2nd International Conference - Water resources and wetlands. 11-13 September, 2014 Tulcea (Romania); Available online at http://www.limnology.ro/water2014/proceedings.html
Editors: Petre Gâştescu ; Włodzimierz Marszelewski ; Petre Bretcan; ISSN: 2285-7923; Pages: 336-343;

INVESTIGATING WELLHEAD PROTECTION AREA (WHPA) ASSESSMENT METHODS, CASE STUDY: BEYZA-ZARGHAN DRINKING WELLS

Morteza Mojarrad*, Gholam Reza Rakhshandehrou, Ramtin Monadi, Mehrdad Ghorbani Musellu
Department of Civil & Environmental Engineering, Shiraz University, Iran.
Zand Street, Shiraz, Iran, Postal Code: 7134851156, Tel.: +98-7116287505.

Abstract
In recent decades, demand for drinking water in agriculture and industry zones in Iran has grown considerably, partly due to rapid population growth, urbanization, and economic developments. Increase in polluting industries accompanied by arid and semi-arid environment and low rainfall has escalated surface and groundwater pollutions. In Fars province, especially in Zarghan plain, the breadth and diversity of various industries, both large and small, such as oil refineries and petrochemical plants is significant. Most existing wastewater treatment plants don't have good performances; therefore, significant contamination enters Zarghan aquifer. In this study, hydraulic and contaminant transport in Beyza- Zarghan aquifer has been modeled numerically utilizing PMWIN. After calibration and verification of the model, flow quality and quantity in the aquifer was investigated. Point and regional WellHead Protection Areas (WHPA) were studied via three methods; calculated fixed radii, simplified variable shapes, and numerical software methods. Point WHPA for a collection of wells was determined based on importance, water usage, and conditions of existing pollutants. Regional WHPA was determined in populated zones of the plain such as Zarghan City and the adjacent karst aquifer. Results showed different extents for WHPAs by each methods (up to 23 km) need for further investigation and remedial considerations in this industrial plain. Also, numerical software results are more rational and accurate in comparison between these three methods.

Keywords: Groundwater, WHPA, Water Resources, PMWIN, Contaminate Transport.

1. INTRODUCTION

Nowadays, preservation of groundwater, one of the primary sources of drinking water in cities, remains as a major concern for regional water resource organizations and water and wastewater companies around the world. The risk on water contamination of wells is expected to increase, when the dedicated protection areas around the wells decrease. On the other hand, using larger areas can be costly and impractical. In this regard, accurate calculation of optimum Well Head Protection Area (WHPA) using scientific principal can minimize both the risk of water contamination of wells and the costs (Alizadeh,. 2001).

In order to preserve aquifers against contamination, it is essential to exert limitations on current and future land use, prevent well over-discharge, and secure well boundaries. it's neither economically nor socially acceptable to ban water discharge in an aquifer zone which used for various applications. Therefore, in determination of the required control level of groundwater quality, it is most logical and cost-effective to use the natural attenuation capacity in vadose zone instead of imposing restrictions to land use and well's water discharge. Land use restrictions can then be only limited to areas which are most susceptible to pollution (US EPA, 1987,1993)

Thus, the WHPA and the protective radius around aquifers should be determined based on the region's exposure to pollution. Groundwater contamination risk could then be considered as a measure to regulate industrial activities in an aquifer region or which activities must be hindered to prevent groundwater pollution (US EPA, 1987,1993).

In scientific references, WHPA, also referred as "Capture Zone", "sanitary zone", or "Zone of Contribution", is a superficial or underground recharge area around a well which supplies groundwater while pumping. These areas provide a route for contamination to pass through and result in water pollution.

In this study,WHPA calculated and compared by three methods including Calculated Fixed Radii (CFR), Simplified Variable Shapes (SVS) and Numerical-Software method.

2. LITERATURE REVIEW

Wuolo et al. (1995) took an analytical approach to illustrate the WHPA process for the groundwater and wells in Brooklyn Park, Minnesota, US, through modeling water Level in steady state flow of the aquifer and using groundwater traveling time in Franconia-Ironton-Galesville. They simulated regional flows for the city’s wells using finite element analysis in regional flow. Moreover, they employed Single Layer Analytic Element Model (SLAEM) to develop and calibrate separate models. Then each of these separate models was combined together using the Multi-Layer Analytic Element Model (MLAEM). As a consequence, WHPA and groundwater traveling time for present wells were calculated using inverse particle tracking (Wuolo et al. 1995).

Livingstone et al. (1995) described terms and methods in WHPA. They provided a hypothetical case study to explain different WHPA approaches. This case study supported that a 3D numerical model would result in a more accurate data compared to a 2D numerical or analytical model. Lastly, possible sources of errors and limitations of the study were discussed (Livingstone et al. 1995)

Barnett et al. (1997) aimed to define the WHPA and contaminant sources in a particular place using GIS software. In this laboratory project, 25 wells were studied for determination of WPHA. A GIS layer containing limited groups of land uses was created for every well using the Ortho-Photos. In this research, basic maps generated to investigate groundwater at first and afterwards generated GIS layer updated with the basic maps. Eventually, using the final GIS layer, potential menacing sources of potable water were specified in the region (Barnett et al. 1997).

There are various methods for determination of WHPA. Miller et al. (2003) created spatial WHPA data using GIS software based on the fixed radius method and compered the calculated capture zone, derived from this approach, with other complicated ones. Results of this study supported that regional health departments could merge present official WHPA and calculated fixed radii method areas, considering land use and also with an emphasis on the groundwater movement areas in 6 months and one year periods. They suggested utilizing determined fix radii as an initial step towards preserving groundwater quality when facing lack of time, financial assets, and technical expertise (Miller et al. 2003)

3. METHODOLOGY

Groundwater and porous media are similar in terms of the governing equations. This groundwater flow depends on the characteristics of the porous material, fluid properties, and flow parameters particularly the hydraulic gradient. The dynamic relation between these parameters can be described as partial differential equations considering the flow domain. These equations are developed by combining Darcy’s law and Continuity equation. By determining the dimensions of aquifer, boundary conditions, initial conditions, and hydraulic properties, the system of equations can be solved to find the hydraulic head at different points (Chiang & Kinzelbach, 2001).

These equations are usually solved by using numerical methods. Finite difference and finite element methods are particularly notable due to their relative simplicity and flexibility among other approaches. Continuous groundwater equation systems are replaced with a set of discrete spatial and temporal points by means of Finite Difference Method (FDM). Along this process, the head values at different points and times can be calculated through a system of linear algebraic differential equations in which mathematical difference rules are utilized to solve the equations (Chiang & Kinzelbach, 2001)..

Processing ModFlow is a powerful and multi-sectional software to simulate groundwater flow and contaminants which is using FDM. The model involves some different sub-models to evaluate groundwater in terms of hydraulic aspects and contaminant transport. They can also be used to calibrate and verify the groundwater simulation. Some of these sub-models are: MODFLOW, MOC3D, MT3D, MT3DMS, PEST, UCODE, PMPATH.

4. MATERIALS AND METHODS

To simulate the Zarghan-Beiza aquifer, the conceptual model was created using the regional water organization data for every modeling step. The next geometrical design steps included specifying initial and boundary conditions, sink and source cells values, hydrodynamic coefficients, water level fluctuation, and time steps.

To solve the governing groundwater differential equation using the numerical Finite-Difference method, the plain area was divided into smaller blocks known as cells. The model used a cell size of 650x745 (meter) and contained 100 rows and columns to generate the mesh network of the Zarghan-Beyza aquifer. In addition, only a single layer was included in the model since the aquifer is unconfined. The total and active cells numbers were 10000 and 3680 respectively with an area of 1783 km^2.The aquifer was assumed to be unconfined and the calculations were based on a steady state assumption. Inputs, however, were entered as a one year interval in the average form since the well's discharge data exist in the annual average form. Furthermore, output data was acquired based on the data from the previous year in the stable form. Cell's sink and source can be caused by 5 main categories: Operating wells (sink), precipitation (Source), agricultural returning water (source), evaporation (sink), river (sink or source). The sink or source effect of rivers was neglected in this study since there is no river in the target area. According to the updated water resource data of the aquifer, there had been 4858 active wells (1213 deep wells and 3645 shallow wells) and 14 inactive and abandoned wells. In the alluvium area, there were 118 qanat networks and 13 water springs. In hard formations of the targeted area, there are 38 wells (37 active and one inactive wells) and 138 water springs. The simulated model doesn't distinguish between wells, qanats, or water spring. Therefore, they were all considered and referred to as wells in this study. Based on the data collected by the Fars Province Meteorology Organization, 5 rain station data were entered into the Surfer software as an average data in millimeters. Then rain contours were drawn by Surfer software. In 2009 Kim and Jang performed a research on the agricultural returning water of rice farms. They found that approximately about 25% of the agricultural water returns to the ground as groundwater. Thus, 25% of the well discharge values were considered as a recharge in the model to account for the return of the agriculturally used water to the ground. Due to the lack of having recorded evaporation data, It was not considered as a separate parameter in this study and was applied as a reduction factor to the rainfall values (about 60% in plain and 80% in mountainous region). Precipitation, returning water, and evaporation were applied to the corresponding cells as a recharge values. The aquifer boundaries were defined as non-water flow boundaries the areas where the aquifer has contact with adjacent aquifer were considered as general head boundaries. By reviewing the topographical maps, basin's geological maps, and satellite images of the whole region, the exact location of the linking boundaries, basin's elevation, and non-permeable formation were defined as non-water flow boundaries.

In this simulation, water-years 2006, 2007, 2008 (October 2006 to September 2009) were selected for calibration. Plain sink and source data (wells, rivers, precipitation and returning water) and also water exchange by adjacent boundaries in these years as an average form were given to the software. Aslo, Study area was divided into 15 different regions. The calibration, verification and prediction processes were performed for each of these regions based on the available geological maps for these areas. Moreover, Groundwater level at the beginning and the end of the time period in the observation wells were used so as to help the calibration process and initial estimation of the hydraulic conductivity coefficient. Table 1 and figure 1 show the hydraulic conductivity coefficients obtained from the calibration process ($K_x = K_y = 10K_z$).

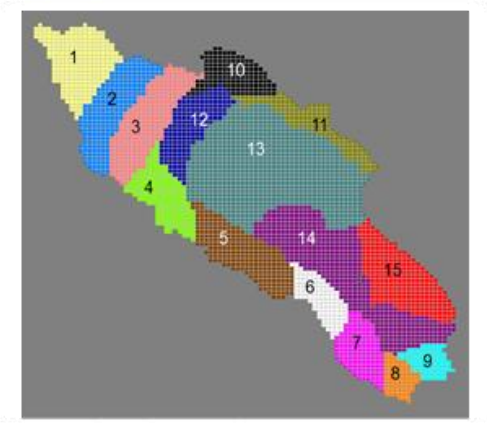

Fig.1 Mesh network of Beyza-Zarghan in order hydraulic conductivity calibration

K_x (m/day)	K_y (m/day)	K_z (m/day)	Zone
1600	1600	160	**1**
900	900	90	**2**
700	700	70	**3**
1250	1250	125	**4**
900	900	90	**5**
1100	1100	110	**6**
1600	1600	160	**7**
1400	1400	140	**8**
700	700	70	**9**
900	900	90	**10**
1500	1500	150	**11**
600	600	60	**12**
250	250	25	**13**
180	180	18	**14**
75	75	7.5	**15**

Table.1 Hydraulic conductivity coefficient calculated, according to model calibration

Figure 2, 3, and 4 show the hydraulic conductivity calibration results. The accuracy of the simulation results can be confirmed by comparing the location of the observed heads in respect to the line on this figure. As it is demonstrated in Table 1, well number 10 has shown the most accurate value while the most inaccurate result was obtained by well number 27. The Root Mean Square Deviation (RMSD) value in calibration years was found to be 0.723, 0.804, 0.678 (meter) which are acceptable based on the amounts of observed and calculated heads that approximately is about 1600 meter. RMSD is a statistical quantity that determines the amount of error in a varying quantity, especially used when error values are either positive or negative. RMSD values can be calculated using the following formula:

$$X_{RMS} = \sqrt{\frac{1}{n}(x_1^2 + x_2^2 + \cdots + x_n^2)}$$ Equation (4-1)

Where n is the number of observed wells and x_1 ،x_2 … x_n are the differences between calculated and observed well head values in wells 1-n.

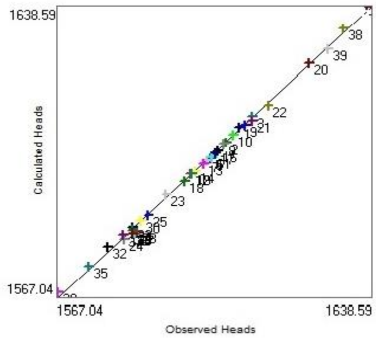

Figure 2 Hydraulic conductivity calibration results in 2006-2007

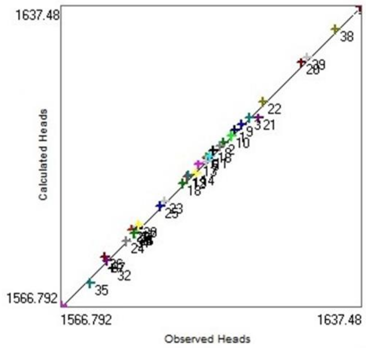

Figure 3 Hydraulic conductivity verification results in 2007-2008

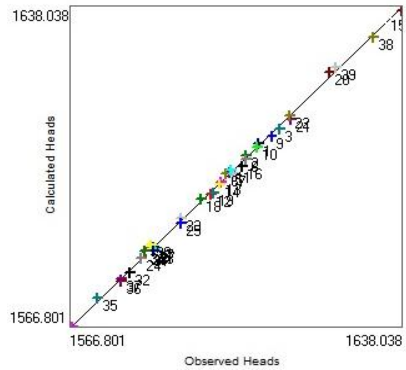

Figure 4 Hydraulic conductivity verification results in 2008-2009

In the calibration process, the difference between the observed and the calculated head values were expected to be negligible. The results found from the verification process in the following year supported the accuracy of the model. Therefore, the plain data obtained from year 2009 was inputted in the software and the results of the calibration process were used to verify the data. The inputted values included the following: well discharge values, river discharge, rainfall values, water exchange in the head boundary, the increase in the number of wells, the number of drying wells, and the agricultural returning water of each year. The verification results based on hydraulic conductivity are shown in Figure 5.

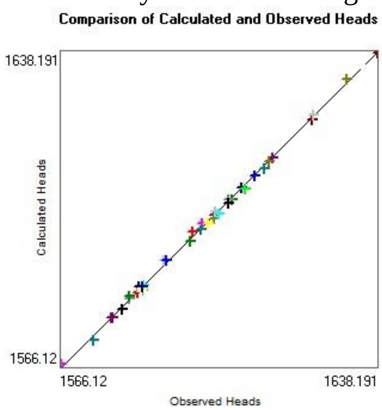

Figure 5 Hydraulic conductivity verification results in 2009-2010

According to the previous diagrams, the root mean square deviation (RMSD) value for 2009 water-year was 0.610 (meter). Considering amounts of observed and calculated heads (1600 meter) it is acceptable.

5. RESULTS AND DISSCUSION

Based on the significant changes in groundwater quality of Beiza-Zarghan plain, it is essential to pay close attention to the WHPA of each well to determine potential sources of contamination that influence the well's water quality. Once the contamination sources around wells are identified and distinguished from the rest, future contaminations may be prevented by halting water-discharge from the identified areas. In addition, knowing the direction of groundwater flow is helpful to determine construction points of new wells. In conclusion, groundwater direction map can be used to obtain a better water quality and minimize pollution. The corresponding capture zone should be calculated for the wells to optimize and determine the WHPA.

5.1. WHPA assessment by software-modeling method

PMWIN 5.1.7, one of the best software for quality and quantity groundwater simulation, is used For WHPA assessment by this method. Precipitation as an average value in whole statistical period and other parameters such as operating well's situation according to the last year of whole statistical period were assigned to simulate the model. The obtained model can calculate the direction and velocity of groundwater flow in different areas of the plain. Figure 6 shows the WHPA for Doshmanziary City, Malusjan industrial zone, and Shiraz refinery in Beiza-Zarghan plain. As demonstrated by figure 6-1, the WHPA for a well, which is nearby Shiraz Refinery, encompasses an extensive area which is almost 19 km^2 (the length is about 23 km). Therefore, in case of having groundwater pollution in this area, the cause of contamination source should be investigated through the corresponding WHPA. In contrast, the wellhead protection areas in Doshmanziary City and Malusijan Industrial zones are 0.97 Km^2 and 1.9 Km^2 respectively which involve smaller areas (2.5 km and 1.6 km).

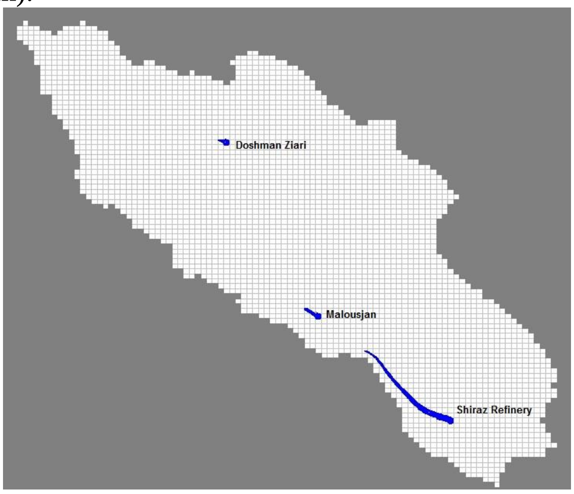

Figure 6 Wellhead protection area by numerical-software modeling

5.2. WHPA assessment by Calculated Fixed Radii (CFR) method

For WHPA delineation by this method, a circle based on determined TOT should be drawn. The circle radius is depends on volume of water which draw down in well in a specific time. Include data including: well's pumping rate, groundwater flow parameters such as porosity, hydraulic conductivity and time period. Time period should be more enough to eliminate pollution before reaching the well.

Parameter values for WHPA calculating by CFR which applied to single wells and industrial zones are in table 2. Calculated WHPA is in figure 7.

Qt=nHπr

Q= well pumping rate
n= porosity
H= well depth
t= specified time for WHPA
r= Fixed Radii for WHPA

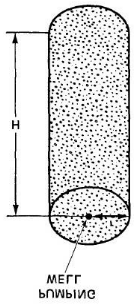

Table.2 WHPA by CFR for single wells

Location	r (m)	t (d)	H (m)	n	Q (m^3/h)
Shiraz Refinery	600	365	15	0.25	450
Malousjan industrial well	300	365	20	0.25	160
Doshman Zirai well	150	365	40	0.25	88

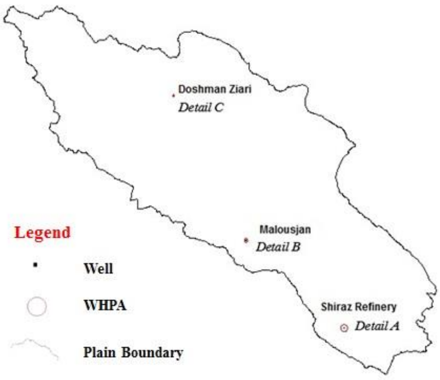

Fig.7 WHPA by CFR for single wells

5.3. WHPA assessment by Simplified Variable Shapes (SVS) method

In the simplified variable shapes methods, "Standardized forms" are generated using analytical models, with both flow boundaries and TOT used as criteria. This method attempts to simplify implementation by selecting a few representative shapes from the large array of potential possibilities. The appropriate "standardized form" is then selected for hydrogeologic and pumping conditions matching or similar to those found at the wellhead. The standardized form is then oriented around the well according to groundwater flow patterns. The variable shapes are calculated by first computing the distance to down gradient and lateral extents of the groundwater flow boundaries around a pumping well (i.e., the ZOC), and then using a TOT criterion to calculate the upgradient extent. Standardized forms for various criteria are calculated for different sets of hydrogeologic conditions. Input data for standardized shapes include basic hydrogeologic parameters and well pumping rates.

The uniform flow equations are used to calculate the zone of contribution to a pumping well. These equation describe the ZOC for a confined, porous media aquifer under uniform flow and steady state conditions. For unconfined aquifers, thickness is replaced by the uniform saturated aquifer thickness, provided that the drawdown at the well is small in relation to the aquifer thickness. These equations do not determine the upgradient limits of the ZOC. Therefore, another technique is necessary to close the upgradient boundary of the ZOC. The Southern Water Authority in England utilizes a TOT equation.

The distance (r_x) defining the upgradient extent of the ZOC is determined by substituting a 50-day TOT criterion for t_x and solving by trial and error the equation

$$t_x = \frac{S}{V}[\pm(r_x - r_w) + Z\ln\frac{(Z\pm r_w)}{(Z\pm r_x)}$$

$$Z = \frac{Q}{2\pi kbi}$$

V= groundwater flow velocity

t_x= travel time from point x to pumping well
S= specific yield or storativity
K= Hydraulic conductivity
b= saturated thickness
i= gradient
r_w= well radius
r_x= distance from point x to pumping well
+ or - = whether point x is upgradient (=) or downgradient (-) from pumping well.
By using Beyza-Zarghan data which are given in table 3, WHPA are calculated. WHPAs are shown in figure 8.

Table.3 WHPA for single wells by SVS

Location	r_x(m)	Q (m^3/h)	i	b (m)	K (m/d)	r_w (m)	t_x(d)	S
Shiraz Refinery	10000	480	0.09	15	200	1	365	0.59
Malousjan industrial zone	5000	160	0.08	20	150	1	365	0.59
Doshman Ziari	2500	88	0.02	40	140	1	365	0.59

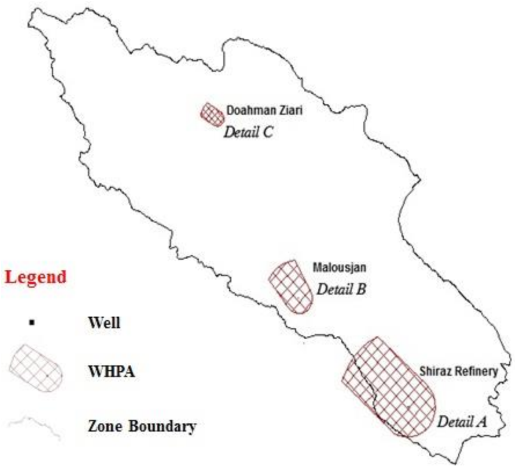

Fig.8 WHPA for single wells by SVS

6. CONCLUSION

After modeling in steady state, a model presented which can predict groundwater direction and flow velocity in acceptable range by unsing input data. Calibration and verification results show accuracy of the model (0.723, 0.804, 0.678, and 0.610).

Calibration results show that hydraulic conductivity reduce from north-west to south-east (1670 m/d to 85 m/d). This reducing is caused by aggregate and kinds of zones which is mountainous or aquifer, seemingly.

Hydraulic head contours, hydraulic conductivity values in different zones, and groundwater flow direction match with Kor-Sivand rever existence in Beyza-Zarghan boundary (It seems that, the river role as powerful drain).

WHPA length for wells which exist in Shiraz refinery, Malousjan Industrial zone, and Doshman Ziari are 23, 2.5, and 1.6 kilometer respectively by software modeling method.

WHPA length for wells which exist in Shiraz refinery, Malousjan Industrial zone, and Doshman Ziari are 0.6, 0.3, and 0.15 kilometer respectively by Calculated Fixed Radii method.

WHPA length for wells which exist in Shiraz refinery, Malousjan Industrial zone, and Doshman Ziari are 10, 5, and 2.5 kilometer respectively by Simplified Varible Shapes method.

With respect to all methods figures and disadvantages of CFR and SVS methods, It seems that software modeling method's results are more reliable (in CFR method there is no difference between upstream and downstream and the WHPA is a circle, in SVS method part of elliptical WHPA drawn out of Beyza-Zarghan boundary which has different parameters values).

REFERENCES

Alizadeh, A. 2001, *applied hydrology principles*, Ferdosi university, Mashhad, Iran [in Persian]

Barnett, Ch., Zhou, Y., Vance, S., and Fulcher, C. 1997, Wellhead protection area delineation for identifying potential contamination sources, http://prceedings.esri.com/library/userconf/proc95/to150/p121.html.

Chiang, W.H. and Kinzelbach, W. 2001. 3D-Groundwater Modeling with PMWIN, New York, Springer-Verlag, pp. 333.

Livingstone, S., Franz, T., and Guiger, N. 1995, Managing ground water resources using wellhead protection, Geosciences Canada, Vol. 22, No.4, pp.121-128.

Miller, C., Chudek, P., Babcock, S. 2003, A comparison of wellhead protection area delineation methods for public drinking water systems in Whatcom County, Washington, *Environmental Health*, Vol. 66, No.2, pp.17-27.

US EPA, 1987,1993, *Guidelines for delineation of wellhead protection areas*, Report no. EPA-440/5-93-001.

Wuolo, R.W., Dahlstrom, D.J. and Fairbrother, M.D. 1995. Wellhead protection area delineation using the analytic element method of ground water modeling. *Groundwater*. vol. 33, no.1, pp.71-83.