WHPA delineation and well vulnerability assessment for drinking water source protection

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ABSTRACT
Accurate delineation of Wellhead Protection Areas (WHPAs) and assessment of well vulnerability are very important for drinking water source protection. The advective particle tracking approach underestimates the "area of contribution" (AOC) as well as the WHPA of the well. A more credible approach for the delineation of AOC and WHPA is the "contribution ratio" (C_r) concept (Muhammad, 2007). The C_r at ground surface is the "recharge contribution ratio" (RC_r) that varies within the AOC. In addition to the accurate and defensible delineation of WHPA, well vulnerability zones can be readily classified on the basis of the ratio of pumped water from the well using the RC_r values.

RÉSUMÉ
La délinéation précise des aires de captage des puits (WHPAs) et l'évaluation de la vulnérabilité des puits sont très importantes pour la protection des sources d'eau. L'approche de traçage des particules advectif sous-estime l'aire réelle de contribution (AOC) de même que le WHPA du puits. Une approche plus réaliste pour la délimitation d'une aire de captage est le concept du rapport de contribution (C_r) (Muhammad, 2007). Le Cr au niveau du sol est le rapport de la contribution de recharge (RC_r) qui varie selon l'AOC. En plus de la présentation précise et défendable de WHPA, les zones de vulnérabilité des puits peuvent être facilement classifiées en se basant sur la proportion d'eau pompée du puits en utilisant des valeurs de RC_r.

1 INTRODUCTION

To protect a wellhead, accurate delineation of the wellhead protection area (WHPA) and assessment of well vulnerability are important. The U.S. Environmental Protection Agency (U.S. EPA) defines a WHPA as the "surface area surrounding a water well or wellfield supplying a public water system, through which contaminants are reasonable likely to move toward and reach such well or wellfield" (U.S. EPA 1987). Delineation of the WHPA is the process of demarcating what ground surface area should be included in a wellhead protection program. This area of land is then managed to minimize the potential of groundwater contamination by any activity that may occur on the land or in the subsurface (Muldoon and Payton 1993).

A WHPA is a projection of a 3-D capture zone onto the ground surface which is not necessarily equal to the area of contribution (AOC) of the well (Figure 1). The AOC represents the source location of water discharging to well at any instant in time (Franke et al. 1998).

There is a basic conceptual requirement that serves as a direct check on the validity of the delineated capture zone. A mass balance check should be performed on the basis that the integral of recharge within the AOC must be equal to the pumping rate *(Q)* of the well:

$$Q = \int_{AOC} \text{Recharge} \times d(AOC) \qquad [1]$$

2 CAPTURE ZONE DELINEATION

The conventional approach to protect a groundwater source is based on the concept of advective WHPA, delineated on the basis of advective time-of-travel (TOT).

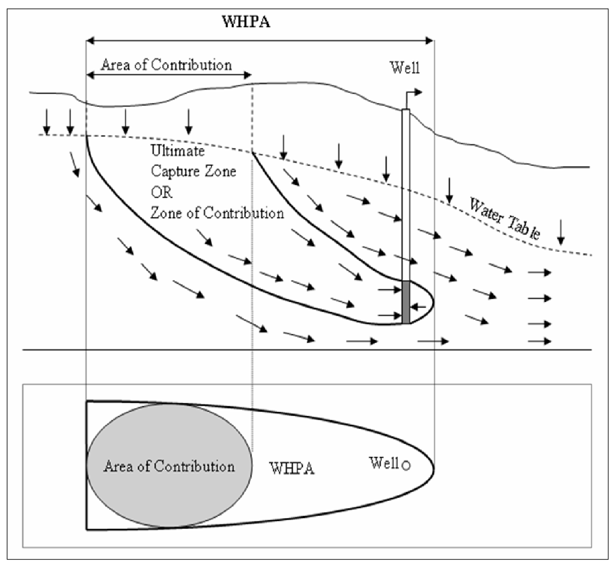

Figure 1: Conceptualization of capture zone, WHPA, and AOC (modified from Franke et al. 1998)

Different zones of TOT may be determined by placing a specified number of particles at the well screen, tracking them in a backward fashion, and then projecting their paths on the ground surface.

2.1 Advective Particle Tracking Approach

Conventionally, the backward advective particle tracking technique is used to delineate WHPAs based on ultimate capture zones and to define isochrones of arrival time.

Advective WHPAs can also be defined by placing tracer particles at the water table and then tracking their path forward through time. In forward particle tracking, where particles are usually placed in each cell/element of the grid, the recharge and area of each cell/element can be used to balance the *Q*.

$$Q = \sum_{i=1}^{n} (\text{Area})_i \times (\text{Rcharge})_i \quad [2]$$

where *n* is the number of particles reaching the well.

Wellhead protection based on advective particle tracking divides the surface area into zones of either capture or no capture. In this interpretation of the capture zone, it is assumed that 100 percent of the recharged water within the defined AOC will eventually be captured by the well. Also, just outside of the defined AOC, recharged water is assumed not captured by the well (see Figure 2). This assumption of recharge contribution to a well underestimates the AOC and consequently the WHPA. The hydraulic properties of the aquifer at the pore level scale cannot be represented to simulate the pore scale variations in velocity and flow path lengths caused by heterogeneities in the aquifer material. To compensate for these unresolved heterogeneities, mechanical dispersion is introduced in the transport equation.

There is a misconception that contaminants originating outside a WHPA, defined on the basis of advective particle tracking, cannot reach a well. A line drawn on a map (see Figure 2) and restricting a specific land use (e.g., a gas station) at a point just inside the line (Point A) and not at a neighboring point (Point B) just outside the line is not reasonable.

2.2 Contribution Ratio (C_r) Approach

Alternatively, a contribution ratio (C_r) approach can be used by solving the advective-dispersive transport equation backward-in-time. This approach has been referred to as a 'probabilistic' approach by Liu and Wilson (1996), Neupauer and Wilson (1999, 2004), Muhammad (2000), Frind et al. (2002) and as the 'adjoint' approach by Frind et al. (2006). In this approach, a hypothetical tracer is introduced at the well at a relative concentration of one (1.0) and allowed to migrate due to advection and dispersion through the aquifer under a reversed velocity field. Frind et al. (2002) presented results of particle tracking and probabilistic approaches for a complex multi-aquifer system. Frind et al. (2006) discussed the concept of well vulnerability using this technique.

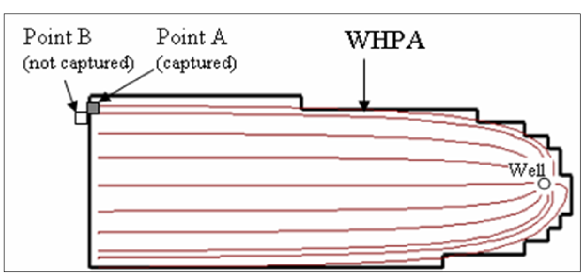

Figure 2: WHPA based on advective backward particle tracking technique

This approach is referred to as the contribution ratio (C_r) approach in this article. The C_r approach is based on the solution of the advection-dispersion equation:

$$\frac{\partial}{\partial x_i}[D_{ij}(\frac{\partial c}{\partial x_j})] - v_i \frac{\partial c}{\partial x_i} - R\lambda c = R\frac{\partial c}{\partial t} \quad [3]$$

where *c* is concentration of the solute, D_{ij} is hydrodynamic dispersion coefficient, v_i is average groundwater velocity, λ is first-order decay constant, and *R* is retardation coefficient

By reversing the velocity field and assigning c = 1.0 at the well screen, the solution of Equation (3) can be interpreted as a contribution ratio (C_r), i.e., the ratio of water from the volume of aquifer(s) being captured by the well. The C_r at ground surface is the recharge contribution ratio (RC_r) that can be used to delineate the area of contribution (AOC) and to assess well vulnerability.

The mass balance equation in this approach will be:

$$Q = \int_{AOC} (Recharge \times AOC \times RC_r) \; d(AOC) \quad [4]$$

The mass balance is calculated using the recharge contribution ratio (RC_r) which varies within the area of contribution. Figure 3 shows the concept of the recharge contribution ratio. RC_r values vary from 1.0 to 0.0. Depending on the hydrogeologic condition within a WHPA, areas of low recharge may contribute more water to a well than the areas of high recharge. Using the RC_r values, significant recharge areas within the WHPA can easily be identified.

Once mass balance for the AOC is checked and the RC_r contour outlined, the advective-dispersive WHPA of any duration can be obtained using the peak (maximum) C_r values projected on the ground surface. This is analogous to the projection of 3-D advective pathlines on the ground surface for the delineation of the advective WHPA. This will account for Dense Non-Aqueous Phase Liquid (DNAPL) sources, which may be present anywhere within the 3-D capture zone. In addition to the defensible WHPA delineation of the well, well vulnerability can also easily be classified using the RC_r values by using any suitable percentage of the pumped water.

3 WELL VULNERABILITY

Frind et al. (2006) presented an imperative discussion on the concepts of 'intrinsic aquifer vulnerability' and 'intrinsic aquifer susceptibility'. In addition to Frind et al. (2006), Trotta (2007) identified pioneering works in well vulnerability completed by U.S. government agencies. To quantify aquifer vulnerability, the common approaches

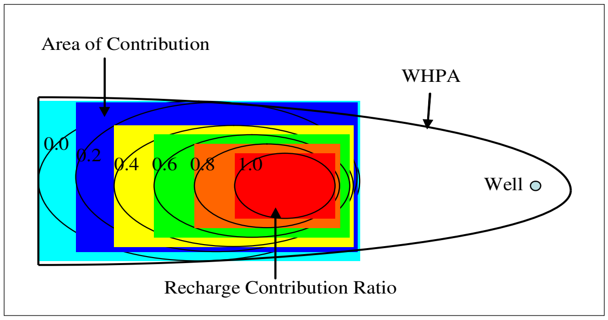

Figure 3: Conceptual understanding of recharge contribution ratio (RC_r)

are: Basic Hydrogeologic Assessment, Aquifer Vulnerability Index (AVI), Intrinsic Susceptibility Index (ISI), DRASTIC, Surface to Aquifer Advection Time (SAAT), and Detailed Hydrological Assessment.

Additional methods are available for assessing the intrinsic vulnerability of aquifers contributing groundwater to the supply wells, including time-of-travel (TOT), and surface-to-well arrival time (SWAT).

The focus of this article is on the well vulnerability. Well vulnerability can be defined as the likelihood that contaminants originating at a specified reference location within the 3-D capture zone (i.e. ground surface, surface water body, surface to water table, water table, and deep within the aquifers/aquitards) can impact to a well.

Capture zones can vary greatly in size, depending on the groundwater flow system, the depth of the well, and the pumping rate. The water captured by a well may be anywhere from days to decades to centuries in age (Frind et al. 2006). For the well vulnerability analysis in source protection, the ultimate capture zone of the well should be considered as contaminants can potentially reach a well originating anywhere within the capture zone.

Well vulnerability zones can be readily classified on the basis of the ratio of pumped water (*Q*) from the well using the RC_r values. Figure 4 shows the conceptualization of well vulnerability using the RC_r approach. The actual contribution of recharge to a well from a particular location is a product of recharge and RC_r

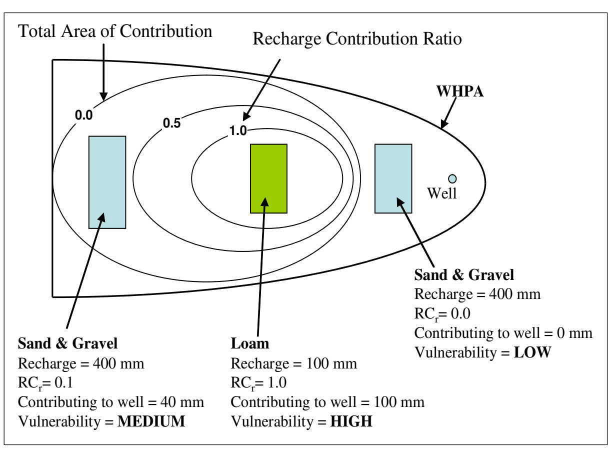

Figure 4: Conceptualization of well vulnerability based on recharge contribution ratio (RC_r)

value at that location. In this understanding, the area of low recharge may contribute more water to a well than the area of high recharge, and thus may classify as high vulnerable area. Also, area of high recharge with lower RC_r may be classified as low vulnerable area.

Areas contributing significant amount of water to the well can also be classified. In Figure 4, an area consisting of loam with relatively low recharge (i.e., 100 mm) is more vulnerable compared to the areas consisting sand and gravel with relatively high recharge (i.e., 400 mm). In this conceptualization, loam with relatively low recharge is contributing significant amount of water compared to the sand and gravel with relatively high recharge.

In this quantitative approach, high, medium and low well vulnerability can be assigned to areas contributing 80 percent, 80 to 95 percent, and 95 to 100 percent of water to the well, respectively.

4 APPLICATION

4.1 Hypothetical Case

A simple hypothetical numerical groundwater model was developed to show the results of advective particle tracking and advective-dispersive RC_r approaches for the delineation of mass-balanced WHPA and well vulnerability assessment. The model domain is 1 km by 1 km with the grid spacing of 10 m by 10 m. Vertically, the domain is 30 m thick and discretized into 3 layers to introduce a lens of low hydraulic conductivity between the upper and lower aquifers (see Figure 5). A well is pumping from the lower aquifer at a rate of 50 m^3/day, and a uniform recharge of 400 mm is applied over the model domain. The near and far boundaries of the model are 'no flow' boundaries and the left and right sides of the model are set at constant heads of 28 m, and 26 m, respectively, so the general groundwater flow direction is from left to right.

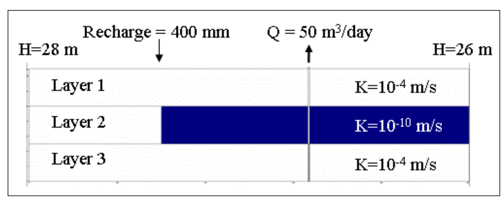

Figure 5: Hypothetical model setup

Figure 6 shows the results of the backward advective particle tracking and zonal budget. In the first case (Figure 6A), particles were placed in the middle of the lower aquifer, and tracked backward. The recharge within the delineated WHPA is 52 m^3/day with the mass balance error (*Q* versus *Recharge*) of 4 percent. If we consider the whole WHPA as a recharge contributing area, the mass balance based on the steady-state WHPA is excellent.

By introducing additional model layers for the lower aquifer, and then placing particles in the centre of each layer, the WHPA and recharge within the WHPA are very different (Figure 6B). The recharge within the delineated WHPA is 73 m^3/day with the mass balance error of 46 percent. By placing the particles at the top and bottom of the well screen (Figure 6C), the recharge within the

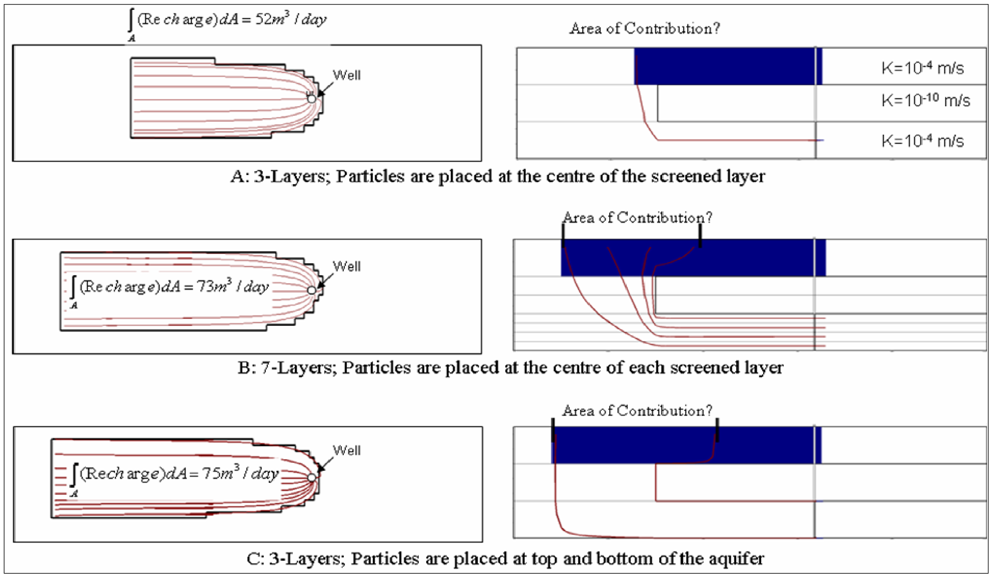

Figure 6: Backward advective particle tracking and mass balance

WHPA is 75 m^3/day with the mass balance error of 50 percent.

The WHPA of Figure 6A may be considered as a mass-balanced WHPA, if the AOC is overlooked, which is not accurate. In fact, it is difficult to find the AOC from the backward particle tracks.

Figure 7 shows the results of the forward particle tracking. In this case, particles were initially placed in the centre of each cell of the finite-difference grid at the water table elevation. There are 481 particles reaching the well; the recharge is 52.7 m^3/day with the mass balance error of 5.4 percent. This approach gives a better mass-balanced advective area of contribution.

If it is assumed that this is a mass-balanced WHPA and AOC, then theoretically, any activity occurring outside that AOC should not impact the pumping well.

Figure 8 shows a setup of land use activities outside

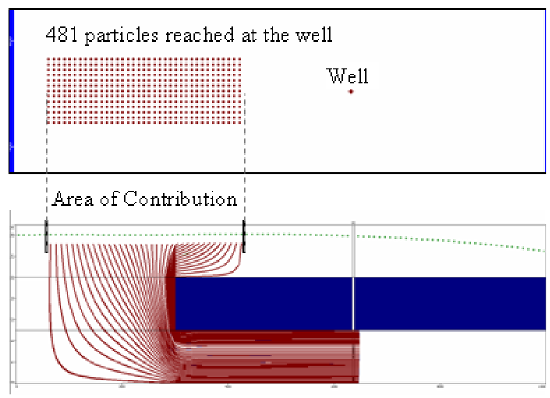

Figure 7: Forward particle tracking and mass balance

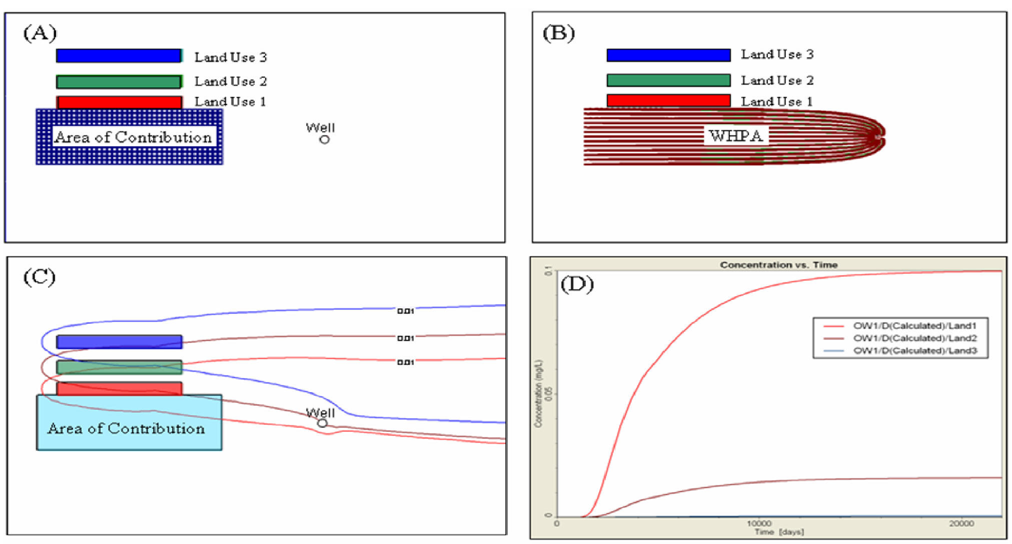

Figure 8: Impact of land use activities on the well

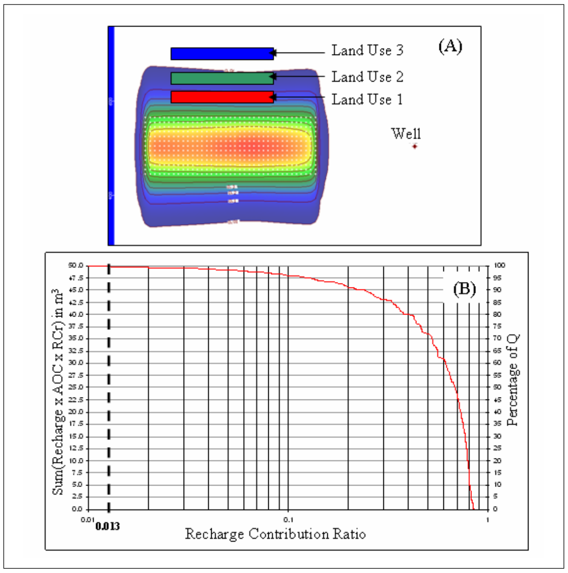

Figure 9: Contribution ratio and mass-balanced area of contribution

the advective AOC and their impact on the well. Three land parcels were selected and used for an application of a 'tracer' of concentration 1.0 mg/L in the recharge. The setup of these land uses is shown in (A) and (B) with respect to the advective AOC and WHPA. The results of the transport model, concentrations in the lower aquifer (C) and breakthrough curves (D), indicate that the activities at Land Uses 1 and 2 are impacting the well. These results showed that the AOC and the WHPA were not properly defined. Accordingly, a wellhead protection

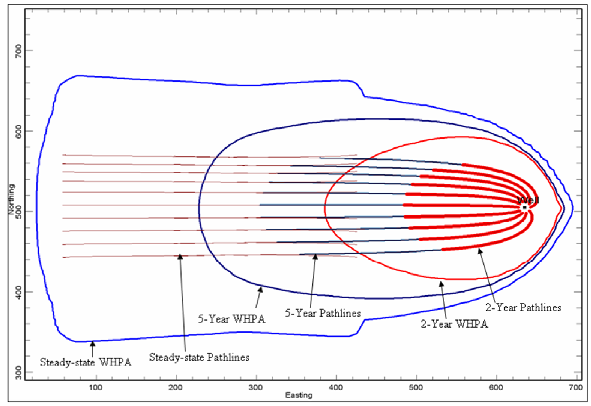

Figure 10: 2-, 5-year, and steady-state pathlines and WHPAs

strategy based on the advective WHPA may have inherited limitations.

Identification of the AOC based on the C_r approach is the solution of this problem (see Figure 9(A)). A C_r value of 1.0 mg/L was assigned at the well and the advective-dispersive transport equation was solved under the reversed velocity field. The results of the model show the C_r values at the water table, Figure 9(A), that are considered as RC_r. Equation (4) is used for the mass balance calculations. The outline of the AOC can be determined from the mass balance curve. Figure 9(B) shows that a C_r value of 0.013 balances the Q of the well.

Forward particles reaching the well are also shown on Figure 9(A). Difference in advective particle tracking and advective-dispersive C_r approaches is clear. Interestingly, areas which are contributing up to 50 percent of the

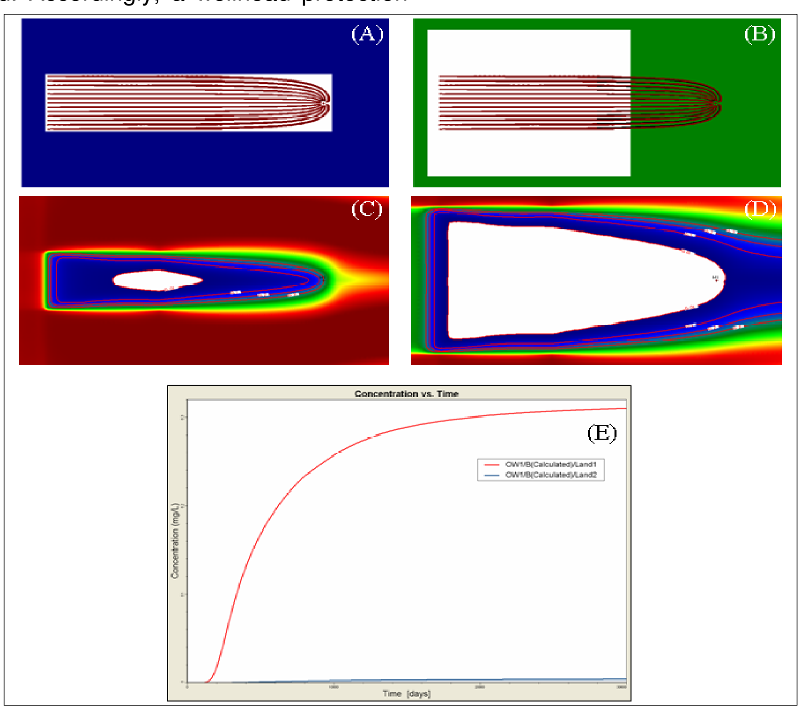

Figure 11: Land use impact on the well; (A) Land use outside the advective WHPA, (B) Land use outside the advective-dispersive AOC, (C) impact of Land Use 1, (D) Impact of Land Use 2, and (E) breakthrough curves for Land Uses 1 and 2 at the pumping well.

recharged water are outside the advective AOC.

Compared to the conventional particle tracking approach, Land Uses 1 and 2 are within the advective-dispersive AOC of the well. The impact of these land use activities is understandable (see breakthrough curves at the well, Figure 8(D)). Land Use 3 is outside the delineated AOC and has no impact on the well.

In this case, about 30 percent (15 m^3/d) of the pumped water originates from areas located outside the advective AOC. Dilution of the groundwater due to mixing of contaminated water with clean water often significantly reduces contaminant concentrations in the well water. The associated dilution factor in this case is about 2.3.

The value of 0.013 can be used to outline the time-specific WHPAs by projecting the peak C_r values on the ground surface. Figure 10 shows 2-, 5-year and steady-state pathlines and advective-dispersive WHPAs. The difference in advective and advective-dispersive WHPAs is very clear in this figure.

To support the idea of advective-dispersive AOC, worst case scenarios were also simulated using the land use activities occurring on the entire land outside the advective WHPA and advective-dispersive AOC. Figure 11 (A) and (B) show these land uses outside the advective WHPA and advective-dispersive AOC, respectively. A tracer of concentration 1.0 mg/L was applied with the recharged water and a transport model was used to determine the impacts of these land uses on the pumping well. Figures 11 (C), (D) and (E) show the impact of these land uses; Land Use 1 almost impacts the entire advective WHPA while Land Use 2 has no impact on the advective-dispersive AOC (the contour values shown on (C) and (D) are for 0.01, 0.1, 0.2 and 0.3 mg/L).

Figure 11(E) shows the breakthrough curves for these land use activities at the well. The concentration of about 0.3 mg/L at the well due to Land Use 1 confirms that about 30 percent of the pumped water originates from this area and impacts the well, while the concentration of less than 0.01 mg/L due to Land Use 2 validates that Land Use 2 is not likely to impact the well.

Figure 12 shows the classification (high, medium, and low) of well vulnerability assigned on the basis of areas contributing 80 percent, 80 to 95 percent, and 95 to 100 percent of water to the well, respectively. In this case, 80 percent, 95 percent, and 100 percent of water to the well is originating from the area under RC_r contour of 0.4, 0.13, and 0.013, respectively. The zone of low vulnerability was adjusted to include all the areas under the peak C_r (projection of 3-D contribution ratio, C_r, on ground surface) to increase the level of protection; compare Figure 9(A) and Figure 12(B). High, medium, and low vulnerability zones can be assigned easily for any time specific protection zone (e.g., 2-year pathogen management zone, 5-year DNAPL/contaminant protection zone) using the peak C_r values and contour values of 0.4, 0.13 and 0.013, respectively.

4.2 Field Case

For the comparison of conventional advective particle tracking and advective-dispersive capture ratio approaches, a wellfield, located within the complex Waterloo Moraine aquifer system, is selected (see Figure 13). This wellfield was pumping at the average rate of 4.6E6 m^3/year. The details of the Waterloo Moraine aquifer system are given in Martin and Frind (1998).

For the flow simulations, a 3-D finite-element code WATFLOW (Molson et al. 2002) was used. For the WHPA delineation, a particle tracking advective transport code, WATRAC (Frind 2000) and an advective-dispersive transport code, WTC (Molson et al. 2000) were used. The details of the model are available in Muhammad (2000).

Figure 14 shows the surface projection of 3-D advective backward particle pathlines. The complex

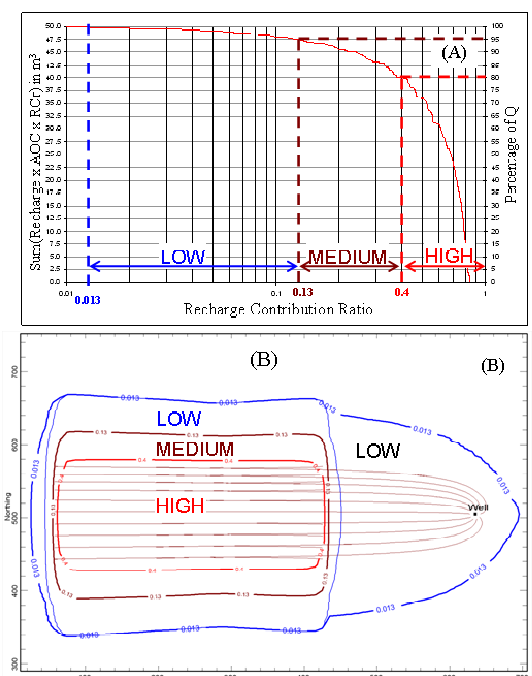

Figure 12: Well vulnerability assessment

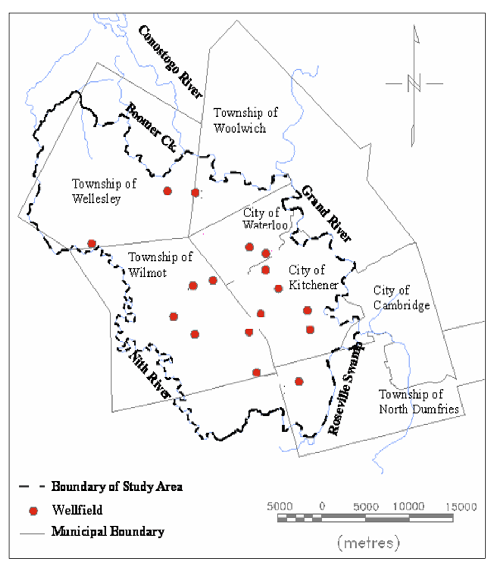

Figure 13: Waterloo Moraine area showing location of wellfields

nature of these pathlines makes it difficult to define the WHPA and particularly the AOC.

Figure 15(A) shows the results (contours of RC_r) simulated by advective-dispersive approach using the WTC model. The AOC is contributing recharge to the wellfield at different proportions, from 1.0 (100 percent) to

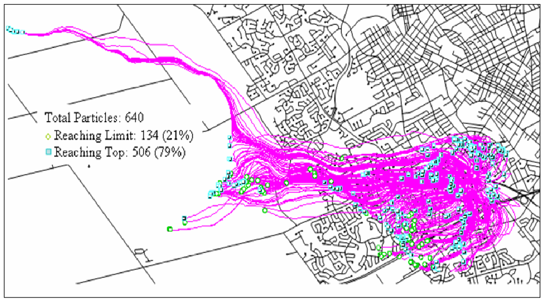

Figure 14: Backward advective particle tracks

less than 0.01 (1 percent). There are areas outside the contour of 0.01 contributing less than 1 percent of the recharged water to the well.

For the validation of the delineated advective-dispersive AOC, a mass balance check was performed using Equation (4). The C_r-based mass balance ($Recharge \times A_{RCr} \times RC_r$) vs. the RC_r, Figure 15(B), shows that the contribution of recharge integrated under the contour of 0.02 equals the pumping rate, *Q*. The capture ratio contour of 0.02 is then taken as an outline for the AOC and time-specific WHPAs. Figure 16 shows 2-, 10-, 40-year and steady-state WHPAs.

Figure 17 shows the well vulnerability classification (high, medium, and low) assigned on the basis of areas contributing 80 percent, 80 to 95 percent, and 95 to 100 percent of water to the well, respectively. In this case, 80 percent, 95 percent, and 100 percent of water to the well

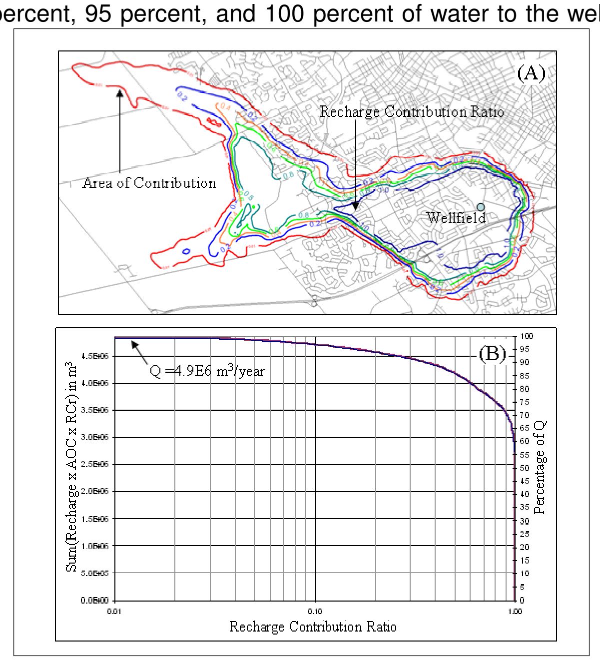

Figure 15: Contribution ratio and mass-balanced area of contribution

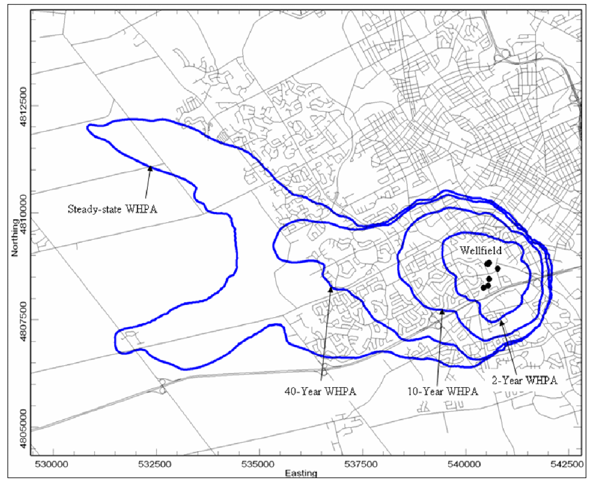

Figure 16: 2-, 10-, 40-year and steady-state WHPAs

is originating from the area under RC_r contour of 0.65, 0.15, and 0.02, respectively. The zone of low vulnerability was adjusted to include all the areas under the peak C_r (projection of 3-D C_r on ground surface) to increase the level of protection.

5 CONCLUSIONS

WHPAs should be validated by mass balance using the recharge occurring within the AOC. The conventional particle tracking technique appears to underestimate the WHPA and AOC, as it relies exclusively on the advective nature of the flow system and ignores the dispersive nature of the groundwater flow conditions. A line drawn on a map which restricts a specific land use at a point just

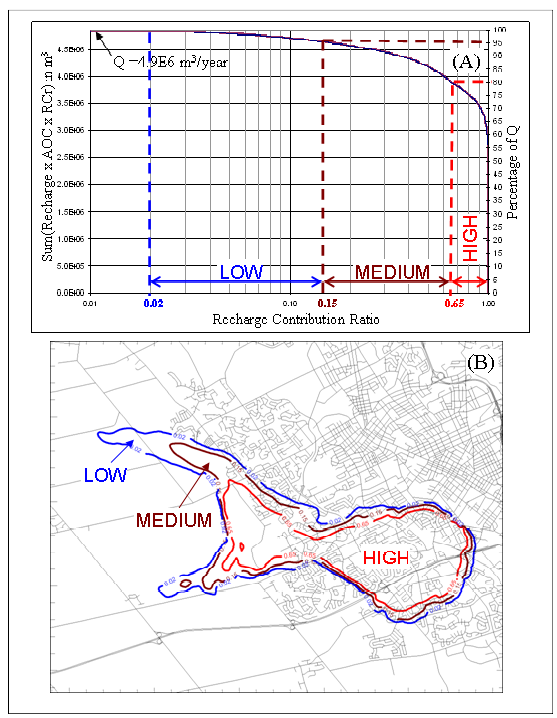

Figure 17: Well vulnerability assessment

inside the line and not at a neighboring point just outside the line may be problematic. There is a misconception that contaminants originating outside a WHPA, defined on the basis of advective particle tracking, cannot reach a well. There is therefore a considerable risk that a land use activity outside the delineated WHPA may impact a well.

The C_r approach that is based on the advective-dispersive nature of the groundwater flow system provides a defensible mass-balanced AOC and WHPA. In this approach, the recharge contribution varies within the delineated AOC. Depending on the hydrogeologic condition within a WHPA, areas of low recharge may contribute more water to a well than the areas of high recharge. Significant recharge areas within the WHPA can easily be identified.

In addition to the defensible delineation of WHPA and AOC, this new approach will be effective for classifying quantitative well vulnerability and developing more realistic wellhead protection strategies. In this approach, high, medium and low well vulnerability can be assigned to areas contributing 80 percent, 80 to 95 percent, and 95 to 100 percent of water to the well, respectively.

DISCLAIMER

This work was not reviewed by the Regional Municipality of Waterloo and the WHPAs presented in this assessment may not be the actual ones used by the Region.
This article is the sole opinion of the author and is not necessarily endorsed by the author's employer.

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