1991–2007 and 1991–98 because the Lower Aquifer near the well had already reached equilibrium by 1991. The same is not true for the Lower Aquifer near wells TH7, TH8, and TH9, which are located approximately along the ground-water divide between the CT and RW well fields (fig. 15). In 1991, 1999, and 2006 these wells showed a pattern of increasing time lags of the annual maximum temperatures with distance from the river (fig. 22). However, during 1991-98, the time lags of the annual maximum temperatures decreased for all three wells (fig. 21*J–L*), ranging from a mean annual decrease of 7.0 days in well TH9 to 10.0 days in well TH8.

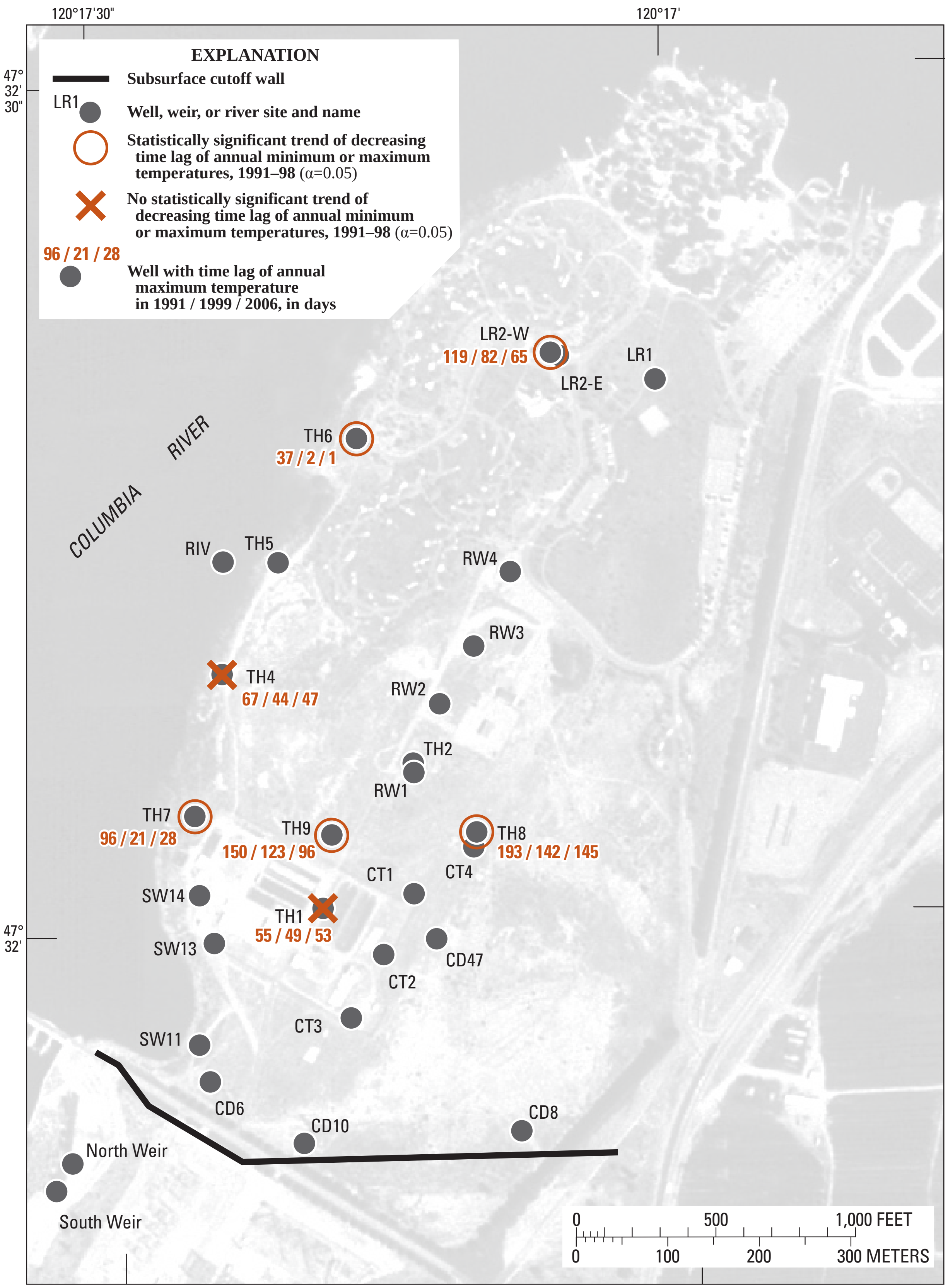
Annual Temperature Ranges

The time series of daily median water temperatures were also used to determine if there were trends in the annual temperature ranges of ground water in wells compared to annual temperature ranges in the river. Time series of ratios of annual temperature ranges in the wells to annual temperature ranges in the river were computed and the results are shown in figure 23. Ratios for wells in which the corresponding annual temperature range spanned more than one calendar year are plotted according to the year of the annual extreme in the river. Data are missing for years when well-temperature records had gaps or when the record was unclear what the magnitude was of the annual minimum or maximum temperature.

Figure 23 indicates that the annual temperature-range ratios for well TH6 have been increasing since 1991. Straight-line linear regressions were performed on each of the time series from 1999 through 2006, to determine quantitatively if there were trends in the time series of annual temperature-range ratios. Values prior to 1999 were not included in the analysis because the monitoring network was recalibrated in July 1998, which may have affected the magnitude but not the timing of annual temperature extremes. The effects of the recalibration are indicated in figure 23 as offsets in 1998 in several of the time series of annual temperature-range ratios. Trends of increasing annual temperature-range ratios that are statistically significant at a confidence level of 95 percent are summarized in table 6. The results indicate that in the Lower and Combined Aquifers, the trends in the annual temperature-range ratios support the 1999-2006 trends in the time lags for 4 of 7 wells (wells LR2-W, TH1, TH7, and TH8). For the remaining 3 wells in the Lower and Combined Aquifers (wells TH4, TH6, and TH9), trends in the annual temperature-range ratios indicate that the Lower and Combined Aquifers near those wells have not reached thermal equilibrium. However, it is assumed that the Lower and Combined Aquifers near wells TH4, TH6, and TH9 are in thermal equilibrium, because trends in time lags are more reliable than trends in annual temperature-range ratios. Trends in time lags are more reliable because time lags are estimated from the relative patterns (and thus timing) of temperature records that are likely accurate within 1 day, and annual temperature-range ratios are estimated from 4 temperature measurements with unknown error. The cumulative errors in annual temperature-range ratios make the metric less reliable and may help explain discrepancies between results of the trend analyses for time lags and annual temperature-range ratios for some of the wells.

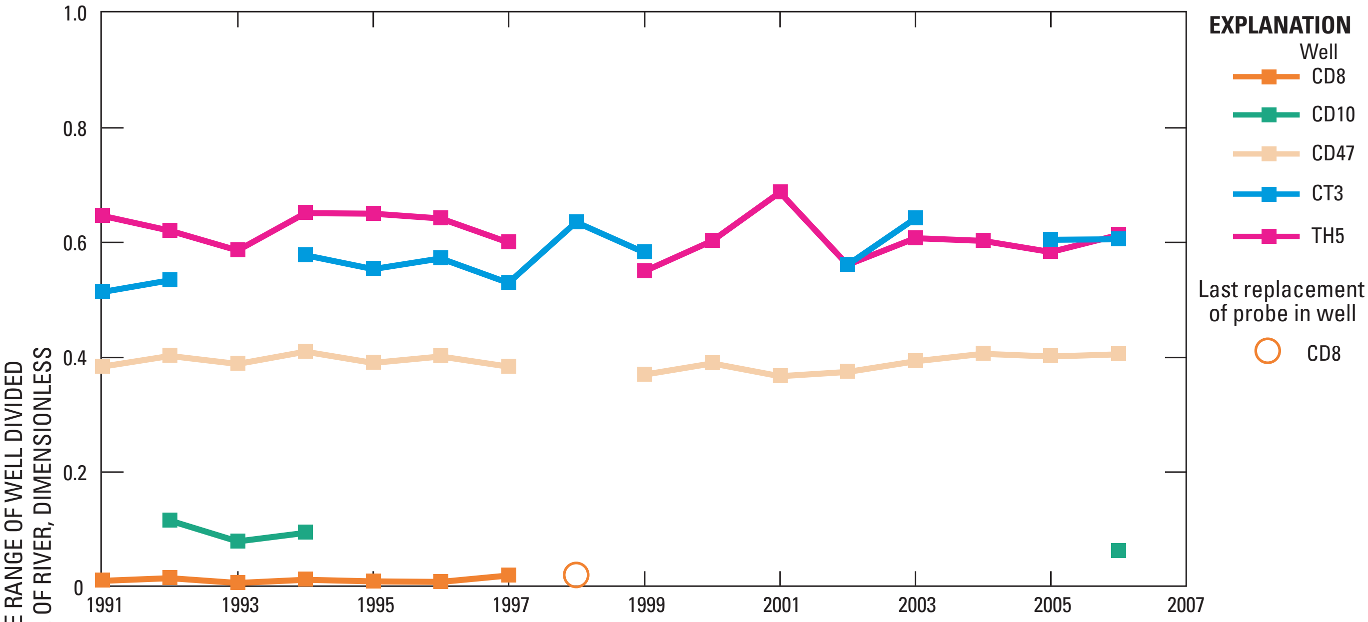
Annual Temperature Extremes

The time series of daily median water temperatures were also used to determine if there were trends in the annual minimum and maximum ground-water temperatures from 1999 through 2006. No statistically significant trends were found in the annual minimum temperatures at a confidence level of 95 percent, but statistically significant trends of increasing annual maximum temperatures were found in all but 3 wells of the monitoring network (fig. 24). Annual maximum temperatures of wells in which the corresponding annual maximum temperature in the river occurred the previous calendar year are plotted according to the year of the annual maximum in the river. Data are missing for years when well-temperature records had gaps or when the record was unclear what the magnitude was of the annual maximum temperature. Mean annual increases in annual maximum temperatures from 1999 through 2006 ranged from 0.12°C in well CD47 to 0.26°C in well TH1 (table 6) and averaged 0.19°C for all wells with statistically significant increases in annual maximum temperatures. The lack of an increasing trend in annual maximum temperatures in Lower Aquifer well TH8 may be due to heat attenuation with distance from the Columbia River that decreases the variability of annual maximum temperatures in this part of the aquifer that is minimally affected by pumping (fig. 20*C*). Alternatively, the lack of a trend could be due to a source of colder water that settled locally in the bedrock depression north and west of well TH8 (fig. 7) and is captured by pumping well CT4.

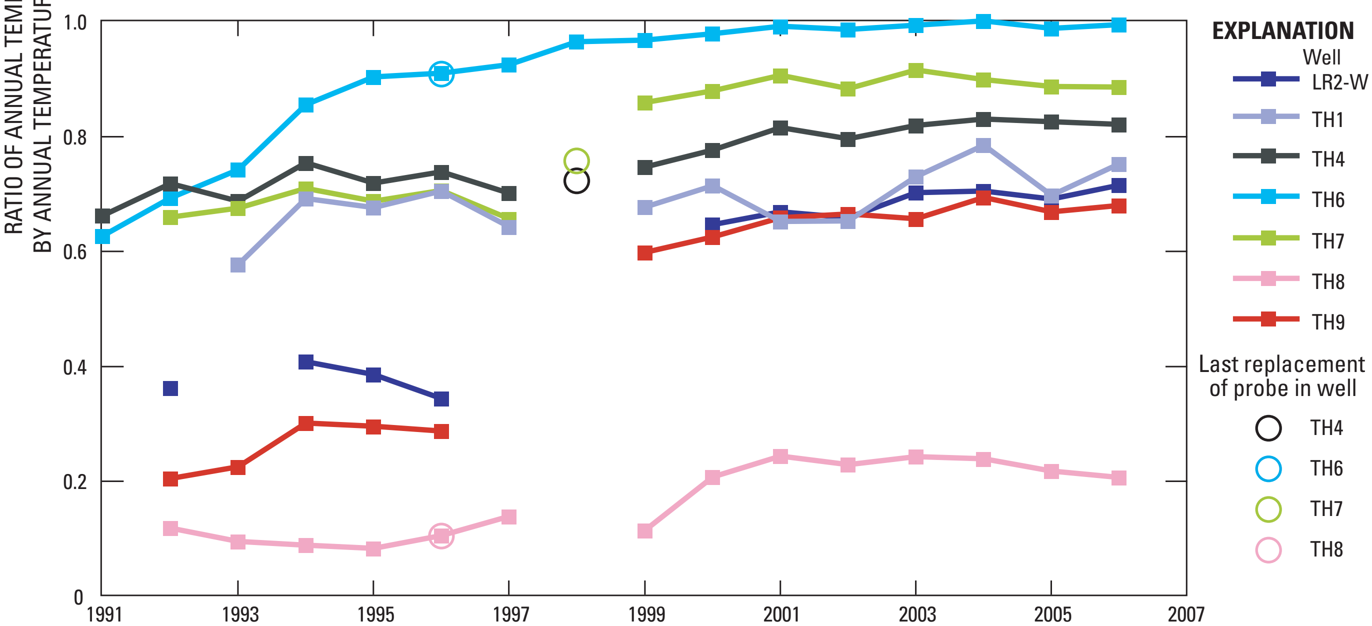


U.S. Forest Service orthophoto, Rocky Reach Dam quad, August 2, 1998
Universal Transverse Mercator projection, Zone 10
Horizontal datum: North American Datum of 1927 (NAD 27)

Figure 22. Spatial distribution of trends in time lags between annual minimum and maximum temperatures measured in the Columbia River at probe RIV and in wells of the monitoring system of the Eastbank Aquifer system with probes in the Lower or Combined Aquifers, 1991–98, and time lags between annual maximum temperatures in the river and wells in 1991, 1999, and 2006, Douglas County, Washington.



A. Temperature probe in Upper Aquifer or Clay Confining Unit



B. Temperature probe in Lower Aquifer or Combined Aquifer

Figure 23. Ratio of annual temperature range between wells of the monitoring network of the Eastbank Aquifer system and the Columbia River at probe RIV for wells with temperature probes at the depth of the Upper Aquifer or Clay Confining Unit and the Lower Aquifer or Combined Aquifer, Douglas County, Washington, 1991–2006.

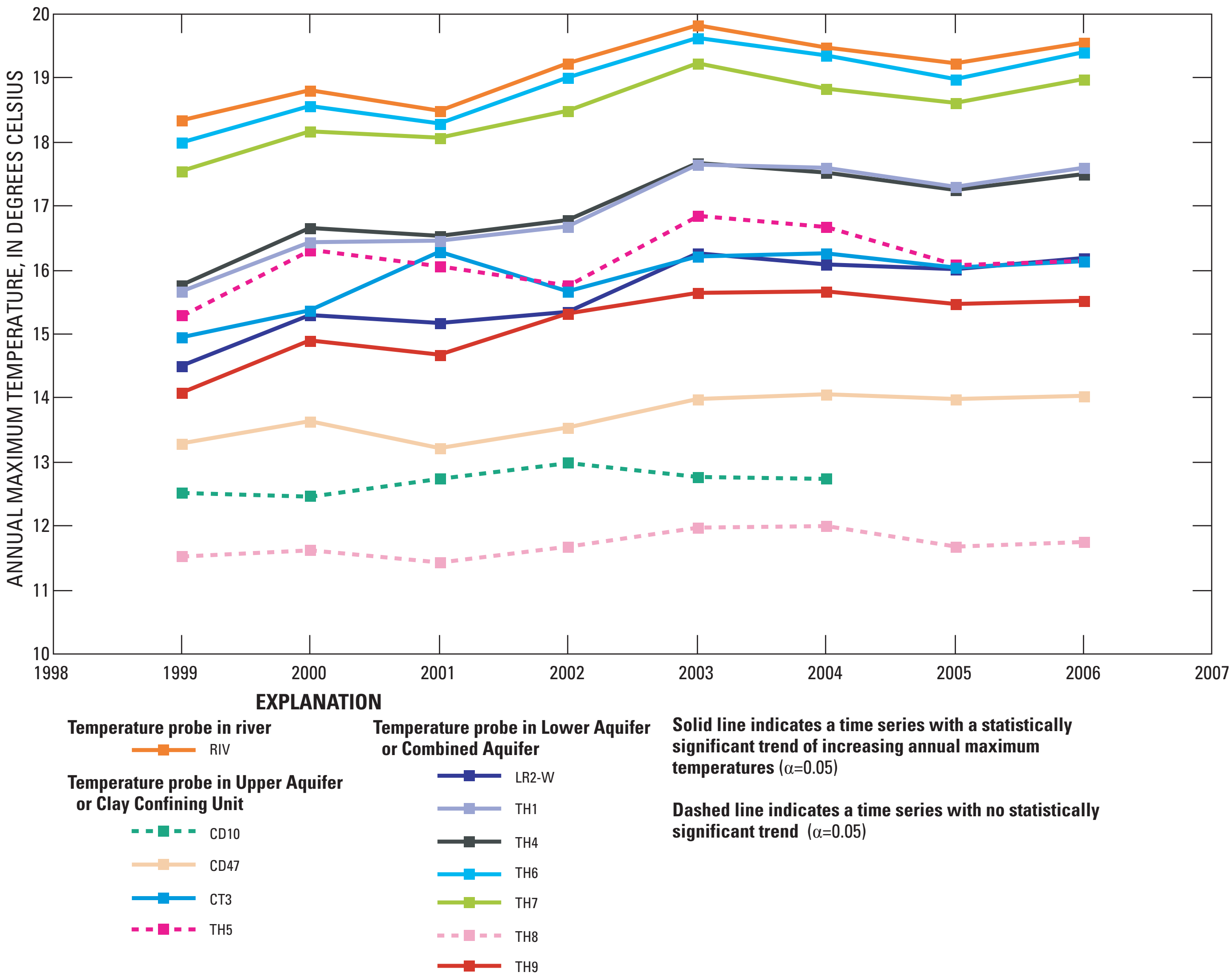


Figure 24. Annual maximum temperature in wells of the monitoring network of the Eastbank Aquifer system and the Columbia River at probe RIV, Douglas County, Washington, 1999–2006.

Increases in annual maximum ground-water temperatures cannot be larger than increases in annual maximum river temperatures. However, the mean annual increases in annual maximum ground-water temperatures in the Lower and Combined Aquifers from 1999 through 2006 ranged from 0.18°C in well TH7 to 0.26°C in well TH1, whereas the increase was 0.17°C in the river; the discrepancy indicates that the trend analysis results in errors in the estimated mean annual increase in annual maximum temperatures of ±0.09°C. Although there is uncertainty in the magnitude of the mean annual increases in annual maximum river and ground-water temperatures, figure 24 and the trend analyses indicate that the river and most annual maximum well temperatures have generally been increasing from 1999 through 2006. Because there was no trend in the annual minimum well temperatures during the same period, the mean annual well temperatures will also have increased in most wells from 1999 through 2006 although less than the annual maximum well temperatures.

Water Quality

Water-quality samples were collected from nine ground-water and one surface-water location in the study area on August 20–22, 2007, to measure the concentrations of selected water-quality constituents, including calcium, magnesium, sodium, potassium, bicarbonate, nitrate, chloride, sulfate, fluoride, and silica. The concentrations of these constituents are present in many natural waters and will vary largely due to the extent of interactions between the water and surrounding rock material (Hem, 1985). The objective of the sampling program was to evaluate the spatial variations in the concentration of these water-quality constituents and verify ground-water flowpaths between areas of ground-water recharge and discharge to and from the Lower Aquifer of the Eastbank Aquifer system.

The source of recharge to the Lower Aquifer is the Columbia River. Concentrations of water-quality constituents in Columbia River water typically are low compared to concentrations in ground water of the Columbia Plateau region (Bortleson and Cox, 1986; Turney, 1986). As ground water moves away from recharge areas through relatively unweathered aquifer material such as the sediments that make up the Lower Aquifer, it accumulates solutes from the dissolution of rock and mineral fragments (Drever, 1988). Conversely, particulate matter such as bacteria that is present in river water will be reduced by filtration from passage through the aquifer material. Thus, ground water at locations along a flowpath downgradient from a recharge area can be expected to have increasing concentrations of dissolved constituents and decreasing numbers of live bacterial cells.

Ground-water samples were collected from one well that supplies the regional water system (RW3), one well that is used to irrigate Lincoln Rock State Park (LR2-E), two wells that supply the Eastbank Hatchery (CT3 and CT4); three wells that are used for dam operations or irrigation (SW11, SW13, and SW14), and one monitoring well (TH4; fig. 25*A*). A sample also was collected from the North Weir, which is assumed to represent ground-water seepage from the Lower Aquifer through the grout curtain of the subsurface cutoff wall. In addition, one sample of Columbia River water was collected near the site where the PUD collects continuous river water-level and water-temperature data, labeled RIV in figure 25*A*.

Spatial Patterns

Concentrations of many of the analyzed constituents showed spatial patterns in the Lower Aquifer. Samples were collected nearly concurrently from wells SW13 and SW14 to establish a baseline of variability, which includes variability due to sampling, sample analysis, and localized spatial variability within the aquifer. Wells SW13 and SW14 are believed to have similar construction and are located within about 200 ft of each other. For many constituents (table 7), the laboratory analysis of samples from wells SW13 and SW14 were nearly identical. Larger variations of more than 2 percent were reported for dissolved oxygen, nitrate, and the bacterial enumeration; the relative percent difference computed for nitrate and dissolved oxygen was 13 and 16 percent, respectively, and about 60 percent for bacterial enumeration. Smaller variations with a relative percent difference of less than 2 percent were reported for concentrations of alkalinity, calcium, magnesium, bicarbonate, chloride, potassium, sodium, silica, fluoride, and sulfate. This level of variation commonly is reported for analysis of duplicate environmental samples. As a result, differences in constituent concentrations greater than those observed between the samples for wells SW13 and SW14 were considered indicative of spatial variations in water quality of the Lower Aquifer. Concentrations of nitrate and dissolved oxygen were not used to assess spatial variation.

Specific conductance is a measure of the ability of water to conduct an electric current and thus provides a general measure of the amount of dissolved matter in water. Specific conductance of the river sample was 127 µS/cm. A survey of 32 vertical profiles distributed throughout the Columbia River near the study area conducted on the same day the river was sampled showed that the specific conductance in the river varied by less than 3 µS/cm. Specific conductance in ground water from wells near the shoreline and from wells near the center of the Lower Aquifer was in the range of 135 to 148 µS/cm and 163 to 167 µS/cm, respectively. This indicates a pattern of lower concentrations of dissolved constituents near the river and larger concentrations near the center of the Lower Aquifer (fig. 25*A*).

A similar pattern also was observed for individual dissolved constituents. Concentrations of all dissolved constituents, except sulfate, were smallest in the river sample and largest in ground-water samples from nearer the center of the Lower Aquifer. The largest concentrations of dissolved constituents were generally measured in wells CT4 or RW3 with generally slightly smaller concentrations in LR2-E and the North Weir. Maps of the spatial distributions of specific conductance, potassium, silica, alkalinity, and chloride are shown in figures 25*A* through 25*E*. Silica (fig. 25*C*) and potassium (fig. 25*B*) show the most pronounced spatial variation, whereas spatial variation is more difficult to discern for sodium (fig. 25*F*). With few exceptions, this pattern was consistent among different constituents, including alkalinity (fig. 25*D*) and chloride (fig. 25*E*). For several constituents, such as sodium (fig. 25*F*), concentrations in ground water were larger than in surface water but did not show a consistent spatial pattern in relation to possible directions of ground-water flow. A generally northeast-southwest gradient of increasing concentrations of dissolved constituents in the direction of predevelopment ground-water flowpaths (fig. 11) was not observed. Instead, data generally indicate ground-water flowpaths from the western shoreline to the pumping centers in the CT and RW well fields.

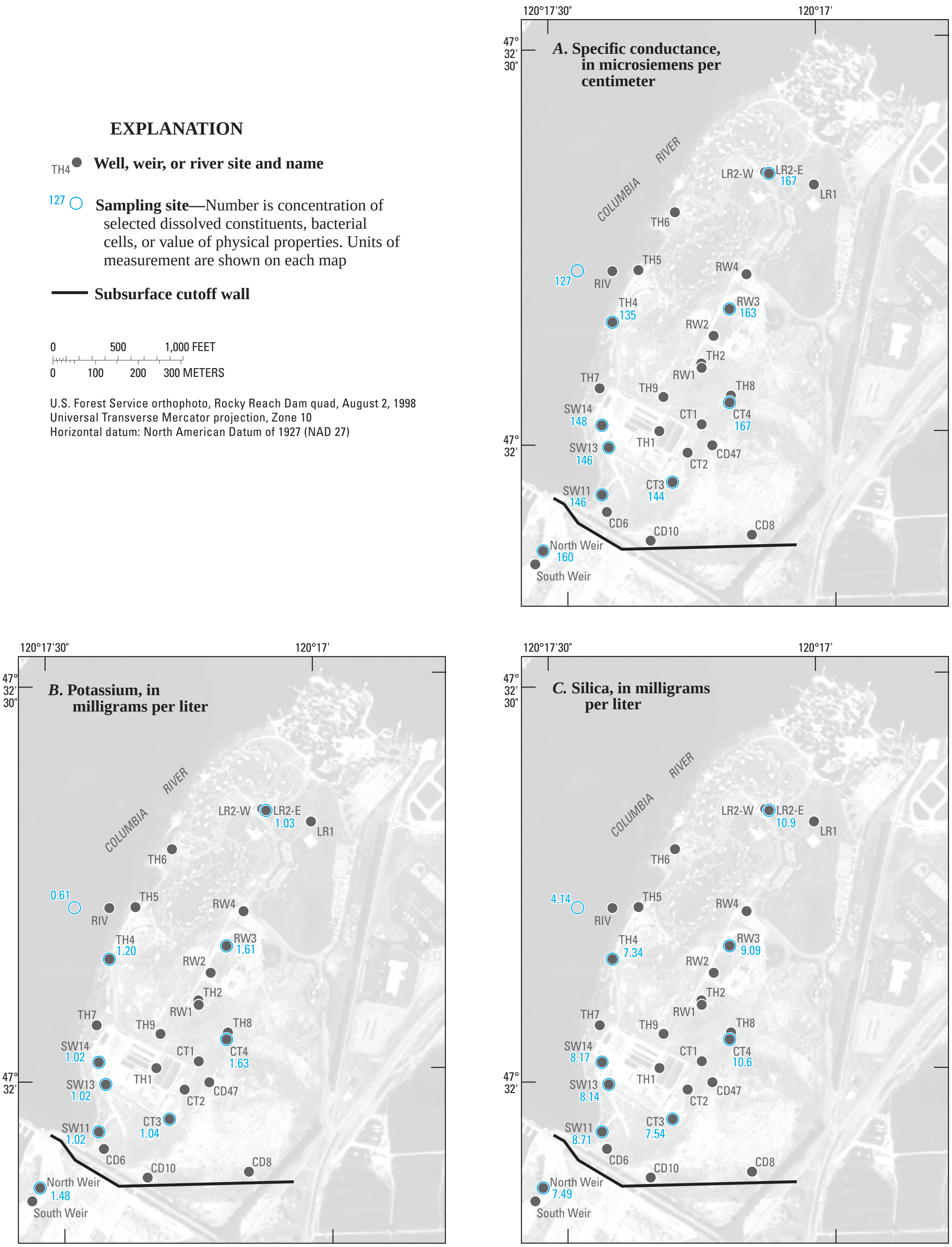


Figure 25. Spatial distribution of water-quality sampling sites and selected water-quality constituents in the Columbia River and Eastbank Aquifer system, Douglas County, Washington, August 20–22, 2007.

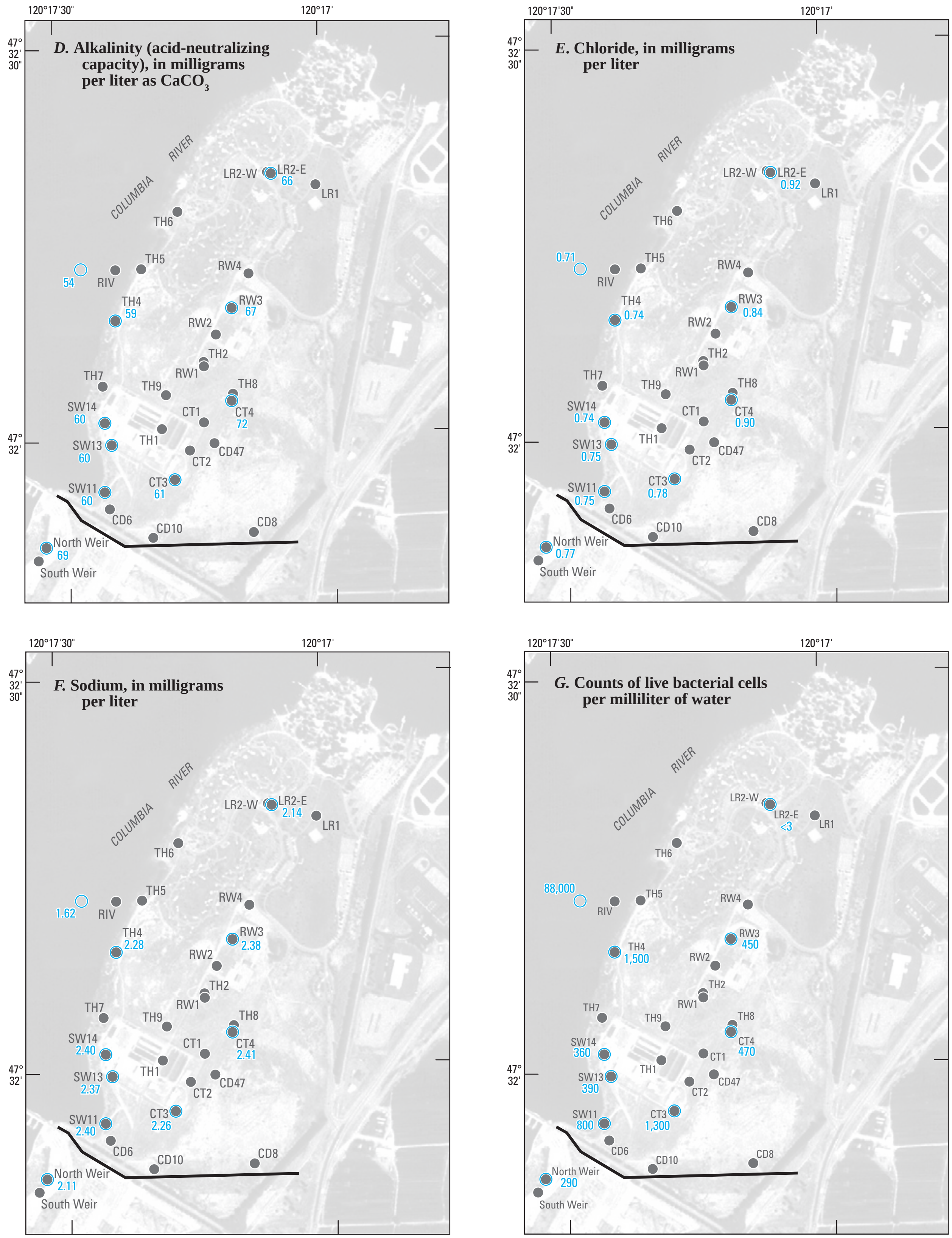


Figure 25.—Continued.

Table 7. Physical properties and concentrations of bacterial cells and selected dissolved constituents in ground-water and surface-water samples, Eastbank Aquifer System, Douglas County, Washington, August 20–22, 2007.

[Locations of wells, weir, and river site are shown in figure 25. **Abbreviations:** $CaCO_3$, calcium carbonate; N, nitrogen; µS/cm, microsiemens per centimeter; –, not measured; <, less than]

	River	CT3	CT4	RW3	SW11	SW13	SW14	TH4	LR2-E	North Weir
Physical properties										
Temperature (degrees Celsius)	19.4	13.4	10.4	12.7	16.1	16.2	16.2	18.4	10.9	15.4
Specific conductance (µS/cm)	127	144	167	163	146	146	148	135	167	160
pH (standard units)	7.5	7.4	7.3	7.5	7.2	7.5	7.3	–	7.3	7.6
Bacteria, per milliliter										
Live bacterial cells	88,000	1,300	470	450	800	390	360	1,500	<3	290
Dead bacterial cells	54,000	7,700	1,000	1,700	380	610	330	730	<3	330
Dissolved constituents, in milligrams per liter										
Dissolved oxygen	–	5.5	3.9	6.0	3.8	4.5	5.3	–	3.7	8.0
Alkalinity, as $CaCO_3$	54	61	72	67	60	60	60	59	66	69
Calcium	17.6	19.3	21.9	22.1	18.9	19.0	18.7	18.9	20.2	21.7
Magnesium	4.10	4.47	4.75	4.64	4.32	4.36	4.36	4.30	4.72	4.44
Sodium	1.62	2.26	2.41	2.38	2.40	2.40	2.37	2.28	2.14	2.11
Potassium	.61	1.04	1.63	1.61	1.02	1.02	1.02	1.20	1.03	1.48
Bicarbonate	65	74	88	82	73	72	73	72	81	84
Nitrate plus nitrite, as N	.04	.15	.16	.16	.14	.16	.14	.18	.14	.19
Chloride	.706	.775	.900	.843	.749	.753	.739	.947	.915	.769
Sulfate	8.43	8.30	8.97	8.38	8.00	8.27	8.29	8.31	7.96	8.57
Fluoride	.058	.066	.079	.097	.075	.076	.076	.068	.075	.080
Silica	4.14	7.54	10.60	9.09	8.71	8.14	8.17	7.34	10.90	7.49

Bacterial concentrations are largest in the river and lowest in wells closer to the center of the Lower Aquifer (fig. 25*G*). In the sample from the well in Lincoln Rock State Park (LR2-E), no viable bacterial cells were observed above the detection limit of 3 cells per milliliter. The occurrence of fewer live bacterial cells in ground-water samples obtained at locations more distant from the surface-water source is consistent with the filtering effect resulting from movement of ground water through an aquifer matrix. As shown in figure 25*G*, live bacterial concentrations increased along the central axis from wells LR2-E to CT3, which is inconsistent with a ground-water flowpath from the northeast to the southwest. Generally, the live bacterial concentrations indicate ground-water flowpaths from the western shoreline to near the center of the Lower Aquifer. In well CT3, however, live bacterial concentrations are larger than those in wells near the shoreline, which may be related to the large pumping rate of the well, its proximity to the river, and preferential flowpaths from the river to the well. This interpretation is supported by dissolved constituent concentrations in well CT3, which were consistently smaller than those found in wells to the north and were similar to the more dilute concentrations in nearby wells adjacent to the river.

The water-quality data indicate that the ground-water flowpaths that end in the CT well field predominantly originate along the shoreline west and southwest from the pumping wells. If the northeast-to-southwest ground-water flowpath present during predevelopment conditions were predominant, then well CT3, which is the most southerly well that pumps at a high rate, should have had the largest concentrations of dissolved constituents and the smallest concentration of live bacterial cells. However, the water-quality results show nearly the opposite and a very short flowpath is indicated for well CT3. Conversely, the lack of substantial live bacterial concentrations and the occurrence of relatively larger dissolved constituent concentrations in well LR2-E indicate that the flowpath from the river to the well is longer and/or less recharge from the river passes through that area. Ground-water seepage through the grout curtain of the subsurface cutoff wall appears to be a combination of water with both long and short flowpaths and is consistent with a collector drain integrating discharge from the Lower Aquifer along a 2,000-foot-long interface.

Conceptual Model of Hydrologic and Thermal Conditions

The hydrogeologic framework of the Eastbank Aquifer system consists of the Upper and Lower Aquifers, which are highly permeable sand-and-gravel aquifers separated by the Clay Confining Unit (fig. 5). In the northwestern part of the study area (fig. 6), the Clay Confining Unit is absent and the Upper and Lower Aquifers merge to form the Combined Aquifer. The lower boundary of the Eastbank Aquifer system is crystalline bedrock that consists of biotite gneiss with low permeability. The bedrock has an undulating surface that forms a basin in the central part of the study area that is deepest near the RW well field (fig. 7). The Lower and Combined Aquifers in the eastern part of the study area are truncated by the bedrock surface (fig. 8) and the Clay Confining Unit and Upper Aquifer continue farther to the east, where they also are truncated by bedrock (fig. 5). The southern boundary of the aquifer system is a subsurface cutoff wall that is a partial barrier to ground-water flow from the Upper and Lower Aquifers. The northern and western boundaries of the aquifer system are the Columbia River. Along the western boundary, the Lower and Upper Aquifers are truncated by the river, and along the northern boundary, the Combined Aquifer extends beneath the river for an unknown distance to the north.

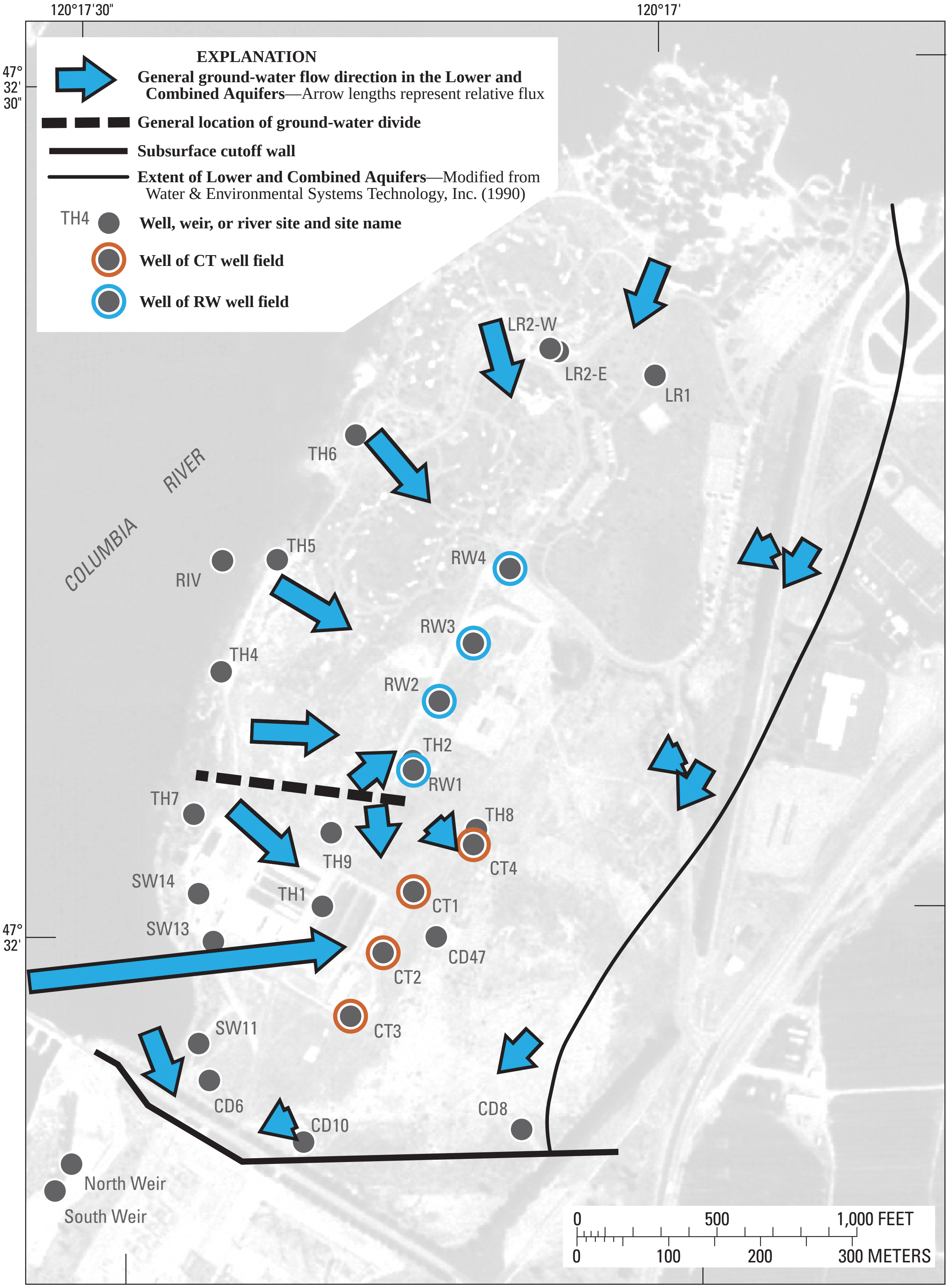
The Upper, Lower, and Combined Aquifers primarily are recharged by water from the Columbia River. Along most of the western boundary of the aquifers, ground-water recharge occurs across a layer of fine-grained, low-permeability sediments. Discharge from the aquifer system is ground-water pumpage from the Lower Aquifer and ground-water seepage from the Upper and Lower Aquifers around and through the subsurface cutoff wall.

During post-dam, predevelopment conditions, ground water generally flowed from the northeast to the southwest, approximately parallel to the river (fig. 11). With the onset of significant pumping from the Lower Aquifer by the RW well field in 1983 and the CT well field in 1989, two overlapping cones of depression have formed in the Lower and Combined Aquifers (fig. 15) and an approximately east-west trending ground-water divide has formed between them. The location of the ground-water divide probably varies slightly over time depending on which wells are pumping and at what rate. In 2006, mean annual pumpage from the RW and CT well fields was about 16 and 43 ft^3/s, respectively. Pumpage from the SW well field from the Lower Aquifer and from the LR well field from the Combined Aquifer is small compared to pumpage from the RW and CT well fields and has a negligible effect on the ground-water flow system. Because of the hydraulic properties of the Clay Confining Unit, water levels in the Upper Aquifer are assumed to be relatively unaffected by pumping in the Lower Aquifer. Data do not exist, however, to confirm this assumption.

The cone of depression in the Lower and Combined Aquifers surrounding the RW well field draws water primarily from the west and secondarily from the north (fig. 26). An additional, smaller amount of water is drawn in from the south and east and, presumably, from beneath the wells. The cone of depression surrounding the CT well field draws water primarily from the west and southwest (fig. 26). An additional, smaller amount of water is drawn in from the north and east. Any water in the Lower Aquifer south of well CT3 not captured by pumping becomes seepage through the subsurface cutoff wall. Because of its proximity to the ground-water divide between the two cones of depression and because the location of the ground-water divide may shift as pumping patterns change, some of the water pumped by well CT4 may originate from a bedrock depression to the north and west.

Most of the Lower and Combined Aquifers have been in thermal equilibrium since 1999 and this equilibrium was reached during 1991–98. The only exceptions are the Lower Aquifer near wells TH1 and TH4, which reached thermal equilibrium prior to 1991, and the Combined Aquifer near well LR2-W, which had not reached equilibrium by 2006. At thermal equilibrium, the time lags between changes in river temperatures and subsequent changes in ground-water temperatures are constant at a given location and the ratios of annual temperature ranges in ground water to annual temperature ranges in the river also are constant at a given location. Because time lags and annual temperature-range ratios vary in three dimensions, the Eastbank Aquifer system is a mosaic of different temperatures at any time of the year. Generally, however, time lags increase and annual temperature-range ratios decrease with distance from the river.

Mean annual minimum and maximum temperatures of source water in the Columbia River that recharges the aquifer system were 2.5 and 19.2°C, respectively, from 1991 through 2006. Typically, the annual minimum temperatures occur in February and the annual maximum temperatures occur in August or September. From 1999 through 2006, there were statistically significant increasing trends in mean annual and annual maximum river temperatures but there were no trends in the annual minimum temperatures. The increases in river temperatures resulted in a corresponding increase in Lower and Combined Aquifer temperatures, except near well TH8. Temperatures in this well may not have increased because they represent a part of the Lower Aquifer minimally affected by pumping at a greater distance from the river or because nearby well CT4 may pump colder water that may have settled locally in the bedrock depression north and west of well TH8. There were no trends in the annual minimum, mean, and maximum river temperatures from 1991 through 1998 and from 1991 through 2007. The mean annual increase in the annual mean and maximum river temperature from 1999 through 2006 was 0.07 and 0.17°C, respectively.



U.S. Forest Service orthophoto, Rocky Reach Dam quad, August 2, 1998
Universal Transverse Mercator projection, Zone 10
Horizontal datum: North American Datum of 1927 (NAD 27)

Figure 26. Generalized horizontal ground-water flow directions and fluxes for current (2008) conditions of the Lower and Combined Aquifers of the Eastbank Aquifer system, Douglas County, Washington.

The dependence of the detection of river-temperature trends on the period of the record selected for analysis indicates that although mean annual river temperatures may increase during multi-year periods and these increases result in corresponding increases in the Lower and Combined Aquifers, the increases in river temperatures and thus ground-water temperatures over relatively short periods of time are within the natural variability of the river temperatures and decreases in mean annual river temperatures are likely during other multi-year periods.

Interannual trends in ground-water temperatures are controlled by interannual trends in river temperatures, interannual trends in seasonal pumpage patterns, and the extent of thermal equilibrium in the aquifer system. From 1999 through 2006, seasonal pumpage patterns were relatively stable and most of the aquifer system was in thermal equilibrium; thus reported trends of increasing temperatures of water pumped by the CT well field are most likely explained by increasing trends in river temperatures.

Data Needs

A numerical model of the Eastbank Aquifer system would be useful for evaluating potential future hydrologic and thermal effects of different ground-water pumping rates, timing, and locations. Specifically, a model would help determine if there may be pumping alternatives that can meet the water demand by the Eastbank Hatchery and the regional water system and also provide sufficiently cool water for the hatchery. Numerical modeling can be achieved by verifying and updating the numerical model of the Eastbank Aquifer system by Water & Environmental Systems Technology, Inc. (1990) or by constructing a new model. Updating or constructing a numerical model would benefit from the following data, collected over a period of at least a year:

1. Daily measurements of pumpage from the RW and CT wells.
2. Daily records of when wells were pumped.
3. Hourly measurements of the temperature of water pumped by the RW and CT wells.
4. Semi-annual or more frequent verification of hourly temperature measurements of water pumped by the RW and CT wells.
5. Monthly manual measurements of vertical temperature profiles and water levels in each monitoring well on the same day, including verification that pumpage data were collected during the previous 24 hours [(1) and (2)]. Although not critical, bi-monthly temperature measurements of the North and South Weirs would be helpful.
6. Hourly measurements of temperature in the river and monitoring wells at constant depths.
7. Semi-annual or more frequent verification of hourly temperature measurements in the river and monitoring wells.
8. Hourly measurements of water levels in the river and monitoring wells using vented transducers.
9. Semi-annual or more frequent verification of hourly water-level measurements in the monitoring wells. As long as USGS gaging station 12453679 continues to record hourly water levels along the west bank of the river at the forebay of Rocky Reach Dam, additional river water-level verification measurements are not necessary.
10. Measurements of continuous discharge from the North and South Weirs.
11. Semi-annual or more frequent verification of weir-discharge measurements.

Regular verification and calibration of instruments and detailed records of the verification and calibration will ensure that reliable data are collected. Detailed records of instrument replacements and other significant events that may affect the pumpage, water-level, and water-temperature data may help explain possible data anomalies.

A numerical model of the Eastbank Aquifer system would be more reliable if detailed information were available about the source of the water flowing through the North and South Weirs and if the presence of a bedrock depression near the RW well field could be determined by drilling a new well. The depth to bedrock, the nature of the sediments above the bedrock, and the age and temperature of ground water in the depression could be evaluated as part of the drilling process.

Summary

The Eastbank Aquifer system covers about 150 acres and is located in a river-terrace deposit along the east bank of the Columbia River near Rocky Reach Dam, about 8 miles north of Wenatchee, Washington. It consists of the Upper and Lower Aquifers, which are highly permeable sand-and-gravel aquifers separated by the Clay Confining Unit. Where the Clay Confining Unit is absent in the northwestern part of the study area, the aquifers merge to form the Combined Aquifer. The primary use of the Eastbank Aquifer system is to supply water from the Lower and Combined Aquifers to the Eastbank Hatchery and the regional water system, which serves more than 65,000 people in and near the cities of Wenatchee and East Wenatchee. The hatchery is owned by the Public Utility District No. 1 of Chelan County (PUD) and compensates for fish losses resulting from the Rocky Reach and Rock Island Hydroelectric Projects. The Eastbank Hatchery needs relatively cool water for successful operations and, reportedly, temperatures of ground water pumped by the hatchery have been increasing. The PUD asked the U.S. Geological Survey to conduct a study of the Eastbank Aquifer system to help understand why the ground-water temperatures may have been increasing and to determine data needs for possible future evaluations of aquifer-system management options that maintain sufficiently cool ground water for hatchery operations.

The Upper, Lower, and Combined Aquifers are primarily recharged by water from the Columbia River. Ground-water discharge occurs as seepage around and through a subsurface cutoff wall and ground-water pumping. The main pumping centers are the RW well field in the central part of the study area, which supplies the regional water system, and the CT well field in the south-central part of the study area, which supplies the hatchery. The RW and CT well fields became operational in 1983 and 1989, respectively. From 1990 through 2000, annual mean pumpage from the RW well field was relatively constant, with a mean annual pumpage of 10.7 ft^3/s. Pumpage increased by about 40 percent to a mean annual pumpage of 15.0 ft^3/s from 2002 through 2006 due to an expansion of the service area to include the city of East Wenatchee. The mean annual pumpage from the CT well field probably has been relatively constant since 1994, although there is greater uncertainty in the historical pumpage estimate for the CT well field than the RW well field. In 2006, mean annual pumpage from the hatchery and regional water system was about 43 and 16 cubic feet per second (ft^3/s), respectively.

Ground-water levels measured on July 18, 2007 indicate that there are two overlapping cones of depression in the Lower and Combined Aquifers with an approximately east-west trending ground-water divide between them. The cone of depression surrounding the RW well field draws water primarily from the west and secondarily from the north, while an additional, smaller amount of water is drawn in from the south, east, and probably from beneath the wells. The cone of depression surrounding the CT well field draws water primarily from the west and southwest, with an additional, smaller amount of water drawn in from the north and east. A spatial analysis of dissolved-constituent and bacterial concentrations in water sampled in nine wells and one river location in August 2007 was consistent with the ground-water flowpaths inferred from the July 18, 2007, water-level data.

The PUD has measured hourly water levels since 1990 in a monitoring network of 1 river site and 12 wells distributed throughout the Eastbank Aquifer system for the purpose of monitoring hydrologic and thermal conditions of the system. Because potentiometric gradients in the Lower Aquifer are small, the uncertainty in the historical water-level measurements was too large to use the data to analyze for possible trends in hydrologic conditions. The uncertainty in the historical water-temperature measurements was less, however, and these data were analyzed for trends in thermal conditions.

Analyses of interannual trends in time lags between changes in river temperatures and subsequent changes in ground-water temperatures showed that most of the Lower and Combined Aquifers have been in thermal equilibrium—defined by constant time lags, since 1999 and the equilibrium was reached during 1991–98. The only exceptions are the Combined Aquifer near well LR2-W, which had not reached thermal equilibrium by 2006, and the Lower Aquifer near wells TH1 and TH4, which reached thermal equilibrium prior to 1991.

Analyses of interannual trends in river temperatures showed increasing trends in annual mean and maximum river temperatures from 1999 through 2006. The mean annual increase was 0.07°C for the annual mean and 0.17°C for the annual maximum river temperature. There were no trends in the annual minimum temperatures from 1999 through 2006, and there were no trends in the annual minimum, mean, and maximum river temperatures from 1991 through 1998 and from 1991 through 2007. The increases in river temperatures from 1999 through 2006 resulted in corresponding increases in Lower and Combined Aquifer temperatures, except near well TH8. The increases in mean annual river temperatures and thus ground-water temperatures over a relatively short, multi-year period are within the natural variability of the river temperatures and decreases in mean annual river temperatures are likely during other multi-year periods.

Interannual trends in ground-water temperatures are controlled by interannual trends in river temperatures, interannual trends in seasonal pumpage patterns, and the extent of thermal equilibrium in the aquifer system. From 1999 through 2006, seasonal pumpage patterns were relatively stable and most of the aquifer system was in thermal equilibrium; thus reported trends of increasing temperatures of water pumped by the CT well field are most likely explained by increasing trends in river temperatures.

A numerical model could be used to evaluate if there may be pumping alternatives that can meet the water demand by the Eastbank Hatchery and the regional water system and also provide sufficiently cool water for the hatchery. Updating or constructing a numerical model would benefit from continued monitoring of the hydrologic and thermal conditions of the Lower Aquifer for at least 1 year. A numerical model would be more reliable if more detail were available about the source of the water flowing through the North and South Weirs and if the presence of a bedrock depression with possible cold-water storage near the RW well field could be confirmed.

Acknowledgments

We thank the following PUD personnel for assistance with this study: Ian Adams, Dan Davies, and Sam Dilly for extensive assistance with compilation of data and information and help in the field, Travis Dolge, Tim Doneen, and Tom Whaley for help in the field, and Steve Hays for compilation of historical Rocky Reach Dam forebay temperatures**.** We also thank Mike Krautkramer and Jim Hay of Robinson, Noble, and Saltbush, Inc. for sharing data and information from their library, Kim deRubertis and Omar Fulton for sharing previous work, and Mike Cockrum, Regional Water Operator of the City of Wenatchee, for sharing historical pumpage data of the regional water system.

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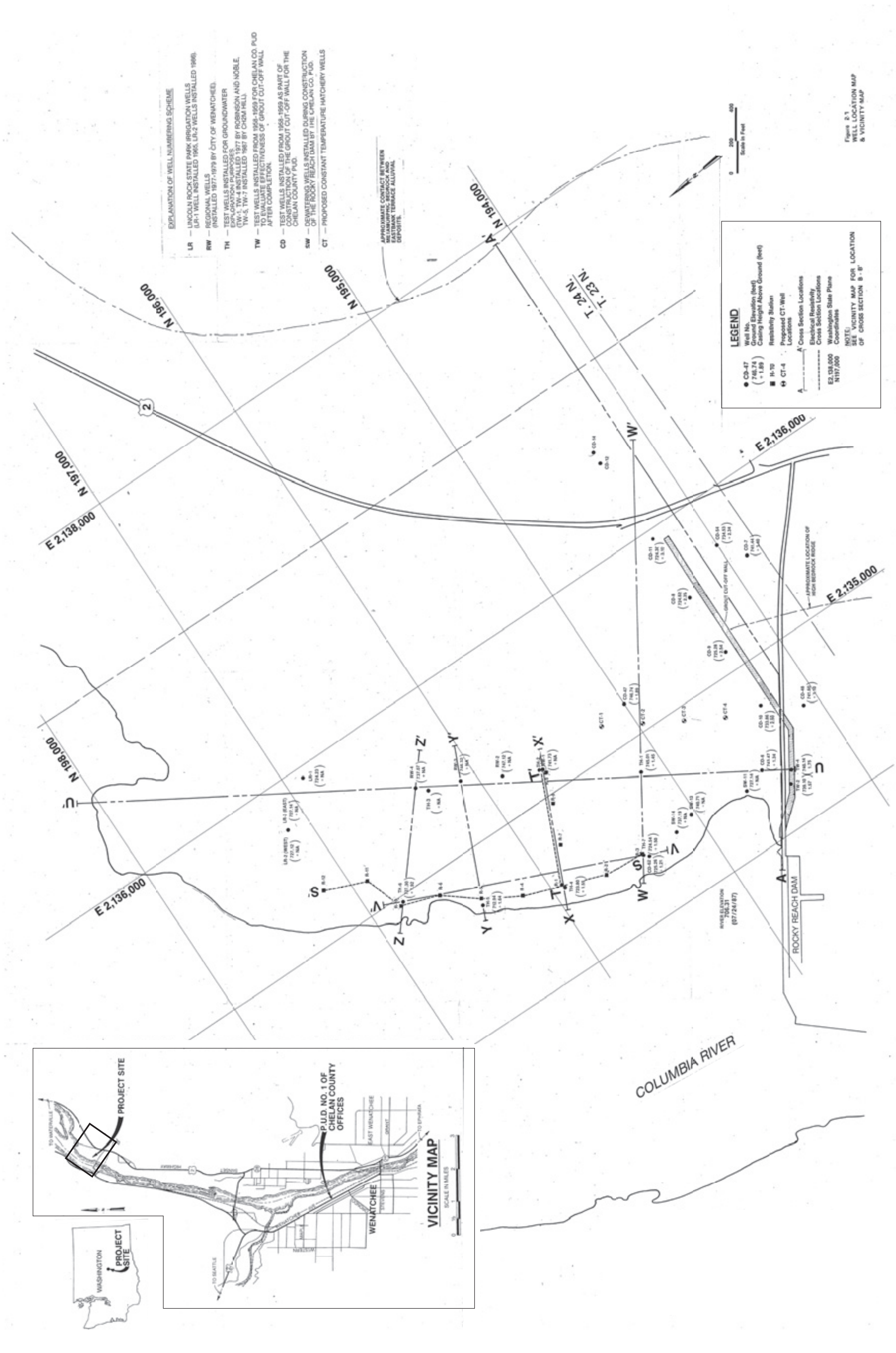
Appendix 1. Hydrogeologic Cross Sections of the Eastbank Aquifer System, Douglas County, Washington.



From CH2M Hill (1988)

Appendix 1.—Continued

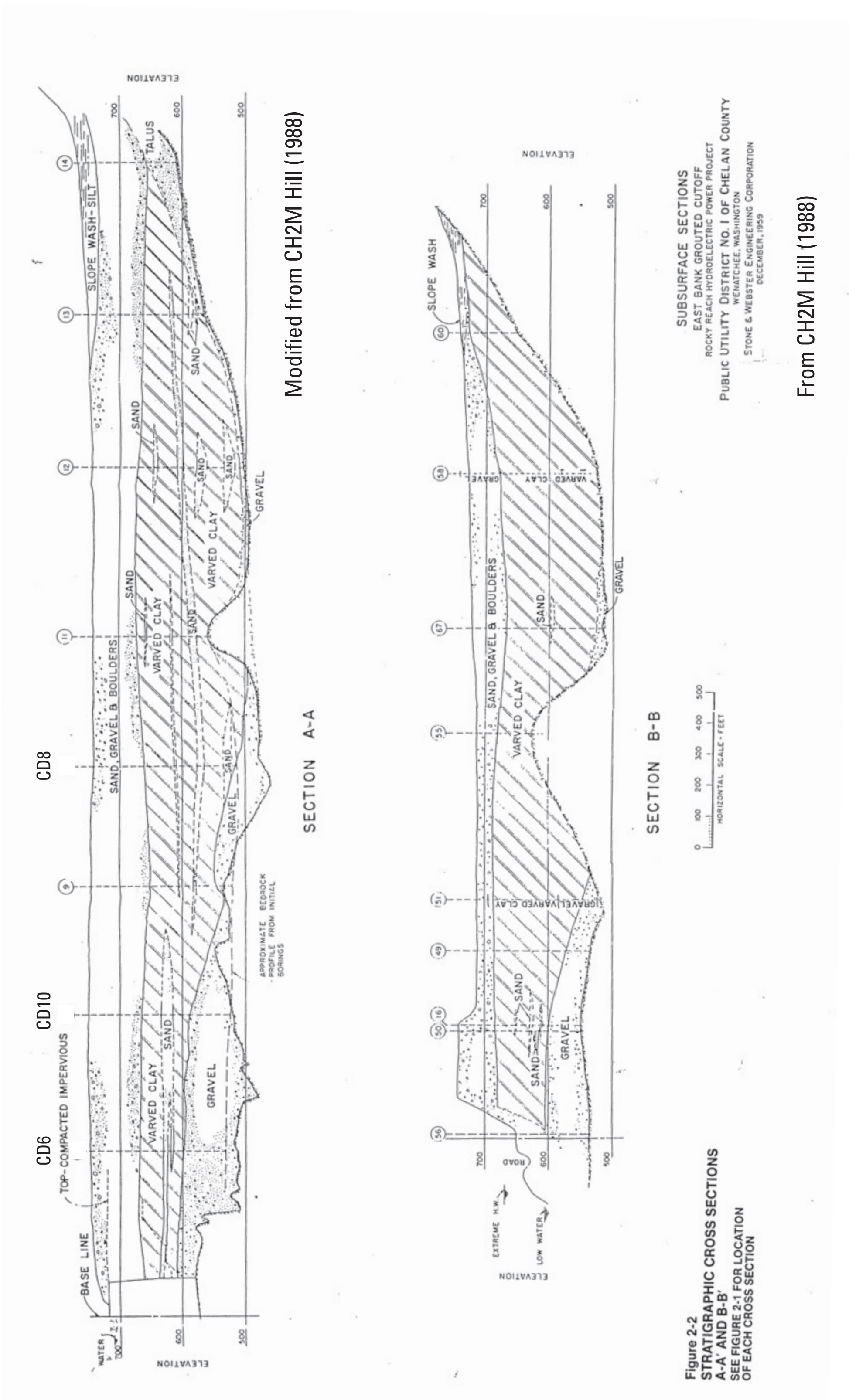
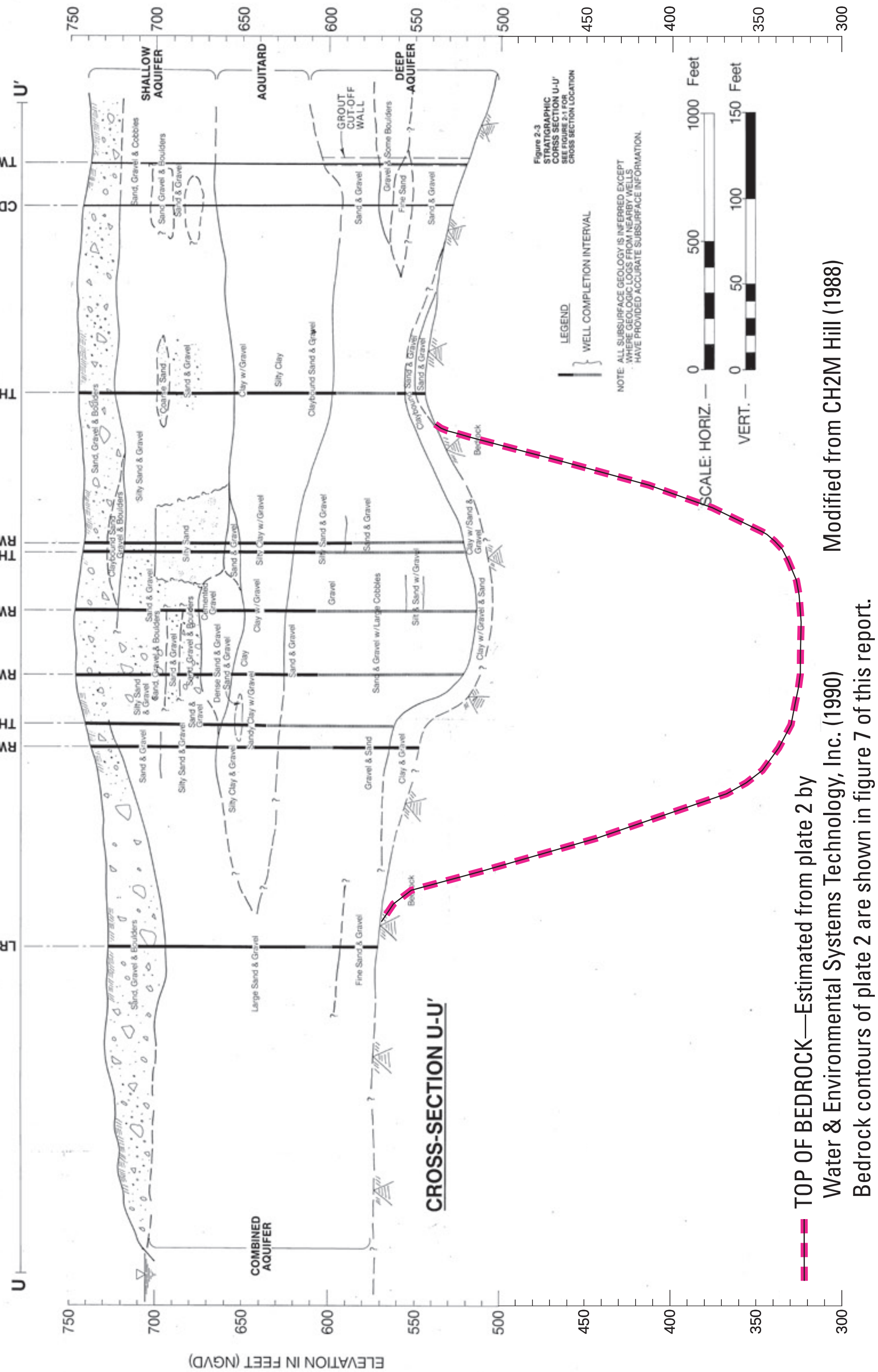


Figure 2-2
STRATIGRAPHIC CROSS SECTIONS A-A' AND B-B'
SEE FIGURE 2-1 FOR LOCATION OF EACH CROSS SECTION

Appendix 1.—Continued



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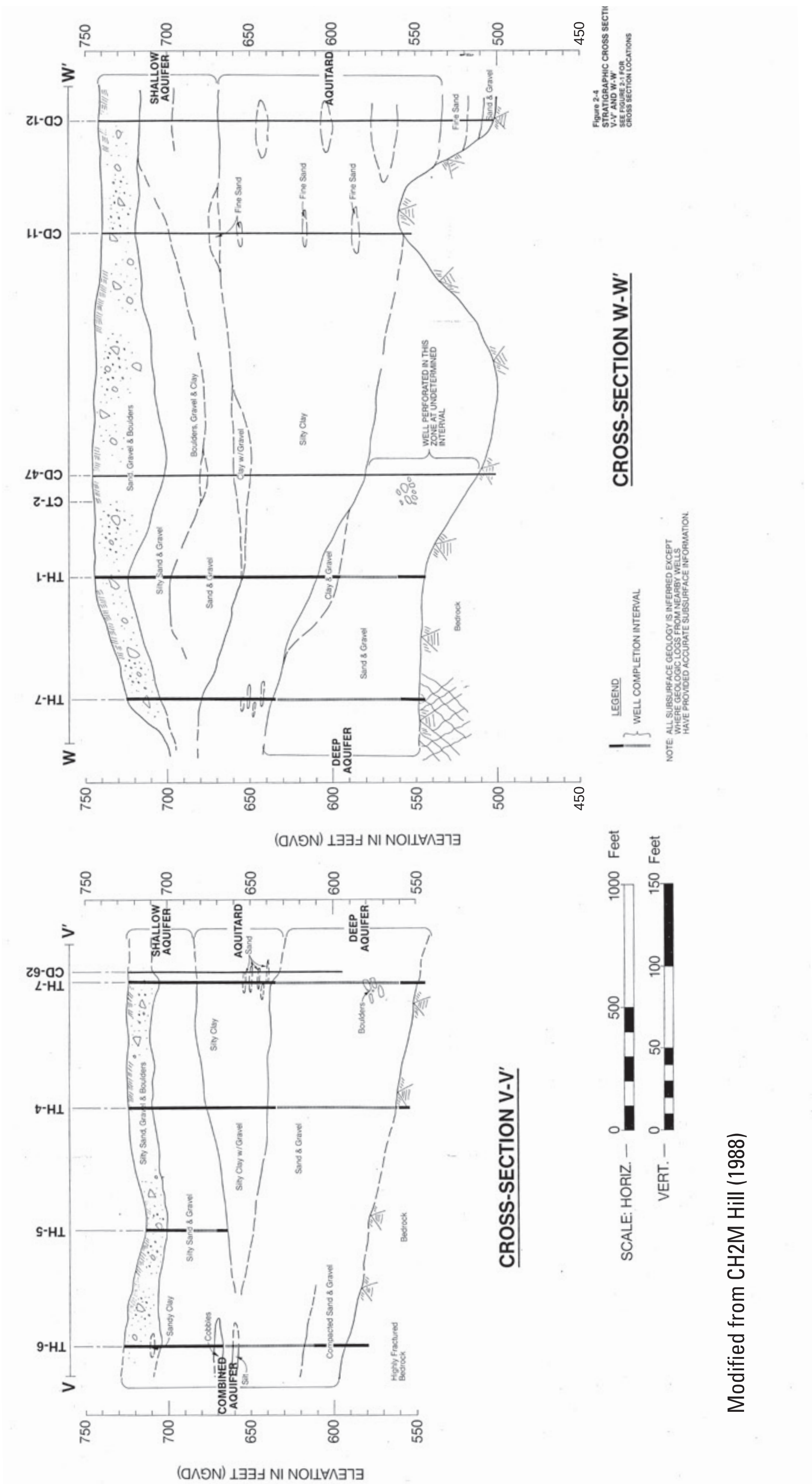
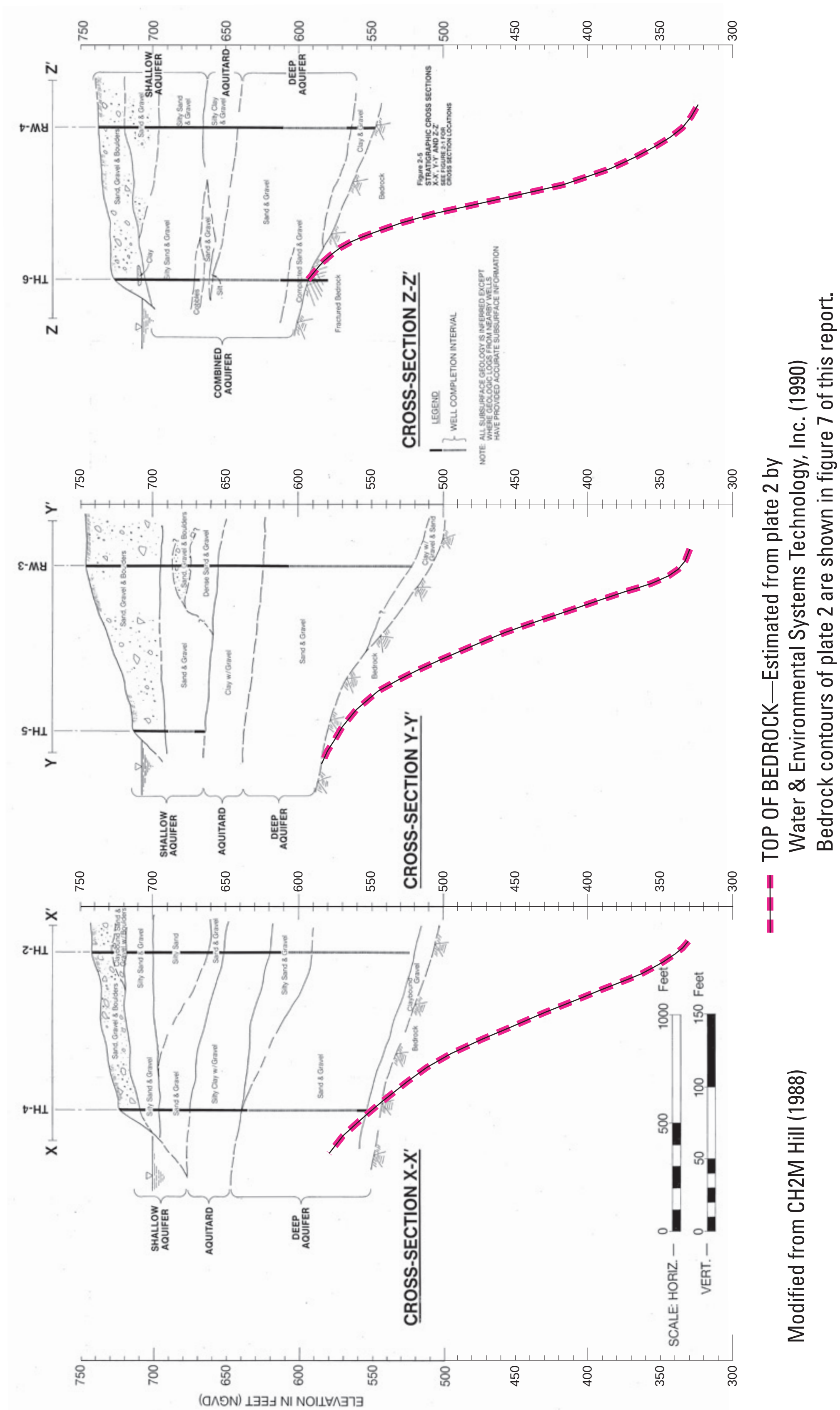


Modified from CH2M Hill (1988)

Appendix 1.—Continued



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Appendix 2. Summary of Down-Hole Camera Surveys of Selected Wells of the Eastbank Aquifer System, Douglas County, Washington, December 11–13, 2007.

Well CD6; USGS Well No. 24N/20E-35Q06

Down-hole camera survey by Kevin D. Knutson, USGS, December 11, 2007.

Survey procedures

The depth reader for the camera was set to zero at the top of the well casing (TOC). After reaching the bottom of the well and bringing the camera back up, the TOC reading was 1.5 feet. Camera-depth readings may thus be as much as 1.5 feet too large. Depth readings on the movie represent the depth below TOC for the top of the camera unit. The downward-looking camera lens is 2.03 feet below the top of the camera unit and the sideward-looking camera lens is 1.68 feet below the top of the camera unit.

Basic information about the well

Well CD6 was drilled to a depth of 216 feet in 1972 or earlier, and probably 1957 or earlier. A 6-inch-diameter steel casing was installed without perforations. The well is a monitoring well and does not have a pump.

Summary of down-hole camera survey

(Depths shown in this section have been corrected for the position of the camera lens and are depths below TOC.)

1. The camera contacted the water surface at 49.2 feet below TOC, and the camera encountered sediments at the bottom of the well at 198.8 feet below TOC.
2. The well casing is in good condition with thin patchy scaling attached to the casing at all depths.
3. No perforations were seen. No animals were seen.

Well CD47; USGS Well No. 24N/20E-35Q02

Down-hole camera survey by Kevin D. Knutson, USGS, December 11, 2007.

Survey procedures

The depth reader for the camera was set to zero at the top of the metal manhole cover (TMMC) of the concrete vault that houses the well. The top of the metal manhole cover is 6.70 feet above the top of the well casing (TOC), which is below land surface. After reaching the bottom of the well and bringing the camera back up, the camera-depth reader indicated a depth of 1.2 feet for the TMMC. The camera-depth readings may thus be as much as 1.2 feet too large. During the second part of the survey, when the camera moved from the bottom of the well to the top, the tripod from which the camera was suspended fell and it was put back up again. Depth readings on the movie represent the depth below TMMCs for the top of the camera unit. The downward-looking camera lens is 2.03 feet below the top of the camera unit and the sideward-looking camera lens is 1.68 feet below the top of the camera unit.

Basic information about the well

Well CD47 was drilled to a depth of 245 feet in 1972 or earlier, and probably 1957 or earlier. A 6-inch-diameter steel casing was installed and perforations were added later at unknown depths across from the Lower Aquifer. The well is a monitoring well and does not have a pump.

Summary of down-hole camera survey

(Depths shown in this section have been corrected for the position of the camera lens and are depths below TOC.)

1. The camera contacted the water surface at 47.6 feet below TOC. The camera did not reach the bottom of the well, because the casing became too narrow due to protruding of scaling. Maximum depth reached was 186.9 feet below TOC.
2. The well casing is in good condition with scaling attached to the casing at all depths. The scaling is patchy and thin to a depth of approximately 115.3 feet below TOC when it gradually became rougher and more three-dimensional. At 134 feet below TOC, there may have been flow. However, it was difficult to be certain because falling scaling was disturbing the water. By 169.5 feet below TOC, there was flow and the scaling was solid instead of patchy. By 179.8 below TOC, the scaling had become hummocky and protruded into the casing by about 0.25 inch. By 180.5 feet below TOC, the water became noticeably clearer, which had been murky until that depth. By 181.3 feet below TOC, the scaling was protruding as much as about 0.5 inch and there was flow. By 186.9 feet below TOC, the protrusions narrowed the casing to the point where the camera could not go down farther. Based on these findings, it is concluded that the perforated interval of this well starts at about 180 feet below TOC and extends to an unknown depth.

3. At 140.2 feet below TOC, a large piece of scaling extended across the casing, which broke into pieces after the camera went through it. This may have been a sliver of corroded casing.

4. Two different types of invertebrate animals were observed in this well, none of which have currently (2008) been sampled and identified.

   a. An arthropod that may be an amphipod without pigment was observed at a depth of 186.9 feet below TOC moving along the well casing from the center right across the top of the picture and disappearing on the left. This animal was different than those seen in well TH6 and may have been the same animal as the second, larger possible amphipod in well TH2. The animal was about 1 inch long.

   b. At the same depth, a second unidentified arthropod moved into view in the upper right-hand corner. This animal was different than any of the animals seen in wells TH6 and TH2. It had no pigment, was about 1 inch long, had a large head and dark eyes, and generally resembled a damselfly nymph (T. DeVries, Burke Museum of Natural History and Culture, oral commun., 2008). The animal appeared to be carrying prey, possibly of the same species. A temperature profile of the water column was measured in well CD47 on December 11, 2007 prior to the down-hole camera survey, with temperatures ranging from 11.9°C between 220 and 230 feet below TOC to 14.4°C at 160 feet below TOC. At the depth the arthropods were seen, temperatures ranged from 13.0°C at 180 feet below TOC to 12.7°C at 190 feet below TOC.

Video 1 of arthropod in well CD47 (http://pubs.usgs.gov/sir/2008/5071/VideoCD47A.wmv). Arthropod is possible amphipod.

Video 2 of arthropod in well CD47 (http://pubs.usgs.gov/sir/2008/5071/VideoCD47B.wmv). Arthropod generally resembles a damselfly nymph.

Well TH2; USGS Well No. 24N/20E-35K06

Down-hole camera survey by Kevin D. Knutson, USGS, December 11, 2007.

Survey procedures
The depth reader for the camera was set to zero at the top of the well casing (TOC). After reaching the bottom of the well and bringing the camera back up, the TOC reading was 1.5 feet. The camera-depth readings may thus be as much as 1.5 feet too large. Depth readings on the movie represent the depth below TOC for the top of the camera unit. The downward-looking camera lens is 2.03 feet below the top of the camera unit and the sideward-looking camera lens is 1.68 feet below the top of the camera unit.

Basic information about the well
Well TH2 was drilled to a depth of 225 feet. An 8-inch-diameter steel casing was installed, with perforations from 135 to 220 feet. The well is a monitoring well and does not have a pump.

Summary of down-hole camera survey
(Depths shown in this section have been corrected for the position of the camera lens and are depths below TOC. The camera survey described here was the second survey of well TH2 that was redone immediately following the first survey, which did not properly record. Well RW1, a public-supply well adjacent to well TH2, was pumping throughout the first and second surveys.)

1. The camera contacted the water surface at 45.3 feet below TOC, and was unable to go deeper than 156.4 feet because of narrowing of the casing due to scaling. It is estimated that scaling protruded into the casing by about 1 inch at this depth.

2. The well casing is in good condition with scaling attached to the casing at all depths. The scaling is thin until about 136 feet below TOC, where it gradually starts to thicken and becomes hummocky. The increase in thickness of the scaling coincides with the start of the reported perforated zone, although no perforations were seen.

3. Two different types of invertebrate animals were observed in this well, none of which have currently (2008) been sampled and identified.

    a. Arthropods that appear to be blind isopods without pigment were observed clinging to the well casing from 117.6 to 155.4 feet below TOC. The estimated length of the possible isopods is about 1 inch.

    b. At 132.7 and 113.3 feet below TOC, a second type of arthropod was observed that may be an amphipod. This animal was shorter than the possible isopods and moved faster. The possible amphipod seen at 113.3 feet below TOC was larger than the one seen at 132.7 feet below TOC. A temperature profile of the water column was measured in well TH2 on December 11, 2007 prior to the first down-hole camera survey, with temperatures ranging from 10.5°C at 50 feet below TOC to 15.1°C at 160 feet below TOC. At the depth range where arthropods were seen, temperatures ranged from 13.5°C at 110 feet below TOC to 15.1°C at 160 feet below TOC. Abundance of the possible isopods appeared to be unrelated to water temperature. Instead, abundance of the possible isopods appeared to be correlated with proximity to the perforated interval, presumably because water that is replenished is richer in oxygen and nutrients and thus can reasonably be expected to be preferred habitat for the possible isopods. The abundance of possible isopods in well TH2 was less than in well TH6.

Video 1 of arthropod in well TH2 (http://pubs.usgs.gov/sir/2008/5071/VideoTH2A.wmv). Arthropod is possible isopod.

Video 2 of arthropod in well TH2 (http://pubs.usgs.gov/sir/2008/5071/VideoTH2B.wmv). Arthropod is possible amphipod.

Video 3 of arthropod in well TH2 (http://pubs.usgs.gov/sir/2008/5071/VideoTH2C.wmv). Arthropod is possible isopod.

Video 4 of arthropod in well TH2 (http://pubs.usgs.gov/sir/2008/5071/VideoTH2D.wmv). Arthropod is possible amphipod.

Well TH4; USGS Well No. 24N/20E-35K02

Down-hole camera survey by Kevin D. Knutson, USGS, December 12, 2007

Survey procedures
The depth reader for the camera was set to zero at the top of the well casing (TOC). After reaching the bottom of the well and bringing the camera back up, the TOC reading was 0.5 foot. The camera-depth readings may thus be as much as 0.5 foot too large. Depth readings on the movie represent the depth below TOC for the top of the camera unit. The downward-looking camera lens is 2.03 feet below the top of the camera unit and the sideward-looking camera lens is 1.68 feet below the top of the camera unit.

Basic information about the well
Well TH4 was drilled to a depth of 170 feet. An 8-inch-diameter steel casing was installed with perforations from 100 to 168 feet. The well is a monitoring well and does not have a pump.

Summary of down-hole camera survey
(Depths shown in this section have been corrected for the position of the camera lens and are depths below TOC.)

1. The camera contacted the water surface at 27.2 feet below TOC, and the camera encountered sediments at the bottom of the well at 161.0 feet below TOC.

2. The well casing is in good condition with scaling attached to the casing at all depths. The scaling is thin and patchy to about 50 feet below TOC, when the scaling starts to protrude more into the casing. By about 60 feet below TOC, the scaling is no longer patchy. The scaling continues to get thicker and more hummocky farther down. By about 110 feet below TOC, the scaling protrudes into the well by as much as about 1 inch. By about 100 feet below TOC, water is relatively clear except for suspended pieces of scaling.

3. One type of invertebrate animal was observed in this well, which has currently (2008) not been sampled and identified. Two arthropods that appear to be small amphipods without pigment were observed moving along the well casing at 101.4 and 130.1 feet below TOC. A temperature profile of the water column was measured in well TH4 on December 12, 2007 prior to the down-hole camera survey, with temperatures ranging from 11.2 to 13.6°C throughout the well and ranging from 12.1 to 11.4°C from 100 to 130 feet below TOC.

Well TH5; 24N/20E-35G01

Down-hole camera survey by Kevin D. Knutson, USGS, December 12, 2007.

Survey procedures
The depth reader for the camera was set to zero at the top of the well casing (TOC). After reaching the bottom of the well and bringing the camera back up, the TOC reading was 0 foot. The camera depth readings were thus correct. Depth readings on the movie represent the depth below TOC for the top of the camera unit. The downward-looking camera lens is 2.03 feet below the top of the camera unit and the sideward-looking camera lens is 1.68 feet below the top of the camera unit.

Basic information about the well
Well TH5 was drilled in 1987 to a depth of 47 feet. An 8-inch-diameter steel casing was installed, with perforations from 25 to 45 feet. The well is a monitoring well and does not have a pump.

Summary of down-hole camera survey
(Depths shown in this section have been corrected for the position of the camera lens and are depths below TOC.)

1. The camera contacted the water surface at 13.1 feet below TOC, and the camera encountered sediments at the bottom of the well at 41.8 feet below TOC.

2. The well casing is in good condition with thin patchy scaling attached to the casing at all depths.

3. No flow was seen from the water surface to as deep as 34.3 feet below TOC. Flow may have been seen at 38.3 feet below TOC and possibly also perforations in the casing. Perforations also may have been seen at 39.3 feet below TOC. Perforations were difficult to see due to scaling, murky water, and a fuzzy image. Water at bottom of the well is clear. No animals were seen.

Well TH6; USGS Well No. 24N/20E-35G02

Down-hole camera survey by Kevin D. Knutson, USGS, December 12, 2007.

Survey procedures
The depth reader for the camera was set to zero at the top of the well casing (TOC). After reaching the bottom of the well and bringing the camera back up, the TOC reading was -0.2 foot. The camera-depth readings may thus be as much as 0.2 foot too small. Depth readings on the movie represent the depth below TOC for the top of the camera unit. The downward-looking camera lens is 2.03 feet below the top of the camera unit and the sideward-looking camera lens is 1.68 feet below the top of the camera unit.

Basic information about the well
Well TH6 was drilled in 1987 to a depth of 148 feet and the hole was sealed below 134 feet. An 8-inch-diameter steel casing was installed, with perforations from 60 to 115 feet. The well is a monitoring well and does not have a pump.

Summary of down-hole camera survey
(Depths shown in this section have been corrected for the position of the camera lens and are depths below TOC.)

1. The camera contacted the water surface at 29.2 feet below TOC, and the camera encountered sediments at the bottom of the well at 121.7 feet below TOC.

2. The well casing is in good condition with scaling attached to the casing at all depths. The scaling is thicker and hummocky where the casing is perforated. Maximum protrusion of scaling into the well is estimated to be about 0.5 inch.

3. Starting at about 59 feet below TOC, horizontal flow was observed in the well. This flow became stronger with depth, with strong currents from about 63 to about 72 feet below TOC. By 76 feet below TOC, the currents were weaker and by about 102 feet below TOC, there was no evidence of horizontal flow. In the zone of strong currents, the flow direction appeared to be spiraling.

4. From 103.6 to 105.6 feet below TOC, open vertical perforations were seen. Additional open vertical perforations were seen from 118.1 to 119.4 feet below TOC.

5. Three different types of invertebrate animals were observed in this well, none of which have currently (2008) been sampled and identified.

    a. Arthropods that appear to be blind isopods without pigment were observed clinging to the well casing from just below the water surface to the bottom of the well. The estimated length of the possible isopods is about 1 inch. The possible isopods were most numerous in parts of the well with strong currents, although the current at times knocked the animals from the casing.

    b. At the bottom of the well, a second type of arthropod was observed that may be an amphipod. This animal was about one-third the length of the possible isopods and moved faster.

c. At the bottom of the well, two worms also were observed. One moved from its hiding place in the sediments and in doing so extended to a length of 5-6 times the length of the possible isopods. The possible amphipods were observed avoiding the moving worms. A temperature profile of the water column was measured in well TH6 on December 12, 2007 prior to the down-hole camera survey, with temperatures ranging from 8.5 to 9.2°C. Abundance of the possible isopods appeared to be unrelated to water temperature. Instead, abundance of the possible isopods appeared to be correlated with water flow, presumably because water that is replenished is richer in oxygen and nutrients and thus can reasonably be expected to be preferred habitat for the possible isopods.

Video 1 of arthropods in well TH6 (http://pubs.usgs.gov/sir/2008/5071/VideoTH6A.wmv). Arthropods are possible isopods.

Video 2 of arthropods and worms in well TH6 (http://pubs.usgs.gov/sir/2008/5071/VideoTH6B.wmv). Arthropods are possible isopods and possible amphipods.

Well TH7; USGS Well No. 24N/20E-35K01

Down-hole camera survey by Kevin D. Knutson, USGS, December 12, 2007.

Survey procedures
The depth reader for the camera was set to zero at the top of the well casing (TOC). No TOC reading was taken when the camera was brought back up and thus the error of the camera depth reading is not known. Depth readings on the movie represent the depth below TOC for the top of the camera unit. The downward-looking camera lens is 2.03 feet below the top of the camera unit and the sideward-looking camera lens is 1.68 feet below the top of the camera unit.

Basic information about the well
Well TH7 was drilled in 1987 to a depth of 180 feet. An 8-inch-diameter steel casing was installed to 176 feet, with perforations from 90 to 165 feet. The well is a monitoring well and does not have a pump.

Summary of down-hole camera survey
(Depths shown in this section have been corrected for the position of the camera lens and are depths below TOC.)

1. The camera contacted the water surface at 28.2 feet below TOC, and the camera encountered sediments at the bottom of the well at 171.5 feet below TOC.

2. The well casing is in good condition, with scaling attached to the casing at all depths. The scaling is thin and patchy until a depth of about 80 feet below TOC, when it starts to become more three-dimensional and less patchy. Scaling was protruding about 0.25 inch into the well at this depth. By about 92 feet below TOC, the scaling had become thicker and hummocky. The thick and hummocky scaling continued until the bottom of the well and protruded as much as about 1 inch into the casing. Scaling in this well appeared to be harder than and did not flake off as easily as scaling seen in other wells of the monitoring network.

3. From 153 to 158 feet below TOC, vertical perforations were seen and water was very clear at this depth. Clear water was first noticed at a depth of 132 feet below TOC and it continued to be clear to the bottom of the well.

4. As many as three different types of invertebrate animals were observed in this well, none of which have currently (2008) been sampled and identified.

    a. Arthropods that appear to be blind isopods without pigment were observed clinging to the well casing. Two possible isopods were seen in the well and perhaps a few more between depths of 88 to 146.1 feet below TOC. The estimated length of the possible isopods is about 1 inch.

    b. A second and third type of arthropod was more numerous in this well and may have been amphipods of two different sizes. One size was about 1 inch and the other about one-third of an inch. Only a few specimens were seen at depths ranging from 94.5 to 114.4 feet below TOC. These animals move faster than the possible isopods. A temperature profile of the water column was measured in well TH7 on December 12, 2007, prior to the down-hole camera survey, with temperatures ranging from 12.9 to 14.2°C throughout the well and ranging from 13.9 to 13.5°C from 90 to 150 feet below TOC. Abundance of the possible isopods and amphipods appeared to be related to proximity to the perforated interval.

Well TH8; USGS Well No. 24N/20E-35K04

Down-hole camera survey by Kevin D. Knutson, USGS, December 13, 2007.

Survey procedures

The depth reader for the camera was set to zero at the top of the well casing (TOC). After reaching the bottom of the well and bringing the camera back up, the TOC reading was -0.6 foot. The camera-depth readings may thus be as much as 0.6 foot too small. Depth readings on the movie represent the depth below TOC for the top of the camera unit. The downward-looking camera lens is 2.03 feet below the top of the camera unit and the sideward-looking camera lens is 1.68 feet below the top of the camera unit.

Basic information about the well

Well TH8 was drilled in 1987 to a depth of 255.5 feet. A 6-inch-diameter steel casing was installed to 255 feet and an 8-inch-diameter steel casing to 217 feet without perforations. Currently (2008), only the 6-inch-diameter casing is visible above land surface. The well is a monitoring well and does not have a pump.

Summary of down-hole camera survey

(Depths shown in this section have been corrected for the position of the camera lens and are depths below TOC.)

1. The camera contacted the water surface at 52.4 feet below TOC, and the camera encountered sediments at the bottom of the well at 258.1 feet below TOC.

2. The well casing is in good condition with thin scaling attached to the casing at all depths. The scaling is more three-dimensional and patchier in about the bottom 10 feet of the well.

3. At about 177.3 and 197.2 feet below TOC, casing sections were connected by some type of collar that was about 1–2 inches wide. Other casing connections were welded seams.

4. No flow was observed. No animals were observed.

Well TH9; USGS Well No. 24N/20E-35K03

Down-hole camera survey by Kevin D. Knutson, USGS, December 12, 2007.

Survey procedures

The depth reader for the camera was set to zero at the top of the well casing (TOC). After reaching the bottom of the well and bringing the camera back up, the TOC reading was 0.1 foot. The camera-depth readings may thus be as much as 0.1 foot too large. Depth readings on the movie represent the depth below TOC for the top of the camera unit. The downward-looking camera lens is 2.03 feet below the top of the camera unit and the sideward-looking camera lens is 1.68 feet below the top of the camera unit.

Basic information about the well

Well TH9 was drilled in 1987 to a depth of 211.5 feet. An 8-inch-diameter steel casing was installed to 92.5 feet and a 6-inch-diameter steel casing was installed from 85 to 211 feet, with perforations from 130 to 165 feet and 180 to 205 feet. The well is a monitoring well and does not have a working pump. During the camera survey, a 1-inch inner-diameter PVC pipe was encountered at depth attached to a heavy object that was presumed to be a pump. The presumed pump and attached pipe fell to the bottom of the well.

Summary of down-hole camera survey

(Depths shown in this section have been corrected for the position of the camera lens and are depths below TOC.)

1. The camera contacted the water surface at 41.9 feet below TOC, and the camera encountered sediments at the bottom of the well at 188.3 feet below TOC.

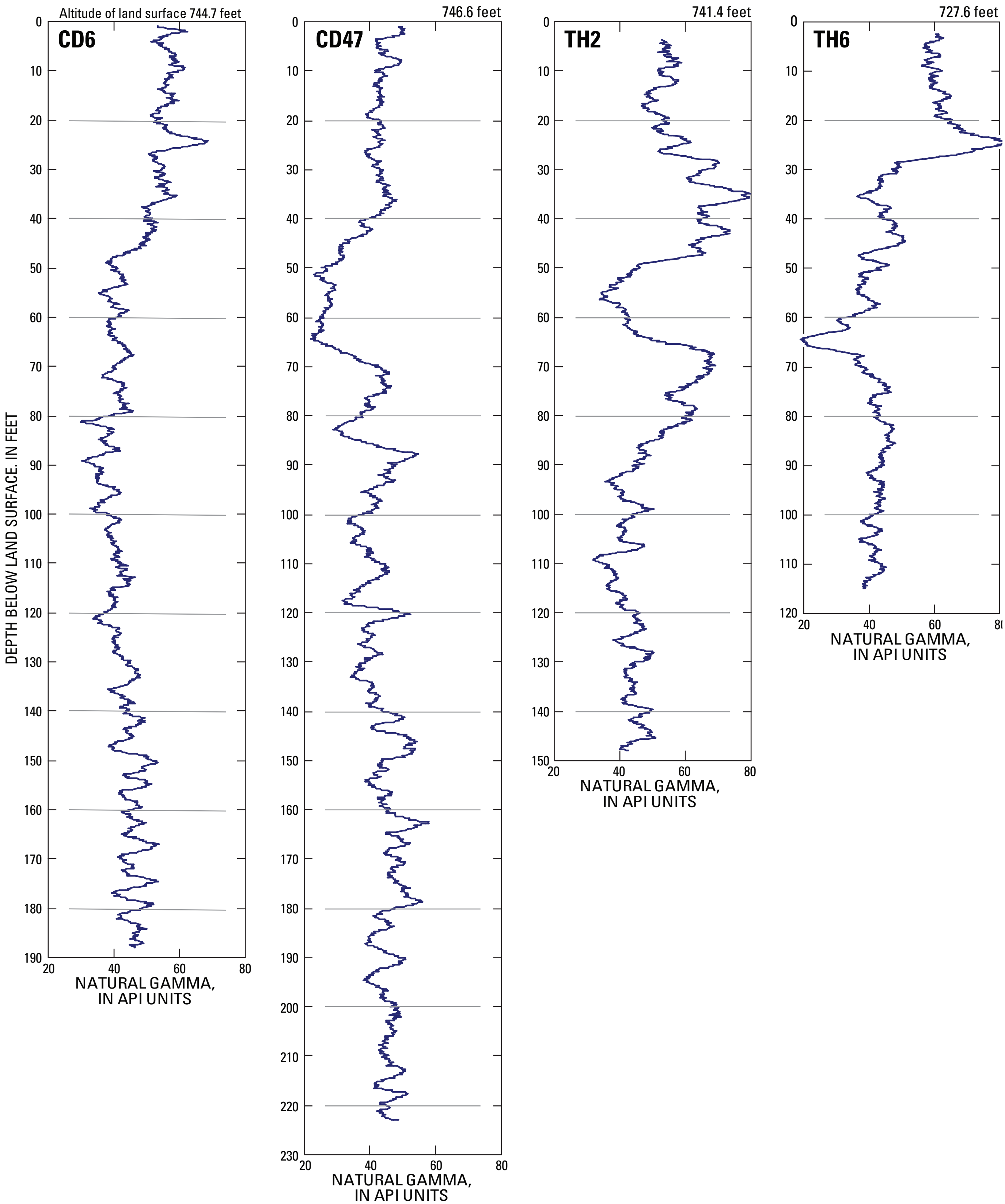
2. The top of the broken off 1-inch-inner-diameter PVC pipe is at 76 feet below TOC. The pipe runs all the way to the bottom of the well into the sediments.

3. At a depth of about 87.4 feet below TOC, the casing appeared to narrow and the camera started getting stuck more frequently.

4. The well casing is in good condition with scaling attached to the casing at all depths. The scaling is generally thin and patchy in places. It is notable that no particularly hummocky scaling was seen at any depth, perhaps indicating limited, if any flow in this well.

5. No perforations and no animals were seen. However, the image was poor because water was murky due to large amounts of suspended matter. The water seemed less murky near the bottom of the well, although it was difficult to be certain due to the large amount of falling and suspended matter in the well.

Appendix 3. Natural-Gamma Logs of Selected Wells of the Eastbank Aquifer System, Douglas County, Washington, December 13, 2007.



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Manuscript approved for publication, April 30, 2008

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van Heeswijk and others— **Hydrologic and Thermal Conditions of the Eastbank Aquifer System, Douglas County, Washington**—Scientific Investigations Report 2008–5071