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Methods for Assessing the Relative Amounts of Groundwater Discharge into the Columbia River and Measurement of Columbia River Gradient at the Hanford Site's 300 Area

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September 2008

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1.0 Introduction

At the Hanford Site in southeastern Washington State, contaminated groundwater discharges to portions the Columbia River after passing through a zone of groundwater/river water interaction at the shoreline (i.e., the hyporheic zone). In the hyporheic zone, river water may infiltrate the riverbank during periods of high-river stage and mix with the approaching groundwater. Contaminants carried by groundwater are diluted by the infiltrating river water, thus reducing concentrations at locations of exposure such as riverbank springs and upwelling through the riverbed. There have been limited studies of contaminant concentrations, physical properties, or the extent of the hyporheic zone near the Hanford Site's 300 Area, yet this zone is the interface for discharge of groundwater contamination into the Columbia River.

The Remediation Science and Technology Project conducts research that meets several objectives concerning the discharge of groundwater contamination (primarily uranium) into the river at the 300 Area of the Hanford Site in Washington State. This report summarizes some of the activities conducted during fiscal year 2008.

The discharge of natural and contaminated groundwater into the Columbia River occurs at various locations along the Hanford Reach (e.g., Fritz et al 2007, Geist 2000, Patton et al 2003, Peterson et al 2008). Groundwater discharge has been observed as riverbank springs and as seepage through the river bed. Several reports have identified a geologic layer that limits the vertical distribution of uranium in the 300 Area (Fritz et al 2007, Williams et al 2007). In previous work, the surface of this assumed confining layer was juxtaposed onto the Columbia River bathymetry to estimate the portion of the riverbed with the potential for uranium discharge to occur (Figure 1). This area is referred to as the contributing area. While the contributing area has the potential for contaminant discharge, there is no physical data available to determine the relative amount of discharge into the river at different locations within the contributing area.

In 2007 and 2008 we conducted two studies to develop methods for evaluating the relative groundwater discharge at different locations, and a third study to help in future uranium discharge modeling efforts. The first study used specific conductance and temperature monitoring probes buried in an array along the river bed to qualitatively differentiate the spatial and temporal distribution of groundwater discharge. The second study developed and applied a slug testing method to small diameter aquifer tubes to determine the hydraulic conductivity of the formation under the river at multiple locations. The slug testing method is similar to methods applied in piezometers, but has never been evaluated for use on aquifer tubes. Given the large number of aquifer tubes installed along the Hanford Reach, a viable slug test method has the potential to identify locations with a high likelihood of groundwater discharge (e.g., high hydraulic conductivity). A third study conducted in 2008 measured Columbia River gradient in the vicinity of the 300 Area. The determination of river gradient provides a means to estimate river stage at varying points along the shoreline. This is necessary for groundwater flow models developed for the 300 Area since river stage fluctuations control groundwater movement in the 300 Area.

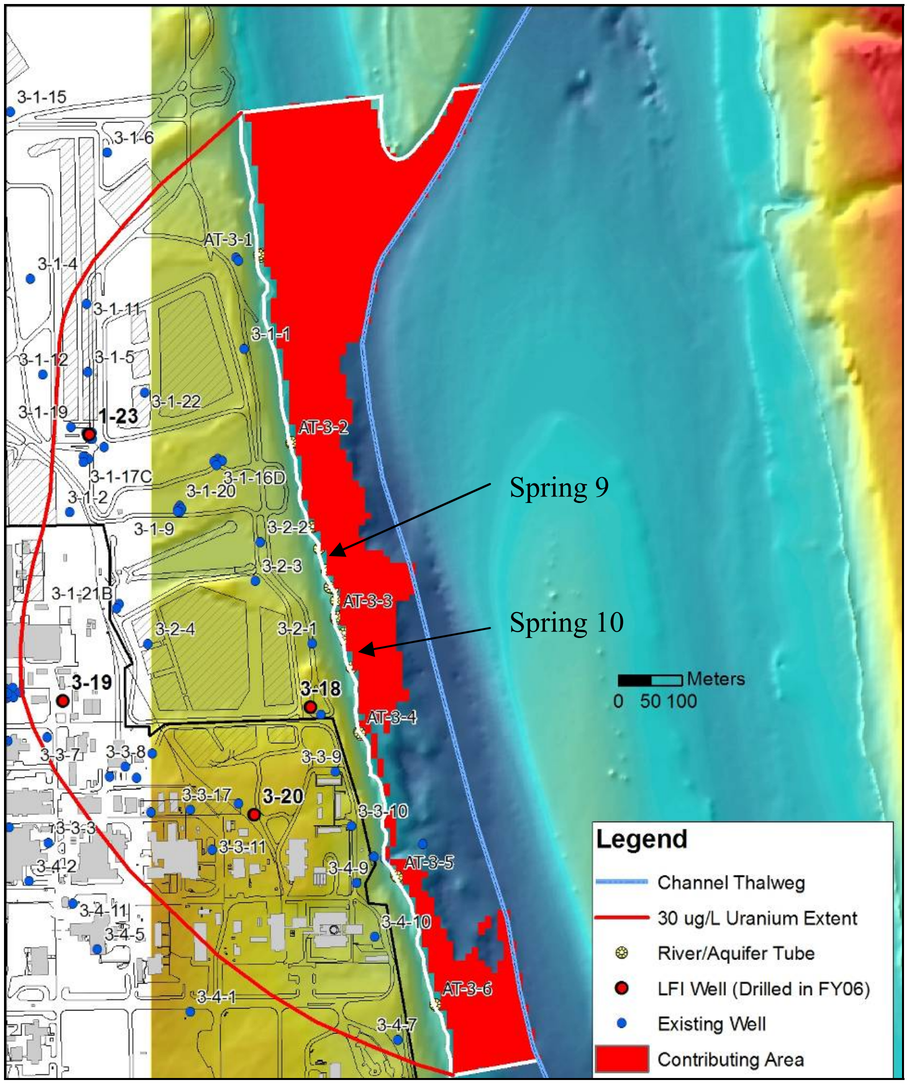

Figure 1. Map of Riverbed Area with the Potential to Discharge Uranium into the Columbia River. This area is between 105 m in elevation and the river thalweg, between the 30 μg/L uranium concentration contour lines onshore, and above the projected Ringold Formation. From PNNL-16805.

2.0 Specific Conductance Array

Two arrays of specific conductance probes were deployed in the 300 Area, in the general vicinity of Spring 9 (Figure 1). The probes were Solinst LTC leveloggers (Solinst Canada, Georgetown, Ontario), which measure pressure (± 0.5 cm water), temperature (± 0.1 ºC), and specific conductance (± 5 μSm/cm). Approximately 30 cm of steel chain was attached to the top of each probe. These chain leaders were then clipped onto a longer chain laid perpendicular to the shore. The specifics of the array locations and distances are summarized below (Table 1). The probes were buried under the active riverbed surface by scraping a 10 cm deep trench. The probes were placed into the trenches and the excavated material was replaced over the top of the probes. In this manner the probes provided a measurement of the conditions in the shallow river bed substrate, and were not in direct hydraulic contact with surface water. Measurements of pressure, temperature, and specific conductance were recorded every 15 minutes between November 14, 2007 and March 24, 2008. In addition to the buried specific conductance probes, hydraulic gradient was also determined by measuring sub-surface head in a piezometer (Fritz and Arntzen 2007), and a specific conductance 'walking-stick survey' was performed on February 25, 2008. This survey used a specific conductance probe tethered to a walking staff, and integrated with a differential GPS to give measurements of specific conductance at points just above the riverbed surface. Similar methods have previously been used on the Hanford Site to assist identification of areas of groundwater discharge (Lee et al. 1997; Poston et al. 2005; and DOE/RL-2005-22).

Table 1. Probe Locations and Elevations for Specific Conductance Arrays. Coordinates in State Plane, Washington South. Elevation in meters above mean sea level.

Location	Easting (m)	Northing (m)	Elevation (m)	Distance from location 1 (m)
Spring 9- 1	594491.7	116209.7	105.2	-
Spring 9- 2	594493.0	116209.9	104.8	1.3
Spring 9- 3	594497.9	116210.9	104.2	6.3
Spring 9- 4	594505.2	116212.2	103.8	13.8
Spring 9- 5	594513.0	116214.0	103.6	21.8
Spring 10- 1	594522.1	116091.7	105.7	-
Spring 10- 2	594527.0	116095.3	104.9	6.1
Spring 10- 3	594533.9	116096.1	104.1	13.0
Spring 10- 4	594541.1	116096.8	103.6	20.3

The results of this study indicated that more groundwater discharge occurred near the edge of the river than farther out in the river. For example, the probe at Spring 9 location 3 consistently had the highest measured specific conductance (Figure 2). However, early in the study the specific conductance was higher at location 2. This time period coincided with Columbia River reverse discharge cycling, which results in higher average river elevation than during the rest of the winter. Based on these results, it would seem that during periods of higher river stage, more groundwater discharge occurred higher up the shore, but as the average river stage (and near shore water table) lowered throughout the winter, the point of maximum groundwater discharge moved farther out into the river. Unfortunately, the probe at location 4 failed partway through the test, so the size of the apparent maximum groundwater discharge area is difficult to estimate. A similar pattern was observed at the Spring 10 transect, with maximum discharge occurring at location 3 (Figure 3).

There are some basic observations that can be made about the results of this study. For example, it is apparent that during rapid cycling of river stage, recharge water may not have time to mix with groundwater before being discharged to the river, resulting in discharge of water with little or no groundwater signature. In figures 2B, 2C, 3B and 3C, there are periods of positive hydraulic gradient (groundwater discharge), but the specific conductance measured at the river bed is not indicative of groundwater discharge. Only after a sustained period of positive hydraulic gradient does water with a higher specific conductance begin to discharge to the river. Another observation is that at both transects, location 2 seemed to behave differently than the other locations. This may be because location 2 (for both transects) was at an elevation that was not inundated all the time. This may result in different hydraulic behavior relative to the other locations farther out in the river.

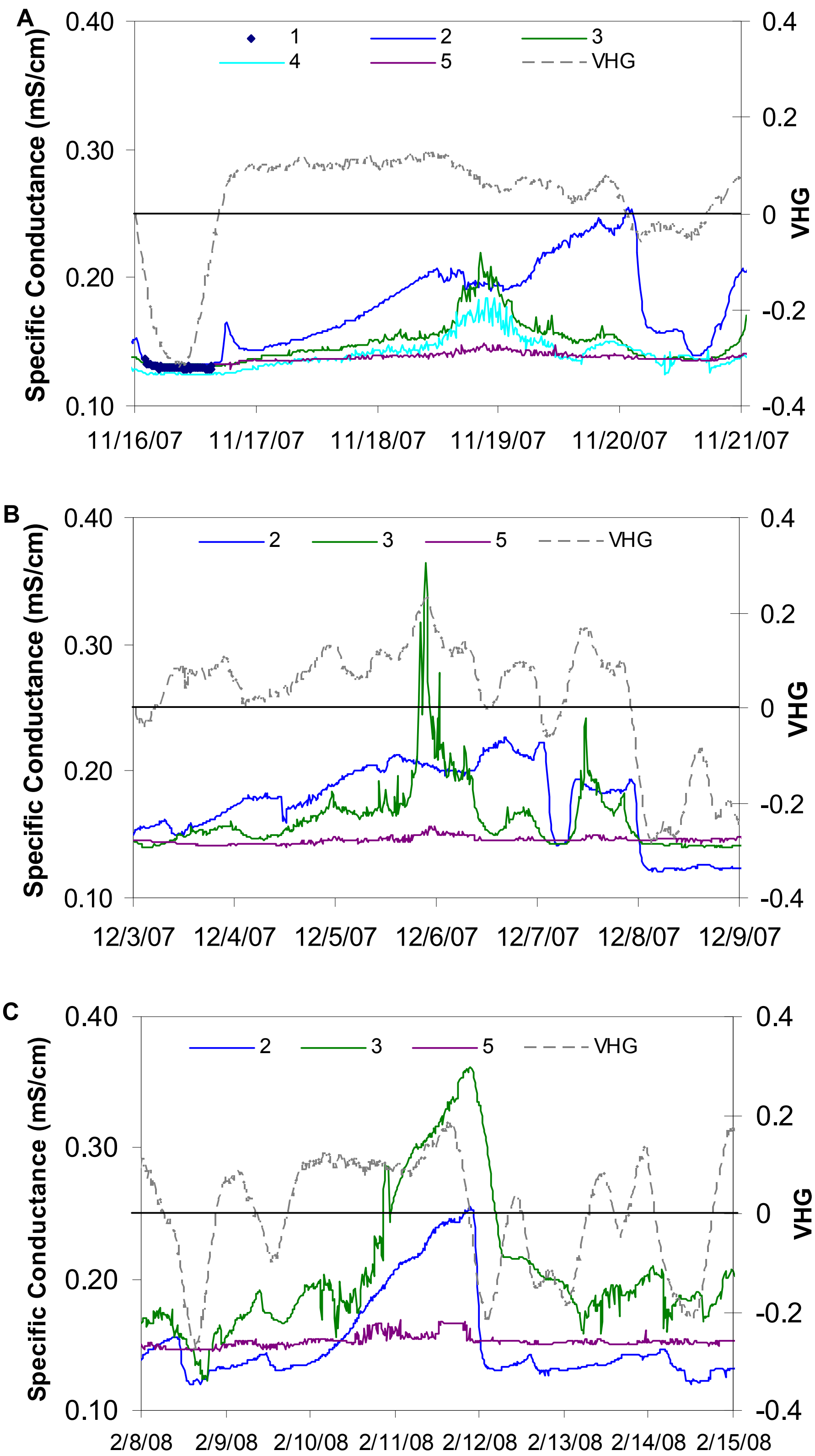

Figure 2. Specific Conductance and Vertical Hydraulic Gradients (VHG) Measured at Spring 9 Buried Probe Array, locations 1 through 5

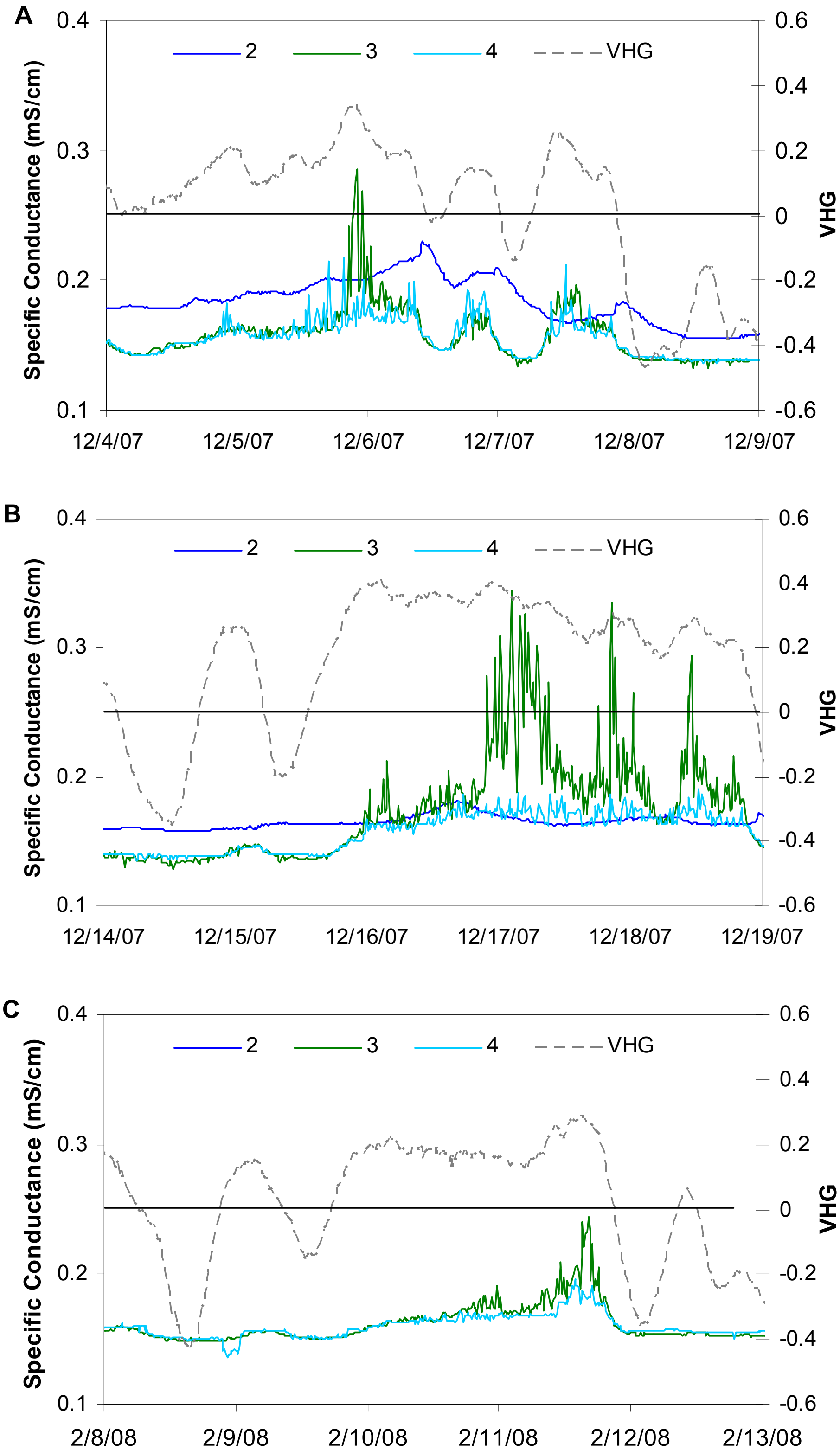

Figure 3. Specific Conductance and Vertical Hydraulic Gradients (VHG) Measured at Spring 10 Buried Probe Array, Locations 2, 3 & 4

The results of the specific conductance walking survey suggest that this method is not a robust method of characterizing areas of groundwater discharge (Table 2). At Spring 10 there was a slightly elevated specific conductance measured by the buried probes, but the walking survey indicated that only river water was present. At Spring 9, the walking survey did show elevated specific conductance at location 2. However, the specific conductance measured by the probe buried at this location was lower than measured by the walking survey. The reason the walking survey was able to measure an elevated specific conductance at Spring 9 is the presence of a small inlet at this location. There was a noticeable amount of actively discharging groundwater on the day of the walking-stick survey due to a recent drop in river level; it is likely that surface and hyporheic discharge was caught and trapped in the slack-water eddy formed by the inlet at Spring 9. At Spring 9 Location 3 (where there was minimal influence from the eddy), there was a strong indication of groundwater discharge measured by the buried probe, yet the walking survey was unable to identify any groundwater discharge at that location.

Table 2. Results of Walking Stick Conductivity Survey and Corresponding Measurements in the Buried Probe Array

Location	Depth	Walking Survey Specific Conductance (μS/cm)	Buried probe Specific Conductance (μS/cm)
Spring 10- 3	bottom	164	180
Spring 10- 4	bottom	165	175
Spring 10- 4	surface	164	*NA*
Spring 9- 2	bottom	309	265
Spring 9- 3	bottom	171	320
Spring 9- 3	surface	170	*NA*

3.0 Aquifer Tube Slug Test

Hydraulic conductivity was measured by conducting pneumatic slug tests in three adjacent aquifer tubes located in a small cluster at Spring 10 (Figure 1). The three aquifer tubes were completed at depths of 100, 200, and 320 cm below the river bed surface, and are hereafter referred to as the shallow, medium, and deep aquifer tubes. Slug tests were conducted in a manner similar to that used in larger diameter piezometers (Fritz and Arntzen 2007; Arntzen et al. 2006; Springer et al. 1999). A pressure sensor (PT2X, Instrumentation NW, Kirkland, WA) was attached to a 'T' fitting on the aquifer tube below the water surface to measure changes in hydraulic head during the slug test at a rate of either 1 or 10 Hz, as necessary (Figure 4). The system was pressurized with compressed air, which depressed the water level in the piezometer. The water was only depressed to a point above the pressure sensor to ensure that initial recovery data was captured. The total head in the line was allowed to equilibrate, and a valve above the water surface was opened and the change in water level was recorded. Based on the results and on past research in similar sedimentary environments, intragravel flow at this location was assumed to be laminar (Vaux 1968). The slug tests were analyzed using the Bouwer and Rice straight-line method (Bouwer and Rice 1976; Bouwer 1989) and the KGS type-curve model of Hyder et al. (1994; Butler 1998). For the solutions, specific storage was assumed to be $3x10^{-6}$ m^{-1} and anisotropy was assumed to be 0.1. Aquifer thickness was assigned as 6 m, but the results were insensitive when aquifer thickness varied between 2 m and 10 m. At each aquifer tube, three or more pneumatic slug tests were performed with varying initial displacements according to the recommendations of Butler (1998). Slug tests within aquifer tubing and screen size of similar dimensions to those installed in the field were also performed in a large lab sink full of water. This provided an infinitely high hydraulic conductivity (K) control case where the only restriction to water level recovery was line friction of the aquifer tube and the small-diameter screen on the end.

The preliminary results from the slug tests in the small-diameter aquifer tubes exhibited responses that were analyzable with established analytical methods. Because of the very small diameter of the tubing and screen used in aquifer tubes, it was expected that there would be some frictional losses, perhaps enough to dominate the formational response – especially in very high-K formations (e.g., Hanford formation). Thus a series of slug tests were conducted in the water-filled lab sink to evaluate this effect. In all cases, slug tests in the lab sink exhibited an initially oscillatory response (critically-damped), recovering to near static conditions within 3 to 4 seconds (Figure 5). This is typical of high-K conditions where the inertial forces of water exceed those offered by the surrounding porous medium (Springer and Gelhar 1991; Butler 1998). Since there is no formational resistance within the water-filled sink, the responses are attributed to the combined inertial forces of the water and the resistive effects of the tubing and screen. In any case, it is conceivable that slug test responses in field settings that are similarly rapid may prove to be difficult or impossible to analyze without taking into account frictional losses of the aquifer tubing and/or screen. In this regard, the lab-sink results serve as a guideline on the appropriateness of quantitative analysis for extremely rapid responses. Slug test responses in aquifer tubes of similar diameter (~ 0.5 cm) and length (1 to 3 meters) that exhibit a recovery to near-static conditions in less than 10 seconds should not be analyzed with this solution.

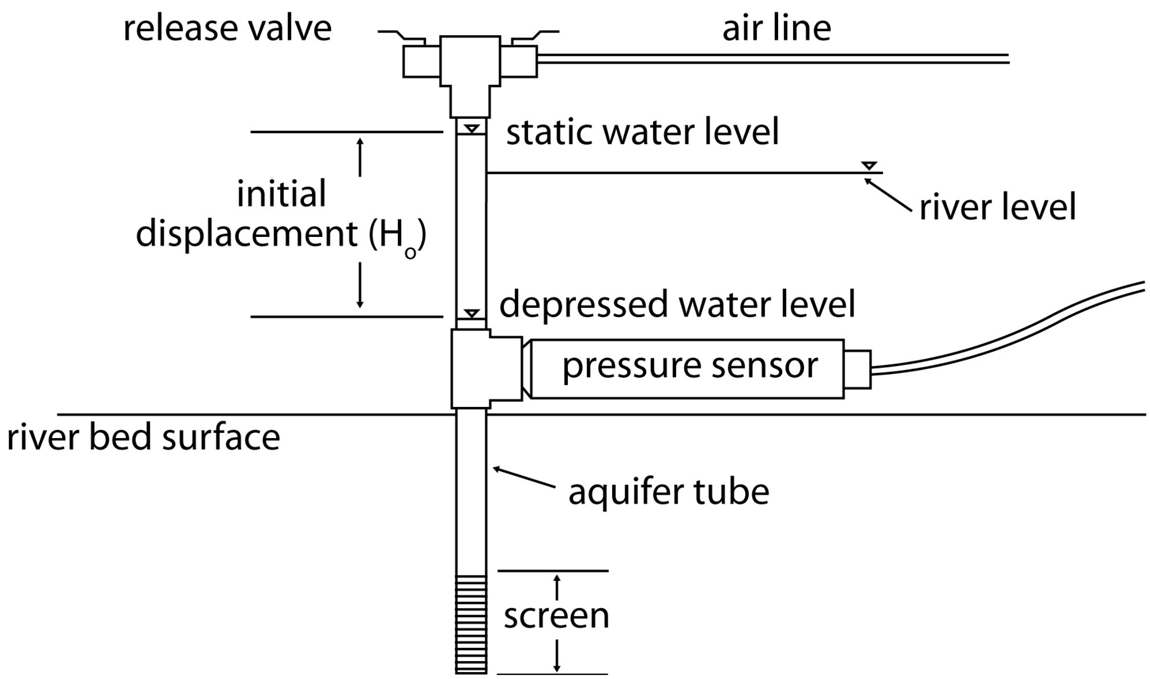

Figure 4. Equipment and Set-up used to conduct Aquifer Tube Slug Tests

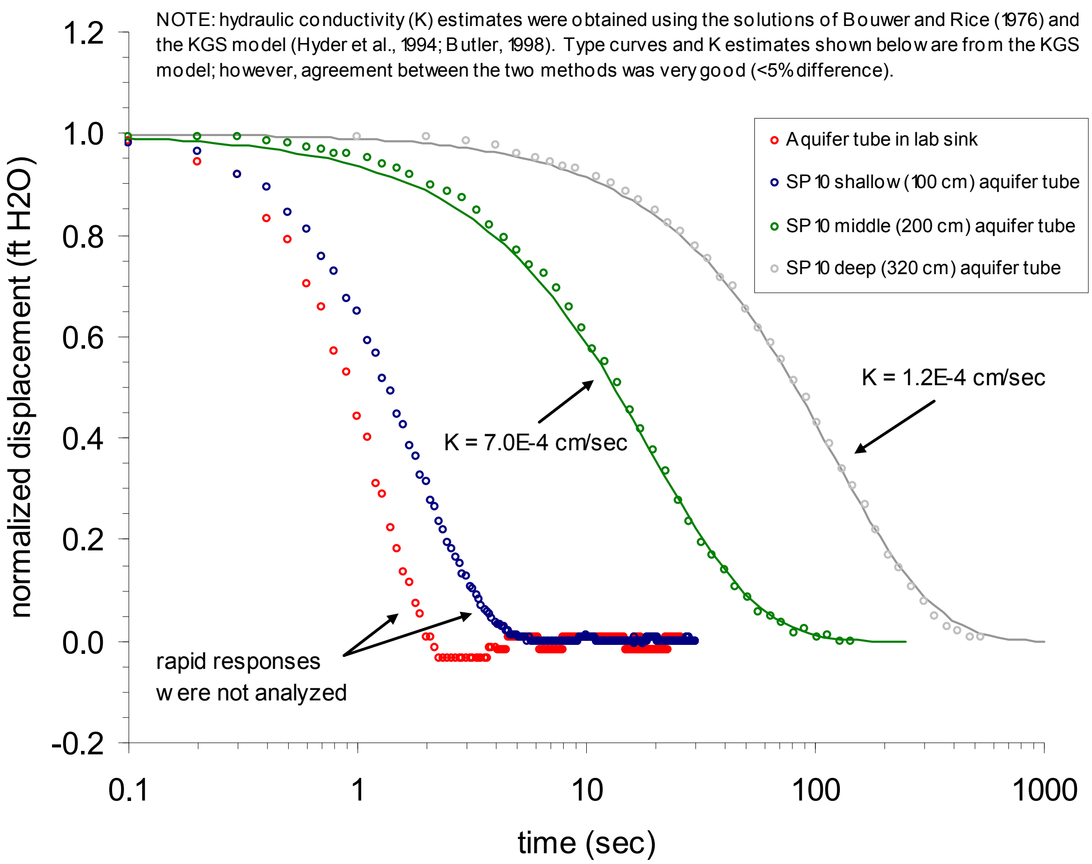

Figure 5. Slug Test Responses in Aquifer Tubes at Depths of 100 (shallow), 200 (middle), and 320 (deep) cm Below the River Bed at Spring 10 and Within a Water-Filled Laboratory Sink (control)

Slug tests in the three aquifer tubes clustered at the Spring 10 location showed responses that varied with depth (Figure 5). Repeat tests with different initial displacements in all aquifer tubes were consistent. The shallowest aquifer tube showed a critically-damped response similar to the infinite-K laboratory-sink control described above. The water-level in the shallow aquifer tube recovered to static within 4 to 6 seconds after test initiation, but without an oscillatory response (Figure 5). The rapid slug test response suggests a high hydraulic conductivity (K) of the surrounding sediments in the immediate vicinity of the aquifer tube screen. Because of the rapid response time, no quantitative estimates of hydraulic conductivity were performed on the shallow aquifer tube.

Response to the slug tests in the middle and deep aquifer tubes were markedly slower than the two previously-discussed examples. Water levels recovered to static conditions at an exponential rate over a duration of minutes rather than seconds (Figure 5). Both aquifer tubes exhibited response patterns that were easily fit with the Bouwer and Rice straight-line and KGS type-curve solutions. Hydraulic conductivity estimates between the two analytical methods agreed to within 5%. The middle aquifer tube took about two minutes to fully recover, resulting in a hydraulic conductivity estimate of 7.0×10^{-4} cm/s (Figure 5). The response from the deeper aquifer tube exhibited a highly-delayed recovery lasting over eight minutes (Figure 5). The hydraulic conductivity estimate for the deep aquifer tube was 1.2×10^{-4} cm/s, or nearly six times lower hydraulic conductivity than the middle tube. These results are consistent with previous measurements of hydraulic conductivity for this fine-grained unit (Williams et al 2007).

A comparison of the slug tests results between the three aquifer tubes indicates a layered heterogeneity in the hydrogeology at Spring 10. This is consistent with previous geologic investigations conducted at and near Spring 10 (Fritz et al 2007; Williams et al 2007). Core samples revealed a coarser layer of loose and poorly-sorted sandy and gravelly alluvium in first meter below the active river bed surface. Below this, there is a prominent fine-grained layer composed of well-indurated fine sand and silt. The middle and deeper aquifer tubes are both installed within the fine-grained layer. The relatively lower hydraulic conductivity estimate from the slug testing indicates that the fine-grained layer is tighter at depth. It was difficult to advance the coring device deeper than about 20 cm into the fine-grained layer, so there is insufficient core sample to confirm this. In fact, the middle aquifer tube is below the depth at which coring was successful. The agreement between the decreased hydraulic conductivity at depth estimated from the aquifer tube slug tests and the existing hydrogeologic conceptual model for Spring 10 give credence to the application of this method. It needs to be mentioned that due to the small volume of water displaced by the slug test, the horizontal hydraulic conductivity estimates presented here are representative of a small-scale radial zone around the aquifer tube screen.

The results from the field-based slug tests highlight several things about the application of slug tests in small-diameter aquifer tubes. First, there appears to be an upper limit on the hydraulic conductivity that can be estimated. Although a quantitative estimate on this upper limit may not be definable based on these preliminary results, subsequent efforts might be successful if they include a theoretical consideration of frictional losses. However, the results are encouraging based on the results from the middle and deep aquifer tubes at Spring 10. In relatively low-K formations where the response is dominated by friction losses in the formation (over-damped), response patterns can be analyzed with well-known and analytically-straight forward methods (e.g., Bouwer and Rice).

4.0 River Gradient

River gradient was measured by installing two river stage gages in the Columbia River. The stage gages were surveyed for positions and elevations using an RTK GPS system, with vertical accuracy of ± 0.5 cm. The stage gages were then outfitted with Solinst absolute pressure gages. A third probe (Solinst Barologger, Solinst Canada, Georgetown, Ontario) was deployed onshore to measure barometric pressure. All probes recorded pressure at a 30 minute frequency for 7+ months (December 2007 to July 2008). The pressure sensors were calibrated prior to deployment, and calibration was checked after retrieval. Accuracy of the individual pressure measurements was ± 1 cm. The river stage gages were located 2109 meters apart, with the downstream stage gage located at Spring 10 (Figure 1). The typical head difference between the two locations was on the order of 30 cm, resulting in potential errors in gradient measurements of less than 5%.

The gradient of the Columbia River in the vicinity of the 300 Area varied between $1x10^{-4}$ and $3x10^{-4}$ m/m over the period of this study (Figure 6). This gradient was consistent with measurements of river gradient along other short stretches of the Hanford Reach (Arntzen 2002). However, the gradient was steeper than the previously estimated Columbia River gradient. One unexpected observation in the river gradient data was the non-linear relationship between river stage and river gradient over the range of observed river elevations (Figure 7). When river stage at the 300 Area water intake (data obtained from Virtual Library) was less than 106 m elevation, there was a near linear relationship between river stage and river gradient. However, when river stage increased above 106 m, the river gradient was essentially constant. This behavior may be explained by the hypothesis that at low-river stage (less than 106 m), the transition from ‘free flowing’ river to impounded lake occurs between the two river stage gages. At high river stage, the transition point is further downstream. This hypothesis is illustrated in Figure 8. The river gradient over the free-flowing stretch is probably relatively constant (and independent of river stage). When the transition point between free-flowing and impoundment occurred between the two river-stage gages, then the average river gradient over that stretch of river was lower. This is important because at lower river stage, assuming a constant river gradient is probably incorrect. However, not accounting for the non-linear river gradient would result in a maximum difference between estimated and actual river stage about 15 cm over the portion of river studied here. That amount of error is small relative to the hourly changes in river stage that occur on the Columbia River.

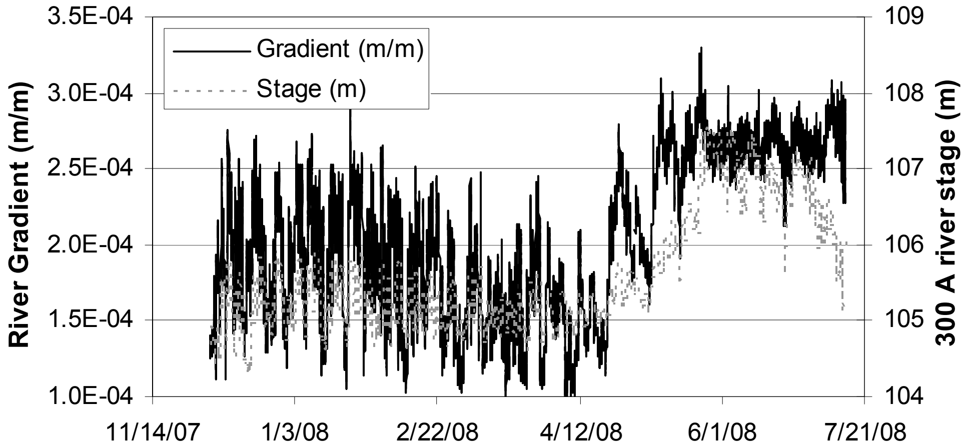

Figure 6. Columbia River Gradient and Stage Near the 300 Area

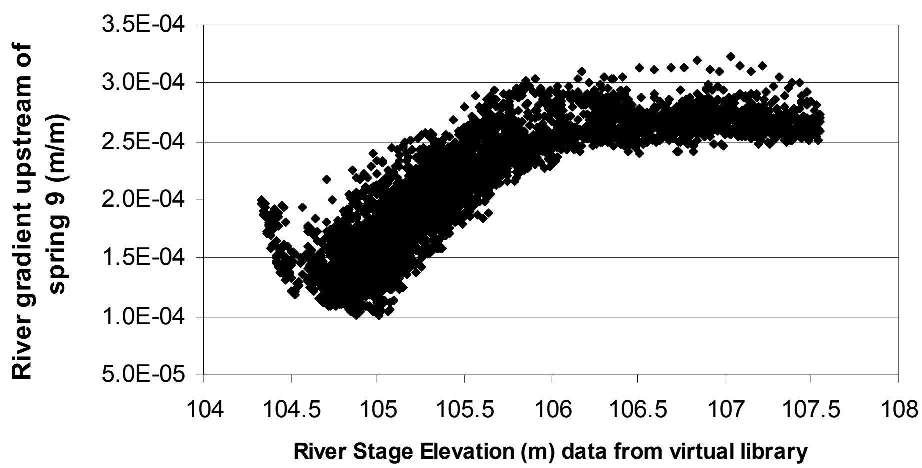

Figure 7. Columbia River Gradient as a Function of River Stage

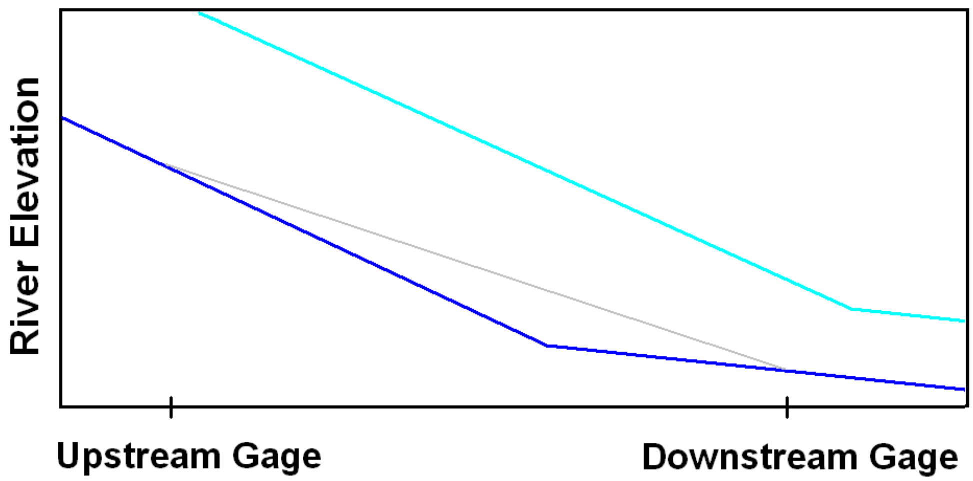

Figure 8. River Gradient Illustration Showing High River Stage (light blue) and Lower River Stage (dark blue). The grey line shows the lower average gradient that results when the transition point between free flowing and impounded river occurs between the two river stage gages.

5.0 Conclusions

The two field methods introduced here have the potential to improve the ability to identify areas of groundwater discharge and to estimate relative contribution of discharge at various locations. In the future, this should allow for more focused research efforts and better data interpretation. Deploying buried specific conductance probes in the river bed appears to be a promising technique for understanding temporal and spatial variability in groundwater discharge to the river. While the results are qualitative in nature, they provide data that could help narrow the area for additional investigations. For example, based on this study it appears that electronic seepage chamber installation 50 feet off-shore would not be necessary, as a closer location would provide a better monitoring location (Fritz et al 2009). The buried probe approach also identified areas of groundwater discharge where river bed surface methods could not.

Slug testing in aquifer tubes appears to be a potentially viable method for determining hydraulic conductivity. Based on preliminary results, the method is capable of determining the relative hydraulic conductivity between aquifer tubes. However, additional testing should be done to determine if the quantitative results of hydraulic conductivity from slug tests in aquifer tubes are accurate and comparable to other methods. Even if the method is ultimately shown to be limited to providing relative estimates of hydraulic conductivity, being able to differentiate between zones of higher and lower hydraulic conductivity would provide a means to identify areas with a higher probability of groundwater discharge. Given the large number of aquifer tubes currently installed along the Hanford Reach (Hartman and Peterson, 2003), an aquifer tube slug test method capable of a qualitative determination of hydraulic conductivity could prove to be beneficial in helping to interpret contaminant concentration results.

The river gradient measurements provide data necessary for establishing river elevation estimates within a modeling domain. Further, it adds some insight to the complex relationship between the 'free-flowing' stretch of river upstream of the 300 Area and the impounded portion of the river downstream of the 300 Area.

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