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ground water

River-Induced Flow Dynamics in Long-Screen Wells and Impact on Aqueous Samples

by Vince R. Vermeul[1], James P. McKinley[2], Darrell R. Newcomer[2], Robert D. Mackley[2], and J.M. Zachara[2]

Abstract

Previously published field investigations and modeling studies have demonstrated the potential for sample bias associated with vertical wellbore flow in conventional monitoring wells constructed with long-screened intervals. This article builds on the existing body of literature by (1) demonstrating the utility of continuous (i.e., hourly measurements for ~1 month) ambient wellbore flow monitoring and (2) presenting results from a field experiment where relatively large wellbore flows (up to 4 L/min) were induced by aquifer hydrodynamics associated with a fluctuating river boundary located approximately 250 m from the test well. The observed vertical wellbore flows were strongly correlated with fluctuations in river stage, alternating between upward and downward flow throughout the monitoring period in response to changes in river stage. Continuous monitoring of ambient wellbore flows using an electromagnetic borehole flowmeter allowed these effects to be evaluated in concert with continuously monitored river-stage elevations (hourly) and aqueous uranium concentrations (daily) in a long-screen well and an adjacent multilevel well cluster. This study demonstrates that when contaminant concentrations within the aquifer vary significantly over the depth interval interrogated, river-induced vertical wellbore flow can result in variations in measured concentration that nearly encompass the full range of variation in aquifer contaminant concentration with depth.

Introduction

Conventional long-screen groundwater monitoring wells, including those that extend over the full saturated thickness of an aquifer, have been used extensively in the environmental field to characterize site hydrogeology and geochemistry, monitor groundwater quality and contaminant plume migration, and assess the performance of remedial technologies. It is generally recognized that long-screened intervals provide a composited concentration for the interrogated depth interval. However, when interpreting aqueous monitoring data from conventional long-screen well installations, both the vertical distribution of transmissivity and the vertical flow within the wellbore need to be considered. Long-screen intervals can act as a conduit for vertical wellbore flow when it connects transmissive zones of differing hydraulic head, even at sites where geologic logging during well installation is unable to identify any significant formational heterogeneity that could account for the observed flows. These flows can result in temporal variability in measured aqueous concentrations that is directly related to changes in wellbore flow direction (i.e., upward vs. downward), redistribution of contaminants within the aquifer adjacent to the well, dilution of measured contaminant concentrations with low concentration waters from an inflow zone, and in extreme cases, cross contamination of discrete zones within the aquifer. In addition, even for cases where wellbore flow is negligible, discrete, highly transmissive zones can dominate the aqueous concentration measured in a long-screen well.

The advantages and disadvantages of long-screen wells relative to adoption of a multilevel, depth-discrete

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monitoring approach have been extensively debated in the literature. Church and Granato (1996) published a summary of previous field investigations and modeling studies evaluating wellbore flows and groundwater sample bias in long-screened wells. An early study (Giddings 1987) concluded that long-screened wells were preferable due to (1) their capability to intersect transmissive zones that might otherwise be missed by depth-discrete measurements and (2) the cost associated with installing and monitoring multilevel well installations. However, the general consensus in the literature was that sampling bias in long-screen wells was problematic and that a move toward multilevel, depth-discrete measurements was warranted.

Numerous field investigations since these early papers were published have evaluated ambient (i.e., natural) wellbore flows in long-screen wells and their potential impact on sampled groundwater concentrations. Elci et al. (2001) summarized borehole flowmeter test results on a total of 142 wells at 16 sites in 12 states that demonstrated a measurable amount of wellbore flow in 73% of the cases. Others have identified ambient vertical flows in long-screen wells based on observed vertical distributions in contaminant concentration and field parameters (Hutchins and Acree 2000; Izbicki et al. 2005; Corcho Alvarado et al. 2009; McDonald and Smith 2009). In addition to these field investigations, several modeling studies (Reilly et al. 1989; Reilly and LeBlanc 1998; Elci et al. 2001, 2003) have been conducted to assess the impacts of wellbore flow on measured concentrations in long-screen wells and the redistribution of contaminants within the aquifer. Results from these modeling studies were consistent with experimental results and support a move toward reliance on more depth-discrete measurements. Elci et al. (2003) showed that the impacts of wellbore flow could be mitigated by increasing hydraulic resistance within the wellbore by installing some type of packer assembly between intercommunicating flow zones.

Electromagnetic borehole flowmeter (EBF) surveys have been used in many hydrologic investigations for measuring ambient and dynamic vertical flow profiles and have been demonstrated effective for measuring the vertical wellbore flow velocity distribution in wells (Molz and Young 1993; Molz et al. 1994; Boman et al. 1997; Young et al. 1998; Crisman et al. 2001). The objective of EBF surveys is to characterize the ambient and/or dynamic (i.e., pump-induced), in-well vertical flow velocity and direction within the saturated portion of a well screen. Wells with very low or no ambient vertical flow conditions are generally assumed to be more viable monitoring facilities for detecting and monitoring groundwater contaminants (Reilly et al. 1989). Vertical wellbore flow measurements obtained from dynamic EBF surveys can be used to infer the lateral groundwater inflow distribution and thus provide information on the vertical distribution of horizontal hydraulic conductivity over the test interval.

Continuous monitoring of ambient borehole flow, which has not been previously reported in the literature, provides a useful tool for identifying and quantifying the temporal variability of vertical wellbore flow. Time-discrete ambient flowmeter surveys can be used to identify wells where combined hydrogeologic and hydrodynamic conditions result in significant intercommunication between separate permeable zones within the aquifer and thus where it is problematic to install long-screened intervals that span multiple productive zones. However, a single ambient flow profile provides no information on how these flows change over time, and if conducted during periods of low-flow conditions, may fail to identify wells where flows would occur under different hydrologic conditions. Wellbore flow trend plots can be compared with other temporal data sets (e.g., river hydrographs, vertical hydraulic gradients) to identify correlations and improve understanding of the hydrologic processes driving the flows. When depth-discrete concentration data are available from a nearby multilevel well cluster, these data can be used to determine whether variations in measured concentration in the long-screen wells are related to the vertical flow of water of different concentrations that is derived from different depth intervals within the aquifer.

In hydrogeologic settings characterized by highly permeable aquifers that transmit the pressure response associated with a nearby fluctuating river boundary for large distances with only limited lag times, the resulting hydrodynamic complexity has the potential to produce relatively large vertical wellbore flows. Under these conditions, the magnitude of wellbore flow can introduce significant sampling bias and intercommunication between separate permeable intervals intersected by long-screen wells. This article presents results from a field experiment conducted at the U.S. Department of Energy (DOE) Integrated Field Research Challenge (IFRC) Hanford test site, which was designed to assess these impacts.

Site Description

The Hanford IFRC, which is supported through DOE's Office of Science (Figure 1), is an experimental investigation of multiscale mass transfer and its role in controlling contaminant behavior in a groundwater system with complex process coupling. Contaminated sediments from the site are coarse-textured, but display remarkably slow, kinetically controlled uranium desorption in the laboratory setting. The aquifer where the uranium plume resides is in direct hydrologic communication with the Columbia River, which exhibits large daily and seasonal stage oscillations. The primary goal of the IFRC project is to characterize, understand, and model a complex field-scale biogeochemical system displaying kinetic processes and dynamic hydrology, driven by groundwater-river coupling. Extensive field hydrologic and geophysical characterization has been performed, which, when integrated with laboratory characterization measurements, will be used to develop a comprehensive three-dimensional hydrogeochemical model of the field site that will be used for knowledge integration, learning, and field experiment evaluation and simulation. Field injection experiments using 300 Area site groundwaters

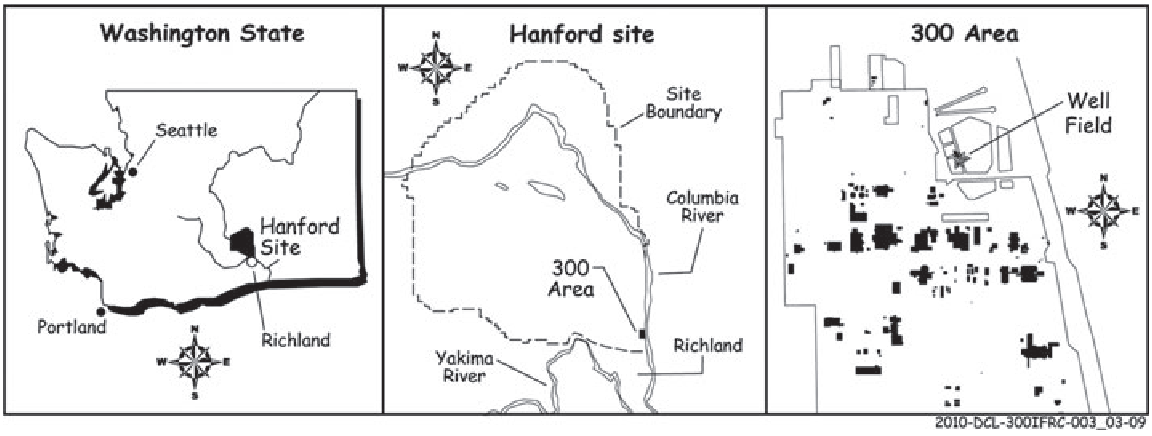

Figure 1. Location of IFRC field site showing test well locations and construction details.

that vary in uranium concentration and have been spiked with nonreactive tracers are being used in combination with passive monitoring experiments to understand coupled processes occurring in the lower vadose zone and saturated zone.

Geologic and geohydrologic characterization performed in support of the Hanford IFRC project, including a detailed description of drilling and well construction activities supporting installation of the wellfield, have been previously reported by others (Bjornstad et al. 2009). In addition to these site-specific characterization activities, previous Hanford 300 Area field investigations and data evaluation reports have documented the evolution and refinement of a site conceptual model of the 300 Area-wide hydrogeology, geochemistry, and contaminant uranium distribution (Williams et al. 2007; Zachara et al. 2007; Brown et al. 2008; Peterson et al. 2008). The primary aquifer of interest beneath the IFRC site resides within the highly permeable unconsolidated sands and gravels of the Hanford formation. This aquifer is underlain at the site by a fine-grained unit of the Ringold Formation, which is several orders of magnitude lower in hydraulic conductivity and thus acts as an effective aquitard and no-flow boundary for the IFRC experimental domain.

The Hanford formation is composed of sediments deposited during Pleistocene-age cataclysmic floods (Bjornstad et al. 2009). These high-energy deposits consist predominantly of unconsolidated sediments that cover a wide range in grain size, from boulder size gravel to clays. A poorly sorted mixture, dominated by gravel, with lesser amounts of sand and silt is the dominant lithology for the Hanford formation beneath the IFRC site. Hydraulic tests conducted at 14 long-screen well locations within the IFRC wellfield provided hydraulic conductivity estimates for the Hanford formation that ranged from 4600 to 11,000 m/d. In addition to these depth-averaged conductivity estimates, an EBF profiling campaign was conducted to provide information on the vertical distribution of formation permeability over the full depth interval at each monitoring well location. These data, in conjunction with depth-averaged hydraulic conductivity results from constant-rate injection tests were used to estimate the vertical distribution of horizontal hydraulic conductivity at each location. Collectively, the EBF data from site wells indicate that the hydraulic conductivity over the central third of the aquifer is significantly lower than the top and bottom thirds. Although thickness and contact depths for this lower permeability material varied across the site, this general distribution was observed to some extent at most of the monitoring well locations. This depth-varying conductivity distribution is also consistent with the observed ambient vertical wellbore flows reported in this article and conservative tracer transport responses that will be the topic of future publications.

A groundwater uranium plume has existed beneath the 300 Area since the early operations of the process ponds; the highest uranium concentrations were observed from the early 1950s to the late 1980s (Peterson et al. 2008). These concentrations decreased rapidly after disposal activities ceased in the early 1990s, and groundwater uranium concentrations have slowly decreased since then. The plume resulted from liquid process waste infiltrating through the 4- to 10-m-thick vadose zone beneath the disposal facilities. Despite source-term removal and elimination of other leak sources, the general shape of the contaminated groundwater plume has not changed significantly over the last 10 years. The plume occasionally experienced sizable water table fluctuations during pre-dam Columbia River flooding and, to a lesser extent, during present day, dam-controlled, river-stage fluctuations. These river-stage fluctuations result in a potential for redistribution of dissolved uranium from beneath the disposal facilities, and from with the zone of historical water table fluctuation (i.e., the “smear zone”), into groundwater.

Approximately 650,000 m^3 of groundwater beneath the 300 Area includes uranium at concentrations that exceeded the drinking water standard of 30 μg/L, with a total estimated total dissolved mass of 45–77 kg (Peterson et al. 2008). Concentrations of uranium in aqueous samples collected from within the uranium plume varied seasonally. Concentrations typically ranged from natural background levels (less than 10 μg/L) up to approximately 200 μg/L. At the IFRC site, solid-phase uranium concentrations were estimated by whole-rock acid digestion and subsequent analysis by inductively coupled plasma-mass spectrometry (ICP-MS; Environmental Protection Agency 2008) and by bicarbonate extraction (Curtis et al. 2004), both procedures involving the less than 2-mm fraction of the material returned during drilling. The results indicated that the extractable, labile uranium concentration (by bicarbonate extraction) comprised approximately one-half or less of the total. Samples from three wells were processed over the entire sedimentary column, and additional samples were processed from only the smear zone. The bicarbonate extraction results (Figure 2) indicated that the maximum subsurface uranium occurred in the vadose zone, but that there was significant uranium present in the smear zone. The smear zone could thus act as a persistent source of uranium to the aquifer, driven by seasonal re-wetting and mobilization. Seasonal and short-term fluctuations in the Columbia River stage correlated to the rise and fall of the water table at the IFRC site have been shown to drive hydrologic variations at the site. Dissolved uranium concentrations within the aquifer varied according to hydrologic zone, with the uppermost zone consistently highest in uranium concentration and the lower zone consistently at lower concentrations (multilevel data discussed in detail in the following section).

Methodology

Ambient EBF surveys indicated the presence of vertical wellbore flows of more than 4 L/min at some well locations during hydrologic characterization activities at the Hanford IFRC test site. It was hypothesized that the flows resulted from site hydrogeologic conditions (i.e., upper and lower permeable zones separated by a zone of lower permeability) and the relatively complex hydrodynamics associated with the site's near-river environment. Wellbore flow has the potential to significantly impact measured concentrations in long-screen wells and result in cross contamination between vertically discrete transmissive zones or between separate aquifer systems. This can compromise field experiments designed to interrogate contaminant transport and mass-transfer processes; it should be noted that the primary objective of the IFRC project is to assess these processes. To address this potential source of monitoring uncertainty, a monitoring program was designed and implemented to assess the impacts of river-induced wellbore flows on groundwater concentration measurements in long-screen wells. The monitoring program extended over a 1-month period during seasonal high water table conditions (mid-May through mid-June, 2009) and consisted of continuous measurements of (1) hourly wellbore flow, (2) hourly river-stage and water-level elevations, and (3) daily aqueous uranium concentrations in the long-screen well and adjacent multilevel well cluster.

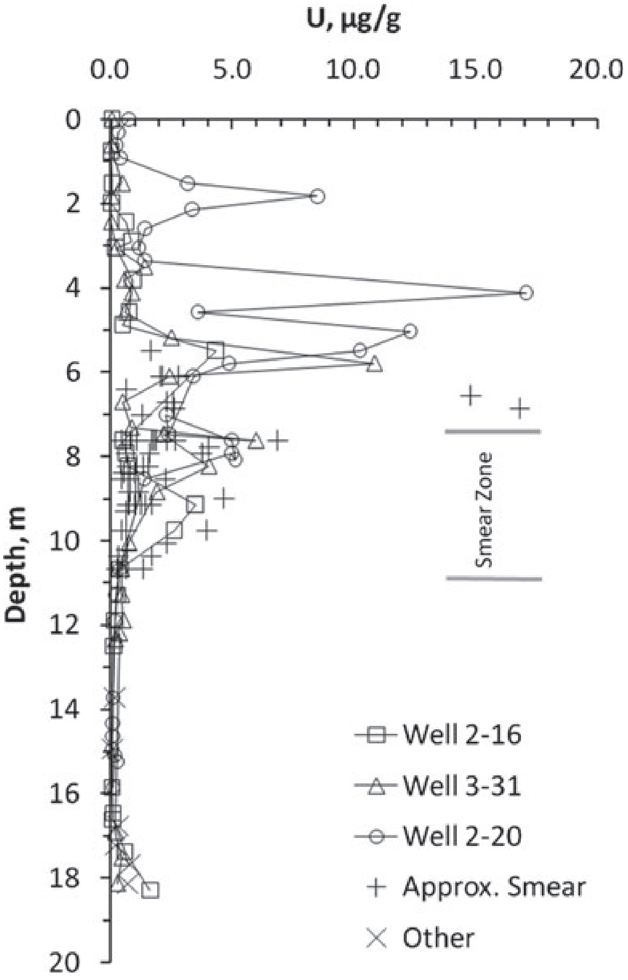

Figure 2. Uranium profile based on sediment samples collected during the installation of wells adjacent to the study area.

Description of Test Wells

The IFRC wellfield consists of 35 well installations oriented in a triangular array (Figures 2 and 3). Most of the wells (26) fully penetrate the average saturated thickness of the highly permeable Hanford formation. The remaining nine wells comprise the multilevel well clusters (three depths) at three separate locations. Figure 3 shows the location and well construction detail for the wells used in this study. The four wells used in this study include a fully screened well (399-2-21) and an adjacent multilevel well cluster with depth-discrete screen intervals completed over the upper, middle, and lower portions of the aquifer. These three discrete monitoring points are located at a radial distance of 8.7, 9.8, and 11.6 m, respectively. Although the lithologic description for well 399-2-21 (Figure 3) and the adjacent multiwell cluster fails to identify the lower permeability material over the central portion of the aquifer, dynamic EBF surveys that resulted in profiles for wells 399-2-21 and 399-3-25 clearly demonstrated this feature (Figure 4), which supports the generalized geohydrologic conceptual model discussed earlier. It should be noted that the dynamic EBF surveys were conducted in support of site

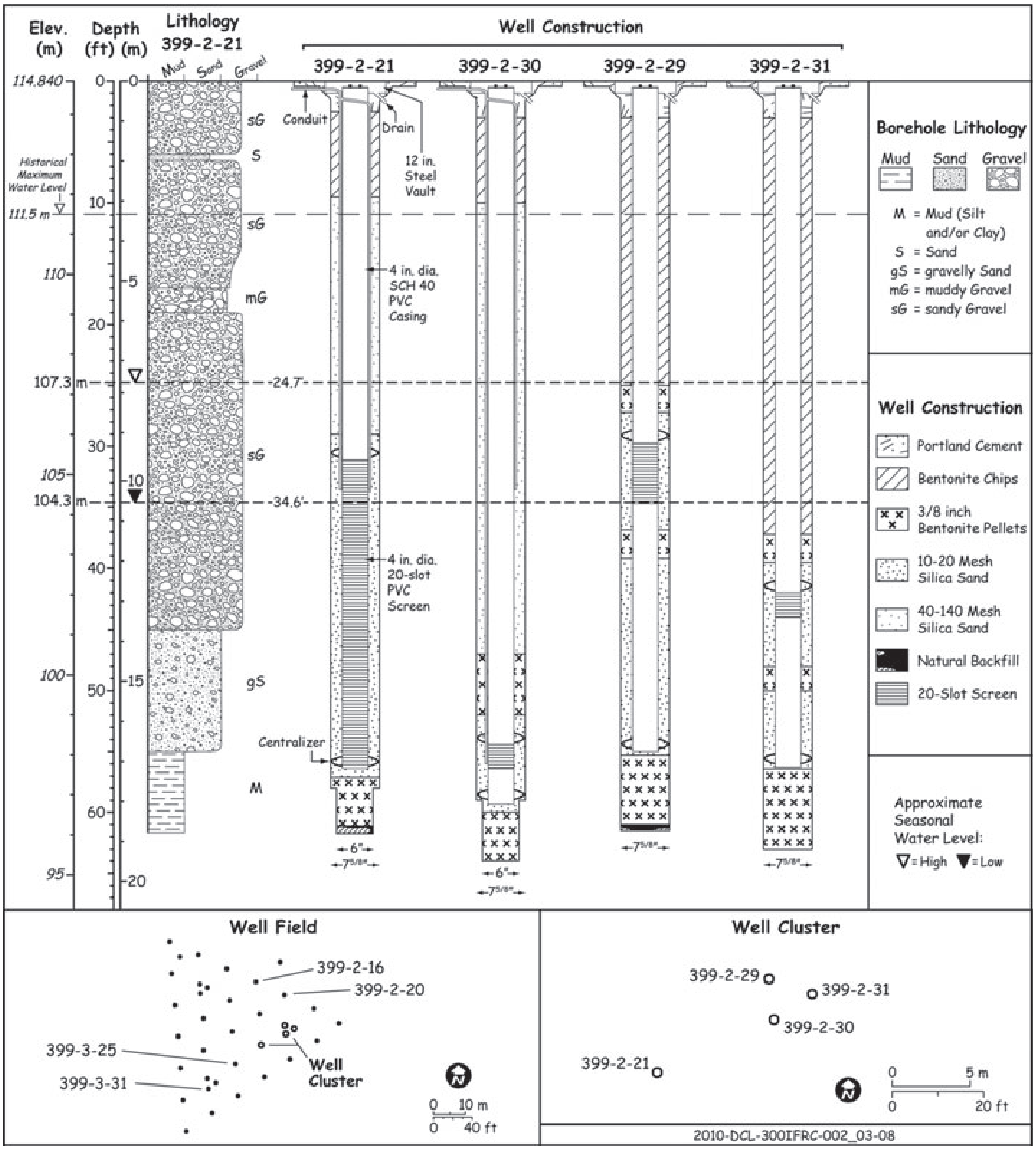

Figure 3. Locations and construction details for wells used in this study.

characterization activities and were not directly related to the continuous EBF monitoring performed during this study. A detailed description of dynamic EBF profiling theory and methodology is provided in Molz and Young (1993) and Crisman et al. (2001).

EBF Monitoring

The theory that governs the operation of the EBF is Faraday's Law of Induction, which states that the voltage induced by a conductor moving orthogonally through a magnetic field is directly proportional to the velocity of the conductor moving through the field. For EBF surveys, flowing water is the conductor, an electromagnet generates a magnetic field, and the electrodes within the flowmeter measure the induced voltage. The electronics attached to the electrodes transmit a voltage signal directly proportional to the velocity of water acting as the conductor through the EBF probe. The probe consisted of an electromagnet and two electrodes 180° apart inside a hollow cylinder. The inside diameter (ID) of the hollow cylinder was 2.5 cm (1 inch), and the outside diameter of the probe cylinder was just under 5.1 cm (2.0 inches). More detailed descriptions of the EBF instrument system and field test applications are provided in Molz et al. (1994) and Young et al. (1998).

The EBF system (Quantum Engineering Corporation, Loudon, Tennessee) was paired with an appropriately configured data acquisition system (Campbell Scientific Inc., Logan, Utah, CR10 datalogger) to measure and record ambient vertical flow within the wells. An

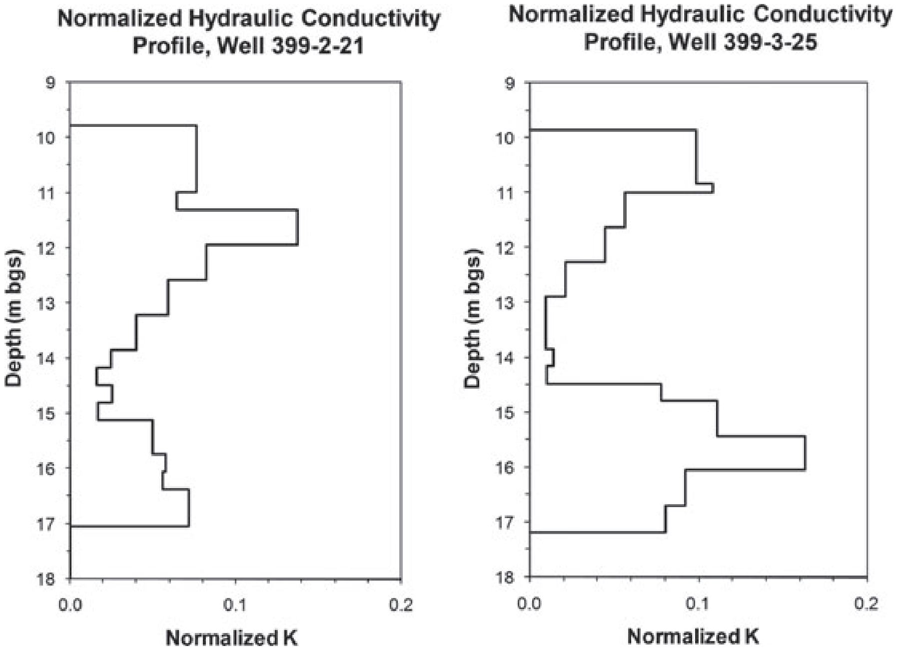

Figure 4. EBF profiles for the fully screened well used in this study (399-2-21) and adjacent well 399-3-25.

inflatable packer was used to minimize bypass flow between the EBF probe and the 4-inch ID well screen. The inflatable packer consisted of a rubber sleeve attached to a stainless steel assembly and sealed with hose clamps. The EBF probe cylinder was mounted inside the stainless steel assembly. Inflation of the packer was controlled with compressed nitrogen gas, a regulator, and inflation tubing. The probe was powered by 110-V AC using an electronic control box at the surface. The data acquisition system was connected to the electronic control box to automatically record the voltage signal.

Ambient EBF surveys (i.e., measurement of ambient or natural flow at multiple depths throughout the screened interval) were performed in the wells before collecting the continuous wellbore flow measurements. The standard ambient surveys procedure is to measure wellbore flow at discrete depth intervals (e.g., 0.3 m) in succession from bottom to top within the saturated well screen section (Young et al. 1998). The purpose of these EBF surveys was not only to characterize the ambient vertical flow conditions within the saturated well screen section, but also to determine the approximate depth of the highest ambient vertical flow. This depth, which represents the transition between ambient flow entering the well screen and ambient flow exiting the well screen, was selected for placing the EBF probe during the hourly vertical flow measurement period. For the long-screen well evaluated in this study, that depth was at 15.1 m below ground surface, which is consistent with the transition zone between the deep permeable zone and the overlying lower permeability materials.

Water-Level Monitoring

Hourly well water-level and Columbia River-stage measurements were automatically recorded with pressure transducer and datalogger systems while the ambient wellbore flows were continuously measured. Data for the Hanford 300 Area river gauge were downloaded from the Hanford Virtual Library, a web-based data acquisition tool that allows the user to access various environmental databases for the Hanford site. In the long-screened well, a Druck (model 1830, 10 psig) pressure transducer was placed within the water column above the EBF probe and was monitored with a Campbell Scientific Inc., CR10 datalogger. Pressure sensors with integrated dataloggers (Instrumentation NW Inc., Kirkland, Washington, Model PT2X, 15 psig) were used in the adjacent multilevel well cluster. The automated water-level monitoring network for site wells was verified with periodic manual water-level measurements referenced to a survey elevation datum. A metal-taped water-level meter that is highly accurate and nonstretchable was used for these measurements. This meter was traceable to the National Institute of Standards and Technology and marked in 0.003-m (0.01-feet) gradations.

Aqueous Uranium Concentration Monitoring

During the study period, uranium concentrations in the aquifer were measured intensively to determine the contribution of deep vadose zone uranium to the aquifer associated with the seasonal spring rise in river stage. A subset (16) of the IFRC wells was sampled daily for components, including uranium concentration (by Kinetics Phosphorescence Analysis, Chemchek Instruments Co., Richland, Washington) and major-ion composition (ICP-MS). The samples were collected by bailing from the uppermost 15 cm of the aquifer, and then the aquifer was re-sampled using dedicated Redi-Flo2 variable speed sampling pumps installed at the approximate center point of each well's screened interval. Purge volumes during collection of pumped samples were based on the stabilization of standard field parameters, which were generally found to stabilize after 3 min of pumping at 3–4 L/min. Specific conductance for the pumped samples was measured using a QED Environmental Systems MP20 flow cell, probe, and meter located in the site's field laboratory. Aqueous samples collected during the study thus represented (1) the uppermost 15 cm of the aquifer (bailed), (2) a conductivity-weighted average of the aquifer composition (pumped from fully screened wells), and (3) depth-discrete samples at three locations that included upper, middle, and lower zones. Samples were collected from 28 March to 18 June, 2009, during which the water table traveled through two large excursions into the vadose zone, for a total elevation change of 1.4 m.

Results and Discussion

Temporal trends in ambient wellbore flow within the long-screen well were first compared with river-stage elevation over the same time period to determine whether the two data sets were correlated. Figure 5 shows the observed wellbore flow and water level in the long-screen well (399-2-21) in relation to trends in Columbia River-stage elevation. As indicated, the observed wellbore flows are clearly associated with fluctuations in river stage, showing a strong inverse relationship. These data show that during times of rising and high river stage, downward wellbore flows generally dominate. As the river-stage elevation decreases, downward wellbore flow decreases and may transition to upward flow. The magnitude of the observed wellbore flow response (i.e., up to 4 L/min) indicates that, under the geohydrologic and hydrodynamic conditions present at the IFRC site, fluctuations in river stage have the potential to significantly impact monitored aqueous concentrations in long-screen wells. A discussion of the spatial and temporal wellbore flow relationships across the IFRC wellfield, and their implications for the site conceptual model, are provided in Newcomer et al. (2010).

The observed wellbore flows were also compared with the measured difference in hydraulic head between the shallow and deep zone monitoring wells in the adjacent multilevel well cluster. Given that these head differences are presumed to be the driving force behind the observed wellbore flows, a strong correlation was expected. Due to the extremely high hydraulic conductivities at this site, and thus the relatively small hydraulic gradients required to drive the observed wellbore flows, obtaining accurate measurements of head differences in the multiwell cluster was challenging. The errors associated with converting transducer pressure measurements to absolute water-level elevations were of the same order of magnitude as the head difference that we were trying to measure. To address this measurement-error limitation, the borehole flowmeter was used to identify periods in the flow record when flows were transitioning between positive and negative when no borehole flow was occurring. During this period of negligibly small borehole flow, it can be assumed that the head difference between the shallow and deep zones was also negligibly small. Based on this assumption, relative head differences were calculated for the rest of the pressure data set. As expected, the head difference between the shallow and deep zones was well correlated with wellbore flow (Figure 6). This figure illustrates that, as was predicted by Reilly et al. (1989), only a small amount of head difference is required to

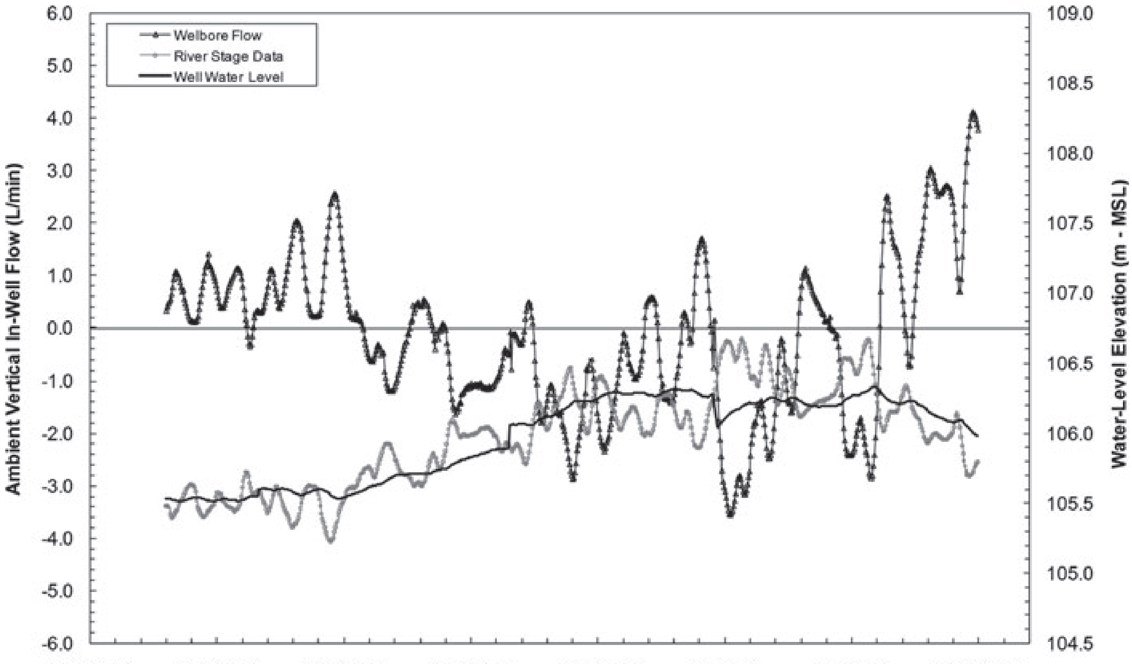

Figure 5. Wellbore flow and water-level elevation in long-screen well 399-2-21 in relation to trends in Columbia River stage.

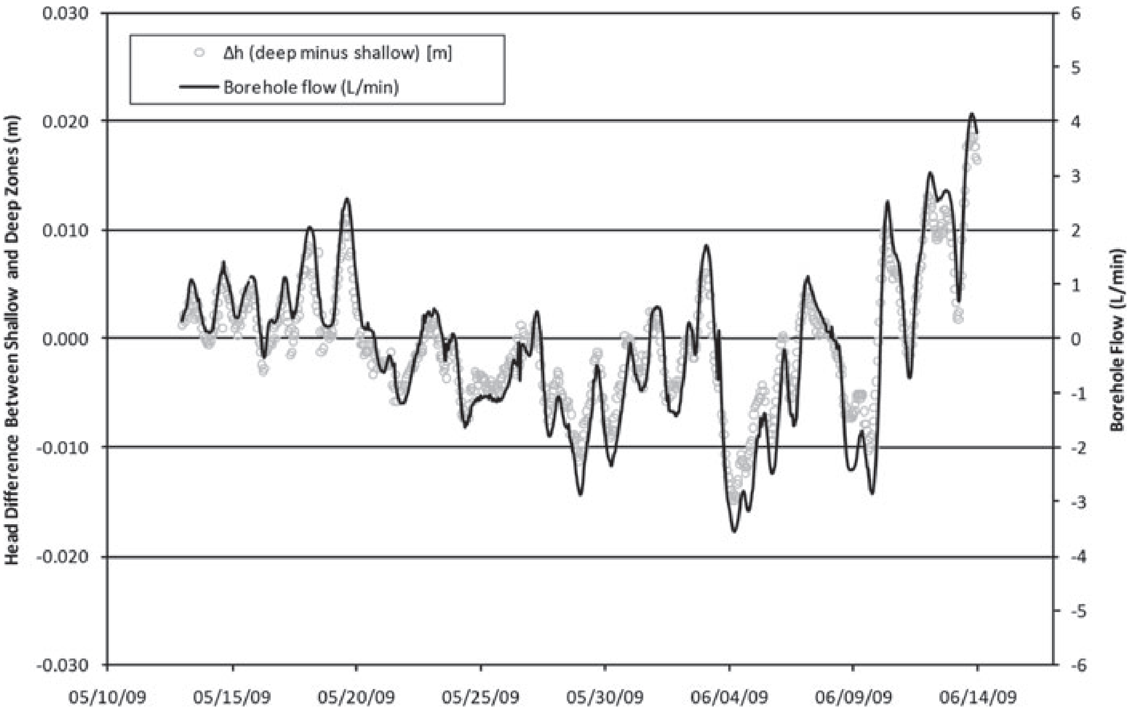

Figure 6. Relationship between wellbore flow in the long-screen well and differences in hydraulic head in the adjacent multilevel well cluster.

generate significant wellbore flows (e.g., 2 cm of head difference results in ~4 L/min of wellbore flow).

The distribution of contaminant source uranium at the site has been shown to reside primarily within the deep vadose zone and the zone of water table fluctuation. This distribution, along with site hydrogeologic conditions that limit vertical migration of contamination, results in distinct differences in aqueous uranium concentration with

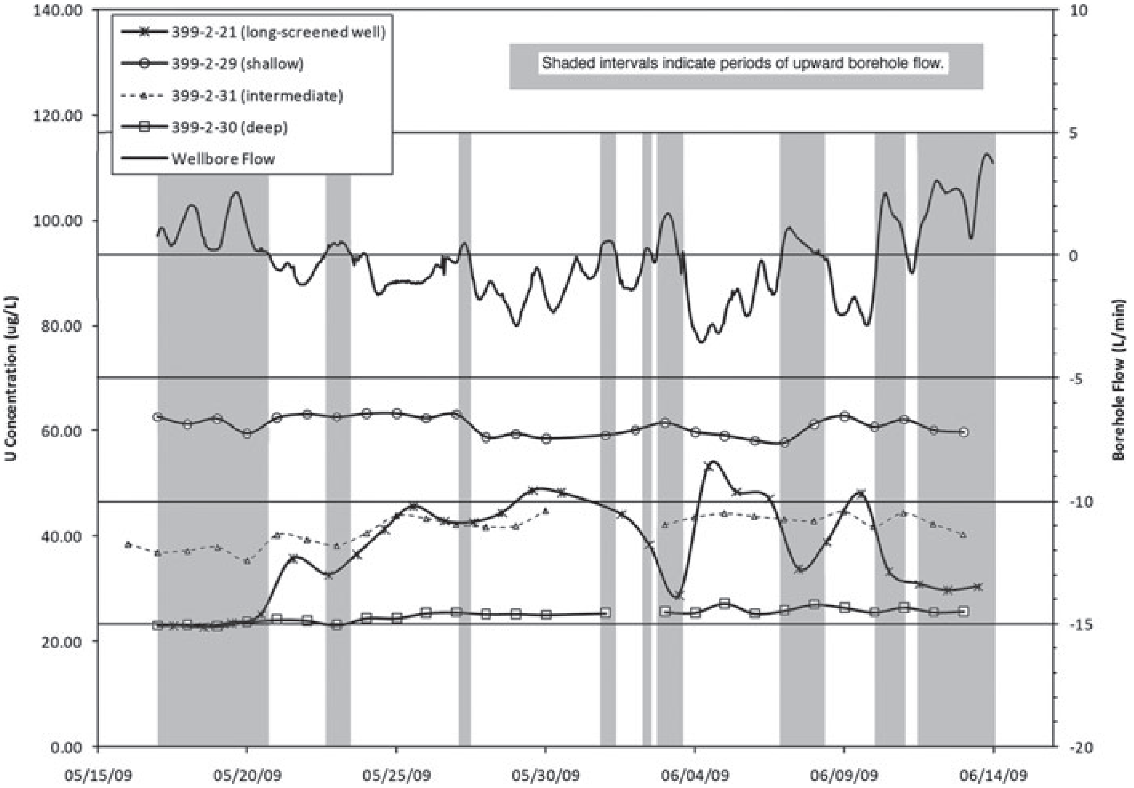

Figure 7. Relationship between vertical wellbore flows and measured uranium concentrations in site monitoring wells.

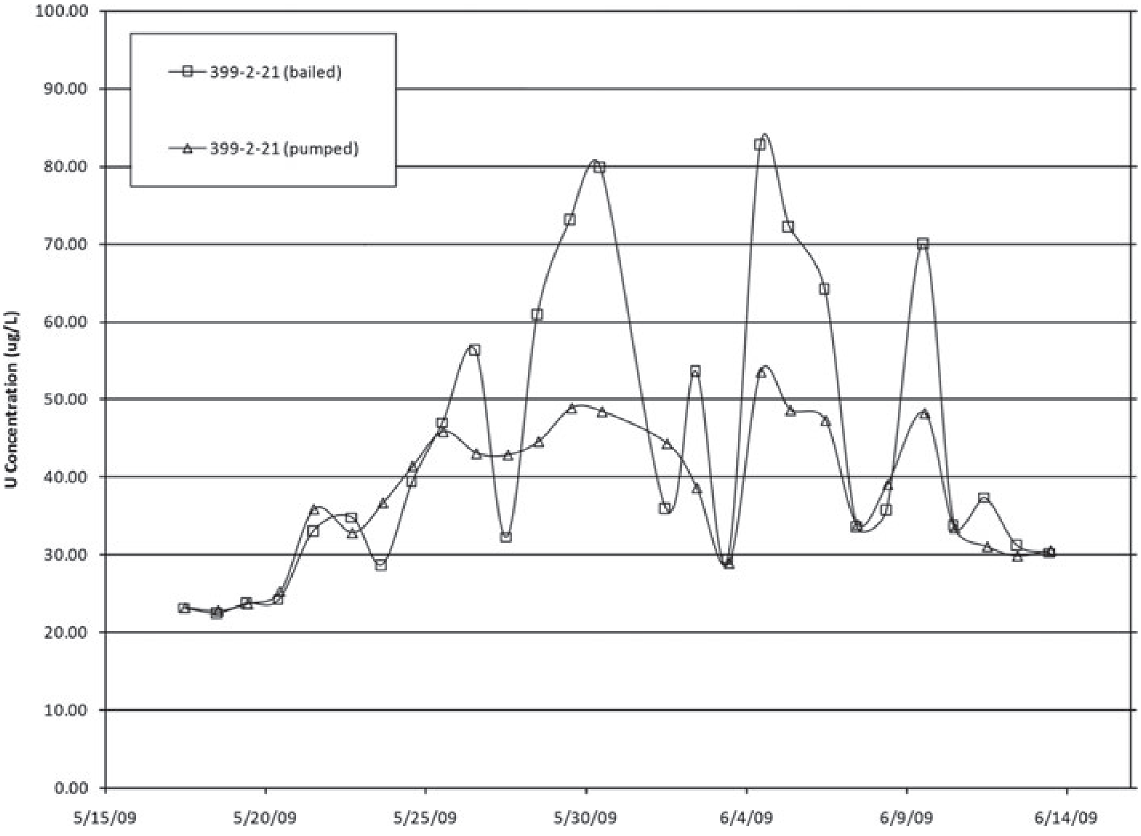

Figure 8. Comparison of uranium concentrations for pumped (composite) and bailed (discrete samples collected at water table) for long-screen well 399-2-21.

depth. During the May to June 2009 high water table monitoring period, uranium concentrations were relatively stable in all three intervals of the multilevel well cluster, with the highest uranium concentration (~60 μg/L) present in the shallow zone, a lower concentration (~40 μg/L) in the intermediate zone, and the lowest concentration (~25 μg/L) in the deep zone. During this same monitoring period, uranium concentrations measured in the adjacent long-screen well were highly variable (Figure 7). Although uranium concentrations in the discrete screen intervals are relatively constant, concentrations in the long-screen well show variations that nearly encompass the full range of variation in aquifer contaminant concentration with depth. Also shown on the plot is vertically oriented shading that identifies portions of the wellbore flow record where flows are positive (i.e., upward). As indicated, observed decreases in uranium concentration occur during, or are immediately preceded by, periods of upward wellbore flow. These upward flows result in measured concentrations that are dominated by the lower concentration waters from the deep zone. Higher concentration waters dominate measured concentrations during times of downward wellbore flow.

As discussed in the Methods section, in addition to aqueous samples that were collected using the standard low-flow purge and sample approach that used a dedicated submersible pump, an approach was developed for collecting a bailed sample from the top 15 cm of the aquifer. A comparison of the pumped and bailed samples is shown in Figure 8. These data provide indication that when upward wellbore flows are occurring, waters from deeper regions of the aquifer migrate within the wellbore all the way to the water table surface. If all of the flow were to exit the well screen deeper within the shallow zone, the observed magnitude of decrease in bailed sample uranium concentrations would not be expected.

Conclusions

This field study demonstrates (1) the utility of continuous EBF monitoring for identifying and quantifying wellbore flow dynamics, (2) that relatively large wellbore flows (up to 4 L/min) can result from a fluctuating river boundary located approximately 250 m from the test well, even for wells with relatively short (7.6 m) well screens, and (3) that river-induced wellbore flows can result in significant temporal variability in measured groundwater concentrations in long-screen wells and thus impact aqueous sampling results.

Continuous EBF monitoring provides for a direct measurement of the magnitude and temporal variability in wellbore flow. This information can be used to evaluate the potential for wellbore flows in long-screen wells in hydrodynamically complex settings, assess their impact on aqueous sampling results, and develop approaches for both accounting for these effects when interpreting field test data sets and mitigating the effects during future experiments. Because wellbore flow has the potential to significantly impact measured concentrations in long-screen wells and result in cross contamination between vertically discrete transmissive zones, these effects can compromise field experiments designed to interrogate contaminant transport and mass-transfer processes. At the IFRC field test site, wellbore flows were shown to be problematic for quantitative evaluation of tracer transport response. Steps will be taken during future passive and dynamic experiments to mitigate these effects.

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