The role of well vulnerability mapping in quantifying the impact of well contamination

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Abstract Well vulnerability expresses the impact due to a well becoming contaminated. The relevant factors which define this impact are the maximum concentration expected at a well due to a nearby source of contamination, the time taken to reach this maximum, and the time taken to reach some critical drinking water limit. These factors, which depend on the physical characteristics of the aquifer system, can be determined by means of transport modelling and are presented in the form of vulnerability maps. These maps provide better quantitative information and more insight into the problem of well contamination than conventional capture zone delineations alone. The methodology for determining well vulnerability is demonstrated.

Key words capture zones; groundwater contamination; groundwater protection; well vulnerability

INTRODUCTION

Groundwater protection is now receiving increasing attention in Europe, as well as in North America. In Ontario, a recent tragic event of bacterial contamination of well water has now led to an accelerated programme for the delineation of well-head protection zones for the wells that provide drinking water for numerous communities.

The conventional approach to well-head protection is to delineate the well capture zones corresponding to travel times of interest. In most cases, this is done by backward particle tracking using a numerical model, followed by drawing an envelope curve around the end points of the particle tracks to define the capture zone. An alternative to particle tracking is backward transport modelling, which directly gives a capture zone (Frind et al., 2002). Time-dependent capture zones are generally adequate to provide protection against bacterial contamination, but the entire well capture zone should be delineated in the case of persistent chemicals (Vassolo et al., 1998).

In addition to the capture zone, the aquifer vulnerability must also be known in order to provide meaningful groundwater protection. Aquifer vulnerability is a function of the natural protection an aquifer has in the form of an overlying aquitard and/or the unsaturated zone. For example, an aquifer overlain by a sound aquitard providing recharge through leakage may have a large capture zone but a relatively low vulnerability because of the protection afforded by the aquitard. On the other hand, an unconfined aquifer recharged directly by precipitation may have a relatively small capture zone but a high vulnerability. In common hydrogeological practice, aquifer vulnerability is defined by assigning qualitative values to system characteristics such as aquitard thickness and permeability (USEPA, 1993).
This qualitative approach may be misleading in the presence of aquitard windows, fractures, or other openings in the aquifer that can provide pathways or shortcuts for contaminants to enter the aquifer. Windows in particular can have a controlling influence on a capture zone (Martin & Frind, 1998). The vulnerability of a thin aquifer overlain by a fractured aquitard could be higher than that of a thick unconfined aquifer that has ample capacity to dilute and attenuate contaminants (Howard, 2001, personal communication). On the other hand, a fractured aquitard can also provide a protective mechanism in the form of matrix diffusion which can store and attenuate a contaminant. These mechanisms must be clearly understood for reliable delineations of well-head protection zones to be made. Because the factors controlling fracture flow/transport, matrix diffusion, and the presence/absence of windows are usually uncertain, the characteristics of the aquitard overlying the aquifer represent one of the largest uncertainties in the delineation of a well-head protection zone. The conventional qualitative definition of aquifer vulnerability does not readily allow for the consideration of these complex mechanisms.

Major advances have been made over the last decade in addressing the problem of uncertainty in the delineation of capture zones using stochastic approaches. On the theoretical front, Franzetti & Guadagnini (1996) assumed the hydraulic conductivity of the aquifer to be a random space function and used Monte Carlo analysis to determine the probability that a solute pulse will be captured by the well. Van Leeuwen et al. (1998) used a similar approach, also based on random space functions and using Monte Carlo analysis, to determine the probability distribution of the stochastic capture zones. Guadagnini & Franzetti (1999) extended the stochastic approach to time-related capture zones. Van Leeuwen et al. (2000) showed how conditioning by use of hydraulic head measurements can constrain the ensemble of possible capture zones. More recently, Feyen et al. (2001) introduced the generalized likelihood uncertainty estimation methodology to the problem of capture zone uncertainty, also addressing uncertainty resulting from imperfect knowledge of the parameters defining the correlation structure, in addition to the variations due to the different realizations. Vassolo et al. (1998) applied stochastic inverse modelling to the delineation of the capture zone for an aquifer in Germany, while Kunstmann & Kinzelbach (2000) applied the first-order second-moment method combined with Kolmogorov backward equation analysis to the same aquifer. All of these studies are based on the assumption of a two-dimensional (2-D) aquifer. For real-world 3-D systems, the analysis is more complex, as a distinction must be made between the surface capture zone that defines where the water comes from, and the 3-D maximum extent capture zone (Kinzelbach et al. 1992; Frind et al., 2002).

WELL VULNERABILITY

In the concept of well vulnerability, we ask the question of what the impact on a well is expected to be if a contaminant source existed anywhere within the well capture zone. For the contaminant to reach the well it must pass through the groundwater flow system from the source to the well, encountering all relevant mechanisms such as dispersion, fracture flow/transport, matrix diffusion, biodegradation, or other forms of attenuation. These processes can all be modelled using a suitable advective–dispersive
transport model. Uncertainty at a local scale will be automatically incorporated in the transport equation through the dispersion term, where the dispersivity will take on an asymptotic value appropriate for the scale of the system (Gelhar & Axness, 1983). Larger-scale sources of uncertainty such as aquitard windows or fracturing, and other discontinuities, can be incorporated explicitly into the transport model. Thus well vulnerability becomes an inherently 3-D concept.

A direct approach to create a map of well vulnerability is to place a number of hypothetical contaminant sources throughout the well capture zone and to run a transport simulation for each of these sources. Each run will yield a breakthrough curve at the well, and for each of these curves we can record the key characteristics necessary to define well vulnerability, namely: (a) the maximum concentration to be expected at the well due to the source; (b) the time taken to reach this maximum; and (c) the time taken to reach a specified drinking water limit (DWL). Provided we have a sufficient number of sources, we can map these key vulnerability characteristics over the capture zone. The resulting maps will provide a quantitative spatial and temporal visualization of the vulnerability of the well, which takes into account all relevant physical factors.

However, this approach would require a large number of transport model runs with sources placed at a sufficient number of locations to allow a smooth contouring of the results. A smarter way to achieve the same result is by means of the adjoint principle (Uffink, 1989; Neupauer & Wilson, 2001), using a single backward transport model run instead of many forward runs. The source is now placed at the well, the transport model is run backwards with a negative velocity field and the same dispersivity as in the forward run, and breakthrough curves are recorded at a number of detection points representing possible source locations. The resulting breakthrough curves are theoretically the same as those obtained with the forward runs, except for a scale factor that must be applied to the backward results (Neupauer & Wilson, 2001). The need for the scale factor arises from the fact that a particle injected within the capture zone of a well in a forward velocity field has a 100% probability of being captured by the well, while a similar particle injected at the well in a backward velocity field has a <100% probability of arriving at a certain detection point within the capture zone (Wilson, 2001, personal communication). For simple systems, the scale factor can be determined analytically (Neupauer & Wilson, 2001), while for complex systems the scale factor is obtained by matching a backward run to the corresponding forward run, and scaling the magnitude of the backward breakthrough curve to the magnitude of the normalized forward breakthrough curve (Frind & Molson, 2003).

APPLICATION TO THE GREENBROOK WELL FIELD

The Greenbrook well field is one of 50 well fields containing a total of 126 wells that provide about 90% of the water supply for the Regional Municipality of Waterloo in Ontario, a community of about 400,000 people. The water source is the Waterloo Moraine, a complex glacial multi-aquifer system extending over about 400 km². The individual members of the system are generally discontinuous layers and lenses of variable thickness and conductivity, ranging from gravel and sand to tills and clay.
Martin & Frind (1998) developed a conceptual model to represent this complex system as a sequence of four continuous aquifers and four aquitards, where each member is spatially continuous but may contain material over the entire range of permeabilities. Accordingly, aquitard windows are represented by high-permeability zones within an aquitard, while clay lenses in the aquifer are represented by low-permeability zones within the aquifer. The Greenbrook well field is one of the most complex within the Waterloo Moraine, with five wells pumping from two different aquifers. Flow was modelled using the finite element model WATFLOW (Molson et al., 2002), which is designed to handle highly complex multi-aquifer systems.

The capture zone for the Greenbrook well field was delineated using two different methods. The first of these is reverse 3-D particle tracking using a locally mass-conservative semi-analytical approach designed for 3-D prismatic finite elements, and able to handle the abrupt conductivity discontinuities ranging over several orders of magnitude that exist within the Waterloo Moraine. The second method is reverse transport modelling based on the adjoint theory of Wilson & Neupauer (2001), which produces contours of cumulative capture probability. Capture zone outlines were extracted from these probability contours by selecting the contour corresponding to the area that would satisfy the mass balance between the recharge and the pumpage. Frind et al. (2002) show the particle tracks, the probability contours, and the resulting capture zone delineations for the Greenbrook well field, in terms of both surface capture and maximum extent over the aquifer depth. The 3-D maximum extent capture zone is reproduced in Fig. 1.

To generate the well vulnerability maps, we follow the procedure outlined above. A sufficient number of detection points are placed throughout the capture zone, and a hypothetical source is placed at one of these points. Using a unit-in-time pulse input function, transport is modelled in both directions between this source and the well field (Fig. 2), and the respective breakthrough curves are generated. Because we are dealing here with a well field consisting of several wells, we record these breakthrough curves at a fence placed a short distance upstream of the well field. Similarly, the breakthrough curves for the source and those corresponding to the rest of the detection points

![Fig. 1 3-D maximum extent capture zone at 2, 10, 40, 100 and 200 years.](image)
are recorded at a control surface placed just below the source. The forward run yields one breakthrough curve, while the backward run yields multiple breakthrough curves.

The scale factor for the backward breakthrough curves is obtained by normalizing the forward breakthrough curve with respect to its magnitude at the control surface, and scaling the magnitude of the backward breakthrough curve to the magnitude of the normalized forward breakthrough curve. The final probability breakthrough curves for the matched pair are shown in Fig. 3. The rest of the backward breakthrough curves are then scaled using the same scale factor. Finally, the vulnerability characteristics (maximum probability of contamination, time to reach maximum, and time to reach DWL) are extracted from the scaled backward breakthrough curves and mapped over the capture zone. In these maps, probability of contamination can be taken as equivalent to concentration expected at the well, relative to source concentration.

The resulting vulnerability maps are shown in Fig. 4, where Fig. 4(a) shows the maximum concentration expected at the well, Fig. 4(b) the time taken to reach maximum, and Fig. 4(c) the time taken to reach a drinking water limit of 10^-4 relative to the source concentration. The time taken to reach maximum, shown in Fig. 4(b), is equivalent to the corresponding time-dependent surface capture zone (Frind et al., 2002), which is somewhat narrower than the maximum extent capture zone shown here in Fig. 1.

Fig. 2 Modelling concept for quantifying well vulnerability.
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By means of these figures we have the choice of expressing the vulnerability of the well to contamination in various ways, depending on the definition we may wish to adopt. If we define vulnerability in terms of the maximum concentration reached at a well, we may use Fig. 4(a) and 4(b) together to express the travel time of a contaminant from source to well, and to determine the expected maximum concentra-
tion. For example, a spill at the tip of the 40-year contour in Fig. 4(b) will show up at the well in 40 years at a relative concentration of about $10^{-2}$ (Fig. 4(a)). Alternatively, if we define the exceedance of a certain drinking water standard as unacceptable, then Fig. 4(c) will provide the time taken until that standard is violated. For example, a spill anywhere on the 40-year contour in Fig. 4(c) will take 40 years to appear at the well at a relative concentration of about $10^{-4}$, and will increase thereafter (assuming the contaminant is conservative). It should be noted that the area enclosed by the 40-year contour in Fig. 4(c) is larger than the corresponding 40-year surface capture zone (see Frind et al., 2002).

These results show that the vulnerability maps contain all the information of a conventional capture zone delineation. In addition, other useful information such as the time associated with a specific value of concentration can be easily extracted from the breakthrough curves. Also, processes such as sorption and biodegradation can be incorporated into the modelling, which is limited only by the capabilities of the transport model being used.

**CONCLUSIONS**

While a conventional capture zone delineates the area that contributes water to a well, a well vulnerability map expresses the impact of contamination on the well. Well vulnerability is a 3-D concept, it can potentially include all controlling processes, and it can be used to quantify the performance of controlling barriers and mechanisms. Uncertainty due to local-scale heterogeneities is included through the dispersion term. While a capture zone represents the effect of advective transport, a well vulnerability map also represents the effect of other transport processes that may be relevant in specific situations. Thus a vulnerability map provides more quantitative information and more insight into the risk of well contamination than a conventional capture zone outline. It may be concluded that, in the development of well-head protection measures, a well vulnerability map will be a good alternative or supplement to the conventional capture zone approach.

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