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HANFORD IFRC QUARTERLY REPORT ~ October 2010
Well Field Mitigation Plan

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I. Overview

This Quarterly Report for the Hanford IFRC project is directed to the issue of vertical flow in the fully screened wells of the 300A well field. The detrimental effects of well-bore flows to the interpretation of monitoring data collected at the Hanford IFRC site became evident after the Spring 2009 passive monitoring experiment and the October 2009 desorption injection experiment. Over the past year, the extent and causes of this phenomenon have been quantified and reported in our FY 2009 annual report. The well-bore flow issue was fully described to reviewers in our March 2010 peer review. The project team was directed in May 2010 by BER to devise a hydraulic fix to the well-bore flow problem in the fully screened wells. The project team has worked hard since that date to devise and document an effective mitigation approach. This report documents the well-bore flow problem and its causes, summarizes its impact on monitoring data, demonstrates the effectiveness of various mitigation strategies, and presents our final recommended mitigation approach. Our mitigation proposal is to grout the lower 2/3 (4 m) of the fully screened interval of the offending wells based on their individual hydraulic conductivity profiles, and to reconfigure the geophysical monitoring array. The resulting groundwater monitoring system will primarily access the upper hydraulic conductivity region of the saturated zone, and the seasonally variable water table zone. Six depth-discrete monitoring wells, distributed in three clusters, will remain in the intermediate and deep hydraulic conductivity zones that may be augmented by additional depth-discrete placements. The geophysics array will be installed at new locations between the existing wells in a configuration that eliminates interferences with the down-hole specific conductivity probes and ion-specific electrodes used to monitor tracer tests.

Background

The IFRC well field was installed over the summer of 2008. The primary well-field contains 35 wells that are approximately 56’ (17.1 m) deep (Figure 1). An additional three wells were drilled to 38 ft (11.6 m) in the spring of 2010 to monitor the upper portion of the aquifer. These are all installed within the uranium groundwater plume. Twenty six of the original wells are fully screened through the saturated zone in the Hanford formation (19.0 ft/5.79 m; Figure 2a), as are Hanford site monitoring wells that have tracked U(VI) concentrations in the plume for over 40 y. The remaining nine wells are depth discrete and are located in three-well clusters (Figure 1). The depth discrete wells were completed at deep, intermediate, and shallow depths within the U plume (Figure 2b). The hydrogeology of the IFRC site and the details of individual well completions were described by Bjornstad et al. (2009). Financial and other constraints prevented the installation of more depth discrete wells during our initial field-site development.

Well-bore flows were first observed in select IFRC wells in November of 2008 during the course of ambient and dynamic electromagnetic borehole flowmeter (EBF) testing to ascertain vertical hydraulic conductivity profiles as part of the hydrologic characterization campaign. When completed, the hydrologic characterization campaign (EBF surveys, pump tests, and preliminary tracer tests) supported an unexpected conclusion that the Hanford formation saturated zone that hosts the U plume was vertically stratified in hydraulic conductivity. An upper high K, an intermediate low K, and a deep high K zone were identified. Comparable results have not been reported for the 300A or the U plume, in spite of several past hydrologic studies of this area. Properties or geologic stratification that might explain the hydraulic conductivity profile were not evident in geologic or geophysical logs taken at the time of drilling (Bjornstad et al., 2009). The depth discrete wells were screened within the approximate depth intervals of the three hydraulic conductivity zones. While these zones are present across the entire IFRC site, they display significant vertical and spatial variability in thickness and properties. The potential for impacts to water composition monitoring from well-bore flows was recognized after the hydrologic characterization campaign; but additional well characterization measurements and tracer and passive experiments were required to quantify impacts.

Vertical flows of groundwater are known to complicate well monitoring data for solute concentrations, source term identification, plume arrivals and geometries, and water levels (Reilly et al., 1989; Elci et al., 2001). Well-bore-flows may render such monitoring data un-interpretable, and/or to lead to contamination of aquifer zones that were previously pristine (Elci et al., 2003). Vertical flow in wells has been observed at a variety of locations (Church and Granato, 1966; Elci et al., 2001; Hutchins and Acree, 2000) including within both confined and unconfined aquifers, but a comprehensive understanding of where and when these flows are likely to occur does not exist. Ours is the first documentation of vertical well flows in long-screened wells at the Hanford site (Newcomer et al., 2010; Vermeul et al., 2011). Vertical well flows were unexpected within the 300 A uranium plume because of the relatively thin, unconfined aquifer thickness (19.0 ft/5.79 m) and the large hydraulic conductivities that have been measured and reported for this zone (e.g., > 19,000 ft/d or 6000 m/d). Additionally, the 300 A U plume has been monitored for over 40 y with fully screened wells without any evidence for vertical flows. Unfortunately, our lack of recognition of this potential problem during IFRC well installation places us in a current position where well-field mitigation is required to establish a groundwater monitoring system that is free of well-bore flow artifacts.

Extent of Vertical Flow and its Causes

The ambient vertical flow profile for one of our most studied wells (2-21), and its normalized hydraulic conductivity profile are shown in Figure 3. The well completion report for well 2-21 is shown in Figure 4. The EBF measurement procedure involved the following sequence: i.) an initial ambient survey (~70 min), ii.) a dynamic test to obtain the K profile (80 min), and iii.) a second ambient survey (~30 min). The positive magnitude of the flow profile in liters per minute (LPM) indicated that groundwater was entering the lower high conductivity region of the well (56-52’), and exiting at the upper high conductivity region (46-32’). The highest velocities (~3.75 LPM) occurred over the depth interval of the low hydraulic conductivity zone (50-46’) where groundwater exchange with the surrounding formation was markedly lower. Profiles such as these have been measured for all wells in IFRC monitoring array, with both upward and downward flows observed. In all cases, the vertical flow profiles correlated with the normalized hydraulic conductivity profiles.

The EBF was also deployed in select wells at a fixed depth where vertical flows were maximum (e.g., 48' in well 2-21; Figure 3) for monitoring periods of approximately 2 weeks. Vertical flows were observed to correlate with river stage magnitude and oscillation (Figure 5). Complex behaviors were observed including highly variable flow velocities (e.g., +4 to -4 LPM) and directions that correlated with river stage changes. No two wells were alike. Some (e.g., 2-10, note well completion report in Figure 6) showed extended periods were flow was consistently in one direction (e.g., downward), but variable in velocity; and others (e.g., 2-21) where flows oscillated frequently between upward and downward directions with highly variable velocities. These patterns also showed seasonal variations related to high (spring) and low (fall and winter) water flow periods. A generalized finding was that vertical flows in some wells became more positive (+) when river stage increased (e.g., 2-10, Figure 5); while in others, vertical flows became more negative (-) when river stage increased (e.g., 2-21, Figure 5). Wells exhibiting similar correlative behaviors (e.g., + or -) were located in the same quadrant of the well-field. Those exhibiting (+) behavior were located within or south-west of the paleo-channel in the Hanford-Ringold contact that splits the site, while those with (-) behavior were located north-east of the channel and closer to the river. The topography of the aquitard at the base of the Hanford formation was apparently an important influence on well-bore flows.

One of our highly monitored, test wells for vertical flow (2-21) is located immediately proximate to a three-well cluster of depth-discrete wells (2-29, 2-30, and 2-31; Figure 1). Water elevations in these wells for the time period of the 2-21 vertical flow monitoring experiment (Figure 5, 5/10/2009-6/14/2009) were used to calculate head differences (Δh) between the upper and lower K zones. The head difference in wells 2-29 and 2-31and the monitored vertical flows in well 2-21 were highly correlated (Figure 7). A head difference of ~2 cm resulted in a wellbore flow of approximately 4 LPM.

These and other measurements not reported herein support a conceptual model for IFRC well-bore flows (Figure 8). The fully screened wells penetrate all three hydraulic conductivity zones present at the site and allow communication between the upper and lower high K zones. Frequent Columbia River stage changes create hydraulic pressure waves that move both inland and toward the river depending on river elevation. Differing degrees of connectivity between the upper and lower high K zones and the river, and an overall complex hydraulic conductivity structure result in head differences that drive well-bore flows both upward and downward. The spatially variable structure and elevation of the Hanford-Ringold contact is important in allowing hydraulic continuity with the river in low elevation erosional channels and in attenuating river effects at higher elevation points. The overall pressure field driving the vertical well-bore flows is a complex effect of the local geologic structure; the intervening structure between the IFRC site and the river; and the temporally variable, highly dynamic river boundary.

Effect of Vertical Flows on Monitoring Data

A passive monitoring experiment was performed in the Spring of 2009 to evaluate whether the deep vadose zone was supplying U(VI) to groundwater during the period of maximum water table elevation associated with the spring high river stage. One of the wells monitored in that experiment was test well 2-21 whose well-bore flow behavior has been previously described (Figures 3, 4, 5, and 7). The spring 2009 high water event occurred between 5/27/09 and 6/10/09. During this period a complex concentration trend for U(VI) was noted in bailed (from the water surface) and pumped (approximately 3 m beneath the highest water table elevation) waters from this well (Figure 9). Well-bore flows were monitored in 2-21 during this period, as were U(VI) concentrations in nearby, depth discrete wells 2-29 (shallow) and 2-30 (deep). In contrast to 2-21, U(VI) concentrations in depth discrete wells were relatively constant with time, averaging 60 µg/L for shallow well 2-29 and 22 µg/L for deep well 2-30. We suspect that groundwaters in the deep low K zone at well 2-21 were equivalent to those in well 2-30 over the monitored period. U concentrations in bailed and pumped groundwater from 2-21 tended to increase over the period of high water, but displayed frequent drops in concentration. These concentration decreases, however, directly correlated with periods of upward flow in the well as monitored by EBF (Figure 9, note shaded regions). Well waters were dominated by lower U concentration groundwater from the deep low K zone during periods of upward flow. Bailed and pumped U concentrations were highest during periods of downward flow, as U that was solubilized from the deep vadose zone (monitored by bailing) was transported to depth in the well. Uranium concentrations in pumped waters from 2-21 oscillated between those observed in 2-29 and 2-30 depending on whether well flow was downward or upward. It is thus clear that well-bore flows strongly influenced data from the passive monitoring experiment and that their effects required explicit consideration for proper experimental interpretation. Downward well-bore flows could also enhance delivery of vadose-zone solubilized U to the deep high K zone, and perturb the natural U concentration profiles that are the focus of IFRC research.

An injection experiment was performed in October 2009 where 264,979 L of upgradient groundwater with 5 µg/L U and Br tracer (180 µg/L) was injected into the upper high K, middle low K, and deep high K conductivity zones of fully screened well 2-9 (Figure 1). The experiment was described in detail in our Fourth Quarterly Joule Report (Q4) that is posted on the SBR and Hanford IFRC web sites. At the time of injection, the average background U(VI) concentrations as determined by sampling and analysis of the depth discrete wells was 44 µg/L in the shallow zone, 40 µg/L in the middle zone, and 26 µg/L in the deep zone. IFRC wells were monitored for approximately 366 h while the injected plume (tracer) was within the domain of the well-field. The desorption plume dissipated by the final, down-gradient well tier (e.g., 3-28, 2-29, and 2-23). However, unexpected river stage oscillations began at approximately 1500 min that increased in intensity throughout the remainder of the experiment and caused complex breakthrough behaviors for approximately 25% of the IFRC wells (e.g., Figure 10). A first assessment the breakthrough curve in Figure 10 might conclude that the data are spurious or a consequence of neglectful analyses. The data, however, can be fully reconciled as a consequence of well-bore flow, and the different U concentrations and Br transport velocities that occur in the upper and lower high K zones. [Note that an uncompromised tracer experiment has shown that transport velocities are faster in the deep high-K zone]. The breakthrough curve is interpreted as follows: i.) 0-1,500 minutes, upward borehole flow – data shows initial breakthrough of low U and Br in the deep low K zone, ii.) 1,500-4,000 minutes, downward flow – data reflects U and Br concentrations in upper high K zone, iii.) 5,000-19,500 minutes, oscillations between upward (low U) and downward (high U) flow – complex Br data reflects differential mobility and mass transfer effects in upper and lower high K zones. While the data in Figure 10 can be qualitatively interpreted, it (and the other wells displaying comparably complex behavior) is not amenable to quantitative modeling or suitable for publication in a top-tier journal. Consequently the well-bore flows compromise data quality to the point that the experiment fails the needs of the Hanford IFRC project.

We have implemented well-bore flow modeling (Zheng, 2006) in the interpretation of our March 2009 tracer experiment (Ma et al., 2011), but the breakthrough behavior of only a few wells can be adequately described. The inability to quantitatively model well-bore flows in the IFRC experimental domain results from its influence by both local and larger scale geologic features. The larger features are outside of the IFRC modeling domain and are not well characterized.

Mitigation Trials

Mitigation studies were initiated in January 2010 to document an action to minimize communication between the upper and lower high K zones at the IFRC site. Our approach was to sequentially evaluate solutions of increasing severity: i.) install inflatable packers to increase hydraulic resistance within the well-bore, ii.) increase the number of inflatable packers within a given borehole to further increase hydraulic resistance, and iii.) seal the entire lower section of the well screen with coated bentonite pellets to eliminate well-bore flow. We also considered a test of the FLUTe system if flow through the sand filter pack of the wells was found to be insignificant. A fifth choice was identified as a last, and most extreme, option – to seal the lower well section and its associated filter pack with bentonite slurry or grout.

In the first phase of the mitigation study, single 19" test ball and 30" Solonist low pressure packers (Figure 11) were deployed in a series of IFRC wells displaying (+) and (-) well-bore flow behaviors (Figure 12) for short-term testing. The packers were generally set within the low K zone, and the EBF was placed approximately 0.4 m above them. The packer deployment was performed in association with our Spring 2010 passive monitoring experiment, and was intended to reduce: i.) inter-zone U transfer and ii.) the complicating effects of well-bore flows on the monitoring data as shown in Figure 9. The 30" packers were observed to reduce borehole flows by 40% or more (Figure 12), with many wells displaying a reduction of over 75%. The 19" packer was less effective. Ambient vertical flow profiles were measured, and observed, in the upper section of select wells containing inflated 30" packers (Figure 13). These also exhibited complex profiles indicating increasing downward flow with depth toward the packer in 2-19, and downward flow above the packer in 2-11 transitioning to upward flow near the water table. These varied results indicated that a single packer was unlikely to solve the vertical flow problem to the extent that was necessary for artifact-free monitoring data.

In the second phase of the mitigation study, we focused on temporal studies of mitigation effectiveness in test well 2-21 where U monitoring in association with the Spring 2010 passive monitoring experiment, and a tracer experiment were performed. Well 2-21 exhibits a bulk hydraulic conductivity of 20,300 ft/d, and a range in vertical hydraulic conductivities of 5000-45,000 ft/d (Figure 14). EBF measurements and U samples were taken in well 2-21 with a 30" packer deployed from 6/5/2010 to 7/10/2010 when the Columbia River displayed its maximum yearly fluctuation. The packer significantly reduced the magnitude of well-bore flows as compared to data collected without a packer the year before (Figure 15), but had little impact on the frequency and oscillation of flow that were controlled by river stage changes. Soon after this single packer experiment, a dual packer string was deployed and a simple tracer intercommunication test performed (Figure 16). A 1000 mg/L Cl^- solution was injected into the lower high K zone at 67 mL/min for 137 min for this test, while simultaneously pumping on the upper zone at a rate of 1 gpm. Chloride and specific conductance were monitored in the upper zone purge water (Figure 16). Their concentrations increased during the period of lower zone injection, albeit in relatively small concentration, verifying solute exchange from the lower to the upper zone in presence of the two packers. Challenges in sampling the lower zone waters during Cl^- injection precluded a quantitative assessment of exchange volume. The occurrence of significant upward vertical flows in excess of 2 LPM were confirmed by EBF monitoring during the two-packer test period (Figure 17) indicating that it did not offer significant improvements over a single packer.

Immediately following the two week test with the dual packer string, the lower portion of well 2-21was filled with bentonite pellets, effectively sealing the well-bore from 37.5 to 56.1 ft bgs (Figure 14). This was considered a rather drastic trial as the bentonite seal is permanent. EBF measurements and U sampling and analysis continued after this action. The resulting EBF data (Figure 17) indicated that significant upward vertical flow still occurred in the bentonite-treated well as it did following deployment of the dual packer string. There were, however, significant differences in the vertical flow responses (e.g., direction and frequency) of the two-packer and bentonite tests as compared to the single packer test. These differences remain unexplained, although they are thought to be associated with the difference in river stage conditions. The presence of vertical flow in bentonite pellet-sealed 2-21 indicated continued water exchange between the upper and lower high K zones through the sand/filter pack (10-20 mesh sand) that filled the annular space. The estimated hydraulic conductivity of the filter pack is 1,400 ft/d, which is apparently sufficient to sustain continued well-bore flows on the order of 1-3 LPM given the vertical head gradients that exist. This was unexpected and unwelcome news.

The aqueous U data collected from above the packer/seal in 2-21 during these three mitigation trials was consistent with the EBF data and observed U concentrations in nearby shallow (2-29) and deep (2-30) wells (Figure 18). U(VI) concentrations in the deep high K zone (2-30) increased slowly over the monitoring period from 20 to 40 µg/L. Those in the upper high K zone were generally higher (20-60 µg/L), but more dynamic, with a major concentration dip occurring around 7/1/10 that was associated with the intrusion of dilute river water. [Note, it was observed during the Spring 2010 passive monitoring experiment that Columbia River water moves into the IFRC site through the upper high K zone only]. The upper high K zone waters also displayed more variations in concentration than did the lower zone waters. As previously described, the concentration trends in Figure 18 can be reconciled by consideration of well-bore flows. Generally U(VI) concentrations in 2-21 well waters fell between those observed for the upper and lower high K zones. During the single packer experiment, well-bore flows were more frequently downward with the consequence that 2-21 waters were more representative of upper zone concentrations. Short-term reversals in flow direction during this period led to expected reductions in 2-21 U(VI) concentrations as deeper waters invaded. In contrast, measured well flows were generally upward during the dual packer and bentonite plug tests, and pumped 2-21 well waters in the upper zone displayed concentrations commensurate to those of the lower zone.

Collectively the trends in U concentration indicated that monitoring data in 2-21 were controlled by well-bore flows regardless of mitigation treatment.

Proposed Solution

The mitigation trails discussed above indicated that well-bore flows cannot be eliminated by sealing the internal well volume with hydraulic barriers or swelling bentonite pellets, because significant vertical flows continue through the sand pack in response to head gradients. Given this conclusion, a test of the FLUTe system was not performed.

Our proposed solution to mitigate the IFRC well-field therefore contains two elements. First, seal the lower 2/3 of the fully screened interval and the associated sand pack with grout. Bentonite slurry was considered, but we concluded that it was insufficiently robust given the severity of the problem. After grouting, a groundwater monitoring system will result that primarily accesses the upper high K zone where U recharge to the aquifer and river water intrusion occurs. [Note, existing depth discrete wells in the intermediate low K and deep high K zones will remain that could be augmented by additional depth-discrete placements.] This solution will compromise the IFRC geophysical monitoring system and prevent future down-hole measurements over the grouted depth intervals. Consequently, the second element is to re-install a complementary geophysical monitoring system that builds upon, improves, and fully integrates the remaining/surviving elements of the original electrode/thermistor array. Details are provided on these two elements below.

Well Grouting: The proposed well remediation process will involve: i) setting a packer within the screen near the upper/central portion of the lower permeability interval, ii) injecting groundwater into the upper zone above the packer (pulled from a distal well field location) to increase pressure and assure downward flow through the filter pack, and iii) gently pumping grout through the packer and into the lower zone until sufficient volume is emplaced to displace fluids in the filter pack and near-well formation. Care will be taken to limit the amount of grout that is pumped into the lower zone to minimize impacts on groundwater chemistry. The grout will be formulated thin enough to effectively penetrate the 20-slot screen and 10-20 mesh sand filter pack, but will be thick enough to remain in place during the cure process and form a competent seal. Cement-based grout products are commonly used in well remediation applications where a hard setting seal is required. In addition to this material, non-cement-based materials will be considered with the overall objective to minimize subsequent effects on local groundwater composition such as pH and sulfate concentration. Once the grout is sufficiently set, the packer will be removed, and coated bentonite pellets will be tremied to seal the remaining wellbore volume up to the bottom of the desired sampling interval. The bentonite plug will separate the upper sampling interval from any direct contact with the grout material. Six inches of pea gravel will be placed on top of the bentonite plug to protect down-hole equipment.

During grouting, pressure will be monitored both above and below the packer to assure that a downward gradient is maintained that prevents upward migration of grout into the sand pack of the desired monitoring interval. If possible, the EBF will be deployed along with the packer string to measure wellbore flow just above the packer, providing additional indication of flow direction, and a real-time indication of grouting effectiveness. Space limitations within the 4-in diameter well screen may prohibit use of the EBF during grouting, but attempts will be made to modify the packer string to accommodate the probe. Once the seal is in place, an ambient EBF survey will be conducted over the upper screen interval to verify that intercommunication with the lower zone has been effectively mitigated. Longer-term aqueous monitoring will be performed to provide definitive evidence of seal performance and to assess effects on groundwater composition.

Geophysical Monitoring System: Thermister and ERT electrode strings will be installed at new locations between the existing wells (Figure 19). The electrode strings will extend from the ground surface to a depth of 60 ft. The proposed layout provides a dedicated geophysical monitoring array that eliminates interferences with the down-hole specific conductivity probes and ion-specific electrodes used to monitor tracer tests that was problematic in our original monitoring system. The boreholes for relocation of the electrode and thermistors strings will be installed by direct push technology using a cone penetrometer technology (CPT) and the Enhanced Access Penetration System (EAPS).

It is critical that the ERT electrodes and thermistors be in intimate contact with the formation. However, the need for a common design that will facilitate measurements in both the unsaturated and saturated zone presents a challenge in maintaining a low contact resistance in the vadose zone. Our preferred methodology is to utilize access tubes where the electrode string is cased with slotted plastic tubing surrounded by neat cement. A geo-textile sock is used to prevent ingress of cement grout into the access tube. With this design, the ERT boreholes can hold water or an agar gel, and the sensor strings can be lowered in place for cross-hole measurements. There are three advantages to this configuration: i) a considerably lower contact resistance in the vadose zone; ii) the ability to change electrode types to allow more specialized measurements like complex resistivity; and iii) access for other geophysical logging tools like radar, as the access tubes would be free of cable over their entire length. As an alternative, the electrodes can be grouted in-place if laboratory testing shows our preferred approach to be impractical or ineffective.

The vertical spacing of electrodes will be changed in the new geophysical monitoring array from a 30 to 15 electrode configuration (Figure 20) to be more cost-effective. This decision was based on a synthetic ERT modeling study where the ability of the 15-electrode configuration to resolve known targets relative to that of the 30-electrode configuration was tested. The simulation utilized a synthetic subsurface bulk conductivity distribution that was representative of the true subsurface conductivity structure at the IFRC site. Modeling results indicated the smaller electrode spacing (30-electrode) resulted in high sensitivities close to the electrode strings and lower sensitivities between wells. The larger electrode spacing (15-electrodes) resulted in a more uniform sensitivity distribution, and comparable resolution of inter-well heterogeneities. A 15-electrode array would be less expensive to construct (≈ $1K per array), easier to install, and would be simpler to operate. It would also allow simultaneous monitoring of 12 wells with the current ERT/IP measurement system, whereas the current 30-electrode configuration allows monitoring of only six wells simultaneously.

Concluding Remarks

In this September 2010 Hanford IFRC Quarterly Report, we have provided a synopsis of field evidence for vertical flows in our fully screened monitoring wells, displayed the effects of these flows on monitoring data from passive and injection experiments, presented test results from field trials of mitigation actions, and concluded with a proposed course of action for well-field mitigation. This action involves grouting the lower domain of the fully screened wells and relocation of the geophysical monitoring system. We seek a review of our proposed course of action, and suggestions for its implementation. As discussed herein, well-bore flows have complicated the interpretation of our field experiments and the problem needs to be rectified before initiating additional experimental campaigns.

The Hanford IFRC would like to perform well-field mitigation in November-December 2010, but the date can be delayed to assure preparedness. An experienced contractor will be needed to perform this activity, as each well will have to be handled individually based on its hydraulic conductivity profile, and finesse will be necessary in grout formulation and monitoring delivery. The composition and properties of the grout will have to be carefully considered, with the possibility that some laboratory experimentation may be required on candidate formulations to assess potential geochemical effects. Project personnel have had discussions with a Hanford group that has over 25+ years in well remediation/decommissioning experience, and they expressed confidence that our mitigation objectives could be meet. While we consider them potential contractors for the work, we are actively searching broadly for the most qualified team to perform the task. Suggestions are welcome.

Mitigation of the well field will yield a monitoring system with primary access to the upper high K zone and the seasonally water-saturated smear zone that is less compromised by vertical flow artifacts. This zone is a most interesting one for research because it controls U recharge to the overall groundwater plume and is a primary apparent conduit for groundwater-river exchange and mixing. Significant opportunities exist in characterizing the in-situ kinetics of groundwater U recharge in this zone, and it's adsorption-desorption behavior in response to changes in groundwater flow directions, rate, and composition. The mitigated monitoring array will also include three depth-discrete wells in both the intermediate low K zone and the deep high K zone that remain from our original well-field installation (Figure 1). These will continue to allow monitoring of water compositional trends in the two deeper aquifer zones. Future plans call for the installation of a series of depth-discrete wells in the deep high K zone along the axis of the erosional channel that cuts through the central region of this site (Blue, Figure 5). Previous tracer experiments have shown this channel feature to be the preferred pathway for solute migration away from our injection well (2-9, Figure 1) in the deep high K zone, and out of the IFRC site domain.

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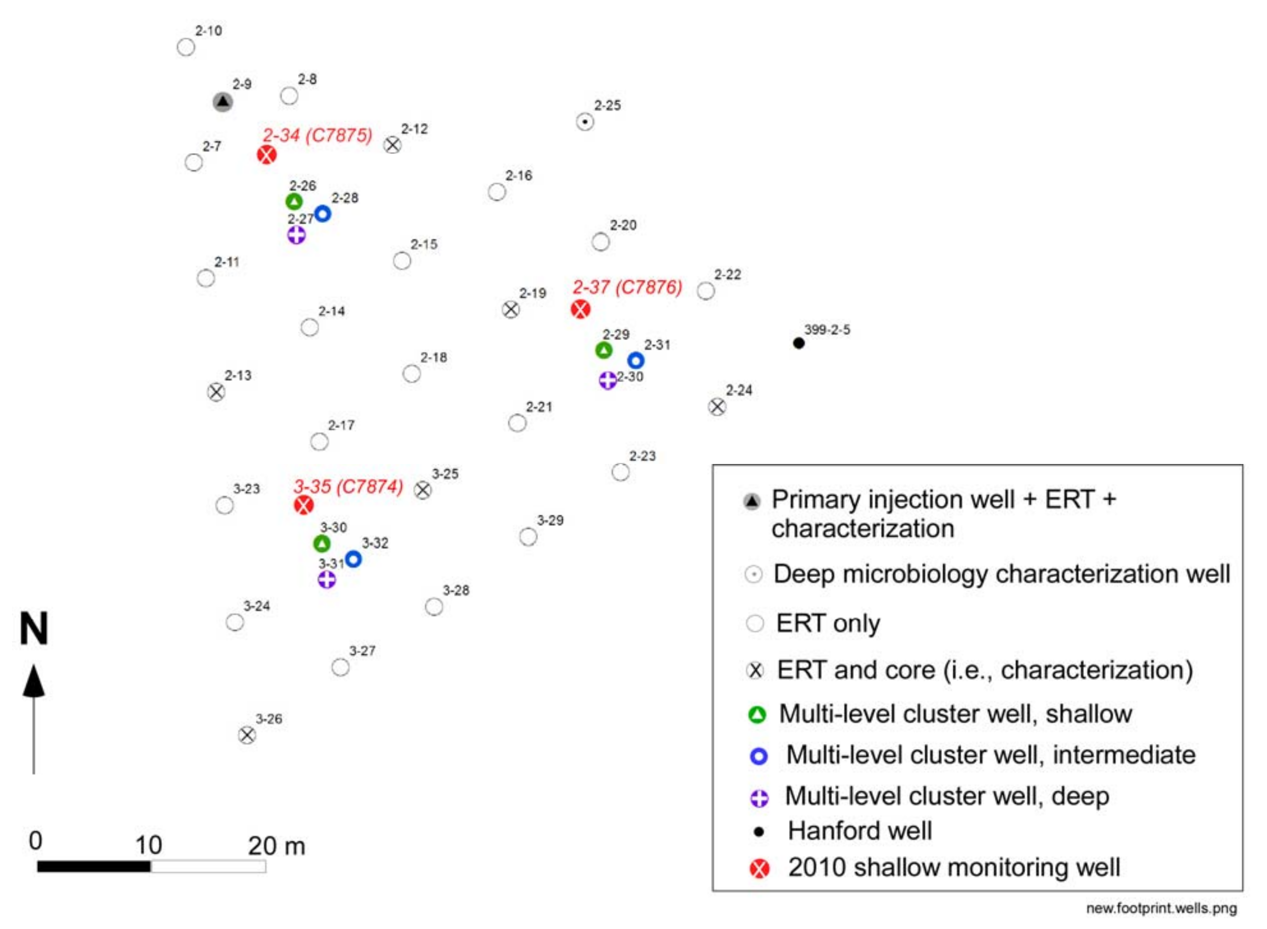


Figure 1. Hanford IFRC well-field.

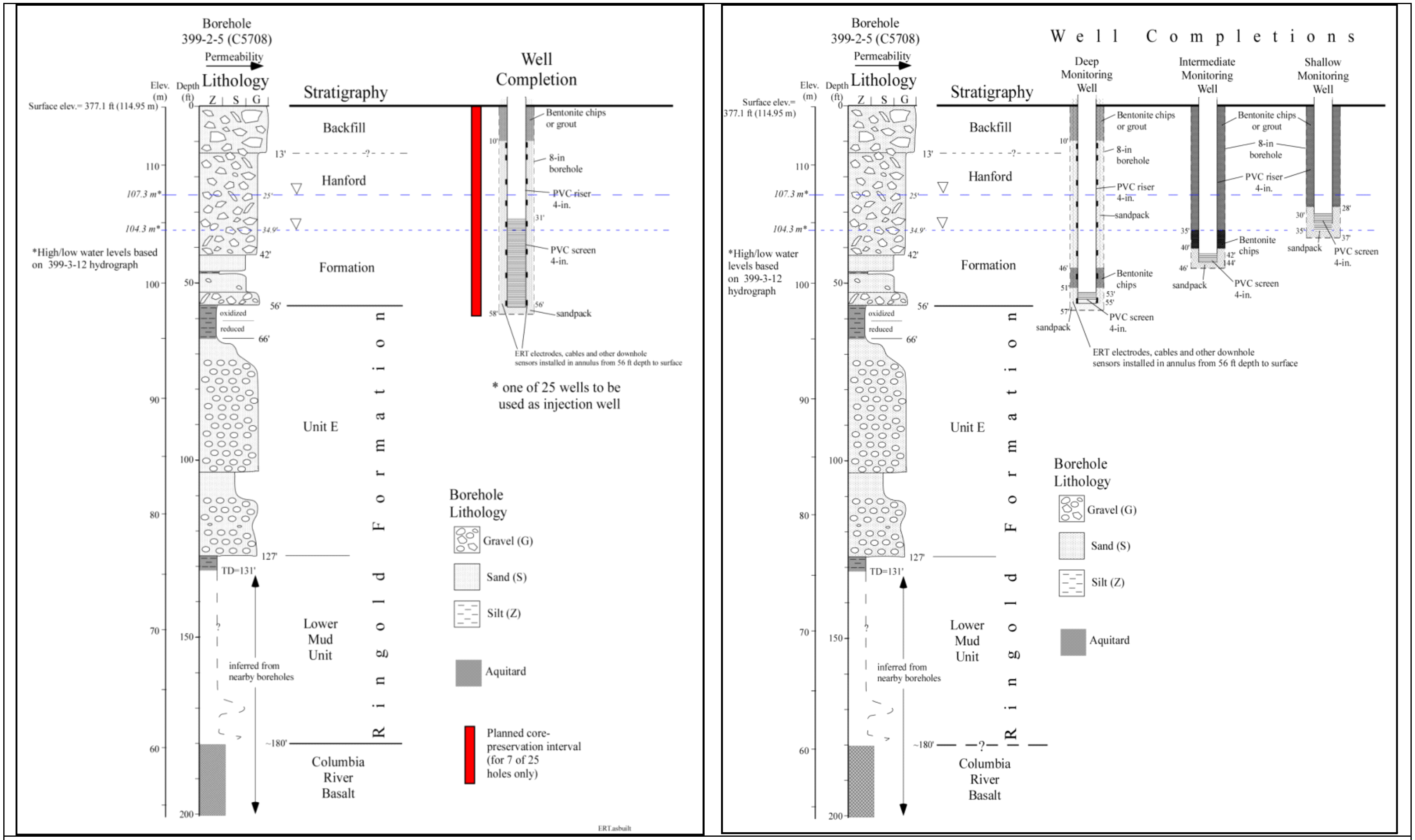


Figure 2. Well design and completion for the fully screened wells (a), and the depth discrete clusters (b). The lithology is shown for well 2-5, but it varied significantly in different well locations.

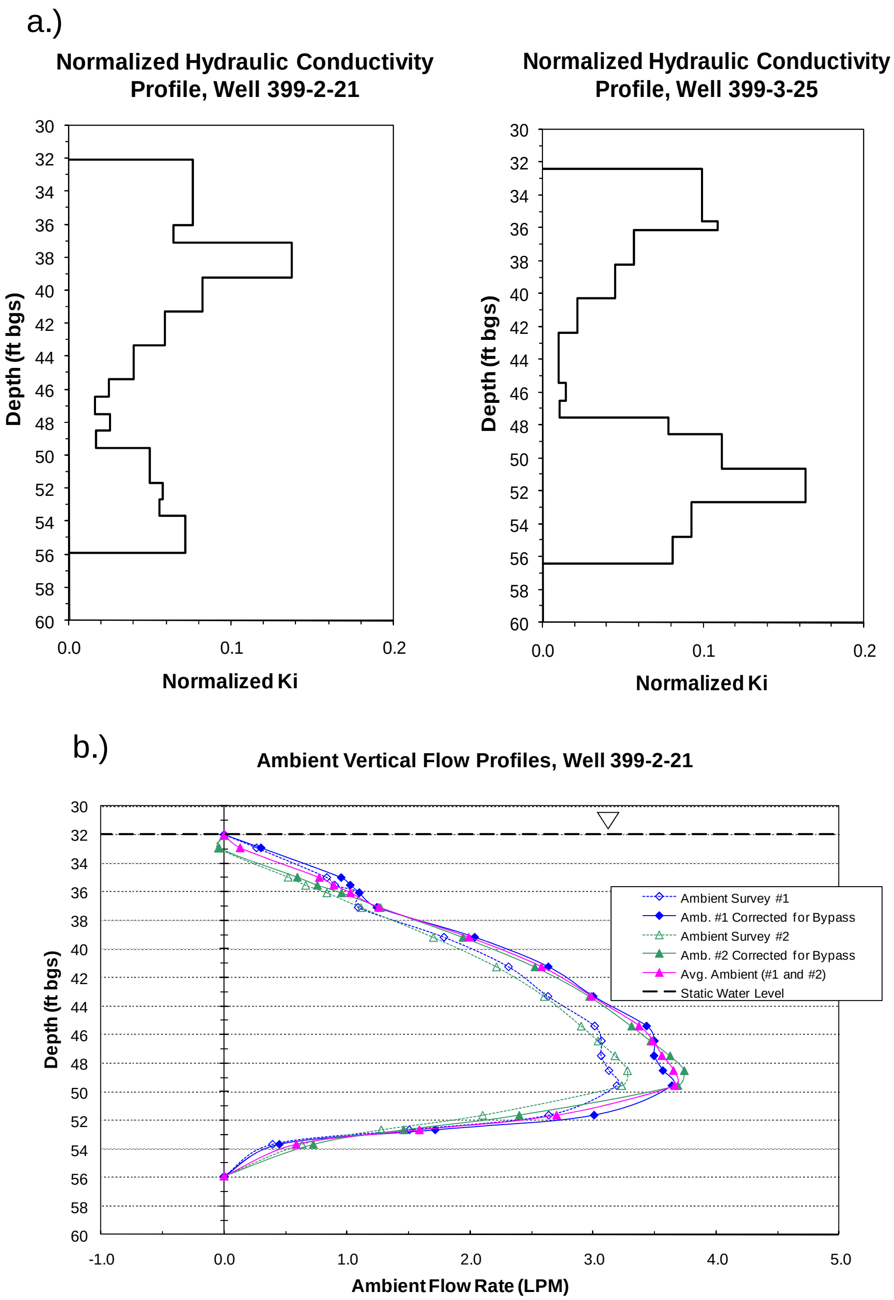


Figure 3. Normalized hydraulic conductivity profiles for two representative IFRC wells measured by EBF displaying the upper high K, intermediate low K, and deeper high K zones (a). Ambient vertical flow profile measured for well 2-21 by EBF (b). The positive values of ambient flow indicate water flow from the lower to upper high K zones.

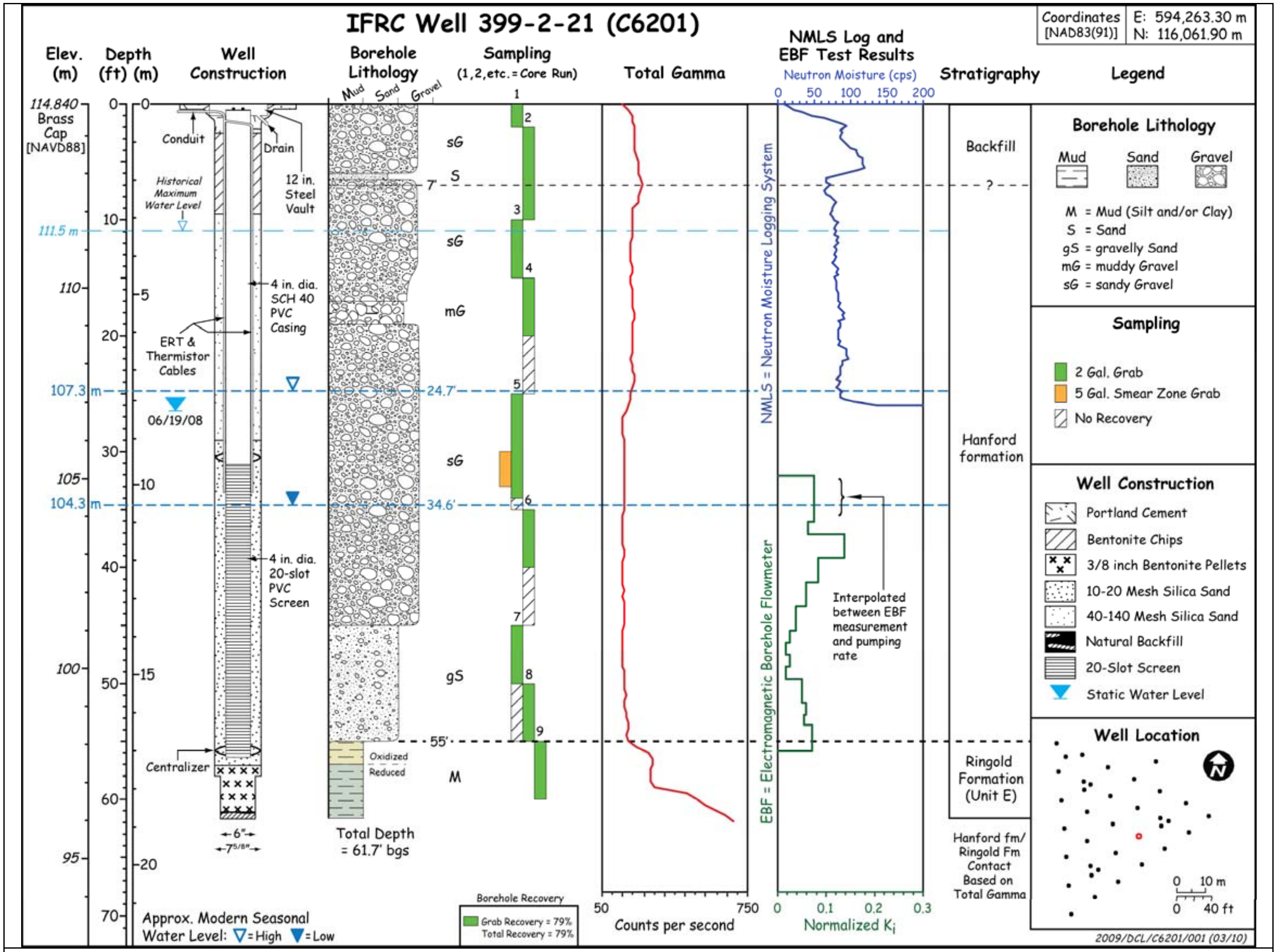


Figure 4. Well completion summary of well 2-21 from Bjornstad et al., (2009). Note lack of obvious correlation between the lithologic log here, and the hydraulic conductivity profile in Figure 3.

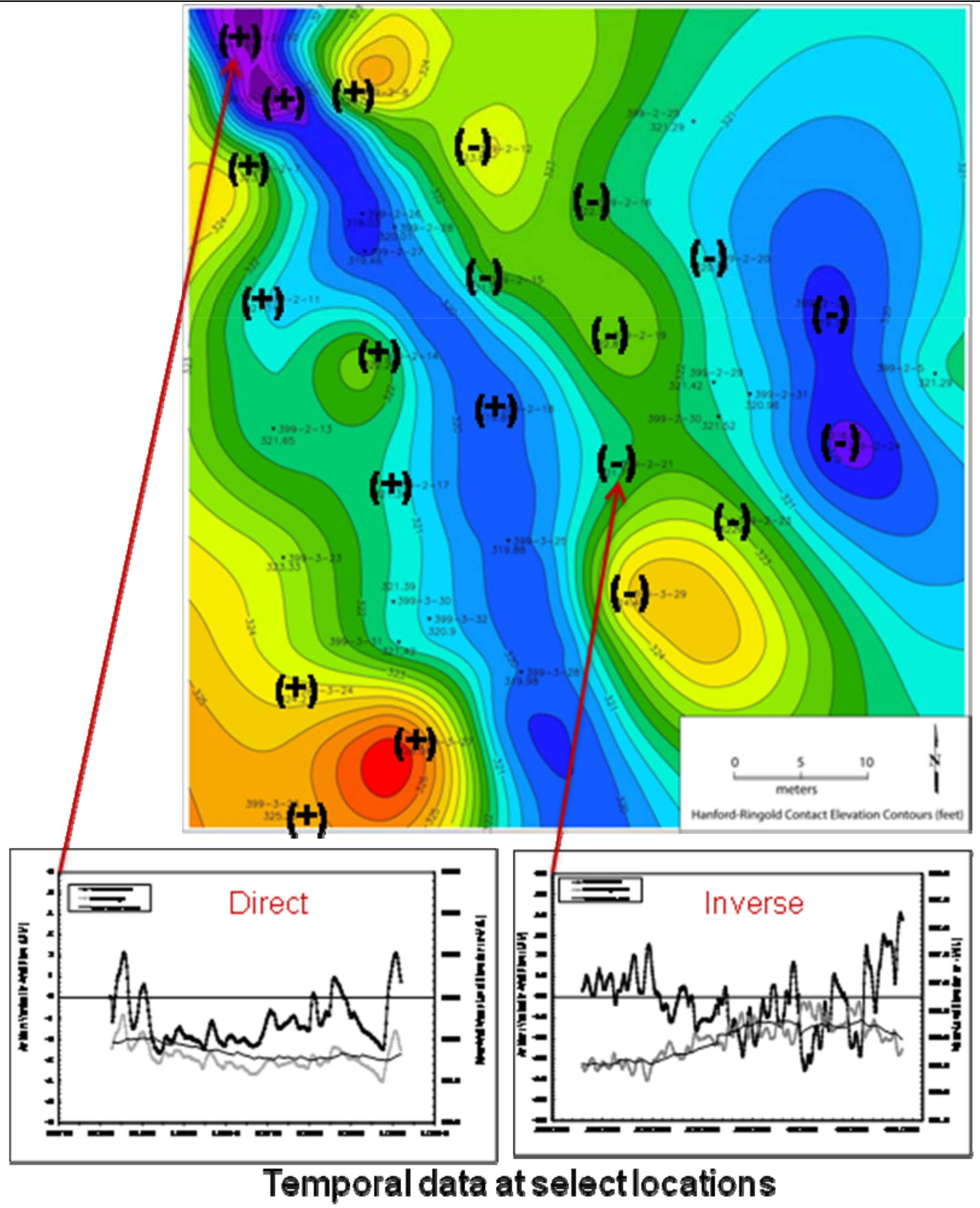


Figure 5. Topography of the Hanford-Ringold contact existing approximately 50-60’ below the IFRC surface. The upper Ringold formation acts as an aquitard at the IFRC site. A topographic low (blue) in the contact runs through the center of the IFRC site that is believed to be a paleo-erosional channel. The lower Hanford formation that fills this channel is a preferential flow path for solute migration from injection well 2-9. The directions of vertical well-bore flows in response to river stage changes, e.g., (+ or- as described in the text) are controlled by well location relative to the channel. The channel is believed to intersect the Columbia River both north and south of the IFRC site, functioning as a conduit for groundwater-river exchange.

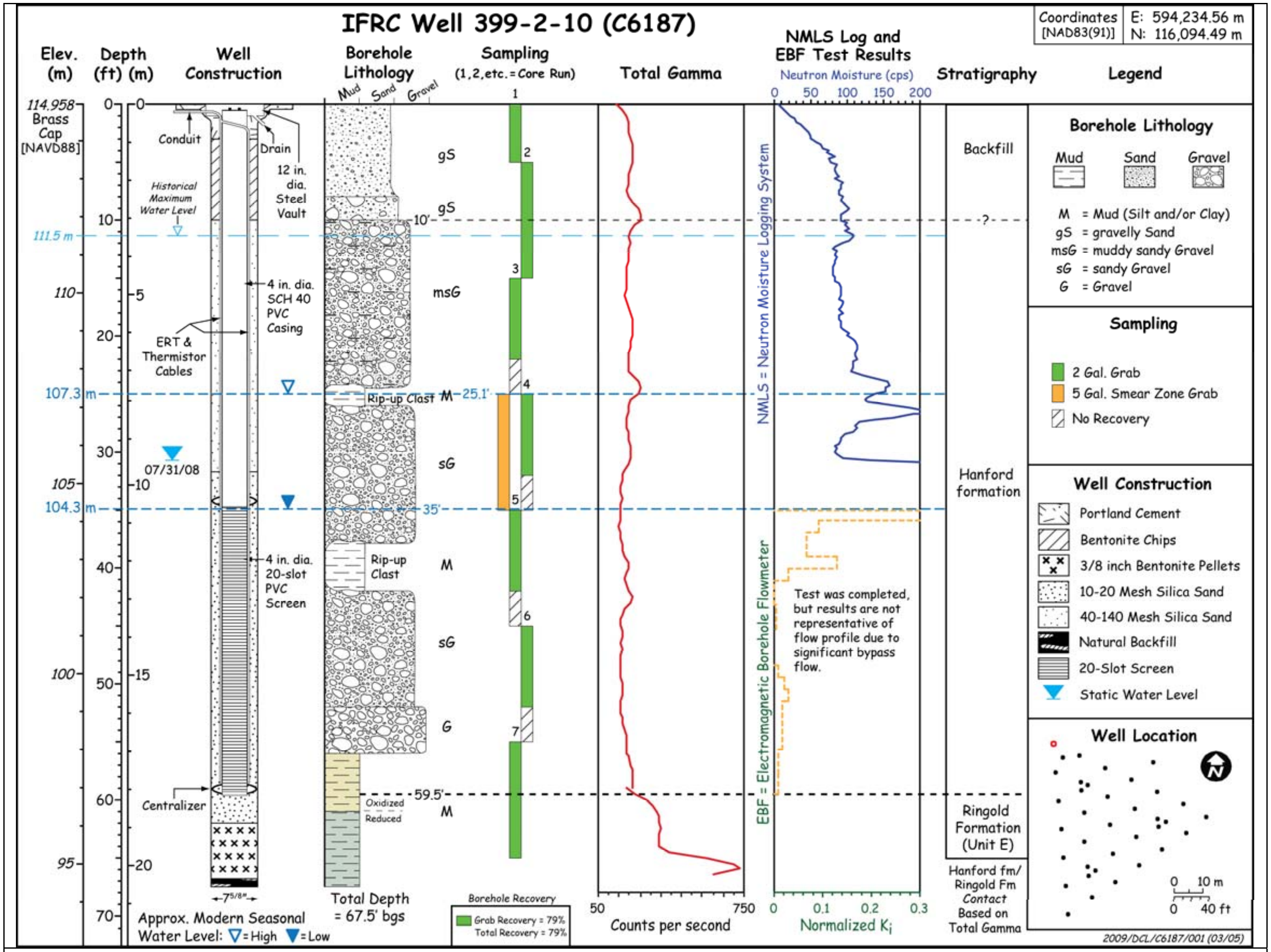


Figure 6. Well completion summary of well 2-10 from Bjornstad et al. (2009).

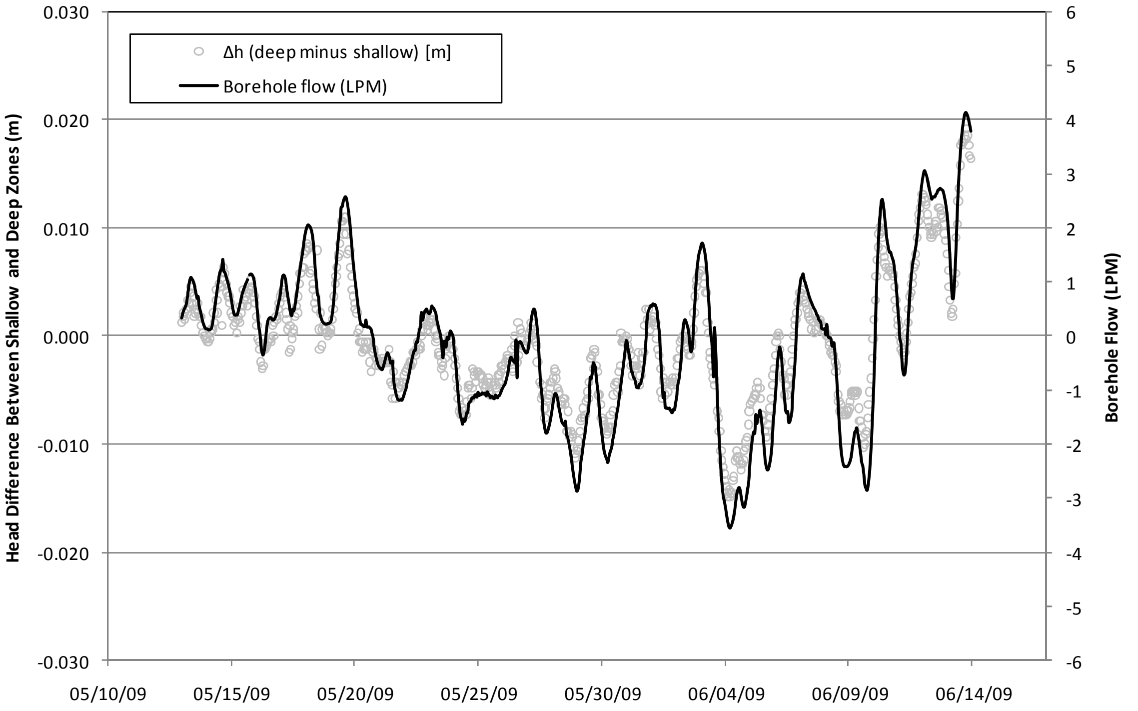


Figure 7. The correlation of vertical head gradient (e.g., Δh from wells 2-29 and 2-30) and borehole flow (LPM) in well 2-21 over the duration of the Spring 2009 passive monitoring experiment.

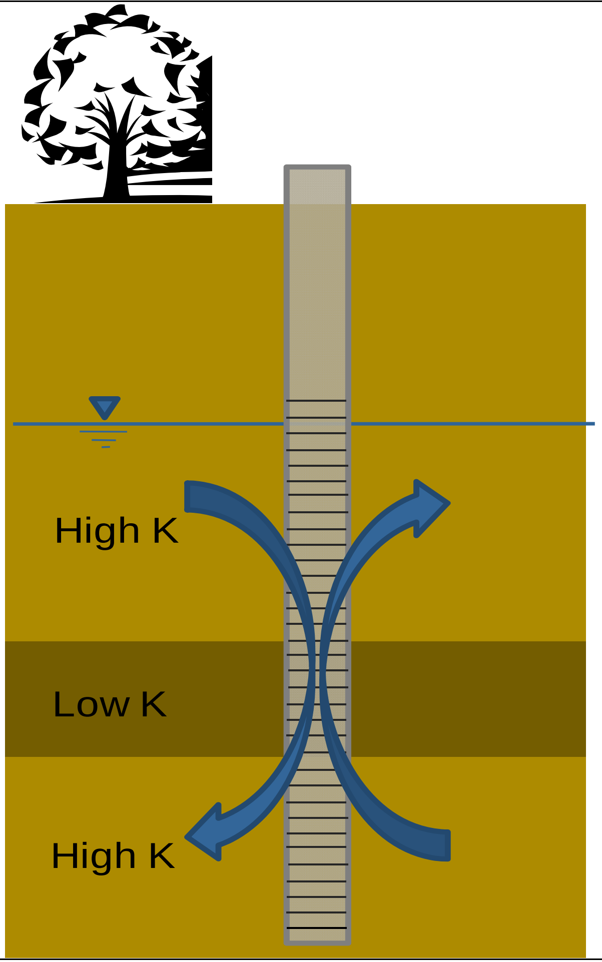


Figure 8. A conceptual model for well-bore flows in the IFRC experimental site where the generalized hydraulic conductivity structure is high K – low K – high K. Positive (+) and (-) correlations of vertical flows with river stage changes result from geologic structures both within the IFRC site, and between the IFRC site and the river. Vertical flows result from head differences between the upper and lower high K zones. The breaching of the low K zone by the fully screened wells provides a conduit for vertical flows between the upper and lower high K zones in response to pressure changes from river stage oscillations.

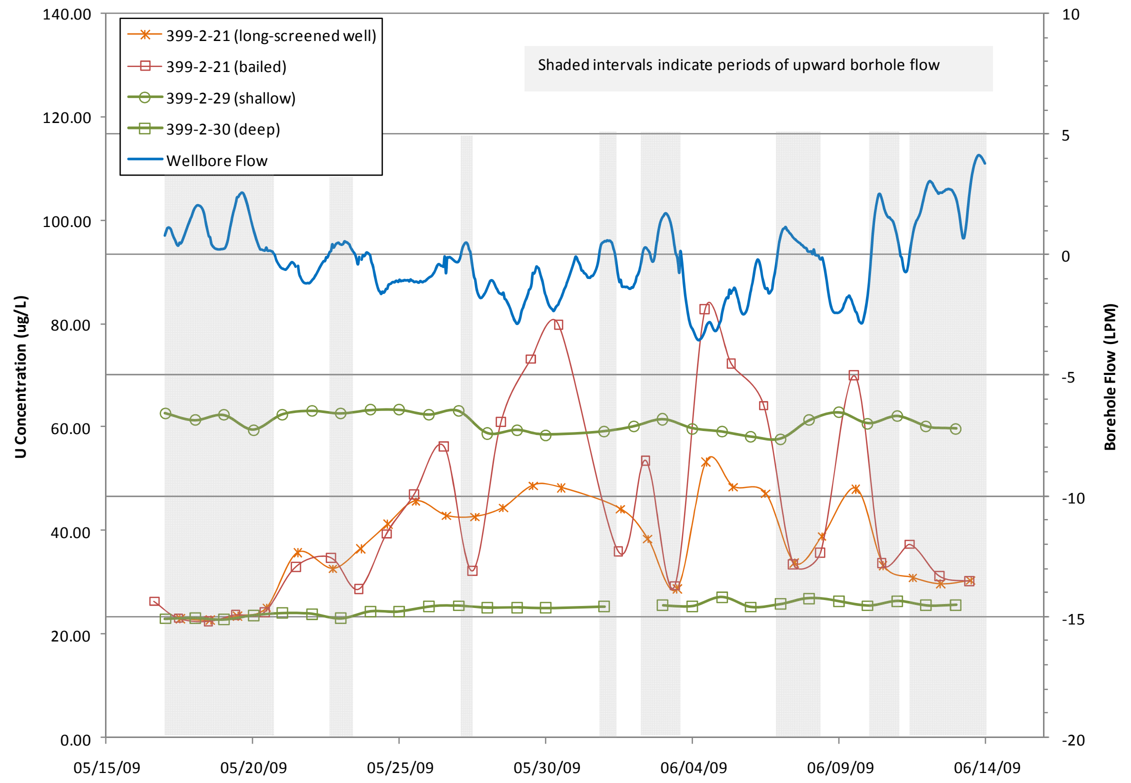


Figure 9. Vertical flow effects on bailed and pumped U(VI) concentrations from well 2-21 during the Spring 2009 passive monitoring experiment. Bailed samples were collected at the top of the water table. Pumped samples were collected three meters below the elevation of high water. Pumped concentrations from depth discrete wells 2-29 (shallow) and 2-30 (deep) are shown for comparison. U concentrations in fully screened 2-21 well waters display distinct inflections that are absent in depth discrete well waters. The inflections correlate with directional changes in well-bore flows that determine whether lower or upper zone waters are dominating U(VI) concentrations.

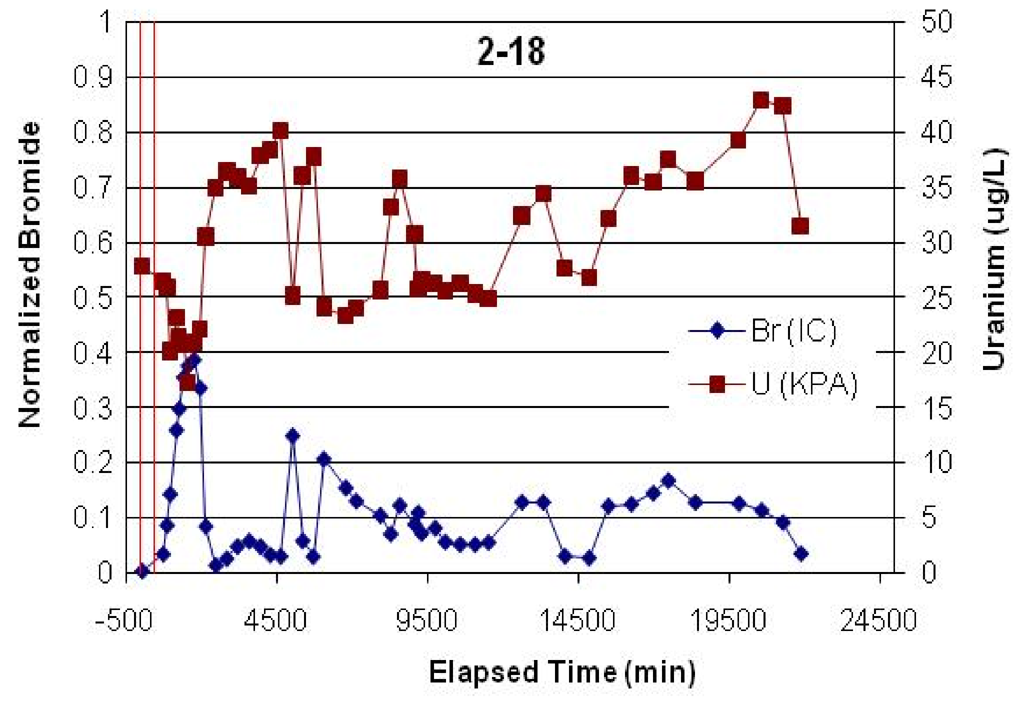


Figure 10. Normalized Br and U(VI) concentrations in well 2-18 during the October 2009 U(VI) desorption experiment. The complex data patterns are not spurious but result from vertical flows that oscillate between the upward and downward directions. The results can be fully rationalized from the compositional differences of groundwaters in the upper and lower high K zones. The results, however, cannot be described with our most robust transport model for the IFRC site domain because the magnitude and directions of vertical flow are not currently predictable within the IFRC domain.

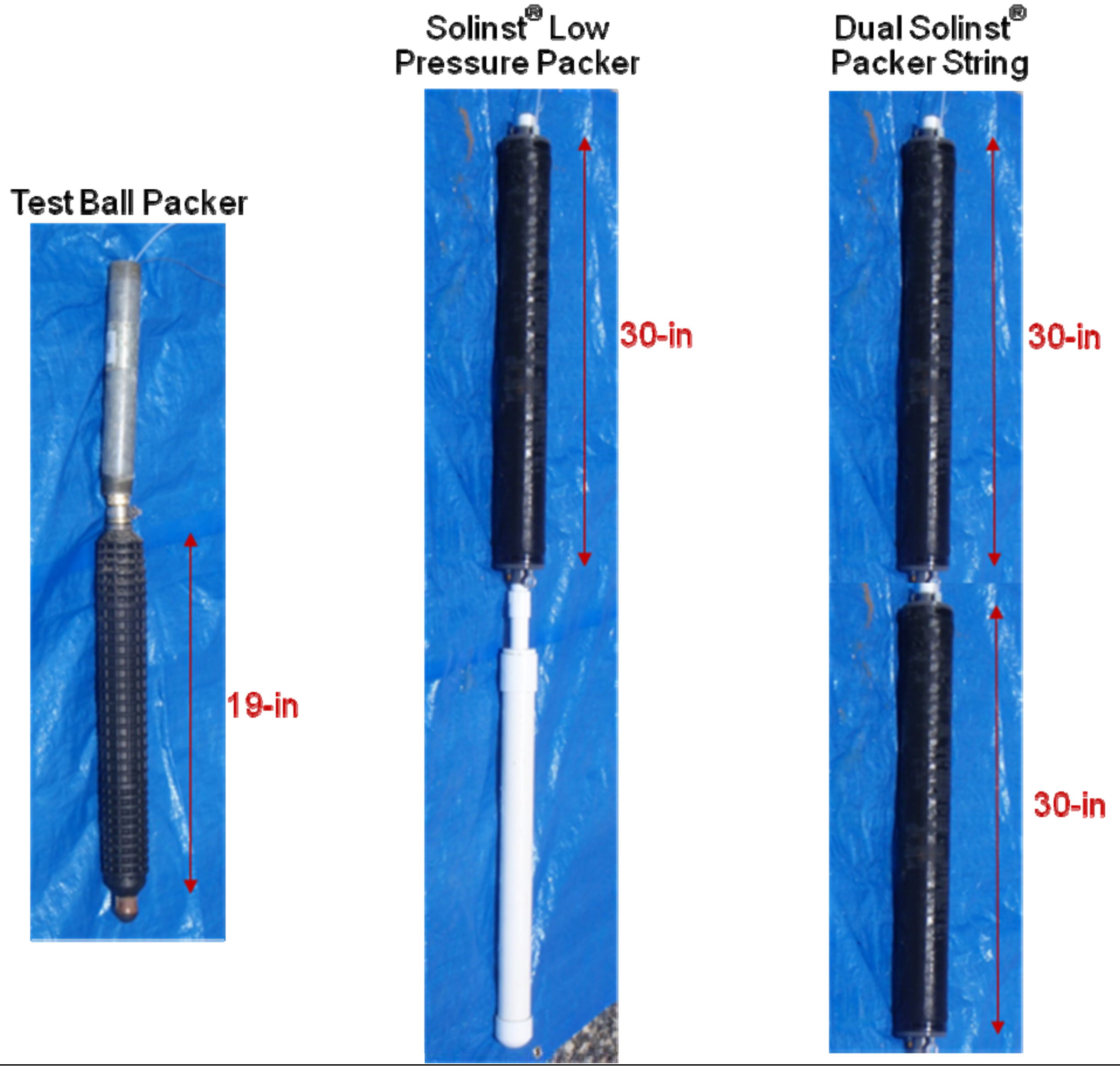
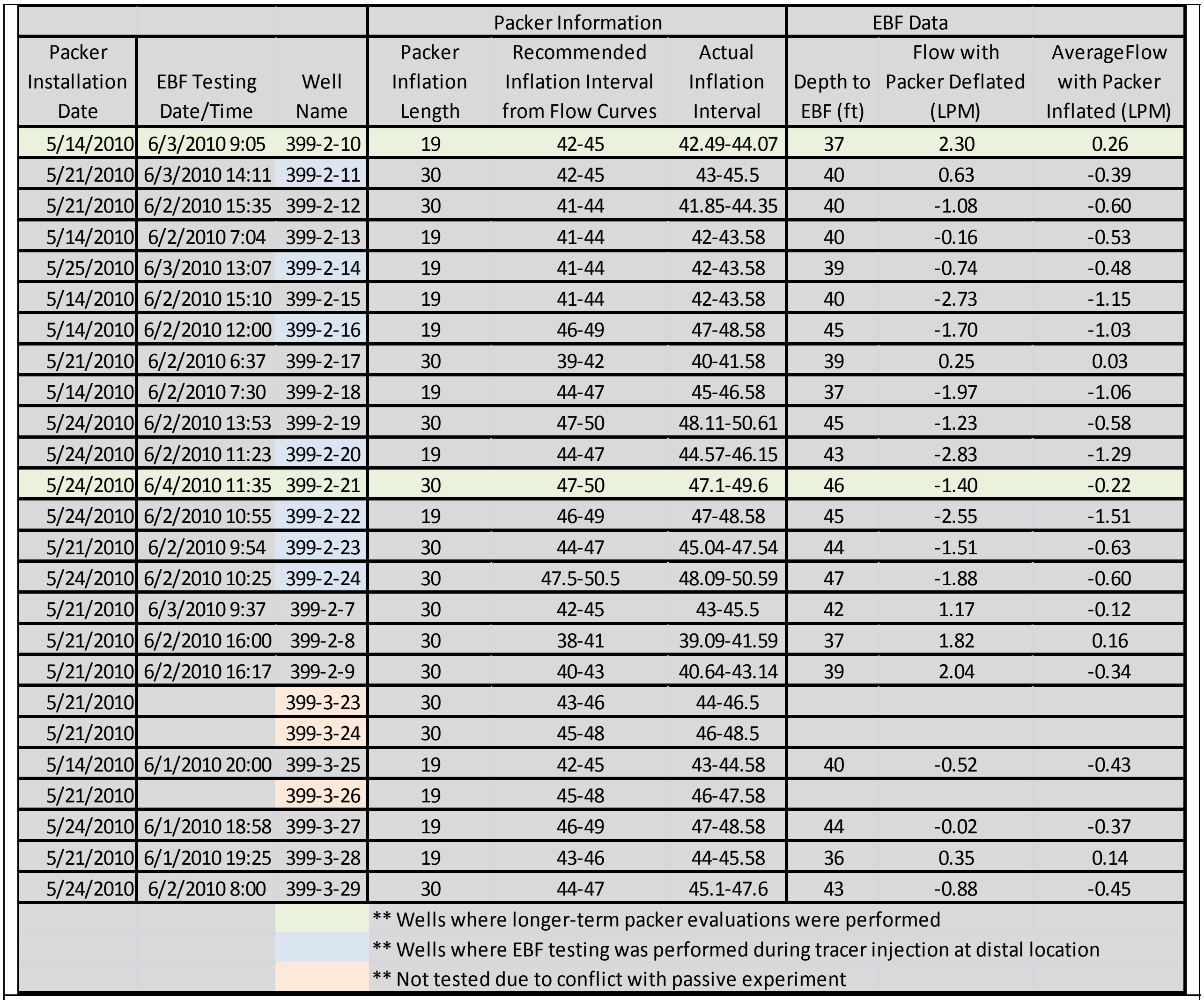


Figure 11. Photographs of the various packers and packer strings used in tests of vertical flow abatement.



			Packer Information			EBF Data		
Packer Installation Date	EBF Testing Date/Time	Well Name	Packer Inflation Length	Recommended Inflation Interval from Flow Curves	Actual Inflation Interval	Depth to EBF (ft)	Flow with Packer Deflated (LPM)	AverageFlow with Packer Inflated (LPM)
5/14/2010	6/3/2010 9:05	399-2-10	19	42-45	42.49-44.07	37	2.30	0.26
5/21/2010	6/3/2010 14:11	399-2-11	30	42-45	43-45.5	40	0.63	-0.39
5/21/2010	6/2/2010 15:35	399-2-12	30	41-44	41.85-44.35	40	-1.08	-0.60
5/14/2010	6/2/2010 7:04	399-2-13	19	41-44	42-43.58	40	-0.16	-0.53
5/25/2010	6/3/2010 13:07	399-2-14	19	41-44	42-43.58	39	-0.74	-0.48
5/14/2010	6/2/2010 15:10	399-2-15	19	41-44	42-43.58	40	-2.73	-1.15
5/14/2010	6/2/2010 12:00	399-2-16	19	46-49	47-48.58	45	-1.70	-1.03
5/21/2010	6/2/2010 6:37	399-2-17	30	39-42	40-41.58	39	0.25	0.03
5/14/2010	6/2/2010 7:30	399-2-18	19	44-47	45-46.58	37	-1.97	-1.06
5/24/2010	6/2/2010 13:53	399-2-19	30	47-50	48.11-50.61	45	-1.23	-0.58
5/24/2010	6/2/2010 11:23	399-2-20	19	44-47	44.57-46.15	43	-2.83	-1.29
5/24/2010	6/4/2010 11:35	399-2-21	30	47-50	47.1-49.6	46	-1.40	-0.22
5/24/2010	6/2/2010 10:55	399-2-22	19	46-49	47-48.58	45	-2.55	-1.51
5/21/2010	6/2/2010 9:54	399-2-23	30	44-47	45.04-47.54	44	-1.51	-0.63
5/24/2010	6/2/2010 10:25	399-2-24	30	47.5-50.5	48.09-50.59	47	-1.88	-0.60
5/21/2010	6/3/2010 9:37	399-2-7	30	42-45	43-45.5	42	1.17	-0.12
5/21/2010	6/2/2010 16:00	399-2-8	30	38-41	39.09-41.59	37	1.82	0.16
5/21/2010	6/2/2010 16:17	399-2-9	30	40-43	40.64-43.14	39	2.04	-0.34
5/21/2010		399-3-23	30	43-46	44-46.5			
5/21/2010		399-3-24	30	45-48	46-48.5			
5/14/2010	6/1/2010 20:00	399-3-25	19	42-45	43-44.58	40	-0.52	-0.43
5/21/2010		399-3-26	19	45-48	46-47.58			
5/24/2010	6/1/2010 18:58	399-3-27	19	46-49	47-48.58	44	-0.02	-0.37
5/21/2010	6/1/2010 19:25	399-3-28	19	43-46	44-45.58	36	0.35	0.14
5/24/2010	6/2/2010 8:00	399-3-29	30	44-47	45.1-47.6	43	-0.88	-0.45

🟩 ** Wells where longer-term packer evaluations were performed

🟦 ** Wells where EBF testing was performed during tracer injection at distal location

🟧 ** Not tested due to conflict with passive experiment

Figure 12. Results of short term single packer tests on vertical flow abatement during the Spring 2010 passive monitoring experiment. Both 19" and 30" packers were evaluated.

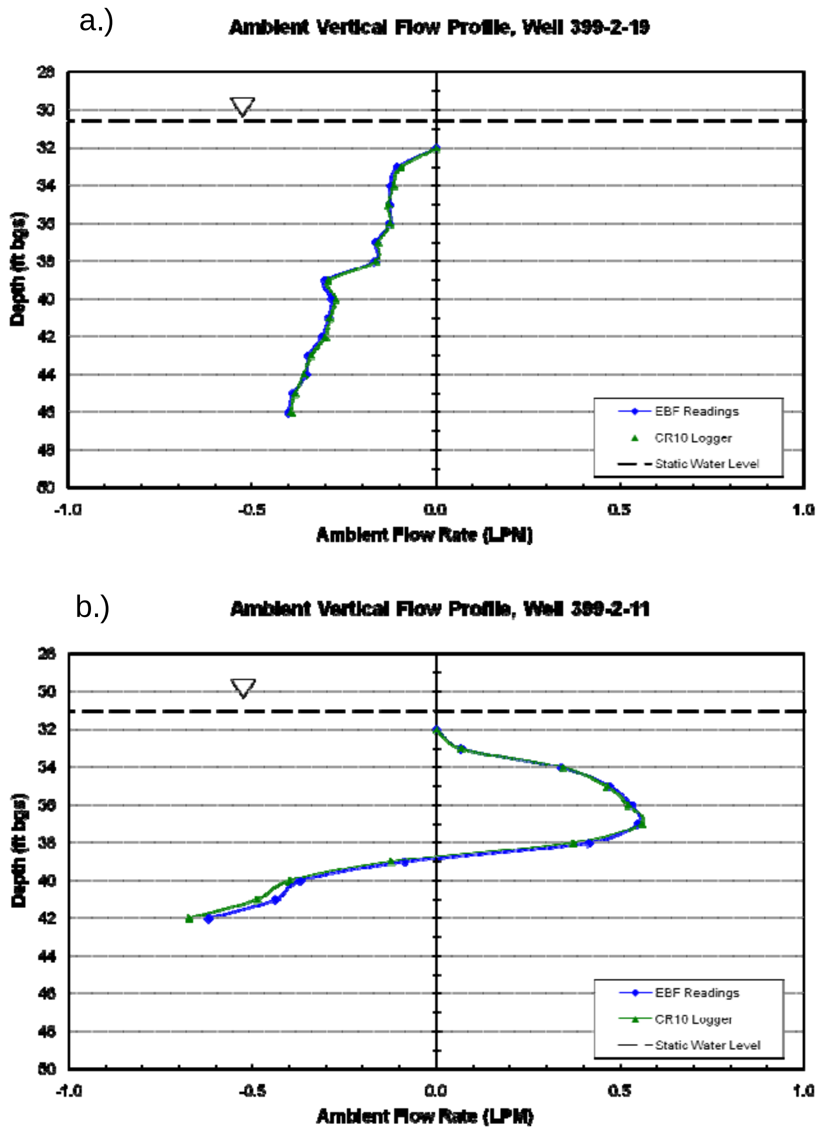


Figure 13. Ambient vertical flow profiles recorded in the upper zone of wells 2-19 and 2-11 in presence of a single 30" packer placed in the center of the low K zone. Active and complex ambient flow patterns were observed in the presence of the packer.

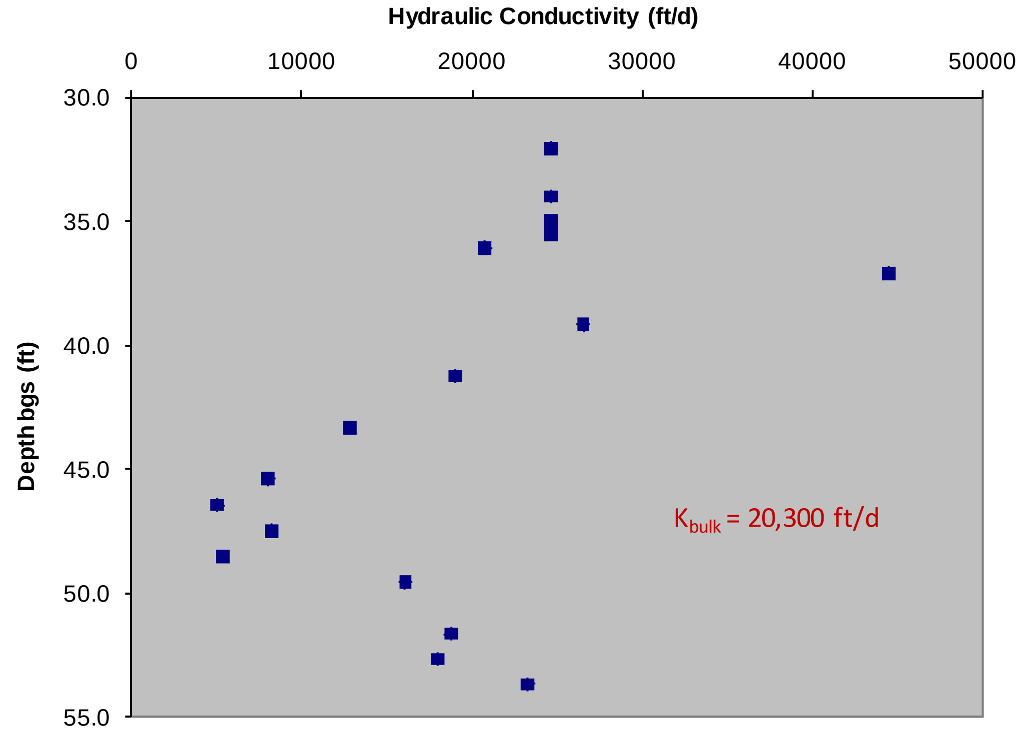
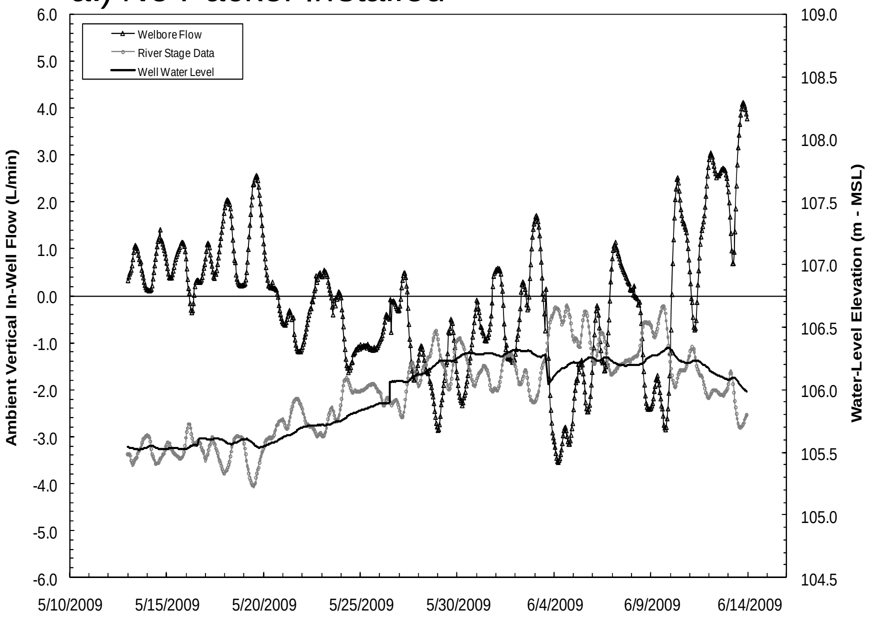


Figure 14. Hydraulic conductivity profile for test well 2-21. The bulk hydraulic conductivity as measured by a constant rate injection experiment was 20,300 ft/d.

a.) No Packer Installed



b.) Single Solinst® Packer Installed

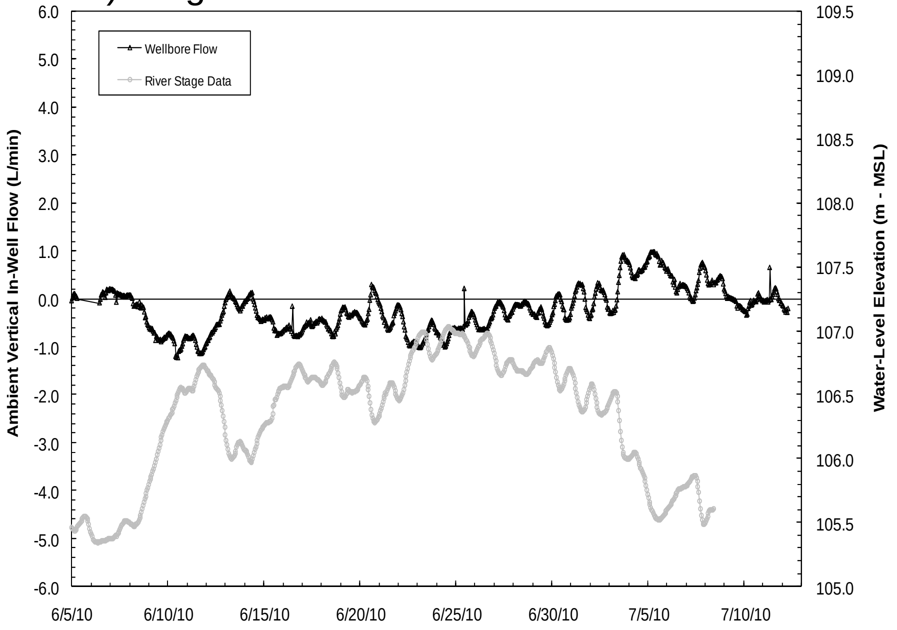


Figure 15. Temporal trends in ambient vertical flows in test well 2-21. (a) no packer installed during the Spring 2009 passive monitoring experiment and (b) with a single 30" packer during the Spring 2010 passive monitoring experiment. River stage data are shown for comparison. Vertical flows in well 2-21 oscillate between the upward and downward directions. Packer deployment reduces but does not eliminate vertical flow.

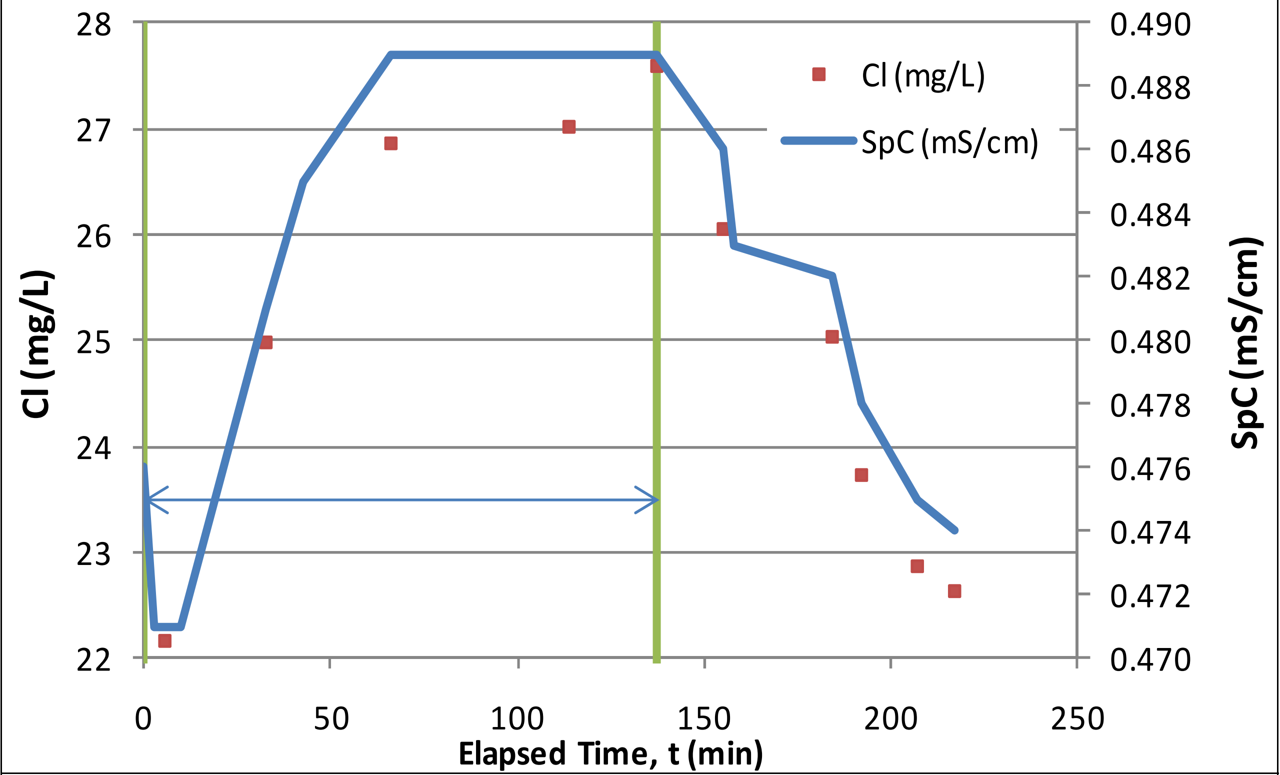


Figure 16. Chloride concentrations and specific conductivity measured above a 2-30" packer string in well 2-21. Tracer (1000 mg/L Cl-) was injected into the lower zone of the well for 137 min. EBF measurements indicated that well-bore flow was upward during the period of injection.

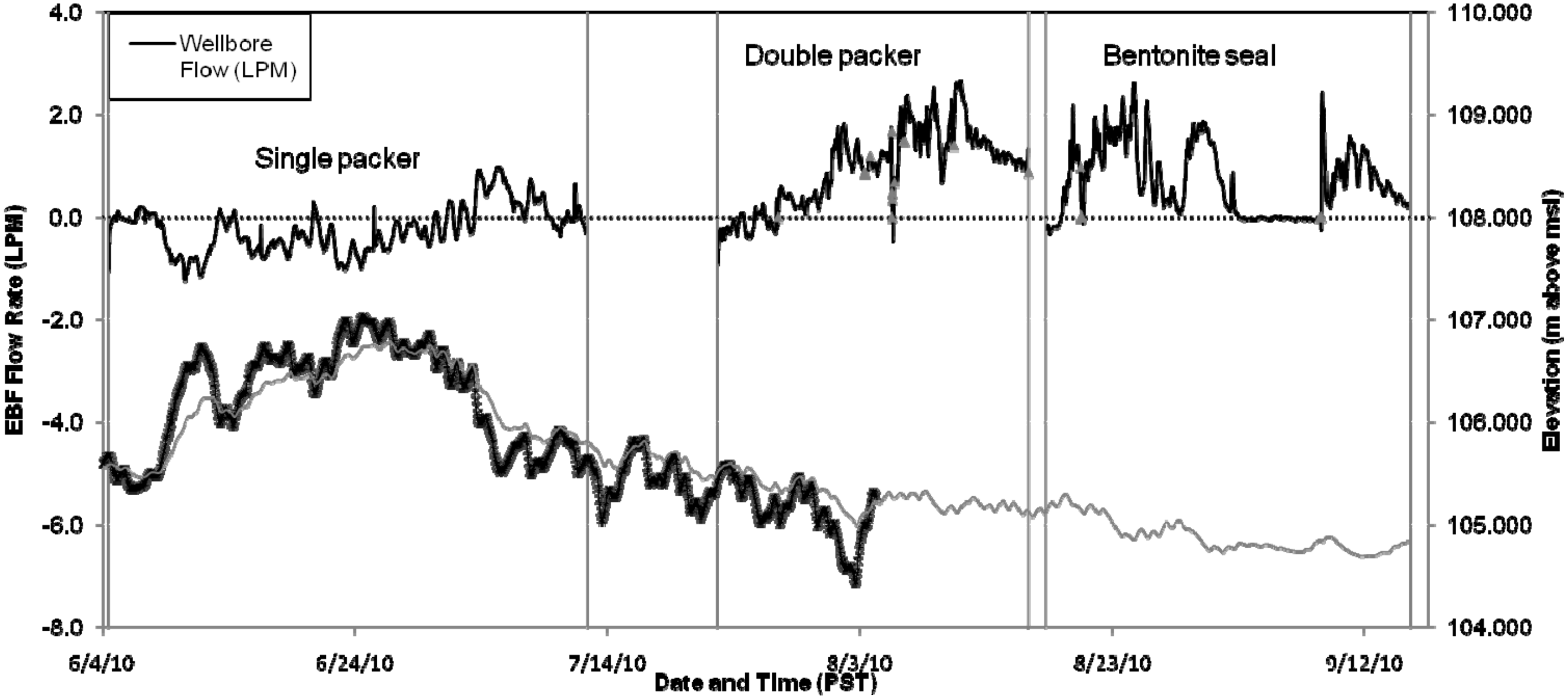


Figure 17. Effectiveness of a single 30" packer, a double 30" packer, and a bentonite pellet seal on well-bore flows in well 2-21. Well-bore flows were higher for the dual packer string and the bentonite seal as these were deployed during a period of decreasing river stage.

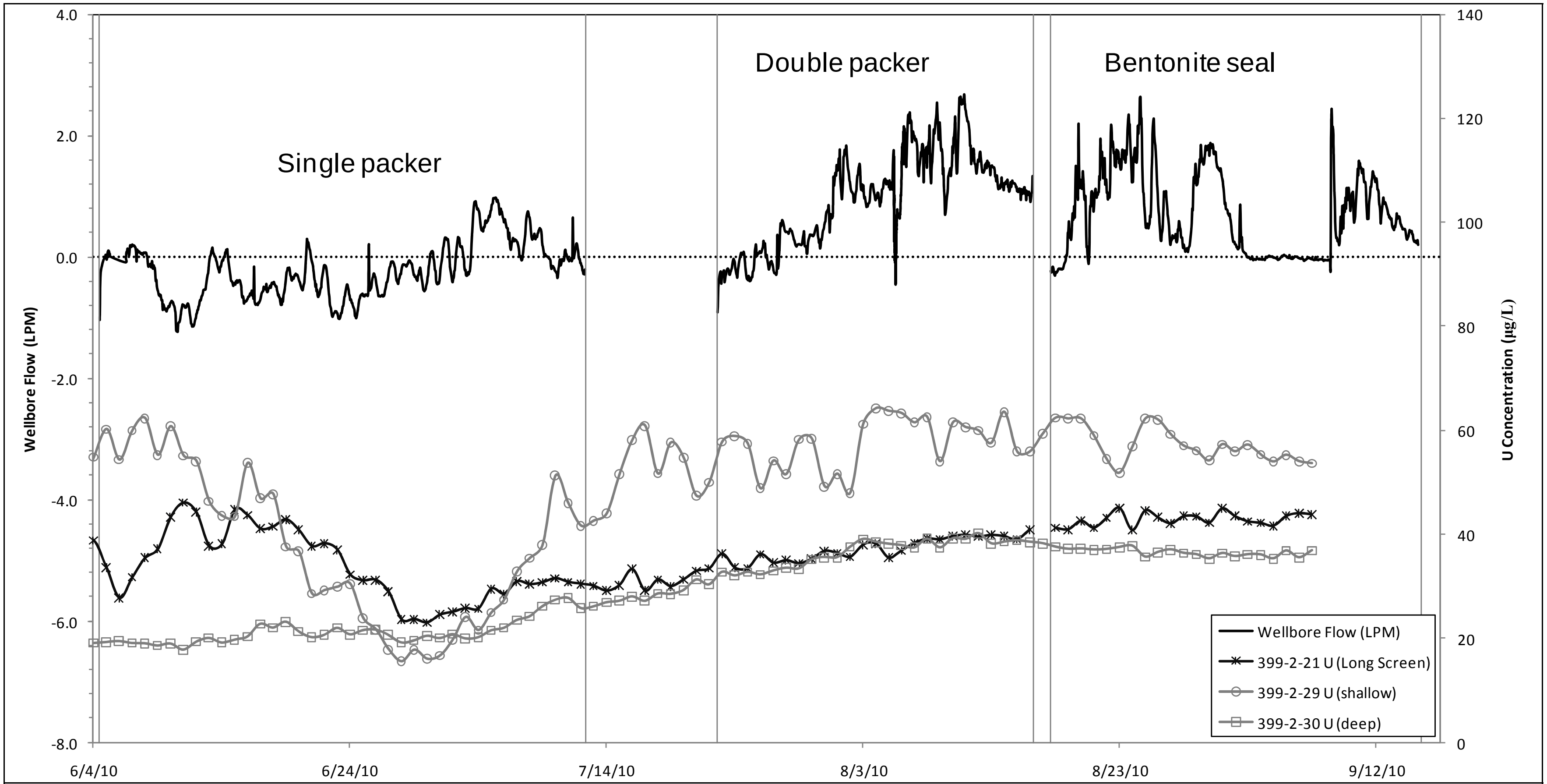


Figure 18. Influence of well-bore vertical flow abatement on monitored U(VI) concentrations in well 2-21 as part of the Spring 2010 passive monitoring experiment. Pumped U(VI) concentrations from nearby depth discrete wells 2-29 (shallow) and 2-30 (deep) are shown for comparison. U(VI) concentrations in well 2-29 display unexplained variability during this period. The concentration of U(VI) in 2-21 waters are more similar to those in the upper aquifer during periods of downward flow, and more similar to lower aquifer waters during periods of upward flow. None of the abatement approaches were successful in eliminating vertical flow.

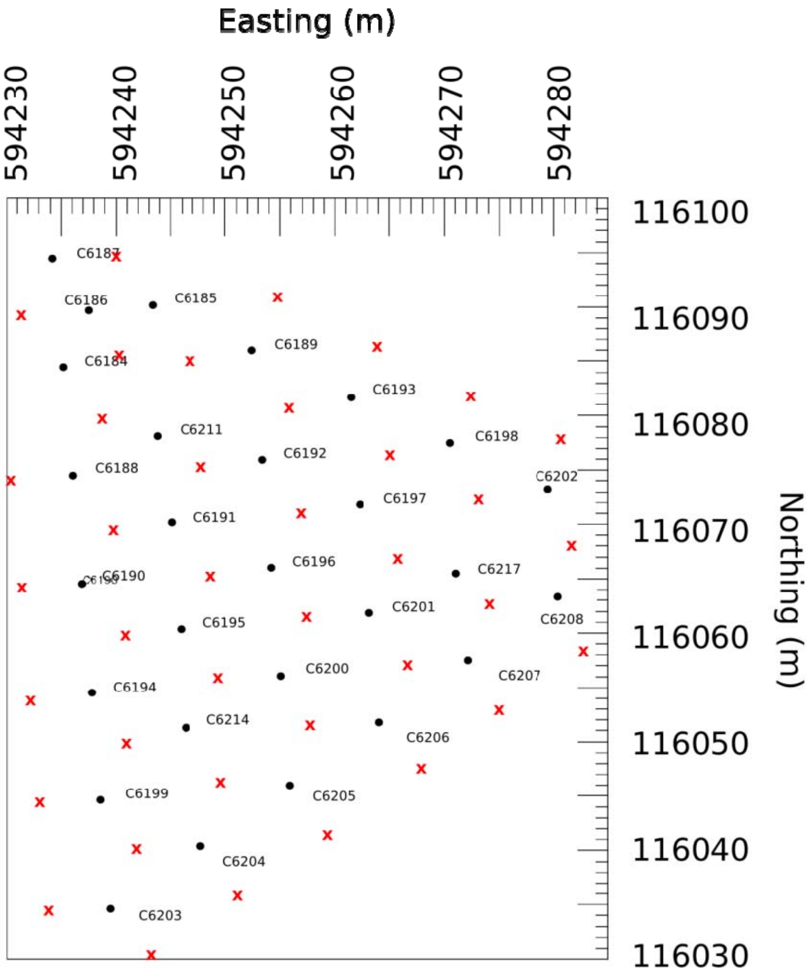


Figure 19. Map of the 300 Area IFRC Well field showing existing wells (dots) and proposed locations of new electrode and thermistors arrays (x).

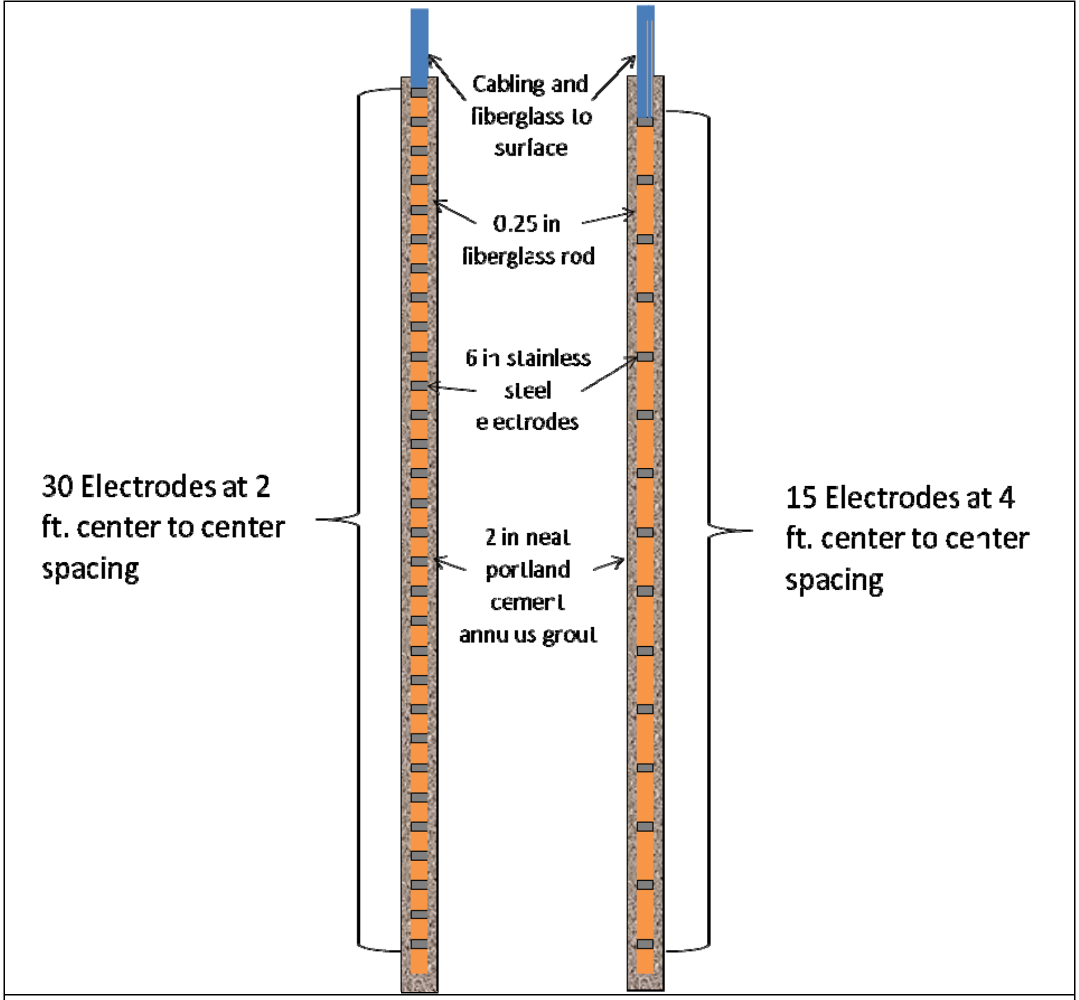


Figure 20. Proposed electrode configurations for new dedicated vertical subsurface electrode arrays at the IFRC well field.