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Using probabilistic well vulnerability criteria for a risk-based preventive drinking water safety concept

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Abstract The most common concept to control the risk of drinking water contamination is the delineation of advection-based well-head protection zones. In 2006 Frind et al. extended this concept by introducing four intrinsic well vulnerability criteria that account for additional advective-dispersive transport information, such as dilution of peak concentrations through diffusion and dispersion. Our approach quantifies the uncertainty of well catchments and protection zones based on these advective-dispersive vulnerability criteria within a probabilistic framework. In order to account for uncertainty and to keep computational costs low at the same time, we combine Monte Carlo simulations with a temporal moment approach for model reduction. Our method allows stakeholders to take informed risk-based decisions in order to better control and manage the risk within their well catchments, which is necessary to develop complete risk management schemes as recommended by current Water Safety Plans.

Key words well catchment delineation; wellhead protection; well vulnerability; uncertainty; risk assessment

INTRODUCTION

In the third drinking water guideline, the WHO (2004) states that “Drinking-water quality is an issue of concern for human health in developing and developed countries world-wide”. According to current Water Safety Plans (Davison et. al, 2004), water suppliers and all other stakeholders should ensure safe drinking water supply by controlling the risk from catchment to tap through a preventive risk management concept. This is our key motivation for introducing an extended risk-based drinking water safety concept within the present study.

The most common concept to reduce the risk towards well contamination a-priori is to delineate advection-based well-head protection zones. This approach does not take the aquifer’s potential for plume dispersion and dilution into account, thus may not accurately reflect the protection zone and the risk of well contamination. In view of this limitation, Frind et al. (2006) introduced four intrinsic well vulnerability criteria that account for additional advective-dispersive information:

(a) The time between a spill event and arrival of peak concentration at the well,
(b) The level of peak concentration relative to the spill concentration,

(c) The time to breach a given threshold concentration (e.g. a drinking-water standard) and

(d) The time of exposure (exceeding the threshold concentration).

These authors also established the context of risk assessment via a multi-barrier approach, as proposed by the Water Safety Plans (Davison et. al, 2004).

For a complete risk assessment it is indispensable to account for uncertainty in the catchment model and parameters (Aven, 2010). Varljen and Shafer (1991) were the first to quantify the uncertainty in well catchment zone delineation by using conditional conductivity fields within a Monte Carlo set-up. Although several numerical, analytical and semi-analytical studies have been completed on uncertainty in well capture zone delineation (e.g. Feyen et al., 2001 and Stauffer et al., 2005), none have yet quantified the uncertainty within an advective-dispersive framework. The aim of the current study is to develop a risk-based preventive drinking water concept by setting the four transport-based well vulnerability criteria into a probabilistic framework.

APPROACH

Due to the heterogeneity of aquifer materials and the scarcity of data, log-hydraulic conductivity is assumed to be a random space function. The most efficient way to calculate the capture zone is to solve the flow and transport problem reversely (Neupauer and Wilson, 2004).

Reilly and Pollock (1996) showed in their study that temporal variations for capture zone delineation can be neglected. We therefore solve the stationary flow and transport problem. Subsequently the reverse advection-dispersion equation is

$$\frac{\partial c}{\partial t} - \nabla \cdot (\mathbf{v}\, c) - \nabla \cdot (\mathbf{D}\, \nabla c) = -r \tag{1}$$

where c is the concentration, $\mathbf{D}$ is the local dispersion tensor after Scheidegger (1961), $\mathbf{v}$ is the seepage velocity and r stands for the source and sink term. The four advective-dispersive well vulnerability criteria are sensitive to the difference between uncertainty in plume location and actual dilution (Kitanidis, 1994), which prohibits solution on the macroscale. Therefore we solve the above equation with the help of Monte Carlo simulations, resolving aquifer heterogeneity on and above the grid scale in each realization. Only the unresolved variability on the sub-grid scale remains parameterized via local (grid-size) dispersivities (Rubin et al., 1999). The time consuming transient computations can be reduced by directly solving for the temporal moments of contaminant transport (Harvey and Gorelick, 1995):

$$\nabla \cdot (v m_k) - \nabla \cdot (D\, \nabla m_k) = k \cdot m_{k-1} \tag{2}$$

where m_k is the k^{th} temporal raw moment. Temporal moments are capable of representing the characteristics of a concentration breakthrough curve. Their physical meaning is further explained by Cirpka and Kitanidis (2000). In order to construct the full time-dependent concentration history at a given point $\mathbf{x}$, Harvey and Gorelick (1995) recommend to set:

$$c(t) = \frac{1}{t} \cdot \exp\left(\sum_{k=0}^{K} \lambda_k \cdot \ln\left(t^k\right) \right) \tag{3}$$

where K is the maximum number of computed temporal moments and $\lambda_k = [\lambda_0, \ldots, \lambda_K]$ are coefficients found by nonlinear optimization, such that $c(t)$ meets the prescribed temporal moments. Given $c(t)$, it is now possible to evaluate the four intrinsic well vulnerability measures in each realization and obtain all required statistics.

ILLUSTRATIVE EXAMPLE AND RESULTS

For simplicity, the approach is demonstrated in a rectangular 2D domain with the size $300\,m \times 300\,m$. A background hydraulic gradient from west to east with $\nabla\varphi = 0.015$ is assumed with constant head boundary conditions. The north and south boundaries are no flow boundaries. A Dirac pulse $\hat{c}$ with normalized unit mass $m_0[-]$ is introduced at the well with a pumping rate of $Q = 5 \cdot 10^{-4}\, m^3 s^{-1}$. The unconditioned permeability fields follow an exponential covariance model with mean hydraulic transmissivity $T = \log\left(2 \cdot 10^{-4}\right)$, variance $\sigma^2 = 2$, integral scale $\lambda_{x=y} = 5$, longitudinal $\alpha_L = 2.5m$ and transversal dispersivities $\alpha_T = 0.25m$. For illustration $n = 100$ Monte Carlo simulations are generated by using the method of Dietrich and Newsam (1996). Actual applications will require more realizations and a formal convergence analysis.

Results

Figure 1 displays the four intrinsic vulnerability isopercentiles $[0.1, 0.5, 0.9]$ based on the illustrative example. Fig. 1 (a) represents the German well-head protection area that a particle is captured by the well within $t_{crit} = 50$ days, taking the arrival of peak concentration into account. The second vulnerability criterion is given in Fig. 1 (b), showing the area over which the contaminant is diluted by the factor of $p_{crit} = 1 \cdot 10^{-6}$. Fig. 1 (c) shows the extent of the capture zone until the threshold value $\phi = 1 \cdot 10^{-8}$ relative to $m_0[-]$ is reached. The fourth criterion is shown in Fig. 1 (d), indicating the potential area where the well is exposed to contamination above the threshold for more than two days.

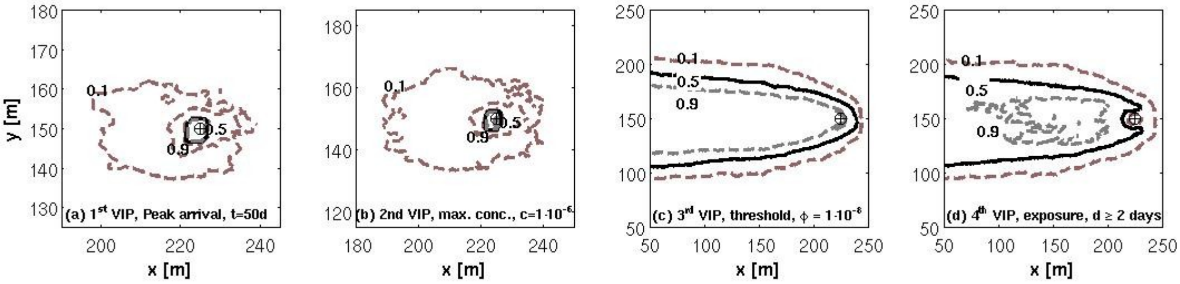

Figure 1: Illustrative map of three isopercentiles $[0.1, 0.5, 0.9]$ for the four intrinsic well vulnerability criteria (a)-(d) from $n = 100$ realizations.

SUMMARY AND DISCUSSION

The risk-based preventive drinking water safety concept introduced in this study provides stakeholders with the necessary tools to develop complete risk management schemes as recommended by the Water Safety Plans (2005). Our vulnerability isopercentiles deliver indispensable information for catchment managers to adopt risk management decisions based on the uncertainty of the system and are easy to understand. They display zones of higher and lower well vulnerability probabilities, and allow for prioritization of contaminated sites and location of protection zones.

The potential for natural attenuation is considered by applying transport-based vulnerability criteria, which also lead to separation of dilution and uncertainty in the location of bulk mass.

Although information is lost by the model reduction due to the temporal moment approach, the gain in computational efficiency and the resulting information on uncertainty in the well vulnerability criteria are more valuable for a complete risk-based drinking water safety concept. Our suggested approach is independent of dimensionality and boundary conditions and can be combined with arbitrary geostatistical conditioning schemes such as EnKF, MCMC, GLUE or others.

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