Geoscience Canada

Managing Ground-water Resources Using Wellhead Protection Programs

Stephen Livingstone, Thomas Franz and Nilson Guiguer

Volume 22, Number 3, September 1995

URI: https://id.erudit.org/iderudit/geocan22_3ser02

See table of contents

Publisher(s)

The Geological Association of Canada

ISSN

0315-0941 (print)
1911-4850 (digital)

Explore this journal

Cite this article

Livingstone, S., Franz, T. & Guiguer, N. (1995). Managing Ground-water Resources Using Wellhead Protection Programs. *Geoscience Canada*, *22*(3), 121–128.

Article abstract

Significant efforts have been completed by the United States to legislate guidelines for the long-term protection of the recharge areas around water supply wells through wellhead protection programs. Currently, Canada does not have national wellhead protection guidelines, and it is the responsibility of proactive local governments, municipalities or regions to implement their own wellhead protection programs.This paper presents the wellhead protection terminology and methodologies currently used to define wellhead protection areas (WHPAs). Delineation methodologies and evaluation techniques for wellhead protection are presented using a hypothetical case study. Based on the case study, it is shown that three-dimensional numerical modelling provides more accurate WHPAs than analytical and two-dimensional numerical models. The risks of delineation errors are discussed and the potential risks of over- or under-protecting the WHPA are demonstrated.

Managing Ground-water Resources Using Wellhead Protection Programs

Stephen Livingstone
Beatty Franz & Associates Limited
315 Zephyr Avenue
Ottawa, Ontario K2B 5Z7

Thomas Franz
Beatty Franz & Associates Limited
18 King Street East
Bolton, Ontario L7E 1E8
and
Waterloo Hydrogeologic Inc.
180 Columbia Street West
Waterloo, Ontario N2L 3L3

Nilson Guiguer
Waterloo Hydrogeologic Inc.
180 Columbia Street West
Waterloo, Ontario N2L 3L3

SUMMARY

Significant efforts have been completed by the United States to legislate guidelines for the long-term protection of the recharge areas around water supply wells through wellhead protection programs. Currently, Canada does not have national wellhead protection guidelines, and it is the responsibility of proactive local governments, municipalities or regions to implement their own wellhead protection programs. This paper presents the wellhead protection terminology and methodologies currently used to define wellhead protection areas (WHPAs). Delineation methodologies and evaluation techniques for wellhead protection are presented using a hypothetical case study. Based on the case study, it is shown that three-dimensional numerical modelling provides more accurate WHPAs than analytical and two-dimensional numerical models. The risks of delineation errors are discussed and the potential risks of over- or under-protecting the WHPA are demonstrated.

RÉSUMÉ

Par l'entremise de programmes de protection des têtes de puits d'aquifères, les États-unis ont consenti d'importants efforts afin d'établir une réglementation et des lignes directrices pour la protection des zones de recharge entourant les puits. Présentement, aucune réglementation nationale n'existe au Canada, et il revient aux instances locales, municipalités ou régions, de prendre l'initiative et d'instaurer leur propre programme de protection des têtes de puits. Le présent article présente la terminologie de la protection des têtes de puits et décrit les méthodes et les techniques utilisées pour définir les zones de protection des têtes de puits (ZPTP). Les méthodes de délimitation et les techniques d'évaluation pour la protection des têtes de puits sont présentées à partir de l'étude d'une histoire de cas fictive. On démontre ainsi que l'utilisation de modèles 3D permettent de définir les SPTP avec plus de précision et que ne le permettent les modèles analytiques ou 2D. On discute des risques des possibilités d'erreur de délimitation et des possibilités de sur-, ou sous-protéger les ZPTP.

INTRODUCTION

Throughout Canada, ground water is an invaluable natural resource that sustains the growth and development of communities, industries and agricultural activities. Ground-water surveys completed in the 1960s and the 1980s indicate that ground-water usage in Canada has grown from approximately 10% to about 26% of the population (Hess, 1986). In addition, about 40% of the municipalities in Canada use ground water for a significant portion of their domestic water supply. In Prince Edward Island, more than 99% of the population uses ground water for domestic use due to a lack of acceptable surface-water sources. Domestic use of ground water is most prevalent in Ontario and Quebec, whereas agricultural activities use the most ground water in the Prairies. Industries are sustained by ground-water use in British Columbia (Cherry, 1987).

The growth and development of communities, industries and agriculture has resulted in the storage and discharge of chemicals in the form of point and non-point sources (Howard, in press; Howard and Livingstone, in press). Point sources include landfill sites and lagoons, storage tanks, snow dumps, septic systems, and chemical discharges. Seasonal applications of road de-icing agents, agricultural fertilizers, and pesticides represent significant non-point sources. These contaminant sources pose a serious threat to the long-term health and potability of ground water as a drinking-water resource.

The management of ground-water resources and the significance of keeping ground-water supplies safe have been relatively recent concerns. As shown in Table 1, many communities in Ontario have had the costly task of finding alternative drinking-water sources due to ground-water contamination of their municipal water wells. Chemicals commonly detected in ground water include PCBs, volatile organic compounds (VOCs), nitrates and bacteria associated with faulty septic system designs. Many of these are known carcinogens (*e.g.*, benzene). In the United States, more than 200 different harmful chemicals have been detected in ground water (United States Environmental Protection Agency, 1993). Monitoring and chemical testing of Canadian drinking-water supplies will likely show the same results with time and with the development of site-specific sampling programs.

Significant efforts have been completed by the United States to legislate guidelines for the long-term protection and risk assessment of the recharge areas around water supply wells through wellhead protection programs. Wellhead protection may be defined as managing a land area around a well or well field to prevent ground-water contamination and guarantee a high-quality water supply source (Cleary and Cleary, 1991; United States Environmental Protection Agency, 1993). Currently, Canada does not have national wellhead protection guidelines. It is the responsibility of proactive local governments, municipalities or regions to implement wellhead protection programs, as, for example, the Kitchener-Waterloo region of Ontario has. This region is the largest urban area in Canada depending entirely on ground water.

Five steps to implementing a wellhead protection program, as defined by the United States Environmental Protection Agency (U.S. EPA, 1993) are 1) forming a community planning team, 2) delineating the wellhead protection area, 3) identifying and locating potential sources of contamination, 4) managing the wellhead protection area, and 5) planning for the future.

In this paper, the methodologies and evaluation techniques used to delineate the wellhead protection area (step 2) will be discussed with an emphasis on the use of computer modelling. A hypothetical case study is presented to illustrate the differences of various modelling techniques.

WELLHEAD PROTECTION TERMINOLOGY

The term wellhead protection can be misleading. It does not refer to the protection of the mechanical equipment or well construction materials used at the individual wells. Rather, wellhead protection is concerned with the land area or zones around a pumping well which supplies ground water to the well. Delineation of the wellhead protection area represents the definition of the geographical limits most critical to the protection of the wellfield from unexpected contaminant releases to the aquifer recharge area of the aquifer. These zones around the wells are referred to as wellhead protection areas (WHPA).

Four terms — cone of depression, zone of influence (ZOI), zone of contribution (ZOC), and zone of transport (ZOT) — are commonly used to assess and describe the risk of contaminants captured by a pumping well (Fig. 1).

When a well is pumped, drawdown of the water table (unconfined aquifer) or potentiometric surface (confined aquifer) occurs. This drawdown in water levels by pumping is called the cone of depression. The size and shape of the cone of depression is related to the well pumping rate and time period, the physical parameters of the aquifer material (*i.e.*, hydraulic conductivity, porosity), the aquifer boundary conditions (*i.e.*, rivers, faults, recharge zones), and the hydrostratigraphic setting (*i.e.*, unconfined, confined aquifers). In general, the cone of depression for unconfined aquifers is relatively small in comparison to confined aquifers. For confined aquifers, the cone of depression may extend outward for kilometres.

The zone of influence (ZOI) is synonymous with cone of depression. ZOI is defined as the distance from the well where changes in the ground-water surface (water levels) can be measured or inferred as a result of pumping (U.S. EPA, 1994). Theoretically, the ZOI in a homogeneous, isotropic porous aquifer will be circular. Most natural hydrogeological settings, however, are complex. Thus, in heterogeneous, anisotrophic porous and fractured aquifers, the ZOI often has an irregular shape. Ideally, the ZOI is measured in the field by means of water level response in monitoring wells and is based on a comparison of pre-pumping and pumping conditions. However, the pumping wells may have been operating for many years and have modified the natural flow conditions. Thus, it may be difficult to determine the exact limits of the ZOI due to pumping of the municipal well or well field.

The zone of contribution or capture (ZOC) is defined as the area of the aquifer that recharges the well or well field (U.S. EPA, 1994). Ground-water contaminants discharged into the ZOC area will be captured by the water well.

Table 1 Municipal ground-water supplies in Ontario: contamination incidents/concerns.

MUNICIPALITY	CONTAMINANT	RESOLUTION/ CURRENT SITUATION
WEST CENTRAL REGION		
Smithville	PCBs	Municipal wells out of operation Extended water from Lake Ontario
Elmira	NDMA	One well field out of operation Extended supply from St. Jacobs
Kitchener/Waterloo	VOCs	Contaminants in a number of well fields
Town of Delhi (spring supply)	VOCs-benzene	Spring supply shut down New municipal well drilled
Town of Simcoe	VOCs	Contaminants at low levels Monitoring municipal wells
Guelph	VOCs-TCE	One well field shut down
Erin	VOCs	One or two wells shut down Two new wells drilled
SOUTHWEST REGION		
Ingersol	VOCs	Contaminants detected in one well Wells monitored
SOUTHEAST REGION		
Trenton	Nitrates Bacteria	Well shut down
Frankford	Nitrates	Well shut down
Manotick	VOCs	Contamination of private wells Surface water extended from Ottawa
MID ONTARIO REGION		
Penetanguishene	VOCs	Well field shut down
Orillia	VOCs	Contamination of two wells
Barrie	VOCs	Contamination of well fields
NORTHWEST REGION		
Manitouwadge	VOCs	Contamination detected (low levels)

Thus, there is a high risk of contamination to the ground water within the ZOC. As shown on Figure 1, the ZOC and the ZOI do not coincide. For the ZOC, ground water is removed from the pumping well from only a relatively small portion of the downstream area of the well, but it may extend as far as the ground-water divide on the up-gradient side of the well. By contrast, the down-gradient portion of the ground water within the ZOI is not drawn toward the pumping well but continues down gradient, while the ZOI does not extend to the up-gradient limit of the ZOC. As a result, the ZOI overprotects the down-gradient ground water and underprotects the up-gradient ground water. In our experience, however, if the ZOC is small, then the ZOC and ZOI will generally overlap.

The ZOC can be further delineated by the time of travel within the ZOC. The time of travel (TOT) is generally presented as isochrones (contours of equal travel time) that indicate the time required for a contaminant to reach a pumping well from a contaminant source within the ZOC. The time of travel depends on the ground-water flow velocity, the contaminant characteristics, and the properties and composition of the aquifer material. Figure 1 depicts the delineation of the travel times (TOT) for contaminants within the ZOC.

Another term used in wellhead protection plans is the zone of attenuation (ZOA). The ZOA is always smaller than the ZOC, because it takes into account that contaminants can be immobilized or attenuated in the subsurface to an acceptable concentration before reaching the pumping well. The chemical processes that reduce the contaminant concentrations along its flowpath include sorption, chemical precipitation and degradation. Such processes are discussed by Howard, in press; Feenstra, in press; and Beck, in press. Typically, the zone of attenuation is ad-

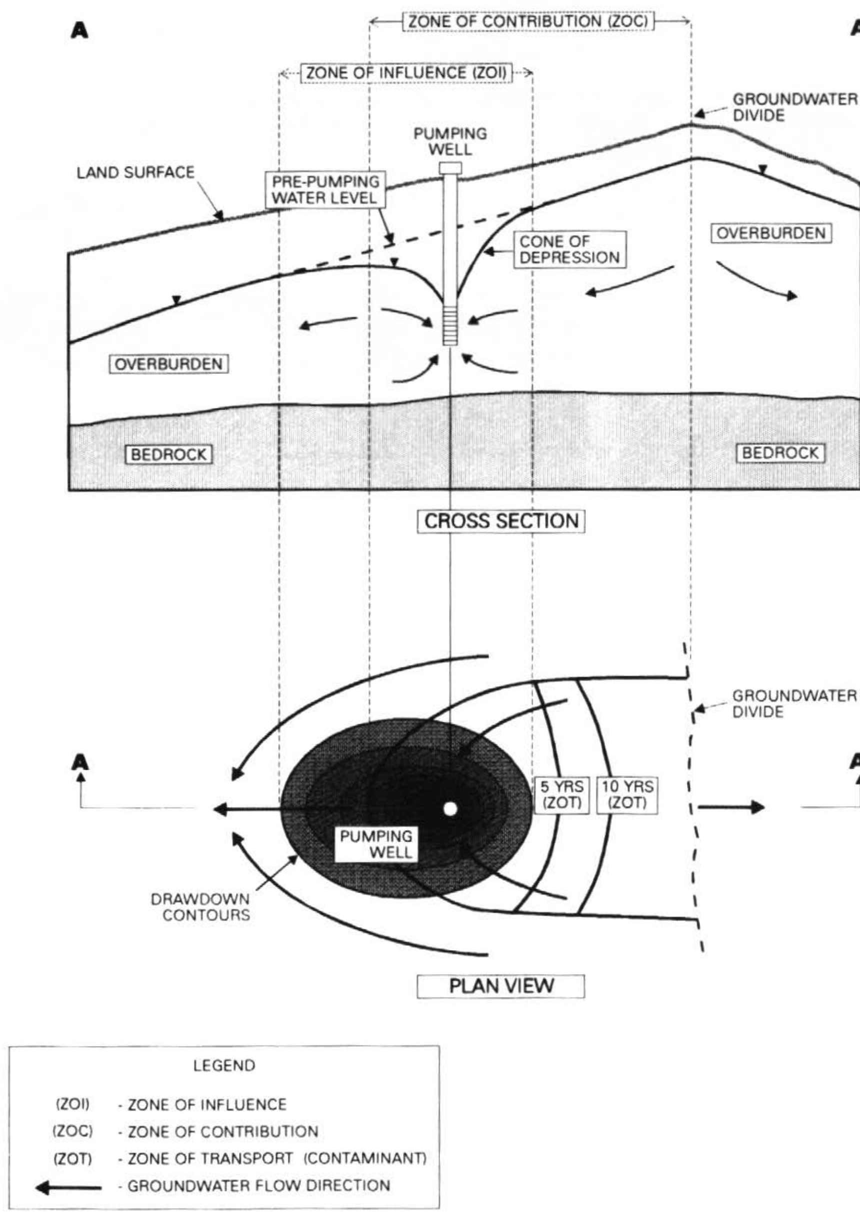

Figure 1 *Conceptual model of wellhead protection areas and terminology.*

justed through the time of travel calculations. Retardation factors, which represent the combined effects of attenuation for the chemicals, are calculated; these shift the isochrones closer to the pumping well. This procedure results in a reduction of the WHPA for certain chemical parameters that may discharge in the ZOC. It is often impossible to predict what types of contaminants may be released within the ZOC, and, therefore, it is often impractical to apply attenuation as a means to reduce the size of the WHPA. This approach does apply, however, when a known potential source is located within the ZOC, and when the contaminants potentially released at that location are known to attenuate.

WELLHEAD PROTECTION DELINEATION METHODS

The U.S. EPA has identified the following methods as practical procedures to delineate wellhead protection zones: 1) hydrogeological mapping, 2) fixed radius around a well, 3) calculated radius, 4) analytical modelling, and 5) numerical modelling.

Hydrogeological mapping (method 1) requires the identification of the zone of contribution (ZOC) based on the physical and chemical characteristics of the aquifer. This approach is sometimes used to develop a conceptual model, which is then simulated in an analytical or numerical computer model. The geometric methods (methods 2 and 3) use pre-determined fixed radius and aquifer geometry without any consideration for the natural ground-water system. The analytical method (method 4) uses simplifications and assumptions to describe the hydrogeological setting for the determination of the time of travel of contaminants and the drawdown calculations for wellhead protection. The fifth method involves computer modelling. Advanced numerical models are employed to simulate ground-water flow and contaminant transport in two or three dimensions (see Mercer and Faust, 1980; Konikow and Mercer, 1988; Bear *et al.*, 1992; Anderson and Woessner, 1992).

Two-dimensional modelling can be completed in plan view or cross-section. The use of a two-dimensional model has some implications in terms of the size and shape of the predicted WPHA. The two-dimensional formulation neglects any vertical gradients and, therefore, usually results in a good representation of the regional scale model when flow predominantly occurs in the horizontal plan. However, in the immediate vicinity of wells and shallow-surface waterbodies, and in strongly variable topography, three-dimensional flow conditions with significant vertical components exist. A two-dimensional horizontal (plan view) model cannot resolve vertical layering of the aquifer sediments. Any vertical variations in hydraulic conductivity, porosity, *etc.*, are averaged over the aquifer thickness.

Three-dimensional models can more fully represent hydrogeological conditions by incorporating multi-layers, partially screened water wells, and horizontal and vertical fluxes. The major advantage of using numerical methods is the greater flexibility and ability to incorporate varying hydrogeological and stress conditions into the computer model. Thus, the result is a more accurate description and simulation of the real physical conditions. Ground-water flow is typically calculated with the finite difference or finite element method, while contaminant transport can be simulated using particle-tracking techniques or finite-difference and finite-element methods.

These methodologies differ in their degree of complexity and accuracy. The U.S. EPA (1987) concluded that numerical modelling achieves the most accurate and reliable WHPA delineation; however, numerical modelling can only achieve reliable results when the following conditions are met:

1. There must be a minimum amount of knowledge of the ground-water flow system that is to be protected. The characterization of a municipal aquifer typically requires the input of professional hydrogeologists. The data required are 1) extent of aquifer (*i.e.*, three-dimensional aquifer geometry), 2) stratigraphy of the subsurface near the well (possibly over several square kilometres, 3) pumping test data, 4) historic information on pumping schedules, 5) data on the interaction of ground water and surface water, 6) ground-water recharge and infiltration data, and 7) regional water level information.
2. An appropriate model must be chosen for the calculation of ground-water flow and well capture zones. The model must be able to reflect the physical conditions in the ground-water system. An important consideration in the selection of a model is the choice of two-dimensional *versus* three-dimensional modelling. While three-dimensional modelling requires greater efforts, it may be the only way to achieve a realistic representation of the ground-water flow system.
3. The model must be set up and calibrated properly by an experienced modeller. Non-calibrated models will not be any better than simplistic methods such as fixed radius or calculated radius.

Risks of Delineation Errors

Errors in the delineation of WHPAs can have two significantly negative effects. For example, if an area is delineated greater than necessary (*i.e.*, when the predicted well capture zone is larger than the true capture zone), then development restrictions in the wellhead protection area will over protect. This could have a negative economic impact on the area, especially if the WHPA lies within a highly developed area, where restrictions on land use and/or monitoring requirements may be required from landowners who are, in fact, outside of the true catchment area of the well.

On the other hand, if a WHPA is underprotected (*i.e.*, when the delineated area is smaller than the true catchment area or if the delineated area is not in the right location), then environmental impacts can still occur and the ground water remains at risk. Thus, it is important to establish the degree of accuracy that may be required in the process of deciding on the WHPA delineation methodology. In this case, ground-water monitoring and chemical analysis programs would be developed which would not reflect the appropriate level of effort. Thus, receptors of the drinking water could be at risk from contaminated ground water.

WHPA Delineation Models

There are several computer models available for the delineation of WHPAs. Table 2 shows the most popular models and categorizes them according to their features and capabilities.

In this paper, we consider WHPA, FLOWPATH and VISUAL MODFLOW to highlight the differences between analytical, two-dimensional numerical, and three-dimensional numerical models. Of the models listed in Table 2, these models are probably the most popular. For example, WHPA was developed by the U.S. EPA and, therefore, is in widespread use in the United States, while the proprietary FLOWPATH and VISUAL MODFLOW have gained acceptance as the most powerful numerical models on the market in the United States, Canada, and Europe (predominantly the United Kingdom).

Hypothetical Case Study

A hypothetical setting that exists near many municipal well fields was constructed to illustrate 1) the differences between analytical, numerical and two-dimensional *versus* three-dimensional modelling, and 2) potential problems associated with ground-water monitoring and chemical sampling programs.

In our example, a residential development is located east of the Beatty River (Fig. 2). All units are on septic systems and supplied water is taken from a municipal water well. South of the residential development, agricultural land (Palmer Farm) is used for growing potatoes and cash crops. Land use on the west side of the river includes Parnham's Gas Bar, Rennie Paints and Dyes Inc., and Fraser and Brown Hardware. All industries and stores were established five to ten years ago. Currently, the municipality samples the water well twice per year for bacteria chemical analysis (fecal and total coliforms) to document the absence or presence of septic system effluent impacting the water supply.

The municipal well pumps at a rate of 250 $m^3 \cdot d^{-1}$ and it is a partially penetrating well with the well screen extending from 20 m to 30 m below ground surface. The surficial aquifer is made up of sand and gravel with a respectable transmissivity of 26 $m^2 \cdot d^{-1}$ (*i.e.*, a hydraulic conductivity of 10^{-3} $cm \cdot s^{-1}$ and a thickness of 30 m). The well is near a river

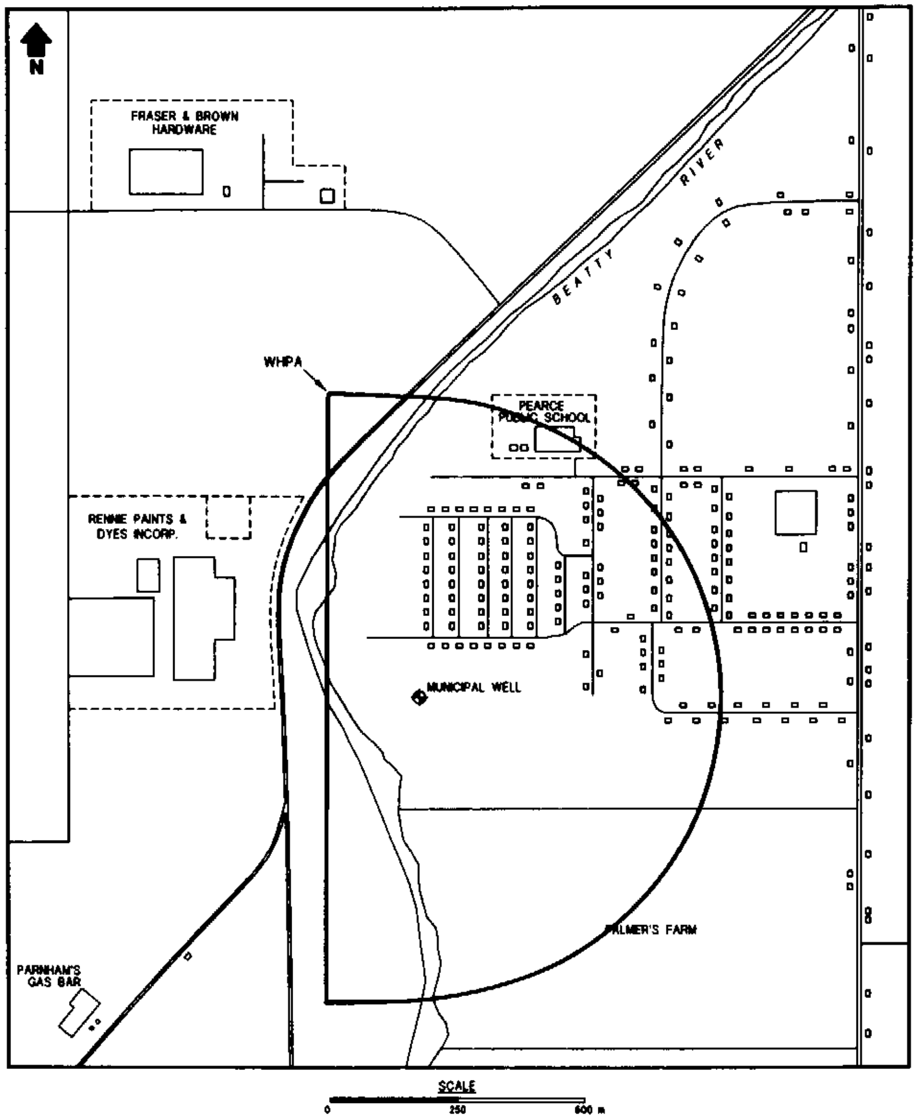

Figure 2 *Wellhead protection area for the community of Beatty, based on two-dimensional analytical WHPA model.*

Table 2 Commonly used models for wellhead protection area delineation.

MODEL	TYPE	DEVELOPER	COMMENTS
FLOWPATH	numerical	Waterloo Hydrogeologic Inc.	2-D, flow and pathlines
VISUAL MODFLOW	numerical	Waterloo Hydrogeologic Inc., USGS	3-D, flow and pathlines
WHPA	analytical, numerical	U.S. EPA	2-D, analytical: flow and pathlines; numerical: pathlines only
GWPATH	numerical	Illinois State Water Survey	2-D, pathlines only
QUICKFLOW	semi-analytical	Geragthy & Miller Inc.	2-D, flow and pathlines

that is situated within an area of alluvial gravel with a hydraulic conductivity of 10^{-5} $cm \cdot s^{-1}$ and a thickness of 10 m.

The ground-water flow conditions were simulated in this relatively simple hydrogeological setting using 1) the two-dimensional WHPA model, 2) the numerical two-dimensional model FLOWPATH, and 3) the fully three-dimensional numerical model VISUAL MODFLOW.

Two-Dimensional Analytical WHPA Model

WHPA is a modular semi-analytical ground-water flow model developed by the U.S. EPA's Office of Groundwater Protection (currently, the Office of Groundwater and Drinking Water) primarily to assist state and local technical staff with WHPA delineation. The WHPA solves analytical equations for two-dimensional flow to a well under various hydrological conditions. The WHPA model contains independent modules such as MWCAP (Well Capture Zone) GPTRAC (General Particle Tracking) and MONTEC (Uncertainty Analysis).

The modelling of the case study involves rotating the model domain such that it best reflects regional ground-water flow, and such that the orientation of the river can be simulated. The WHPA resulting from this relatively quick simulation is shown in Figure 2. The figure suggests that all ground-water path lines captured by the municipal well originate on the east side of the river, and that the river contributes a substantial amount of water to the well. Based on this capture zone, it appears that ground-water protection efforts should be focussed on the area on the east side of the river. Industries on the west side of the river do not require any further attention. Sampling of the water well for bacteria alone is unsatisfactory considering that the major impacts on ground-water in the capture zone include septic system effluent and pesticides and fertilizers associated with agricultural land in the south.

Two-Dimensional Numerical FLOWPATH Model

Ground-water flow and the wellhead capture zone were as simulated using FLOWPATH Version 5.11 (Franz and Guiguer, 1989). FLOWPATH is a two-dimensional steady-state ground-water flow model based on the finite-difference method. The model can simulate horizontal ground-water flow in heterogeneous, anisotrophic, confined/unconfined and leaky aquifers. It can handle withdrawal and injection of water at multiple wells, contaminant particle tracking and capture zones (WHPA).

Initially, FLOWPATH was calibrated to reflect the physical conditions described above. This was achieved by selecting appropriate boundary conditions along the edges of the model domain and by assigning a leakage factor to the river bed. The leakage factor assumes that a limited rate of ground-water flow is drawn from the river; this rate is simply based on Darcy's Law, and is in relation to the hydraulic conductivity of the river bed and the hydraulic-head difference between the water level in the river and the head in the underlying aquifer.

In contrast to the analytical solution discussed above, the FLOWPATH model results (Fig. 3) now indicate that the capture zone extends significantly to the north, following the Beatty River, and to the south within the agricultural land. Due to the added capability of the FLOWPATH model to simulate limited leakage from the river bed, the FLOWPATH model is more accurate than the WHPA modelling package in this situation. Based on this capture zone, it appears that ground-water protection efforts should be focussed on the area on the east side of the river and to the north and south. Industries on the west side of the river do not require any further attention. Sampling of the water well for bacteria alone would not be sat-

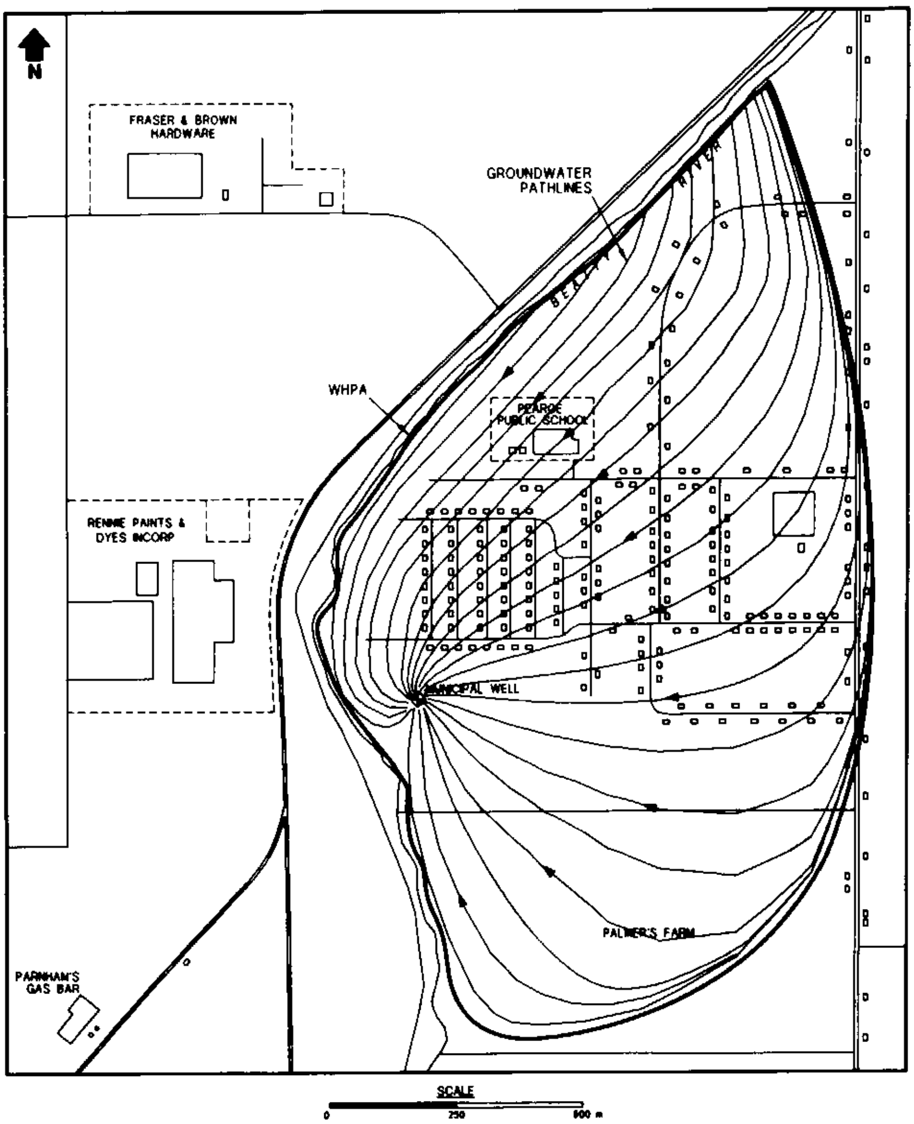

Figure 3 *Wellhead protection area based on two-dimensional numerical FLOWPATH model.*

isfactory, considering the major impact on ground-water in the capture zone would include both septic system effluent and agricultural chemicals, including pesticides and fertilizers.

Three-Dimensional Numerical VISUAL MODFLOW Model

As a final step in the comparison, a fully three-dimensional model is used to simulate the three-dimensional ground-water flow and contaminant migration using particle tracking. VISUAL MODFLOW Version 1.1 (Guiguer and Franz, 1995) is a fully integrated modelling platform which unites the USGS's MODFLOW and MODPATH in a graphical modelling environment. Ground-water flow within the aquifer is simulated using a block-centred finite-difference approach. Layers can be simulated as confined, unconfined or a combination of both. Flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains and flow through riverbeds, can also be simulated.

Using MODFLOW, it is possible to explicitly represent the alluvial sand and gravel overlying the aquifer near the river. The results of this simulation reveal that a significant area on the west side of the river contributes to the water pumped at the well, and, therefore, should be protected (Fig. 4). This capture zone configuration shows that ground-water protection efforts should be focussed on the area on the west and east side of the river. Industries on the west side of the river, specifically the Rennie Paints and Dyes Inc. plant, require further attention considering the capture zone now includes this property. It is important to note that both the analytical and numerical 2-D approaches failed to identify this area. Sampling of the water well for bacteria would not be satisfactory, considering the major impacts on ground-water in the capture zone would include septic system effluent and industrial chemicals, including carcinogenic volatile organic compounds (VOCs). Thus, the present ground-water monitoring and sampling program is inadequate, and additional chemicals may be present in the ground water which pose a significant risk to human health.

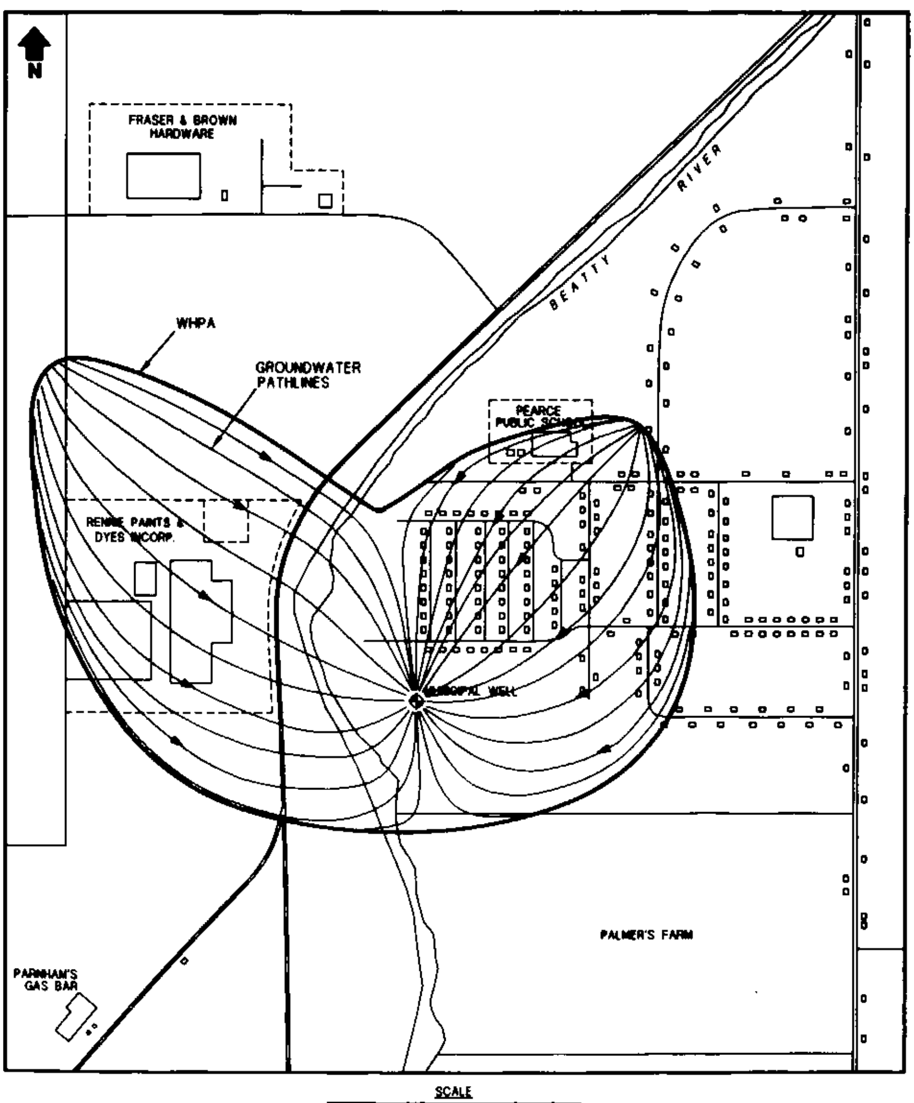

Figure 4 *Wellhead protection area based on three-dimensional numerical visual MODFLOW model.*

DISCUSSION

Canada currently does not have mandatory national guidelines or regulations for the implementation of wellhead protection programs. As a result, communities in urbanized areas without wellhead protection programs will continue to be faced with the difficult and costly task of finding alternative drinking-water sources due to ground-water contamination of their municipal water wells. Many chemicals affecting the ground-water supplies are known carcinogens. Coupled with the lack of effective remediation technologies for removing the contaminants from the deep subsurface, contaminated aquifers will remain non-potable for potentially hundreds of years.

This paper has demonstrated that the choice of model may result in significant differences in WHPA delineation. Two-dimensional analytical, two-dimensional numerical, and three-dimensional numerical models have been used to simulate a hypothetical, but realistic, hydrogeological setting where a municipal pumping well is located near a river. Due to the three-dimensional nature of the hypothetical setting, the three-dimensional numerical model was able to describe the ground-water flow pattern near the stream accurately, while the two-dimensional analytical and numerical models had to use approximations in order to idealize the hypothetical setting. The approximations involved the simulation of the shallow river bed as a fully penetrating feature, and the partially penetrating well was simulated as a fully penetrating well. By definition, there are no vertical gradients in the two-dimensional model (*i.e.*, the model is a plan view model) and, therefore, the two-dimensional models were unable to represent the vertical flow components near the river. The three-dimensional model shows that a significant portion (approximately 40%) of the pumped water is withdrawn from an area on the opposite side of the stream; thus, this area should be protected as part of the WHPA. The two-dimensional models failed to identify this area on the opposite side of the river.

The use of numerical models, and specifically three-dimensional models, is only possible if sufficient data are available to develop a valid conceptual model and to properly calibrate the analytical or numerical model. It is important to properly characterize the hydrogeological system in the field using monitoring wells and appropriate tests (*e.g.*, pumping tests). The level of effort in characterizing and modelling a well or wellfield should be in proportion to the potential risks associated with over- or under-protecting the zone of capture. For example, near industrial facilities it is cost-effective in the long run to establish an accurate WHPA in order to 1) minimize risks of contamination and 2) minimize the required monitoring effort by focussing on the potential sources that really present a risk to the water supply.

The use of simple delineation methods, such as fixed radius or calculated radius, has not been discussed herein because the WHPAs illustrated in this paper have rather complex shapes, despite a relatively simple hydrogeological setting. Such simplistic methods are inappropriate unless they are applied in a highly conservative (*i.e.*, over-protective) manner.

REFERENCES

Anderson, M.P. and Woessner, W.W., 1992, Applied Groundwater Modelling: Academic Press, New York, 256 p.

Bear, J., Beljin, M.S. and Ross, R.R., 1992, Fundamentals of groundwater modeling: EPA-540/S-92-005, 11 p.

Beck, P., in press, Ground-water and Soil Remediation Techniques, *in* Eyles, N., ed., Environmental Geology of Urban Areas: Geological Association of Canada, St. John's, in press.

Cherry, J.A., 1987, Groundwater occurrence and contamination in Canada, *in* Healy, M.C. and Wallace, R.R., eds., Canadian Aquatic Resources: Canadian Bulletin of Fisheries and Aquatic Science, v. 215. p. 387-426.

Cleary, T.C.B.F. and Cleary, R.W., 1991, Delineation of wellhead protection areas: theory and practice: Water Science and Technology, v., 24, p. 239-250.

Feenstra, S., in press, Chlorinated Solvents in Urban Ground Waters, *in* Eyles, N., ed., Environmental Geology of Urban Areas: Geological Association of Canada, St. John's, in press.

Franz, T. and Guiguer, N., 1989-1995, FLOWPATH Version 5.11: Steady state two-dimensional horizontal aquifer simulation model: Waterloo Hydrogeologic Software.

Guiguer, N. and Franz, T., 1995, VISUAL MODFLOW, The integrated modelling environment for MODFLOW and MODPATH: Waterloo Hydrogeologic Software.

Hess, P.J. 1986, Groundwater use in Canada, 1981: Environment Canada, Inland Waters Directorate, Bulletin 140, 43 p.

Howard, K.W.F., in press, Impacts of urban development on ground water, *in* Eyles, N., ed., Environmental Geology of Urban Areas: Geological Association of Canada, St. John's, NF, in press.

Howard, K.W.F. and Livingstone, S., in press, Contaminant source audits and groundwater quality assessment, *in* Eyles, N., ed., Environmental Geology of Urban Areas: Geological Association of Canada, St. John's, NF, in press.

Konikow, L.F. and Mercer, J., 1988, Groundwater flow and transport modeling: Journal of Hydrology, v. 100, p. 379-409.

Mercer J. and Faust, C.R., 1980, Groundwater modeling: applications: Ground Water, v. 18, p. 486-497.

United States Environmental Protection Agency, 1987, Guidelines for delineation of wellhead protection areas: Office of Groundwater Protection, Washington, DC, EPA 440/6-87/010, 98 p.

United States Environmental Protection Agency, 1993, Wellhead Protection: A Guide for Small Communities: Seminar Publication EPA/625/R-93-002, 406 p.

United States Environmental Protection Agency, 1994, Groundwater and Wellhead Protection: Office of Research and Development, Office of Water, Washington, DC. EPA/625/R-94/001, 115 p.

Accepted, as revised, January 1996.