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UNCERTAINTIES IN THE TRANSIENT CAPTURE-ZONES OF GROUNDWATER SUPPLY WELLS

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Capture zones of water-supply wells are a widely used analysis tool for protection of groundwater resources. Transient analyses of capture zones provide a more complete assessment than the more commonly applied steady-state analyses. Previously, we have demonstrated that advection-only analyses can produce biased transient capture-zone estimates. Therefore, it is important to consider the dispersion of contaminant plumes. Here, we extend our study to incorporate temporal and spatial distribution in the contaminant sources and their respective uncertainties. Our analysis indicates that the capture-zone estimates can be very sensitive to the transients in contaminant releases. Even relatively small uncertainties in the contaminant source, when combined with transient flow effects associated with natural variability of gradients or water supply well pumping, can cause significant uncertainties in capture-zone estimates. This conclusion has important practical implications. The locations and times at which contaminants reach the aquifer are often very uncertain, especially in cases for which upstream source release history and vadose zone transport rates are poorly known. The resulting capture-zone estimates in such systems can be, in effect, completely uncertain. Our current work demonstrates some of the theoretical and computational challenges that we face in the estimation of predictive uncertainties.

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UNCERTAINTIES IN TRANSIENT CAPTURE-ZONE ESTIMATES OF GROUNDWATER SUPPLY WELLS

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ABSTRACT

Capture zones of water-supply wells are a widely used analysis tool for protection of groundwater resources. Transient analyses of capture zones provide a more complete assessment than the commonly applied steady-state analyses. Previously, we have demonstrated that advection-only analyses can produce biased transient capture-zone estimates. Therefore, it is important to consider the dispersion of contaminant plumes. Here, we extend our study to incorporate temporal and spatial distribution in the contaminant sources and their respective uncertainties. Our analysis indicates that the capture-zone estimates can be very sensitive to the transients in the contaminant releases. Even relatively small uncertainties in the contaminant source, when combined with transient flow effects associated with natural variability of gradients or water-supply pumping, can cause significant uncertainties in the capture-zone estimates. This conclusion has important practical implications. Furthermore, we investigate the impact of uncertainty in the longitudinal and transverse dispersivities on the transient capture estimates.

1. INTRODUCTION

Capture zones are important for the efficient protection of groundwater resources produced by wells and springs. Typically, the capture zones are delineated using mathematical models. The models are based on simplifying assumptions for representation of real hydrogeological systems. For example, the transients are commonly ignored in the flow and transport models assuming a steady-state flow. Actually, substantial transients might exist, for example, due to variability in the pumping rates of water-supply wells, and, as a result, there might be a substantial bias in the steady-state capture-zone estimates (Fig.1). Furthermore, even if the transients are incorporated in the model, the groundwater transport might be represented by advection-only flow paths. The advection-only analysis might not provide an acceptable representation of mean plume behaviour of potential transport because of the impact of transients on the effective plume dispersion. As a result, we might have an additional bias in the capture-zone estimates (Vesselinov & Robinson, 2006).

Here we analyse numerically the impact of the transients in the groundwater flow and transport on the capture zone estimates for a series of synthetic cases. We also investigate the impact of uncertainty in the longitudinal and transverse dispersivities on the transient capture estimates.

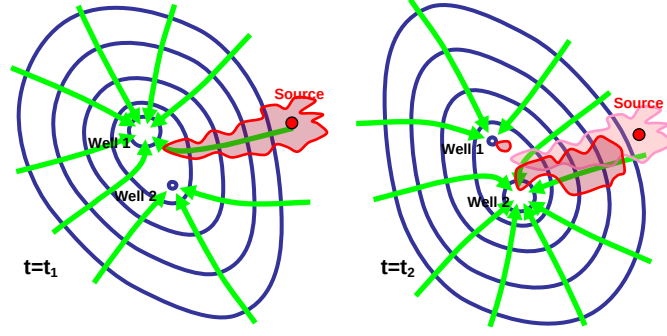


FIGURE 1. Schematic representation of the impact of flow transients on the contaminant plume. The contaminant source is within the capture zones of both wells but steady-state/advective-only capture zone analyses will give us an incorrect result.

2. METHODOLOGY

To delineate the transient capture zones, we follow the methodology outlined by Vesselinov & Robinson (2006). We solve numerically the partial differential equations describing transient groundwater flow and transport within a two-dimensional confined uniform and isotropic domain (Fig.2). There are two wells with pumping regime as presented in Fig.3. The 2-D model domain (Fig.2) is defined to be large enough to minimize the boundary effects (about 20 times the distance between the wells). The grid is fine in the well vicinity and the grid cells increase geometrically with the distance from the wells. Dimensionless analyses performed by Vesselinov & Robinson (2006) demonstrated that in this case the capture zone estimates depend on a series of dimensionless groups:

- $Qt_C/(md^2\phi)$ [–] – this parameter characterizes dimensionless pumping rate or dimensionless advective velocity. It is obtained by comparison of quasi-steady-state advective velocity $Q/(md\phi)$ [L T⁻¹] and velocity required for a water particle to move advectively the distance d for time t_C .
- $t_C a/d^2$ [–] – this parameter defines dimensionless hydraulic diffusivity or dimensionless time interval in pumping regime.
- $x/d, y/d$ [–] – dimensionless Cartesian coordinates:
- $\alpha_L/d, \alpha_T/d$ [–] – dimensionless longitudinal / transverse dispersivities

where a is hydraulic diffusivity [L² T⁻¹] ($a = k/S_S$; where k is hydraulic conductivity [L T⁻¹]; S_S is specific storage [L⁻¹]); α_L and α_T are the longitudinal and transverse dispersivities [L]; ϕ is porosity [–]; Q is well pumping rate [L³ T⁻¹]; d is the distance between the two pumping wells [L]; and t_C is the size of the pumping steps [T]. We assume that there is no molecular diffusion. We solve the flow using a standard finite-volume computational scheme (Zyvoloski et al., 1997). We use a Lagrangian (particle-tracking) technique to solve the transport equations. The pumping periods t_C are discretized using 10 geometrically increasing simulation time steps.

The capture zones are delineated using instantaneous ($t = 0$) and transient releases of plumes at multiple initial locations defining a rectangular area (shown in green on Fig.2) around the wells. The size of the rectangular area is $4d \times 2d$. In the advective-only case, we

use 80 000 (400×200) regularly spaced initial locations. In the advective–dispersive case, 4000 (80×50) initial locations are used, and 1000 particles per release location are applied to characterize the plume distribution. The transient flow and transport are simulated for a series of pumping cycles until all the particles are captured. The capture-zone analyses are computationally very demanding. To achieve computational efficiency, we have used supercomputer clusters to parallelize the capture-zone delineation.

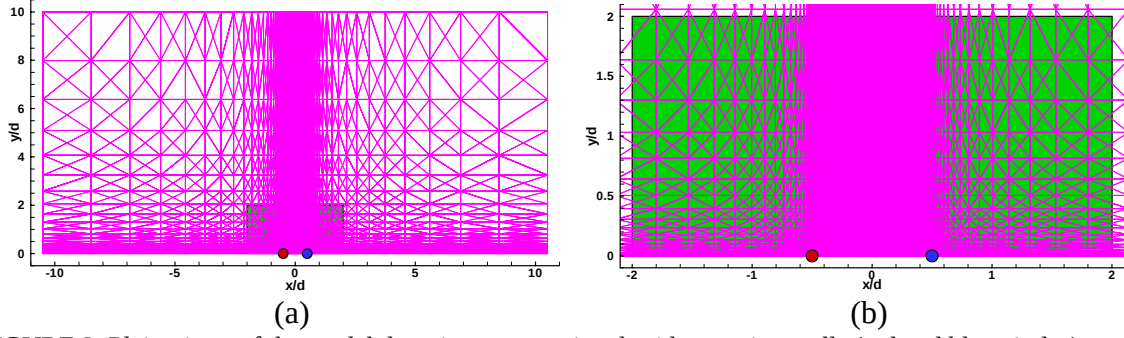


FIGURE 2. Plain views of the model domain, computational grid, pumping wells (red and blue circles), and area for capture zone analysis (green rectangle).

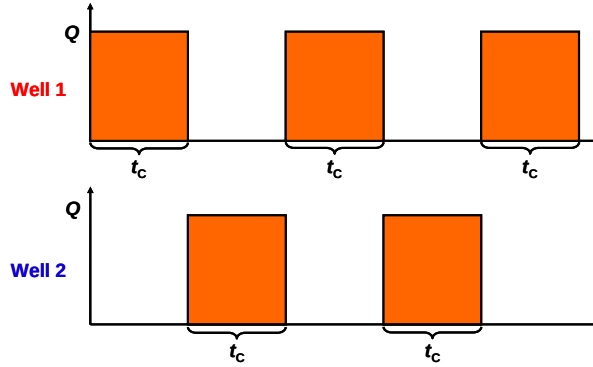


FIGURE 3. Temporal variability of pumping rates of Well 1 and 2.

3. RESULTS

First, we assume advective-only groundwater transport. Capture-zone results using constant $t_c a / d^2 = 86.4$ are presented on Fig.4. In these plots, the red and blue portions of the domain are captured by the blue and red wells respectively. If the dimensionless pumping rate is very low ($Q t_c / (m d^2 \phi) = 0.864$), the boundary between the capture zones is almost a straight line (Fig. 4a; in the case of steady-state capture-zone estimation, the boundary will be exactly a straight line). However, higher pumping rate ($Q t_c / (m d^2 \phi) > 0.864$) cause the level of interfingering between the capture zones to increase substantially. $Q t_c / (m d^2 \phi)$ also impacts the number of fingers and the size of the fingers observed over our domain. The impact of dimensionless hydraulic diffusivity $t_c a / d^2$ is explored on Fig.5, assuming constant $Q t_c / (m d^2 \phi) = 8.64$. The figure shows that the dimensionless hydraulic diffusivity $t_c a / d^2$ impacts the thickness of the fingers.

The results presented on Figures 4 and 5 represent capture zones associated with instantaneous contaminant release at $t=0$. However, we might have transient contaminant

releases at different times. Figure 6 shows the transient capture zones associated with instantaneous releases at multiple dimensionless times distributed between 0 and $2t_c$. The figure demonstrates the impact of release times on the capture zone estimates. Note that for any given spatial release location, there is a probability that contaminant release will be captured by either of the wells; this is especially important for locations within the central portions of the domain. The analysis indicates that the capture-zone estimates can be very sensitive to the transients in contaminant releases. Even relatively small uncertainties in the contaminant source release can cause significant uncertainties in capture-zone estimates.

Now we will further investigate the impact of the dispersive nature of groundwater transport on capture-zone estimates. Figures 7 and 8 show the impact of dimensionless longitudinal and transverse dispersivities in two cases. The colour scales between red and blue define the ratio of the plume captured by the left well (for the right well, the ratio is 1 minus the ratio for the left well). On Fig. 7, the dimensionless pumping rate is very low ($Qt_c/(md^2\phi) = 0.0864$); in this case the capture zone predictions are close to what will be estimated if we assume a state-state flow model and constant pumping at both wells. On Fig. 8, the transients are substantial ($Qt_c/(md^2\phi) = 8.64$). The various plots on both figures are for different sets of dimensionless longitudinal and transverse dispersivities. Note that in the case when the transients are minor (Fig 7), the smearing between the capture zones is impacted substantially by transverse dispersivity (Fig 7a vs 7b vs 7c); however, variability in longitudinal dispersivity has almost no affect on the capture zone estimates (Fig 7b vs 7d). Reversely, when the transients are dominant (Fig 8), transverse dispersivity has a minor affect on capture zone estimates (Figures 8a, 8b, and 8c are very similar); however, longitudinal dispersivity has a dominant affect on the capture zone estimates (Fig 8b vs 8d). Comparison of the plots on Figures 7 and 8 also reveals the effect of transient flow on the capture zone estimates.

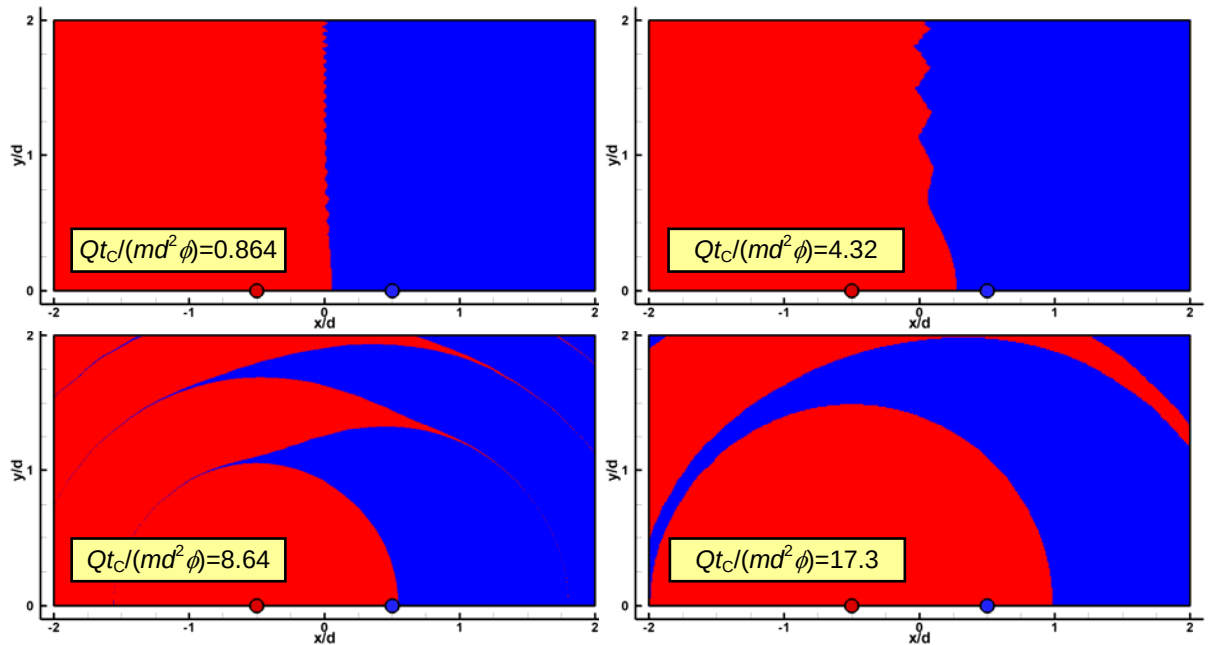


FIGURE 4. Impact of dimensionless pumping rate on transient capture zones ($t_c a/d^2 = 86.4$).

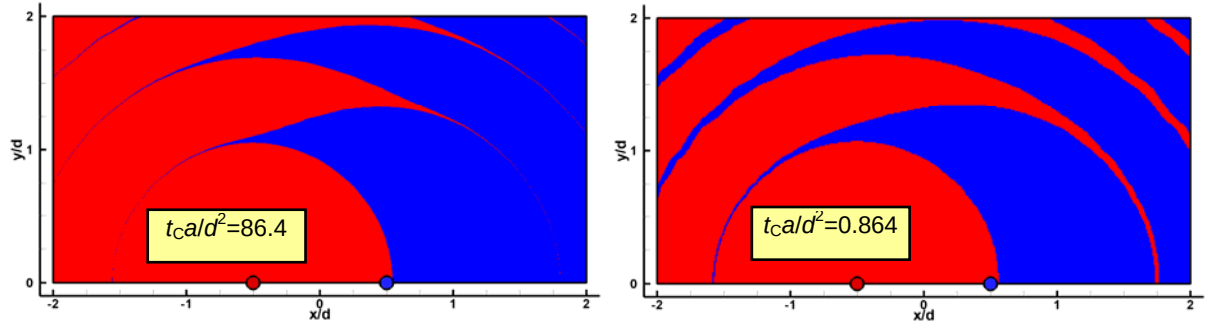


FIGURE 5. Impact of dimensionless hydraulic diffusivity on transient capture zones ($Qt_c/(md^2\phi)=8.64$).

4. FINDINGS AND CONCLUSIONS

Our results demonstrate the importance of transients and plume dispersion to capture zone analyses. In the investigated cases, a key parameter characterizing the importance of transients in capture zone estimates is a dimensionless factor $Qt_c/(md^2\phi)$ which depends on the pumping rate and advective transport velocity. The dimensionless hydraulic diffusivity $t_c a/d^2$ impacts the rate (velocity) of propagation of the transients away from the pumping wells, but it has limited impact on the capture-zone estimates once a quasi-steady state flow regime is achieved in the vicinity of the wells. We have also investigated the impact of transients in release time on the capture zone estimates. Our analysis indicates that the capture-zone estimates can be very sensitive to the transients in contaminant releases. Even relatively small uncertainties in the temporal variability of contaminant source, when combined with transient flow effects associated with natural variability of gradients or water-supply pumping, can cause significant uncertainties in the capture-zone estimates. Transients in the flow field also impact the effective dispersion of the contaminant plumes. When capture zones are estimated assuming advective-dispersive contaminant transport, transients increase the smearing in the capture zone estimates. Furthermore, in the studied cases the longitudinal and transverse dispersivities have different impacts on the capture zone estimates depending on the level of transients. When the flow is less transient, transverse dispersivity has a much more dominant impact on the capture zone estimates. When the flow is more transient, longitudinal dispersivity has a more dominant effect on the capture zone estimates. This is a very important conclusion which will be investigated more elaborately in the future.

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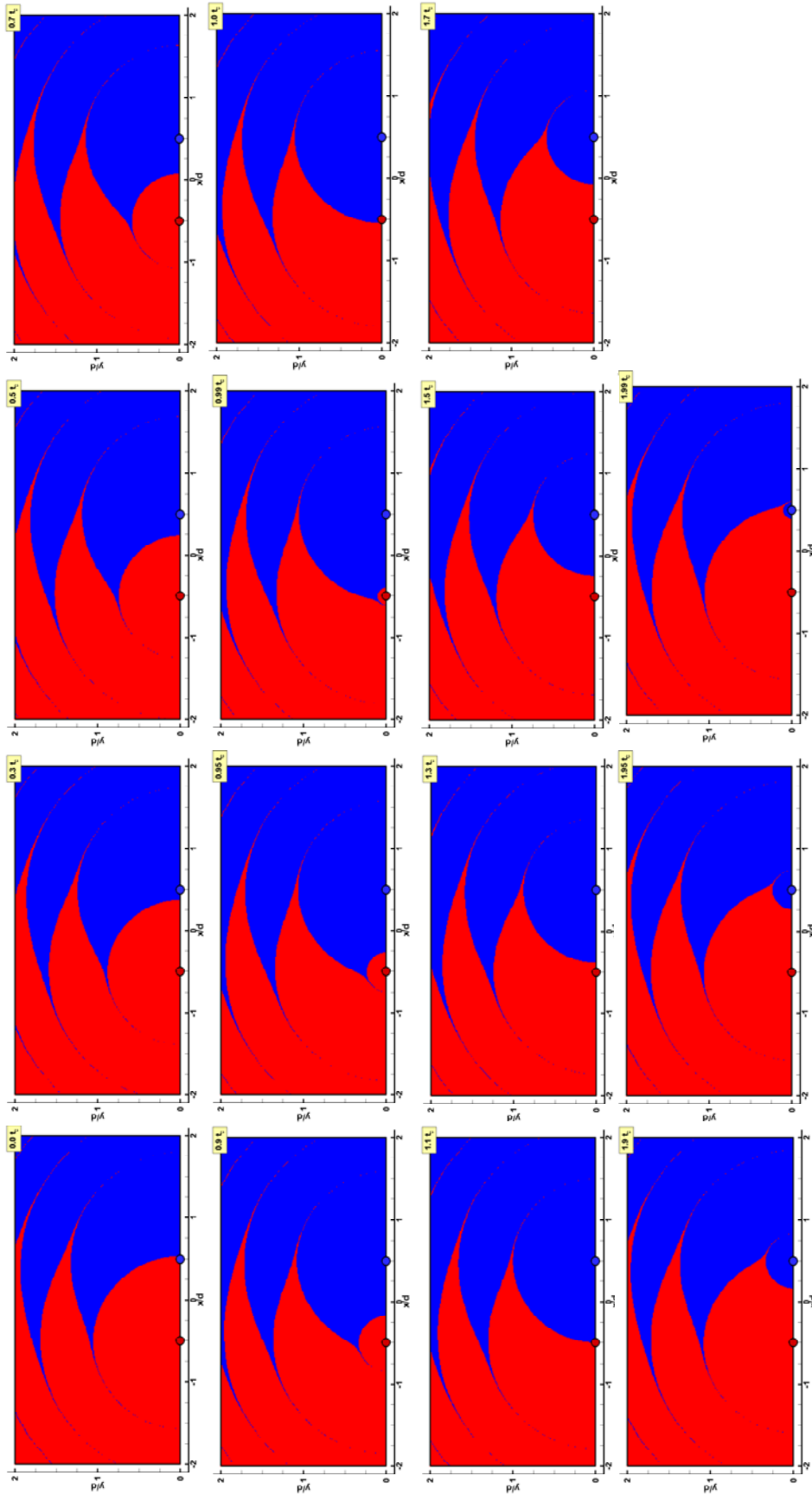
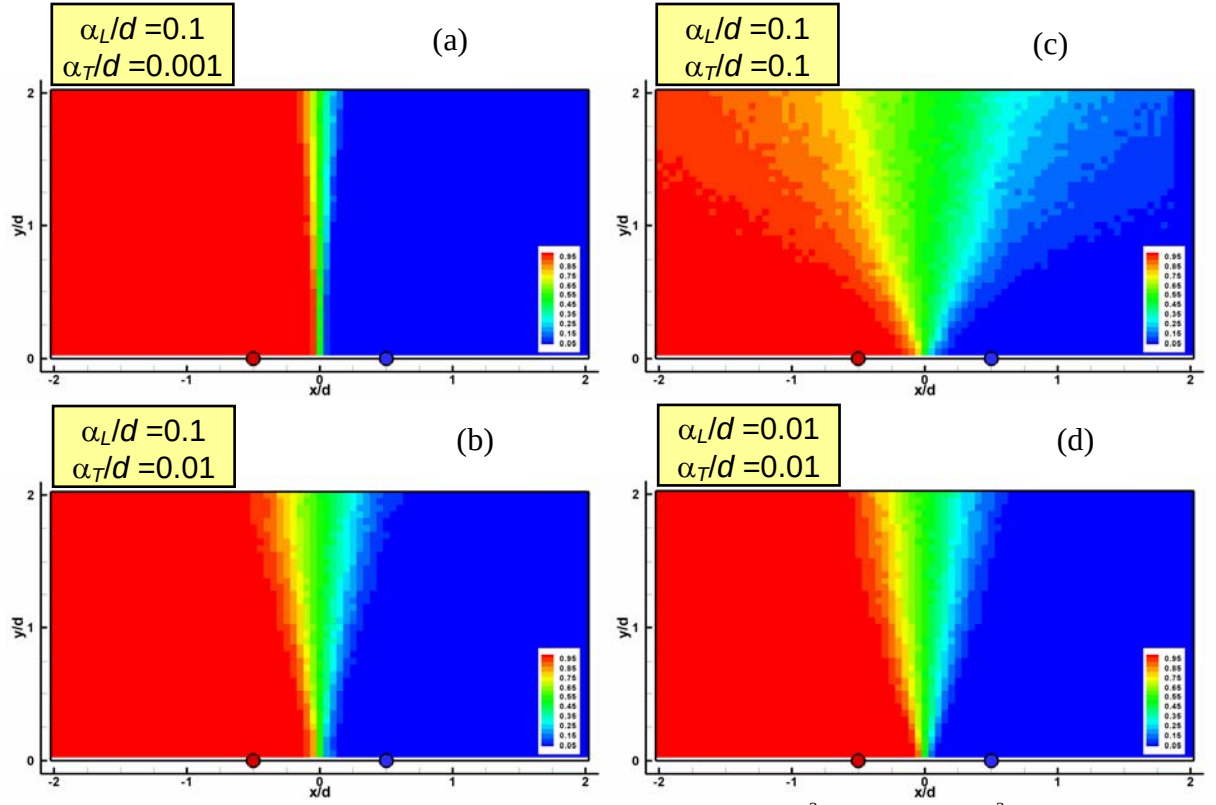
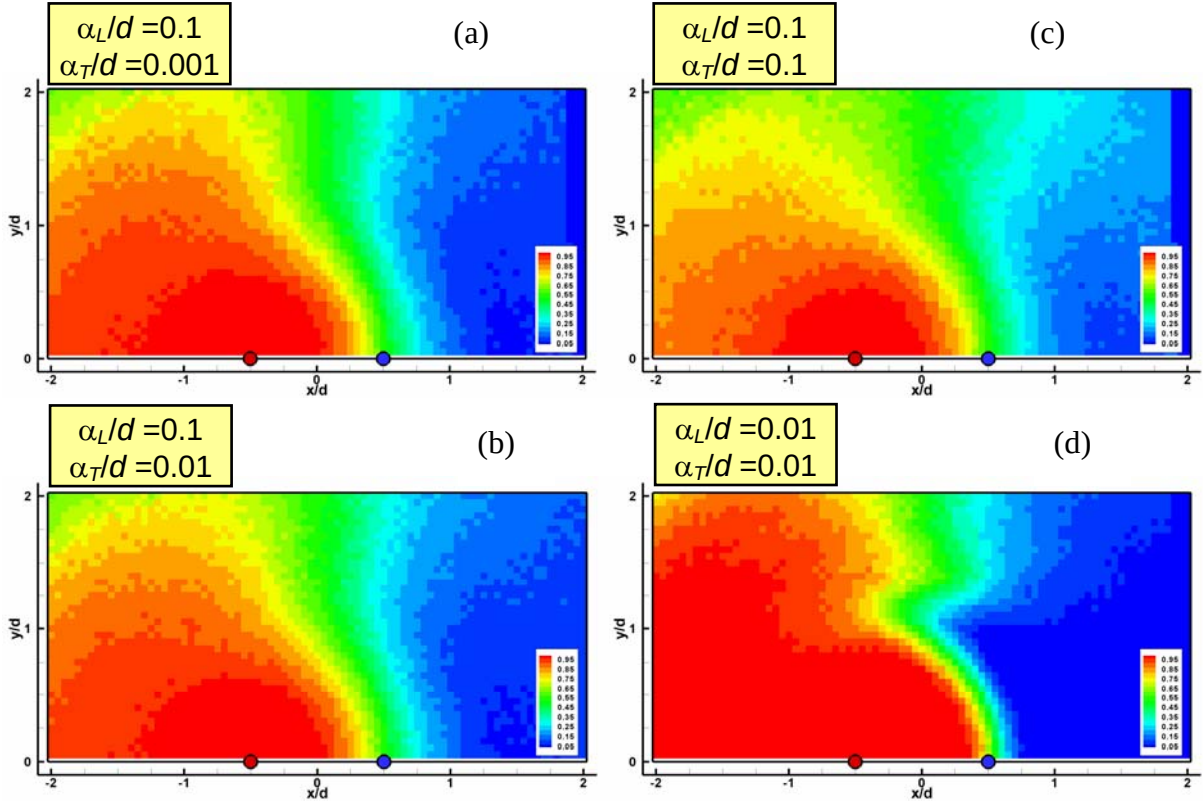


FIGURE 6. Impact of transients in contaminant release times on capture zone estimates ($Q_{t_c}/(m d^2 \phi) = 8.64$; $t_c/d^2 = 86.4$). Release times vary from 0 to $2t_c$.

FIGURE 7. Impact of dispersivities on transient capture zones ($Qt_c/(md^2\phi)=0.0864$; $t_c a/d^2=86.4$).FIGURE 8. Impact of dispersivities on transient capture zones ($Qt_c/(md^2\phi)=8.64$; $t_c a/d^2=86.4$).