Effects of intraborehole flow on groundwater age distribution

Brendan A. Zinn · Leonard F. Konikow

Abstract Environmental tracers are used to estimate groundwater ages and travel times, but the strongly heterogeneous nature of many subsurface environments can cause mixing between waters of highly disparate ages, adding additional complexity to the age-estimation process. Mixing may be exacerbated by the presence of wells because long open intervals or long screens with openings at multiple depths can transport water and solutes rapidly over a large vertical distance. The effect of intraborehole flow on groundwater age was examined numerically using direct age transport simulation coupled with the Multi-Node Well Package of MODFLOW. Ages in a homogeneous, anisotropic aquifer reached a predevelopment steady state possessing strong depth dependence. A nonpumping multi-node well was then introduced in one of three locations within the system. In all three cases, vertical transport along the well resulted in substantial changes in age distributions within the system. After a pumping well was added near the nonpumping multi-node well, ages were further perturbed by a flow reversal in the nonpumping multi-node well. Results indicated that intraborehole flow can substantially alter groundwater ages, but the effects are highly dependent on local or regional flow conditions and may change with time.

Résumé Les traceurs environnementaux sont habituellement utilisés pour estimer les âges des eaux souterraines et les temps de résidence. Cependant, la nature hautement hétérogène de nombreux environnements souterrains peut engendrer des mélanges entre des eaux d'âges très disparates, complexifiant par-là même le processus d'estimation des âges. La présence de puits peut exacerber le phénomène de mélange : de longues sections en trou nu ou crépinées exploitant plusieurs niveaux productifs distincts peuvent transporter rapidement l'eau et les solutés sur une grande distance verticale. Les conséquences de flux intra-forages sur les ages des eaux souterraines ont été étudiées numériquement en couplant les simulations directes de temps de résidence avec le "Multi-Node Well Package" de *MODFLOW*. Dans un aquifère homogène et anisotrope, les âges ont atteint un régime permanent étroitement dépendant de la profondeur. Un puits multinœud au repos a ensuite été inséré dans l'une des trois zones du système. Dans les trois cas, les transports verticaux par le puits ont entraîné des modifications substantielles des distributions des âges dans le système. Enfin, après ajout d'un puits en pompage à proximité du puits au repos, les âges ont été perturbé davantage, par une inversion du flux dans le puits au repos. Les résultats ont montré que les flux intra-forages peuvent modifier substantiellement les âges des eaux souterraines, mais leurs effets sont hautement dépendants des conditions locales ou régionales d'écoulement, et peuvent de surcroît changer dans le temps.

Resumen Los trazadores ambientales pueden usarse para estimar el tiempo de viaje y las edades del agua subterránea pero la naturaleza fuertemente heterogénea de muchos ambientes subsuperficiales puede causar mezcla entre aguas de edades altamente dispares, añadiendo complejidad adicional al proceso de estimación de edades. La mezcla puede exacerbarse por la presencia de pozos debido a que intervalos largos abiertos o mallas largas con aberturas a profundidades múltiples pueden transportar agua y solutos rápidamente a lo largo de grandes distancias verticales. Se examinó numéricamente el efecto de flujo entre pozos en la edad del agua subterránea usando la simulación de transporte de edades directa acompañada con el Paquete de Pozos Multi-Nodo de MODFLOW. Las edades en un acuífero anisotrópico y homogéneo alcanzaron un régimen de predesarrollo permanente con fuerte dependencia de la profundidad. Luego se introdujo un sistema de pozos multi-nodo sin bombeo en uno de tres lugares dentro del sistema. En todos los tres casos, el transporte vertical a lo largo del pozo dio por resultado cambios substanciales en las distribuciones de edad dentro del sistema. Después de que se añadió un pozo de bombeo cerca del pozo multi-nodo sin bombeo se perturbaron las edades aún más por inversión del flujo en el pozo multi-nodo sin bombeo. Los resultados indican que el flujo entre los pozos puede

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alterar substancialmente las edades del agua subterránea pero que los efectos son altamente dependientes en las condiciones de flujo regional o local y pueden cambiar con el tiempo.

Keywords Groundwater age · Numerical modeling · Solute transport · Groundwater flow

Introduction and background

The highly heterogeneous nature of many subsurface environments adds significant complexity to the task of estimating flow and transport parameters. Estimates of regional-scale transport characteristics must incorporate smaller-scale variability into models of the system (some examples of upscaling methods include Gelhar and Axness 1983; Li et al. 1994; Haggerty and Gorelick 1995; Berkowitz et al. 2000; Haggerty et al. 2000). Studies have shown that accurate upscaled transport modeling often requires detailed knowledge of the magnitude and the structure of small-scale heterogeneity (e.g., Goltz and Roberts 1987; Li et al. 1994; Di Federico et al. 1999; LaBolle and Fogg 2001; Becker and Shapiro 2001; Guswa and Freyberg 2002; Zinn and Harvey 2003; Liu et al. 2004; Zinn et al. 2004).

To avoid the cumbersome and often infeasible requirements of conventional tracer tests, groundwater investigations sometimes make use of environmental age tracers to estimate flow rates and residence times in the subsurface. Depending on the tracer used, age dating techniques can be used to date relatively young groundwater (e.g., Busenberg and Plummer 1992; Plummer and Friedman 1999; Shapiro et al. 1999) or can target longer, basin-scale transport times (Castro et al. 1998; Sanford et al. 2004).

As with other tracers and contaminants, age tracer concentration is affected by molecular diffusion, mechanical dispersion, and differential advection (at multiple distance scales) once it enters the subsurface. Age-tracer concentration at a particular point will therefore represent a mixture of different water ages, potentially with a large variance in age, which may have important implications for travel-time estimation and model calibration (e.g., Sanford 1997; Bethke and Johnson 2002; Weissmann et al. 2002). This mixing of water with substantially different ages may be particularly prevalent in groundwater systems that possess preferential flow paths. In addition to geologic factors that may contribute to the formation of preferential paths for flow and transport (heterogeneous bedding, fractures, facies prone to possessing a channeled structure, etc.), wells can also create such pathways. Wells may possess open screens, permeable gravel-packed annular spaces, and/or uncased sections over long vertical intervals or may have openings at multiple depths. The potential of intraborehole flow to act as a preferential transport path has been discussed and modeled by others, including Gass et al. (1977), Reilly et al. (1989), Lacombe et al. (1995), Church and Granato (1996), and Konikow and Hornberger (2006a). Depending on the hydrogeologic structure of the system, a well acting as a vertical conduit may have more influence on the vertical redistribution of solutes than local-scale geologic heterogeneities.

Preferential vertical transport of environmental age tracers along open boreholes has been clearly observed in some field sites, including in the High Plains Aquifer in Nebraska (Clark et al. 2006). This area draws both municipal and irrigation water primarily from a confined aquifer, and, during heavy pumping, the heads in this confined aquifer fall more than 10 m below the head of the overlying unconfined aquifer. Because of its agricultural history, the area also contains a number of abandoned wells, which can act as conduits for downward flow from the unconfined aquifer to the confined aquifer, particularly during times of substantial pumping. The effect of this rapid vertical flow was observed through the detection of surprisingly large amounts of CFC-11 in the waters of the confined aquifer. Because the vertical velocity in the confining layer was slow even with the large head gradients, the CFC-11 concentrations caused problems initially in model calibration. Once intraborehole flow through the confining layer was added to the model, much stronger agreement was found between the model and the observed CFC-11 concentrations, indicating that preferential vertical transport along boreholes was a major contributor to concentrations of this particular groundwater age tracer in the deeper confined part of the groundwater system.

The objective of the study was to assess the possibility that intraborehole flow in long wells can alter the distribution of groundwater age in a groundwater system. It was hypothesized that wells spanning a significant fraction of an aquifer's thickness will, depending on the head gradient along the well, transport groundwater of one age to a different part of the aquifer containing water with a substantially different age. Age-tracer samples collected from other wells in affected areas might give incorrect estimates of natural residence time if the presence of the long wells was not accounted for. The hypothesis was tested using numerical experiments in which age transport was simulated in a hypothetical three-dimensional anisotropic groundwater system. Constant flow conditions were imposed on the system to allow a predevelopment steady-state distribution of ages to develop. Wells with long open intervals were then placed at three different locations—a recharge area, a discharge area, and a medial lateral flow area. Transient flow and transport simulations were then run to assess the effect of intraborehole flow on groundwater ages.

Methods

Problem description

The hydrogeologic setting was designed to represent an unconfined regional flow system in which surface recharge drives horizontal and vertical flow to an outflow boundary (Fig. 1). The selected size and shape of the groundwater flow system is arbitrary, but the geometry and boundary conditions for the test problem were chosen to be representative of a range of typical conditions. A constant-head boundary condition (analogous to a river) was imposed at the top edge of the downstream side of the regional groundwater flow system; no-flow conditions were imposed on all other model boundaries. A constant rate of recharge was applied to all cells along the top of the model. These conditions led to a predevelopment steady state regional flow field that was conceptually similar to the side of a river valley or other simple groundwater basin—a groundwater divide with primarily downward infiltration of water at the upstream end of the system, predominantly horizontal flow near the middle part of the system, and predominantly upward flow near the constant-head boundary. The system was assigned constant values of hydraulic conductivity in the horizontal direction (K_h), hydraulic conductivity in the vertical direction (K_v), and porosity (θ).

The values for the model parameters are shown in Table 1. Because flow mostly varied in the x- and z-directions, the width of the system was kept only large enough (61 m) to ensure that boundary effects did not interfere with the changes to the system's flow and transport caused by the open borehole. Because the system possesses a plane of hydrologic symmetry (Fig. 1), computational efficiency was achieved by placing the well directly on the symmetry boundary and calculating changes in groundwater flow and age over one-half of the original model domain. A grid spacing of 3.05 m was specified in the x- and y-directions and 1.52 m in the z-direction.

The predevelopment age distribution in the system was first estimated using a steady-state flow and transport simulation. These ages were then used as the initial conditions for the transient simulations, and the influence of the wells on ages within the system was evaluated relative to these initial ages. Three simulations were run for 20-year time periods, each testing the presence of a well at different locations in the system. Wells were placed 10% of the distance from the upgradient no-flow boundary to the constant-head boundary (termed the upgradient case, see also Fig. 2); halfway to the constant-head boundary (midgradient case); and 90% of the distance to the constant-head boundary (downgradient case). In all three cases a single nonpumping well was placed with a relatively long screen (or open interval) spanning a depth of −16.8 to −50.3 m. Each well therefore spanned slightly more than half of the total thickness of the system.

No pumping was simulated in the wells to help isolate the effects of intraborehole flow, rather than intraborehole flow coupled with effects from pumping. Such nonpumping conditions might be representative of a monitoring well or an abandoned well, which are common in many areas, particularly agricultural regions—see, for example, Government of Alberta (2001), which estimates tens of thousands of these wells just in Alberta, Canada.

Table 1 Flow and transport parameters

Parameter	Symbol	Value
System length	L	762 m
System thickness	b	62.5 m
System width	W	61 m
Recharge rate	R	0.00139 m/day
Porosity	θ	0.2
Horizontal hydraulic conductivity	K_h	76.2 m/day
Vertical hydraulic conductivity	K_v	7.62 m/day
Longitudinal dispersivity	α_L	0.305 m
Horizontal transverse dispersivity	α_{T_H}	0.0762 m
Vertical transverse dispersivity	α_{T_V}	0.0305 m
Effective diffusion coefficient	d^*	0.0
Well radius[a]	r	0.041 m
Dimensionless skin coefficient[a]	–	2.6

[a] See Halford and Hanson (2002) for details about these parameters

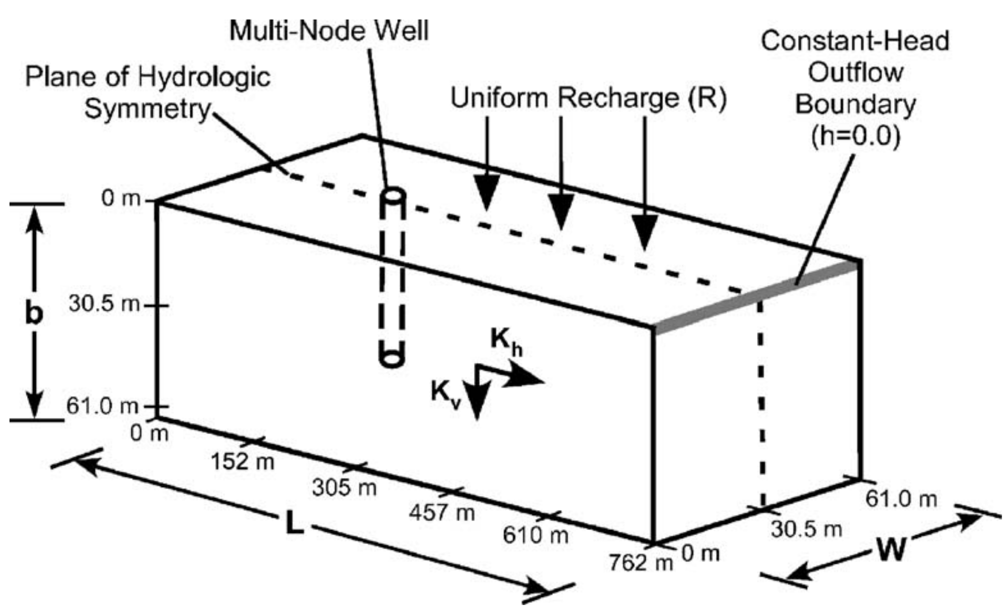

Fig. 1 Conceptual model of groundwater system showing boundary conditions and dimensions; location of multi-node wells varies

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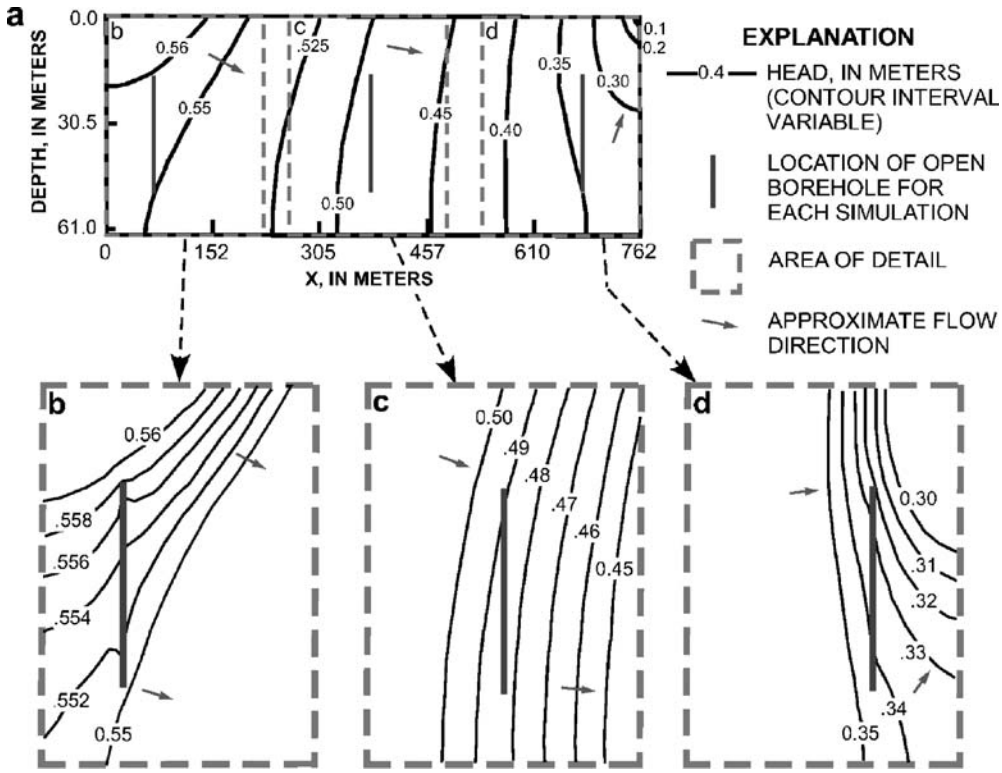

Fig. 2 Calculated head (in meters) on the vertical plane of hydrologic symmetry **a** prior to introduction of multi-node wells. Details of heads in proximity of multi-node wells after the wells had been present for 20 years are shown for **b** upgradient case, **c** midgradient case, and **d** downgradient case

Computer modeling

Groundwater flow was simulated using the MODFLOW-2000 model developed by the US Geological Survey, a public-domain three-dimensional block-centered finite-difference code (Harbaugh et al. 2000). Intraborehole flow was simulated using the Multi-Node Well (MNW) Package of MODFLOW (Halford and Hanson 2002). The MNW model allows a well spanning multiple vertical grid blocks to be represented as a single borehole, which allows the fluxes into and out of the well at each node to be calculated as a function of head gradients at that node.

Solute transport was simulated using the Ground-Water Transport (GWT) Process of MODFLOW-2000 (Konikow et al. 1996; Kipp et al. 1998; Heberton et al. 2000; Konikow and Hornberger 2003). MODFLOW-GWT uses a solution algorithm based on the method-of-characteristics, which tracks particles moving along the advective paths of the flow field. Each particle represents a volume-based weight, with the average concentration in each cell computed using a volume-weighted average, assuring a global mass balance for the solute. Recently, the MNW Package has been integrated into MODFLOW-GWT (Konikow and Hornberger 2006a), coupling the MODFLOW-derived fluxes at the multi-node well to the method-of-characteristics particle-tracking algorithm. Solute can move within a long well or borehole during pumping or in the absence of pumping. Results with solute-transport simulations (Konikow and Hornberger 2006b) using this new capability have agreed with earlier work suggesting that intraborehole flow can provide a preferential pathway for vertical solute migration.

Groundwater ages were calculated using the MODFLOW-GWT Age Package, which uses direct age simulation within the transport model (Goode 1999). The method simulates age as a nonreactive solute species coupled with a zero-order production term that reflects the inherent increase in groundwater age as a function of time. Age (which is treated as analogous to concentration) is modeled using the classic advection-dispersion equation (for an incompressible fluid) with an additional zero-order production term:

$$\frac{\partial A}{\partial t} = \frac{\nabla \times [\theta(\mathbf{D} + d^*) \times \nabla A]}{\theta} - \mathbf{v} \times \nabla A + 1 + \frac{W(A' - A)}{\theta} \quad (1)$$

where **D** is the mechanical dispersion tensor, d* is the effective molecular diffusion coefficient, **v** is the velocity, θ is the effective porosity, and A is the age. The term WA' is a source/sink term, with W being the volumetric flux and A' being the age of the source or sink water. The "+1" term is the aforementioned age production term. MODFLOW-GWT follows the method of Burnett and Frind (1987) to calculate three components for the mechanical dispersion tensor to account for anisotropy in the system's dispersive parameters—dispersivity in the longitudinal direction of flow (α_L), dispersivity transverse to the direction of flow in the horizontal direction (α_{T_H}), and dispersivity transverse to the direction of flow in the vertical direction (α_{T_V}). Because of the scale of the

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problem and the lack of explicit small-scale heterogeneity, diffusion was neglected in the simulations.

Results

The introduction of a nonpumping multi-node well into the system did not substantially alter the regional heads in the system in any of the three cases, but did appear to influence local-scale heads (Fig. 2). Basin-scale heads both prior to and after introduction of the multi-node wells showed predominantly downward gradients near the upgradient (left side of the system in Fig. 2a) end of the system, predominantly horizontal head gradients near the middle of the system, and strong upward head gradients at the downgradient end of the system as flow converged toward the constant-head boundary (top-right corner in Fig. 2a).

The presence of multi-node wells did, however, affect the local heads around the open intervals of the wells (Fig. 2b–d). The local-scale head maps show that the head gradients in proximity to the well were different in all three cases. In the upgradient (Fig. 2b) and midgradient (Fig. 2c) well cases, head near the well decreases with depth (Table 2), which will lead to downward flow in the well (though the magnitude and direction at each node will differ). In the downgradient well case (Fig. 2d), head gradients (Table 2) indicate that flow will move up the well. The total inflow and outflow at each multi-node well (Table 2) were proportional to the head differences, with the downgradient well case producing a higher flux, by a factor of about 3.1, than the fluxes in the midgradient and upgradient well cases.

Plots of the ages in the system (Fig. 3) confirm the behaviors suggested by head contours. Prior to the introduction of the multi-node wells, the system had an initial steady-state distribution of ages that was highly depth-dependent (Fig. 3a), though at the downgradient end of the system, flow paths for many different travel times converge at the outflow boundary. At all three locations, the introduction of a long open well caused a substantial change to age distributions after 20 years, particularly in proximity to and downgradient from each well.

In the upgradient well case (Fig. 3b), the presence of the multi-node well created a conduit for relatively young water near the top of the well to move downward into lower parts of the aquifer, driven by the head gradients (Fig. 2) around the well. Although the area near the bottom of the well experienced the greatest effect, younger water exited the multi-node well to some extent along the entire lower half of the well. The predominant regional directions of flow near this well, as indicated by Fig. 2b, were downward and in the positive x-direction. This drove the movement of the younger water once it exited the well, as the plume of younger water that developed around the lower end of the well appeared to spread in both of those directions.

The results of the midgradient simulation (Fig. 3c) were similar in many respects to the upgradient case. Heads were higher at the top of the well than at the bottom, and therefore intraborehole flow drove younger water from the top elevations of the well downward into the bottom portion of the well. Regional head gradients in this part of the aquifer, however, were mostly in the horizontal rather than vertical direction, and the age map indicates that this reduced the downward propagation of the younger water and instead promoted increased horizontal transport of solute in water exiting the well.

The downgradient well case (Fig. 3d) behaved in an opposite fashion to the other two cases because heads were highest at the bottom of the well and lowest at the top. Consistent with the head data, older water entered through the lower parts of the well and then exited through the upper portion. The converging flow paths in proximity to the top of the well constrained the older water exiting the well along a progressively focused path as it migrated away from the upper part of the well.

A more quantitative illustration of the age changes caused by the multi-node wells can be seen by examining the percent change in age in the aquifer after 20 years for each of the three scenarios (Fig. 4). The overall pattern of the percent change in age mirrored the behaviors seen in the calculated age maps (Fig. 3). The upgradient well case (Fig. 4a) produced a plume of relatively large decrease in age focused around the lower portion of the well that moved both downward and horizontally. The midgradient well case (Fig. 4b) showed a smaller maximum decrease with less downward penetration than the upgradient well case, but the area affected covered a longer distance horizontally. The downgradient well case (Fig. 4c) showed increases in age around the top half of the multi-node well, with the plume of age increase getting narrower as it moved toward the converging flow at the outflow boundary.

Of the three simulations, the midgradient simulation displayed the least intense change in age. It also possessed the longest horizontal extent of effect, but the smallest vertical extent, because of the predominant direction of the head gradients in that region of the aquifer. The upgradient and downgradient cases, by contrast, occurred in areas with strong vertical gradients, and, therefore, the water that exited from the well in both cases had significant components of movement in both the vertical and horizontal directions. This vertical component is what

Table 2 Aquifer heads at multi-node wells and total well fluxes

Well location	Head at top (m)	Head at bottom (m)	H_{top}-H_{bottom} (m)	Head in well (m)	Total flux in/out (m^3/day)
Upgradient case	0.5562	0.5516	0.0046	0.5534	16.90
Midgradient case	0.4897	0.4853	0.0044	0.4871	16.49
Downgradient case	0.3273	0.3408	−0.0135	0.3351	51.81

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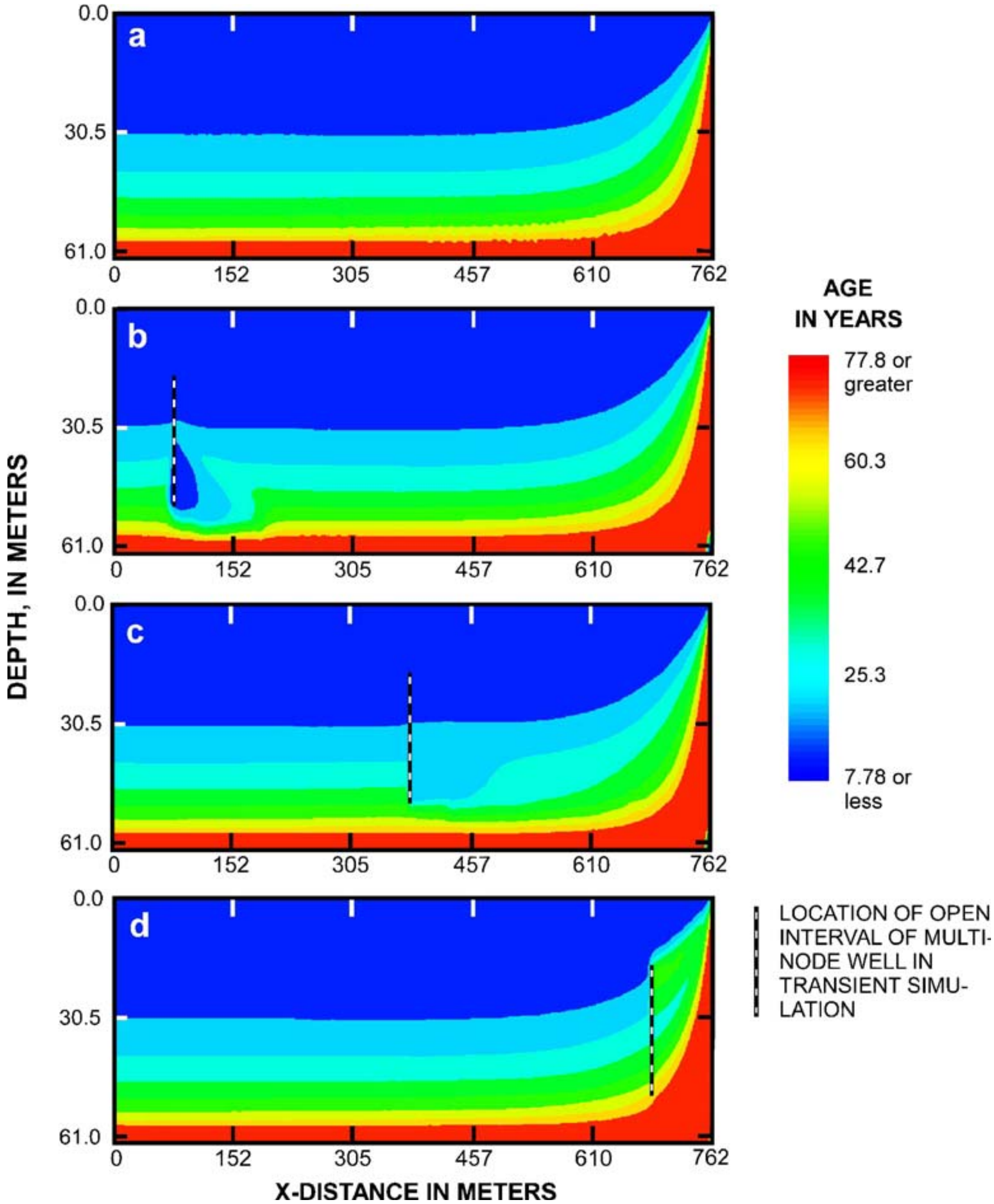

Fig. 3 Groundwater ages on the vertical plane of hydrologic symmetry **a** prior to introduction of multi-node wells (predevelopment steady state) and after a multi-node well existed for 20 years for **b** upgradient case, **c** midgradient case, and **d** downgradient case

caused the percent age change of the upgradient and downgradient cases to be larger than in the midgradient case. The downward motion in the upgradient well case brought the young water into contact with older, deeper water than did the mostly horizontal movement in the midgradient well case, whereas the downgradient well case brought deeper, older water into contact with shallower, younger water through upward vertical movement. The predominantly horizontal flow in the midgradient well case, however, allowed the change in age to spread over a larger area. In effect, the spatial distribution of the age change varied depending on the location of the well relative to the regional gradients of the system, leading to a more dilute plume of age change in the midgradient case, a tightly focused but gradually spreading age change in the upgradient case, and a progressively tightening plume of age change in the downgradient case.

Age change at point locations

Spatial maps of age (Fig. 3) and age change (Fig. 4) show the overall behavior of groundwater age in the presence of the multi-node well over a relatively large area. However, groundwater age at specific locations was also examined to see how age evolved over time in a more localized fashion. For the upgradient and midgradient cases, age at the bottom node of the multi-node well was recorded, and in the downgradient case age at the top node of the multi-node well was recorded (see Fig. 2). In all three cases, additional observations were also made 15.2, 30.5, and 61.0 m in the positive x-direction from the observation point at the well. Although head changes and solute transfer through the borehole begin immediately, and the presence of intraborehole flow would rapidly influence environmental tracer concentrations in samples drawn from or very near the multi-node well, the

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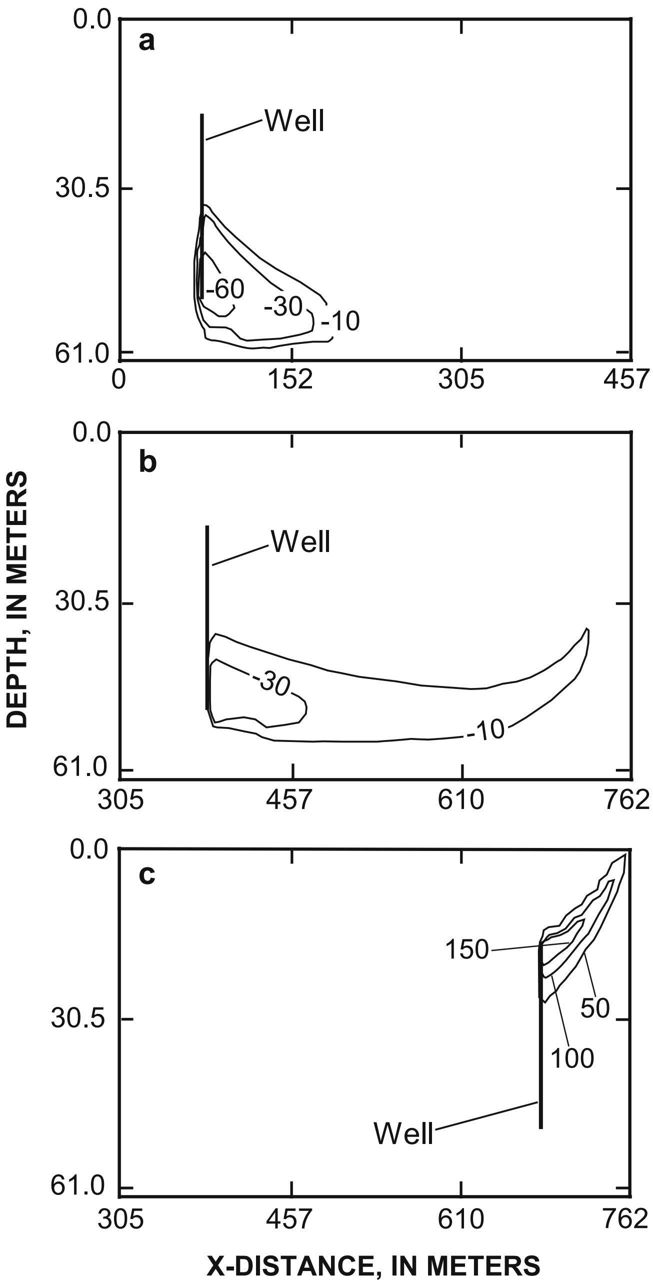

Fig. 4 Percent change in groundwater age from predevelopment steady state after multi-node wells had been present for 20 years for **a** upgradient case, **b** midgradient case, and **c** downgradient case

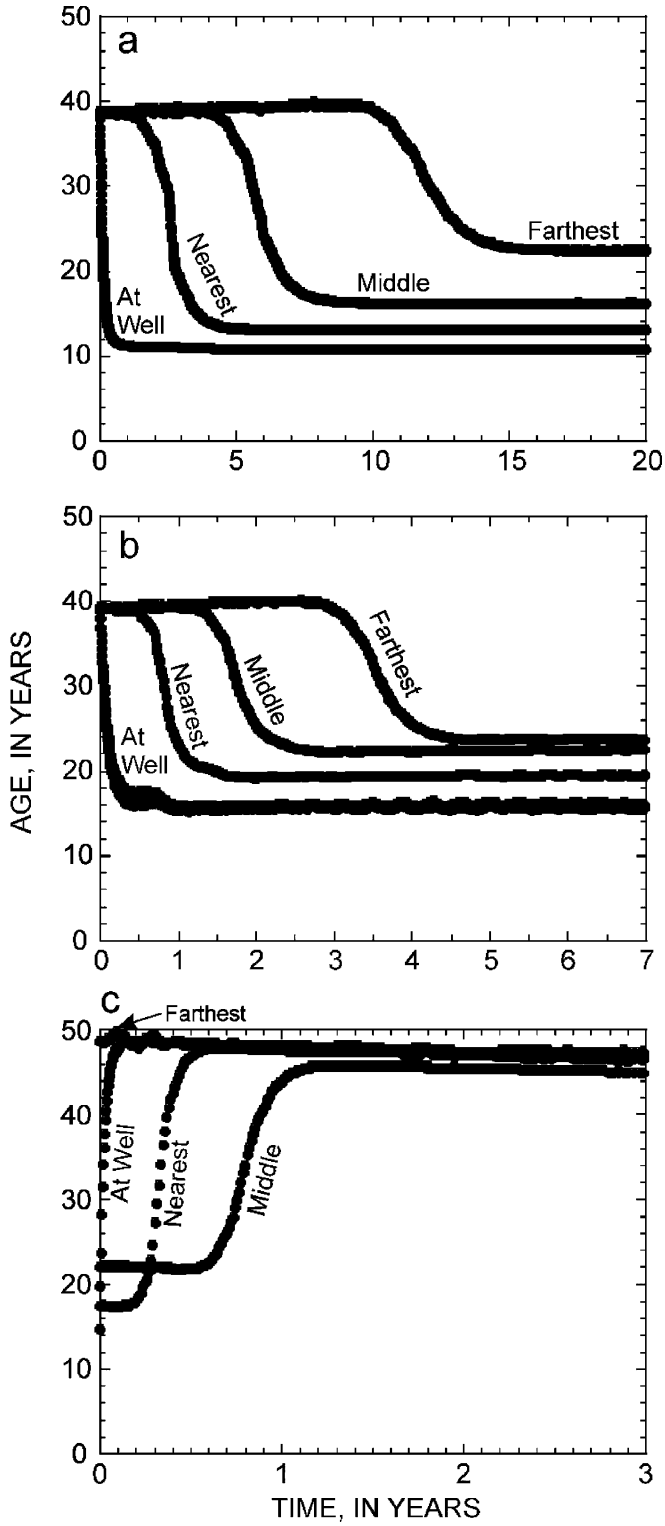

Fig. 5 Groundwater age as function of time at four points for **a** upgradient case, **b** midgradient case, and **c** downgradient case. *Curves* show age at the bottom (cases **a** and **b**) or top (case **c**) node of the multi-node well, along with age at distances of 15.2 m (nearest), 30.5 m (middle), and 61.0 m (farthest) in the positive x-direction from the well location. Note that the *horizontal scale* differs among the three plots

20-year simulation shows that the effects propagated downgradient at rates equivalent to the local groundwater velocity.

Ages decreased in all four observation locations in both the upgradient (Fig. 5a) and midgradient (Fig. 5b) cases. Age showed a consistent progression as a function of distance from the well—as distance from the well increased, the response time also increased. In both cases, age at the bottom of the well decreased quite rapidly, reaching an approximate asymptotic value in about 100 days. At the farthest measurement point (61.0 m in the x-direction), responses occurred at least an order of magnitude later.

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The magnitude of the response consistently decreased as distance from the well increased in both the midgradient and upgradient cases. In the upgradient case, age decrease at the farthest location was about half of the decrease at the well, whereas in the midgradient case, age decrease at the farthest location was approximately two-thirds of the decrease at the well. The upgradient and midgradient cases also had different magnitude decreases at the well itself—age dropped by a factor of 3.5 in the upgradient case, but only by a factor of 2.3 in the midgradient case.

Both the time lag and magnitude are consistent with the results observed from the age maps and age-change plots. The larger decrease in age directly at the upgradient well (compared to that at the midgradient well) agrees with the larger relative change observed near the bottom of that well. In the midgradient case, the predominantly horizontal movement of younger water once it exited the bottom of the well resulted in a more rapid response at observation points located in the positive x-direction from the well bottom, as well as more similarity in the magnitude of age decrease between the well and the more distant observation points observed in the midgradient case and a smaller response magnitude at the well.

For the downgradient well case (Fig. 5c), a similar set of observations were taken, but in this case at the top of the open interval of the well (and 15.2, 30.5, and 61.0 m in the positive x-direction from the top of the well's open interval). Ages at observation points in this case increased rather than decreased because of preferential flow of older water up the well. One major difference for the observations in this case was that the farthest observation point showed almost no response to the presence of the multi-node well. This is a result of the strong vertical component of flow near the downgradient well. The water discharging from the top part of this well was transported vertically above the farthest observation point (at the same elevation as the top of the well) and therefore that particular location experienced minimal effect from the water leaving the multi-node well. With the exception of the farthest observation point, the trends of age behaviors as a function of distance in the downgradient case were similar to the other two cases (though the change was an increase rather than a decrease in age)—as distance from the multi-node well increased, the magnitude of the age increase diminished and the time lag for the effect to take place increased.

Intraborehole flow in a pumped system

Large transient changes to the flow field could potentially lead to major changes in the effects of intraborehole flow on a groundwater system. The initial simulations demonstrated that intraborehole flow in nonpumping wells may act as a mechanism for transporting water of one age into areas with substantially different ages in a steady-state flow system, but some settings may also undergo large transient changes in flow resulting from human development of the aquifer system. In such cases, multi-node wells may act as preferential flow and transport conduits, but the effect of the well will change to accommodate the new flow field. This means that the presence of a multi-node well could potentially lead to a completely new set of behaviors once the flow field of the system shifts.

To illustrate this type of effect, a new set of simulations was run using the downgradient case from the previous set of simulations. In this case, the multi-node well was introduced as before and the system was maintained at steady flow conditions for 2 years. After the elapsed 2 years, a multi-node production well was introduced into the system 30.48 m in the upgradient direction from the bottom of the multi-node well. The depth of the pumping well spanned the bottom third of the nonpumping well depth, plus an additional 6.96 m below the bottom of the nonpumping well (Fig. 6). A total pumping rate of 36.81 m^3/day (18.41 m^3/day on each side of the plane of hydrologic symmetry) was assigned to the well, which was equivalent to approximately half of the total recharge to the system. The pumping was maintained at a constant rate for 6 years.

Heads in the system substantially changed after the introduction of the pumping well (Fig. 6). In the presence of pumping, the distance to the lateral boundary (30.5 m) was small enough that the drawdown near the pumping well was greater than if that boundary had been much further away; however, the effect of the boundary on flow in the nonpumping well was minimal. Although the regional component of flow observed in the absence of pumping (see Fig. 2) was partly maintained, a local decrease in head occurred in the proximity of the pumping well. The head gradients indicate substantial downward flow to the pumping well, as would be expected given that all of the external sources of water for this model originated along the top of the model boundary. Prior to pumping, flow at the downgradient end of the system was in the positive x-direction and upward, but the heads after pumping started

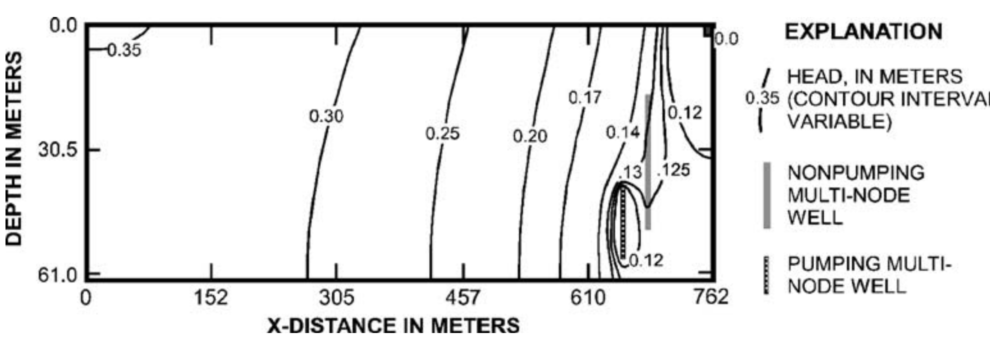

Fig. 6 Heads on the vertical plane of symmetry after 6 years of pumping a multi-node well located 30.5 m upgradient of the downgradient-case nonpumping multi-node well

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indicate that the direction of flow reversed in proximity to the pumping well, and the area of reversal encompassed the nonpumping well. Head gradients indicate that the flow in the nonpumping well, which was upward prior to pumping, became downward after pumping started.

The reversal of the direction of flow in the nonpumping well means that the well, which acted as a conduit for upward transport prior to pumping, will act in the opposite way after pumping is introduced and carry shallower, younger water downward into the older, deeper parts of the aquifer (similar to the behavior observed in the upgradient and midgradient cases). The maps of age concentrations (Fig. 7) confirm the behavioral trends indicated by the head contours. In the 2 years prior to the introduction of pumping, deeper older water flowed up the borehole (Fig. 7a). After the pumping well was introduced, intraborehole flow in the nonpumping well reversed direction and shallow groundwater flowed into the deeper parts of the aquifer (Fig. 7b and c). This water was substantially younger than the original water located near the bottom the nonpumping well, and, therefore, the net effect of the nonpumping multi-node well was decreased groundwater age in the area around the bottom of the well. The pumping well clearly drew water from more than just the nonpumping well, as the ages indicate that water was also pulled into the pumping well from the aquifer both above and below. The nonpumping well, however, acted as a particularly effective vertical transport conduit for younger water in this new configuration, just as it provided a means of preferential transport of older water prior to pumping. The volumetric extent of the younger water exiting the nonpumping well was constrained by the location of the pumping well—the plume of younger water was primarily confined to the area directly around the bottom of the nonpumping well and the area between the two wells.

Discussion and conclusions

Environmental age tracers in groundwater are solutes, and, therefore, hydrogeologic features of concern for traditional contaminant transport will also require consideration when using age tracers to estimate natural residence times or to calibrate flow models (examples can be found in Sanford 1997; Bethke and Johnson 2002; Weissmann et al. 2002). Intraborehole flow has been recognized in previous studies (Gass et al. 1977; Reilly et al. 1989; Lacombe et al. 1995; Church and Granato 1996; Konikow and Hornberger 2006b) as a mechanism for rapidly transporting contaminants

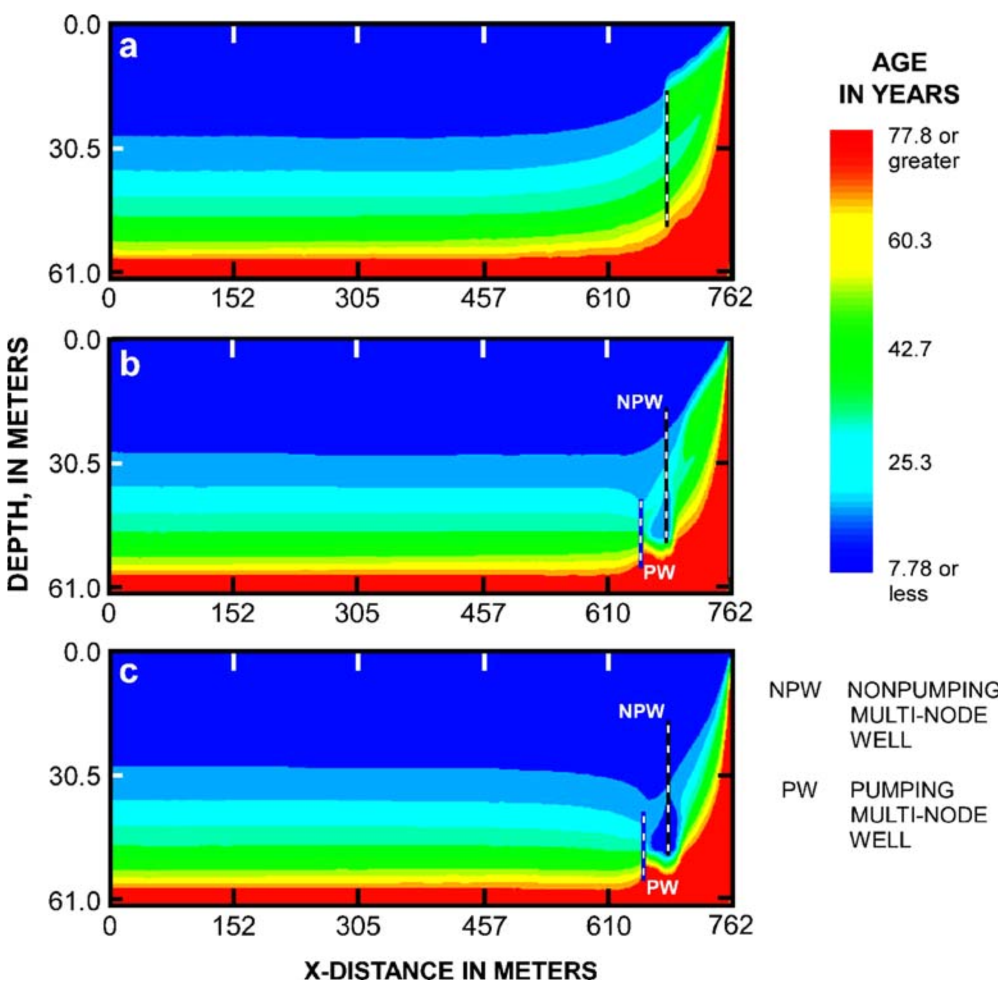

Fig. 7 Groundwater ages on the vertical plane of hydrologic symmetry **a** 2 years after the introduction of a nonpumping multi-node well, at which time a pumping well was introduced; and age after pumping for an additional **b** 2 years and **c** 6 years

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in the subsurface. In this study, the concept of preferential transport along boreholes was applied to the problem of groundwater age and mixing in the subsurface, making use of recent additions to the MODFLOW-GWT solute-transport model that allows simulation of transport (including groundwater age) in multi-node wells.

In a hypothetical, anisotropic, homogeneous setting, the presence of multi-node wells with intraborehole flow was found to have an effect on spatial distributions of groundwater age, but the nature of the effect differed for the three representative locations that were evaluated. For the well located near the upgradient end of the system, the multi-node well transported younger water downward and mixed it with older water in deeper parts of the aquifer. The well located near the midgradient part of the system also carried younger water downward, but the water leaving the bottom of the well migrated away from the well along a more horizontal path, leading to less intense changes in age spread out over a larger volume of the aquifer. The well located near the discharge point of the system (the downgradient case) transported older water from the deeper parts of the aquifer upward, mixing it with younger water near the top of the well.

The different behaviors in the three cases demonstrate that the effect of intraborehole flow is highly dependent on the location of the borehole within the system, particularly in relation to the head field of the system. In the case of this simple hydrogeologic setting, the primary determinants of the head gradients were the boundary conditions of the system and the anisotropy of the hydraulic conductivity. Head gradients controlled the direction of flow along the borehole and the subsequent movement of the water once it exited the well. In a more complicated system, other factors could also play a major role in how water and age tracers move along the well, and how those waters migrate away from the discharging sections of the borehole. For example, heterogeneity in the structure of hydraulic conductivity could cause variability in inflows and outflows along the well screen, a deep confined aquifer with relatively high head could drive upward flow in a borehole open to multiple geologic layers, and additional sources and sinks in the system might change the directions and magnitudes of flows. This indicates that the presence of wells with intraborehole flow could substantially affect groundwater ages in a system, but that the changes will be highly dependent on a number of local factors that must be carefully quantified to accurately determine the effect.

One such factor that was investigated in this work was a transient change in the system flow field, in this case caused by a pumping well in proximity to the nonpumping multi-node well in the downgradient case. Pumping substantially altered the system heads, particularly in areas around the pumping well. The nonpumping well, which had acted as a conduit for upward flow of older water prior to pumping, reversed its behavior once pumping began. While pumping was occurring, the nonpumping well acted as a conduit for downward flow, transporting younger water to deeper parts of the aquifer. Many systems possess the potential for large transient shifts in heads and flow rates, due to natural fluctuations or human development. The simulation results indicate that sufficiently large transient changes in the flow field may be able to substantially alter effects from intraborehole flow.

The use of environmental tracers to measure groundwater age can potentially provide improved estimates of flow and transport in many settings. Knowledge of the important hydrogeologic features of the system, however, is critical to account for all processes occurring in the subsurface. Abandoned wells with leaky casings, wells with long open intervals, or monitoring wells with long well screens are common examples of manmade structures that may influence subsurface environmental tracer concentrations, as these types of boreholes can act as preferential pathways for fluid and solutes. Accurate knowledge of the location of such wells is critical because the effect of intraborehole flow is highly dependent on location within the system, with the local head gradient dictating the nature of flow in the well, and larger-scale heads dictating the migration and subsequent mixing of the well outflow. Temporal factors must also be accounted for, as transient changes in the head field can lead to major shifts in both the magnitude and direction of intraborehole flow. The presence of long open boreholes in a groundwater system should be considered when evaluating and interpreting groundwater ages based on concentrations of environmental tracers in samples collected from that groundwater system, even if the samples were collected at discrete points. Using environmental tracers without accounting for these effects may lead to inaccurate estimates of key subsurface flow and transport parameters.

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