Advancing the science of source water protection: the well vulnerability technique and its application to a complex multi-aquifer watershed

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ABSTRACT
The well vulnerability technique unifies the concepts of aquifer vulnerability and time-of-travel (TOT), while also accounting for the processes these concepts neglect. Well vulnerability is based on the source-pathway-receptor concept which analyses the processes acting on a contaminant travelling through a multi-barrier system and determines the actual impact on the well. Measures to express the impact are the time for drinking water standards at the well to be breached, the dilution experienced by the contaminant, and the exposure time of the well to the contaminant.

RÉSUMÉ
Bien la technique de vulnérabilité représente une façon d'unifier les concepts de vulnérabilité aquifer et de TOUT PETIT ENFANT, en représentant aussi les processus cette négligence de concepts. Bien la vulnérabilité est fondée sur le concept de récepteur de sentier source qui analyse les processus agissant sur un polluant voyageant par un système de multibarrière et détermine l'impact réel sur bien. Les mesures pour exprimer l'impact sont le temps pour les normes d'eau potable à bien pour être faites une brèche, la dilution connue par le polluant et le temps d'exposition de bien au polluant.

1 INTRODUCTION

Aquifer resource protection is a high priority for Canadians. A key element towards this protection is the evaluation of the vulnerability of a given receptor (e.g. aquifer or water supply well) to surface and subsurface contamination. In Ontario, current source water protection strategies are centered upon two key concepts: aquifer vulnerability and the delineation of WHPA's. However, these two concepts are decoupled from one another. Most commonly used aquifer vulnerability techniques generate maps of distributed 'vulnerability indices' which partition the target aquifer into zones of high, medium or low vulnerability. The degree to which these indices reflect the physical properties and hydrological processes that govern contaminant migration varies depending on the technique employed, however, most aquifer vulnerability techniques make a number of simplifying assumptions. Conversely, WHPA's are expressed in terms of time-of-travel (TOT). The TOT concept is based solely on advective transport and thus neglects a number of processes that tend to affect the actual impact of contamination on a well. These processes include dispersion, chemical reactions, and dilution at the well by the mixing of contaminated water with clean water. All of these processes are important and they affect the actual risk a given contaminant poses to a well. Well vulnerability provides a means of unifying these two concepts while simultaneously addressing their drawbacks. In this paper we will briefly discuss the concept of well vulnerability and show some results from an application of the technique to a complex multi-aquifer system using a fully-integrated surface water-groundwater model.

2 WELL VULNERABILITY CONCEPT

Well vulnerability is based on the analysis of the pathway a contaminant travels in a multiple barrier system from a contaminant source to a receptor while being influenced by various processes along the way, and it quantitatively describes the expected impact of a contamination event on a well by means of certain parameters. Well vulnerability differs from the conventional concept of aquifer vulnerability in that the target is the well (rather than the drinking water aquifer), and the pathway is the complete pathway from the contamination source to the well (rather than just the layers overlying the drinking water aquifer). The well vulnerability parameters can be defined in terms of concentration at the well or mass flux reaching the well with dilution experienced by the contaminant. The parameters include the maximum expected value ($Conc_{peak}$), time to reach the maximum value (T_{peak}), the time for drinking water standards at the well to be breached (T_{exceed}) and the exposure time at the well due to contamination (T_{comp}). These parameters are displayed graphically in Figure 1. The impact on a well can be assessed on the basis of this method by applying a standard advective-dispersive model including all relevant physical and chemical processes and determining the corresponding contaminant mass flux entering the well. The final impact assessment is done on the basis of contaminant breakthrough curves generated at the well. A more detailed discussion of the well vulnerability concept is given by Frind et al. (2006).

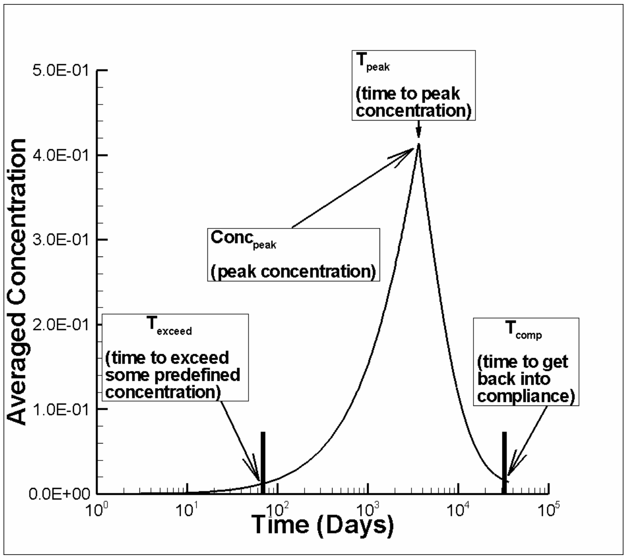

Figure 1. Well vulnerability parameters.

2.1 Numerical Model

The model used to demonstrate the utility of the well vulnerability technique is HydroGeoSphere (Therrien et al., 2005) which was developed by a consortium of researchers at the University of Waterloo in Ontario, the Université Laval in Quebec and Hydrogeologic, Inc. in Virginia. HydroGeoSphere (HGS) is capable of simulating water flow and solute transport within the three-dimensional dual continua subsurface (porous medium-macropore/fracture interactions) and over the two-dimensional land surface. The 2-D form of the nonlinear diffusion-wave equation linked to the Manning's equation to calculate overland flow velocities, is employed on the surface while Richards' equation and Darcy's law govern subsurface processes. Unlike most other surface water-groundwater interaction models, HGS fully integrates the entire land phase of the hydrologic cycle by simultaneously solving one system of nonlinear discrete equations evolving from the control-volume finite element method to describe flow and solute transport in both flow regimes, as well as the water and solute fluxes between continua.

2.2 Site Description

The site used in this research is the Alder Creek Watershed, which covers approximately 79 km^2 within the Grand River basin in Southern Ontario, Canada (Figure 2). This watershed was chosen because it has been reasonably well characterized by previous studies in addition to being the focus of extensive data collection efforts by groups such as the Grand River Conservation Authority (GRCA), the Regional Municipality of Waterloo (RMOW), and the Ontario Ministry of the Environment (MOE). The watershed also contains a number of critical well fields that supply about 30% of the water needs for over 500,000 residents in the Kitchener-Waterloo and surrounding areas, thereby making it a priority candidate for source water protection work. In addition to the Alder Creek and its tributaries, the watershed contains some wetlands in its southern area. However, surface water features are relatively minor components in the overall Alder Creek system.

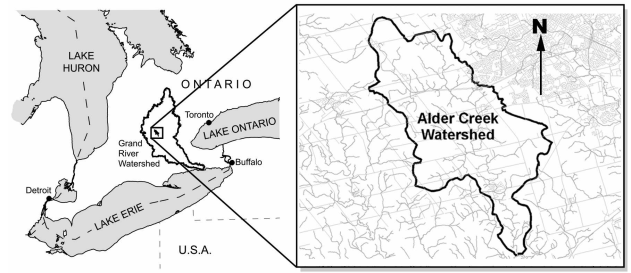

Figure 2. Location of the Alder Creek Watershed.

The Alder Creek Watershed is located in the south-central portion of the Waterloo Moraine which sits along the western edge of the cities of Kitchener and Waterloo. Surface elevations in the Alder Creek Watershed range from about 410 metres in the headwater regions to 290 masl where Alder Creek discharges into the Nith River. Local relief in the watershed ranges up to 30 metres. The overburden, which ranges in thickness from 35 to over 140 metres, is bounded below by the Salina Formation consisting of dolomites and limestone, interbedded with shales and gypsum lenses where the top few metres are fractured (Karrow et al. 1986). The overburden geology of the watershed is highly complex and has been altered by the advance and retreat of several glacial ice sheets that deposited a number of till units. Silty and clayey tills form the major aquitards, while the aquifers consist primarily of reworked tills, glacio-fluvial sands, and gravels (Karrow, 1989).

The complex hydrostratigraphy of the watershed (and the Waterloo Moraine as a whole) has been previously conceptualized as four aquifers bounded by four aquitards (e.g. Martin 1994; Martin and Frind 1998; Radcliffe 2000). The conceptual model employed in these previous studies is also used in this study. As was noted in those previous studies, some of the hydrostratigraphic units present in the system are laterally discontinuous (i.e. they 'pinch out'). Therefore, in order to maintain lateral continuity throughout the subsurface, layers are taken to be continuous in the conceptual model and discontinuities are represented by means of windows in the aquitards and lenses of low-conductivity material in the aquifers, as required. The aquitard windows provide direct conduits between the shallow and deep flow systems, allowing recharge of the deeper aquifers.

2.3 Populating the Model

The lateral extents of the Alder Creek Watershed were identified using a 25-metre Digital Elevation Model (DEM) provided by the Grand River Conservation Authority (GRCA). The resulting watershed boundary was then used to define a two-dimensional triangular-element mesh representing the top of the model domain (ground surface). A watercourse overlay (also provided by the GRCA) was then used to generate control points within the mesh in order to locate nodes along the stream channels in the two-dimensional mesh. The mesh was designed such that regions near the streams have finite element sizes on the order of 25 metres (in plan view), while finite elements further away from the drainage network are approximately 200 metres in size. This design strategy was employed to better capture surface water – groundwater interactions at the land surface interafce. Additional mesh refinement was also carried out in the regions surrounding the pumping wells and observation wells to improve the accuracy of the flow and solute transport solutions in these critical areas. After the generation and subsequent refinements to the mesh were completed, the topography of the watershed was mapped onto the mesh using data from the DEM.

A digital land usage map provided by the Ministry of the Environment of Ontario (MOE) was interpolated onto the surface mesh, and six distinct land-use categories were identified. This interpolation process was then further refined by using a watercourse overlay to incorporate the finer details of the watershed's drainage network (i.e. 2nd- and 3rd-order streams) which were not part of the digital map. The land usage distribution in Alder Creek is very diverse with significant regions of agricultural, urban, forested and grasslands.

The value of the Manning's surface roughness coefficient assigned to each land-use category was determined from tables provided in McCuen (1989). Stream discharge exits the watershed through three surface nodes in the two-dimensional surface mesh, which coincide with the segment of the surficial domain where Alder Creek discharges into the Nith River. A nonlinear critical-depth boundary condition is applied at these outflow nodes which constrains neither the flow rate nor the surface water depth. Instead, discharge leaving the domain is allowed to vary naturally throughout a given simulation period depending on the calculated depth of water at the outlet.

In HGS, the two-dimensional surface flow mesh is draped over the three-dimensional triangular prism mesh used to simulate subsurface flow. The top of the three-dimensional mesh is coincident with the two-dimensional mesh such that dual surface-subsurface interaction nodes exist at the land surface. Twenty-nine layers separate the surface and the base of the three-dimensional subsurface mesh, which is defined by the bedrock surface. The vertical distribution of these layers conforms to the hydrostratigraphy of the system as interpreted by Martin and Frind (1998) for the Waterloo Moraine. As noted above, discontinuities in the layers are represented by means of windows in the aquitards and low-conductivity lenses in the aquifers, and a minimum thickness of 1 metre was assigned in discontinuous regions. The bottom of the model is assumed to be impermeable, while the lateral headwater and discharge regions of the subsurface mesh (from Aquifer 1 to the bedrock) were assigned constant head values of 351.9 and 284 metres, respectively. These constant-head values were determined during calibration.

The hydraulic conductivity field of the Alder Creek Watershed was mapped onto the subsurface mesh using results of previous saturated-zone modelling studies conducted in the Waterloo Moraine (Martin 1994; Martin and Frind 1998; Radcliffe 2000). These studies employed a borehole log database maintained by the MOE to construct over 300 vertical cross-sections of the Waterloo Moraine, which were then used to build the 3D hydraulic conductivity field within the 3D conceptual model of the Waterloo Moraine. The resulting K-field for this work contains twelve distinct lithologic categories and exhibits complex spatial interconnectivity between the shallow and deep flow regimes of the system. The hydraulic conductivity values assigned to each lithologic category in the Alder Creek watershed were based on the values used by Radcliffe (2000) and the corresponding porosity and specific storage values were estimated from tables in Freeze and Cherry (1979) and Mercer et al. (1982). The wetting and drying characteristics of the watershed's coarse sands were drawn from Mace et al. (1998), while the wetting and drying characteristics of the other sediments were estimated using pedo-transfer functions (Schaap et al., 1999).

2.4 Steady State Flow Results

For calibration of the HGS model, a uniform net rainfall rate of 315 mm/year was applied to the surface of the initially saturated system. The model was ran until steady-state flow conditions were achieved. As the system equilibrated, HGS computed the position of the water table, the steady-state head distribution throughout the system, the moisture content distribution in the vadose zone, and the distribution of water infiltrating or exfiltrating across the land surface (termed exchange fluxes-See Figure 3). It also established the distribution of base flow in the surface water drainage network.

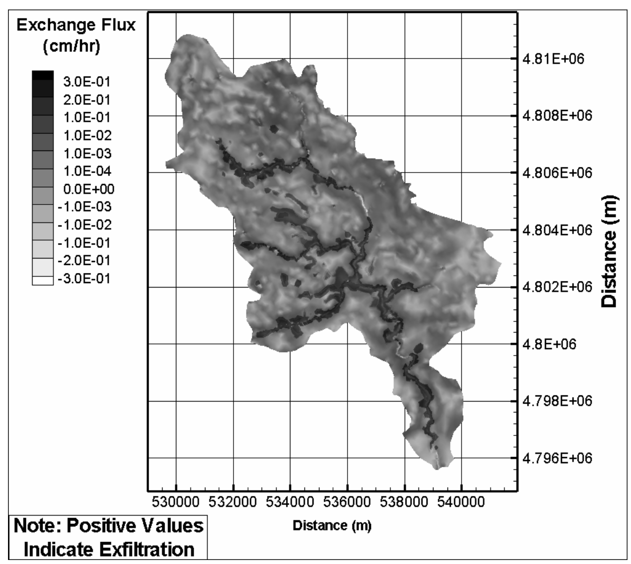

Figure 3. The steady state exchange fluxes at the land surface interface.

The steady state subsurface hydraulic head distribution was then compared to long-term average heads calculated from a network of 28 observation wells distributed across the watershed. A number of manual adjustments were made to hydraulic conductivity values, followed by running the model to steady state conditions, until a satisfactory fit between the simulated and observed subsurface heads was achieved. Figure 4 presents the results of the subsurface calibration process. As can be seen in Figure 4, there is good agreement between the simulated and observed hydraulic head data. A good fit is also indicated by a R^2 value of 0.98 achieved during calibration. Similarly, the 4.4 m mean absolute error produced by the steady-state model is also acceptable for a watershed-scale simulation. However, the 4.2 m mean residual error indicates that the residuals are positively biased in that the simulated hydraulic head data are, on average, larger than the corresponding observed values. It should be noted that the observed head values used for calibration were derived from a previous study of the Alder Creek Watershed by CH2MHill and S.S. Papadopoulos and Associates (2004). In that study, the hydrographs from a number of observation wells which had been continuously monitored for over 10 years were temporally averaged to determine the long-term average hydraulic head values. These temporally averaged values are typically more representative of steady-state conditions than data extracted from borehole logs which represent water level measurements taken during installation of individual observation wells. In the early stages of developing the flow model, we attempted to supplement the temporally-averaged calibration data with data extracted from borehole logs. However, this approach was abandoned because the observation wells in this data set were installed over a period of several years (decades) and the data were not correlated to one another temporally.

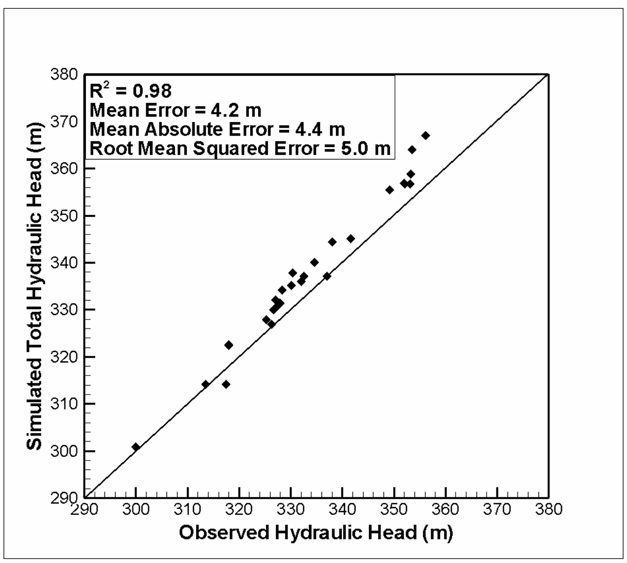

Figure 4. Steady state calibration results for the flow model.

2.5 Application of Well Vulnerability Technique and Results

Using the calibrated steady state flow model as the initial condition, four numerical mass transport experiments were performed to demonstrate the utility of the well vulnerability technique as a source water protection tool. For each simulation, a conservative contaminant source assigned an initial concentration of 1.0 was introduced into a tributary located in the upper north-eastern reaches of the watershed (Figure 5). Each simulation was conducted over a one hundred year time period. In the first experiment, the contaminant source is applied to the stream for one year while the remaining simulation time was spent flushing the contaminant out of the watershed. This procedure is repeated for a 5-, 10-, and 20-year contaminant source application period, respectively, for the remaining experiments. During each experiment, breakthrough curves are computed at two water supply wells located near the stream network and the well vulnerability parameters are calculated (wells W1 and W2 shown on Figure 5).

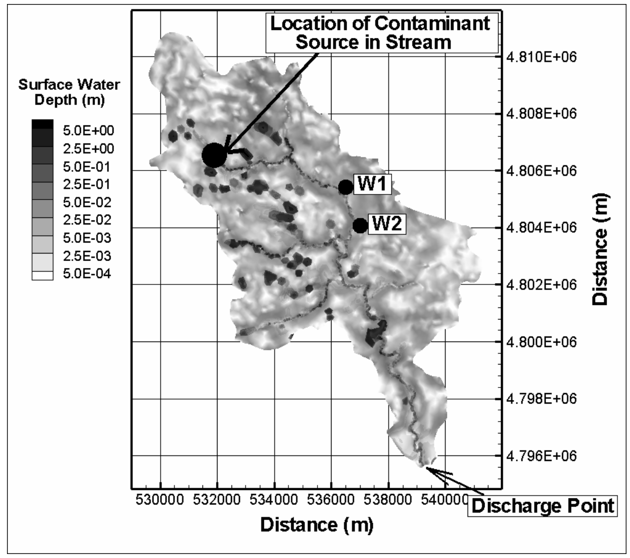

Figure 5. Locations of the contaminant source in the stream and the water supply wells where breakthrough curves were calculated.

The breakthrough curves generated for each well by the experiments are shown on Figures 6 and 7.

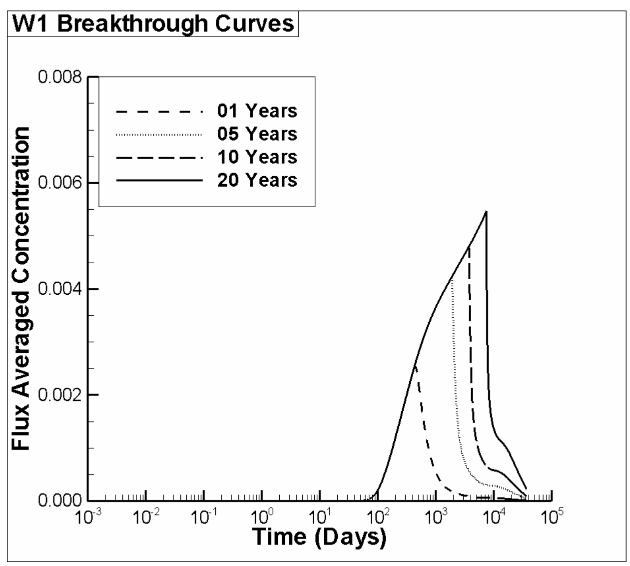

Figure 6. Well vulnerability breakthrough curves for well W1.

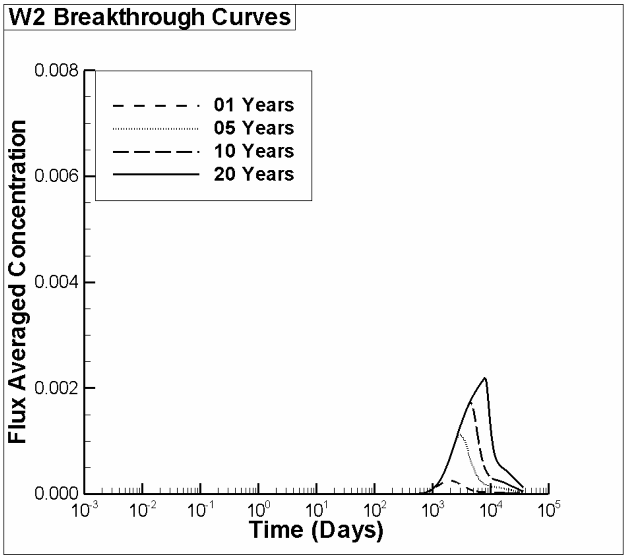

Figure 7. Well vulnerability breakthrough curves for well W2.

The corresponding well vulnerability parameters calculated for the numerical experiments are tabulated in Table 1.

Table 1. Computed Well Vulnerability Parameters*

	Well	T_{exceed} (d)	T_{peak} (d)	$Conc_{peak}$	T_{comp} (d)
1-yr	W1	180	439	2.5E-03	743
Src	W2	N/A	2016	2.5E-04	N/A
5-yr	W1	180	1875	4.2E-03	2716
Src	W2	2472	2956	1.1E-03	3542
10-yr	W1	180	3696	4.8E-03	5308
Src	W2	2452	4449	1.7E-03	6151
20-yr	W1	180	7344	5.5E-03	16399
Src	W2	2452	7915	2.2E-03	10566

*Note: The concentration threshold used to calculate the parameters T_{exceed} and T_{comp} was set at 0.001.

2.6 Discussion

As might be expected, Figures 6 and 7 both show that progressively longer contaminant source application times yield larger peak concentrations ($Conc_{peak}$), longer times to peak concentration (T_{peak}) and longer times before the well comes back into compliance (T_{comp}). These observations are confirmed upon an examination of the tabulated results shown in Table 1. The effect that hydrodynamic dispersion has on contaminant migration can also be seen in Table 1 when examining the T_{exceed} values for well W2. For the one-year contaminant source application, the concentration values at well W2 do not exceed the concentration threshold (which can be adjusted to match some prescribed drinking water limit for a given contaminant but is arbitrarily set at 0.001 in this work). In the five-year contaminant source application experiment, the time to exceed this threshold is 2472 days while the ten- and twenty-year source applications only require 2452 days. This discrepancy between the 5-year and the 10- and 20-year results can be explained by considering the physical processes that govern conservative solute migration in the subsurface; namely, advection which is simply the bulk displacement of solute due to flowing ground water, and hydrodynamic dispersion which is dependent on concentration gradients (and which combines mechanical dispersion and molecular diffusion into a single term). For all of the runs, the influence of advection on solute migration is identical because the velocity distribution in a steady state flow field is constant. Conversely, the concentration gradients driving the leading edge of the contaminant plume towards well W2 for the 5-year source application run are of a smaller magnitude than those driving the plumes for the 10- and 20-year runs. This is because the contaminant source is shut off after 1825 days (i.e. 5 years) in the 5-year run which results in diminished concentration gradients.

It is also worth comparing the information resulting from an application of the well vulnerability to the information that would be produced by either a WHPA or aquifer vulnerability analysis. As was noted earlier, WHPA analyses are expressed in terms of TOT which, in turn, is based solely on advective transport. Because the advective component driving solute migration is identical for all of the simulations, a WHPA analysis would have yielded identical results in all four cases. Moreover, a WHPA analysis produces no data concerning concentration levels at the well, how long it would take the leading edge of the plume to breach drinking water standards at the well or how long the well will be out of compliance with those standards. A similar argument can be made when comparing well vulnerability results to the ‘vulnerability indices’ created by aquifer vulnerability techniques. Overall, it is concluded that the well vulnerability technique could be a valuable tool to watershed managers and policy makers performing source water protection work.

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