

Sampling in Long-Screened Wells: Issues, Misconceptions, and Solutions

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Abstract

The issues associated with long-screened wells (LSWs) (and open boreholes) at contaminated sites are well documented in the groundwater literature but are still not fully appreciated in practice. As established in seminal and review papers going back over three decades, the interpretation of sampling results from LSWs is challenging in the presence of vertical hydraulic gradients and borehole flow; furthermore, LSWs allow for vertical redistribution of contamination between aquifer layers. Acknowledgment of these issues has led to the development of new technologies and well designs to enable discrete-zone monitoring (DZM), yet LSWs remain common for many reasons, for example, as multipurpose wells, for geophysical logging, and (or) as legacy installations. Despite the literature on LSWs and despite the adoption of DZM at many sites, the use of LSWs persists and the challenges of interpreting sampling results from LSWs remain. In this issue paper, we provide a conceptual overview of the problems posed by LSWs and review existing literature and past work to improve the interpretation of sampling in LSWs. We draw on experience from previous studies at the Hanford Site in eastern WA, USA, and use synthetic examples to illustrate key concepts and challenges for interpretation. A recently published analytical modeling framework is used to develop illustrative synthetic examples and demonstrate a workflow for building scientific intuition to understand issues around interpreting samples from LSWs, which is critical to effective characterization and groundwater remediation at sites with LSWs.

Introduction

Over the 1980s and 1990s, hydrogeologists began to assess and question the use of long-screened wells (LSWs) at contaminated sites (e.g., Giddings 1987; Reilly et al. 1989; Reilly and Gibs 1993; Church and Granato 1996). Over this period, scientific consensus developed that intraborehole flow in LSWs (1) results in sampling bias with respect to contaminant

concentration (e.g., Reilly et al. 1989; Martin-Hayden and Robbins 1997) and (2) may redistribute contaminant mass between aquifer layers (e.g., Lacombe et al. 1995; Sterling et al. 2005). Driven by growing recognition of these issues in the 1990s and 2000s, multilevel sampling became common, and new technologies emerged for discrete-zone monitoring (DZM), including well liners (Cherry et al. 2007) and both permanent and temporary packer systems (Einarson and Cherry 2002; Elci et al. 2003; Einarson 2005; Johnson et al. 2005). Despite increasing adoption of DZM technologies, LSWs remain common for reasons that involve legacy installations, the cost or perceived cost of DZM, and the continued need for multipurpose wells, for example, for pump-and-treat or geophysical logging. Although we focus in this paper on LSWs, there are similar issues with openboreholes.

A major concern with LSWs is cross contamination (e.g., Lacombe et al. 1995) between aquifer layers or fractures connected by the well. LSWs allow for hydraulic communication between aquifer layers or fractures, driven by natural (ambient) differences in hydraulic head

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Received October 2023, accepted June 2024.

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doi: 10.1111/gwat.13427

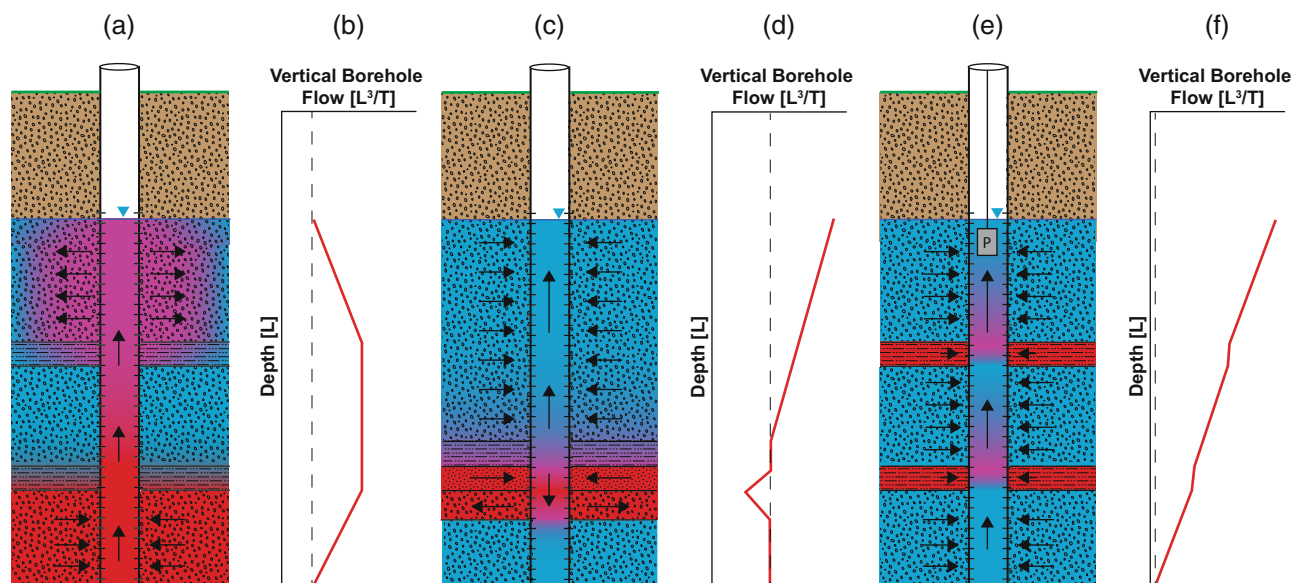


Figure 1. Schematic illustrating several issues with LSWs and associated intraborehole flow profiles. (a,b) Cross contamination (red) between different aquifer layers can occur when intraborehole flow moves water from contaminated to previously uncontaminated layers. (c,d) Outflow zones may act as ‘blind spots’ and mask the presence of contamination depending on locations of samples. (e,f) Under pumping, sampled effluent is biased toward the concentrations of more transmissive layers, which in this hypothetical scenario are uncontaminated. In (b,d,f), the dashed line indicates zero flow, with positive flow upward and downward flow negative, by convention.

between hydraulic features connected by the well or borehole. In the absence of pumping, vertical hydraulic gradients can drive flow into and from LSWs; hence, LSWs serve as conduits for water and, potentially, for contamination (Figure 1a,b). In effect, an LSW can act as a hydraulic “short-circuit” that allows for rapid exchange between features otherwise in less efficient communication.

A second major issue with LSWs is inference of groundwater chemistry based on sampling. Exchange between LSWs and the surrounding formation may occur through zones of both inflow and outflow, with water entering from one or more zones and exiting from one or more zones depending on hydraulic gradients. In the presence of ambient flow, the interpretation of sampling results is complicated because samples represent flow-weighted averages over the zones that contribute water to the sample. In the presence of outflow zones, sampling can miss contamination that enters the well from one layer and exits to another (Figure 1c,d). On the other hand, samples are biased toward the concentrations of inflow zones in proportion to their relative flows. Under pumping sufficient to overcome ambient intraborehole flow and draw water into the well or borehole over the entire screen or open interval, sampled concentrations approximate transmissivity-weighted averages of aquifer-layer or fracture concentrations; consequently, sampled concentrations are biased toward the concentrations of high hydraulic conductivity (K) (Figure 1e,f). Different sampling protocols (e.g., low-flow, passive, pumped) may therefore result in different and contradictory concentration values and assessments of contaminant distribution.

The groundwater literature is replete with papers discussing the challenges of interpreting sampling results

in LSWs; this literature, as discussed above, dates back to seminal work in the 1980s and 1990s (Reilly et al. 1989; Reilly and Gibs 1993; Church and Granato 1996) but also includes many contributions since (e.g., Zinn and Konikow 2007; McDonald and Smith 2009; Mayo 2010; Newcomer et al. 2010; Vermeul et al. 2011; McMillan et al. 2014) and even recent papers (Poulsen et al. 2019; Day-Lewis et al. 2023). Despite decades of documentation and appreciation for the issue among hydrogeologic subject matter experts, wider recognition remains an issue, confusion persists, and we contend that another paper on the topic is warranted. In this brief issue paper, we aim to promote greater awareness and provide the reader with illustrative examples and a workflow to develop intuition for the impact of intraborehole flow (i.e., vertical flow within the well) on concentration sampled in LSWs. We aim also to raise awareness of the utility of borehole flowmeter logging for providing hydraulic context in which to interpret samples from LSWs. Using the recently published analytical framework of Day-Lewis et al. (2023), we present a series of synthetic examples which are documented in easy-to-use and extensible Python Jupyter notebooks in the Supporting Information accompanying this paper.

Approach

In this section, we briefly review an analytical model and solution (Day-Lewis et al. 2023) for concentrations sampled in LSWs in the presence of intraborehole flow under ambient and pumped conditions. For a more detailed presentation of the development of the model, the reader is referred to the original paper,

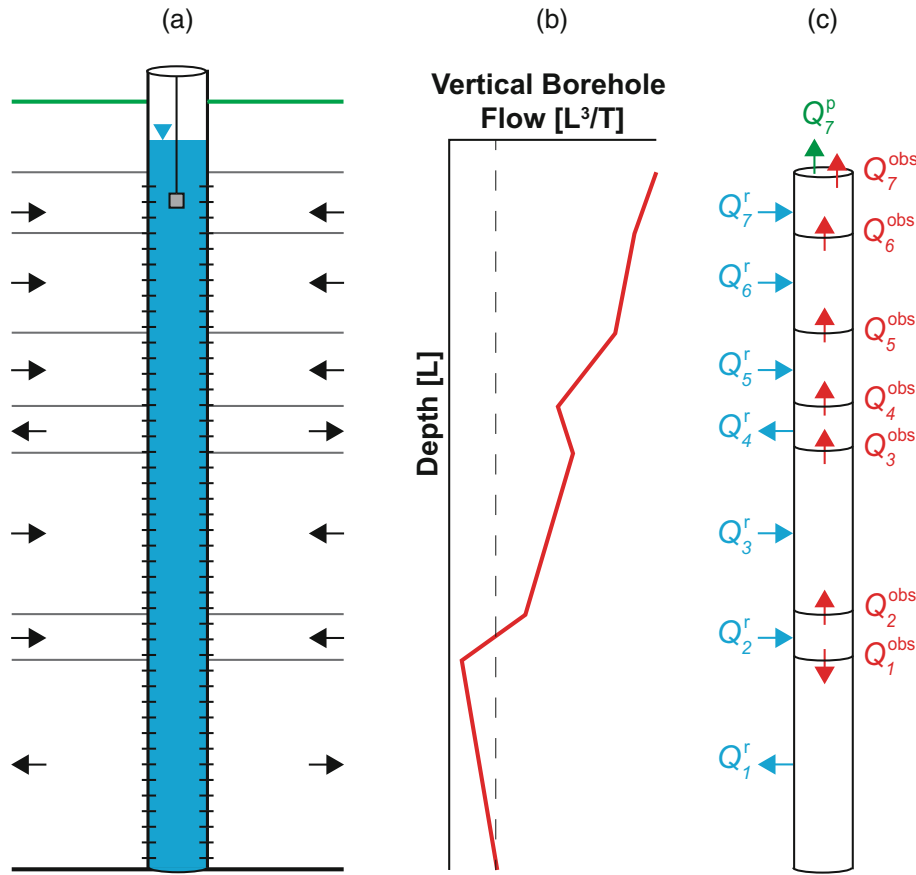


Figure 2. Schematic explanation and hypothetical example of (a) aquifer/well exchange in a long-screened well; (b) vertical flow in the well, with downward flow to the left of the dashed zero-flow line and upward flow to the right; and (c) the setup of the analytical model illustrating the numbering system for variables describing radial exchange between the well and aquifer (blue), vertical flows within the well (red), and pumping for sampling (or other purposes) (green) (Day-Lewis et al. 2023).

which also includes an inverse framework not discussed here.

A simple model for sampled concentrations in LSWs can be derived from principles of water and mass balance and steady-state radial flow between the well and aquifer (Reilly and Gibs 1993; Reilly and LeBlanc 1998; Sukop 2000). Building on these past developments, Day-Lewis et al. (2023) formulated a state-space model to simulate concentrations in an LSW with intraborehole flow and flow (potentially bi-directional) between the well and aquifer. The model setup is depicted in Figure 2. We note that other models, some more sophisticated, have been applied to this problem, including analytical models that consider incomplete mixing (e.g., Martin-Hayden 2000) and numerical models of fully 3D flow and/or transport (e.g., Konikow and Hornberger 2006; McMillan et al. 2014; Poulsen et al. 2019). For this issue paper, we use a simple and publicly available analytical model, which is well-suited for demonstrating a workflow to test hypothetical scenarios and build intuition. Of course, more complicated models could be used in future efforts.

Writing the conservation equation for solute mass in each interval i of an LSW or open borehole for the n intervals yields a system of first-order ordinary differential equations:

$$V_i \frac{dc_i}{dt} = \sum_j Q_{j,i}^b c_j - \sum_j Q_{i,j}^b c_i + \max(Q_i^r, 0) c_{0,i} + \min(Q_i^r, 0) c_i - Q_i^p c_i, \forall i, \quad (1)$$

where,

c_i is the concentration in well interval i [M/L³];
 $c_{0,i}$ is the concentration in the formation in contact with well interval i [M/L³]; and
 V_i is the volume of well interval i [L³]; that is, $2\pi r^2 b_i$, where r is the well radius [L] and b_i is the thickness of layer i .

The maximum and minimum functions in Equation 1 account for whether flow is coming from the aquifer into the well, in which case mass flux is $Q_i^r c_{0,i}$, or flow is leaving the well, in which case mass flux is $Q_i^r c_i$. Separating the terms with c and c_0 in this way facilitates the formulation of a state-space model as described subsequently.

Under the assumption of steady-state flow, Equation 1 written for i intervals gives a system of first-order linear differential equations with constant coefficients; thus, it can be expressed in the form of a state-space system where the states are well concentrations, the inputs are aquifer concentrations, and the coefficient matrices' elements

comprise vertical flows and exchanges between the well and aquifer:

$$\dot{\mathbf{c}}(t) = \mathbf{A}\mathbf{c}(t) + \mathbf{B}\mathbf{c}_0(t), \quad (2a)$$

$$\mathbf{c}^{\text{obs}}(t) = \mathbf{H}\mathbf{c}(t), \quad (2b)$$

where,

$\dot{\mathbf{c}}(t)$ is a vector of the derivatives with respect to time of well-interval concentrations at time t ;

\mathbf{A} is the transition matrix, which has dimensions of n by n , and whose elements are the coefficients of \mathbf{c} in Equation 1 [L^3/T];

\mathbf{B} is the input matrix, which has dimensions of n by n , and whose elements are the coefficients of \mathbf{c}_0 in Equation 1 [L^3/T];

\mathbf{c}_0 is the vector of formation concentrations, as above [M/L^3];

$\mathbf{c}^{\text{obs}}(t)$ is the vector of predicted concentrations at sampling (observation) locations [M/L^3];

\mathbf{H} is a matrix that selects or spatially interpolates from $\mathbf{c}(t)$ the predicted observations $[-]$, and has dimensions n^{obs} by n ; and

n^{obs} is the number of concentration sampling locations within the well.

The transient problem described by Equation 2 can be solved analytically (Day-Lewis et al. 2023), but our focus here is on equilibrium concentration. The steady-state concentration profile in the well, \mathbf{c}^{ss} , is found by setting the time derivative in Equation 2a to 0 and solving:

$$\mathbf{c}^{\text{ss}} = -\mathbf{A}^{-1}\mathbf{B}\mathbf{c}_0, \quad (3)$$

where, \mathbf{A}^{-1} is the matrix inverse of \mathbf{A} , which is non-singular for physically consistent inputs, \mathbf{Q}^b . Under equilibrium conditions, concentrations in the well represent flow-weighted averages of aquifer concentration, per Equation 3. To calculate the sampled concentrations, we combine Equations 2b and 3, obtaining the forward model for $\mathbf{c}^{\text{ss,obs}}$:

$$\mathbf{c}^{\text{ss,obs}} = \mathbf{H}\mathbf{c}^{\text{ss}} = -\mathbf{H}\mathbf{A}^{-1}\mathbf{B}\mathbf{c}_0 = \mathbf{G}\mathbf{c}_0, \quad (4)$$

where,

$$\mathbf{G} = -\mathbf{H}\mathbf{A}^{-1}\mathbf{B}. \quad (5)$$

Equation 5 shows that each sampled concentration ($c_i^{\text{ss,obs}}$) is a linear combination, that is, weighted average, of the concentrations in the aquifer (\mathbf{c}_0), where the weights are simply the elements of the corresponding row i of \mathbf{G} . Examination of \mathbf{G} is useful for understanding the sensitivity or insensitivity of samples to concentration in the aquifer and the sources of water to each sample.

In practice, calculation of \mathbf{G} would require information that is commonly unavailable without field measurements; rather, \mathbf{G} could be derived from a flowmeter log (e.g., Molz et al. 1989; Hess 1990; Molz

et al. 1994; Paillet 1998) using any of a variety of flow-measurement technologies, for example, impeller (Molz et al. 1989), electromagnetic (Young and Pearson 1995), and heat-pulse (Hess 1990). Alternatively, dilution logging has also been used to quantify flows between LSWs and surrounding aquifer layers (e.g., Tsang et al. 1990; Paillet and Thomas 1996; Paillet 2012). Here, we calculate \mathbf{G} for different hypothetical scenarios based on an axisymmetric analytical model for flow to/from a well in a layered system (Day-Lewis et al. 2023). The analytical model combines a multilayer Thiem equation (Thiem 1906) and uses the Hagen-Poiseuille equation for head losses associated with laminar intraborehole flow. For more details, see Day-Lewis et al. (2023). Different hydraulic head values are assumed for boundary conditions at an assumed radius of influence, as detailed in the Data S1 Supplementary Material.

Several assumptions and approximations underlie the analytical model and potentially limit its utility in some applications. In assessing the sources of water contributing to samples, the equilibrium model does not account for transient flow, which could be important depending on aquifer storage properties. Furthermore, the water/mass-balance model is based only on advective transport and complete mixing in the wellbore; thus, it neglects diffusion and partial mixing. Nor do we consider variability in concentration within aquifer layers/fractures. We also assume access to vertical flow measurements and that these measurements are reliable. In practice, it may be advantageous to interpret flowmeter logs in terms of a limited number of flow zones (e.g., Paillet 1998; Day-Lewis et al. 2011) in the presence of data scatter. These assumptions could be relaxed or addressed more fully in future work, but the analytical model is well suited to building insight into the impact of intraborehole flow on sampled concentration for a range of realistic conditions.

Type Scenarios for Borehole Flow

Intraborehole flow has been documented at field sites in diverse hydrogeologic settings spanning open boreholes in fractured-rock sites (e.g., Paillet 1998) to LSWs in unconsolidated sedimentary aquifers (e.g., McDonald and Smith 2009; Newcomer et al. 2010; Vermeul et al. 2011). It is beyond the scope of this paper (and impossible) to enumerate all possible configurations of aquifer/well exchange. Water moves between wells and the surrounding formation as a function of head differences and hydraulic properties, particularly hydraulic conductivity, which is known to vary by orders of magnitude over short distances in many settings; hence, complexity should be anticipated in most field settings. Here, we seek to present a series of archetypal configurations of inflow and outflow zones to illustrate the range of possibilities and build intuition. We refer to these configurations subsequently as “type scenarios.” A given well could exhibit any number of the different type scenarios in different intervals of the well. Indeed, some of these configurations would be unphysical without

others above or below them because inflows and outflows must balance; thus, the scenarios can be conceptualized as the components or building blocks of an intraborehole flow profile as measured by a flowmeter log.

Five type scenarios (Figure 3) are considered: (1) increasing upward flow, (2) increasing downward flow, (3) convergent flow (outflow), (4) divergent flow (inflow), and (5) complex inflow/outflow. We present each scenario in turn and discuss its implications for interpretation of sampled concentration. For details on model specifications, including boundary conditions and hydraulic parameters, see the Supporting Information for the Jupyter notebooks used to generate the examples and Figures 4 through 9. Note, however, that the insights derived from the examples are general and do not depend on the details of assumed specifications.

Increasing Upward Flow

The first type scenario (Figures 3a,b and 4) considers upward intraborehole flow that increases in magnitude over some length of the screened (or open) interval of the well, as could occur with abstraction of water from a pump with an intake set at the top of the interval. This scenario could also occur in the absence of pumping under artesian conditions. As depicted in Figure 4a and 4b, water enters the well over the screened interval, in proportion to the hydraulic conductivity, K , of each layer. In this first example, we assume homogeneity and do not consider the role of K heterogeneity. Water in the well near the bottom of the screen is derived from the aquifer surrounding the bottom of the well, whereas water in the well near the top of the screen derives from a thicker section of the aquifer.

The provenance of water sampled in an LSW is quantitatively described by G , which is visualized in Figure 4c for the type scenario of increasing upward intraborehole flow. If we consider passive or low-flow sampling, such that the well/aquifer flow is negligibly disturbed by sampling, a sample derived from Point A in Figure 4a would accurately reflect the local aquifer concentration. Indeed, this is evident by inspection of the row of G corresponding to Point A (Figure 4d). At Point B, higher in the well, the sampled concentration represents an average over the aquifer layers up to Point B (Figure 4d). Moving higher still to Point C, the averaging becomes even more pronounced, with sampled concentration representing an average over the entire well (Figure 4d). The weighting functions show the fraction of each sample derived from each aquifer layer. The localization of samples varies significantly; however, the implications for assessment of contamination depend not only on G but also on spatial variation in aquifer concentration. If contamination were present only in the deeper aquifer, for example, around Point A, sampling at Point A would resolve the contaminant concentration. Sampling would exhibit increasing dilution moving up to Point B or Point C. If contamination were present only in the upper aquifer, for example, around Point C, the concentration sampled at Point C would be highly diluted by the clean water flowing into the well below this point.

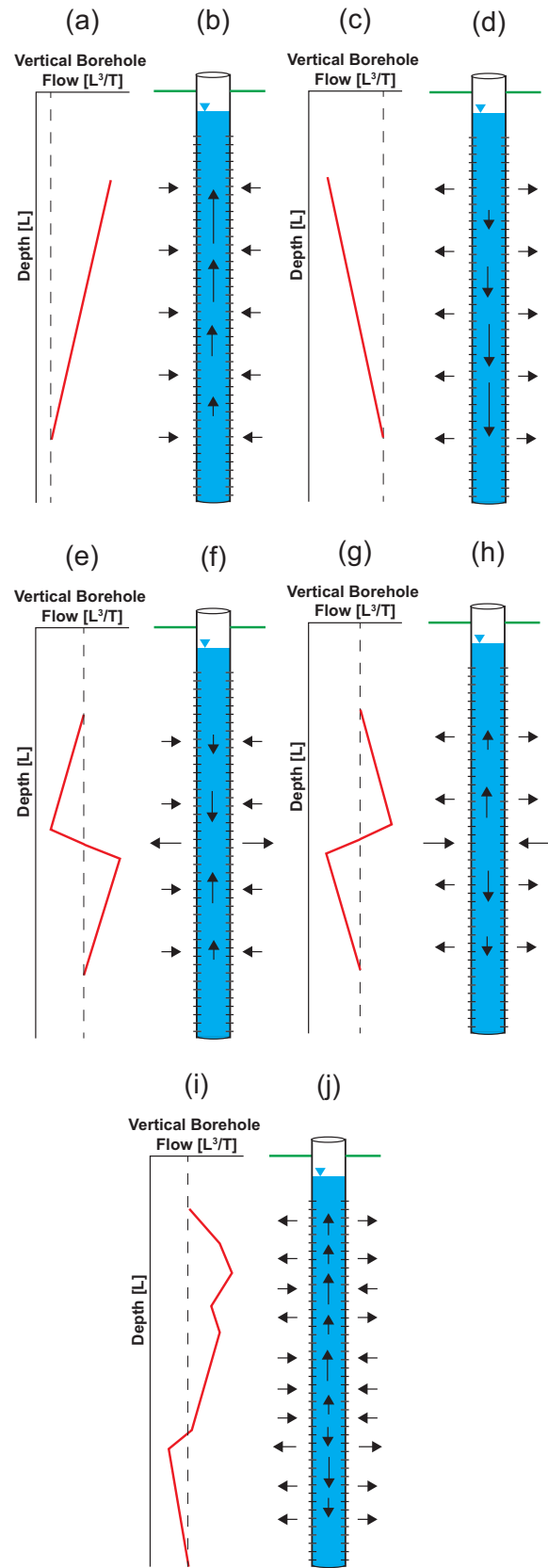


Figure 3. Schematic illustrating type scenarios for intraborehole flow including (a,b) increasing upward flow, (c,d) increasing downward flow, (e,f) focused outflow, (g,h) focused inflow, and (i,j) complex inflow/outflow. In (a,c,e,g,i), the dashed line indicates zero flow, with positive flow upward and downward flow negative, by convention.

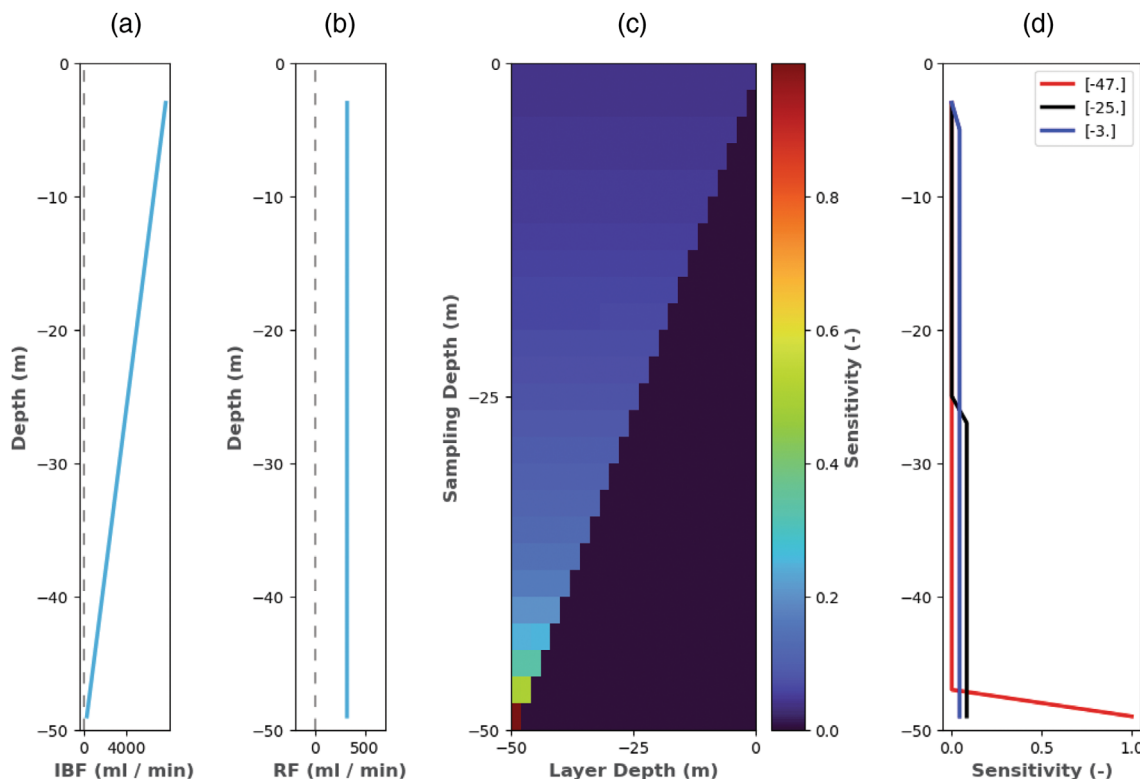


Figure 4. Scenario for upward intraborehole flow including (a) intraborehole flow (IBF), with positive values indicating upward flow; (b) radial flow (RF) exchanged with the aquifer, with positive values indicating flow into the well; (c) the G matrix; and (d) the averaging weights from rows of G for Points A, B, and C at depths of 47, 25, and 3 m, respectively.

Again, we have not yet considered K heterogeneity, which plays an important role in the weighting process and, thus, the potential bias of sampled concentration toward the concentration of certain aquifer layers.

Increasing Downward Flow

The second type scenario (Figure 3c,d and 5) considers increasing downward flow over the entire screened interval. This scenario could occur under pumping conditions with the pump intake set at the bottom of the interval. In the absence of pumping, natural gradients between aquifer layers (or fractures) could drive flow downward over a portion of a well. This example is, obviously, the obverse of the previous example for increasing upward flow. Consequently, the insights are essentially the same but with the opposite pattern with respect to the top vs. bottom of the well. Whereas sampling at Point A was more representative of local aquifer concentration than at Points B and C under the upward flow scenario, now it is less representative (Figure 5d). The dilution effect observed previously is more enhanced with increasing depth.

Focused Outflow Zone

The third type scenario considers a single focused outflow zone (Figures 3e,f and 6) where water exits the well. In this scenario, intraborehole flow is upward below the outflow zone and downward above it convergent (Figure 6a). In the absence of pumping, this situation

could result from natural head gradients. Alternatively, focused outflow from a well could occur into a high- K layer that connects to an extraction well. As for previous type scenarios, we again consider sampling at Points A, B, and C (Figure 6a) and assess the provenance of water constituting those samples using G (Figure 6c and 6d). The samples taken at Points A and C are derived from the aquifer below and above the corresponding, respective sampling depths, and thus have some local sensitivity to aquifer conditions. Approaching Point B, dilution is enhanced, and at the point of outflow there is no local sensitivity to concentration in the aquifer; this hydraulic context is important for the correct interpretation of sampling results.

Focused Inflow Zone

The fourth type scenario considers a single focused inflow zone where water enters the well (Figures 3g,h and 7). In this scenario, intraborehole flow is upward above the inflow zone and downward below it, that is, divergent (Figure 7a). This example is the obverse of the previous example. Under pumping, focused inflow could occur from a high- K layer (or fracture) that connects to an injection well. As for previous type scenarios, we again consider sampling at Points A, B, and C (Figure 7a) and assess the provenance of water constituting those samples using G (Figure 7c and 7d). The sample taken at Point B, at the inflow zone, is derived entirely from the aquifer at that depth, and thus the concentration

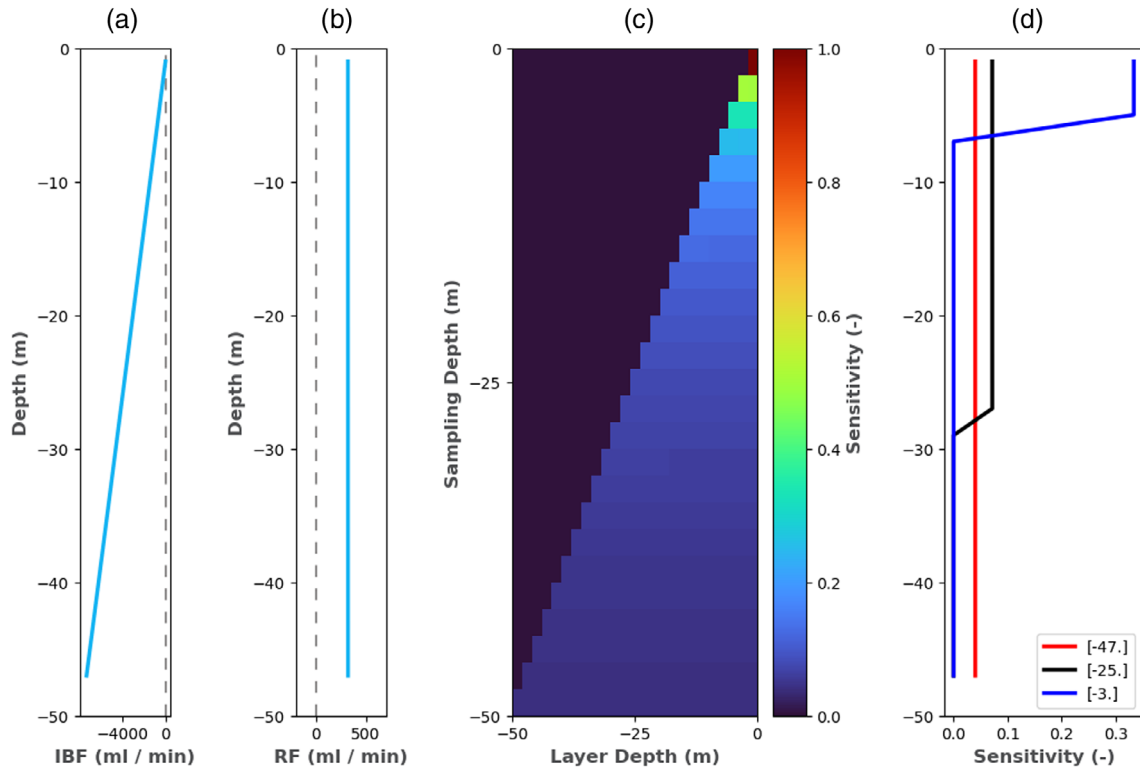


Figure 5. Scenario for downward intraborehole flow including (a) intraborehole flow (IBF), with positive values indicating upward flow; (b) radial flow (RF) exchanged with the aquifer, with positive values indicating flow into the well; (c) the G matrix; and (d) the averaging weights from rows of G for Points A, B, and C at depths of 47, 25, and 3 m, respectively.

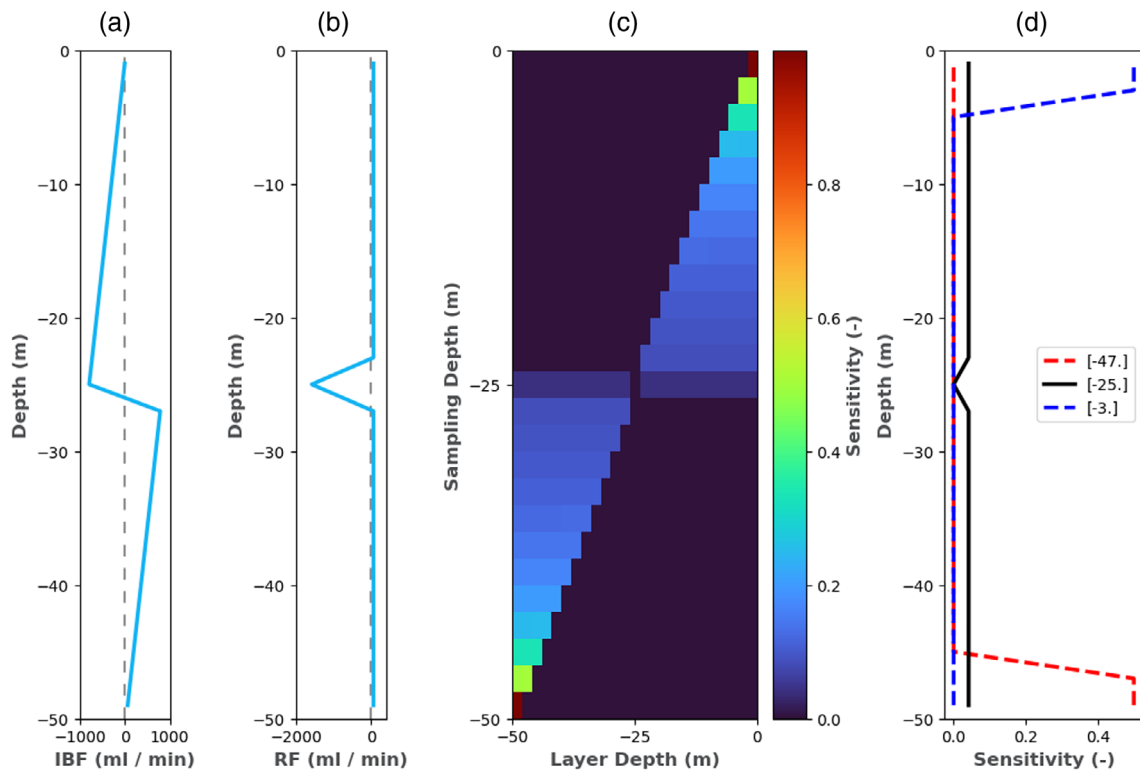


Figure 6. Scenario for a single, discrete outflow zone including (a) intraborehole flow (IBF), with positive values indicating upward flow; (b) radial flow (RF) exchanged with the aquifer, with positive values indicating flow into the well; (c) the G matrix; and (d) the averaging weights from rows of G for Points A, B, and C at depths of 47, 25, and 3 m, respectively.

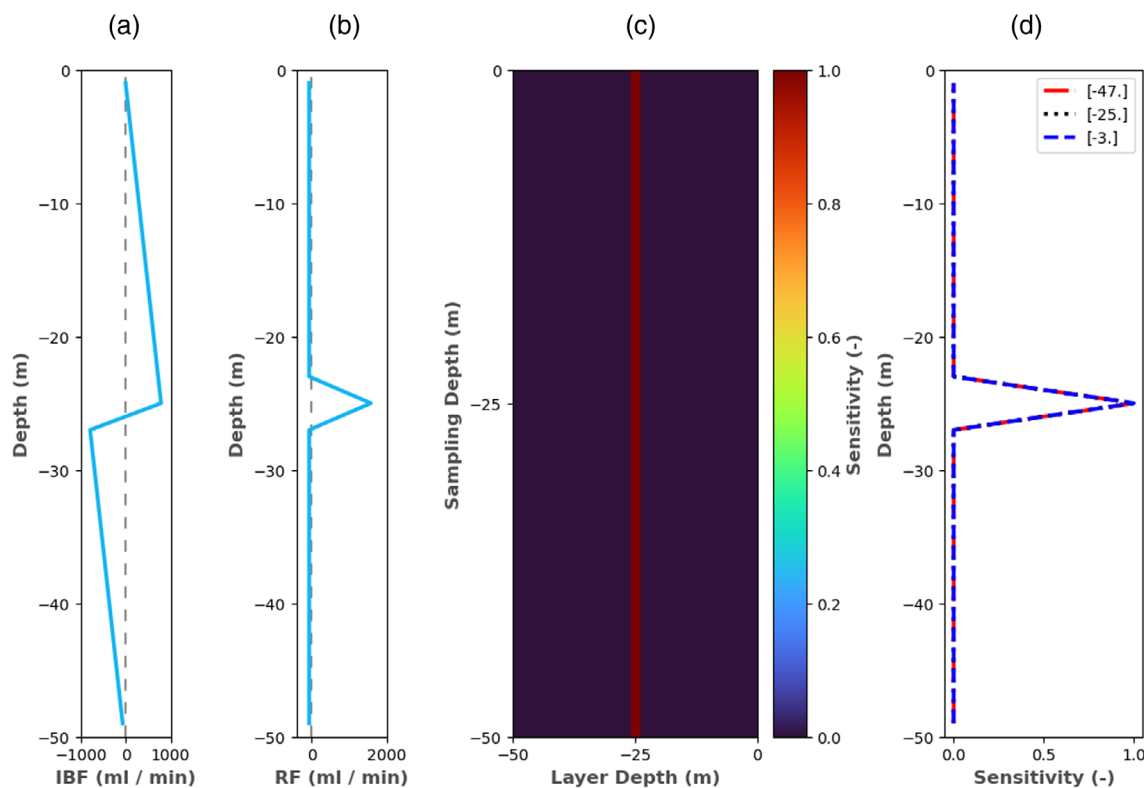


Figure 7. Scenario for a single, discrete inflow zone including (a) intraborehole flow (IBF), with positive values indicating upward flow; (b) radial flow (RF) exchanged with the aquifer, with positive values indicating flow into the well; (c) the G matrix; and (d) the averaging weights from rows of G for Points A, B, and C at depths of 47, 25, and 3 m, respectively.

measured would accurately reflect local conditions. We see, however, that the rows of G for Points A and C are identical to the row for Point B. In fact, the rows of G are all identical; thus, concentrations sampled over the entire well are representative of the inflow zone regardless of sampling location. Consequently, for this type scenario, sampling provides no information about concentrations in the aquifer except for that of the inflow zone. Without knowledge of the intraborehole flow (e.g., from a flowmeter log), one might mistakenly interpret the concentration profile in the aquifer as being vertically uniform. This could be highly misleading. For example, if the inflow zone were contaminated, one might interpret samples from Points A, B, and C to indicate the entire aquifer is contaminated. On the other hand, if the inflow zone were uncontaminated, one might interpret the samples to indicate that no contamination is present anywhere.

Complex Inflow/Outflow

The previous examples presented highly idealized flow systems where only inflow or outflow occurred in well-defined zones. In this type scenario, we consider a more realistic field-based example from the Hanford Site in eastern WA, USA. The scenario is based on the intraborehole flow measured in well 299-W15-225 (Figure 8a) under ambient hydraulic conditions using an electromagnetic borehole flowmeter (EBF) (Spang and Newcomer 2009). Intraborehole flow of up to ~ 1 L/min

was observed, which is large relative to typical pumping rates for low-flow sampling. Flow is seen to be downward (negative-valued flow in Figure 8a) over the entire screened interval; however, deflections in the plot of vertical flow versus depth indicate the presence of multiple inflow and multiple outflow zones. One could inspect the flowmeter log within the framework of the type scenarios above and label segments of the flowmeter log in those terms. Calculating the difference in vertical flow between adjacent EBF measurements yields estimates of the well/aquifer exchange (Figure 8b), from which G is calculated using Equations 1 through 4 (e.g., Day-Lewis et al. 2011). Four rows of G , corresponding to four depths, are visualized in Figure 8d. At very shallow depths in the well (e.g., 246.1 m), samples accurately reflect concentration in the surrounding aquifer, consistent with the first type scenario above. In general, with increasing depth, samples are drawn from a larger section of the aquifer. Given the complexity of the flow log and radial exchange with the aquifer, most samples at most locations would represent complex averages over different aquifer layers, and some aquifer layers contribute no water to the well or else are outflow zones and take water from the well. Where column j of G contains only zeros, there are no samples to which layer j contributes water, and thus sampling provides no information about aquifer concentration at that depth. Although outflow zones tend to decrease sensitivity, they can also enhance sensitivity at some locations, as seen at 379.5 m depth. As seen in

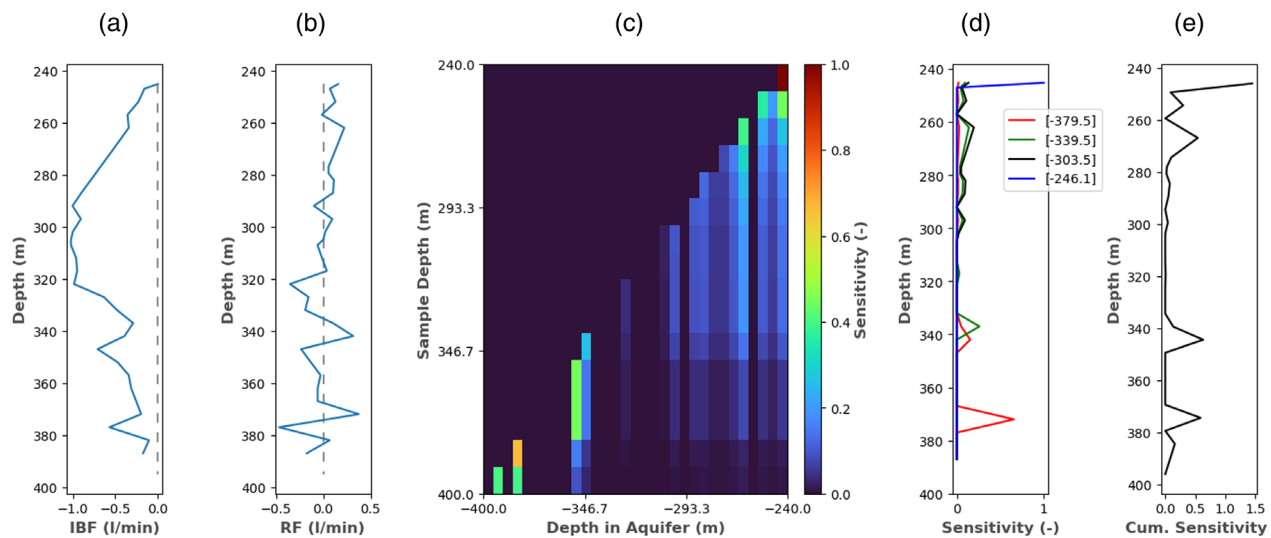


Figure 8. Field-based scenario for complex inflow/outflow including (a) intraborehole flow (IBF), with positive values indicating upward flow; (b) radial flow (RF) exchanged with the aquifer, with positive values indicating flow into the well; (c) the G matrix; (d) the averaging weights from rows of G for points at four depths, respectively, labeled on the plot; and (e) cumulative sensitivity. These data come from well 299-W15-225 at the Hanford Site in eastern Washington state, USA.

Figure 8d, 8a large fraction of water sampled from this location would be derived from an interval of the well extending about 10 m above. In addition to examination of G , we can also calculate and examine the diagonal of the matrix $G^T G$, called the cumulative sensitivity (Figure 8e). Cumulative sensitivity is larger at depths where sampling provides more information and is smaller at depths where measurements convey less information.

Additional Insights for Effluent Sampling

In the previous examples, we focused on low-flow or passive sampling. In this section, we assess the implications of intraborehole flow on samples collected from the effluent of an extraction well where the pumping dominates over ambient borehole flow. The type scenarios for intraborehole flow and the mathematical framework used previously are also relevant to this problem.

We evaluate sampling of effluent concentration for two scenarios to provide insight into the importance of K heterogeneity and the insignificance of pump-intake location (Figure 9). In both scenarios, we consider the presence of a low- K layer (0.0001 cm/s) in which contamination is present at higher concentration than in the high- K (0.001 cm/s) aquifer layers above and below. In the first scenario (Figure 9a through 9d), we model the extraction as coming from a pump intake at the top of the screened interval (1 m depth). In the second scenario (Figure 9e through 9h), we model the extraction as coming from a pump intake at the bottom of the screened interval (49 m depth). The intraborehole flow profile, radial exchange with the aquifer, and G matrices are compared for the scenarios in Figure 9. For one of these scenarios, the G matrix is a single row, as there is only one sample (the effluent); thus, the averaging function can be visualized as a single

profile of sensitivity (i.e., fraction of water contributing to the sample) versus depth. Note that the averaging functions for the two scenarios (Figure 9d and 9h) are identical, irrespective of the pump location; consequently, the sampled concentrations are also identical, 1.34 and 1.34, with very small differences explained by the minor influence of well losses, which are greater for layers farther from the pump-intake. The radial exchange profiles (Figure 9b and 9f) are also identical because water moves to (or from) the well from each layer in proportion to the layer transmissivity and the head difference between the aquifer layer and the head in the well. These findings are to be expected. Regardless of the intake location, sampled concentration is closely approximated by a K -weighted average of concentrations of aquifer layers (or fractures) intersecting the well (or open borehole), with small deviations from the K -weighting resulting from head losses in the borehole. This K -weighting is well understood among hydrogeologists but may be unintuitive to others unfamiliar well hydraulics.

The effluent concentrations (1.34) in the examples show a strong bias toward the concentration in high- K materials (0) versus that of the low- K materials (100) as a result of the dominance of high- K layers on radial exchange to the well (Figure 9b and 9f). This issue has important implications for the quantification of contaminant mass based on sampling from LSWs. At sites where contamination is found primarily in low- K zones or rock matrix, sampling may poorly resolve contaminant mass and underestimate the extent of contamination given the dilution driven by the K -weighting and dominance of high- K layers on sensitivity (Figure 9d and 9h). On the other hand, at sites where contamination is found predominantly in high- K materials, sampling may be biased toward high concentration and thus overestimate the contaminant mass—hence the need

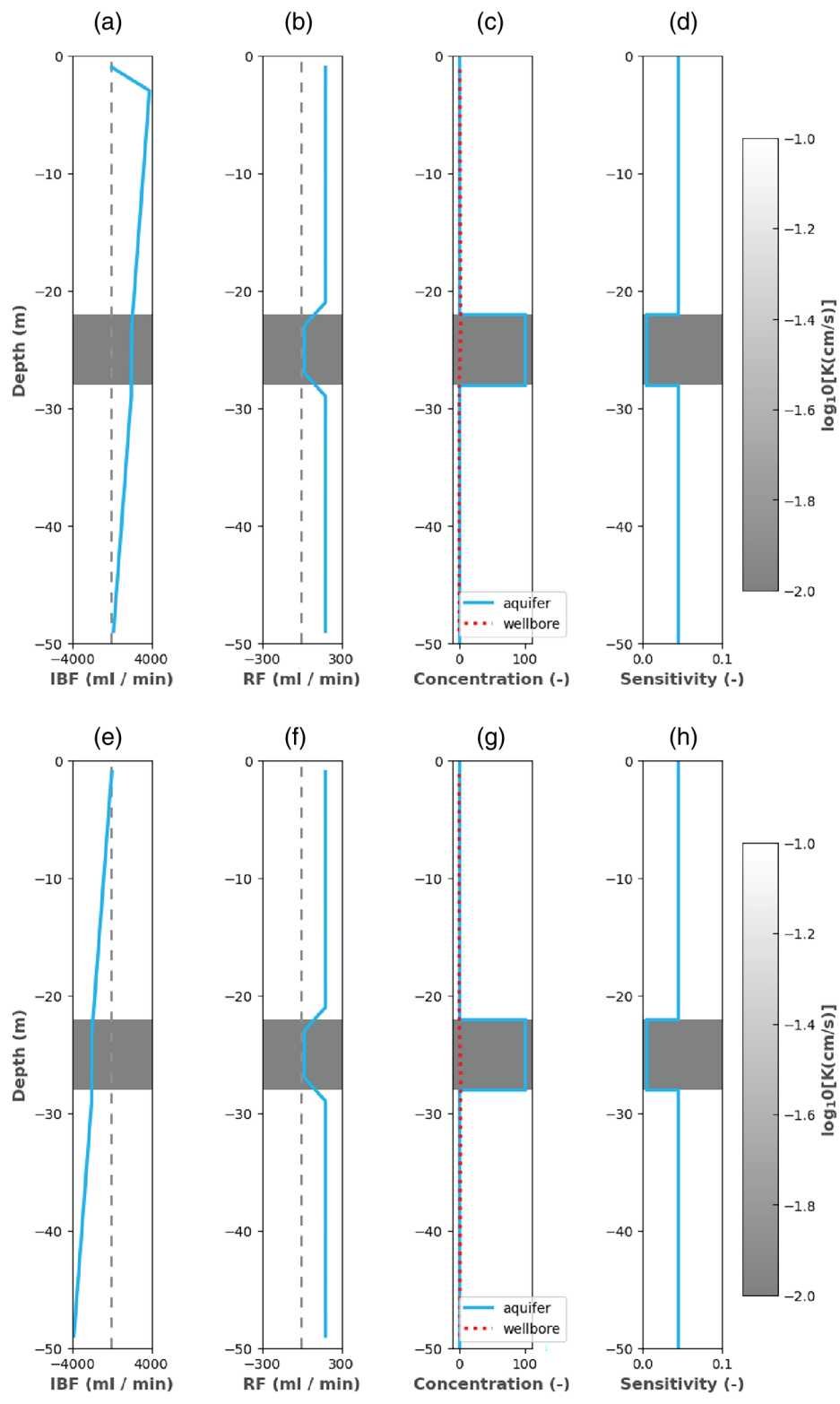


Figure 9. Scenario for assessment of effluent concentration. The top row shows results with pumping from the top of the well (1 m depth): (a) intraborehole flow, with positive values indicating upward flow; (b) radial exchange with the aquifer, with positive values indicating flow into the well; (c) concentration profiles in the aquifer and wellbore; and (d) the averaging weights from rows of G for effluent concentration. The second row shows results for pumping from the bottom of the well (49 m depth): (e) intraborehole flow, with positive values indicating upward flow; (f) radial exchange with the aquifer, with positive values indicating flow into the well; (g) concentration profiles in the aquifer and wellbore; and (h) the averaging weights from rows of G for effluent concentration.

for the interpretation of sampling results in hydraulic context.

Discussion and Conclusions

Concentration samples collected from LSWs represent flow-weighted averages of the concentrations in aquifer layers (or fractures) contributing to a well (or open hole). Under ambient flow conditions, low-flow or passive sampling may produce results that are difficult to interpret without knowledge of intraborehole flow. The water contributing to a sample may derive from the aquifer above or below the sample location, depending on whether flow is downward or upward in the well. Sampling may miss solute mass that is lost to outflow zones. Even with pumping that is sufficient to overwhelm ambient intraborehole flow, sampling may not effectively see solute mass in low- K zones that contribute water to the well proportional to the zones' respective transmissivities. Understanding these issues and the potential bias in sampling in LSWs is critical to the correct interpretation of sampling results and, in turn, the effective selection and design of groundwater remediation operations. In this issue paper, we demonstrated a workflow to assess the implications of intraborehole flow on sampling and presented a series of type scenarios to build intuition.

The insights offered in this issue paper are not novel. Indeed, these ideas have been raised and reiterated in the literature on LSWs for several decades. The examples provided do not cover all possible configurations of inflow and outflow zones or patterns of intraborehole flow; that is, an infinite number of combinations of inflow and outflow zones are possible. Nor do the examples explicitly address dynamically changing flow systems. Although we present the type scenarios as distinct, intraborehole flow can be dynamic in some settings, and a given well can vary between upward, downward, or more complex flow behaviors over time as a function of local pumping/injection, seasonal dynamics, tidal influences, and (or) aquifer/river interaction (e.g., Newcomer et al. 2010).

Understanding intraborehole flow is critical to placing sampling results in hydraulic context. Borehole flowmeter logging (e.g., Molz et al. 1989; Molz et al. 1994; Paillet 1998) provides a means to directly measure vertical flow in a well and to infer well/aquifer exchange and the hydraulic heads associated with different aquifer layers or fractures. Commercial borehole flowmeters and open-source/public-domain software (e.g., Day-Lewis et al. 2011; Barbosa et al. 2020) are available. The model and tools developed by Day-Lewis et al. (2023) and used in this paper further provide a framework for assessing the sources of water contributing to samples and quantifying sampling bias. Although the challenges of interpreting samples from LSWs persist, we have an expanding toolbox—both experimental (e.g., electromagnetic and heat-pulse flowmeters) and analytical (e.g., G)—to place sampling results within a well-hydraulic context and interpret them appropriately.

Acknowledgments

The authors are grateful to Xuehang Song for constructive internal reviews of the draft manuscript. This document was prepared under the Deep Vadose Zone—Applied Field Research Initiative at Pacific Northwest National Laboratory. The Pacific Northwest National Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC05-76RL01830. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof, or Battelle Memorial Institute. This work was performed in accordance with the Pacific Northwest National Laboratory (PNNL) Nuclear Quality Assurance Program (NQAP). The NQAP complies with the U.S. Department of Energy Order 414.1D, Quality Assurance. The NQAP uses NQA 1 2012, Quality Assurance Requirements for Nuclear Facility Application as its consensus standard and NQA 1 2012 Subpart 4.2.1 as the basis for its graded approach to quality. This work emphasized acquiring new theoretical or experimental knowledge. The information associated with this report should not be used as design input or operating parameters without additional qualification.

Authors' Note

The authors do not have any conflicts of interest or financial disclosures to report.

Data Availability Statement

The data that supports the findings of this study are available in the supplementary material of this article.

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article. Supporting Information is generally *not* peer reviewed.

Data S1. The electronic supporting information includes links and instructions to access the Jupyter notebooks and Python codes used to generate the examples. The Supporting Information was not peer reviewed by Groundwater.

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