Uncertainties in transient capture zones

Velimir V Vesselinov
Hydrology, Geochemistry, and Geology Group
Earth and Environmental Sciences (EES-6)
Los Alamos National Laboratory, Los Alamos NM 87545, USA
vvv@lanl.gov

LA-UR-06-2305

CMWR XVI
Computational Methods in Water Resources
Copenhagen, Denmark, June 19-22 2006
Capture zones
Background

- delineation of capture zones of water supply wells is important for the efficient protection of groundwater resources
- capture zones are typically estimated using models
- frequently, transients in groundwater flow and their effect on the dispersion of the potential contaminant plumes are ignored in the capture-zone analyses
Capture zone definitions:

- **Steady-state** zones are delineated using (future?) steady-state flow field

- **Transient** zones are delineated using transient flow field:
  - transients in the flow field
  - transients in the contaminant releases
    - instantaneous releases: snapshots of the capturing associated with a given release time
    - continuous releases: cumulative capturing of contaminants over the release period
Contaminant source is within capture zones of both wells ... ... but steady-state / advective-only capture zone analyses will give us an incorrect result.
Methodology

- 2D synthetic capture-zone analysis
- uniform medium
- 2 wells with temporally varying rates
- confined groundwater flow is solved numerically (for convenience); analytical solutions are available as well
- capture zones are delineated using forward particle tracking under both advective and advective-dispersive regimes
- dimensionless model parameters are derived based on analytical expressions

Codes

- grid-generation: LaGriT (Trease et al., 1996)
- flow simulation: FEHM (Zyvoloski et al., 2001)
- particle-tracking: FEHM (Robinson, 2002)
Model domain

dimensionless coordinates: $x/d$, $y/d$, where $d$ is the distance between wells
Region of capture-zone analyses

![Graph showing the region of capture-zone analyses with x/d and y/d axes and various grid lines indicating different zones.](image-url)
Temporal variability of pumping rates

To reduce the effect of initial conditions, 10 pumping cycles are applied before the analysis of transient capture-zone commences.
Dimensionless model parameters

- **pumping rate / advective transport velocity**: \( \frac{Q t_C}{md^2 \phi} \) [-]
  obtained by comparison of quasi-steady-state advective velocity \( \frac{Q}{md\phi} \) [L/T] and velocity required for a water particle to move distance \( d \) for time \( t_C \), i.e. \( \frac{d}{t_C} \) [L/T]

- **pumping time interval**: \( \frac{t_C a}{d^2} \) [-]

- **coordinates**: \( \frac{x}{d}, \frac{y}{d} \) [-]

- **longitudinal / transverse dispersivities**: \( \alpha_L/d, \alpha_T/d \) [-]

- **where**:
  - \( k \) = permeability [L/T]
  - \( a \) = hydraulic diffusivity [L^2/T] (\( a = k/S_S \), \( S_S \) = specific storage [L^{-1}])
  - \( Q \) = pumping rate [L^3/T]
  - \( t_C \) = pumping time interval [T]
  - \( d \) = distance between the pumping wells [L]
  - \( m \) = aquifer thickness [L]
  - \( \phi \) = advective porosity [-]
Particle-tracking simulation of impacts of transients on the contaminant plumes
Steady-state capture zones

- steady-state flow field
- instantaneous/continuous releases

In this case, steady-state capture zones are not affected by the uncertainties in the model parameters
Transient capture zones

- transient flow field
- instantaneous (after 10 pumping cycles) and continuous releases

Investigated uncertainties

- transport velocity
- hydraulic diffusivity
- longitudinal/transverse dispersivities
- release times: instantaneous/continuous
Impact of transport velocities

The slower the transport velocities, the higher the number of capture-zone fingers

$$\frac{Qt_{C}}{(md^2 \phi)} = 0.864$$

$$\frac{Qt_{C}}{(md^2 \phi)} = 4.32$$

$$\frac{Qt_{C}}{(md^2 \phi)} = 8.64$$

$$\frac{Qt_{C}}{(md^2 \phi)} = 17.3$$
Steady-state vs transient capture zones

Transient capture zones obtained for the case of very low transport velocities and steady-state capture zones are equivalent.
Impact of hydraulic diffusivity

- faster propagation of pressures
  - confined conditions

The lower the hydraulic diffusivity, the wider the capture-zone fingers

- slower propagation of pressures
  - unconfined conditions

\[ \frac{Q t}{\sqrt{md^2 \phi}} = 8.64 \]
Impact of dispersion

Low velocity (Steady-state)  High velocity

\[ \frac{Q_{tC}}{(md^2 \phi)} < 0.01 \quad t_{Ca/d^2} = 86.4 \]

\[ \frac{t_{Ca}}{d^2} = 86.4 \]

LEGEND:
Color range between RED and BLUE represents the capturing percentage

\[ \alpha_L/d = 0.1 \]
\[ \alpha_T/d = 0.01 \]
In the high velocity transient case, $\alpha_L$ is important, while $\alpha_T$ has a minor effect on the estimates.
In the low-velocity transient (steady-state) case, $\alpha_T$ is important, while $\alpha_L$ has a minor effect on the estimates. 

$\frac{Q t_C}{(m d^2 \phi)} < 0.01$ 
$t_{C a}/d^2 = 86.4$
Transient capture zones: Impact of release times

Capture zones change with the release time

\[ \frac{Q t_c}{m d^2 \phi} = 8.64 \]

\[ t_{Ca} / d^2 = 86.4 \]
Transient capture zones: Impact of release times

Animation of transient capture zones at different release times
Transient capture zones: Continuous releases

Smearing of the capture zones due to continuous releases

\[ \frac{Q t_c}{(m d^2 \phi)} = 8.64 \]
\[ \frac{t_{cal}}{d^2} = 86.4 \]

**LEGEND:**
Color range between RED and BLUE represents the capturing percentage.
Transient capture zones: Continuous releases

Variance in the capture-zone estimation due to continuous releases

\[ Qt_c / (md^2 \phi) = 8.64 \]
\[ t_{cal} / d^2 = 86.4 \]
Los Alamos Nat’l Lab (LANL) case study

- multiple water-supply wells with variable pumping rates
- multiple contaminant sources in their vicinity with uncertain and variable release history
- unknown contaminant fate in the saturated and unsaturated zones
- capture-zone predictions are made using complex 3D UZ/SZ models
Transient capture zones at the water-table
Transient capture zones at the water-table

Number of wells capturing contamination from each location

Mortandad Canyon

 número de pozos
Findings/Conclusions

- Transients are important to consider in capture zone analyses.

- Significance of transients for capture-zone analyses depends on:
  - amplitude/frequency of the transients in the groundwater flow and transport (well pumping/contaminant releases),
  - rate of propagation of contaminants (pore velocities),
  - contaminant dispersion (dispersivities),
  - rate of propagation of hydraulic pressures (hydraulic diffusion).

- Uncertainties in the transient capture zone estimates depend predominantly on:
  - transport velocities,
  - longitudinal dispersivity in the case of high transport velocities, and transverse dispersivity in the case of low transport velocities,
  - release times.

- Transient capture zones can be effectively delineated even for very complex models through parallelization.