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In Situ Hydraulic Testing and Water Quality Sampling in the Hyporheic Zone of the Columbia River, Hanford Reach, Washington

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THESIS APPROVAL

The abstract and thesis of Evan V. Arntzen for the Master of Science in Geology presented December 5, 2001, and accepted by the thesis committee and the department.

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Abstract

An abstract of the thesis of Evan V. Arntzen for the Master of Science in Geology presented December 5, 2001

Title: In situ Hydraulic Testing and Water Quality Sampling in the Hyporheic Zone of the Columbia River, Hanford Reach, Washington

Several chemical and radiological contaminants are present in an unconfined aquifer underlying the U.S. Department of Energy's Hanford Site in southeast Washington State. Hexavalent chromium [Cr(VI)], previously used as an anti-corrosive in plutonium production reactors on the shoreline of the Columbia River, is of particular concern because of its conservative nature, toxicity to humans and aquatic life, and proximity to protected salmon spawning habitat. Hydrogeologic data are abundant from the unconfined aquifer, but are lacking from the hyporheic zone through which Cr(VI) is transported into the river. A hydrogeologic study was conducted near one known Cr(VI) plume to determine the concentration and extent of Cr(VI), effect of anisotropy on transport of Cr(VI) into the river, and the relationship between changing river stage and water quality within the hyporheic zone.

Forty-one piezometers were installed along a 4,000 m reach of the river at depths from 0.2 m to 2.0 m below the riverbed. The piezometers were used to sample Cr(VI), specific conductance, dissolved oxygen, and temperature. Cr(VI) concentrations ranged from undetectable to >0.7 mg/L, with 75% of the samples above the federal standards for protection of aquatic life and 25% above federal drinking water standards. Vertical hydraulic gradients ranged from -0.01 to +0.30. Hydraulic conductivity values, estimated using slug tests, ranged from 2.8 x 10^{-5} cm/s to 4.3 x 10^{-2} cm/s and were largest in areas with high Cr(VI) concentrations. Specific discharge values were estimated using borehole dilution and ranged from 4.0 x 10^{-3} cm/s to 1.5 x 10^{-1} cm/s. In general, an inverse correlation was determined for river stage versus Cr(VI) and other water quality parameters; further investigation determined the relationship to be hysteretic. Results showed that 0.044 kg/d Cr(VI) entered the river, and the concentration of Cr(VI) in the Columbia River downstream of the 100D Area was 1.8 x 10^{-7} mg/L . This study produced results which will allow managers to make better risk-based decisions on Cr(VI) impacts to the biota living in the hyporheic zone.

IN SITU HYDRAULIC TESTING AND WATER QUALITY SAMPLING IN THE HYPORHEIC ZONE OF THE COLUMBIA RIVER, HANFORD REACH, WASHINGTON

by

EVAN V. ARNTZEN

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requirements for the degree of

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in
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Chapter 1: Introduction

In 1943 the first of nine nuclear plutonium production reactors was constructed at the United States Department of Energy's Hanford site in southeastern Washington (Figure 1). The reactors were operational from 1944 to 1984 and produced weapons

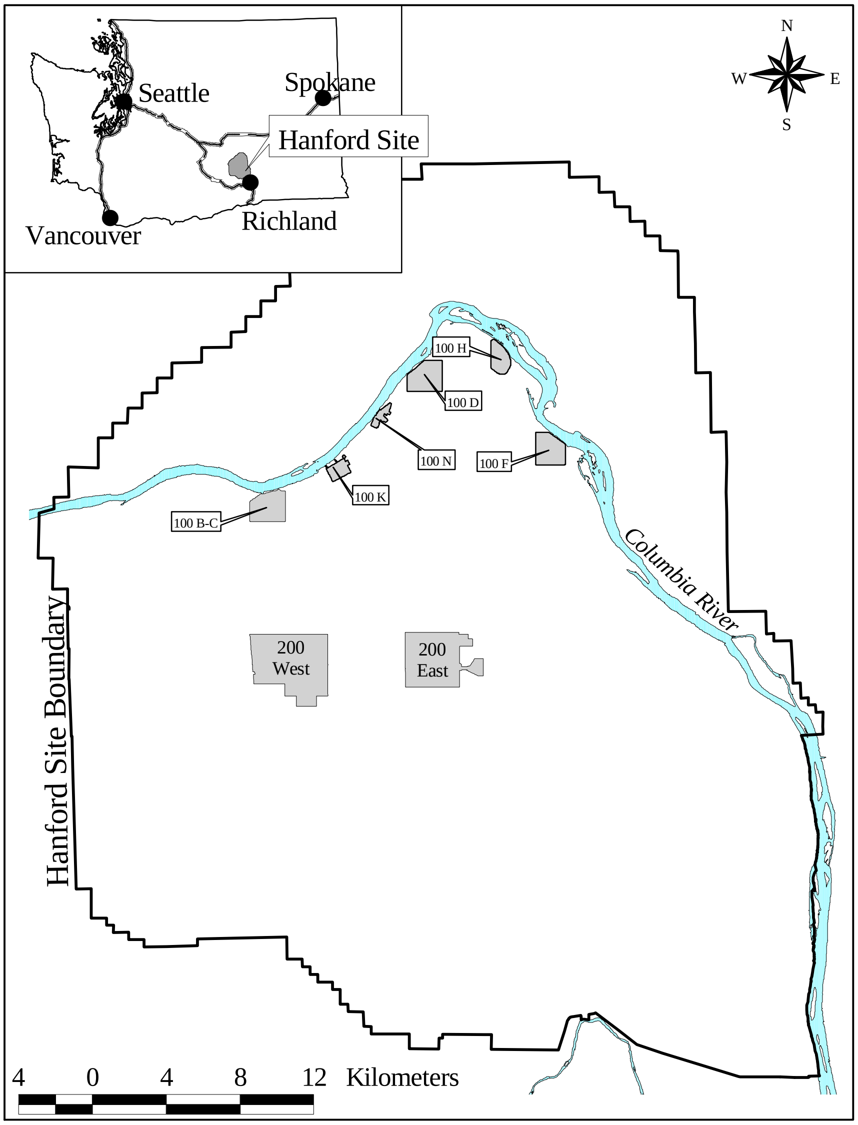

Figure 1: Former plutonium production reactor areas on the Hanford Site, southwest Washington State.

grade plutonium for World War II and the cold war (Becker, 1990). All nine reactors were constructed along the bank of the Columbia River because large volumes of water were needed for cooling and removing waste. Treatment, storage, and disposal of liquid and solid waste during the reactor operation period have resulted in extensive contamination of the unconfined aquifer the reactors are built upon (Dirkes et al., 1998).

Hanford site-wide monitoring efforts test for the presence of several chemical and radiological substances in the ground water (Table 1). Among these

Table 1: Radiological and chemical contaminants at Hanford.

Radiological	Chemical
Americium-241	Ag, Al, As, B, Ba, Be, Br-, Ca, Cd
Antimony-125	Co, Cu, Cr, Cr(VI), Cl-, CN-
Beryllium-7	Fe, F-, Hg, K, Li, Mg, Mn
Carbon-14	Na, NH4+, NO3-, Pb, Sb, Se, Si, Sn
Cesium-134	Sr, SO4-2, Ti, Tl, V, Zn
Cobalt-58, Cobalt-60	Alkalinity
Europium isotopes	Chemical oxygen demand
Gross alpha	Diesel oil
Gross beta	Dissolved oxygen
Iodine-129	Electrical Conductivity
Iron-59	Gasolene
Neptunium-237	Oil and grease
Plutonium isotopes	Pesticides/herbicides
Potassium-40	pH
Radium isotopes	Polychlorinated biphenyls
Ruthenium-106	Semivolatile organic compounds
Strontium-90	Total carbon, Total organic carbon
Technetium-99	Total Dissolved Solids
Tritium	Total organic halogens
Uranium (total)	Total petroleum hydrocarbons
Uranium isotopes	Volatile organic compounds

Notes: Modified from the 1998 Hanford Site Environmental Report.

substances, many have concentrations exceeding federal maximum contamination levels (MCLs) determined by the Environmental Protection Agency (EPA). These standards provide a reference concentration and are useful for the interpretation of water quality data. Table 2 lists Hanford Site contaminants that have been measured in excess of federal drinking water standards.

Table 2: Hanford contaminants exceeding EPA drinking water limits.

Constituent	Chemical standard (mg/L)	Radiological standard (pCi/L)
Chemical constituents		
1,1-Dichloroethane	0.001	NA
1,2 cis-Dichloroethylene	0.07	NA
1,4-Dichlorobenzene	0.075	NA
Aluminum	0.050	NA
Antimony	0.006	NA
Antimony	0.006	NA
Arsenic	0.050	NA
Bis(2-ethylhexyl)phthalate	0.006	NA
Cadmium	0.005	NA
Carbon tetrachloride	0.005	NA
Chloroform	0.100	NA
Chromium	0.100	NA
Fluoride	4	NA
Iron	0.300	NA
Manganese	0.050	NA
Methylene chloride	0.005	NA
Nickel	0.100	NA
Nitrogen in nitrate	10	NA
Pentachlorophenol	0.001	NA
pH	8.5*	NA
Sulfate	250	NA
Thallium	0.002	NA
Total Dissolved Solids	500	NA

Table 2: Continued

Trichloroethylene	0.005	NA
Radiological constituents		
Gross alpha	NA	15
Gross beta	NA	50
Iodine-129	NA	1
Ruthenium-106	NA	30
Strontium-90	NA	8
Technetium-99	NA	900
Tritium	NA	20,000

Notes: Modified from the 1997 Hanford Site Groundwater Monitoring Report.
*Unitless hydrogen ion concentration, not mg/l.

The most widespread contaminants in the unconfined aquifer are nitrate, tritium, and iodine-129 (Hartman et al., 2001). There are also significant contaminant plumes originating near former production reactors, commonly referred to as the 100 Areas (Figure 1). Contaminants in the 100 areas often include chromium and strontium-90 (Hartman et al., 2001). Of particular concern is the presence of hexavalent chromium (the CrO_4^{2-} ion; hereafter represented as Cr(VI)) in sediments underlying the Columbia River near several of the 100 areas (Hope and Peterson, 1996a; Peterson et al., 1998; Hartman et al., 2001). Cr(VI) is a remnant of reactor operations when sodium dichromate was used to treat reactor cooling water to prevent corrosion in pipes (Hartman et al., 2001). Water contaminated with sodium dichromate is thought to have leaked into the ground near facilities where it was used, and from retention basins and ditches where it was stored or disposed of (Hartman et al., 2001). Cr(VI) is now present in the groundwater adjacent to the Columbia River, as well as present in the groundwater-surface water mixing zone (Figure 2). This zone of mixing is also referred to as the hyporheic zone, or the subsurface region of streams and rivers that exchanges water with the surface (Valett et al., 1993). Contaminant transport through the hyporheic zone into the Columbia River is not well understood, and is

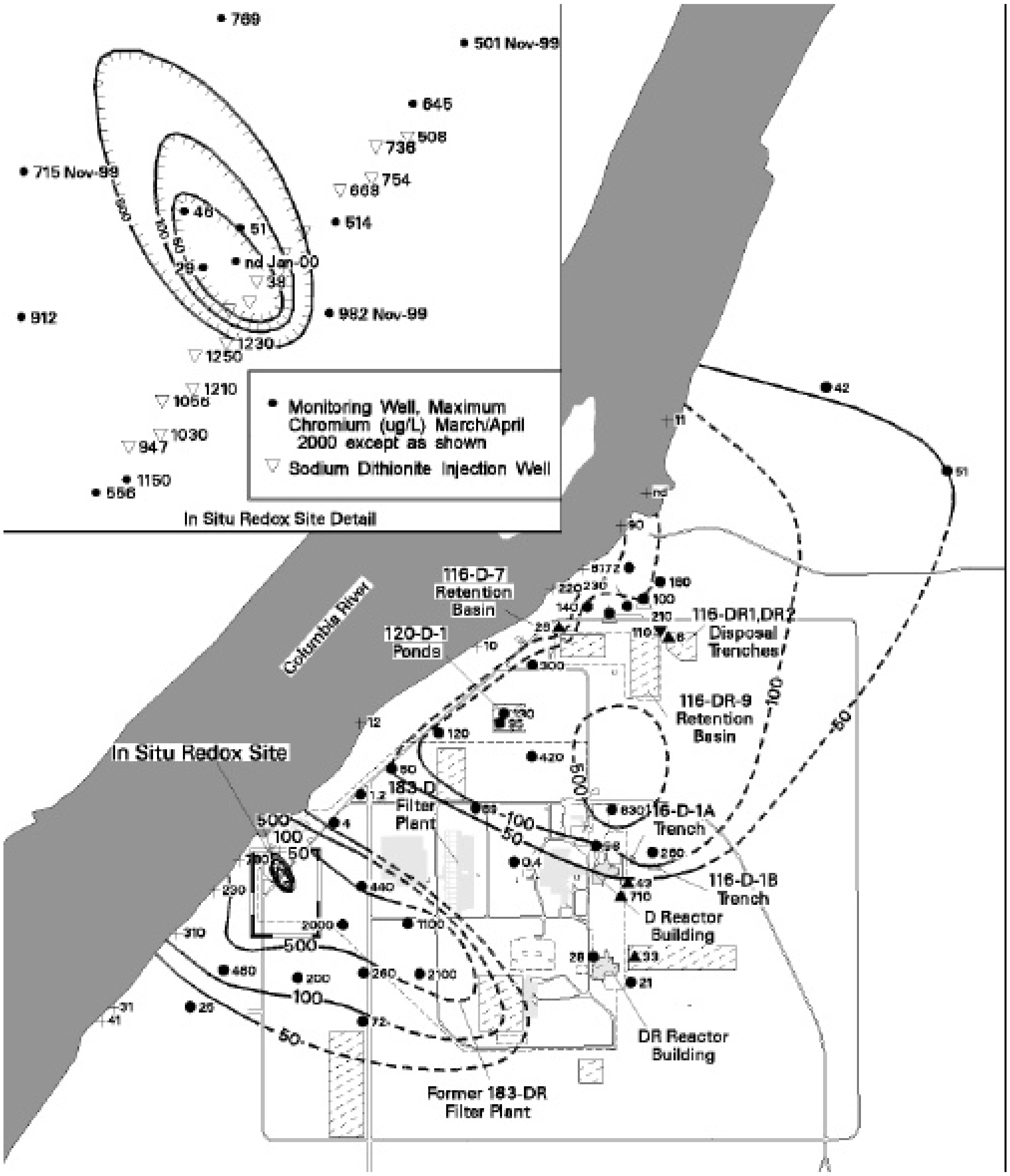

Figure 2: 100D wells and Cr(VI) results in ? g/l (Hartman et al., 2001).

complicated by frequent hydraulic gradient reversals caused by river stage fluctuations. The stage fluctuations are controlled by hydroelectric projects upstream of the Hanford Reach. Fluctuations in power production can change the river stage by up to 2 m each day. Despite frequent gradient reversals, the net movement of groundwater is from the adjacent aquifer toward the Columbia River. Thus, groundwater containing Cr(VI) is migrating into the Columbia River.

Cr(VI) is a concern near the 100 Areas because it is toxic to humans and aquatic life, very mobile, and highly soluble (Palmer and Wittbrodt, 1991; Hope and Peterson, 1996b; Hartman and Dresel, 1998). In addition, the Hanford Reach provides habitat for fall chinook salmon (*Oncorhynchus tshawytscha*) that spawn in highly selective areas of the riverbed (Geist et al., 1994). In some cases salmon spawn near known Cr(VI) plumes (Figure 3). Hyporheic chromium concentrations as high as 0.130 mg/L have been detected near dense fall chinook salmon spawning areas in the vicinity of the 100H Area reactor (Hope and Peterson, 1996b). Near the 100D Area reactor values as high as 0.6 to 0.8 mg/L have been detected close to less dense spawning areas (Hartman and Dresel, 1998; Arntzen unpublished data, 2000). These values exceed the U.S. EPA's 0.01 mg/L chronic ambient water quality criteria (AWQC) for chromium by up to 60 times and exceed the EPA's 0.1 mg/L federal MCL for chromium in drinking water (EPA 1986; WAC 173-201A-040).

Unpublished data collected from fall 1997 to winter 2000 suggest that concentrations of Cr(VI) entering the river vary significantly on a scale of tens of

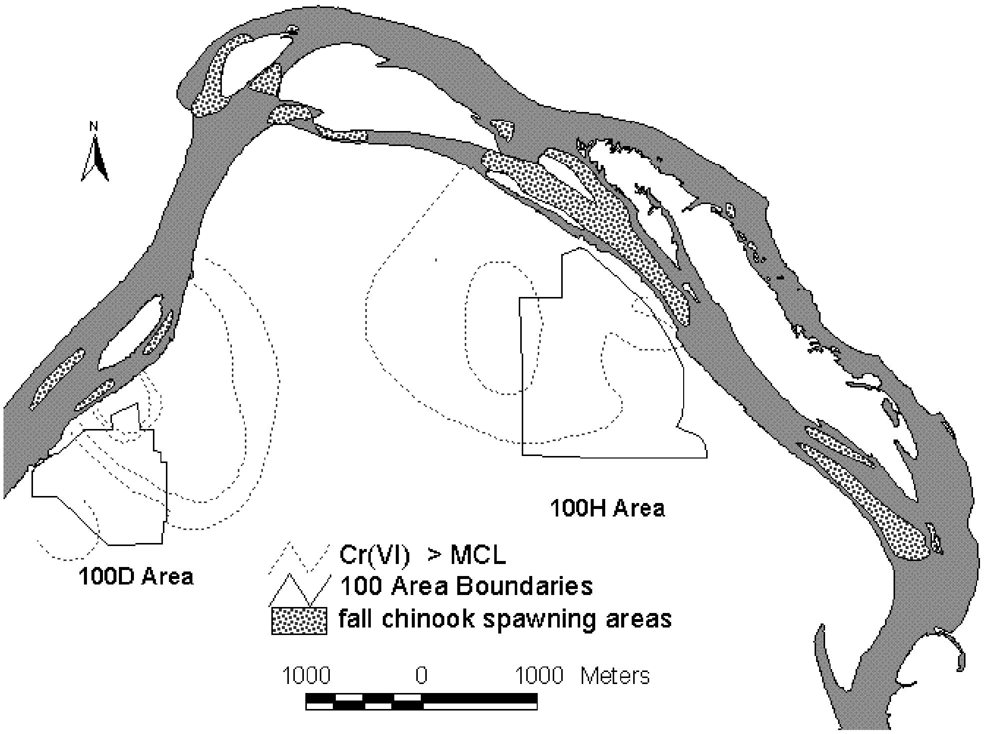

Figure 3: Salmon spawning near Cr(VI), Hanford Reach Washington.

meters or less. Although concentrations are diluted below detection limits upon entry into the river, potentially damaging chromium levels exist within sediment underlying the river. Therefore it is possible that aquatic life, especially salmon eggs and fry which are present within river gravel, are coming into contact with significant levels of Cr(VI). The potential damage inflicted by Cr(VI) is affected by the duration, concentration, and life stage of the salmon during exposure. The problem is that few data exist to help predict the nature and magnitude of that contact. Spatial variability of Cr(VI) contamination in the riverbed, the physical properties of the environment that control the

Cr(VI) variability, and the effect of changes in river stage control the interaction of aquatic organisms with Cr(VI).

Statement of the Problem

Evidence suggests that physical properties (e.g. hydraulic conductivity and hydraulic gradient) of the hyporheic zone influence the concentration and quantity of contaminants discharging into the Columbia River via specific discharge of subsurface waters. The problem is that these relationships are not well understood. The purpose of this study was to collect empirical data from the hyporheic zone that can be used to reduce the uncertainty of how physical properties (e.g. hydraulic conductivity and hydraulic gradient) influence the specific discharge and consequently the quantity of Cr(VI) reaching the river. This thesis addresses five working hypotheses:

1) Cr(VI) and specific conductance are inversely correlated with river stage

   ?? Null hypothesis: there is no significant correlation between water quality and river stage

2) Cr(VI) and specific conductance are positively correlated with depth below the riverbed

   ?? Null hypothesis: there is no significant correlation between water quality and depth

3) Hydraulic conductivity varies spatially

   ?? Null hypothesis: all hydraulic conductivity values are equal

4) Cr(VI) concentrations are higher in zones of higher permeability

    ?? Null hypothesis: hydraulic conductivity does not correlate with Cr(VI)

5) Values of specific discharge are higher in zones of higher permeability

    ?? Null hypothesis: hydraulic conductivity does not correlate with specific discharge

Hanford Site Hydrogeology

The Hanford Reservation lies adjacent to the Columbia River within the Pasco Basin of the Columbia Plateau (Figure 1). Hanford is bordered by basalt ridges comprising the Saddle Mountains to the north and Rattlesnake Mountain to the south. Major geologic units present within the Hanford Site include the Miocene Columbia River Basalt Group, the Miocene to Pliocene fluvial deposits of the Ringold Formation, and Pleistocene flood gravels of the Hanford Formation (Hartman and Dresel, 1997; Figure 4). Within the Hanford Reservation the Ringold and Hanford formations contain an unconfined aquifer while confined aquifers exist between Columbia River Basalt flows. The stratigraphy of the Hanford Site has been developed using well log data from many groundwater monitoring wells (Figure 5). In an effort to further explore the role of heterogeneity on contaminant transport across the zone of ground water-river water interaction, geologists are revisiting well log data to construct more detailed cross-sections (Robert E. Peterson, personal communication, January, 2000). The Hanford Reach of the Columbia River is a gaining stream whose stage is influenced by Priest Rapids Dam, a power production facility located 30.6 km upstream of the 100D area. Discharge from Priest Rapids

Dam varies on the order of tens of thousands of cubic feet per second both seasonally and hourly, as water management is maximized for power production (Figure 6).

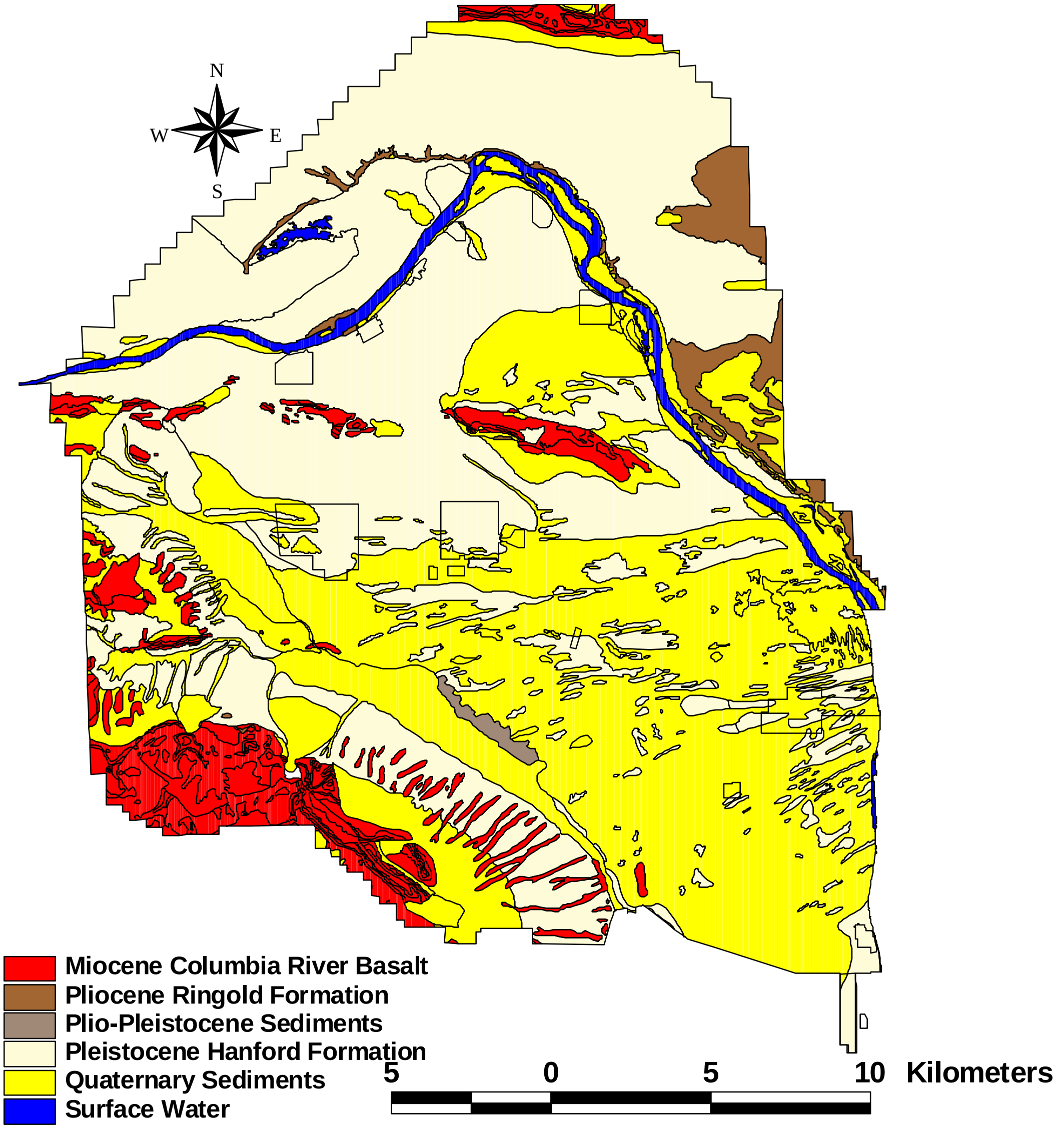

Figure 4: Hanford Site surface geology. The 100D Area is underlain by Pleistocene sand and gravel from the Hanford Formation and Pliocene silt, sand, and gravel from the Ringold Formation.

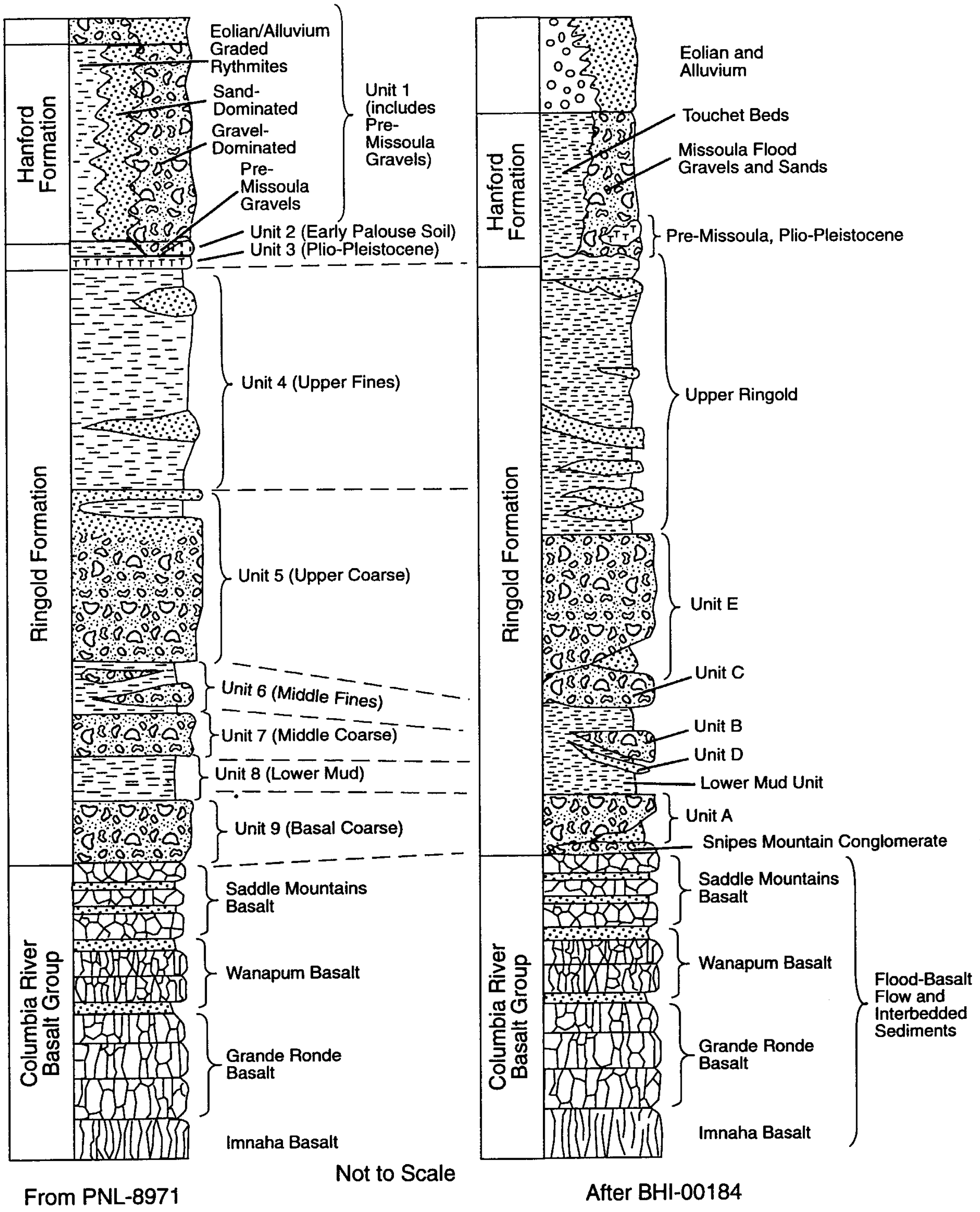

Figure 5: Hanford Site stratigraphy developed using well log data (Thorne et al., 1993).

Hyporheic Zone as a Control on Contaminant Transport

Water Quality Sampling

The hyporheic zone can be described in terms of site-specific parameters, including biologic indicators and physicochemical properties (Gilbert et al., 1994). One important indicator differentiating ground water from river water in the Hanford Reach is specific conductance (Hope and Peterson, 1996a). Columbia River water in the Hanford Reach has a specific conductance from 125 to 150 ?S/cm while local ground water ranges from 300 to 500 ?S/cm (Peterson and Johnson, 1992; Hartman and Dresel, 1997). Another important indicator in the 100D Area is Cr(VI) with concentrations ranging from 0 mg/L to over 0.6 mg/L. The hyporheic zone in the Hanford Reach can be defined using specific conductance because it is a property that can be measured everywhere, while contaminants such as Cr(VI) are only present at certain locations. For purposes of this study the hyporheic zone is the subsurface zone adjacent to the Columbia River in which specific conductance or Cr(VI) values were lower than in the adjacent aquifer but higher than in the river.

Environmental controls on water quality include sediment heterogeneity, hydraulic gradients, and the interaction of ground water and river water. The concept of sediment heterogeneity was addressed using *in situ* hydraulic techniques (see following section). The relationship between water quality and subsurface hydraulic gradients was explored by comparing water quality data to changes in river stage. Surface water chemistry of the river is different from the chemistry of the contiguous groundwater (Dirkes et al., 1999), and large changes in river stage change the hydraulic gradients affecting the magnitude and direction of hyporheic water flow. Consequently, the nature and concentration of water quality parameters such as temperature, specific conductance, pH, Cr(VI), and dissolved oxygen vary as a function of river stage. The objectives of collecting water quality data were to (1) collect and analyze empirical data describing properties of the hyporheic zone, (2) determine the relationship between water quality data and changing river stage and (3) determine the relationship between water quality and depth below the riverbed.

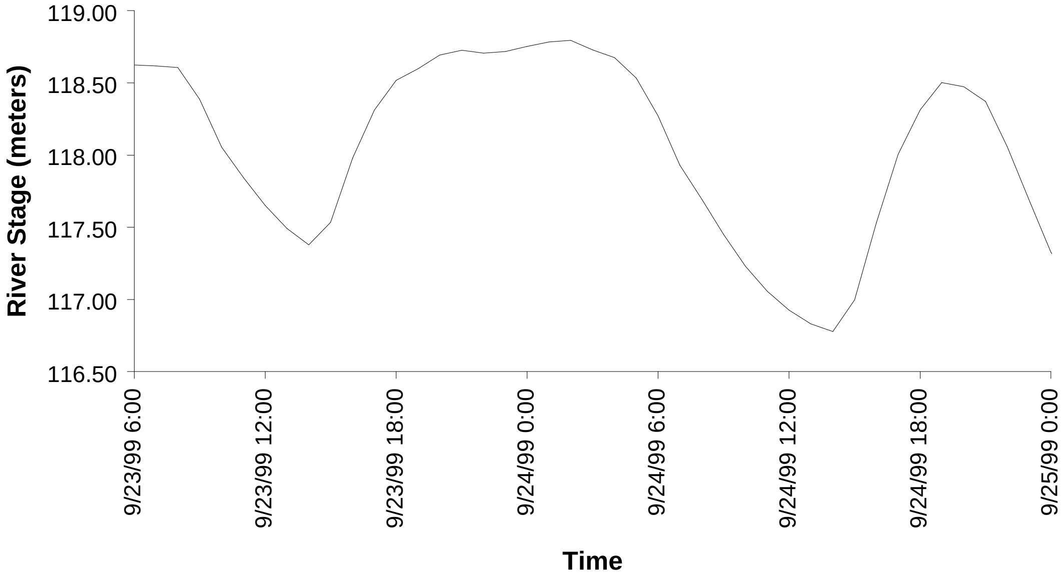

Figure 6: Daily Columbia River stage variation at the 100D Area.

Hydraulic Testing

The extent to which Cr(VI) is toxic to aquatic life depends on biotic as well as abiotic facters. Abiotic influences are controlled mostly by the physical environment through which Cr(VI)is transported within sediment pore water flowing through the hyporheic zone (Figure 7). Sediment heterogeneity, hydraulic conductivity, and ground water/surface water interactions all affect interstitial flow within the hyporheic zone (Peterson and Johnson, 1992; Geist, 2001).

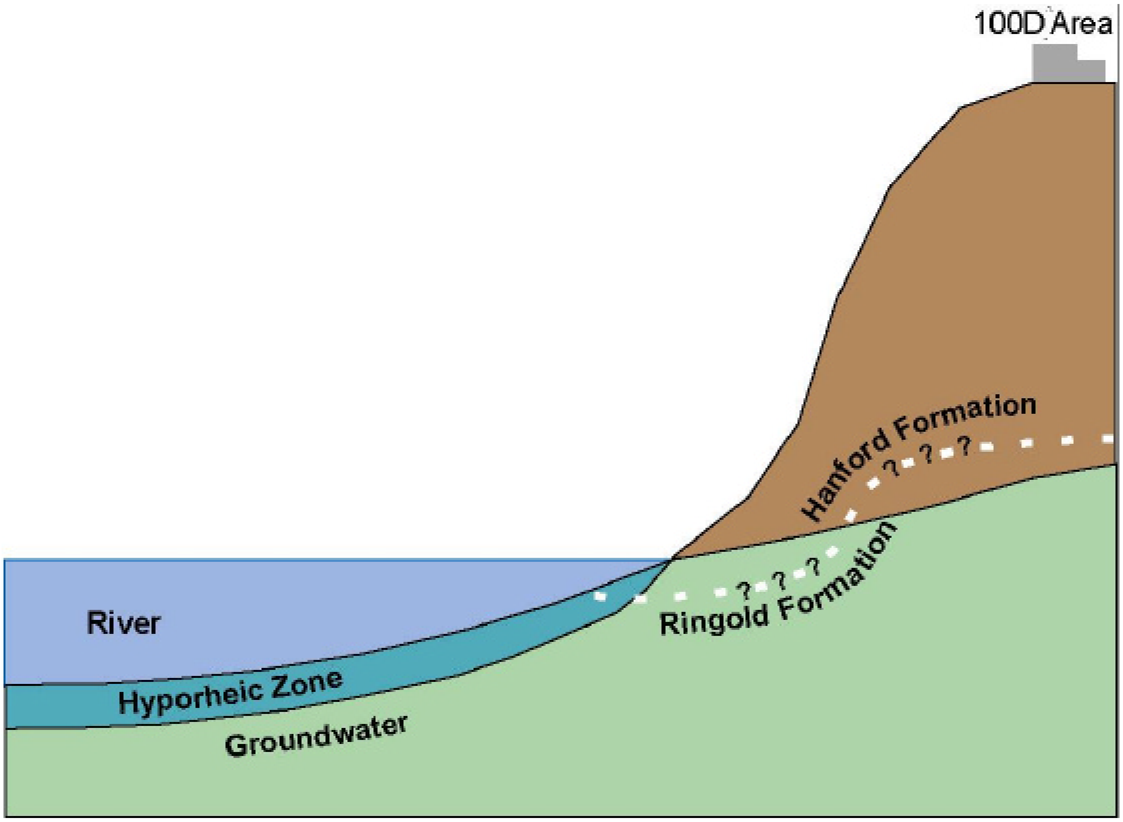

Figure 7: Conceptual model of a cross-section through the hyporheic zone.

Although estimates of sediment hydraulic conductivity, specific discharge of groundwater, and hydraulic gradients have been measured extensively in the aquifer containing the Cr(VI) plumes, similar estimates in the hyporheic zone are lacking. For Hanford site modeling purposes, data were used from the adjacent aquifer, and have assumed large areas of shoreline sediments to be homogeneous (Peterson and Connelly, 2001). The Hanford site-wide three dimensional groundwater flow model utilized stratigraphic data from well logs (Figure 5) to establish 10 major hydrogeologic units, each with an associated estimate of hydraulic conductivity, for use in the three dimensional groundwater flow model (Hartman and Dresel, 1998). Site stratigraphy data for the 100D Area (Figure 8) were used to correlate the entire 100D Area shoreline with Ringold Unit E (Hartman and Dresel, 1998). The estimated hydraulic conductivity for Ringold Unit E is 9.3×10^{-3} cm/s, and that is the hydraulic conductivity value that has been used to estimate groundwater flow rates from the unconfined aquifer at 100D Area, through the hyporheic zone, into the Columbia River (Hartman and Dresel, 1998).

Within the hyporheic zone, advection and dispersion of contaminant plumes depend on the hydraulic gradient, hydrogeology of sedimentary layers, and geomorphic structures (Dahm and Valett, 1996; Dauble and Geist, 2000). These complications could be accounted for more effectively if the effects of heterogeneity were better understood in shoreline environments such as the 100D Area. The purpose of conducting slug tests, borehole dilution, and hydraulic gradient measurements was to improve estimates of hydrogeologic properties in areas where Cr(VI) enters the river, to better understand the nature and extent of heterogeneity. The two primary objectives were (1) to evaluate the applicability and effectiveness of slug tests and borehole dilution when deployed in the unconventional riverbed environment and (2) given that the hydraulic tests were capable of detecting differences in that environment, to determine what, if any, relationships exist between hydraulic properties of the environment and water quality data. These objectives were designed to address the lack of knowledge regarding groundwater flux through the hyporheic zone, which impairs the ability to establish relevant biological, physical, and chemical models. Improving our understanding of the hyporheic zone will allow managers to make better risk-based decisions on contaminant impacts to biota living in the hyporheic zone.

Chapter 2: Background

Water Quality Sampling

Various studies have been conducted to measure shoreline contamination and the interaction of ground water with the Columbia River. Previous work on the Hanford Reach has included the use of devices to detect differences in river-bottom specific conductance, temperature, hydraulic gradients, and dissolved oxygen content. Studies to determine hyporheic water quality have generally been conducted for one of three reasons. First, researchers wished to determine the location, concentration and nature of contaminants entering the Columbia River from the adjacent contaminated aquifer (Hope and Peterson, 1996b; Peterson et al., 1998). Shoreline sampling has been conducted extensively along the shoreline of the Hanford Reach including the 100 Areas. Data collected from the 100D Area shoreline were used to describe the 100D Area Cr(VI) “hot spot”, where particularly high Cr(VI) concentrations are present in the hyporheic zone (Figure 8; Hartman and Dresel, 1998). Additionally, water

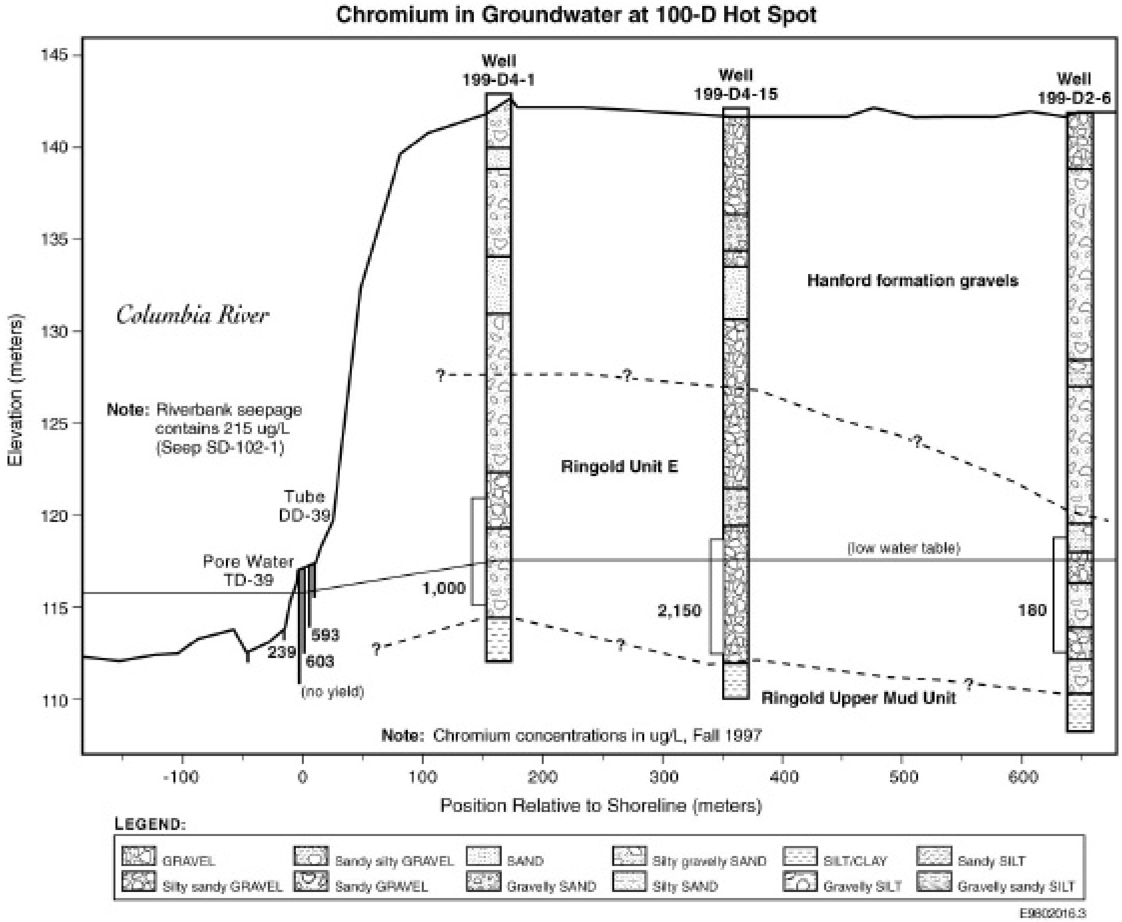

Figure 8: 100D Cr(VI), stratigraphy, and well data (Peterson et al., 1998)

samples have been collected from the Columbia River and from seeps and springs along its banks in the Hanford Reach, including the 100D Area (Patton, 1999). I have participated in some preliminary work of this nature that was conducted in the vicinity of the 100 Area reactors during the fall of 1997 through 1999 (Arntzen, unpublished data). Approximately 100 piezometers were installed and tested for Cr(VI). The second reason the hyporheic zone has been studied was to model the affect of changing river stage on contaminant transport across the hyporheic interface (Connelly, 1998). Finally, research in the hyporheic zone has been used to explain how water quality affects aquatic life. This includes a direct impact (i.e. the potential harm to fall chinook salmon by Cr(VI)) and indirect impact such as changes in habitat selection caused by subtle water quality differences (Geist et al., 1994; Geist et al., 2001).

The toxicological and biological effects of Cr(VI) are complex. Published research indicated that Cr(VI) exposures as low as 0.077 mg/L significantly affect the mortality of chinook salmon during the first several months of life, and concentrations of 0.18 mg/L have a more pronounced impact on mortality, growth, and development (Olson and Foster, 1956). Similar research on rainbow trout (*Oncorhynchus mykiss*) from the fertilized egg to feeding fry life-stage found concentrations of 0.089 mg/L total chromium to have a statistically significant impact on mortality, 0.157 mg/L to cause over 50% mortality, and 0.271 mg/L to cause 97% mortality (Stevens and Chapman, 1984). A recent study completed by the Pacific Northwest National Laboratory (PNNL) tested exposure of early life stage fall chinook salmon to Cr(VI). The results showed that Cr(VI) levels up to 0.266 mg/L had no significant impact on survival, development, or growth (Patton et al., 2001). The PNNL results reflected the protection juvenile salmon experience while at the egg stage prior to emerging into river gravels and the overlying water column of the river (Patton et al., 2001). Organisms are not only exposed to contaminants such as Cr(VI) directly, but they are also susceptible to Cr(VI) uptake through the aquatic food chain (i.e. fish feed on meiofauna, meiofauna feed on microorganisms, and microorganisms accumulate metals through passive sorption and other biologic processes). Ultimately, environmental controls such as hydraulic gradients and sediment heterogeneity determine the location of Cr(VI), and are the largest control on biological interactions with Cr(VI).

Hydraulic Testing

The hydraulic characteristics of the hyporheic zone are largely dependent on the size and structure of sediments underlying the Columbia River. River velocities exceeding 2.0 m/s and the highly permeable nature of riverbed material contribute to a lack of knowledge regarding the flow of water and transport of ions in the hyporheic zone. Traditional methods used to measure the permeability of subsurface material include tracer tests, grain size analysis, permeameter testing, slug tests, geophysical methods, and borehole dilution methods (Palmer, 1993). Tracer methods have successfully produced the most accurate estimates of hydraulic properties, however they are time consuming and involve the use of regulated substances (Pickens and Grisak, 1981; Sudicky et al., 1985; Molz et al., 1986; Ronen et al., 1991). Methods of obtaining sediment samples for grain size analyses using freeze coring are well documented in the literature (Stoker and Williams, 1972; Walkotten, 1976; Lotspeich and Reid, 1980; Carling and Reader, 1981; Rood and Church, 1994). Although time consuming and labor intensive, freeze core samples have provided sample sizes large enough to be statistically significant in large cobble size riverbed material (Kondolf, 2000). Grain size analyses, however, are difficult to correlate with hydraulic properties and provide order of magnitude estimates at best (Palmer, 1993). Ground penetrating radar is a feasible geophysical technique for collecting subsurface structure data from the surface of the river (Naegeli et al., 1996, Geist et al., 1999 unpublished data), however, relating sediment structure to permeability is only a qualitative proposition. Hydraulic techniques, including slug tests and borehole dilution, were deemed the most cost effective of all the methods reviewed.

Slug tests have been used with wide success in the past, and provide fast, inexpensive estimates of hydraulic conductivity (Bouwer and Rice, 1976; Bouwer, 1989; Fetter, 1994; Butler et al., 1996; Weight and Wittman, 1999). Butler (1998) summarized popular slug test methodology in the literature, and pointed out that the appropriate method was dependent first upon the fundamental response of the aquifer to a slug test, and secondly on site specific considerations. The fundamental response is a function of conservation of momentum, and can be represented the same way a damped spring has been in classic physics (Kabala et al., 1985; Kipp, 1985; Butler, 1998). Aquifer responses have been categorized, based on their fundamental response, into under damped, critically damped, and over damped responses (Figure 9; Van der Kamp, 1976; Kabala et al., 1985; Kipp, 1985; Butler, 1998; Weight and Wittman, 1999). Aquifer responses must be categorized into one of these three response groups before appropriate radial flow solutions (i.e. the Bouwer and Rice method) can be selected.

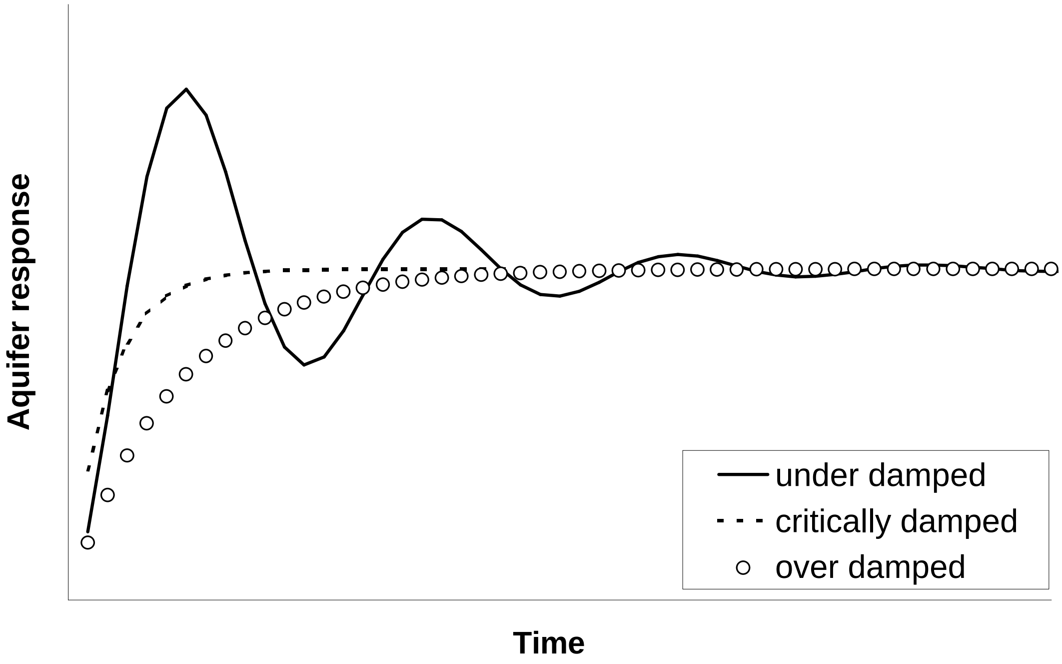

Figure 9: Theoretical fundamental aquifer responses to slug tests. Functions are based on modifications of the Van der Kamp (1976) and Kabala (1985) solutions to conservation of momentum equations. Under damped responses are oscillatory by nature, over damped responses approximate exponential decay, and critically damped responses are transitionary between the other two (Butler, 1998).

The majority of the research has been conducted on overdamped responses (Hvorslev, 1951; Cooper et al., 1965; Bouwer and Rice, 1976) and underdamped responses (Van der Kamp, 1976; Kipp, 1985; Weight and Wittman, 1999), although the critically damped case was evaluated by Kabala et al., (1985). For overdamped data, the Hvorslev method (Hvorslev, 1951) and Bouwer and Rice methods (Bouwer and Rice, 1976; Bouwer, 1989) are reasonable techniques for the case of a partially penetrating well in an unconfined aquifer (e.g., Hanford riverbed conditions). Both methods involve plotting the natural logarithm of the head response against time. The slope of these data and the piezometer geometry are used to solve for hydraulic conductivity. Bouwer and Rice improved estimates for the effective radius (e.g., the effective radial distance from the well over which the average hydraulic conductivity is measured) by conducting an electric analog experiment. The experiment improved estimates for the effective radius, given the well diameter and the length of the well. Because of improved effective radius estimates, the Bouwer and Rice method is generally considered an improvement over Hvorslev (Brown et al., 1995). Various researchers have presented solutions for underdamped data in highly permeable formations, such as the alluvium found in riverbeds (Van der Kamp, 1976; Kipp, 1985; Weight and Wittman, 1999). Weight and Wittman (1999) assert that the Bouwer and Rice and Hvorslev methods are suitable for overdamped, nonoscillatory data sets, however for underdamped, oscillatory responses they propose a simplified approach to the Kipp (1985) solution for oscillatory data, and suggest that the Kipp method is applicable to unconfined aquifers. Kabala et al. (1985) presented a solution for critically damped aquifer responses to slug tests.

Spane (1996) described a method by which the vertical hydraulic conductivity could be determined using interference slug testing and has successfully used this technique on the Hanford site. This method analyzes the head versus time curve obtained via an observation well when a slug test is performed in an adjacent well producing a pressure wave within the aquifer. The shape of the interference curve provides insight into aquifer properties such as hydraulic conductivity, storativity, specific yield and vertical anisotropy.

Borehole dilution techniques, while requiring large amounts of time in low conductivity formations, have been completed in reasonable amounts of time in high permeability formations such as alluvial sediments (Palmer, 1993). Time estimates for individual tests range from over 1000 hours in mud and clay to only a few minutes for coarse sand and gravel mixtures (Halevy et al., 1967). Halevy et al. (1967) summarized the theory, application, and accuracy of borehole dilution techniques. Drost et al. (1968) used dye tracer tests to demonstrate how the presence of the borehole skewed the flow lines of water flowing through the well screen. Subsequent research has refined the methodology used to conduct borehole dilutions, including the use of multiple layer dialysis cells in lieu of mechanically mixed single chamber devices (Ronen et al., 1986). Estimates of flow line distortion near the borehole (skin effects) have been further improved (Bidaux and Tsang, 1991). Palmer (1993) evaluated borehole dilution theory, methodology, application, and potential for use near an extraction well that allowed tests to be conducted in shorter time periods.

Chapter 3: Methodology

Sampling Strategy

The first data set collected for this thesis defined the boundary of the study site along the 100D Area shoreline. This was accomplished by testing hyporheic water samples for Cr(VI) within and beyond the 100D Area chromium “hot spot” (Figure 2).

The shoreline was sampled using an interval of approximately 100 m upstream and downstream from the center of the high Cr(VI) area during October 18-27, 1999. Samples were collected at these intervals away from the center of the hot spot, until Cr(VI) was undetectable. The results defined a 4,000 m reach of shoreline adjacent to the 100D Area. Additionally, four sites established during October 1997 were also used for this thesis. The previously established sites were located near the center of the study site and each site had a minipiezometer installed at two depths, for a total of eight piezometers. The 1997 sites used polyethylene tubes that were reinforced with electrical conduit, and the ends of the tubes guided out of the river above the high water mark, so they could be sampled at changing river stage. Water samples were collected from the subsurface through 0.64 cm outside diameter (O.D.) polyethylene tubes (minipiezometers) and were installed using a Geoprobe? driving system (Figure 10). The tubes were first attached to screens by inserting the tube into the end

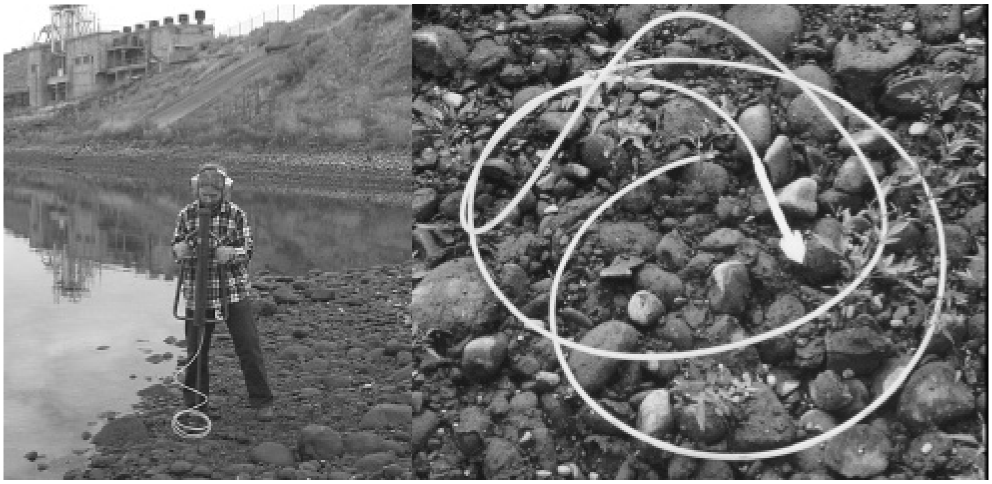

Figure 10: Minipiezometer and Geoprobe? driving system using a post-pounder.

of a 0.95 cm outer diameter polyethylene tube with approximately 10 holes punched through it. The 15 cm long screens were wrapped in approximately four layers of #240 nylon mesh and secured to the 0.95 cm polyethylene tubes with hot glue. The screen apparatus was then secured to the 0.635 cm diameter tube with stainless steel welding wire. The opposite end of the screen was then pushed over the barbed end of a 2.54 cm outer diameter brass point that was secured to the screen using a stainless steel welding wire. Several 0.91 m long sections of 2.54 cm outer diameter Geoprobe? internally threaded drive rod were then threaded together. One end was attached to a slotted Geoprobe? drive cap, while the brass tip was placed in the other end. The drive cap allowed the rods to be driven into the sub-surface without cutting the tubing. The polyethylene tubing was passed through the rods and out of the drive cap. A post pounder or pneumatic hammer was then used to pound on the drive cap until the screen was driven to the desired depth, and then the drive rods were removed with a pipe wrench. If the resistance to removal was too great the rods were removed using a tripod, lever chain hoist, and specially designed pull cap (Figure 11). The pull cap was similar to the drive cap but had a sturdy welded loop on the top that the lever chain hoist was attached to.

Once the boundary of the study site was determined using minipiezometers, larger, galvanized steel piezometers were installed for water quality testing as well as for *in situ* hydraulic testing. The budget allowed for the installation of 20 galvanized piezometers. The shoreline was divided into roughly 300 m increments. This allowed for two galvanized piezometers to be installed at most locations, one shallow and one deeper below the riverbed. Locations were established on the Hanford shoreline and on one adjacent island. Near the Cr(VI) hot spot, a nested sampling scheme was employed to look for smaller scale heterogeneity. Five galvanized piezometers were installed in intervals of approximately 75 m for the nested scheme.

Figure 11: Piezometer extraction equipment used to remove the Geoprobe? driving system.

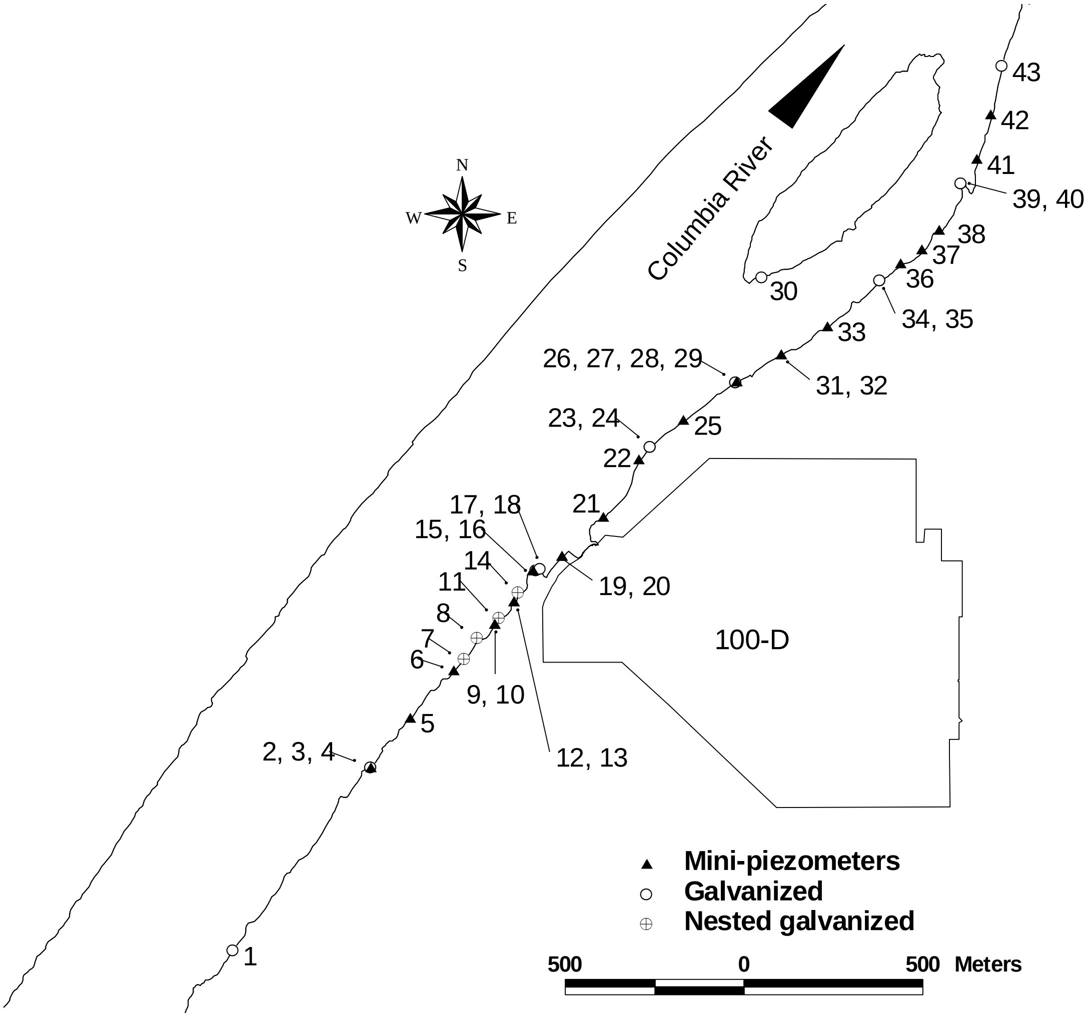

Figure 12: Piezometers installed along the 100D Area shoreline. Minipiezometers were installed first to help determine where the larger, galvanized piezometers would be installed.

Nineteen galvanized piezometers were installed along the 100D shoreline (Figure 12). The galvanized piezometers were constructed by either Midwest Well Supplies or by Johnson Screens™. The Midwest piezometers consisted of a cast iron drive point threaded onto a 30.5 cm long stainless steel screen. The screen was in turn threaded onto a galvanized steel riser pipe (5 cm I.D.; Figure 13). The top of the riser pipe was threaded so that galvanized extensions could be attached and the piezometer installed to the desired depth. The Johnson piezometers (3.0 cm I.D.) consisted of a tip welded to the shaft of the piezometer and had threaded tops so that extensions could be attached (Figure 13 a). Both galvanized types were driven by pounding on a 2.54 cm steel drive rod inserted into the piezometer (Figure 13 b). A post pounder or pneumatic hammer was used to pound the rod and piezometer into the sediment (Geist et al., 1998). Piezometers were installed such that the bottom of the screen was between 0.52 m and 2.3 m, with an average depth of 1.57 m below the riverbed and a standard deviation (? ??of?0.47 m. The piezometers were driven to the depth where their threaded tops

Figure 13: Galvanized piezometers and their installation. (a) Galvanized piezometers had an inside diameter of either 5.0 cm or 3.0 cm. (b) Installation of a Midwest piezometer using a pneumatic hammer.

extended slightly above the riverbed. In most cases the length of piezometer left extending above the riverbed was approximately 0.1 m and was always less than 0.5 m. An extension pipe was threaded onto the piezometer to extend it above the surface of the river and the piezometers were developed using a bucket and a hand pump. Approximately 2.5 L of river water were poured down the top to assure that the screen was not plugged for the Midwest piezometers, and about 1 L was used for the Johnson piezometers.

The study site was also defined in terms of depth into the riverbed. Data regarding the subsurface geology of the Hanford Site were available (Figure 8), however, they were compiled at a scale exceeding that of this project. Bounds for sampling with respect to depth were defined in terms of water quality criteria measured during the preliminary data collection period (using minipiezometers). The preliminary data showed that groundwater (high specific conductance) was often reached at depths of 1.8 m, and river water (low specific conductance) often penetrated to depths of 0.6 m. This meant that in order to relate sediment properties (e.g., heterogeneity) to water quality parameters, the sampling interval had to be no greater than approximately 0.6 m to 0.9 m. This fact, coupled with the limited number of galvanized piezometers available for the study, led to the decision to install one galvanized piezometer at a depth of just over 1 meter and one galvanized piezometer to approximately 2 m below the riverbed for each location.

The horizontal positions of all piezometers were recorded using a Trimble Pathfinder^{TM} Pro XR Global Positioning System (GPS). All data were stored using the North American Datum 1983, state plane meters, Washington south zone. In order to compare the elevations of water levels measured in different piezometers, the vertical elevations of all galvanized piezometers were surveyed relative to stakes that were installed above the high water mark of the riverbank. Surveying was completed using the differential level technique. A Sokkia model B2$_1$ automatic level was used to determine the elevation change between each piezometer and its associated survey stake. The elevation difference was determined two times for each piezometer, and the associated error between the two measurements was computed. The Sokkia level was then used to survey the elevation change between survey stakes. The distance between survey stakes varied and was often greater than 300 m, so a survey interval of approximately 70 m was used to minimize survey error. The interval between stakes was surveyed twice so the most probable error could be computed (? 2.33 cm). The Research and Education Association's 1983 Handbook of Field Surveying was used to determine the appropriate corrections to make for curvature of the Earth and the refraction of light by the atmosphere. The correction for both refraction and Earth curvature was accounted for using the following relationship from the handbook:

$$h=M^2(0.0000676) \tag{1}$$

where h is the correction for both refraction and earth curvature (mm) and M is the distance between points (m). Procedures outlined in the handbook were used to calculate the most probable difference, and the most probable error using the sum of the squares of the residuals from the actual measured difference and the most probable difference (the arithmetic mean). Survey data are included in Appendix A.

To tie the elevation data to a known datum, I compared my elevations to water stage data recorded at the same time at a surveyed recording gage operated at 100D Area reactor by Bechtel Hanford, Inc (hourly data from the 100D Area gage for the entire study period are included in Appendix B). Although the Bechtel gage only recorded values once per hour, the water surface of the river was relatively stable during the survey; the standard deviation of the river stage (Bechtel stage gage) during time periods in which water level measurements were recorded in piezometers was 6.2 cm.

Water Quality Sampling

Galvanized piezometers were sampled within two weeks of installation and tested for specific conductance, Cr(VI), temperature, and hyporheic head. Piezometer location, depth, sample time, and water quality data collected are documented in Appendix C. Sub-surface water samples were obtained from the minipiezometers using a peristaltic pump or a hand powered suction pump. Representative samples were collected by removing approximately three piezometer volumes of water from the piezometer before any sample was taken. For galvanized piezometers, the volume removed was 7.5 L for Midwest piezometers and 3 L for Johnson piezometers. Water samples were analyzed for Cr(VI) within 24 hours of collection using a Hach model DR2000 spectrophotometer with a cell path length of 2.54 cm. In order to obtain better resolution Cr(VI) measurements, a calibration curve (Figure 14) was constructed using

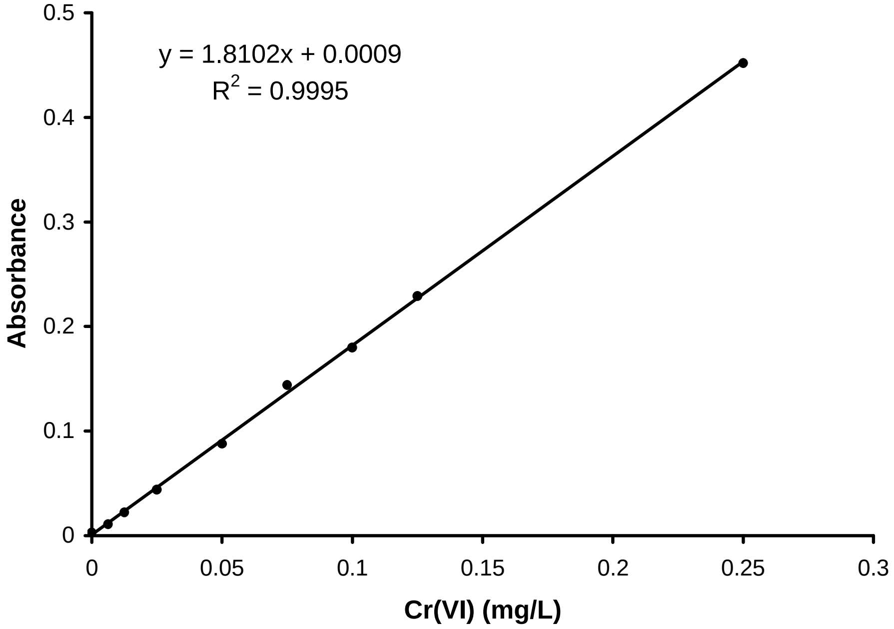

Figure 14: Calibration curve used to determine the Cr(VI) concentration of hyporheic water samples.

an existing method for the determination of Cr(VI) (BHI-EE-05 Field Screening Procedures Procedure No. 1.17). The calibration curve was used to obtain a minimum detection limit (MDL) of 0.0014 mg/L. The MDL was determined by preparing seven standards near the expected limit (0.005 mg/L), measuring the standard deviation of the seven samples, and using three times the standard deviation as the minimum detection limit (Eaton et al., 1995). The accuracy of the method was equal to twice the standard deviation of the residuals in Figure 14. The error associated with accuracy was +/- 0.003 mg/L. The error associated with precision was determined by preparing six replicates each of five different standards (0.005, 0.01, 0.02, 0.04 and 0.1 mg/L). All 30 standards were analyzed using Figure 14. Twice the standard deviation was computed for replicates of each standard. The maximum value for error obtained using this method was 0.0047 mg/L. Thus the maximum error expected due to accuracy and precision of the method was +/- 0.0077 mg/L.

Electrical conductivity and temperature were determined in the field using a Yellow Springs, Incorporated (YSI) conductivity/temperature meter. Electrical conductivity, the inverse of electrical resistivity, is usually expressed in terms of specific conductance. Specific conductance is the conductance of one cubic centimeter of a given substance compared to one cubic centimeter of pure water, and values must be normalized to a similar temperature in order to be compared (Driscoll, 1995). Specific conductance was determined by correcting electrical conductivity for differences in temperature. The YSI meter was corrected for temperature in freshwater using the following relationship (Eaton et al., 1995):

$$\text{specific conductance @}25^{\circ}\text{C} = \frac{\text{conductivity}}{1 + 0.0191(\text{water temp.} - 25)} \tag{2}$$

The YSI instrument was equipped with a probe that was either lowered into the full sized piezometers or used to test water samples pumped from mini-piezometers. The meter was calibrated using two different concentration standards at least once every three days while fieldwork was conducted. The standards were 100 ?S/cm and 1000 ?S/cm Fisher brand specific conductance potassium chloride solution.

To determine the temporal variation of water quality with respect to changing river stage, multiple samples from four sites were collected on different dates. As previously mentioned, piezometers were installed at two different depths at each of the four sites (Figure 12). Each of the eight piezometers was sampled bi-weekly between November 10, 1999 and February 4, 2000. A minimum of three to five samples were collected between these dates. Additionally, one or two samples were collected during initial surveys of the multiple-sample mini-piezometers. The additional samples were collected during November 1998 or between November 1997 and December 1997. Samples were collected at different river stages and tested for Cr(VI) and specific conductance, using the same methodology that was used for the spatial variation sampling.

In addition to repeated sampling of the individual piezometers, short-term temporal variability in the water quality was examined using a data logger in piezometer 17 (Figure 12) for a two day period from February 4-6, 2000. A Hydrolab Minisonde data logger, capable of recording specific conductance, temperature, pH, pressure head, and dissolved oxygen was used for the deployment. The Minisonde recorded data once every 30 minutes. Prior to its deployment it was calibrated using 100 ?S/cm and 1000 ?S/cm Fisher brand specific conductance potassium chloride solutions. The Hydrolab data logger was corrected for temperature in freshwater using the following factory installed relationship:

$$\text{specific conductance @ } 25^{?}\text{C ? conductivity ? f(T) ?} \qquad (3)$$

where f(T) was a function equal to $C_1T^5 + C_2T^4 + C_3T^3 + C_4T^2 + C_5T + C_6$ and C_1=1.43x10^{-9}, C_2=-6.072x10^{-8}, C_3=-1.067x10^{-5}, C_4=1.094x10^{-3}, C_5=-5.3091x10^{-2} , and C_6=1.82.

Hydraulic Testing

Slug Tests

Hydraulic conductivity was determined by conducting slug tests in 18 galvanized piezometers that were also used for water quality sampling. A total of 46 slug tests (average 2.4 tests per piezometer) were conducted between November 11, 1999 and November 18, 1999. To perform the test, an airtight pressure-regulating wellhead assembly was threaded to the top of each piezometer (Figure 15). The assembly consisted of a 5.0 cm ball valve coupled to a 20.0 cm section of schedule-40 PVC containing a small valve stem for pressurizing. A pressure transducer (Instruments NW model 9800) was lowered into the piezometer to measure changes in hydraulic head during the test (Figure 15). A modified rubber stopper was used to seal the transducer cable’s entry into the well assembly. The system was pressurized with a portable battery-powered air compressor (Black and Decker VersaPak cordless inflator), causing the water level in the piezometer to be depressed downward. The change in water level was measured by the transducer and recorded by an electronic data logger (Campbell CR10x). When the water level in the well was sufficiently depressed, the air compressor was shut off and the ball valve simultaneously opened, marking the beginning of the slug test. When the pressure was released, the data logger recorded the pressure response (rising water level) with respect to time.

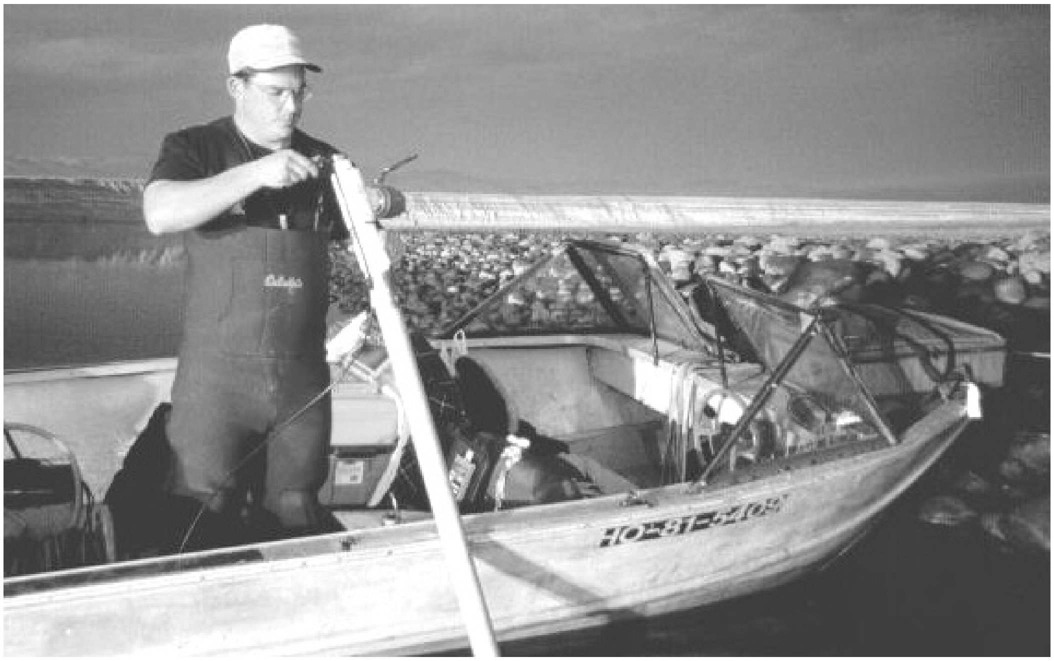

Figure 15: Slug test pressure regulating device with pressure transducer lowered inside to record head response vs. time. The Columbia River undercuts the Ringold Formation in the background, exposing ancient alluvium in an area now known as the White Bluffs.

The slug tests were all overdamped, and were therefore analyzed using the Bouwer and Rice method (Bouwer and Rice, 1976; Bouwer, 1989). Data were then compared using the Hvorslev method (Hvorslev, 1951).

Hydraulic conductivity using the Bouwer and Rice method was determined via the Bouwer and Rice equation:

$$K = \frac{r_c^2 \ln(R_e/R)}{2L_e}\frac{1}{t}\ln ? \frac{H_0}{H_t} ? \tag{4}$$

where K is hydraulic conductivity (cm/s), r_c is the radius of the well casing (cm), R_e/R is the dimensionless ratio of radius of gravel envelope to distance away from the well over which the average value of K is being measured (this was obtained as outlined in Fetter 1994), L_e is length of the screen or open section of the well (cm), H_0 is the drawdown at time t = 0, H_t is the drawdown at time t = t, and t = time from H_0.

The hydraulic conductivity was also determined via the Hvorslev slug test method:

$$K ? \frac{r^2 \ln ? L_e / R ?}{2L_e T_0} \tag{5}$$

where K is hydraulic conductivity (cm/s), r is the radius of the well casing (cm), R is the radius of the well screen (cm), L_e is the length of the well screen (cm), and T_0 is the time for the water level to rise or fall to 37% of the initial change (Fetter, 1994). Note that $1/T_0$ is equivalent to the slope of $LN(H_0/H_t)$ versus time for the case where (H_0/H_t) is

0.37 (Butler 1998) and where H_0 is drawdown at time t = 0, and H_t is equal to drawdown at time t = t.

Since the environment sampled was very close to the riverbed, I assumed that subsurface flow was mostly vertical, either from the overlying river column into the hyporheic zone, or from the hyporheic zone out into the overlying water column. The vertical hydraulic gradient (VHG) was estimated using:

$$\text{VHG} = \frac{dh}{dl} = \frac{\left(\text{head inside piezometer - river head}\right)}{\text{distance from riverbed to top of piezometer screen}} \tag{6}$$

The hydraulic gradient was determined so that hydraulic conductivity values, together with the hydraulic gradient, could be used to determine the specific discharge (q). The specific discharge was determined by first using Darcy's equation,

$$\text{Q} = \text{-K}\left(\frac{dh}{dl}\right)A \tag{7}$$

where Q is volumetric discharge, K is hydraulic conductivity, dh/dl is the gradient of hydraulic head, and A is cross-sectional area. Because specific discharge equals the quotient of volumetric discharge (Q) and the cross-sectional area (A), the product of hydraulic conductivity (K) and hydraulic gradient (dh/dl) is equal to the specific discharge (q):

$$q = -K\left(\frac{dh}{dl}\right) \tag{8}$$

Two errors are associated with hydraulic conductivity estimates. The standard error associated with linear regressions of the natural logarithm of the aquifer's response versus time was determined for one replicate in each piezometer. This value represented the standard error on the y-axis, which was the natural logarithm of drawdown. In order that the value be compatible with a solution for hydraulic conductivity (i.e., Bouwer and Rice or Hvorslev), it was divided by the time interval over which the error was measured. The value (standard error of the slope) was then inserted into the Bouwer and Rice equation to determine the standard error due to regression in units of centimeters per second, allowing the error to be compared to results determined in the same units. The second error is the standard deviation of hydraulic conductivity estimates for piezometers with replicates. These two sources of error were added together to obtain a measure of total precision.

Results were summarized based on the order of magnitude of the calculated hydraulic conductivity, in order to present only distinctly different response data. Results for every piezometer are included in Appendix D.

Borehole Dilution

A single borehole dilution test was conducted in one Midwest piezometer at each location. A total of nine borehole dilution tests were conducted. The depths of piezometers sampled using borehole dilution are shown in Table 3.

Table 3: Piezometers used for borehole dilution testing. Depths below the river bottom to the bottom of the piezometer screen are included.

Piezometer number	Depth to bottom of screen (m)
43	1.62
40	1.56
35	1.68
27	1.65
23	2.18
18	2.32
2	1.55
1	1.46
30	1.65

Borehole dilution tests were only conducted in the larger, Midwest piezometers because the necessary instrumentation would not fit inside the smaller diameter piezometers. Following installation of the piezometers, a Minisonde downhole water quality data logger was deployed. The data logger was fitted with four polyethylene tubes that extended from the downhole end of the logger to the surface of the piezometer, and allowed for injection of a potassium chloride (KCl) tracer. Specific conductance was measured via the data logger. The specific conductance is directly related to the concentration of KCl (660 mg/L KCl is equivalent to 1000 ?s/cm specific conductance). The logger was connected to a laptop computer via a cable at the study site.

The probes on the downhole end of the logger were located at the top of the screened interval of the piezometer (Figure 16). An inflatable packing device was fixed to the tubes and cable immediately above the logger, so that after deployment the packing device could be inflated and the volume of water in the screened interval known. A small hand-held pump was used to inflate the packer. The volume of the sealed interval inside the piezometer screen was estimated in the lab and remained constant in the field, as the logger was lowered to the same level above the screen in

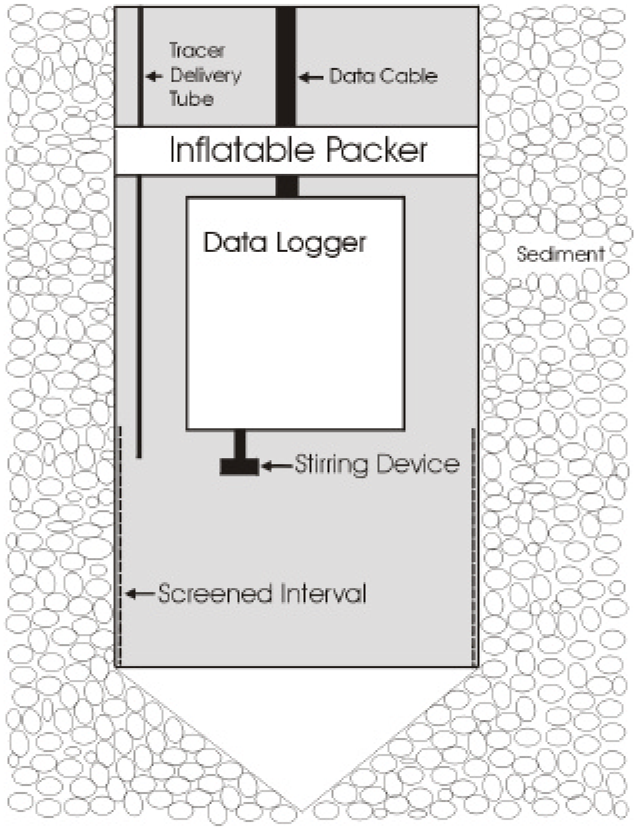

Figure 16: Schematic diagram of a borehole dilution device.

each piezometer during each test. The volume of the sealed interval around the screen included the volume inside the screened interval of the piezometer, plus the volume of water above the screen surrounding the data logger, minus the volume occupied by probes that extended below the bottom of the logger. The volume of the screened interval inside the piezometer was determined empirically using four trials, and averaged 792.5 ml. The volume surrounding the logger, determined theoretically using the difference between the inside radius of the piezometer and the outside radius of the data logger, was determined to be 203.2 ml. The volume occupied by the sensor probes was determined by displacement to be 40 ml. Thus, the net volume of the sealed area of the screen was 955.7 ml (792.5 ml + 203.2 ml – 40 ml).

After the packer was inflated and prior to the test the logger monitored the background specific conductance. The data logger was equipped with an electronically controlled stirring device within the sealed interval, and was used to keep the tracer well mixed within the sealed interval. Approximately 200 ml of tracer was injected using a peristaltic pump, and the specific conductance was logged and viewed real-time via the logger and a laptop computer. Specific conductance, temperature, dissolved oxygen, pressure head, and pH were logged in 10 second intervals.

The borehole dilution method involves installing a standpipe into the subsurface with an isolated volume of tracer (such as KCl) within it. The tracer is stirred continuously and allowed to dilute. The change in concentration with respect to time is related to the specific discharge (q) via the equation:

$$\frac{dC}{dt} = \frac{-Aq'(C - C_b)}{V} \tag{9}$$

where C is the concentration of the tracer within the standpipe, C_b is the concentration of the tracer in the background groundwater, t is time, q' is the specific discharge of the water in the borehole, A is the cross-sectional area of the borehole, and V is the volume of the isolated section. Assuming C_b and q' are constants, if the equation is integrated from t_0 to t and solved for q', the result is:

$$q' = \frac{-V\ln\left(\frac{C - C_b}{C_0 - C_b}\right)}{A(t - t_0)} \tag{10}$$

The specific discharge is corrected by dividing q' by a borehole factor related to the geometry of the standpipe (Palmer 1993), and the result is the corrected specific discharge within the aquifer. In the case of an undeveloped well lacking a filter pack, the borehole factor is equal to 2 and the specific discharge of the aquifer (q) is equal to ½ q' (Halevy et al., 1967). Results were summarized based on the order of magnitude of the calculated specific discharge, in order to present only distinctly different response data. Results for every piezometer are included in Appendix E.

The hydraulic gradient and hydraulic conductivity were used to estimate the total mass of Cr(VI) entering the river. First, the 4,000 m shoreline adjacent to 100D Area was broken into 13 cells, with the location of each piezometer used to determine the center of each cell. The zone of discharge into the river was assumed to be from the river bed to a depth of 1 m below the river bed, thus the depth of each cell was 1 m. The volume of water discharging into the river was then calculated by:

$$Q\ ?\ L \text{ x } D \text{ x } K \text{ x } I \tag{11}$$

where Q is hyporheic discharge into the river (cm^3/s), L is cell length (cm), D is cell depth (cm), K is hydraulic conductivity (cm/s), and I is the vertical hydraulic gradient (unitless). The total discharge (Q) for each cell was then multiplied by average Cr(VI) concentrations for piezometers within the cell and the results summed to determine total estimates of Cr(VI) entering along the shoreline.

Chapter 4: Results

Water Quality Sampling

Twenty five percent of the one-time samples contained Cr(VI) concentrations above the 0.10 mg/L federal drinking water standard, and 77% contained Cr(VI) concentrations above the 0.01 mg/L limit for aquatic life (EPA, 1986; Figure 17).

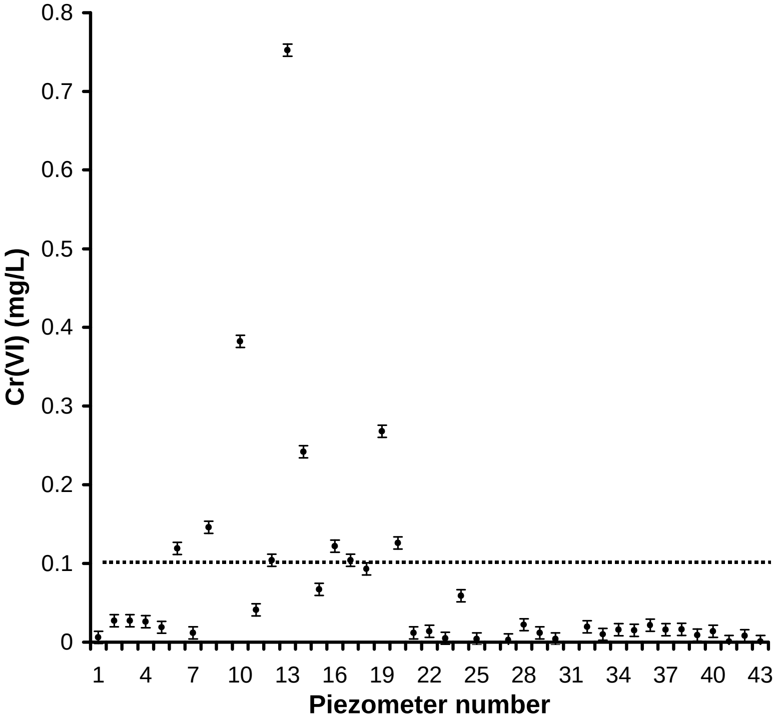

Figure 17: Cr(VI) results for piezometers sampled along the 100D Area shoreline. The higher concentrations in piezometers 8 through 20 reflect the Cr(VI) "hot spot" adjacent to 100D reactor (Figure 2). Error bars show the error associated with Cr(VI) accuracy and precision (+/- 0.0077 PPM). The EPA's maximum contamination limit for Cr(VI) in drinking water is 0.10 mg/L, represented by a dashed line.

Cr(VI) content was plotted against screen depth to verify that samples with high chromium concentrations were not simply collected from greater depths but that they represented spatial variation of the contaminant as it entered the river. Results of this comparison showed no statistical evidence that Cr(VI) increased as depth below the riverbed increased (R^2=0.0039; p=0.7).

Of the 33 piezometers sampled one-time for specific conductance, three values were over 300 ?s/cm and were classified as groundwater, nine samples were less than

150 ? s/cm and were classified as river water, and the remaining 21 samples represented hyporheic water that had undergone some mixing (Figure 18). A

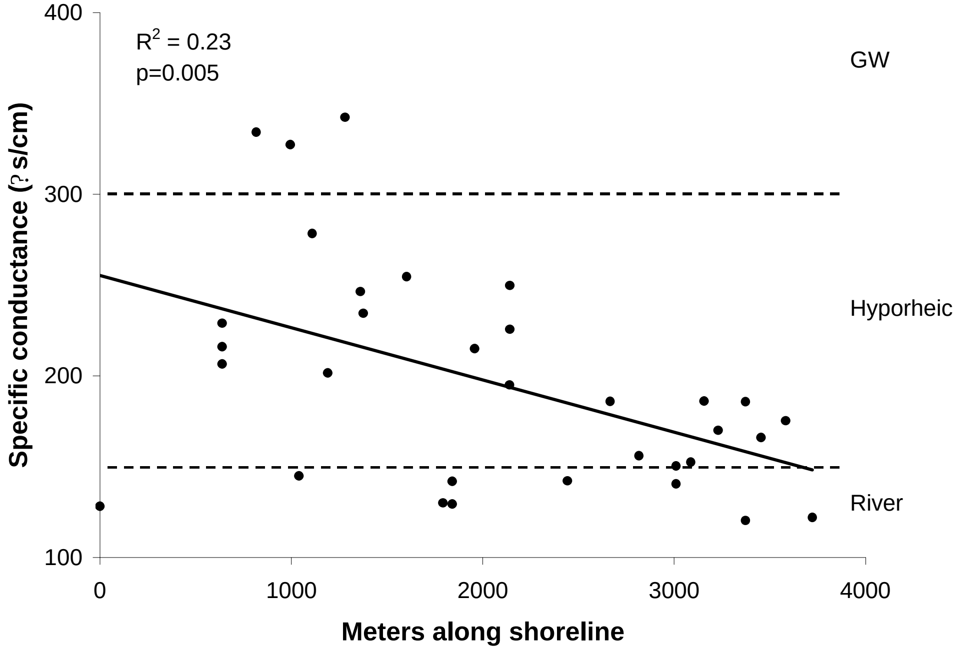

Figure 18: Specific conductance relative to shoreline position. Zero m represents the upstream terminus of study site, 3,700 m represents downstream terminus. Specific conductance increased in an upstream direction.

significant trend related specific conductance to shoreline position, with specific conductance increasing from downstream to upstream (R^2=0.23; p=0.005; Figure 18). Specific conductance was compared to screen depth, with results showing no evidence that specific conductance increased with increasing depth (R^2=0.06; p=0.16). One-time data were collected during periods of similar river stage to make them comparable. The average river stage during specific conductance data collection was 116.94 m (? =0.19 m).

The effect of changing Columbia River stage on pressure head, specific conductance, temperature, dissolved oxygen, and hydrogen ion concentration was evaluated using a Minisonde data logger to record water quality changes with respect to changing river stage at a fixed location (Figure 19 and Figure 20). The results of regressions between all water quality parameters logged by the Minisonde are shown in Figure 21. All of the relationships were very significant (p<<0.05) except for the relationship between hydrogen ion concentration and temperature, which was not significant (p=0.2). Although grossly linear, the relationship between water quality and

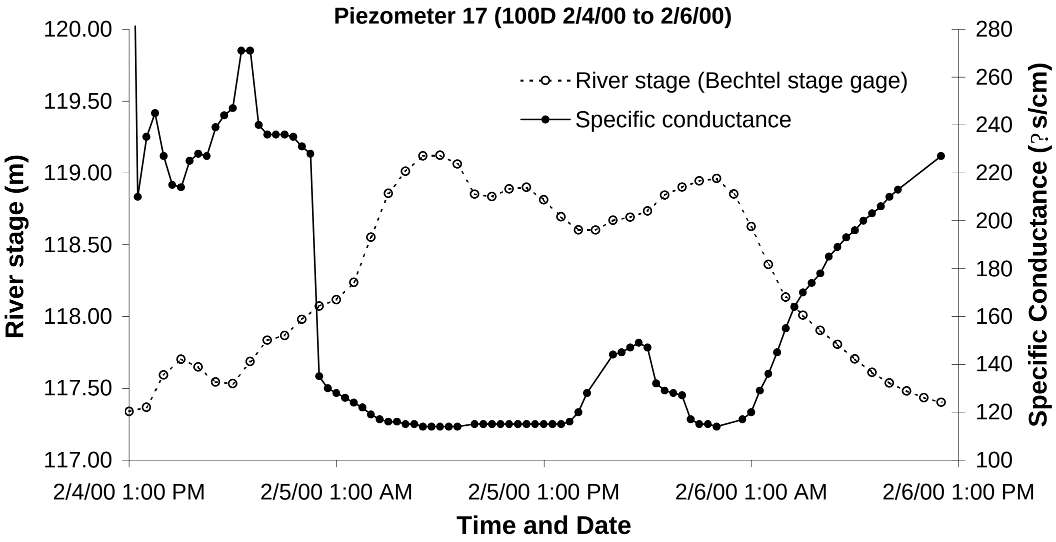

Figure 19: Specific conductance and river stage versus time, piezometer 17.

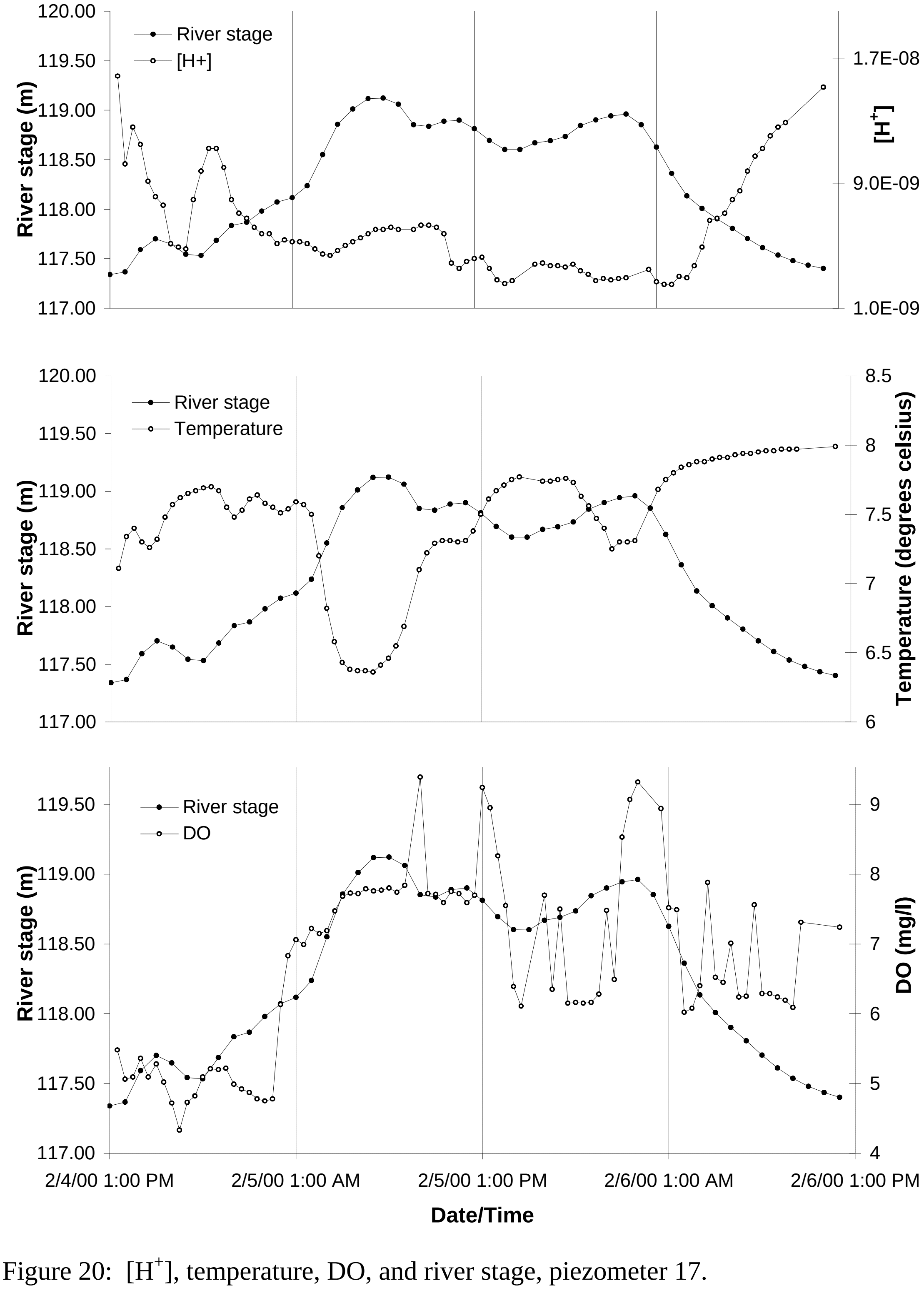

Figure 20: [H^+], temperature, DO, and river stage, piezometer 17.

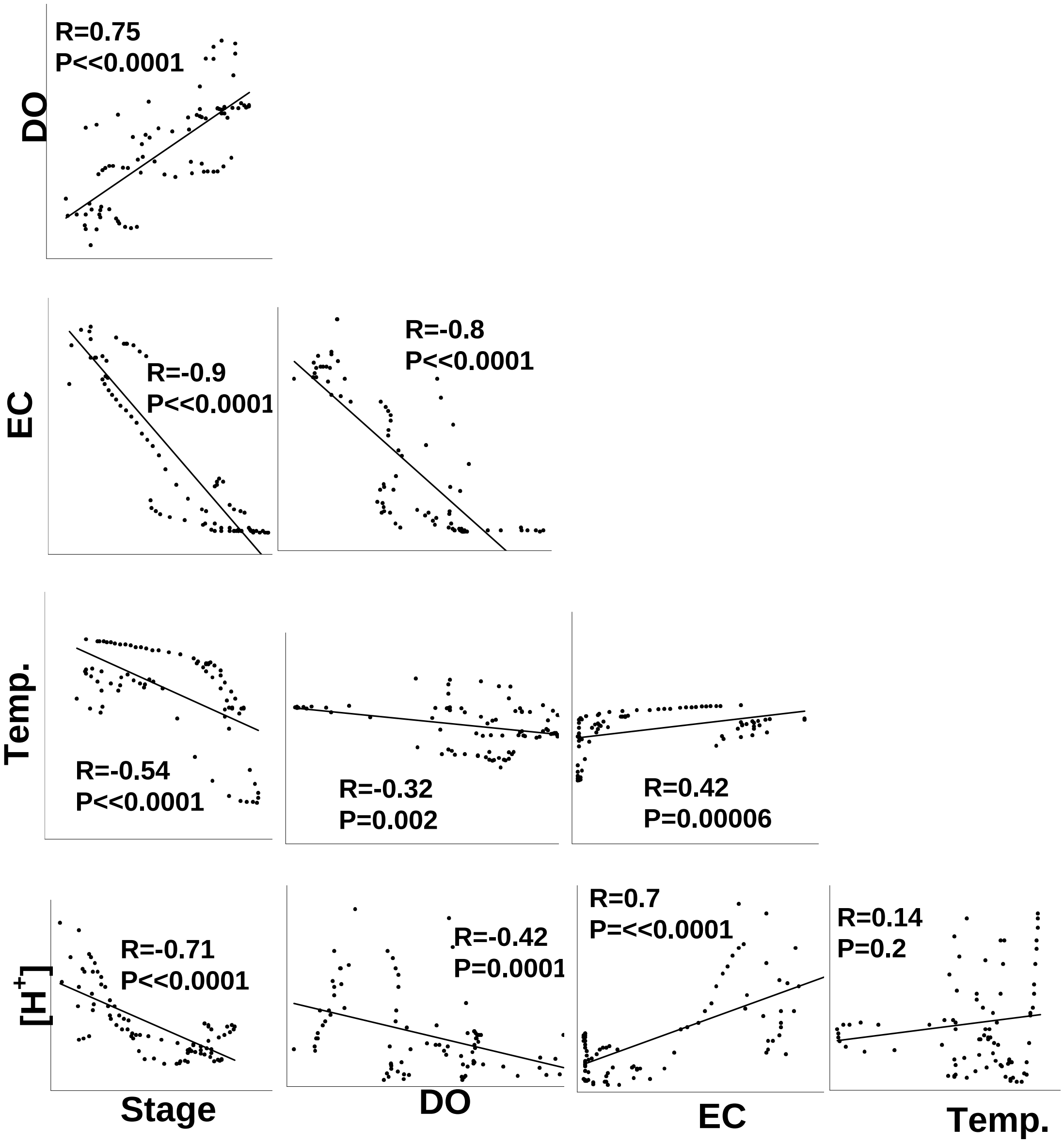

Figure 21: Regression of water quality variables using Minisonde data. Values for the x and y axes increase up and to the right. Most of the data show correlation reflecting a difference in water chemistry between the river and hyporheic water.

river stage was also hysteretic. The hysteresis is most evident between temperature and river head recorded by the Minisonde logger, however, it also occurred between river head and the other water quality parameters (Figure 21 and Figure 22). The hysteretic

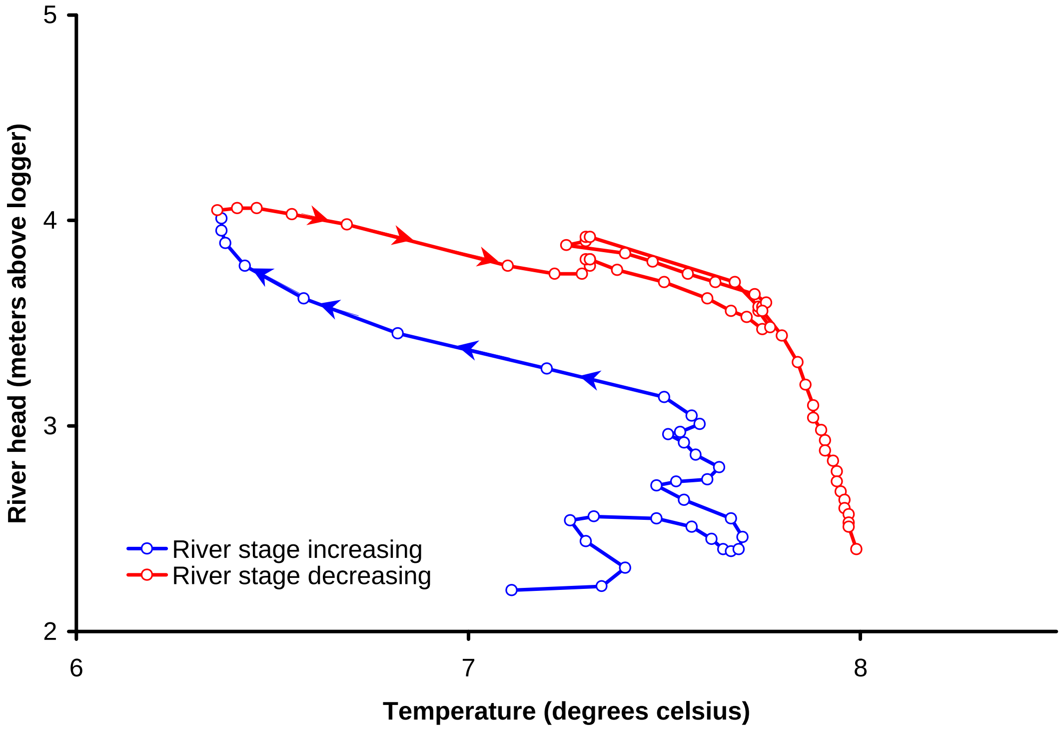

Figure 22: Hysteresis between river head and hyporheic temperature, piezometer 17. The hysteresis is caused by a combination of changes in the river stage and temperature differences between river water and groundwater.

relationship shows that as the river head increased, initial hyporheic temperature remained relatively constant. The mixing zone between groundwater and surface water was above the piezometer screen. The temperature at the depth of the data logger began to cool only after the head difference caused by the rising river stage was sufficient to depress the mixing zone down to the depth of the data logger. Once the mixing zone front reached the logger, the stage continued to increase and the hyporheic temperature continued to cool. The water became increasingly like that of the river. After the stage increased nearly 2 m, the hyporheic zone was in a state of dynamic thermal equilibrium (the temperature remained constant while the head continued to increase). Eventually the stage stopped rising and remained constant for a short time. The insulative properties of the surrounding sediments caused the temperature to slowly increase. The stage then dropped and the temperature increased more quickly, influenced by insulative sediment properties and the rise of the mixing front. Water mixed with warm groundwater began to reach the logger. Minor river stage fluctuations caused the temperature to reverse its direction several times until the stage began to drop more quickly. The hyporheic temperature continued to increase slowly as it approached that of the groundwater, until the logger stopped recording data.

Additional insight into the effect of stage on water quality was gained from the results of the temporal mini-piezometer sampling. Water samples (n=46) from eight piezometers were tested (Figure 23 and Figure 24). Results generally show that as stage decreased, Cr(VI) and specific conductance increased. The relationship was complicated by hysteresis and was difficult to discern due to a lack of data.

Vertical elevations were determined for the river surface and hyporheic water surface for each piezometer (Figure 25). The difference between the two water surface elevations was used to calculate the vertical hydraulic gradient.

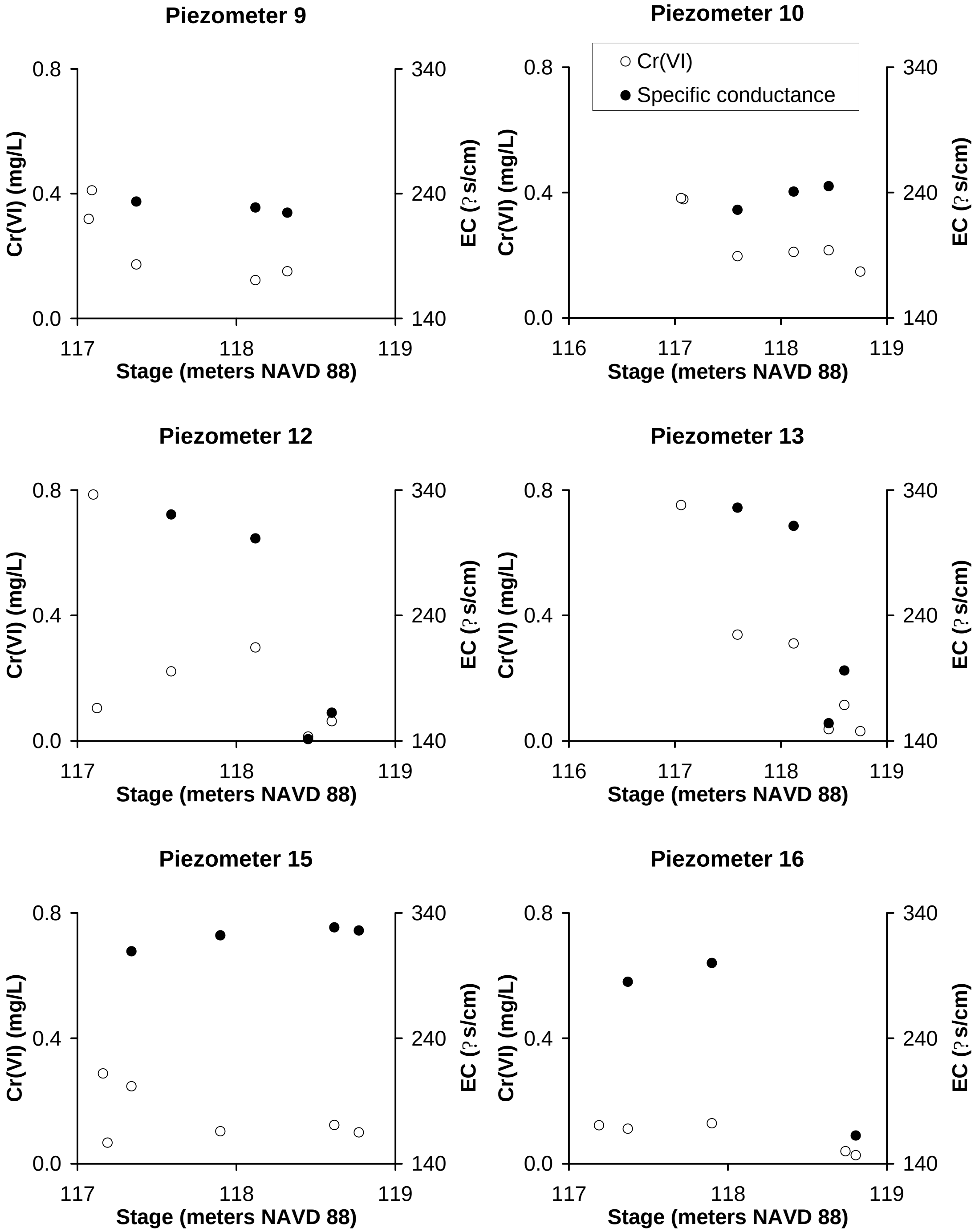

Figure 23: Cr(VI) and specific conductance versus stage for mini-piezometers 9, 10, 12, 13, 15 and 16. Open circles show Cr(VI) concentrations while closed circles show specific conductance.

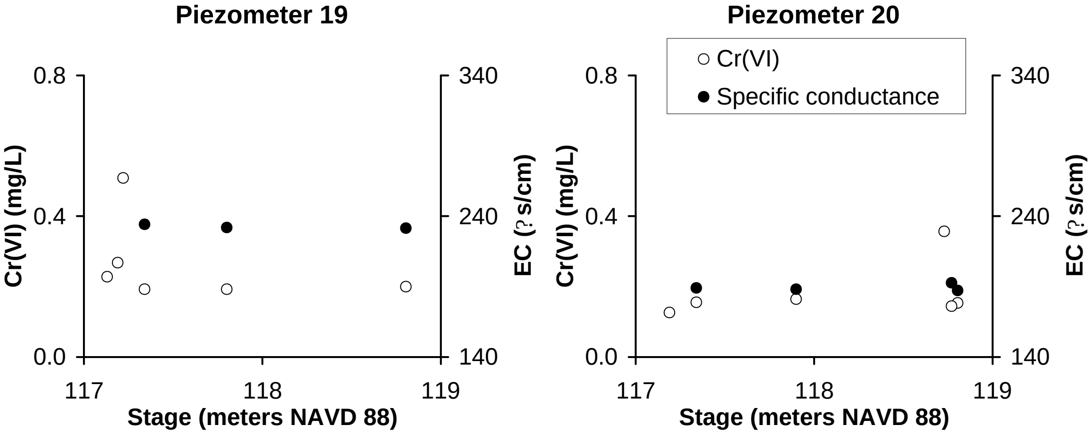

Figure 24: Cr(VI) and specific conductance versus stage for mini-piezometers 19 and 20. Open circles show Cr(VI) concentrations while closed circles show specific conductance.

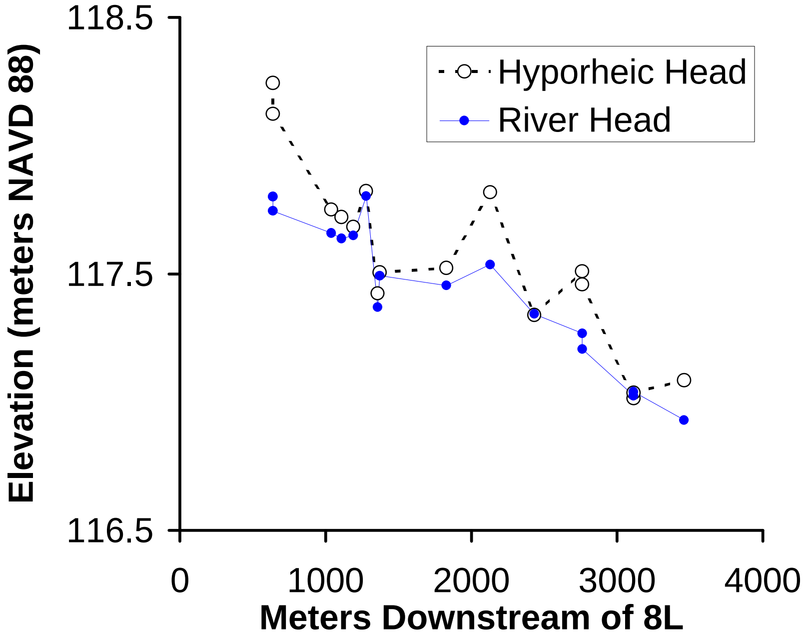

Figure 25: Vertical water surface elevation results (presented in NAVD88). The difference between hyporheic and river surface elevations is shown. The average slope of the river surface was 0.0003, or about 30 cm/km.

Hydraulic Testing

Slug Tests

The recovery data for all 100D Area slug tests displayed an exponential form, and by definition were overdamped (Kabala et al., 1985; Butler, 1998; Weight and Wittman, 1999). Plots of head versus time for overdamped responses had the shape of an exponential decay curve, and plots of the logarithm of drawdown versus time were straight lines or slightly concave up, both indicating overdamped data (Butler, 1998). The response in piezometer 18 exhibited this form, and in general represented the overdamped responses observed in all piezometers tested (Figure 26).

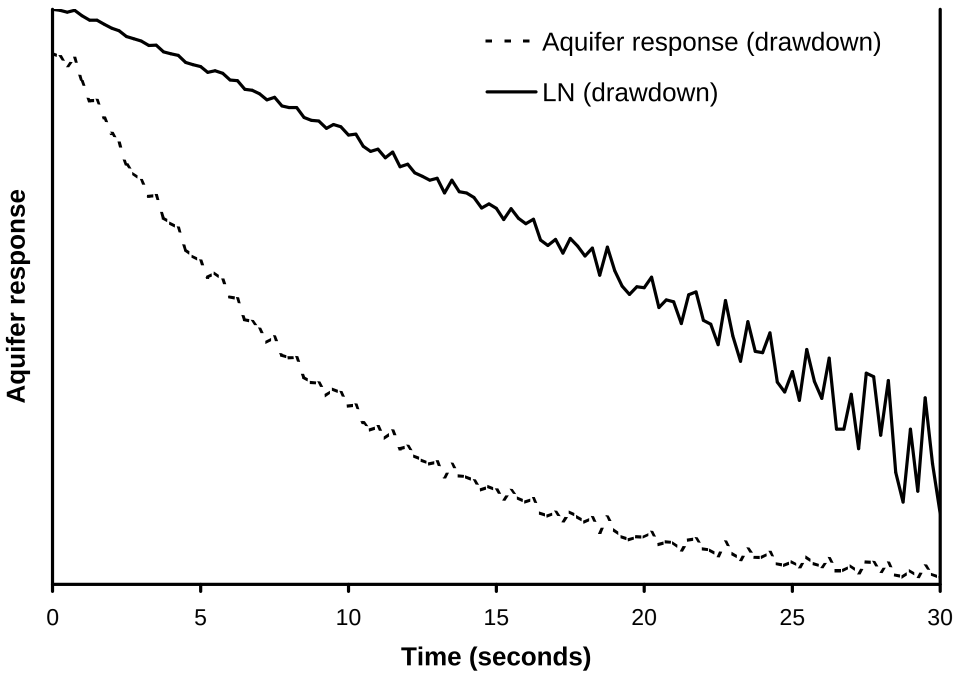

Figure 26: Overdamped response in piezometer 18 during a slug test. The drawdown curve, closely matching the form of an exponential decay curve, together with the linear plot of LN(drawdown) show that the response was overdamped. All other piezometer responses were also overdamped.

Other responses were grouped into four categories, based on the amount of time required for the aquifer to recover after the pressure test was initiated, and the resulting estimate of hydraulic conductivity. Fast responses were classified as having hydraulic conductivity (K) values greater than 1 x 10^{-2} cm/s. High mid-range responses had values between 1 x 10^{-2} cm/s and 1 x 10^{-3} cm/s, low mid-range responses were between 1 x 10^{-3} cm/s and 1 x 10^{-4} cm/s, and slow responses had values between 1 x 10^{-4} cm/s and 1 x 10^{-5} cm/s. An example of each response range has been included in Figure 27. All other responses were included in Appendix D.

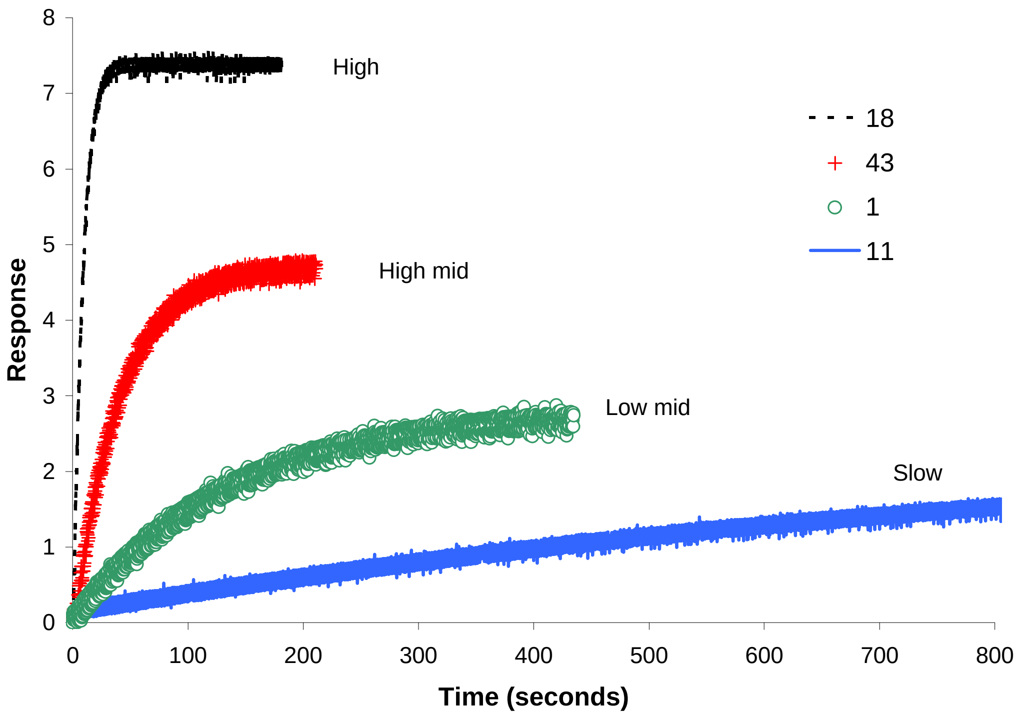

Figure 27: Head recovery of slug tests. Piezometer responses were categorized into 4 groups, based on the time necessary for recovery to occur and the resulting hydraulic conductivity estimates.

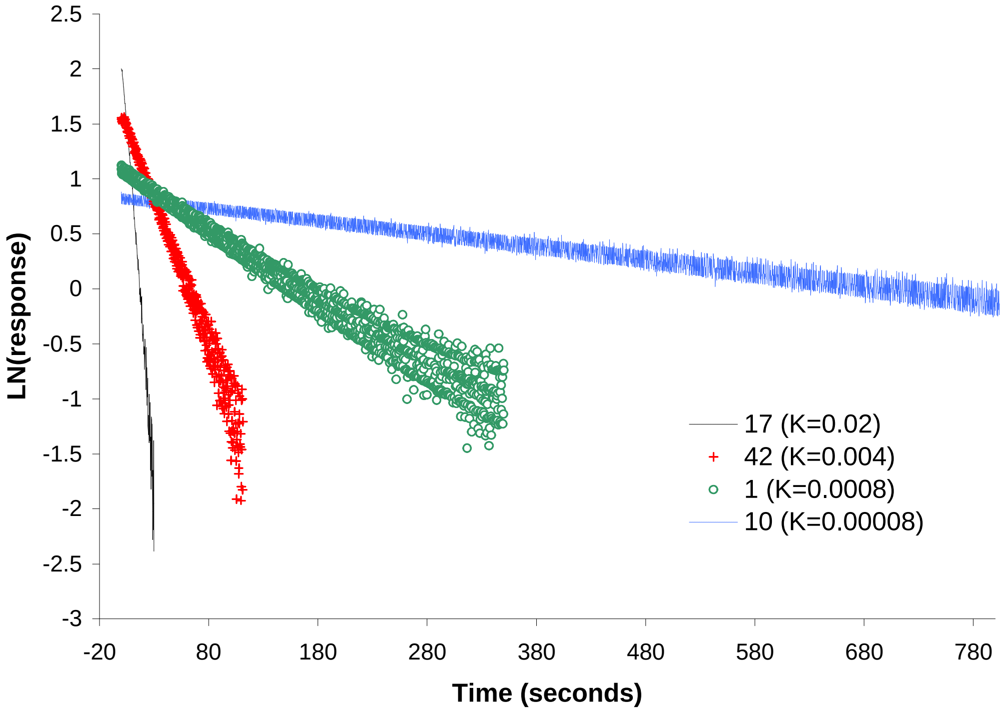

Figure 28: Examples of several different aquifer responses to Hanford Reach slug tests. The natural logarithm of the response versus time produced a straight line, the slope of which was used to determine hydraulic conductivity (K) as outlined in the Bouwer and Rice method (Bouwer and Rice, 1976; Bouwer, 1989).

Faster responses were characterized by steeper slopes and higher hydraulic conductivity values (Figure 28). Hydraulic conductivity values using Bouwer and Rice ranged from 2.8 x 10^{-5} cm/s to 4.3 x 10^{-2} cm/s, and Hvorslev results ranged from 5.4 x 10^{-5} cm/s to 7.7 x 10^{-2} cm/s (Figure 29; Table 4). Results using Hvorslev were consistently 1.9 times the Bouwer and Rice results. This finding was consistent with other studies comparing the two methods (Palmer and Paul, 1987).

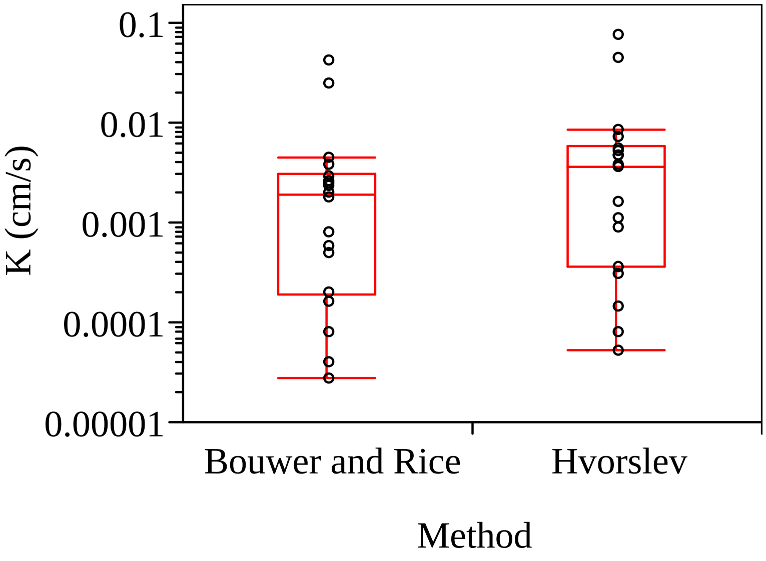

Figure 29: Box plots showing hydraulic conductivity values determined using the Bouwer and Rice and Hvorslev methods. The ends of the boxes are the 25th and 75th quartiles. The difference between the quartiles is the interquartile range. The whiskers, or lines above and below each box, extend to (+) 1.5 the interquartile range, and to (-) 1.5 the interquartile range. The line across the box is the sample median. Points outside the whiskers are possible outliers.

Table 4: Geometric mean hydraulic conductivity values with the standard error of regression for responses analyzed using Bouwer and Rice. The standard deviation for each group of replicates was also included. Piezometer 26 was damaged during installation and was not tested. Standard deviations were not listed for piezometers having only 1 replicate.

Piezometer (in order of increasing K)	Depth (m)	n	Mean K using Bouwer and Rice (cm/s)	Mean K using Hvorslev (cm/s)	Standard Error due to regression (cm/s)	Standard deviation of replicates (cm/s)
26	1.58	NA	NA	NA	NA	NA
27	1.34	1	0.000028	0.000054	0.0000061	NA
24	1.35	1	0.000042	0.000081	0.0000198	NA
11	0.56	1	0.000081	0.000147	0.0000180	NA
35	1.37	2	0.000162	0.000310	0.0000204	0.0001219
34	1.95	2	0.000203	0.000378	0.0000044	0.0000562
8	0.66	3	0.000504	0.000900	0.0000827	0.0000960
23	1.87	1	0.000593	0.001106	0.0000237	NA
1	1.16	3	0.000827	0.001609	0.0001036	0.0000474
30	1.34	3	0.001870	0.003596	0.0001242	0.0002798
40	1.26	3	0.002004	0.003875	0.0001114	0.0001293

Table 4: Continued

3	1.48	3	0.002452	0.004675	0.0002252	0.0001449
7	0.21	3	0.002509	0.004854	0.0004472	0.0001296
17	1.22	3	0.002676	0.005188	0.0003597	0.0000788
39	1.57	3	0.002897	0.005493	0.0002590	0.0005191
43	1.31	4	0.003896	0.007505	0.0006357	0.0003497
2	1.25	3	0.004415	0.008541	0.0004302	0.0001975
18	2.01	3	0.024440	0.045268	0.0013287	0.0068008
14	0.68	4	0.043480	0.077394	0.0074167	0.0076850

The error in determining hydraulic conductivity was determined for the slope regression and for variance between replicates in each piezometer. Error estimates were made for results using the Bouwer and Rice method. The errors were small and represented an insignicant fraction of the hydraulic conductivity (Figure 30).

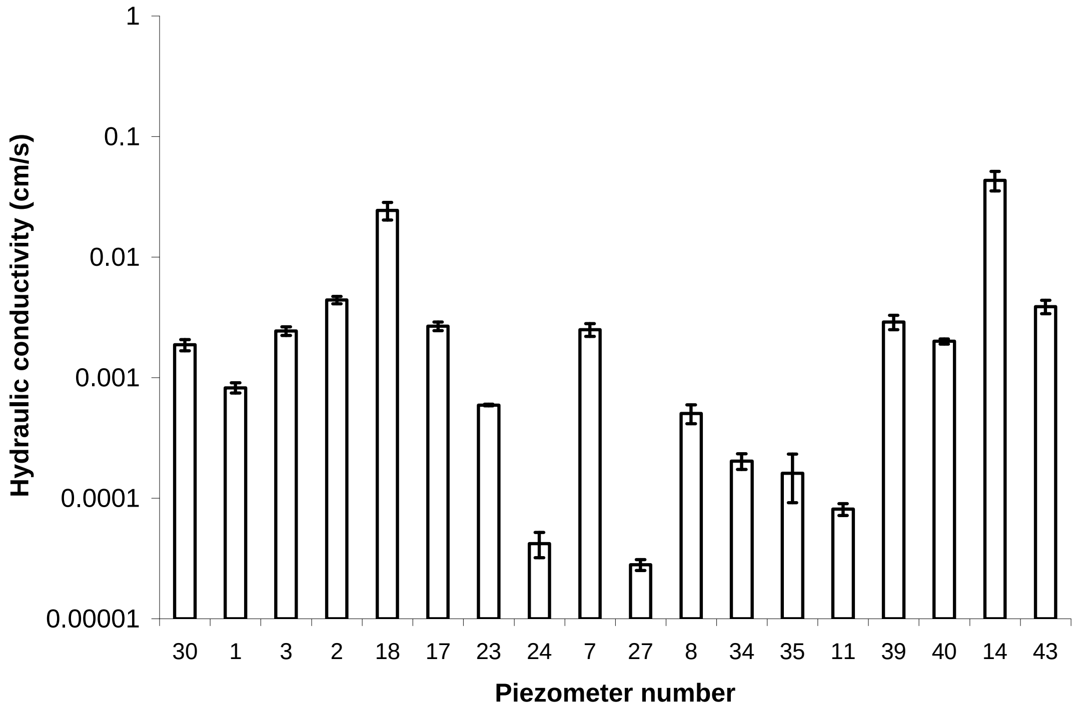

Figure 30: Error due to regression of slope estimates and variance among replicates for each piezometer analyzed using the Bouwer and Rice method. Error was calculated using the sum of the standard error for slope regressions and one standard deviation for replicates.

There was no significant correlation (R=0.08; p=0.75) between hydraulic conductivity and depth of piezometer screen. The highest hydraulic conductivities were near the center of the study site, where the 100D Area is closest to the river. The lowest values were found adjacent to a flood plain just downstream of the 100D Area. Mid range values were scattered throughout the study site (Figure 31).

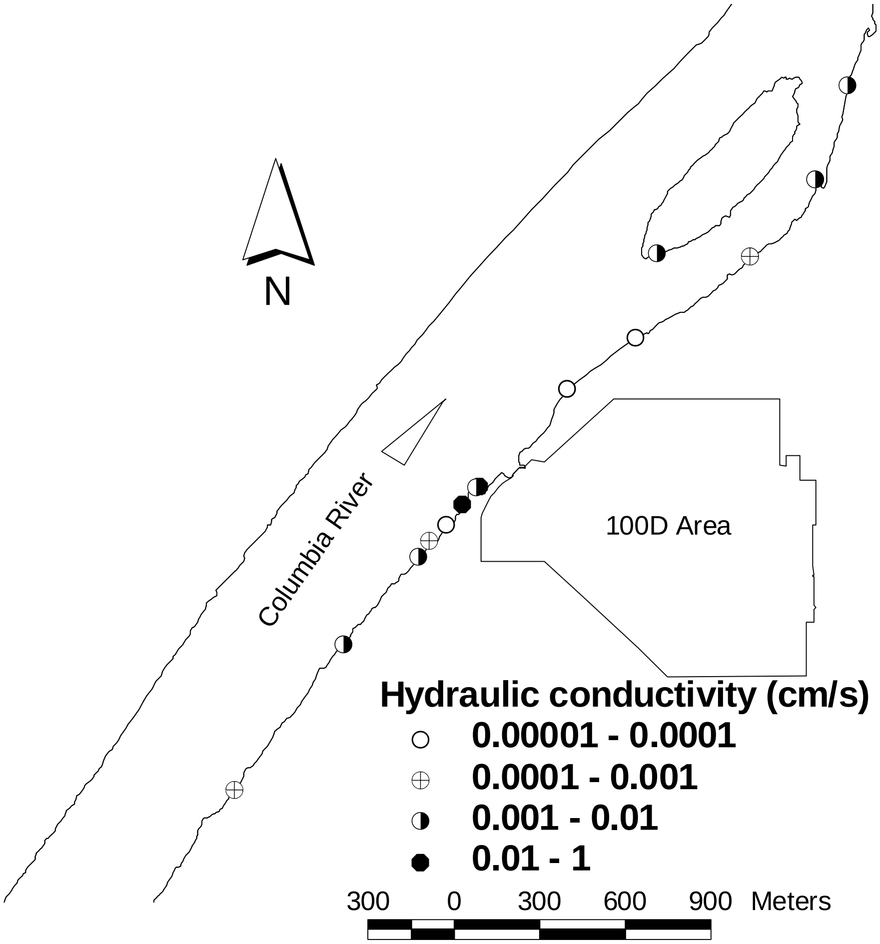

Figure 31: Hydraulic conductivity results for the 100D Area. The lowest values were adjacent to a flat bench downstream of the 100D Area, and the highest values were near the center of the study site.

Borehole Dilution

Borehole dilution data generally approximated the shape of exponential decay curves (Figure 32). Fast responses were considered greater than 1 x 10^{-2} cm/s. Slower responses had values between 1 x 10^{-2} cm/s and 1 x 10^{-3} cm/s. One example of a semilogarithmic plot of tracer concentration versus time was included for each response range (Figure 33). All other responses are included in Appendix E.

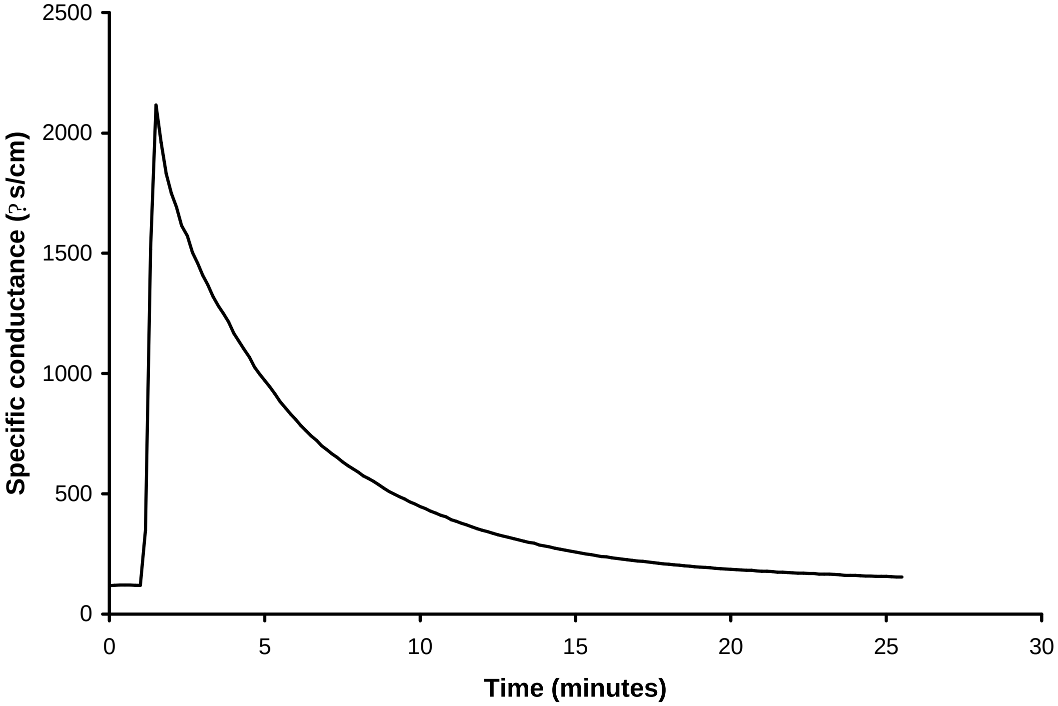

Figure 32: Exponential decay of tracer concentration with time in piezometer 23. The peak in the curve represents the introduction of potassium chloride tracer into the borehole, and the decay was due to the velocity of subsurface water passing through the screened interval of the borehole, diluting the tracer. Specific conductance was used as an analog for KCl.

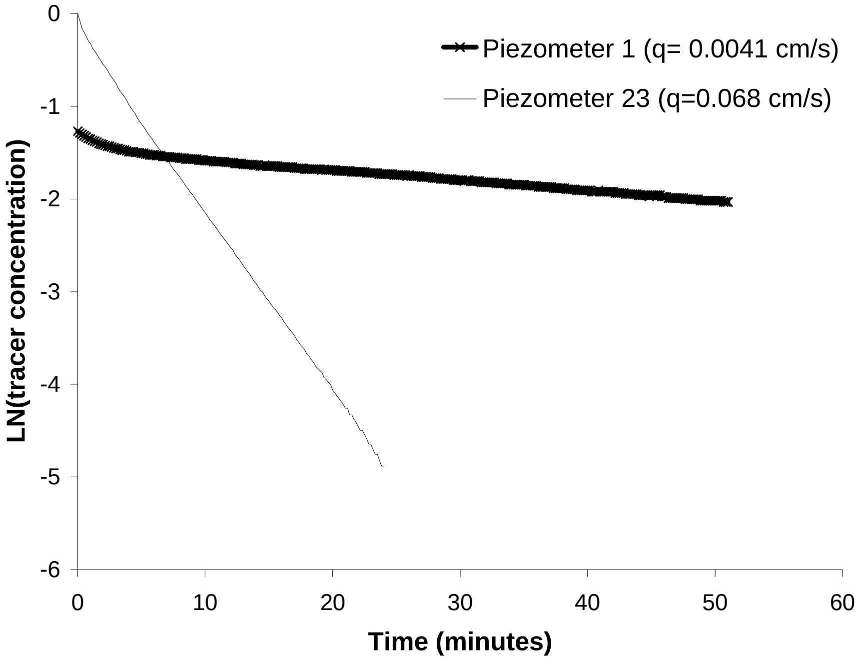

Figure 33: Specific discharge was determined using the slope of the plot of natural logarithm of tracer concentration versus time. Piezometer 23 was in the fast response range (q=0.068 cm/s), and piezometer 1 was in the slower range (q=0.0041).

Specific discharge estimates ranged from 0.004 cm/s to 0.145 cm/s (Figure 34; Table 5). All of the "fast response" areas were downstream of the 100D Area, suggesting more movement of hyporheic water there (Figure 35). Because there was only one replicate for each borehole dilution test, replication error could not be computed. The standard error associated with regression was computed in the same manner as for slug test results (Table 5).

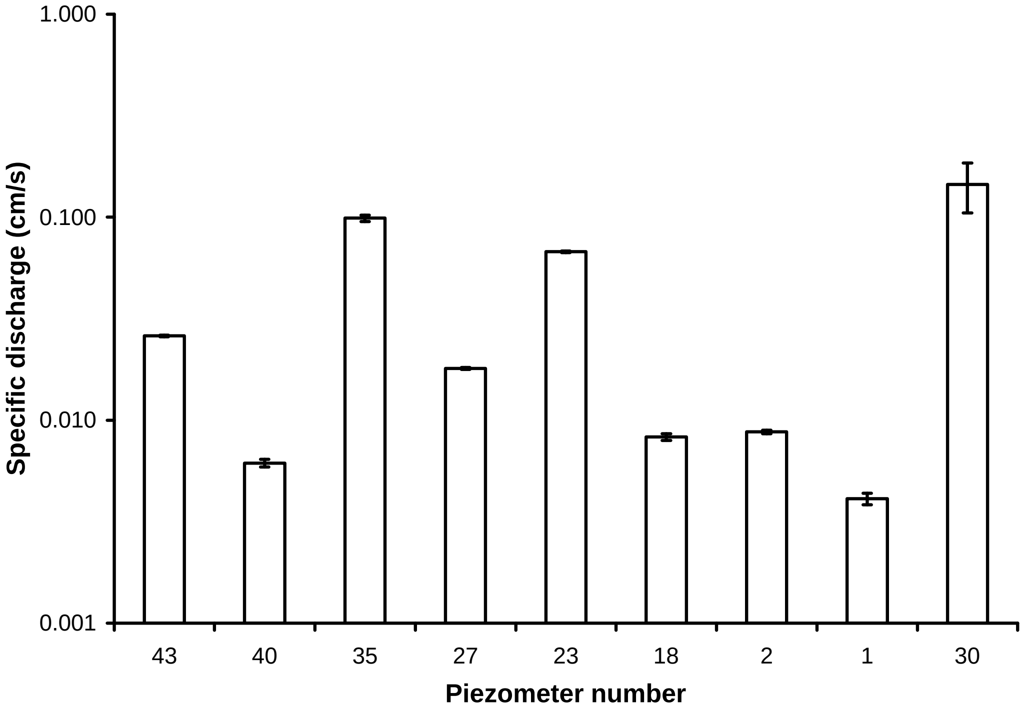

Figure 34: Specific discharge results for Hanford Reach piezometers. Error bars show the standard error associated with the regression of natural logarithm versus time.

Table 5: Specific discharge determined using borehole dilution tests. The standard error (SE) was determined for the slope of LN[tracer concentration]/time.

Piezometer number	Specific discharge (cm/s)	SE (cm/s)
43	0.026	0.00044
40	0.006	0.00051
35	0.099	0.00734
27	0.018	0.00040
23	0.068	0.00129
18	0.008	0.00062
2	0.009	0.00032
1	0.004	0.00053
30	0.145	0.08000

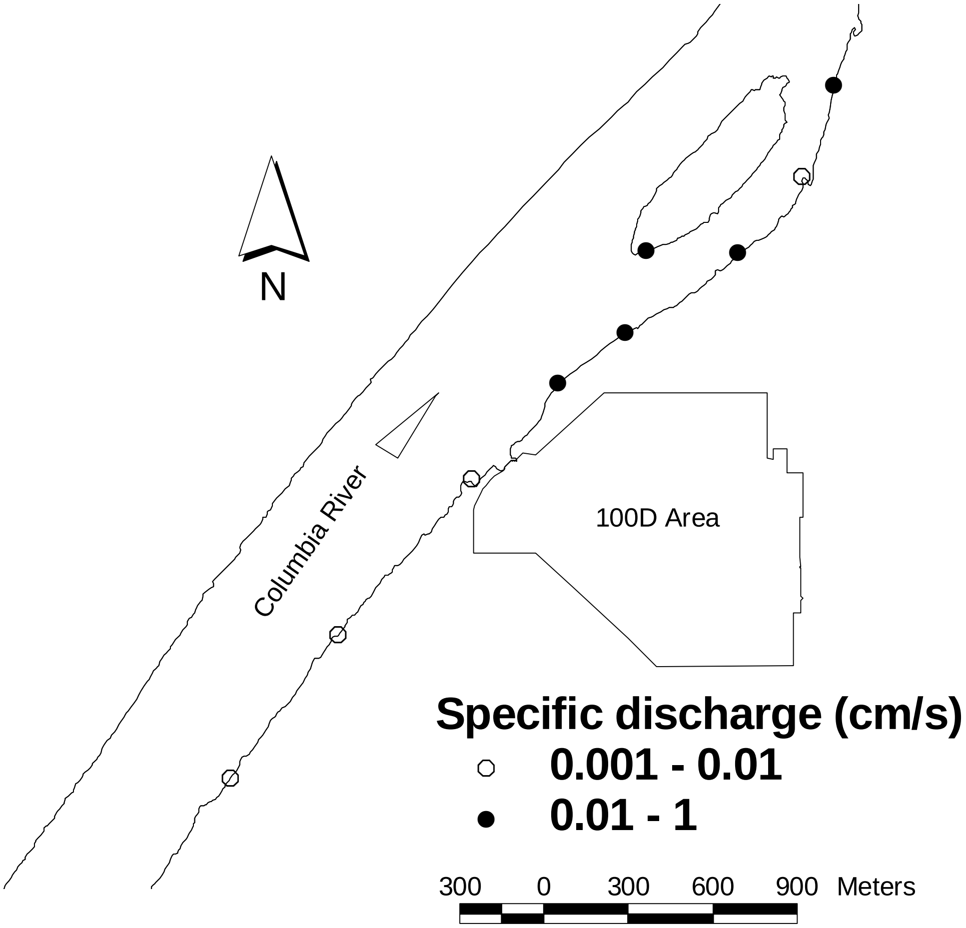

Figure 35: Specific discharge results for the 100D Area. The highest values were downstream of the 100D Area, suggesting higher subsurface water velocities in those locations.

Mass flux estimates of Cr(VI) from the hyporheic zone into the river were made using hydraulic conductivity and Cr(VI) results. The total mass of Cr(VI) entering the river along the 100D Area shoreline study site was 0.044 kg/d using equation 13 and the data from Table 6 (Figure 36). The concentration of Cr(VI) in the Columbia River from the 100D Area downstream to the river's mouth in the Pacific Ocean was estimated by dividing total mass flux of Cr(VI) at the 100D Area (0.044 kg/d) by the volumetric discharge of the Columbia River flowing at a rate of 100,000 ft^3/s near the 100D Area (2.4×10^{11} L/d). The result was 1.8×10^{-13} kg/L (1.8×10^{-7} mg/L) Cr(VI). The quantity did not consider seasonal changes in river discharge or input from downstream tributaries. The assumption was also made that all Cr(VI) remained in the river water column from discharge at the 100D Area to discharge into the Pacific Ocean.

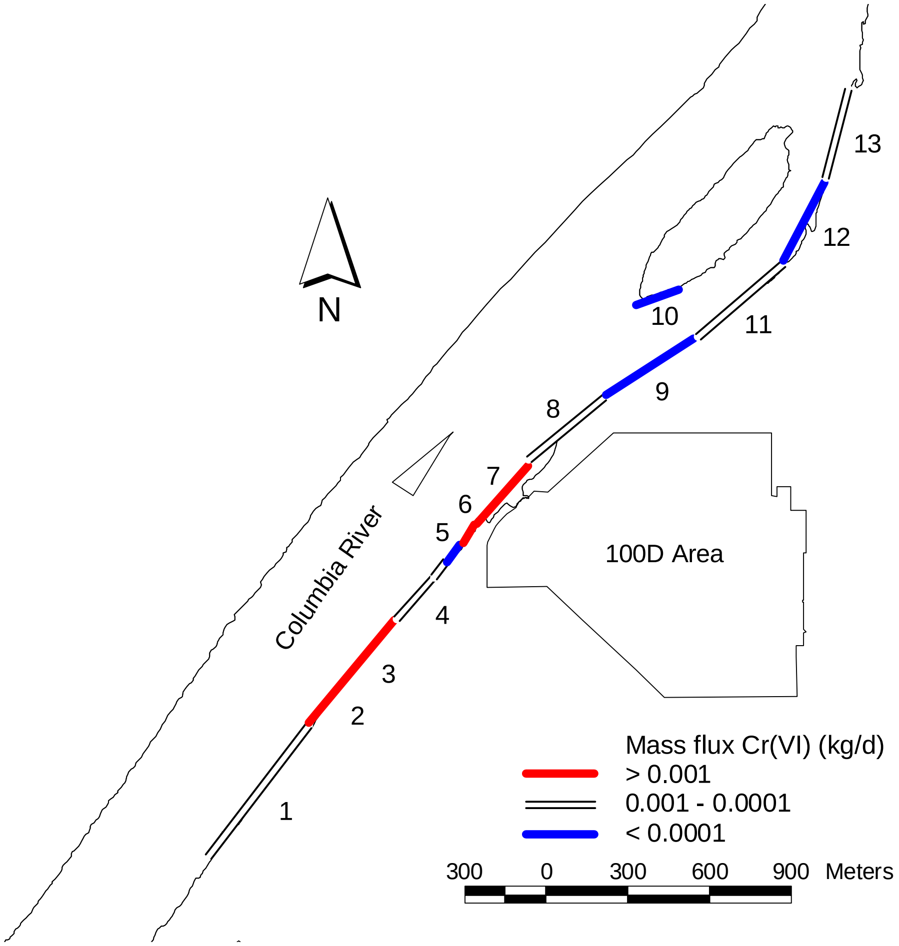

Figure 36: Mass flux of Cr(VI) into the Columbia River through the hyporheic zone at the 100D Area. Shoreline cell labels correspond to cell numbers in Table 6.

Table 6: Variables used to estimate mass flux of Cr(VI) into the Columbia River near the 100D Area. Values represent averaged data collected from piezometers within each cell.

Cell number	Length (km)	Depth (m)	VHG	K (cm/s)	Cr(VI) (mg/L)	Mass flux Cr(VI) (kg/d)
1	0.6	1	0.10	0.00083	0.006	0.000274
2	0.5	1	0.30	0.00343	0.027	0.012491
3	0.2	1	0.24	0.00251	0.012	0.001460
4	0.1	1	0.12	0.00050	0.146	0.000592
5	0.1	1	0.06	0.00008	0.041	0.000014
6	0.1	1	0.02	0.04348	0.242	0.020543
7	0.3	1	0.03	0.01356	0.099	0.007951
8	0.4	1	0.04	0.00032	0.032	0.000117
9	0.3	1	0.21	0.00003	0.003	0.000005
10	0.3	1	0.00	0.00187	0.004	-0.000009
11	0.3	1	0.15	0.00018	0.016	0.000125
12	0.4	1	0.00	0.00245	0.012	0.000026
13	0.3	1	0.12	0.00390	0.001	0.000140
Total						**0.0440**

Chapter 5: Discussion

Water Quality Testing

Cr(VI) concentrations determined for this thesis match closely with other chromium concentrations reported near the 100D Area on the Hanford Site (Figure 37). Past water concentration results varied along the margins of the 100D Area shoreline because of temporal variation in river stage, chromium plume migration, and differences in analysis techniques. The results of this study and previous work all show Cr(VI) water concentrations consistently over 0.1 mg/L along a 400 m reach of 100D Area shoreline. In addition, Cr(VI) water concentrations over 0.4 mg/L have been consistently observed along a narrower 200 m zone along the 100D Area shoreline (Hartman and Dresel, 1998; Peterson et al., 1998; Arntzen unpublished data, 2000; Patton, 1999; Figure 37).

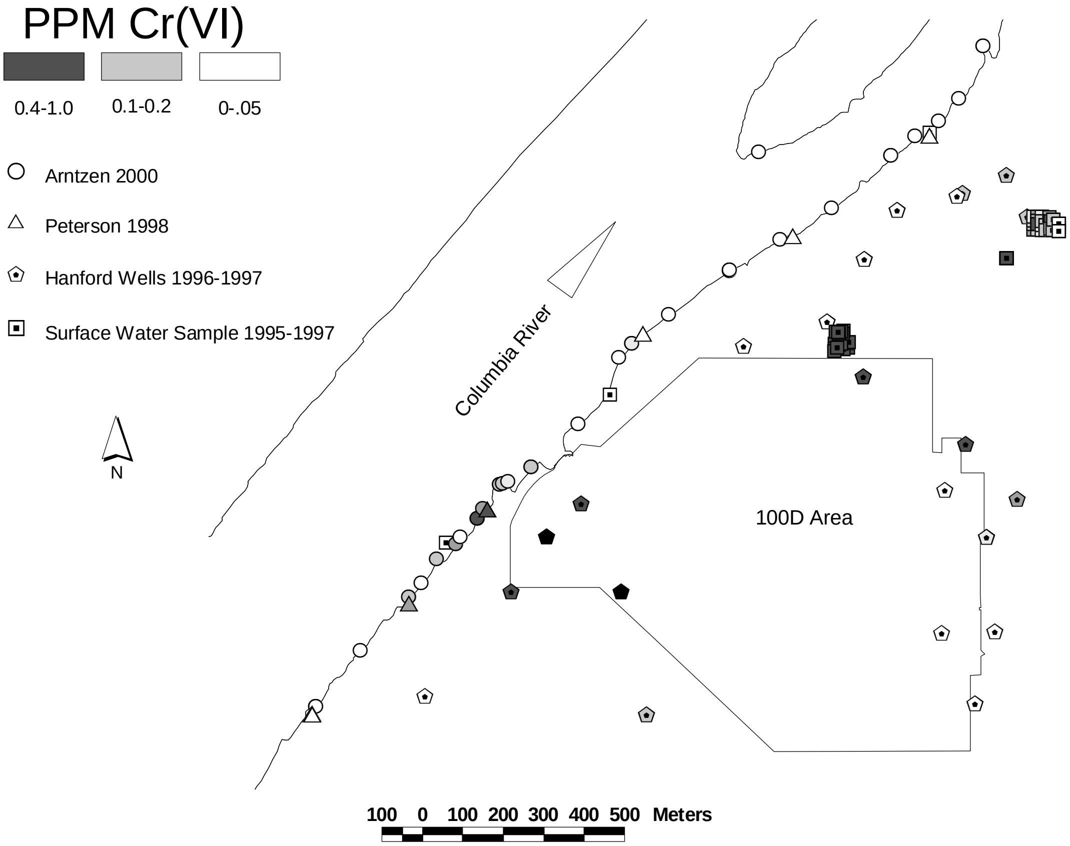

Figure 37: Cr(VI) water concentration results from this study, adjacent Hanford monitoring wells, surface water samples, and past shoreline sampling efforts. Results show good correlation between Cr(VI) water concentrations determined from independent sources.

Understanding the relationship between Cr(VI) and river stage is important because Cr(VI) concentrations in the hyporheic zone are influenced by river stage controlled hydraulic gradients. For example, Cr(VI) concentrations were generally higher during periods of low river stage (Figure 23 and Figure 24). The relationship between Cr(VI) and river stage is probably hysteretic, similar to the relationship between river stage and the other water quality variables (Figure 22). By understanding this relationship, estimates of Cr(VI) discharge into the river could be made simply by monitoring river stage. This would be valuable because currently modelers must rely on expensive Cr(VI) concentration data from nearshore wells, and river stage changes have a more immediate and pronounced effect on water quality in the hyporheic zone than in the adjacent aquifer.

Comparisons between river stage, specific conductance, and Cr(VI) were made for individual piezometers because there was a large amount of variability in water quality data between piezometers. However, general comparisons were possible between specific conductance and Cr(VI) because these data were collected from the same locations at approximately the same times. The specific conductance and Cr(VI) data presented in Figure 23 and Figure 24 were compared to confirm their suspected positive correlation (Figure 38). The result was a positive correlation (? =0.05; R^2=0.32; p=0.0017). Understanding the correlation between these variables would provide a potential cost effective tool that could be used to search for areas of contaminant discharge into the river. However, caution must be exercised when generalizing these relationships. The most effective approach would evaluate relationships between water quality and surface hydrology on the smallest reasonable spatial scale.

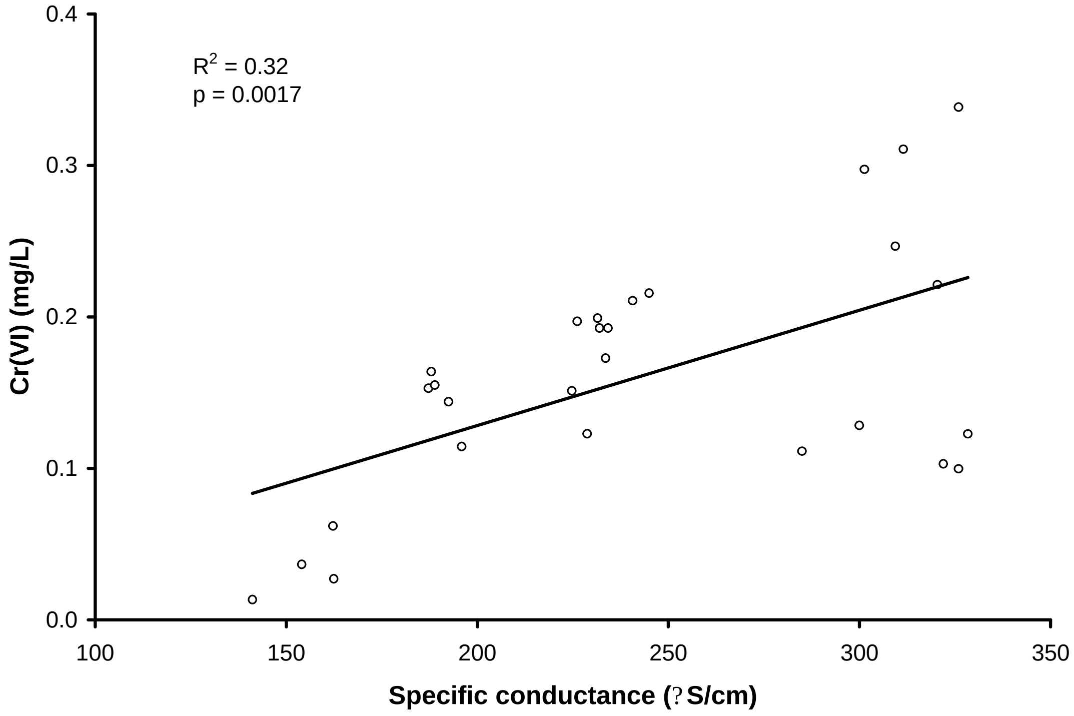

Figure 38: Cr(VI) versus specific conductance in minipiezometers 9, 10, 12, 13, 15, 16, 19, and 20.

Hydraulic Testing

The objective of this project was to demonstrate the application of hydraulic methods used to determine hydrogeologic properties of the hyporheic zone in a large river, and to compare hydraulic data to water quality data collected for this project in the same locations. This objective was evaluated by comparing estimates of hydraulic conductivity using slug tests to those using borehole dilution methods, and by evaluating the reliability of each method individually.

Hydraulic conductivity is directly comparable to specific discharge using Darcy's equation (equation 7). However, my data did not correlate and differed by several orders of magnitude at all locations. The comparison was complicated by differences between slug test methods and borehole dilution techniques, and also by potential problems with the hydraulic gradient data that were collected. The vertical hydraulic gradient (VHG) measurements may have complicated the comparison for two reasons: First, VHG values were determined using a single measurement and there was no statistical control over the results. Second, although vertical flow through the borehole undoubtedly played an important role in the subsurface hydraulics, the horizontal component of flow was not accounted for by the VHG data;

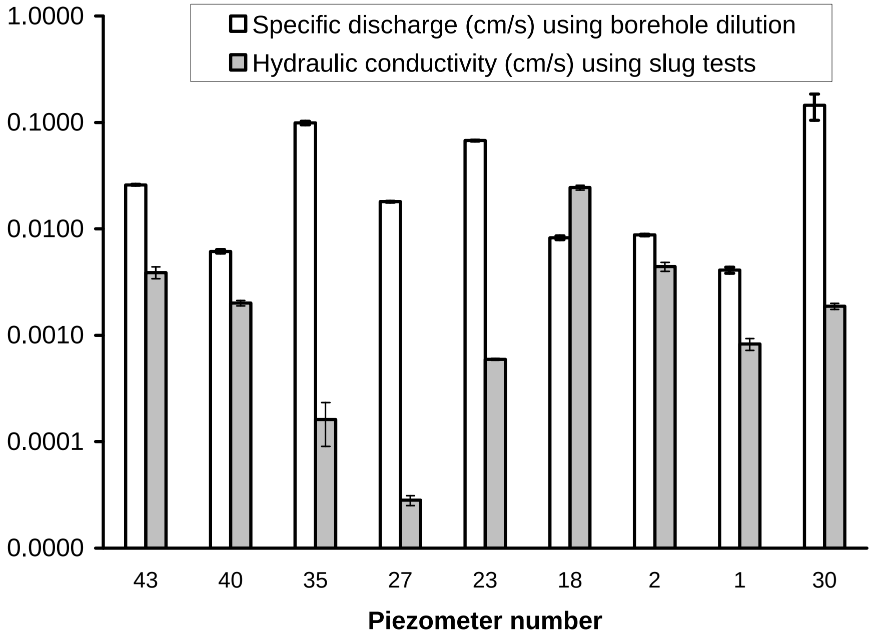

Figure 39: Specific discharge and hydraulic conductivity at piezometer locations in the 100D Area. Specific discharge was determined from borehole dilution results and hydraulic conductivity was determined using the Bouwer and Rice solution for slug tests.

thus the total gradients were probably under estimated. For these reasons, specific discharge determined using borehole dilution data were compared directly to hydraulic conductivity determined using slug tests (Figure 39).

Given the small number of borehole dilution tests it is not surprising that the data sets were not significantly correlated (p=0.43). The important result of the comparison is that most of the results are within an order of magnitude; it is not uncommon for specific discharge results determined using borehole dilution to differ from hydraulic conductivity estimates by orders of magnitude (Dexter and Kearl, 1988). This is largely a consequence of error sources collectively causing net increases in specific discharge estimates (Halevy et al., 1967). In general, errors in borehole dilution tests are caused by unknown hydrogeologic properties (heterogeneity), variables associated with well construction, instrumental influences (mixing), and physical influences (diffusion, density effects, and adsorption of tracer ions onto the probe and piezometer wall) (Halevy et al., 1967). For this project, errors in the borehole dilution methodology caused the tracer to fail to return to the pre-test concentrations in the borehole. This caused the semi-logarithmic plot of tracer concentration versus time to be non-linear. For about half of the tests, this non-linearity was minimal and probably occurred due to some residual tracer caused by adsorption or non-uniform mixing. In some cases this problem was severe, suggesting an event such as packer failure (Figure 40). If packer failure occurred, it is likely that the well-mixed salt solution in the borehole diffused into the water above the sensor, providing a relatively constant tracer supply that redefined the background concentration. To compensate for this, the background concentration was assumed to be the concentration that the borehole dilution test was approaching at the end of the test, rather than the initial value (Borowczyk et al., 1965). The adjusted background values maximized the linear record of the response and allowed the data to be analyzed. The majority of the values were within one order of magnitude of hydraulic conductivity estimates from slug tests. However, despite corrections for background concentrations, some values of specific discharge were three orders of magnitude greater than hydraulic conductivity estimates (Figure 39).

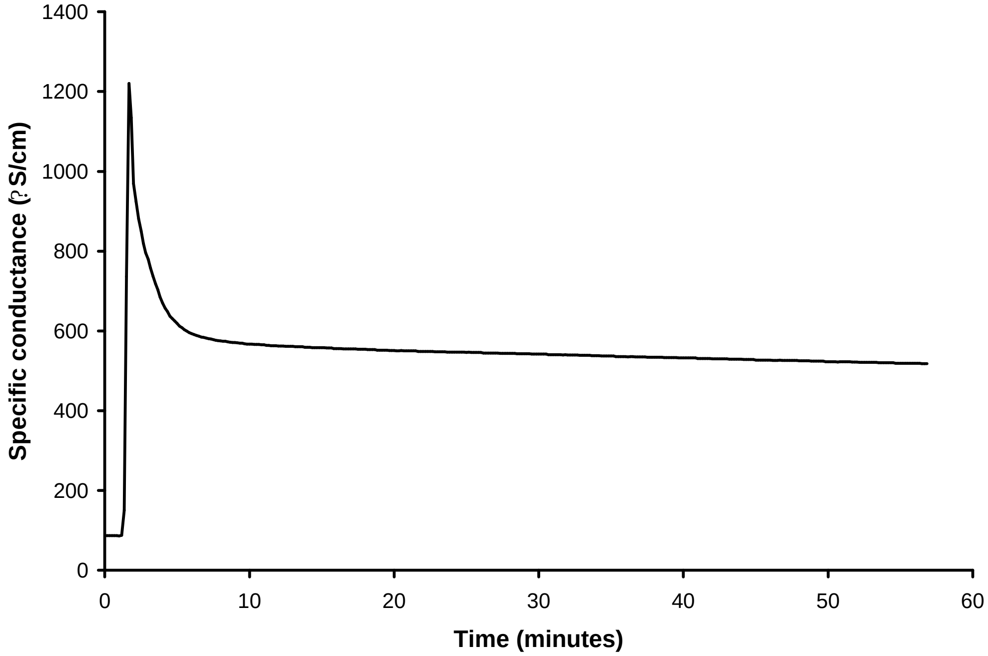

Figure 40: Tracer response for a borehole dilution in piezometer 1. There was a problem (i.e., possible packer failure) that caused the ending concentration to be much higher than the background level prior to tracer injection.

Overdamped slug test data collected for this project demonstrated that the hydraulic conductivity of fluvial Hanford Reach sediments varied over four orders of magnitude. This is significant because typical groundwater modeling assumptions include the assertion that river boundary zone sediments are homogeneous (e.g., the Hanford site three dimensional groundwater flow model uses an estimate of 9.3×10^{-3} cm/s for the hydraulic conductivity of the 100D Area). Hydraulic conductivity results from 100D Area piezometers were between 2.8×10^{-5} cm/s and 4.3×10^{-2} cm/s and were within the range of values other researchers have determined in similar alluvial environments (Table 7; Fetter, 1994; Barrash et al., 1997; Morrice et al., 1997; Springer et al., 1999; Weight and Wittman, 1999).

Table 7: Published values of hydraulic conductivity that were determined in alluvial environments similar to that of the Hanford Reach.

Reference	Location	Sediment type	Hydraulic Conductivity (cm/s)
Fetter, 1994	General	Sands	1.0×10^{-5} to 1.0×10^{-3}
Weight & Wittman, 1999	Alluvial valley, Dillon Montana	Alluvial silt, sand, and gravel	7.1×10^{-5} to 8.6×10^{-2}
Springer et al., 1999	Colorado River	Sand Bars	7.0×10^{-4} to 4.9×10^{-2}
Morrice et al., 1997	Headwater Streams	Sand and Cobble sized gravel	1.3×10^{-4} to 4.1×10^{-3}
Barrash et al., 1997	Boise River	Alluvial sands	1.0×10^{-2} to 1.0×10^{-1}
Arntzen, 2002 (this thesis)	Hanford Reach, Columbia River	Alluvial silt, sand, and cobble sized gravel	2.8×10^{-5} to 4.3×10^{-2}

Although comparisons to other research lend confidence to the methodology and results of this thesis, one primary concern was that all of the Hanford Reach data were overdamped. This fact alone was not alarming; however, it cast some doubt over the sensitivity of the methodology. It would be helpful to know if the methodology is capable of detecting fundamentally different aquifer responses. During 2000, some slug tests were conducted on the Snake River, Idaho, using the same equipment and identical methods as for the Hanford Reach work. The Snake River alluvial sediments were contained in a relatively high gradient, bedrock confined river reach and were more permeable than those tested on the Hanford Reach. Some of the Snake River slug tests produced oscillatory, underdamped response data (Figure 41). The fact that

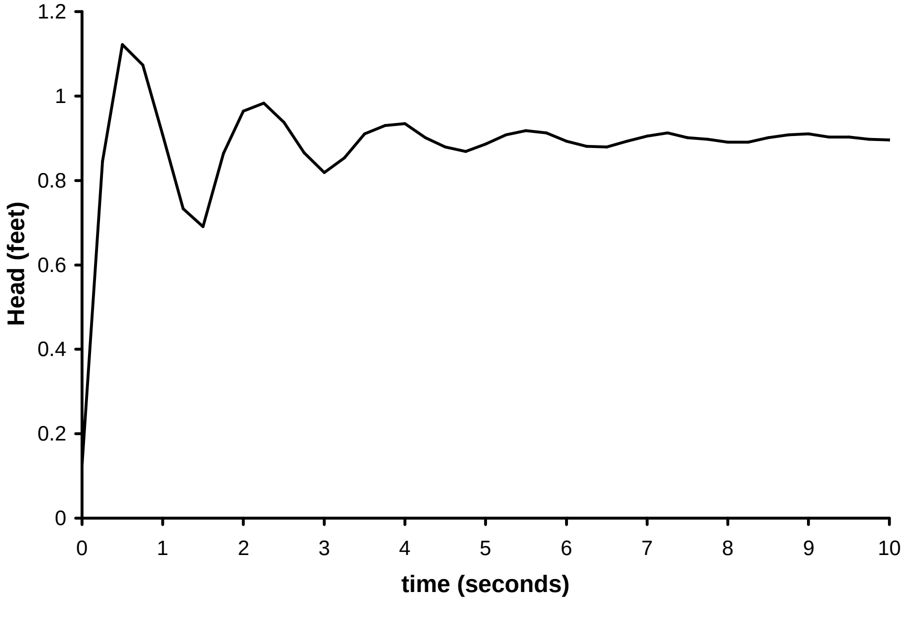

Figure 41: This response, clearly oscillatory in nature, was collected in very permeable Snake River alluvium, and represents underdamped data.

the same instrumentation and methodology were capable of detecting fundamentally different types of aquifer responses (i.e., underdamped responses) lends credence to the reliability of the Hanford Reach methodology, and thereby the results.

Inexpensive techniques (such as those presented in this thesis) have commonly been used to determine the heterogeneity and hydrogeology of aquifers (Fetter, 1994; Butler, 1998). These methods, when applied to the zone of groundwater-surface water mixing (i.e., the hyporheic zone of the Columbia River), may be of valuable to remediation managers by improving estimates of the quantity and concentration of contaminants entering the river. For example, remediation efforts are currently underway at the 100D Area site. These efforts include pump and treat as well as *in situ* redox manipulation (chemical reduction and consequent immobilization of Cr(VI) to Cr(III); Hartman and Dresel, 1998).

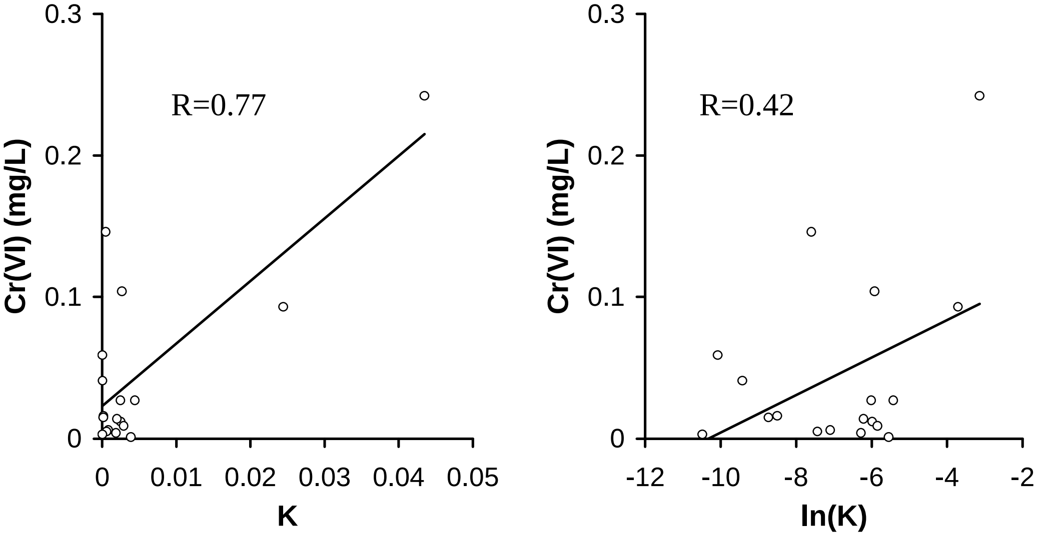

Figure 42: Hydraulic conductivity values versus Cr(VI). The correlation between the variables was significant but weak, suggesting the need for additional data collection.

Future efforts to evaluate the success of these technologies will need to consider the quantity of Cr(VI) entering the river. Improved estimates of hydraulic conductivity along the shoreline in the zone where Cr(VI) flows into the river are necessary in order to predict this quantity accurately. Hydraulic conductivity data collected adjacent to the 100D Area were compared with Cr(VI) data collected from the same locations to determine if there was a correlation between hydraulic conductivity and Cr(VI) (Figure 42). The correlation coefficient for hydraulic conductivity and Cr(VI) was 0.77 (p=0.0002). Typically, due to large-scale differences in hydraulic data, the logarithm of hydraulic conductivity is used for comparisons with other data. The correlation coefficient for the natural logarithm of hydraulic conductivity and Cr(VI) was 0.42 (p=0.085). Based on these data, a significant relationship was determined at a confidence level of ? =0.05 for hydraulic conductivity and Cr(VI), and the relationship between the natural logarithm of hydraulic conductivity and Cr(VI) was not significant. A similar relationship was found between hydraulic conductivity and specific conductance (Figure 43). For K versus specific conductance R^2 was 0.45 (p=0.002). The natural log of K versus specific conductance had an R^2 value of 0.17 (p=0.09).

The scatter about the regression was large for both comparisons, suggesting limitations on the attached significance. It is recommended that future efforts to collect hydraulic data along the shoreline of the 100D Area sample as densely as possible, especially in the vicinity of the 100D Area chromium "hot spot", in order to improve our understanding of the relationship between Cr(VI), specific conductance, and hydraulic conductivity.

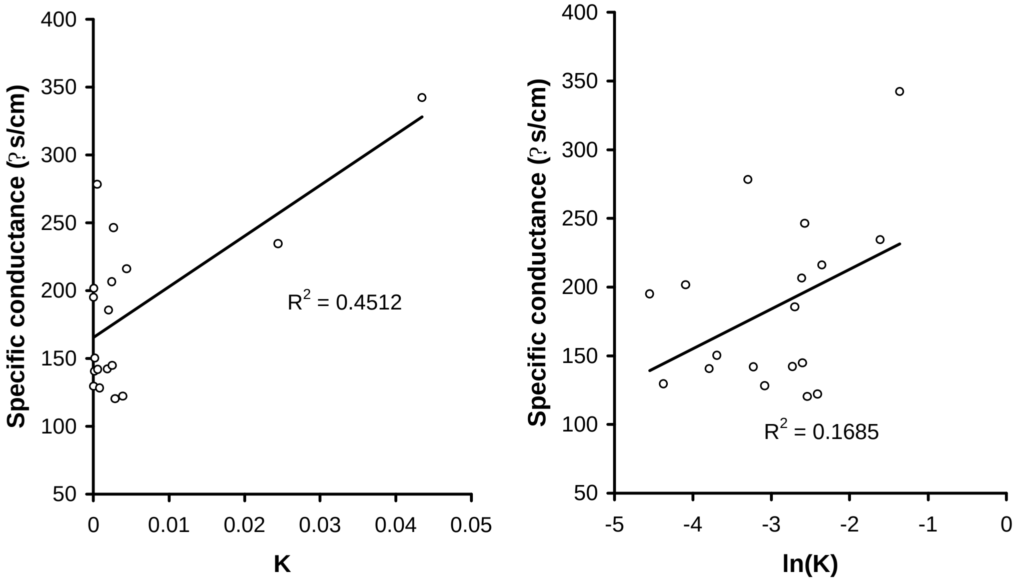

Figure 43: Hydraulic conductivity (K) versus specific conductance. The relationship was similar to that of K and Cr(VI).

Chapter 6: Conclusions

Cr(VI) is present in Columbia River gravels near the 100D Area and exceeded the U.S. EPA's 0.01 mg/L limit for exposure to aquatic life by over 50 times; one quarter of all samples exceeded the EPA's federal 0.1 mg/L drinking water standard. Cr(VI) water concentrations were correlated with position along the river shoreline, with the highest concentrations centered at the upstream end of the 100D Area over a 400 m reach of shoreline. These results are consistent with past research that found similar Cr(VI) in the groundwater-surfacewater mixing zone and in riverbank seeps and springs. Cr(VI) was below detection limits in water samples collected from the overlying water column of the river, thus potential impacts to aquatic life were limited to those in contact with contaminated hyporheic water immediately beneath the river bed. Location and concentration of Cr(VI) were likely a function of small scale variation in sediment heterogeneity, hydraulic gradients, and contaminant source location.

A hysteretic relationship was found between river stage and specific conductance, dissolved oxygen, temperature, and hydrogen ion concentration, suggesting that although there is a gross negative correlation between river stage and water quality, the relationship is complex and requires further research before the river stage would be suitable for use as an analog to Cr(VI) for monitoring purposes in areas where Cr(VI) is known to exist.

A significant positive correlation was determined for the relationship between Cr(VI) and specific conductance (R^2=0.32; p=0.0017). This relationship was not affected by the same variability that hindered general stage versus specific conductance and Cr(VI) comparisons, because values were collected from the same piezometers at essentially the same time and date.

Hydraulic sampling techniques including slug tests and borehole dilution were evaluated in the riverbed of the Columbia River, Hanford Reach, Washington to determine whether they were capable of discerning hydrogeological variability in the ecologically sensitive hyporheic zone beneath the river, and if so, to determine that variability. Borehole dilution results resulted in specific discharge estimates ranging from 4.0 x 10^{-3} cm/s to 1.5 x 10^{-1} cm/s. Relatively few borehole dilution tests were conducted, resulting in no estimates of precision. Additionally, there was a problem with the borehole dilution methodology, speculatively the result of packer failure during some tests. Due to the lack of data, and the presumed packer failure, attempts to relate hydraulic conductivity values determined using slug tests to specific discharge values using borehole dilution failed. In order to determine the success of the borehole dilution methodology in hyporheic environments, more borehole dilution experiments would have to be conducted in the future. The determination of horizontal hydraulic gradients between hyporheic water surface elevations and the potentiometric surface of the adjacent aquifer would help explain borehole dilution results.

Hydraulic conductivity was determined using the Bouwer and Rice solution and was reproducible and highly variable, and showed that Hanford Reach response data were overdamped (Kabala et al., 1985; Butler, 1998; Weight and Wittman, 1999). Values ranged from 2.8 x 10^{-5} cm/s to 4.3 x 10^{-2} cm/s, and the precision associated with replicates reinforced the confidence placed in these data. The accuracy of the data was a function of the solution used to solve for hydraulic conductivity and was largely unknown, although values were comparable to others collected in similar alluvial environments, and the chosen solution has commonly been used in similar environments (Butler et al., 1996; Weight and Witman, 1999). The methodology used for this thesis was used in the Snake River to successfully detect fundamentally different oscillatory response data, which demonstrated the capability of the method and provided further confidence to the data collection technique. This methodology is inexpensive, not labor intensive, and provides a practical means by which managers can collect additional hydrogeologic data in the groundwater surface water zone to improve groundwater modeling efforts.

Hydraulic conductivity determined using slug tests correlated positively with Cr(VI) estimates made in the same locations on the Columbia River shoreline near the 100D Area ($r=0.77$, $p=0.0002$). This relationship may complement point source location data and help explain the location of the elevated Cr(VI) area that has been detected in shallow riverbed sediments near the center of the study site adjacent to the 100D Area reactor (Peterson et al., 1998; Arntzen unpublished data 2000). Although more data is needed to definitively correlate contaminant interaction with the hydrogeology of Columbia River sediments on the Hanford site, these results show that the hydrogeology of the shoreline environment is highly variable, may correlate with contaminant concentrations in some areas, and should be considered when modeling contaminant transport into the river.

Estimates to determine the effects of heterogeneity on Cr(VI) discharge into the river were made based on hydraulic conductivity measurements determined using slug tests, and Cr(VI) determined using a colorimetric technique. Data were collected during low periods of river stage (approximately 117 m above MSL; NAVD 88) when vertical hydraulic gradients were at seasonal highs. The estimate for total mass of Cr(VI) entering the river was 0.044 kg/d. The concentration of Cr(VI) in the Columbia River downstream of the 100D Area was 1.8×10^{-7} mg/L.

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Appendix A: Survey Data

Data for vertical elevation survey between piezometer and survey stake.

Survey pin/piezo number	Survey 1 ? L (cm)	Survey 2 ? L (cm)	AVG. ? L (cm)	Dist. Pin-piezometer (m)	Correction* (cm)	Corrected ? L (cm)
1LS/1	-271.7	-272.0	-271.9	67.41	0.0307	-271.8
2LS/4	-243.0	-242.3	-242.7	56.04	0.0212	-242.6
2LS/5	-272.0	-271.3	-271.7	56.04	0.0212	-271.6
3LS/9	-331.0	-330.5	-330.8	18.48	0.0023	-330.7
3LS/10	-331.2	-332.0	-331.6	18.48	0.0023	-331.6
3LS/12	-329.5	-328.9	-329.2	342.95	0.7951	-328.4
4LS/17	-336.8	-336.6	-336.7	10.99	0.0008	-336.7
4LS/18	-344.4	-344.3	-344.4	10.99	0.0008	-344.3
5LS/20	-208.2	-208.3	-208.3	8.78	0.0005	-208.2
5LS/21	-214.3	-213.9	-214.1	8.78	0.0005	-214.1
6LS/26	-616.7	-617.0	-616.9	24.61	0.0041	-616.8
6LS/27	-637.2	-636.0	-636.6	27.30	0.0050	-636.6
1NS/30	-467.6	-466.9	-467.3	29.11	0.0057	-467.2
2NS/33	-441.0	-442.5	-441.8	21.69	0.0032	-441.7
2NS/36	-442.0	-443.0	-442.5	88.32	0.0527	-442.4
2NS/37	-416.5	-417.0	-416.8	153.09	0.1584	-416.6
7LS/41	-478.5	-478.5	-478.5	13.80	0.0013	-478.5
7LS/42	-503.9	-502.9	-503.4	13.80	0.0013	-503.4
8LS/43	-425.1	-424.5	-424.8	19.07	0.0025	-424.8

Notes:

* Correction is for errors due to light refraction and curvature of the earth

The following table includes data for vertical elevation surveys between survey pins.

Survey pins were established above the high water mark for future reference.

Survey pins	Survey 1 ? L* (cm)	Survey 2 ? L* (cm)	AVG. ? L (cm)	Correction^ (cm)	Corrected ? L (cm)
1LS-2LS	8.0		8.0		8.0
2LS-3LS	53.5	50.0	51.8	0.2015	53.3
3LS-4LS	46.8	46.5	46.7	0.2190	46.6
4LS-5LS	-119.0	-122.0	-120.5	0.2227	-119.2
5LS-6LS	419.6	419.0	419.3	0.1381	419.5
6LS-1NS	-167.0	-169.0	-168.0	0.2581	-167.3
1NS-2NS	-11.5	-12.5	-12.0	0.0237	-11.5
2NS-3NS	212.0	211.5	211.8	0.0276	212.0
3NS-4NS	-310.5	-308.0	-309.3	0.0331	-310.5
4NS-7LS	144.0	142.0	143.0	0.0275	144.0
7LS-8LS	-39.5	-36.0	-37.8	0.1818	-39.7

Notes:

*? foresights and backsights

^? corrections for all foresights and backsights

Appendix B: Priest Rapids Discharge and Columbia River Stage at 100D

Date/Time	Q* (KCFS)	Stage^ (m)	Date/Time	Q* (KCFS)	Stage^ (m)
10/18/99 0:00	124.7	117.99	11/3/99 1:00	103.1	117.69
10/18/99 1:00	104.1	117.97	11/3/99 2:00	94.8	117.55
10/18/99 2:00	109.9	117.91	11/3/99 3:00	95.2	117.53
10/18/99 3:00	111.6	117.88	11/3/99 4:00	103.9	117.53
10/18/99 4:00	109.7	117.86	11/3/99 5:00	103.5	117.56
10/18/99 5:00	98.8	117.83	11/3/99 6:00	57.4	117.61
10/18/99 6:00	58.8	117.73	11/3/99 7:00	37.7	117.53
10/18/99 7:00	41.9	117.47	11/3/99 8:00	50.5	117.27
10/18/99 8:00	53.6	117.37	11/3/99 9:00	53.8	117.06
10/18/99 9:00	50.4	117.20	11/3/99 10:00	53.3	116.91
10/18/99 10:00	53.0	117.08	11/3/99 11:00	54.3	116.82
10/18/99 11:00	52.9	117.02	11/3/99 12:00	55.2	116.72
10/18/99 12:00	52.7	116.91	11/3/99 13:00	54.2	116.73
10/18/99 13:00	52.6	116.88	11/3/99 14:00	54.1	116.71
10/18/99 14:00	52.7	116.78	11/3/99 15:00	54	116.69
10/18/99 15:00	52.8	116.74	11/3/99 16:00	54.1	116.64
10/18/99 16:00	52.9	116.75	11/3/99 17:00	54.1	116.63
10/18/99 17:00	52.7	116.73	11/3/99 18:00	116.1	116.62
10/18/99 18:00	52.7	116.66	11/3/99 19:00	161	116.72
10/18/99 19:00	76.1	116.69	11/3/99 20:00	146.4	117.29
10/18/99 20:00	184.2	117.15	11/3/99 21:00	113.9	117.85
10/18/99 21:00	183.6	117.96	11/3/99 22:00	110.6	118.00
10/18/99 22:00	182.9	118.42	11/3/99 23:00	110.3	117.99
10/18/99 23:00	149	118.60	11/4/99 0:00	115.4	117.96
10/19/99 0:00	130.9	118.50	11/4/99 1:00	134.6	117.92
10/19/99 1:00	140.4	118.45	11/4/99 2:00	133.5	118.00
10/19/99 2:00	167.1	118.53	11/4/99 3:00	155.6	118.05
10/19/99 3:00	163.3	118.57	11/4/99 4:00	161.7	118.24
10/19/99 4:00	156.7	118.61	11/4/99 5:00	158.8	118.43
10/19/99 5:00	169.5	118.67	11/4/99 6:00	84.8	118.55
10/19/99 6:00	146	118.70	11/4/99 7:00	38.4	118.37
10/19/99 7:00	36.2	118.57	11/4/99 8:00	38.7	117.92
10/19/99 8:00	36.6	117.73	11/4/99 9:00	51.3	117.50
10/19/99 9:00	48.7	117.34	11/4/99 10:00	54.4	117.15
10/19/99 10:00	51	117.08	11/4/99 11:00	54.1	116.98
10/19/99 11:00	51.7	116.95	11/4/99 12:00	54.4	116.86
10/19/99 12:00	52.5	116.79	11/4/99 13:00	54.6	116.76
10/19/99 13:00	54.4	116.73	11/4/99 14:00	54.5	116.72
10/19/99 14:00	53.1	116.70	11/4/99 15:00	53.9	116.69
10/19/99 15:00	51.8	116.67	11/4/99 16:00	54.7	116.68
10/19/99 16:00	53.1	116.70	11/4/99 17:00	55.3	116.66
10/19/99 17:00	52.8	116.63	11/4/99 18:00	124	116.66
10/19/99 18:00	52.7	116.62	11/4/99 19:00	167.5	116.77
10/19/99 19:00	78	116.62	11/4/99 20:00	170	117.39

10/19/99 20:00	177.2	117.12	11/4/99 21:00	175.8	117.99
10/19/99 21:00	171.5	117.84	11/4/99 22:00	182.5	118.37
10/19/99 22:00	182.4	118.35	11/4/99 23:00	169.4	118.64
10/19/99 23:00	175.5	118.61	11/5/99 0:00	158.4	118.76
10/20/99 0:00	173.5	118.74	11/5/99 1:00	142.9	118.74
10/20/99 1:00	163.2	118.78	11/5/99 2:00	146.5	118.66
10/20/99 2:00	114.7	118.58	11/5/99 3:00	151	118.57
10/20/99 3:00	136.7	118.43	11/5/99 4:00	166.4	118.54
10/20/99 4:00	168.8	118.49	11/5/99 5:00	146.7	118.59
10/20/99 5:00	153.3	118.57	11/5/99 6:00	67.2	118.59
10/20/99 6:00	153.8	118.57	11/5/99 7:00	36.7	118.29
10/20/99 7:00	45.9	118.21	11/5/99 8:00	38.9	117.82
10/20/99 8:00	50	117.79	11/5/99 9:00	54.3	117.39
10/20/99 9:00	49.1	117.47	11/5/99 10:00	51.8	117.10
10/20/99 10:00	54.9	117.17	11/5/99 11:00	53.9	116.92
10/20/99 11:00	55.3	117.05	11/5/99 12:00	53	116.82
10/20/99 12:00	54.7	116.89	11/5/99 13:00	54.4	116.76
10/20/99 13:00	54.8	116.86	11/5/99 14:00	52.9	116.72
10/20/99 14:00	55	116.77	11/5/99 15:00	54.2	116.70
10/20/99 15:00	55	116.73	11/5/99 16:00	55.1	116.68
10/20/99 16:00	55	116.71	11/5/99 17:00	124.3	116.68
10/20/99 17:00	55	116.70	11/5/99 18:00	167	116.79
10/20/99 18:00	54.8	116.69	11/5/99 19:00	144.8	117.44
10/20/99 19:00	118.9	116.78	11/5/99 20:00	123.1	117.89
10/20/99 20:00	159.6	117.34	11/5/99 21:00	124.3	118.07
10/20/99 21:00	165	117.93	11/5/99 22:00	138.1	118.06
10/20/99 22:00	174.5	118.33	11/5/99 23:00	118.8	118.11
10/20/99 23:00	182.2	118.61	11/6/99 0:00	126.6	118.10
10/21/99 0:00	182	118.79	11/6/99 1:00	171.2	118.07
10/21/99 1:00	181.9	118.91	11/6/99 2:00	178.5	118.25
10/21/99 2:00	182.3	118.96	11/6/99 3:00	174.6	118.47
10/21/99 3:00	182.7	119.01	11/6/99 4:00	175.8	118.63
10/21/99 4:00	182.3	119.03	11/6/99 5:00	208.1	118.74
10/21/99 5:00	182	119.04	11/6/99 6:00	155	118.94
10/21/99 6:00	181.7	119.06	11/6/99 7:00	65.9	118.94
10/21/99 7:00	106.8	118.83	11/6/99 8:00	66.4	118.47
10/21/99 8:00	47	118.32	11/6/99 9:00	54.3	118.06
10/21/99 9:00	51.3	117.87	11/6/99 10:00	56.1	117.67
10/21/99 10:00	53.7	117.51	11/6/99 11:00	60.3	117.36
10/21/99 11:00	54.1	117.25	11/6/99 12:00	65.4	117.16
10/21/99 12:00	53.5	117.02	11/6/99 13:00	67.5	117.04
10/21/99 13:00	53.4	116.90	11/6/99 14:00	77.1	116.99
10/21/99 14:00	53.2	116.81	11/6/99 15:00	122.3	116.99
10/21/99 15:00	53.9	116.75	11/6/99 16:00	121	117.16
10/21/99 16:00	56	116.72	11/6/99 17:00	99.6	117.46
10/21/99 17:00	56.6	116.69	11/6/99 18:00	142.9	117.59
10/21/99 18:00	59.3	116.73	11/6/99 19:00	164.8	117.75
10/21/99 19:00	133.3	116.85	11/6/99 20:00	166.2	118.07
10/21/99 20:00	172	117.55	11/6/99 21:00	167.4	118.33
10/21/99 21:00	176	118.10	11/6/99 22:00	168.7	118.51
10/21/99 22:00	180	118.48	11/6/99 23:00	169.9	118.61

10/21/99 23:00	178.9	118.69	11/7/99 0:00	172.2	118.70
10/22/99 0:00	172.4	118.78	11/7/99 1:00	174.6	118.75
10/22/99 1:00	178	118.85	11/7/99 2:00	178.3	118.79
10/22/99 2:00	180	118.92	11/7/99 3:00	170.2	118.86
10/22/99 3:00	180.4	118.96	11/7/99 4:00	154	118.88
10/22/99 4:00	179.8	118.99	11/7/99 5:00	146.5	118.79
10/22/99 5:00	179.4	118.99	11/7/99 6:00	83.7	118.69
10/22/99 6:00	166.5	118.96	11/7/99 7:00	36.6	118.40
10/22/99 7:00	39.9	118.49	11/7/99 8:00	46.1	117.93
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10/22/99 9:00	37.5	117.48	11/7/99 10:00	54.9	117.20
10/22/99 10:00	50.4	117.14	11/7/99 11:00	54.9	117.02
10/22/99 11:00	53.5	116.94	11/7/99 12:00	54.8	116.90
10/22/99 12:00	52.6	116.83	11/7/99 13:00	54.6	116.82
10/22/99 13:00	53	116.76	11/7/99 14:00	54.4	116.77
10/22/99 14:00	53.9	116.72	11/7/99 15:00	54.5	116.73
10/22/99 15:00	53.7	116.70	11/7/99 16:00	54.3	116.73
10/22/99 16:00	53.6	116.69	11/7/99 17:00	54	116.69
10/22/99 17:00	53.7	116.68	11/7/99 18:00	95	116.68
10/22/99 18:00	53.8	116.67	11/7/99 19:00	135.2	116.75
10/22/99 19:00	90.7	116.69	11/7/99 20:00	143.1	117.11
10/22/99 20:00	179.3	117.24	11/7/99 21:00	144.9	117.58
10/22/99 21:00	182.9	118.00	11/7/99 22:00	146.3	117.90
10/22/99 22:00	182.4	118.45	11/7/99 23:00	144.3	118.11
10/22/99 23:00	181.8	118.71	11/8/99 0:00	130	118.23
10/23/99 0:00	181.2	118.85	11/8/99 1:00	108.6	118.24
10/23/99 1:00	180.9	118.92	11/8/99 2:00	110.9	118.13
10/23/99 2:00	180.4	118.97	11/8/99 3:00	114.1	118.01
10/23/99 3:00	180.1	118.99	11/8/99 4:00	130.5	117.94
10/23/99 4:00	178.8	119.01	11/8/99 5:00	113.9	117.96
10/23/99 5:00	177.5	119.00	11/8/99 6:00	65.8	117.97
10/23/99 6:00	166.4	118.96	11/8/99 7:00	37.7	117.81
10/23/99 7:00	40.3	118.49	11/8/99 8:00	57.6	117.49
10/23/99 8:00	37.4	117.94	11/8/99 9:00	59.3	117.20
10/23/99 9:00	37.6	117.48	11/8/99 10:00	59.5	117.02
10/23/99 10:00	50.5	117.14	11/8/99 11:00	59.8	116.92
10/23/99 11:00	53.1	116.94	11/8/99 12:00	59.6	116.86
10/23/99 12:00	52.9	116.82	11/8/99 13:00	59.8	116.82
10/23/99 13:00	53.9	116.76	11/8/99 14:00	59.9	116.79
10/23/99 14:00	53.5	116.72	11/8/99 15:00	59.6	116.78
10/23/99 15:00	53.8	116.70	11/8/99 16:00	59.7	116.77
10/23/99 16:00	54	116.69	11/8/99 17:00	60.7	116.76
10/23/99 17:00	53.9	116.68	11/8/99 18:00	156.7	116.79
10/23/99 18:00	53.9	116.67	11/8/99 19:00	181.8	117.03
10/23/99 19:00	88.1	116.69	11/8/99 20:00	182.1	117.76
10/23/99 20:00	166.8	117.18	11/8/99 21:00	138.5	118.31
10/23/99 21:00	172.4	117.89	11/8/99 22:00	97.5	118.47
10/23/99 22:00	175.8	118.34	11/8/99 23:00	90	118.30
10/23/99 23:00	179.6	118.63	11/9/99 0:00	118.5	118.02
10/24/99 0:00	178.2	118.79	11/9/99 1:00	132	117.87
10/24/99 1:00	129	118.71	11/9/99 2:00	121	117.94

10/24/99 2:00	135.6	118.57	11/9/99 3:00	137.2	117.97
10/24/99 3:00	137.6	118.43	11/9/99 4:00	168.7	118.05
10/24/99 4:00	138.7	118.44	11/9/99 5:00	165.7	118.25
10/24/99 5:00	115.1	118.33	11/9/99 6:00	117.4	118.45
10/24/99 6:00	101.3	118.16	11/9/99 7:00	38.2	118.43
10/24/99 7:00	40.9	117.84	11/9/99 8:00	40.9	118.01
10/24/99 8:00	38	117.46	11/9/99 9:00	59.3	117.56
10/24/99 9:00	38	117.14	11/9/99 10:00	59.3	117.23
10/24/99 10:00	38.1	116.86	11/9/99 11:00	59.6	117.04
10/24/99 11:00	38.3	116.66	11/9/99 12:00	59.8	116.93
10/24/99 12:00	38.2	116.57	11/9/99 13:00	63.4	116.86
10/24/99 13:00	47.3	116.47	11/9/99 14:00	65	116.83
10/24/99 14:00	54	116.41	11/9/99 15:00	65.1	116.85
10/24/99 15:00	54.1	116.46	11/9/99 16:00	65	116.87
10/24/99 16:00	54.4	116.52	11/9/99 17:00	65.6	116.85
10/24/99 17:00	53.7	116.62	11/9/99 18:00	158.4	116.86
10/24/99 18:00	54.7	116.61	11/9/99 19:00	180.1	117.13
10/24/99 19:00	91.7	116.66	11/9/99 20:00	181.4	117.81
10/24/99 20:00	159	117.14	11/9/99 21:00	181.1	118.33
10/24/99 21:00	162.4	117.76	11/9/99 22:00	165.2	118.63
10/24/99 22:00	150.9	118.12	11/9/99 23:00	136.6	118.72
10/24/99 23:00	148.9	118.27	11/10/99 0:00	144.3	118.63
10/25/99 0:00	137.9	118.33	11/10/99 1:00	172.2	118.54
10/25/99 1:00	116.4	118.26	11/10/99 2:00	179.2	118.60
10/25/99 2:00	106.5	118.12	11/10/99 3:00	178.8	118.72
10/25/99 3:00	106.2	117.99	11/10/99 4:00	168.5	118.83
10/25/99 4:00	120.1	117.94	11/10/99 5:00	163.8	118.86
10/25/99 5:00	127.8	117.97	11/10/99 6:00	124	118.84
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10/25/99 7:00	46.3	117.72	11/10/99 8:00	53	118.20
10/25/99 8:00	41.5	117.38	11/10/99 9:00	62.1	117.72
10/25/99 9:00	53.9	117.11	11/10/99 10:00	62.4	117.40
10/25/99 10:00	51.5	116.94	11/10/99 11:00	62.6	117.19
10/25/99 11:00	52.7	116.82	11/10/99 12:00	62.4	117.06
10/25/99 12:00	58.2	116.76	11/10/99 13:00	62.4	116.97
10/25/99 13:00	51.5	116.73	11/10/99 14:00	62.3	116.91
10/25/99 14:00	54.1	116.70	11/10/99 15:00	61.8	116.88
10/25/99 15:00	55.2	116.70	11/10/99 16:00	62.1	116.85
10/25/99 16:00	53	116.67	11/10/99 17:00	63.4	116.87
10/25/99 17:00	52.4	116.66	11/10/99 18:00	91.9	116.86
10/25/99 18:00	53.2	116.64	11/10/99 19:00	150	116.91
10/25/99 19:00	101.4	116.68	11/10/99 20:00	166.7	117.21
10/25/99 20:00	171.7	117.26	11/10/99 21:00	174.1	117.83
10/25/99 21:00	174.4	117.93	11/10/99 22:00	159.2	118.27
10/25/99 22:00	175.5	118.35	11/10/99 23:00	145.5	118.44
10/25/99 23:00	175.4	118.60	11/11/99 0:00	144.1	118.47
10/26/99 0:00	176.4	118.73	11/11/99 1:00	137	118.46
10/26/99 1:00	152.9	118.72	11/11/99 2:00	162.6	118.40
10/26/99 2:00	161.9	118.70	11/11/99 3:00	176.7	118.46
10/26/99 3:00	158.7	118.71	11/11/99 4:00	168.5	118.60
10/26/99 4:00	143	118.63	11/11/99 5:00	165.1	118.70

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10/26/99 6:00	125	118.48	11/11/99 7:00	36.8	118.65
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10/26/99 8:00	36.4	117.71	11/11/99 9:00	60.9	117.72
10/26/99 9:00	46.9	117.32	11/11/99 10:00	60.8	117.39
10/26/99 10:00	53.9	117.08	11/11/99 11:00	60.7	117.18
10/26/99 11:00	52.7	116.93	11/11/99 12:00	60.6	117.04
10/26/99 12:00	52.7	116.80	11/11/99 13:00	60.4	116.96
10/26/99 13:00	52.6	116.74	11/11/99 14:00	60.2	116.90
10/26/99 14:00	52.6	116.73	11/11/99 15:00	60.2	116.86
10/26/99 15:00	52	116.67	11/11/99 16:00	60	116.83
10/26/99 16:00	53.2	116.65	11/11/99 17:00	60.4	116.81
10/26/99 17:00	56.2	116.64	11/11/99 18:00	141.7	116.79
10/26/99 18:00	55.2	116.64	11/11/99 19:00	159.1	116.98
10/26/99 19:00	98.6	116.69	11/11/99 20:00	160.9	117.54
10/26/99 20:00	157.9	117.20	11/11/99 21:00	162.1	118.00
10/26/99 21:00	160.9	117.81	11/11/99 22:00	162.9	118.29
10/26/99 22:00	163.2	118.21	11/11/99 23:00	163.9	118.45
10/26/99 23:00	163.6	118.45	11/12/99 0:00	163.6	118.55
10/27/99 0:00	161.3	118.57	11/12/99 1:00	150.1	118.61
10/27/99 1:00	161.8	118.65	11/12/99 2:00	170.8	118.60
10/27/99 2:00	162.4	118.69	11/12/99 3:00	175.6	118.64
10/27/99 3:00	162.2	118.73	11/12/99 4:00	177.6	118.74
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10/27/99 6:00	157.9	118.73	11/12/99 7:00	36.6	118.74
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10/27/99 10:00	52.1	117.15	11/12/99 11:00	62.7	117.22
10/27/99 11:00	52.6	116.98	11/12/99 12:00	63.9	117.07
10/27/99 12:00	53.6	116.87	11/12/99 13:00	63.8	117.03
10/27/99 13:00	53.9	116.78	11/12/99 14:00	63.8	116.99
10/27/99 14:00	54.3	116.72	11/12/99 15:00	63.8	116.97
10/27/99 15:00	56.7	116.70	11/12/99 16:00	63.7	116.95
10/27/99 16:00	53.7	116.69	11/12/99 17:00	63.7	116.95
10/27/99 17:00	53	116.68	11/12/99 18:00	130.2	116.94
10/27/99 18:00	53.3	116.66	11/12/99 19:00	179.4	117.08
10/27/99 19:00	102.5	116.70	11/12/99 20:00	181.3	117.70
10/27/99 20:00	165.2	117.26	11/12/99 21:00	180.9	118.27
10/27/99 21:00	164.5	117.91	11/12/99 22:00	180.4	118.60
10/27/99 22:00	164.2	118.29	11/12/99 23:00	180	118.74
10/27/99 23:00	163.9	118.50	11/13/99 0:00	163.3	118.84
10/28/99 0:00	164	118.62	11/13/99 1:00	154.1	118.87
10/28/99 1:00	163.6	118.69	11/13/99 2:00	148.7	118.78
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10/28/99 5:00	162.3	118.77	11/13/99 6:00	105.1	118.53
10/28/99 6:00	156.3	118.75	11/13/99 7:00	36.3	118.40
10/28/99 7:00	41	118.35	11/13/99 8:00	56.8	117.97

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10/28/99 12:00	54.5	116.91	11/13/99 13:00	63.7	116.99
10/28/99 13:00	54.2	116.84	11/13/99 14:00	63.5	116.93
10/28/99 14:00	53.9	116.79	11/13/99 15:00	63.5	116.91
10/28/99 15:00	54	116.74	11/13/99 16:00	63.4	116.94
10/28/99 16:00	54	116.72	11/13/99 17:00	63.3	116.93
10/28/99 17:00	54.2	116.71	11/13/99 18:00	116	116.92
10/28/99 18:00	58	116.70	11/13/99 19:00	163.7	117.01
10/28/99 19:00	101.6	116.74	11/13/99 20:00	162.2	117.51
10/28/99 20:00	162.5	117.32	11/13/99 21:00	158.7	118.00
10/28/99 21:00	164	117.95	11/13/99 22:00	136.6	118.27
10/28/99 22:00	163.8	118.32	11/13/99 23:00	146.4	118.33
10/28/99 23:00	163.6	118.54	11/14/99 0:00	128.6	118.35
10/29/99 0:00	163.5	118.64	11/14/99 1:00	106.8	118.28
10/29/99 1:00	163.5	118.72	11/14/99 2:00	167.5	118.14
10/29/99 2:00	163.2	118.77	11/14/99 3:00	181.2	118.21
10/29/99 3:00	161.4	118.79	11/14/99 4:00	177	118.49
10/29/99 4:00	151.7	118.70	11/14/99 5:00	180.7	118.68
10/29/99 5:00	127.2	118.56	11/14/99 6:00	94	118.80
10/29/99 6:00	64.6	118.23	11/14/99 7:00	38.1	118.58
10/29/99 7:00	37.2	117.78	11/14/99 8:00	54	118.08
10/29/99 8:00	49.7	117.38	11/14/99 9:00	62.2	117.64
10/29/99 9:00	55.1	117.12	11/14/99 10:00	61.8	117.35
10/29/99 10:00	55.2	116.97	11/14/99 11:00	61.7	117.17
10/29/99 11:00	55	116.87	11/14/99 12:00	61.4	117.05
10/29/99 12:00	54.7	116.80	11/14/99 13:00	61.5	116.98
10/29/99 13:00	54.7	116.80	11/14/99 14:00	62.2	116.93
10/29/99 14:00	54.3	116.77	11/14/99 15:00	63.1	116.89
10/29/99 15:00	53.8	116.75	11/14/99 16:00	63.1	116.88
10/29/99 16:00	54.3	116.73	11/14/99 17:00	62.8	116.88
10/29/99 17:00	54.8	116.69	11/14/99 18:00	111.8	116.88
10/29/99 18:00	54.8	116.68	11/14/99 19:00	108.7	116.99
10/29/99 19:00	123.3	116.81	11/14/99 20:00	114.5	117.22
10/29/99 20:00	158.9	117.38	11/14/99 21:00	102.9	117.44
10/29/99 21:00	162.7	117.95	11/14/99 22:00	108.2	117.56
10/29/99 22:00	162.7	118.29	11/14/99 23:00	96.2	117.63
10/29/99 23:00	162.1	118.49	11/15/99 0:00	84	117.63
10/30/99 0:00	161.4	118.59	11/15/99 1:00	92.5	117.58
10/30/99 1:00	148.6	118.61	11/15/99 2:00	143.8	117.52
10/30/99 2:00	125.1	118.49	11/15/99 3:00	182.5	117.66
10/30/99 3:00	119.4	118.36	11/15/99 4:00	182	118.10
10/30/99 4:00	107.4	118.18	11/15/99 5:00	181.7	118.48
10/30/99 5:00	85.3	117.98	11/15/99 6:00	144.2	118.70
10/30/99 6:00	59.4	117.71	11/15/99 7:00	37.8	118.68
10/30/99 7:00	43.8	117.40	11/15/99 8:00	54	118.21
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10/30/99 9:00	51.8	116.99	11/15/99 10:00	61	117.44
10/30/99 10:00	51.8	116.87	11/15/99 11:00	63.6	117.23

10/30/99 11:00	51.8	116.76	11/15/99 12:00	63.5	117.09
10/30/99 12:00	51.9	116.71	11/15/99 13:00	63.3	117.01
10/30/99 13:00	51.7	116.67	11/15/99 14:00	63.4	116.96
10/30/99 14:00	53	116.65	11/15/99 15:00	64.7	116.93
10/30/99 15:00	54.5	116.64	11/15/99 16:00	64.4	116.91
10/30/99 16:00	54.2	116.64	11/15/99 17:00	64.5	116.91
10/30/99 17:00	54	116.65	11/15/99 18:00	110.7	116.90
10/30/99 18:00	54	116.65	11/15/99 19:00	117.5	117.02
10/30/99 19:00	53.9	116.65	11/15/99 20:00	118.6	117.30
10/30/99 20:00	53.6	116.65	11/15/99 21:00	104.5	117.56
10/30/99 21:00	53.6	116.64	11/15/99 22:00	91.4	117.68
10/30/99 22:00	53.6	116.64	11/15/99 23:00	79.9	117.67
10/30/99 23:00	53.5	116.64	11/16/99 0:00	94.7	117.57
10/31/99 0:00	53.5	116.66	11/16/99 1:00	124.8	117.50
10/31/99 1:00	53	116.64	11/16/99 2:00	182.5	117.58
10/31/99 2:00	53.1	116.65	11/16/99 3:00	182	118.00
10/31/99 3:00	79.2	116.66	11/16/99 4:00	181.8	118.40
10/31/99 4:00	77.3	116.78	11/16/99 5:00	181.6	118.66
10/31/99 5:00	69.8	116.97	11/16/99 6:00	148.5	118.81
10/31/99 6:00	39.9	117.01	11/16/99 7:00	37.9	118.78
10/31/99 7:00	37.3	116.97	11/16/99 8:00	38.5	118.30
10/31/99 8:00	36.8	116.82	11/16/99 9:00	63.2	117.79
10/31/99 9:00	36.8	116.65	11/16/99 10:00	62.9	117.42
10/31/99 10:00	36.7	116.52	11/16/99 11:00	63.8	117.21
10/31/99 11:00	37.6	116.40	11/16/99 12:00	63	117.08
10/31/99 12:00	37.4	116.33	11/16/99 13:00	63.1	117.01
10/31/99 13:00	50.2	116.26	11/16/99 14:00	64.3	116.96
10/31/99 14:00	51.6	116.27	11/16/99 15:00	64.6	116.93
10/31/99 15:00	51.4	116.30	11/16/99 16:00	64.7	116.94
10/31/99 16:00	51.4	116.39	11/16/99 17:00	75.7	116.94
10/31/99 17:00	51.3	116.46	11/16/99 18:00	176.2	116.94
10/31/99 18:00	65.7	116.51	11/16/99 19:00	182.1	117.33
10/31/99 19:00	78.8	116.56	11/16/99 20:00	181.8	118.00
10/31/99 20:00	81.9	116.65	11/16/99 21:00	181.5	118.46
10/31/99 21:00	48.1	116.87	11/16/99 22:00	181.1	118.70
10/31/99 22:00	41.6	116.91	11/16/99 23:00	175.9	118.81
10/31/99 23:00	41.5	116.83	11/17/99 0:00	178.4	118.85
11/1/99 0:00	41.5	116.75	11/17/99 1:00	180.2	118.90
11/1/99 1:00	41.3	116.58	11/17/99 2:00	180	118.93
11/1/99 2:00	92.1	116.49	11/17/99 3:00	180.2	118.95
11/1/99 3:00	110.6	116.47	11/17/99 4:00	180.4	119.01
11/1/99 4:00	112.4	116.78	11/17/99 5:00	179.9	119.01
11/1/99 5:00	70.6	117.16	11/17/99 6:00	167.1	119.03
11/1/99 6:00	38.8	117.34	11/17/99 7:00	40.5	118.97
11/1/99 7:00	53.4	117.24	11/17/99 8:00	37.5	118.48
11/1/99 8:00	51.8	117.05	11/17/99 9:00	58.7	117.91
11/1/99 9:00	50.6	116.91	11/17/99 10:00	63	117.50
11/1/99 10:00	46.2	116.81	11/17/99 11:00	63.8	117.25
11/1/99 11:00	47.3	116.73	11/17/99 12:00	64.1	117.14
11/1/99 12:00	54.7	116.65	11/17/99 13:00	64.1	117.02
11/1/99 13:00	54.9	116.60	11/17/99 14:00	64.5	116.98

11/1/99 14:00	54.8	116.60	11/17/99 15:00	64.4	116.95
11/1/99 15:00	54.3	116.62	11/17/99 16:00	64.2	116.96
11/1/99 16:00	54.8	116.64	11/17/99 17:00	144.1	116.95
11/1/99 17:00	55.2	116.65	11/17/99 18:00	191.8	117.12
11/1/99 18:00	94	116.67	11/17/99 19:00	250	117.78
11/1/99 19:00	163.1	116.72	11/17/99 20:00	249.8	118.63
11/1/99 20:00	164.5	117.19	11/17/99 21:00	249.7	119.20
11/1/99 21:00	163.8	117.88	11/17/99 22:00	240.6	119.50
11/1/99 22:00	163.7	118.25	11/17/99 23:00	214.8	119.65
11/1/99 23:00	163.6	118.47	11/18/99 0:00	211.9	119.63
11/2/99 0:00	158.2	118.60	11/18/99 1:00	210.9	119.54
11/2/99 1:00	157	118.65	11/18/99 2:00	210.5	119.50
11/2/99 2:00	156.3	118.67	11/18/99 3:00	212.8	119.47
11/2/99 3:00	156.7	118.65	11/18/99 4:00	214.3	119.50
11/2/99 4:00	159.6	118.66	11/18/99 5:00	190.8	119.45
11/2/99 5:00	92.9	118.67	11/18/99 6:00	154.2	119.38
11/2/99 6:00	41.8	118.44	11/18/99 7:00	41.3	119.16
11/2/99 7:00	43.2	118.00	11/18/99 8:00	37.9	118.60
11/2/99 8:00	54.5	117.60	11/18/99 9:00	58.6	118.01
11/2/99 9:00	54.4	117.25	11/18/99 10:00	64.2	117.56
11/2/99 10:00	54.5	117.04	11/18/99 11:00	63.4	117.30
11/2/99 11:00	54.6	116.91	11/18/99 12:00	63.1	117.14
11/2/99 12:00	54.6	116.83	11/18/99 13:00	63.5	117.04
11/2/99 13:00	53.7	116.78	11/18/99 14:00	63.8	116.98
11/2/99 14:00	53.8	116.74	11/18/99 15:00	64.1	116.95
11/2/99 15:00	57.2	116.72	11/18/99 16:00	64	116.95
11/2/99 16:00	53.6	116.70	11/18/99 17:00	68.6	116.95
11/2/99 17:00	52.8	116.68	11/18/99 18:00	170.8	116.94
11/2/99 18:00	101.5	116.67	11/18/99 19:00	181.7	117.27
11/2/99 19:00	161.6	116.72	11/18/99 20:00	181.8	117.95
11/2/99 20:00	167.5	117.22	11/18/99 21:00	181.4	118.42
11/2/99 21:00	158.3	117.84	11/18/99 22:00	181.3	118.69
11/2/99 22:00	102.1	118.22	11/18/99 23:00	178.7	118.84
11/2/99 23:00	86.5	118.19	11/3/99 1:00	103.1	117.69
11/3/99 0:00	57.9	117.98	11/3/99 2:00	94.8	117.55

Notes:

* Priest Rapids Dam discharege in thousand of cubic feet per second

^ Columbia River stage at 100D (NAVD 88, meters) from Bechtel, Hanford, Inc.

Appendix C: Water Quality Data

Piezometer Number*	Piezo ID*	Easting^	Northing^	Depth` (m)
1	8L 2.0 3.8	571798.0	150630.0	1.2
2	7L 2.0 4.1	572183.0	151140.2	1.2
3	7L 2.0 4.85	572183.0	151140.2	1.5
4	18M 0.25 3.6	572183.0	151140.2	1.1
5	17M 0.25 3.6	572293.7	151279.4	1.1
6	16M 0.25 1.5	572414.4	151409.8	0.5
7	4N 1.25 0.7	572443.3	151444.4	0.2
8	3N 1.25 2.17	572481.9	151501.6	0.7
10	15M 0.25 3.0	572529.7	151540.0	0.9
11	2N 1.25 1.84	572541.2	151557.1	0.6
12	14M 0.25 4.6	572583.2	151603.0	1.4
13	14M 0.25 3.3	572583.2	151603.0	1.0
14	1N 1.25 2.24	572595.5	151627.6	0.7
15	13M 0.25 6.0	572636.7	151687.8	1.8
16	13M 0.25 3.0	572636.7	151687.8	0.9
17	6L 2.0 4.0	572645.0	151689.0	1.2
18	6L 2.0 6.6	572658.0	151693.5	2.0
19	12M 0.25 6.0	572716.3	151730.8	1.8
20	12M 0.25 3.3	572716.3	151730.8	1.0
21	11M 0.25 2.6	572832.0	151837.6	0.8
22	10M 0.25 5.0	572931.8	151999.7	1.5
23	5L 2.0 6.15	572965.5	152034.0	1.9
24	5L 2.0 4.42	572965.5	152034.0	1.3
25	9M 0.25 6.3	573056.4	152108.3	1.9
26	4L 2.0 5.2	573204.8	152214.0	1.6
27	4L 2.0 4.4	573204.8	152214.0	1.3
28	8M 0.25 6.0	573205.2	152215.8	1.8
29	8M 0.25 2.0	573205.2	152215.8	0.6
30	9L 2.0 4.4	573277.5	152507.5	1.3
31	7M 0.25 6.0	573331.3	152291.0	1.8
32	7M 0.25 2.0	573331.3	152291.0	0.6
33	6M 0.25 2.4	573459.1	152370.0	0.7
34	3L 2.0 6.4	573606.0	152497.5	2.0
35	3L 2.0 4.5	573606.0	152497.5	1.4
36	5M 0.25 3.0	573663.9	152547.2	0.9
37	4M 0.25 2.2	573722.6	152584.7	0.7
38	3M 0.25 2.7	573771.9	152638.9	0.8
39	2L 2.0 5.15	573834.0	152768.0	1.6
40	2L 2.0 4.13	573834.0	152768.0	1.3
41	2M 0.25 1.2	573876.6	152837.0	0.4
42	1M 0.25 2.5	573915.7	152960.4	0.8
43	1L 2.0 4.3	573946.9	153095.8	1.3

Notes:

* Original piezometer label was replaced with piezometer number to simplify text and figures. The number is ordered by easting, or meters downstream along the 100D shoreline. Use this appendix to cross reference with the original piezometer labels in appendix D and appendix E.. ^ Coordinate system and datum are NAD 83, State Plane Meters, WA south. ` Depth is to the top of piezometer screen.

		Ec* (ms/cm)		Temperature* (c)		Piezo DO		River DO		Cr(VI) (mg/L)
						mg/L	%	mg/L	%	
N	Date/time	P	R	P	R					
1	11/17/99 13:15	128.2	116.4	13.2	12.0	8.5	81.6			0.006
2	11/17/99 13:30	216.1	116.2	13.1	12.1	9.0				0.027
3	11/17/99 13:00	206.5	116.2	13.1	12.1		88.9			0.027
4	10/27/99 16:00	229.0	125.0	11.8	13.3					0.026
5	10/27/99 15:00	334.2	125.8	12.4	13.4					0.019
6	10/26/99 15:00	327.3	121.9	13.0	13.7					0.119
7	11/18/99 15:45	144.9	107.9	12.4	11.4	9.2	85.7			0.012
8	11/18/99 15:00	278.3	107.1	12.7	12.3	9.1	84.0			0.146
10	11/10/99 11:45									0.382
11	11/18/99 13:30	201.6	106.7	12.7	11.4	6.5	60.7			0.041
12	11/10/99 11:30									0.104
13	11/10/99 11:35									0.752
14	11/18/99 12:30	342.3	106.4	13.3	11.8	9.0	84.4			0.242
15	11/10/99 10:45									0.067
16	11/10/99 11:10									0.122
17	11/15/99 15:30	246.4	121.5	12.9	12.6					0.104
18	11/14/99 15:30	234.5	119.3	13.1	12.6					0.093
19	11/10/99 11:00									0.268
20	11/10/99 11:15									0.126
21	10/26/99 14:00	254.6	120.1	14.1	13.8					0.012
22	10/26/99 13:00	130.0	125.2	14.2	14.2					0.014
23	11/14/99 12:30	141.9	120.0	13.7	12.6					0.005
24	11/14/99 12:35	129.5	120.0	13.4	12.6					0.059
25	10/25/99 16:00	215.0	121.0	15.0	14.0					0.004
26										
27	11/13/99 16:00	195.0	119.2	13.5	12.8					0.003
28	10/18/99 17:30	225.6		16.3						0.022
29	10/18/99 17:00	249.7		18.8						0.012
30	11/18/99 13:30	142.2	106.4	13.0	11.3	0.9	8.7	10.5	95.9	0.004
31	10/18/99 16:30									
32	10/18/99 16:00	185.9		19.9						0.019
33	10/25/99 15:00	156.0	120.1	14.1	14.0					0.010
34	11/13/99 12:00	150.3	118.7	13.3	12.5	7.5		9.8		0.016

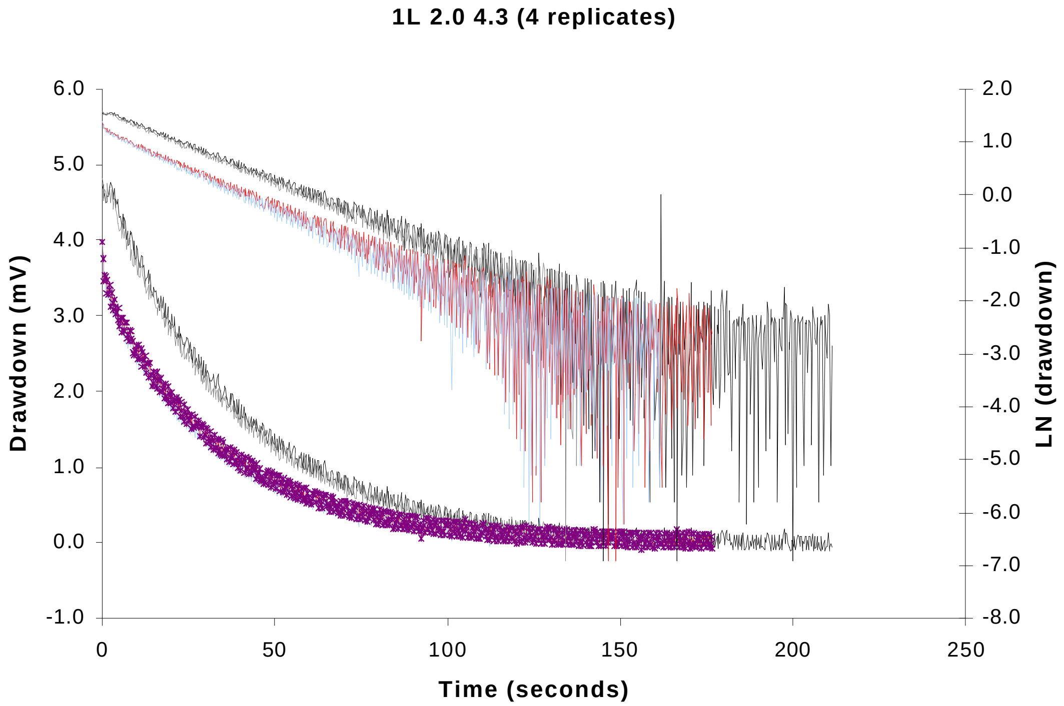
35	11/13/99 11:30	140.6	118.7	12.9	12.5	7.6		9.8	0.015
36	10/18/99 15:00	152.5		18.1					0.022
37	10/18/99 14:00	186.2		16.9					0.016
38	10/18/99 13:00	170.0		17.4					0.016
39	11/12/99 16:00	120.3	119.0	12.6	12.5	1.3			0.009
40	11/12/99 14:30	185.7	119.0	13.1	12.5	2.3			0.014
41	10/25/99 14:00	166.0	119.6	13.9	14.0				0.001
42	10/25/99 13:00	175.3	119.7	14.3	14.0				0.008
43	11/11/99 13:34	122.1	118.4	13.2	12.1		81.9		0.001

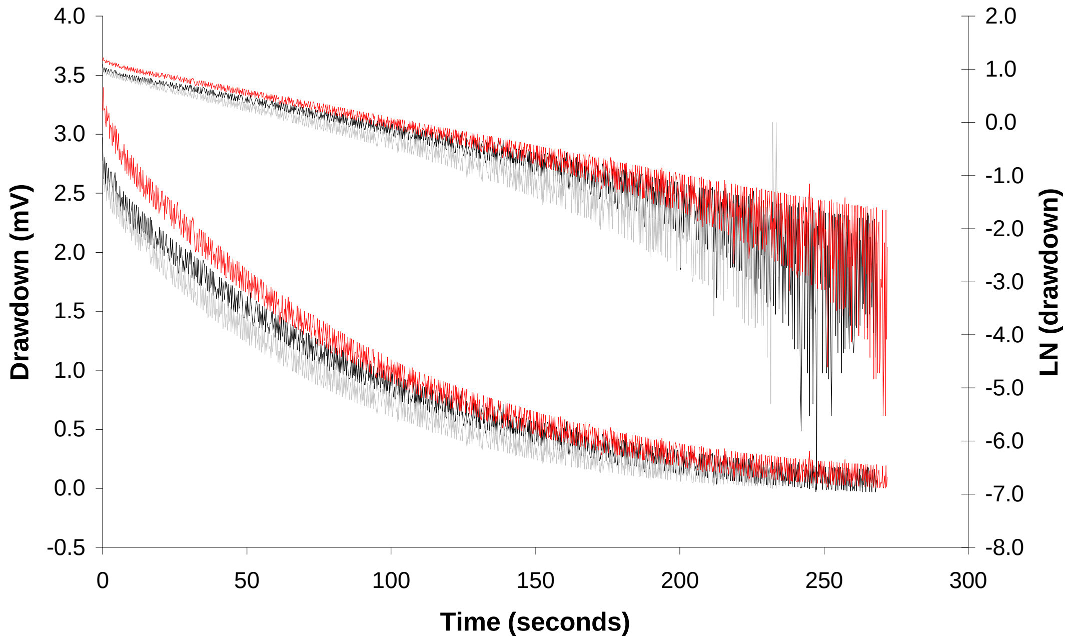
Notes:

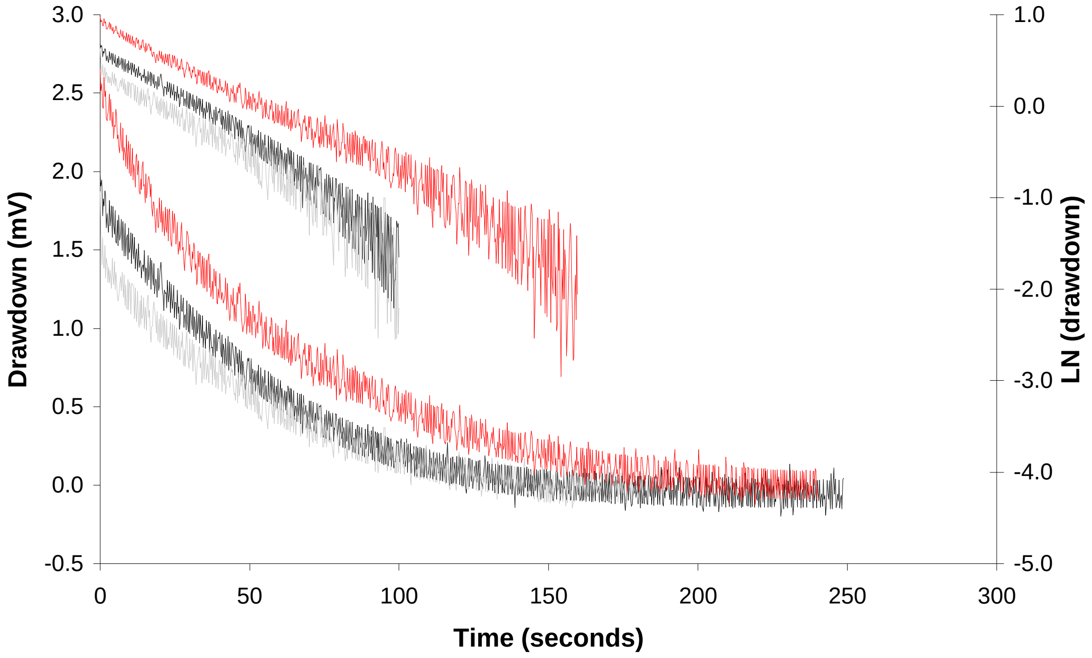
* P=measurement collected from a piezometer; R=measurement from the river contiguous to the piezometer

Appendix D: Slug test data

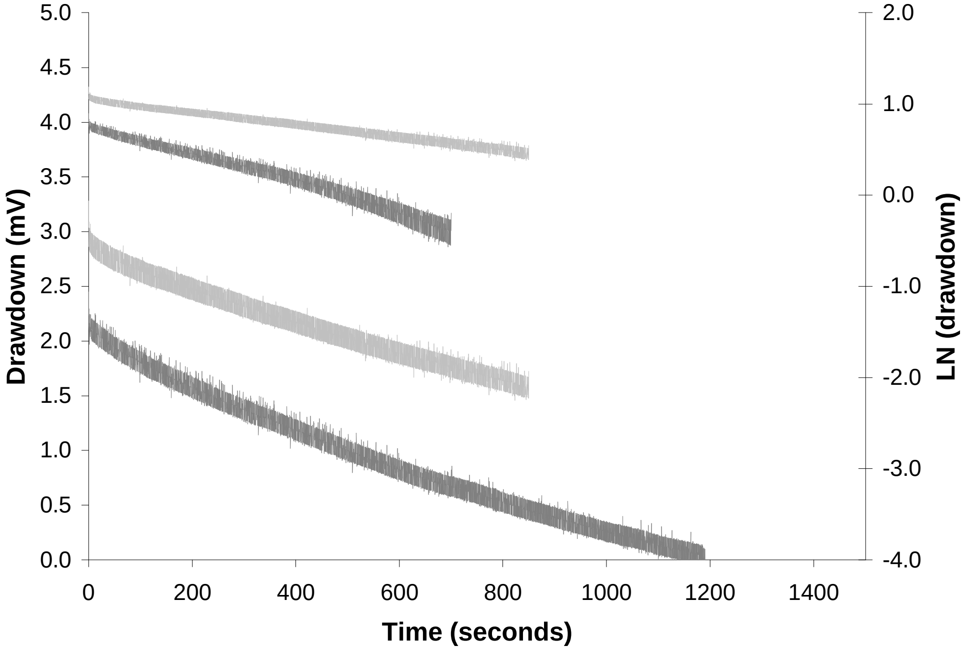
Charts show drawdown data (units are millivolts recorded by the pressure transducer and correlate directly with pressure) and the natural logarithm of drawdown. Curved lines represent drawdown, and resemble exponential decay functions. Straight lines represent the natural logarithm of drawdown. The slope of the straight segments was used to calculate hydraulic conductivity using the Bouwer and Rice and Hvorslev methods.



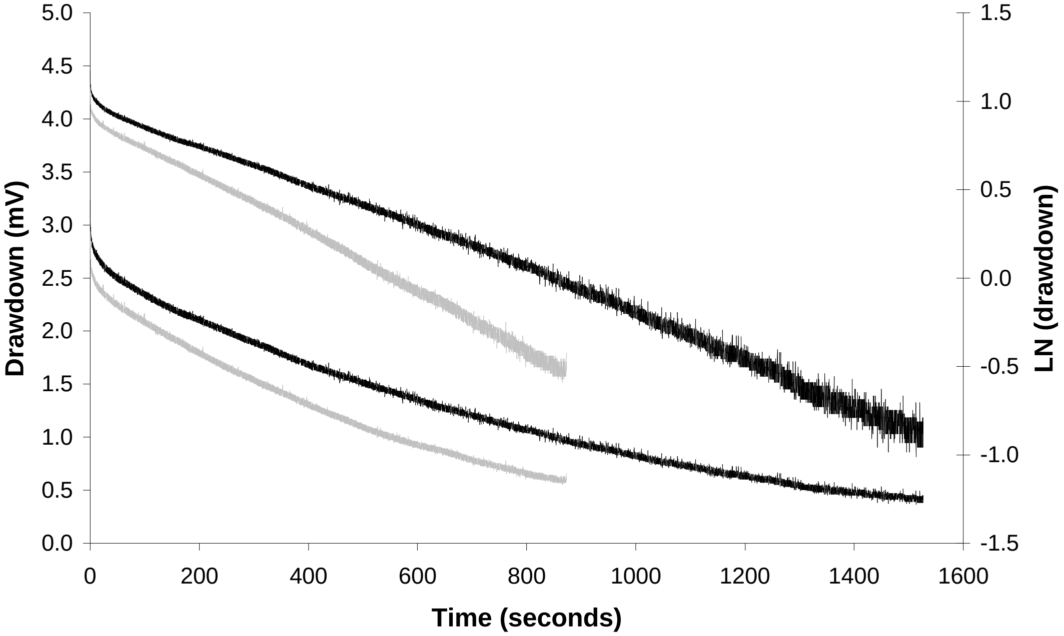

2L 2.0 4.13 (3 replicates)

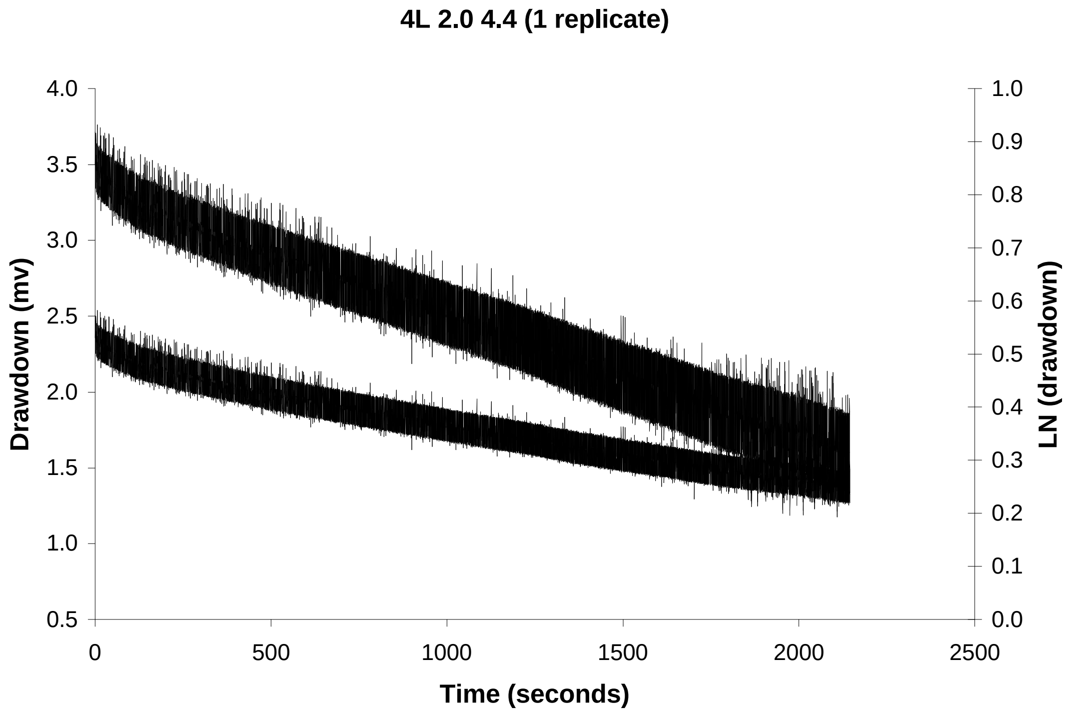

2L 2.0 5.15 (3 replicates)

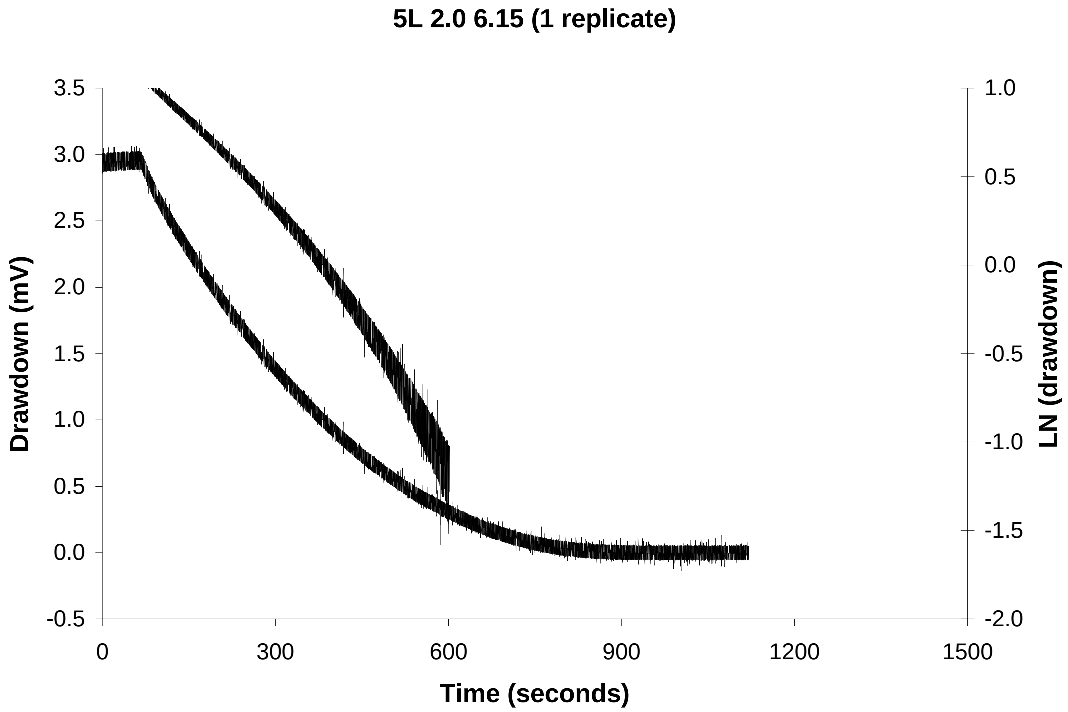
3L 2.0 4.5 (2 replicates)

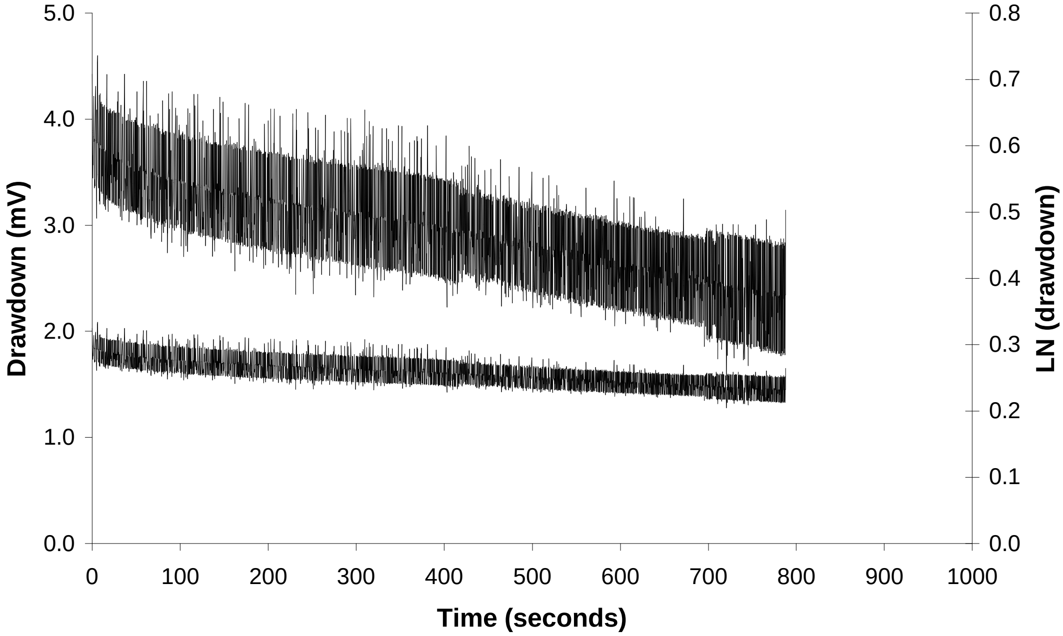


3L 2.0 6.4 (2 replicates)

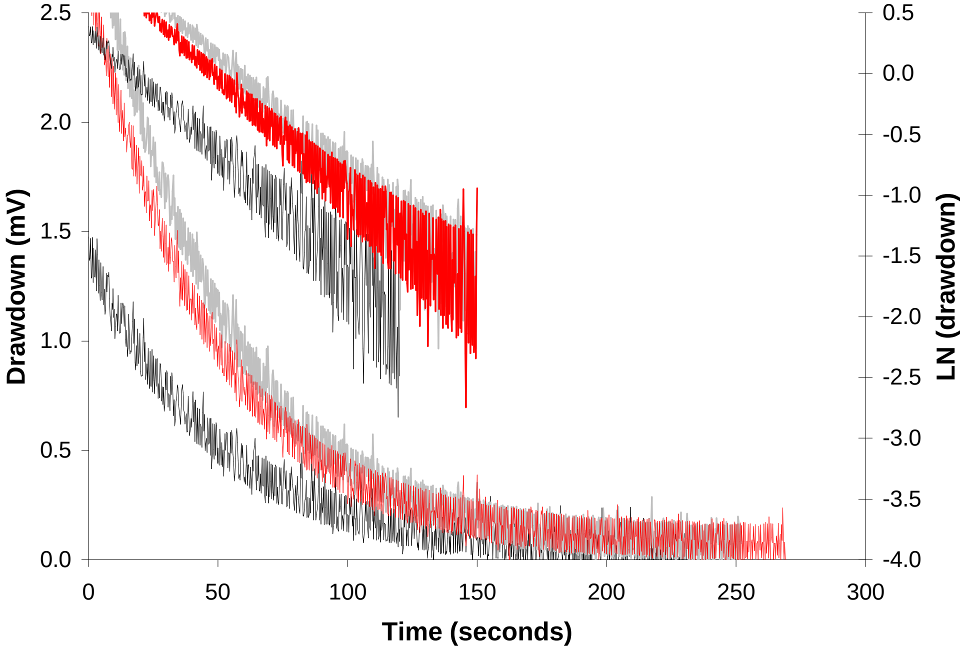



4L 2.0 4.4 (1 replicate)

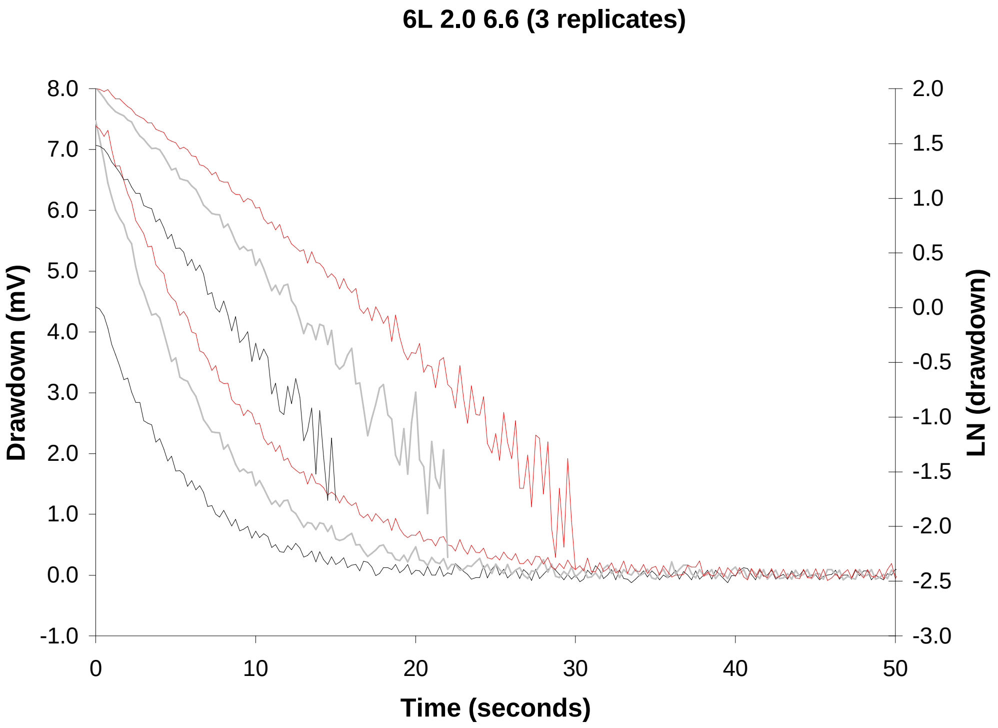

5L 2.0 6.15 (1 replicate)

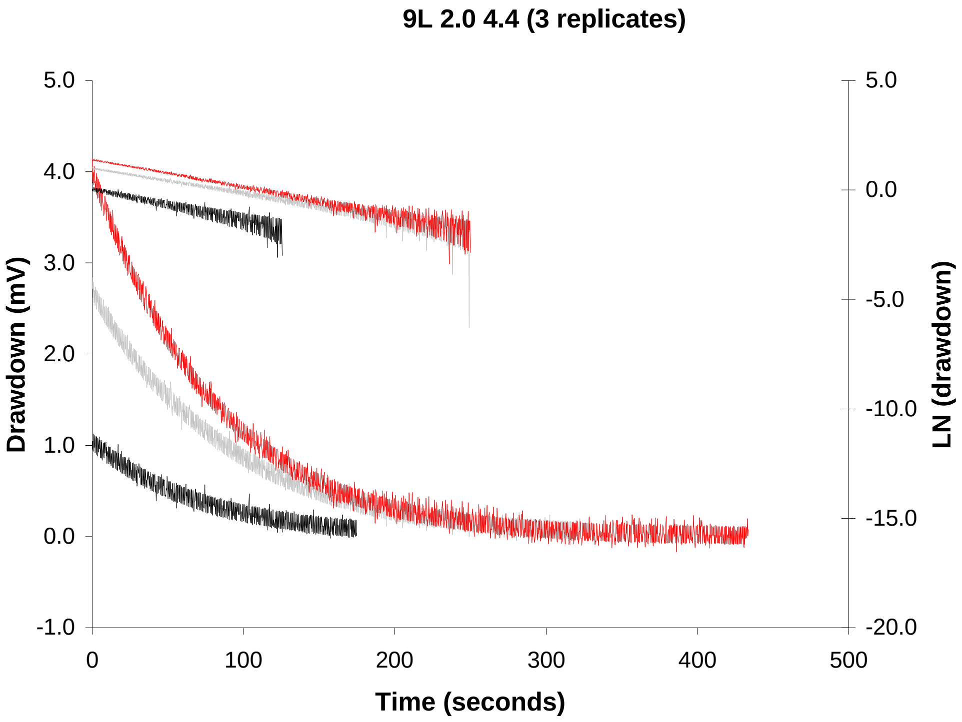


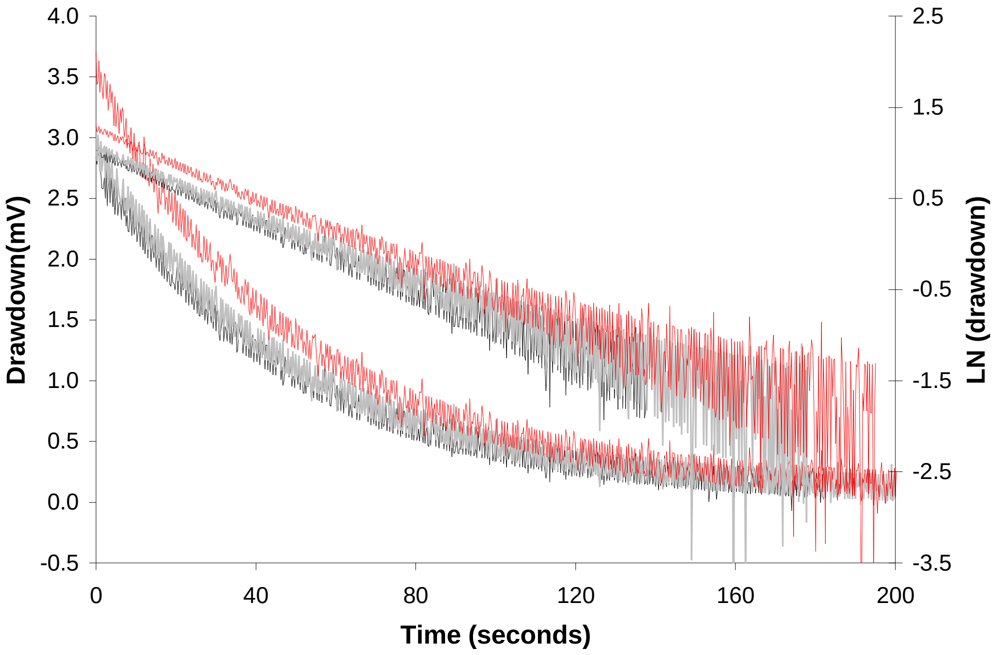
5L 2.0 4.42 (1 replicate)



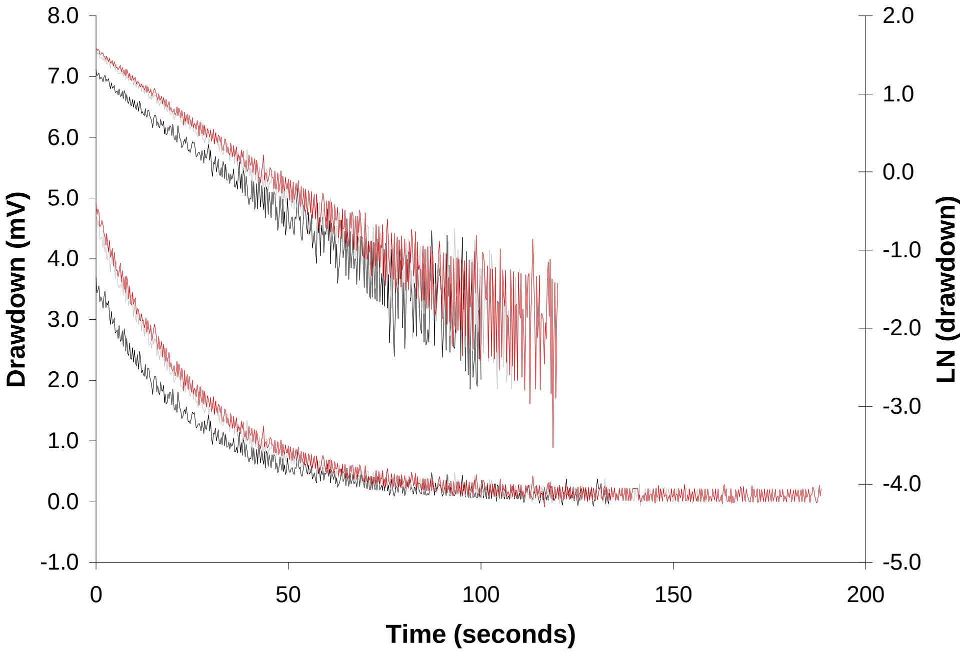
6L 2.0 4.0 (3 replicates)


6L 2.0 6.6 (3 replicates)

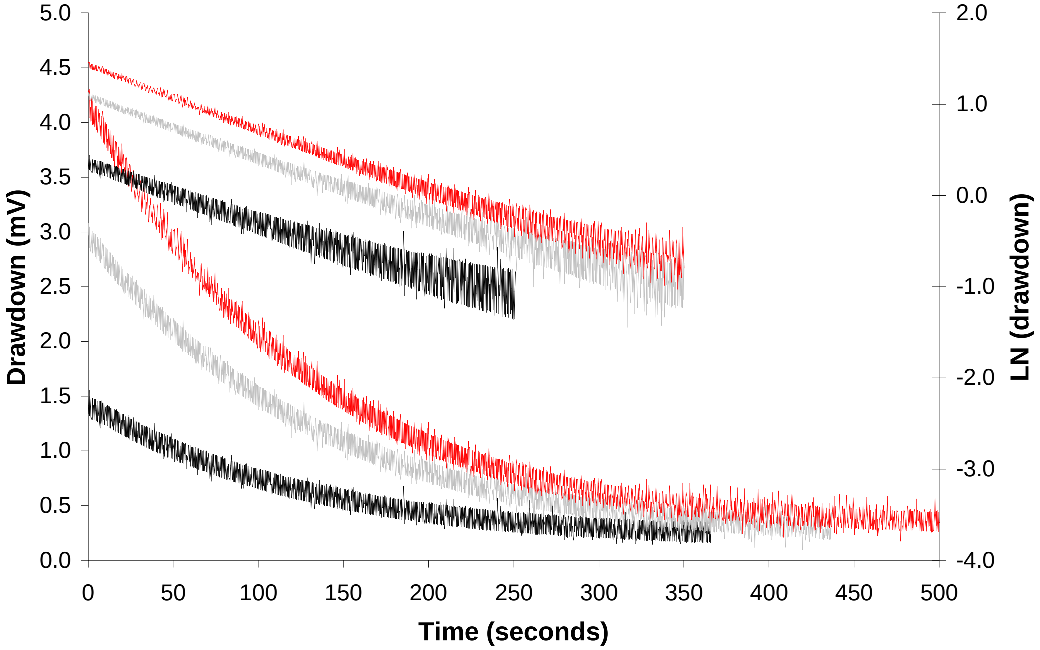

9L 2.0 4.4 (3 replicates)



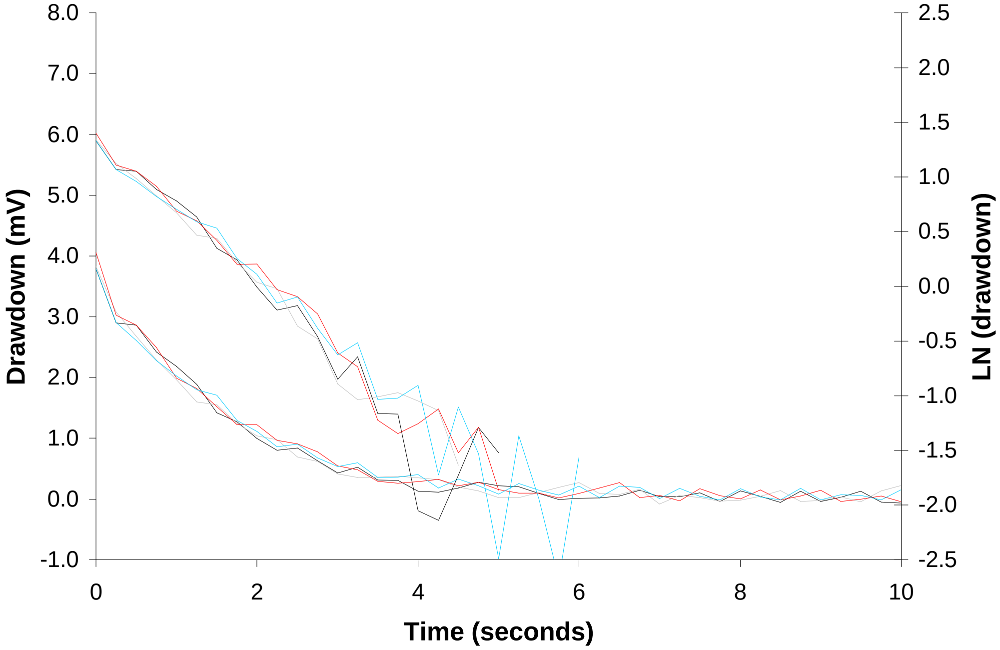
7L 2.0 4.85 (3 replicates)



7L 2.0 4.1 (3 replicates)

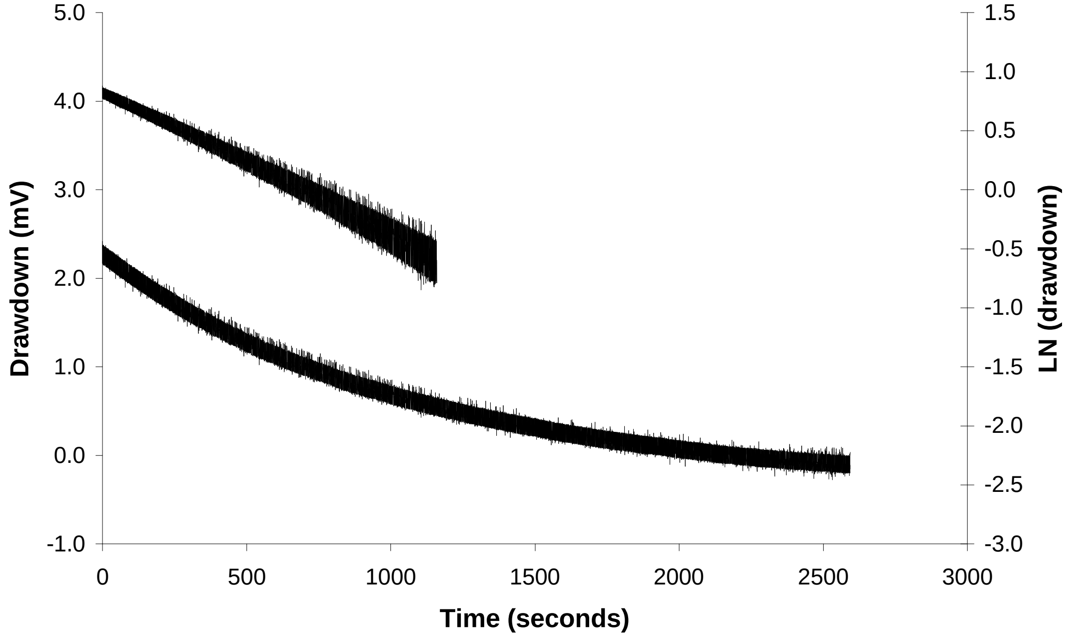


8L 2.0 3.8 (3 replicates)

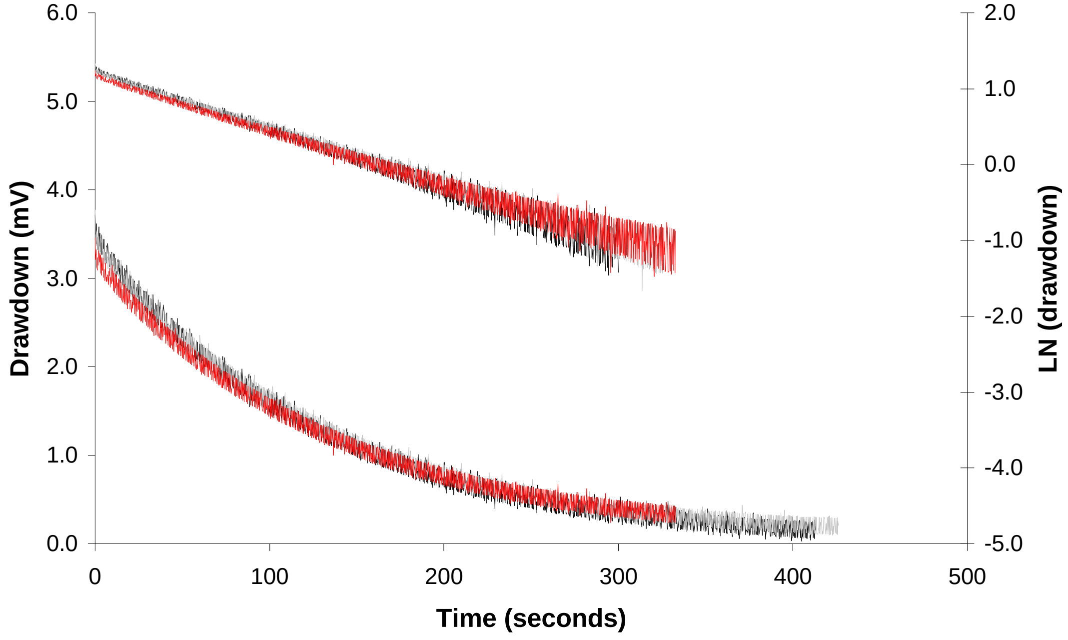


1N 1.25 2.24 (4 replicates)

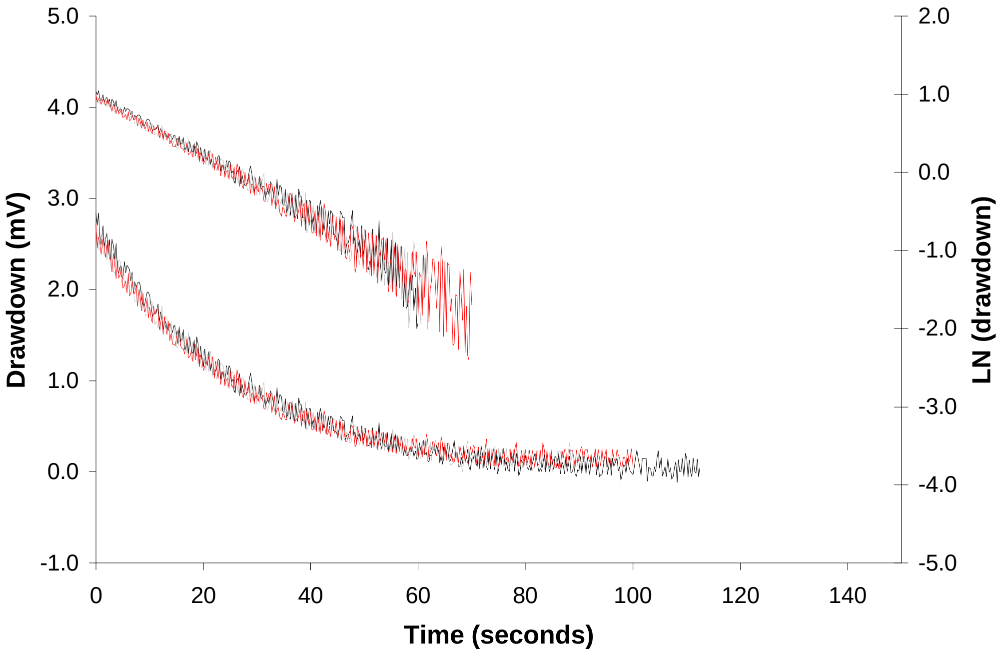
2N 1.25 1.84 (1 replicate)



3N 1.25 2.17 (3 replicates)

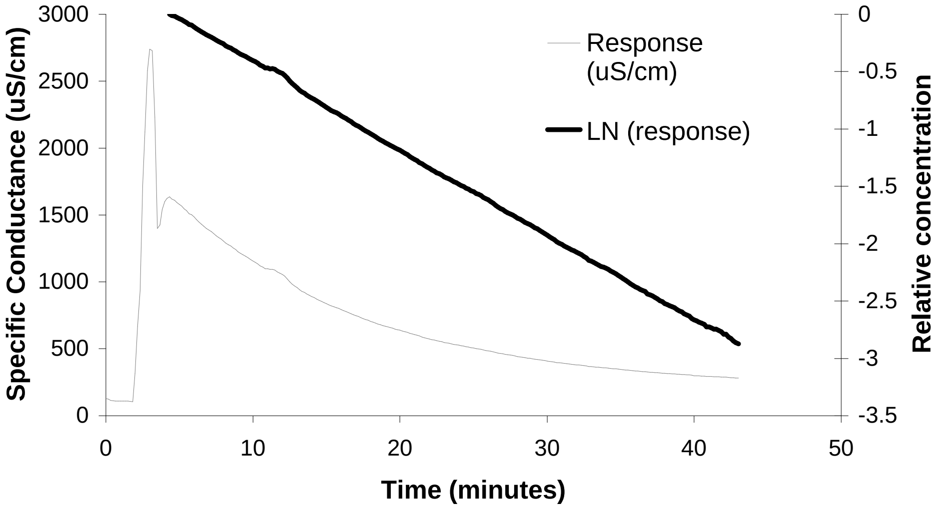


4N 1.25 0.7 (3 replicates)

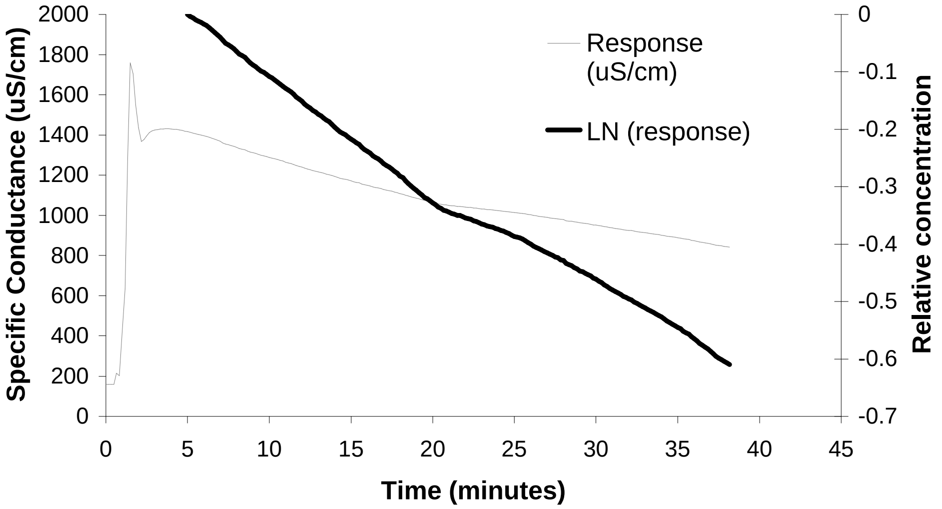


Appendix E: Borehole dilution data

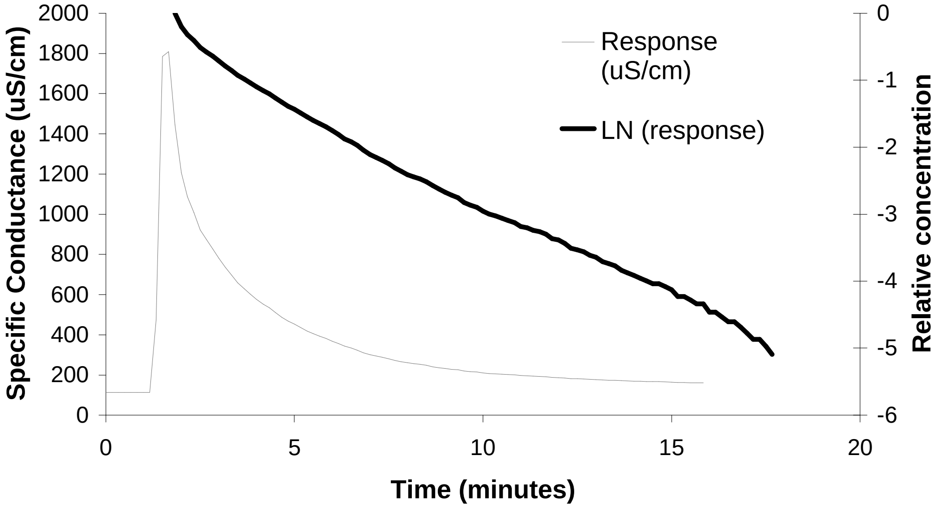
1L 2.0 4.3



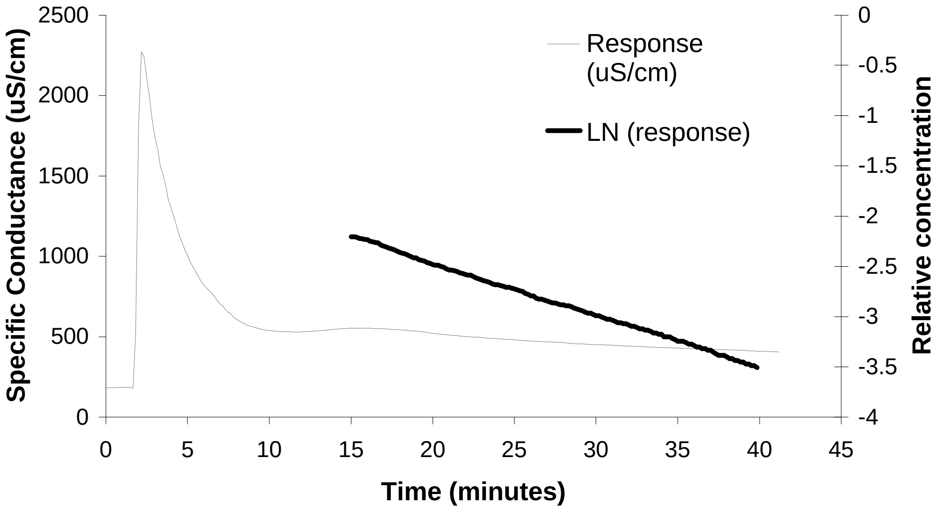
2L 2.0 4.13

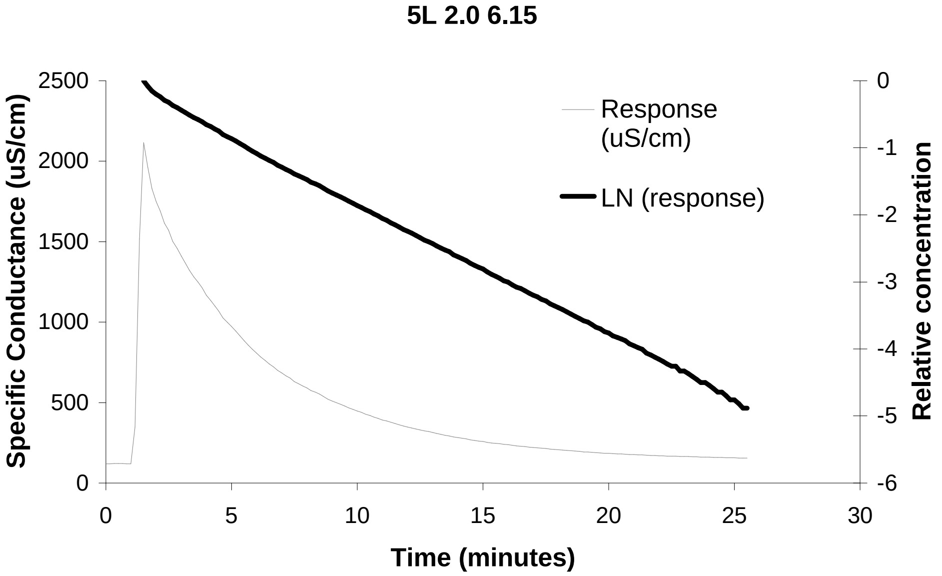


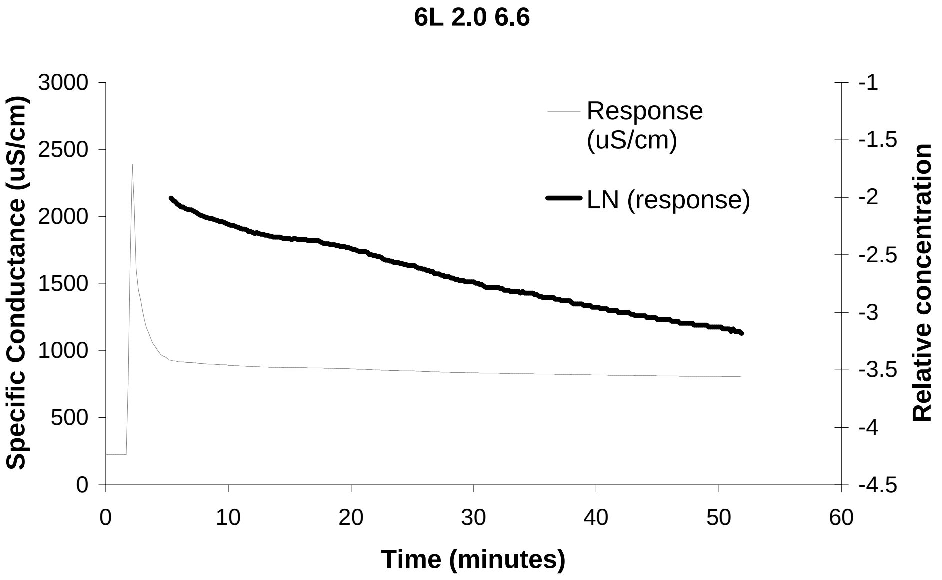
3L 2.0 4.5



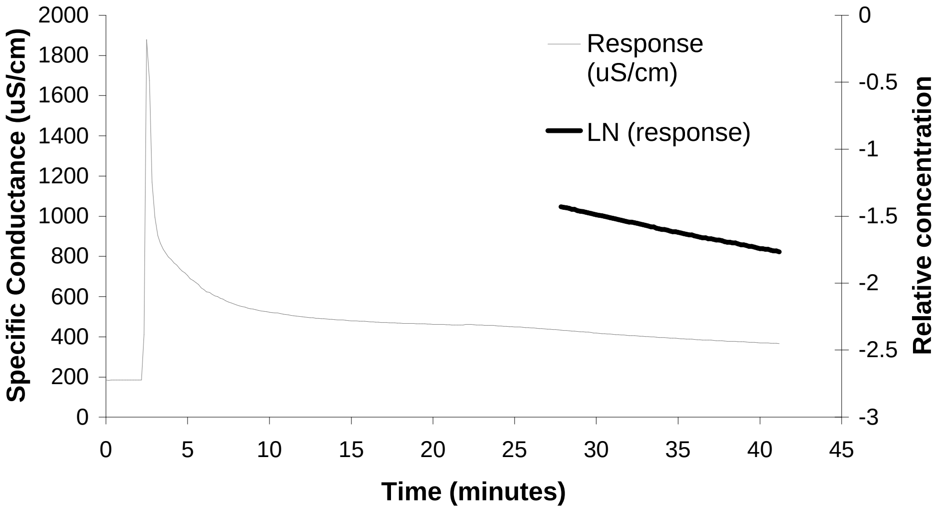
4L 2.0 4.4



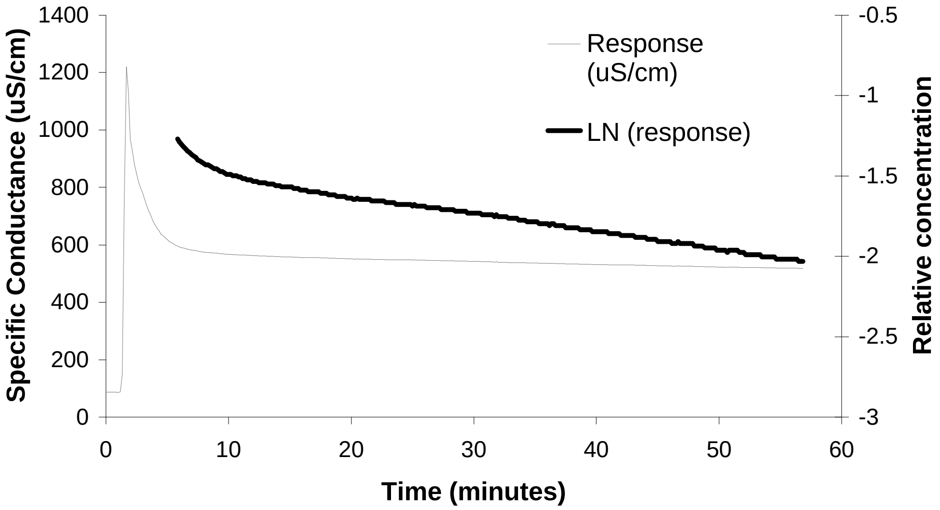

5L 2.0 6.15
Specific Conductance (uS/cm)
Relative concentration
Time (minutes)
Response (uS/cm)
LN (response)
2500
2000
1500
1000
500
0
-1
-2
-3
-4
-5
-6
0
5
10
15
20
25
30

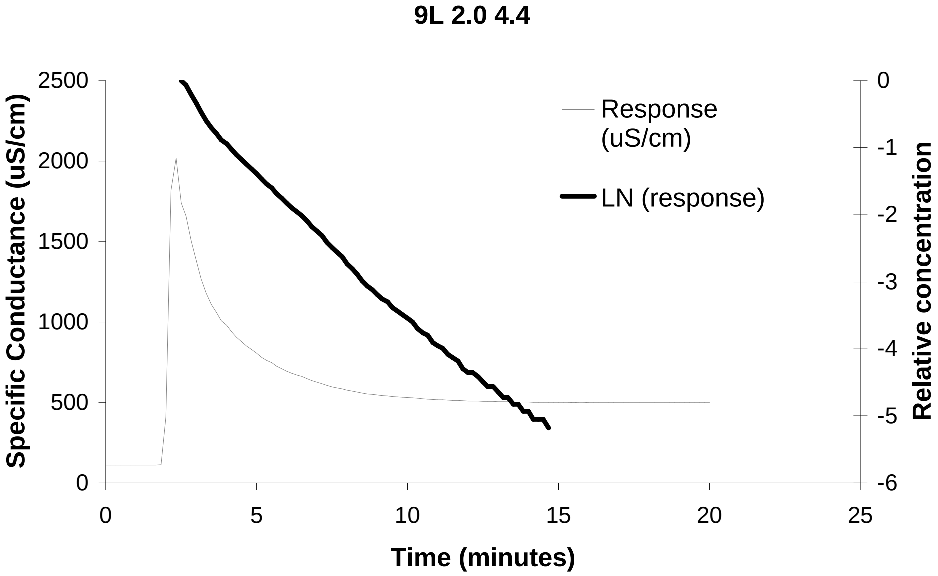

6L 2.0 6.6
Specific Conductance (uS/cm)
Relative concentration
Time (minutes)
Response (uS/cm)
LN (response)
3000
2500
2000
1500
1000
500
0
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
0
10
20
30
40
50
60

7L 2.0 4.1



8L 2.0 3.8





9L 2.0 4.4
Specific Conductance (uS/cm)
2500
2000
1500
1000
500
0
Response (uS/cm)
LN (response)
0
-1
-2
-3
-4
-5
-6
Relative concentration
0
5
10
15
20
25
Time (minutes)