Research Paper/

**Effects of intraborehole flow on purging and sampling long-screened or open wells**

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**Article Impact Statement:** This paper provides new insight, cautionary advice and an informed approach for using long-screened wells in groundwater studies

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Abstract

Hydraulic head differences across the screened or open interval of a well significantly influence the sampled water mixture. Sample bias can occur due to an insufficient pumping rate and/or, due to native groundwater displacement by intraborehole flow (IBF). Proper understanding of the sampled water mixture is crucial for accurate interpretation of environmental tracers and groundwater chemistry data, and hence groundwater characterisation. This paper uses numerical modelling to quantify sample bias caused by IBF in an un-pumped high-yield well, and the influence of pumping rate and heterogeneity on the volume of pumpage required to purge an IBF plume. The results show that (1) the pumping rate must be at least an order of magnitude greater than the IBF rate to achieve permeability-weighted yield, (2) purge volume was 2.2 - 20.6 times larger than the IBF plume volume, with the ratio depending on plume location relative to hydraulic conductivity and head distributions, and (3) after an example 1,000-day un-pumped period, purging required removal of at least three orders of magnitude more water than the common practice of three to five well volumes. These results highlight the importance of knowing the borehole flow regime to identify IBF inflow and outflow zones, estimate IBF rates, and to develop a strategic sampling approach.
**Introduction**

Vertical hydraulic head gradients are ubiquitous in groundwater systems. Thus, if a well has an appreciable screen length or open interval, the groundwater inflow distribution during pumping will be a function of the hydraulic head and conductivity distribution across the screened or open interval. A sample may not be drawn from the whole interval in proportion to the permeability distribution unless the pumping rate is high enough to overcome the influence of the head gradient (McMillan et al. 2014). Further, if the well is left un-pumped, it creates a short circuit for vertical flows between permeable zones connected by the well. This phenomenon is known as intraborehole flow (IBF) and it can significantly influence the flow system chemistry in the local area within and around a well. Over time, a plume of invading water (herein termed the “IBF plume”) develops in zones with lower head, displacing native groundwater. When the well is pumped, water produced from zones at lower heads actually originated from zones with higher heads.

Previous work has established that IBF is an important factor to consider when sampling wells that have been left un-pumped, even in relatively homogeneous aquifers with small vertical head gradients (Church and Granato 1996; Elçi et al. 2001; Lerner and Teutsch 1995; Reilly et al. 1989). An indication of its prevalence is given by Elçi et al. (2003), who reported measurable IBF (0.01 - 6.2 L/min) in 73% of tested wells (142 monitoring wells at 16 sites across the USA).

Water sampled from a well is an inflow-weighted mixture from all contributing zones. Aside from the challenge of correctly apportioning water composition to each zone, the presence of an IBF plume around a well can further complicate interpretation of chemical analyses (Collar and Mock 1997; Ma et al. 2011; Reilly and LeBlanc 1998), either exacerbate or mask the presence of a contaminant (Hutchins and Acree 2000; Konikow and Hornberger 2006; Lacombe et al. 1995) and substantially alter the mix of groundwater ages sampled (Corcho Alvarado et al. 2009; Zinn and Konikow 2007). If a long screened or open well is left un-
pumped, it could take a long time to fully purge the resulting IBF plume so the well yields native groundwater from all contributing zones (Jones and Lerner 1995; Mayo 2010). Although a nest of short-screened monitoring wells is preferred to secure accurate samples, this is an expensive installation. Despite potential complications arising from IBF, use of available infrastructure is the economical approach to study a groundwater system. Environmental tracer studies attempting to characterise groundwater flow systems may use wells that were installed for different purposes, which have a longer-than-ideal screen length (e.g., Cook et al. 2017). In such a situation, it would be helpful to assign tracer concentrations to specific depths in the aquifer. If the well has been left un-pumped, it is also important to properly consider the effects of the IBF regime on the sample. Failure to do so could result in erroneous conclusions and unrealised potential for better understanding of a groundwater flow system. Whether or not purging an IBF plume is feasible, it is important to understand the true origins of the water mixture being sampled, in addition to knowing the zones that contribute to the sample. However, there is little published literature on improving the quality of data and knowledge obtained from high-yield long-screened wells.

This paper characterises the effects of IBF on purging and sampling of a long-screened well, and provides insight that can be used to develop an informed sampling approach. A numerical model is used to highlight the importance of understanding the borehole flow regime, the location and extent of an IBF plume, and the sampled water mixture at the chosen pumping rate. The focus is on a homogeneous aquifer as a “base case”, but the principles also apply to heterogeneous systems of porous media or fractured rock. An example of variability due to aquifer heterogeneity is included, as are some practical considerations for improving purging and sampling strategies.
Methods

Conceptual model

A three dimensional, synthetic regional groundwater flow system was used to investigate the effects of IBF on sampled groundwater mixtures from a long-screened, high-yield well in a recharge area (Figure 1). Groundwater age was used as a convenient way to identify water from different depths, with recharge assigned an age of zero and age naturally increasing with depth in the aquifer. However, with the non-zero, graduated background concentrations in the age simulation, the exact spatial extent of IBF in the aquifer and its subsequent contribution to well pumpage was not always clear. Therefore, IBF was also tracked explicitly in a separate simulation by setting the background concentration to zero and assigning a constant concentration (of one) to all water leaving the well. Thus, the fraction of IBF in each model cell and in water sampled from the well was quantified. The flow system was created by applying recharge across the top of the model and setting a constant-head boundary of 0 m on the right hand side, analogous to a spring or river at the land surface. Groundwater flows from left to right through the model. The land surface was assigned a 13.5 m elevation to ensure that the water table was completely within the model domain, allowing for unconfined conditions to occur. All lateral sides and the bottom of the model are no-flow boundaries. A long-screened well was positioned centrally 105 m from the left hand side of the model, in an area with a downward vertical flow component. With a 0.2-m diameter, 36-m-long screen (from -1.5 to -37.5 m), the well was similar in construction to production wells that may be co-opted for water chemistry sampling. The model grid was refined to 1.5 m horizontally near the well, geometrically increasing to a maximum size of 15 m. All 50 model layers are 1.5 m thick. Table 1 gives the model dimensions and parameters.

The model design is loosely based on that of Reilly et al. (1989) and Konikow and Hornberger (2006) with regard to the general model dimensions, position of the multi-node well, constant-
head boundary, amount of recharge, and anisotropy ratio. Differences include simulation of the water table, a longer well screen, slightly less grid refinement (as explained below), and reduced overall hydraulic conductivity ($K$). Another significant difference is that the previous studies did not pump the well except to obtain a sample, whereas in this study the well was pumped with the goal of purging the IBF plume. As a consequence, small boundary effects were observed in the model during pumping. For example in the homogenous system, at the completion of purging there was $\sim0.8$ m head drawdown at the lateral and up-gradient boundaries. This resulted in relatively more water being drawn from the down-gradient area, in which most of the IBF plume resided. Although purge volume to remove the IBF plume was slightly less than a no-boundary-effect situation, the key concepts and outcomes demonstrated in this paper are unaffected.

**Numerical simulation**

Steady-state and transient flow was simulated in three dimensions using the MODFLOW 2005 (Harbaugh 2005) computer code, with a long-screened well represented by the Multi-Node Well Package (MNW2) (Konikow et al. 2009). Groundwater movement was tracked in two ways using MT3DMS (Zheng 2010; Zheng and Wang 1999): (1) direct simulation of groundwater age with a zero order reaction was used to examine the effects of IBF on groundwater age, and (2) the code was modified to assign a constant concentration of one to all water leaving the well, thereby identifying the fraction of IBF in each model cell and in the resulting pumped discharge. MT3D assigns a single composite solute concentration for the well, based on the flux-weighted concentrations of inflows, so differential solute movement through the well was not simulated. The flow and transport models were developed, executed and post-processed with the Python FloPy package (Bakker et al. 2016). Steady-state groundwater head and age distribution (without the well) were used as initial conditions for transient simulations. Transient simulations included stress periods for sampling
the well immediately after installation (pumping for 1 hr at 60 m$^3$/d), an un-pumped period (nominally 1,000 days), followed by pumping at 60 m$^3$/day until the IBF plume was fully purged (Figure 1). Full purging was taken to be the point when the composite age of the sample was again equal to the age immediately after well installation.

The flow equations were solved using the Preconditioned Conjugate Gradient solver, achieving a 1x10$^{-5}$ m head change and residual convergence criterion. A limit on model convergence was a function of the cell-to-well conductance (CWC) term calculated by the MNW2 package. This term governs interaction of a well node with the local model cell because the volumetric flux between the two is a multiple of CWC and head difference. All else being equal, CWC increases as model cell size decreases, and MODFLOW can become numerically unstable when cell size approaches the specified well diameter (Halford and Hanson 2002). Konikow and Hornberger (2006) used 0.75 m cells near the well, but here it was increased to 1.5 m to improve numerical stability for the heterogeneous systems. This change did not significantly affect model results, but it illustrates a limitation of the MNW2 package when simulating a long-screened well. The CWC value is also a function of the $K$ of the well skin ($K_{\text{skin}}$), an assessment of which is provided below in the context of IBF.

The standard finite difference method in MT3DMS was used for solute transport simulation. With a longitudinal dispersivity of 1.5 m and characteristic length of 1.5 m (grid Peclet number $= 1$), numerical dispersion was not an issue (Anderson and Woessner 2002; Zheng and Wang 1999). This longitudinal dispersivity value is appropriate for an observation scale of tens to hundreds of metres (Gelhar et al. 1992), which is consistent with the extent of the simulated IBF plumes.

**Hydraulic conductivity**

The “base-case” model was assigned a homogeneous $K$ distribution of 10 m/d. Vertical $K$ was assigned to be five times lower than horizontal $K$. To test the effect of aquifer heterogeneity on
the development and purging of an IBF plume, two horizontal model layers (1.5 m thick) intersecting the well were systematically assigned various higher $K$ combinations over three orders of magnitude. The layers were positioned near the extremities of the range of aquifer hydraulic heads intersected by the well. Each layer extended throughout the model domain. This simple approach allowed an exploratory study of factors controlling potential variability in IBF plume extent and purge times, without requiring exhaustive stochastic modelling of a fully heterogeneous aquifer, which was beyond the scope of this paper.

**Well skin**

The well skin parameter in the MNW2 package allows the influence of the well screen, borehole annulus and surrounding disturbed zone to be simulated. The well skin can be a reduced $K$ zone due to aquifer disturbance and/or a restrictive well screen (well losses), or an enhanced $K$ zone where a gravel pack effectively increases the well diameter and/or fines are washed out of the surrounding aquifer during well development. A negligible skin zone was intended in this modelling exercise ($K_{skin}$=K), but the model would not converge when $K_{skin}$ was more than 60% of $K$ due to excessive cell-to-well conductance. Thus, for all modelled scenarios, $K_{skin}$ = 6 m/d. The effect of the well skin on IBF rate was tested by applying a range of $K_{skin}$ values in models with different homogeneous $K$ (Figure 2). IBF is driven by the vertical head gradient, which is governed by $K$ and recharge, so it approaches an upper limit as $K_{skin}$ approaches $K$ (0.68 m$^3$/d in the homogeneous system). For a given $K_{skin}$, increasing $K$ reduces the vertical hydraulic gradient, and thus reduces IBF. However, the primary concern here was not the factors controlling IBF, but rather its influence on purging and sampling a well. Therefore, it was sufficient that a range of IBF rates were generated.

**Results**

The homogeneous regional flow system had an overall horizontal hydraulic gradient of 0.0036 toward the constant head boundary “at the surface” on the right hand side. Vertical gradients
were downward on the left hand side of the model, negligible through the central area, and upward to the discharge feature. At the location of the well, the downward vertical gradient was 0.00014 over the 36 m screened interval. The standing water level in the well was 10.465 m. In comparison, aquifer head at the top of the well was 10.469 m and at the bottom of the well it was 10.464 m. That is, aquifer head was greater than well head in the top half of the well, and vice versa in the lower half, and this downward vertical head gradient drove IBF through the well. During pumping (60 m³/d) there was minimal water level difference between aquifer and well (~0.05 m), which showed that well losses were minimal. Drawdown in the well was 0.86 m at the completion of purging.

**Intraborehole flow**

If the well is left un-pumped, a plume of IBF develops in the zone with lower head, driven by the vertical hydraulic gradient. For example, in the homogeneous system a head difference of just 5 mm between the top and bottom of the screen was sufficient to drive downward IBF of 0.68 m³/d (0.47 L/min). These results are shown in Figure 3a, as the borehole flow profile in the well – negative values denote downward flow, increasingly negative values with depth indicate inflow and decreasingly negative values with depth indicate outflow to the aquifer. The IBF rate is given as the maximum absolute value reached on the x-axis. Flow in the well is zero at the top and bottom of the screen because it is not being pumped.

Figure 3b shows groundwater age after a 1,000-day (2.7-year) un-pumped period, during which 680 m³ of IBF has occurred. This longitudinal cross-section at the well location shows the IBF plume extending several tens of metres into the aquifer. A plume of younger (shallower) water was introduced into a zone with otherwise older (deeper) groundwater. The composite age of IBF is 12.1 years, compared to native groundwater in the receiving zone of 30 to 50 years. The extent of the IBF plume (indicated by the black polygon in Figure 3b and Figure 4b) was defined by the model cells containing at least 1% IBF by volume. The full extent of the IBF
plume is not apparent in the groundwater age distribution mainly because of the limited ability of a graduated colour-map to show subtle age changes as the IBF water is increasingly diluted.

**Pumping rate**

When a well is pumped, inflow is a function of $K$ and the local head gradient between aquifer and well. In this homogeneous aquifer, there is potential for uniform inflow over the whole screened interval. But to achieve this, the pumping rate must be high enough to overcome the vertical head gradient and make $K$ the limiting factor. For example, Figure 4a shows a permeability-weighted borehole flow profile, with flow increasing almost linearly from zero at the bottom to the pumping rate (60 m$^3$/d) at the top of the screen. But as the pumping rate was reduced the flow profile became increasingly non-linear as it was increasingly influenced by the vertical head gradient in the aquifer (Figure 5). The threshold for negligible head influence in the inflow profile was at a pumping rate of about 14.4 m$^3$/d (10 L/min) in this model. When the pumping rate was similar to the IBF rate (0.68 m$^3$/d), all flow was sourced from the higher head zone in the upper part of the screen, while at the same time some downward IBF continued. For reference, Figure 5 includes the un-pumped profile, when the natural head gradient fully controlled flow in the well.

**Purging an IBF plume**

The volume of water forming a plume in the zone of lower hydraulic head is given by multiplying the IBF rate by the length of time the well is un-pumped. However, Figure 4 illustrates two key reasons why purging an IBF plume requires pumping a much larger volume of water than the volume of the plume itself. First, some parts of the screen still yield native groundwater, so IBF is only a fraction of pumped water. Second, the IBF plume is skewed in the direction of regional groundwater flow, so the up-gradient area will purge sooner than down gradient.
Figure 6 shows the evolution of IBF in pumpage, as a fraction of sample volume, and the composite age of the sample during purging after the well is left un-pumped. With no un-pumped period, there is no IBF fraction and the sampled age is the same as the initial age for a few hundred well volumes, after which it slowly increases, as pumping alters the flow field in the area around the well and draws in more older water. With a 1,000-day un-pumped period, the sample initially contains just under 50% IBF and sample age is reduced by 40%. Purging of about 3,000 well volumes (4,500 m³) is required for sample age to return to the initial age, at which point about 4% IBF remains in the sample. This apparent contradiction simply illustrates that the composite age mixture is not unique, and a slightly higher proportion of older water in pumpage causes the sample age to equal the initial age before the IBF plume is completely removed. This purge volume is 6.6 times the actual volume of IBF of 680 m³ (0.68 m³/d for 1,000 days).

**Sampled mixtures**

The presence of an IBF plume around a well causes significant sample bias because it replaces the contribution of native groundwater, and associated solutes or contaminants, from some parts of the well screen. In this case the well is in a recharge area and downward IBF forms a plume of anomalously young water surrounding the bottom half of the well screen. The reverse would occur in a discharge area where an upward hydraulic gradient would drive an IBF plume to develop around the upper part of the screen.

To illustrate sample bias due to IBF, Figure 7 shows how the proportion of different groundwater ages in the pumped sample changes with time – immediately after installation, after a 1,000-day un-pumped period, and at increasing purge volumes. In this example, if the well is sampled immediately (initial), composite age is 24.4 years, with a fairly even distribution of 9 to 47 years due to the stratified system. However, if the well is un-pumped for 1,000-days before pumping commences, the fraction of younger water is much higher, with a
reduced age range of 8 to 23 years and just over half the composite sample age. As purging progresses, younger water is gradually removed, with the sampled age mixture returning to that of native groundwater after about 3,000 well volumes have been pumped.

**Effect of heterogeneity**

In a heterogeneous aquifer, well fluxes occur more in zones with higher $K$, in response to natural or induced head gradients. To examine the effect of $K$ contrasts on the development and purging of an IBF plume, two model layers were assigned various combinations of higher $K$ (50-5,000 m/d) compared to the homogeneous $K$ of 10 m/d everywhere else. Figure 8 shows the range of effects on the flow system at the location of the un-pumped long-screened well. Figure 9 shows key relationships drawn from this exercise using results from all combinations of $K$, expressed as a ratio ($K_1/K_2$), with values greater than one indicating higher $K$ in the upper layer than the lower layer and vice versa.

In all cases, the modelled water table was lower than the homogeneous system because the average aquifer $K$ was increased without changing any other boundary conditions. For the range of $K$ combinations tested, the vertical head gradient was steepest when the highest $K$ layer coincided with the lowest head intersected by the well (Figure 8a, Figure 9a), and this translated to a maximum IBF rate (1.3 m$^3$/d, Figure 9b). In this situation, the wellbore provided a path of less resistance than the surrounding aquifer for recharging water to reach the higher $K$ layer. Despite the larger IBF plume, the purge volume was minimised because IBF was a large fraction of well pumpage (Figure 8a, purge vol. / plume vol. ratio = 2.2). Conversely, the minimum IBF rate occurred when the highest $K$ layer coincided with the highest head (Figure 8c, Figure 9b). This was because more inflowing IBF simply exited the well at the same level, to continue flowing in the high $K$ layer, rather than taking a downward path of more resistance. A gentler downward vertical gradient in the system (Figure 9a) generated a lower IBF rate (0.3 m$^3$/d) and a smaller IBF plume. However, a smaller IBF plume did not equate to a smaller
purge volume. The reason is that IBF is a smaller fraction of pumpage – well influx comes from all permeable zones whereas the IBF plume resides only in the zone with lower head (Figure 4b). Thus, it is evident that purge volume can be exceedingly large (Figure 8c, purge vol. / plume vol. ratio = 20.6) if the high K zone and IBF plume location do not coincide.

**Discussion**

This paper uses example models to examine the relationship between pumping rate, purge time and sample composition (age and IBF fraction) from a long-screened well that has been left un-pumped for varying periods of time up to 1,000 days. The well is in the recharge area of a groundwater system and is subject to downward IBF. The modelled IBF rates of 0.3-1.3 m$^3$/d (0.2-0.9 L/min) are a conservative example of commonly measured rates (e.g., 0.01-6.3 L/min, Elçi et al. 2003). In this work, aquifer geometry was simple and K variance was limited by numerical stability issues with the MNW2 package. Real-world aquifers can be more structurally complex, with larger K contrasts and different boundary conditions resulting in larger vertical head gradients driving higher IBF rates. These factors all influence the extent and position of an IBF plume, and hence the specifics of purging and sampling.

The results clearly cast the concept of “purging” in a new light when IBF is present. It is not so much about removing stagnant water in the well as it is about removing a plume around the well. For example, to remove the 3,000 well volumes required to purge the IBF plume in the homogeneous system, the well would need to be pumped for about 5 days at 10 L/s. Clearly, this is an entirely different paradigm than the common well-purging practice of removing three to five casing volumes (Neilsen and Neilsen 2007). The cost and logistics of pumping such a large volume of water could be prohibitive, so the sampling objectives and strategy need to be carefully considered.

To optimize sampling of long-screened or open wells, it is important to measure the flow profile in un-pumped conditions and at the pumping rate used for sampling. Methods to
measure flow profiles include borehole flowmeter (Boman et al. 1997; Molz et al. 1994; Newhouse et al. 2005), tracer-dilution tests in un-pumped conditions (Maurice et al. 2011), tracer-pulse tests while pumping (Izbicki et al. 1999) and tracer-dilution tests while pumping. The latter can be performed with a constant injection of tracer (Brainerd and Robbins 2004) or with single replacement of the borehole fluid column (e.g., Doughty and Tsang 2005; Paillet 2012). In un-pumped conditions the flow profile shows the inflow and outflow zones, which are the high and low head zones respectively, and the IBF rate(s) between them. In pumped conditions the flow profile shows the inflow distribution in the well at the applied pumping rate. These data enable informed decisions to be made about whether or not to attempt purging an IBF plume, how best to sample a well and how to interpret the sample.

Once the IBF rate and outflow zone(s) are established, the plume volume can be estimated if the pumping history is known. It is difficult to accurately determine the purge volume without knowing the specific structure and hydraulic properties of the aquifer system. However, this paper shows that purge volume is a multiple of the plume volume, depending on the position of the plume relative to the K distribution across the well (Figure 9c). To reduce the purge volume it is necessary to increase the fraction of pumped water that is derived from the plume. One way to do this is to isolate the interval containing an IBF plume with packers. Another solution is to insert a flexible, impermeable, water filled liner into the well to prevent IBF from occurring (e.g., Keller et al. 2014). This would not prevent IBF within the gravel pack of a cased well, but it would greatly reduce the overall volume. The liner is removed for sampling and native groundwater is pumped from all depths after a modest purge.

It is also worth noting that well influx from the IBF plume (lower head) zone is not optimised unless the pumping rate is sufficient to overcome the head related influence. For example, in this model the pumping rate needed to be at least \( \sim 14.4 \, \text{m}^3/\text{d} \) to fully overcome an IBF rate of \( 0.68 \, \text{m}^3/\text{d} \) (Figure 5). This is about the maximum rate achievable with the commonly used
Grundfos MP1 sampling pump. In practice IBF rates can easily run into many cubic metres per day, so purging an IBF plume may require a higher pumping rate.

Whether or not purging an IBF plume is feasible, the IBF regime in a well can be used to advantage when sampling. That is, the high head (IBF inflow) zones produce native groundwater without purging, so it could be beneficial to sample these specifically. This has been alluded to previously (e.g., Paillet, 2004), but the practice is not widely reported. A single IBF inflow zone may be sampled with a “grab sampler”, or by pumping the well more slowly than the IBF rate. In principle, this would produce an accurate groundwater sample from a known depth interval. For example, in this model, when pumping at a rate of 1 m$^3$/d (Figure 5), all inflow was sourced from the IBF inflow zone in the top one third of the well.

If an IBF plume is purged, a well provides a composite mixture of native groundwater from all depths according to the inflow distribution at the pumping rate used for sampling. However, the remaining challenge is to identify water composition at specific depths, in addition to the IBF inflow zones. Packers are an established method of sampling specific depth intervals, where they can be isolated. However, this is not always possible (e.g. due to gravel pack in a cased well or an irregular borehole wall) so an alternative that works in the open wellbore is necessary. In such cases, the borehole flow and solute mass-balance method (Collar and Mock 1997; Gossell et al. 1999; Izbicki 2004; Sukop 2000) could be an effective solution.

**Conclusion**

A long-screened well was simulated in the recharge area of a synthetic groundwater flow system to quantify the effects of vertical hydraulic head gradient, and IBF in particular, on the sampled water mixture for different pumping rates and un-pumped periods. The modelling results show that:

- The pumping rate must be at least an order of magnitude higher than the IBF rate to minimise hydraulic head bias in the sample and minimise the purge volume.
• After an example 1,000-day un-pumped period in a homogeneous system, purging an IBF plume required removal of at least three orders of magnitude more water than the common practice of three to five well volumes.

• A basic assessment of heterogeneity showed that purge volume depends both on the proportion of well influx drawn from the IBF plume location and the volume of the plume itself. Purge volume ranged from 2.2 - 20.6 times the volume of the IBF plume for the range of K combinations tested (10 - 5,000 m/d), and was at a maximum when the IBF plume location did not coincide with the high K zone.

• An IBF plume resides only in lower head zones so, even if purging is not feasible, native groundwater samples can be obtained from high to intermediate head (IBF inflow) zones.

These results highlight the importance of knowing the borehole flow regime in un-pumped conditions and at the pumping rate used for sampling, to enable proper understanding of the water mixture sampled from wells in which IBF is active.

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Figure 1: Diagram of model dimensions, sources and sinks and the multi-node well pumping regime over the duration of the simulation.

Figure 2: Relationship between well skin hydraulic conductivity ($K_{skin}$) and IBF for three different aquifer hydraulic conductivities ($K$).
Figure 3: (a) Borehole flow profile and (b) longitudinal cross-section at the well showing head contours (interval = 0.002 m), flow lines through the well (white arrows), groundwater age, and extent of the IBF plume (black polygon) after a 1,000-day un-pumped period (homogeneous system). Dashed lines indicate the screened interval.

Figure 4: (a) Borehole flow profile and (b) longitudinal cross-section at the well showing head contours (interval = 0.02 m), flow lines to the well (white arrows), groundwater age, and extent of the IBF plume (black polygon), upon commencement of pumping after a 1,000-day un-pumped period (homogeneous system). Dashed lines indicate the screened interval.
Figure 5: Borehole flow profiles in un-pumped conditions (pumping rate = 0) and while pumping at different rates (homogeneous system). Cumulative flow normalised to the percentage of pumping rate, or IBF rate for the un-pumped profile. Dashed lines indicate the screened interval.

Figure 6: Purging after an un-pumped period (homogeneous system): solid curves are fraction of IBF in the sample; dashed curves are sample age as a fraction of the initial composite age, both shown as a function of well volumes pumped (well vol. = 1.5 m³). For reference, pumping the well without a preceding un-pumped period (0 days) is also shown.
Figure 7: Proportion of different groundwater ages in the sample, as a cumulative fraction younger (homogeneous system). “Init.” represents groundwater sampled immediately after well installation (no preceding un-pumped period), “0” shows the sampled mixture after a 1,000-day un-pumped period, and the other curves indicate the sampled mixture after different well volumes purged (well vol. = 1.5 m³), with composite age of each sample in brackets.

Figure 8: Influence of IBF, driven by a vertical head gradient (black contours), on groundwater age in the vicinity of a well (black rectangle) after a 1,000-day un-pumped period, for three different combinations of higher K in two layers in an otherwise homogeneous aquifer with K of 10 m/d.
Figure 9: Results of testing the effect of two higher K layers intersecting the well (positions indicated in Figure 8) in an otherwise homogeneous aquifer with K of 10 m/d: relationship of (a) vertical head gradient, (b) IBF rate and (c) the ratio of purge volume to plume volume, for the range of K combinations tested, plotted against the ratio of K in the upper layer (K1) to K in the lower layer (K2).