United States
Environmental Protection Agency

Office of Water
(4606)

EPA 816-R-98-021
December 1998

EPA

LITERATURE REVIEW OF METHODS FOR DELINEATING WELLHEAD PROTECTION AREAS

LITERATURE REVIEW OF METHODS FOR DELINEATING WELLHEAD PROTECTION AREAS

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

Page

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

EXECUTIVE SUMMARY

This document supports both the Wellhead Protection Program and the Source Water Protection Program. This document presents the results of a bibliographic search of the technical literature for publications, papers and other documents addressing the technical aspects of wellhead protection area delineation. The document is a companion to the review of technical literature addressing delineation of surface-water source water protection areas found in Appendix 2 of *State Methods for Delineating Source Water Protection Areas for Surface Water Supplied Sources of Drinking Water*.

INTRODUCTION

This document presents the results of a bibliographic search of the technical literature for publications, papers, and other documents addressing the technical aspects of wellhead protection area delineation. The literature summaries appear in the following sections: theory, case studies, land use/mapping/geographic information systems (GIS), analytical, numerical/modeling, hydrogeologic/geologic analysis, and miscellaneous. Some summaries appear in more than one section.

The literature search methodology for compiling information on Delineating Wellhead Protection Areas was as follows:

1. Conducted an online literature search using the keywords "wellhead protection (and/or) delineation." The following databases were searched:
   - a) AGRICOLA
   - b) AppSciTechAbs
   - c) BASICBIOSIS
   - d) BiolAgrIndex
   - e) Article1st
   - f) WORLDCAT
   - g) GenSciAbstract
   - h) DISS
   - i) ERIC
   - j) GEOBASE
   - k) GEOREF (2 different versions)
   - l) PERABS
   - m) PapersFirst
   - n) ReadGuideAbs
   - o) NewsAbs
   - p) EBSCO
   - q) DIALOG
   - r) Journal of Water Resources Database
2. Queried Environmental Protection Agency (EPA) Regional specialists and specialists at EPA's Robert S. Kerr Environmental Research Center/Office of Research and Development and EPA's National Exposure Research Laboratory/Office of Research and Development.
3. Searched the world-wide web using keyword searches of environmental abstracts, "wellhead protection," and "wellhead protection delineation." From this, the University of Toronto homepage was accessed and the Environmental and Pollution abstracts database was searched.

LITERATURE SUMMARIES

Theory

Blandford, Neil T. 1990. Semi-analytical model for the delineation of wellhead protection areas: Version 2.0. Report prepared for U.S. EPA Office of Ground Water Protection, 62 pp.

Wellhead Protection Area (WHPA) is a modular, semi-analytical ground water flow model designed to assist State and local technical staff with the task of WHPA delineation. The WHPA model consists of four independent computational modules that may be used to delineate capture zones. Three of the modules contain semi-analytical capture zone solutions; they are applicable to homogeneous aquifers that exhibit two-dimensional, steady ground water flow in an areal plane. Barrier or stream flow conditions which exist over the entire aquifer depth may be simulated. Available aquifer types include confined, leaky-confined, and unconfined with areal recharge. One of the modules contains a Monte Carlo module that provides for uncertainty analysis capability. The fourth module is a particle tracking module that may be used as a postprocessor for two-dimensional numerical models of ground water flow.

Caswell, B. 1992. Protecting fractured-bedrock wells. Water Well Journal. v. 46, no. 5, pp. 42-45.

Ground water protection in crystalline bedrock terrain is complex due to the unpredictability of water-bearing fractures. Pump tests of wells drilled in fractured crystalline bedrock reveal a zone of depressed bedrock which is elongated in the direction of major water-bearing fractures. Zones of protection are hard to assign because of natural anisotropic and heterogeneous characteristics. Travel times of ground water are dependent on direction of a fracture and on unconsolidated deposits for ground water storage. According to field investigations, an arbitrary radius will not protect high-yielding wells in fractured crystalline bedrock. Certain levels of protection may need to be established based on protective zones within the contributing area. Outer zones may limit density and the type of development while the inner zones may exclude any development. Sub-zones are recommended to be elliptical and oriented NNW-SSE along the major water-bearing fracture zones.

Cleary, T.C. and R.W. Cleary. 1991. Delineation of wellhead protection areas: theory and practice. Water, Science, and Technology. v. 24, no. 11, pp. 239-250.

The Wellhead Protection Program, a preventative approach in ground water protection, has been established to protect ground water within the WHPA of a well. Sources of potential pollution within the delineated WHPA are defined as threats and need to be monitored for safe operation of a wellfield. A conceptual standard, assigned a numeric value called the criterion threshold, serves as the basis for the WHPA delineation. The simplest method used to define a WHPA is the fixed radius method. With increasing sophistication, a WHPA may be defined by hydrogeological mapping and by analytical and numerical modeling. FLOWPATH and other models which simulate the effects of different hydrogeological scenarios were used to demonstrate how subtle changes in field conditions may have large impacts on shape, size, and orientation of the WHPAs.

Lennox, J.B., C.F. Adams, and T.V. Chaplik. 1990. Overview of a wellhead protection program. From the determination of recharge areas to the development of aquifer protection regulations. Journal of English Water Works Association. v. 104, no. 4, pp. 238-247.

The public water utility has requested that the town of Cheshire, Connecticut implement a multi-faceted regulatory program which would increase protection of the aquifer. Of the 21,200 residents, 82 percent are served by the public water supply within Cheshire. Numerical modeling, the most accurate way to determine recharge area boundaries, was used to delineate the aquifer recharge area for the water-supply wells. According to the public utility, a technically sound recharge area map and education of both municipal officials and residents are the key elements for convincing a town to adopt a wellhead protection strategy.

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

The terminology and methodologies used in wellhead protection to delineate wellhead protection areas are explained. A hypothetical case study is presented to show different methodologies for delineation and evaluation. This hypothetical study proves that a numerical three-dimensional model provides a more accurate WHPA than a two-dimensional numerical or an analytical model. Delineation errors and potential risks of protecting the WHPA are also discussed.

McElwee, C.D. 1991. Capture zones for simple aquifers. Ground Water GRWAAP. v. 29, no. 4, pp. 587-590.

Analytical expressions to define well capture zones cannot be explicitly solved for the coordinates of the capture zone boundary. An iterative scheme was developed which allows the solution in a timely manner. To cover the entire region of interest, three forms of the analytic solution must be used. A smooth definition of the capture zone requires 100-1,000 intervals along the x-axis. A FORTRAN program was written which works in a variety of computing environments. No user interface is included. If the spacing of wells is not too close, capture zone superposition is expected to be adequate. The program is a good first step in wellhead protection or cleanup scenarios.

Miller, D.W. Principles of ground water protection. 1992. In: ASCE National Conference on Irrigation and Drainage, Baltimore, Maryland, August 2-6, 1992. Publ. ASCE, New York, NY.

A thorough knowledge of ground water flow systems and an understanding of how contaminants migrate through geologic formations leads to successful wellhead protection programs. Once there is a thorough understanding of the mechanics involved, areas of contribution can be mapped and controls, such as limitations on land use, can be imposed.

Reilly, T.E. and D.W. Pollock. 1996. Sources of water to wells for transient cyclic systems. Groundwater. v. 34, no. 6, pp. 979-988.

State agencies are adopting wellhead protection programs. The focus of many of these programs is to protect water supplies by determining the area contributing recharge to the water-supply wells. Another thrust is to specify regulations to minimize contamination of the recharge water by activities at the land surface. Recharge water protection is the focus of this document.

Schleyer, R., G. Milde, and K. Milde. 1992. Wellhead protection zones in Germany: delineation, research and management. Journal of the Institution of Water and Environmental Management. v. 6, no. 3, pp. 303-311.

Germany has much legislation to provide adequate protection of ground water. Up to four wellhead protection zones may be delineated within the recharge area of a well. New scientific data on ground water protection has been obtained in a few areas: (1) interactions of bacteria and viruses in aquifers; (2) organic and inorganic pollutants in soils and aquifer behavior; (3) effects on ground water quality of non-point and point source pollution from hazardous substances; and (4) influences of atmospheric pollutants on ground water quality. New wellhead protection areas should be assigned for both public and private well supplies. Strict requirements should be placed on agriculture that takes place within the catchment areas of drinking water wells. A system should be established for systematically inspecting and observing catchment areas.

Swanson, R.D. 1992. Methods to determine wellhead protection areas for public supply wells in Clark County, Washington. Intergovernmental Resource Center.

Wellhead protection area boundaries can be based on the area of contribution to the well (zone of contribution) or a more arbitrary consideration such as a manually drawn circle around a well. To determine the zone of contribution, the hydrologic and hydrogeologic factors must be considered. A zone of influence is an area where the pumping well influences the water level. The Department of Health in Washington State is responsible for designing and implementing a state wellhead protection program. The Wellhead Policy Advisory Committee and the Wellhead Technical Advisory Committee were established by the Department of Health to assist in assuring that the program is appropriate for conditions in Washington State.

USEPA. 1993. Guidelines for delineation of wellhead protection areas. EPA Report /440-5-93/001, Office of Water, Office of Ground Water Protection, USEPA.

This document is a reprint of the document of the same name, published in 1987 (see below).

USEPA. 1993. Wellhead protection workbook. Report prepared for U.S. EPA Region III Water Management Division, 46 pp.

This is a workbook to help resource managers and residents develop and understand water resource protection programs for their local and regional aquifers. The following four steps of a successful program are discussed: (1) organization of local committee; (2) mapping of ground-water protection areas; (3) identification of existing and potential contamination sources; and

(4) development and implementation of protection strategies. This workbook is to be used in conjunction with the video "The Power to Protect," a 30- minute presentation of successful case studies of ground water protection in three communities. Information, interpretations, and graphics on ground water protection are presented with follow-up exercises, to reinforce the user's understanding of terminology, issues, and applications.

USEPA. 1991. Delineation of wellhead protection areas in fractured rocks. EPA Report /570-9-91/009, Office of Ground Water and Drinking Water, USEPA, 144 pp.

This document provides technical assistance to help address the hydrogeological aspects of the Wellhead Protection Program. Six methods for delineating wellhead protection areas were studied at two sites in Wisconsin to determine which are most appropriate for application to unconfined, fractured-rock aquifers.

USEPA. 1991. Protecting local ground water supplies through wellhead protection. EPA Report /570-09-91/007, Office of Water, USEPA, 18 pp.

This is a user friendly, five-step approach to ground water protection and an excellent resource for community discussion. Mayors, water supply managers, other agency officials, or interested citizens can use it to introduce the wellhead protection program to their communities. It provides an overview of the steps taken in developing a program for wellhead protection starting with forming a team and then delineating the wellhead protection area.

USEPA. 1991. Wellhead protection strategies for confined-aquifer settings. EPA Report /570-9-91/008, Office of Water, USEPA.

This document provides methods for delineating wellhead protection areas for wells or wellfields in confined-aquifer settings. The document also presents approaches for distinguishing between confined and unconfined aquifers; a methodology is presented for determining the degree of aquifer confinement.

USEPA. 1988. Developing a state wellhead protection program: A user's guide to assist state agencies under the Safe Drinking Water Act. EPA Report /440-6-88/003, Office of Ground Water Protection, USEPA, 44 pp.

This technical assistance document shows users how to tailor a wellhead protection program containing the requisite elements. It supplements the June 1987 *Guidance for Applicants for State Wellhead Protection Program Assistance Funds under the Safe Drinking Water Act*, illustrates a range of options from which states can choose, and gives examples of different approaches for developing each specific element of the program. Illustrations and case studies provide additional guidance on how a state can maintain its flexibility in meeting these requirements. The document ends with a one-page road map showing how the submittal can be put together from beginning to end.

USEPA. 1987. Guidelines for delineation of wellhead protection areas. EPA Report /440-6-87/010, Office of Ground Water Protection, USEPA.

This document provides state, local, and tribal water managers assistance in implementing the WHPA provisions of the Safe Drinking Water Act. The basics of contaminant movement and ground water are discussed, as are technical approaches to delineating WHPAs in different hydrogeologic settings.

Wuolo, R.W. Flow modeling for wellhead protection delineation. (Internet download, 1997)

The Minnesota Department of Health administers the management of WHPAs. Detailed information on ground water velocity and direction, aquifer hydraulics, geology, well interference effects, and ground water-surface water interaction is required for delineation of a WHPA. Most ground water models use existing information which can easily be managed by geographic information systems. Model representation of the features is designed to best simulate the various hydrologic conditions; in effect, modeling ground water flow. Calibration improves the match between simulated and observed ground water flow characteristics. The model must also be verified to further test its predictive capabilities, and a sensitivity analysis should be performed to evaluate model uncertainty. Development and use of a ground water model for WHPA delineation is exemplified by the North Dakota County Groundwater Model.

Case Studies

Bailey, Z.C. 1993. Hydrology of the Jackson, Tennessee area and delineation of areas contributing ground water to the Jackson Well Fields. USGS Water-Resources Investigations Report 92-414, 54 pp.

A hydrologic investigation of the Jackson area in Madison County, Tennessee was conducted to provide information for the development of a wellhead protection program for two municipal wellfields. Estimates of hydraulic conductivity for the Memphis Sand range from 80 to 202 ft/d, and for the Fort Pillow Sand, from 68 to 167. Estimates of transmissivity of the Memphis Sand range from 2,700 to 33,000 sq ft/d, and for the Fort Pillow Sand, from 6,700 to 10,050. A finite-difference, ground water flow model was calibrated to hydrologic conditions of April 1989, and was used to simulate hypothetical pumping plans for the North and South Well Fields. More than half the inflow to the system is underflow from the boundaries. Slightly less than half of the inflow is from areal recharge and recharge from streams. About 75% of the discharge from the system is into the streams, lakes, and out of the model areas through a small quantity of ground water underflow. The remaining 25% is lost to pumping. A particle-tracking program was used to delineate areas contributing water to the North and South Well Fields for the calibrated model and the three pumping simulations, and to estimate distances for different times-of-travel to the wells. The size of the area contributing water to the North Well Field, defined by the 5-year time-of-travel capture zone, is about 0.8 by 1.8 miles for the calibrated model and pumping plan 1; 1.1 by 2.0 miles for pumping plan 2; and 1.6 by 2.2 miles for pumping plan 3. The size of the area contributing water to the South Well Field is about 0.8 by 1.4 miles for the calibrated model, 1.6 by 2.2 miles for pumping plans 1 and 3, and 1.1 by 1.7 miles for pumping plan 2.

Barlow, P.M. 1989. Delineation of contributing areas to public supply wells in stratified glacial-drift aquifers. Protecting Ground Water from the Bottom Up: Local Responses to Wellhead Protection. Proceedings of the Conference, October 2-3, 1989, Danvers, Massachusetts. Underground Injection Practices Council, Oklahoma City, Oklahoma, pp. 145-166. 11 fig, 1 tab, 12 ref.

There are several numerical and analytical methods available to delineate contributing areas to public supply wells. Each of these methods uses different levels of computational complexity and requires differing degrees of data specification. Coupling particle tracking algorithms to numerical ground water flow models is a recent advance in analyzing contributing areas. This method was demonstrated on the stratified drift aquifer on Cape Cod, Massachusetts. The results were that: (1) the location of the recharge and discharge areas for the aquifer with respect to the well has a significant effect on the size of the well's contributing area, (2) the pumping rate of the well and the recharge rate of the aquifer has a great effect on the size of the well's contributing area, (3) the determination of a well's contributing area must take into consideration all the wells within an aquifer, and (4) the lithology of the aquifer must be characterized. The modeling produced similar results to the numerical modeling with particle tracking for wells pumping from a thin, single layer, uniform aquifer; it may not be needed to delineate contributing areas in such an aquifer. For conditions encountered in the field, numerical models with particle tracking are still better tools than analytical models. These conditions include thick heterogeneous aquifers in which wells are pumped simultaneously and have complicated boundary conditions. In these conditions, sufficient detail leading to an accurate determination of the land area that contributes water to a well can not be provided by analytical models.

Begey, M.D., M. Cargnelutti, and E. Perastru. 1996. Ground water model for management and remediation of a highly polluted aquifer (organo-chlorine compounds) in an urban area, using radioactive tracers (super(131)I) for hydrodynamic parameters and dispersivity measurements. In: Isotopes in Water Resources Management Vol. 2. Vienna (Austria). International Atomic Energy Agency, pp. 229-248.

Monitoring of pollution caused by TCE leakage from a broken sewage pipeline in an Italian chemical plant utilized a mathematical model developed to evaluate the extent of pollution and to determine which other public wells would become contaminated. Radioactive tracers were used to define wellhead protection areas.

Bogue, Kevin Scott. 1994. Evaluation of wellhead protection models; a case study, Xenia, Ohio. Wright State University. Dayton, Ohio, 121 pp.

Delineation of one year travel time related capture zones was performed using numerical, analytical, and semi-analytical models of a buried valley aquifer, along with stream function programs and particle tracking. The results of each of these methods were used to determine their abilities to delineate wellhead protection areas. The numerical flow model incorporates a three-dimensional steady-state finite-difference solution with leakage to and from streams between the three model layers. The analytical flow model defines two-dimensional transient drawdown surrounding a well in a leaky confined aquifer along with superposition of the regional flow field using the Hantush-Jacob equation. The semi-analytical flow model uses the Theis equation, which

describes two-dimensional, transient drawdown surrounding a well in a fully confined aquifer, and superposition of a regional flow field. The appropriate method to use requires a procedure that takes into account the complexity of the hydrogeology, the amount of hydrogeologic data, and the required accuracy of the results. Minimal data are available for this study. Questions arise as to whether it is more practical to use a time intensive, accurate numerical model, or a less precise method which would save time and money but may not accurately represent the flow system. Abilities of the flow models are determined using the one year capture zones for each method. The results prove that the numerical model more accurately represents the flow system; yet, the semianalytical and analytical models perform adequately in delineating capture zones. The analytical method requires less time and effort than the numerical method. The analytical methods on the other hand, can not be upgraded and improved as additional data are gathered.

Bowker, Joel A. 1993. A preliminary wellhead protection program for the village of Enon, Ohio. Wright State University. Masters Thesis, 189 pp.

To protect its water supply, the village of Enon, Ohio is developing a wellhead protection/ground water management program. The small community of Enon is located in northeastern Clark County and has a population of approximately 2,000 people. Within the productive Mad River buried-valley aquifer are three production wells. The composition of the aquifer is mainly permeable sand and gravel outwash of glacial-fluvial origin. The aquifer is very prone to contamination due to its high conductivity and location of the water table near the surface. To determine wellfield protection boundaries, GPTRAC and MONTEC models were used to predict ground water flow. Protection boundaries for the wellfield were estimated using a one year time-of-travel of ground water. Using this information, strategies and management plans are suggested for the town of Enon to use in its selection of potential management options.

Bradley, M.D. and S.M.K. Bobiak. 1997. WHPA delineation methodology development for large wells completed in stratified drift in Rhode Island. Journal of Soil Water Conservation. v. 52, no. 1, pp. 55-58.

Mathematical equations and hydrogeologic mapping methods were used in delineating wellhead protection areas in Rhode Island. The identified areas will be used in future wellhead protection programs.

Edson, D.F. 1989. Aquifer protection through large scale computer modeling. Protecting Ground Water from the Bottom Up: Local Responses to Wellhead Protection. Proceedings of the Conference, October 2-3, 1989, Danvers, Massachusetts. Underground Injection Practices Council, Oklahoma City, Oklahoma, pp. 119-121.

One of the largest aquifers in central and western Massachusetts is the Barnes Aquifer which covers the eastern area of the City of Westerfield. The City of Westerfield developed a wellhead protection program and a series of bylaws aimed at protecting the aquifer based on topography and surficial geology in 1985. In 1989, a more thorough approach to delineating wellhead protection areas was enacted using large scale hydrogeologic computer modeling. MODFLOW, a three-dimensional, finite difference model developed by the U.S. Geologic Survey, was used for detailing wellhead protection areas. The modeled area was 14,000 feet by 32,000 feet represented by a 33 by

70 grid. The node spacing was between 400 and 900 feet. Characteristics of the aquifer incorporated into the model included: saturated thickness, aquifer permeability, initial head distribution, storativity, till barrier boundaries, induced infiltration from surface water bodies, and pumping well withdrawals. A USGS resources investigation of the area and City well testing records served as sources for the data. Development of wellhead protection districts were done using criteria for Zone II in Massachusetts. Zone II state guidelines include 180 days of continuous pumping with no recharge from precipitation.

Freethey, G.W., L.E. Spangler, and W.J. Monheiser. 1994. Determination of hydrologic properties needed to calculate average linear velocity and travel time of ground water in the principal aquifer underlying the southeastern part of Salt Lake Valley. USGS Water Resources Investigations Report: 92-4085.

A 48-square-mile area in the southeastern part of the Salt Lake Valley, Utah, was studied to determine if generalized information obtained from geologic maps, water-level maps, and drillers' logs could be used to estimate hydraulic conductivity, porosity, and the slope of the potentiometric surface: the three properties needed to calculate average linear velocity of ground water. Estimated values of these properties could be used by water management and regulatory agencies to compute values of average linear velocity, which could be further used to estimate travel time of ground water along selected flow lines, and thus to determine wellhead protection areas around public-supply wells. The methods used to estimate the three properties are based on assumptions about the drillers' descriptions, the depositional history of the sediments, and the boundary conditions of the hydrologic system. These assumptions were based on geologic and hydrologic information determined from previous investigations. The reliability of the estimated values for hydrologic properties and average linear velocity depends on the accuracy of these assumptions.

Hydraulic conductivity of the principal aquifer was estimated by calculating the thickness-weighted average of values assigned to different drillers' descriptions of material penetrated during the construction of 98 wells. Using these 98 control points, the study area was divided into zones representing approximate hydraulic-conductivity values of 20, 60, 100, 140, 180, 220, and 250 feet per day. This range of values is about the same range of values used in developing a ground water flow model of the principal aquifer in the early 1980s. Porosity of the principal aquifer was estimated by compiling the range of porosity values determined or estimated during previous investigations of basin-fill sediments, and then using five different values ranging from 15 to 35 percent to delineate zones in the study area that were assumed to be underlain by similar deposits. Delineation of the zones was based on depositional history of the area and the distribution of sediments shown on a surficial geologic map. Water levels in wells were measured twice in 1990, during late winter when ground water withdrawals were the least and water levels the highest, and again in late summer, when ground water withdrawals were the greatest and water levels the lowest. These water levels were used to construct potentiometric-contour maps and subsequently to determine the variability of the slope in the potentiometric surface in the area.

Values for the three properties, derived from the described sources of information, were used to produce a map showing the general distribution of average linear velocity of ground water moving through the principal aquifer of the study area. Velocity derived ranged from 0.06 to 144 feet per day with a median of about 3 feet per day. Values were slightly faster for late summer 1990 than for the later winter 1990, mainly because increased withdrawal of water during the summer created slightly steeper hydraulic-head gradients between the recharge area near the mountain front and the wellfields farther to the west. The fastest average linear-velocity values were located at the mouth of Little Cottonwood Canyon and south of Dry Creek near the mountain front, where the hydraulic conductivity was estimated to be the largest because the drillers described the sediments to be predominantly clean and coarse grained. Both of these areas also had steep slopes in the potentiometric surface. Other areas where average linear velocity was fast included small areas near pumping wells where the slope in the potentiometric surface was locally steepened. No apparent relation between average linear velocity and porosity could be seen in the mapped distributions of these two properties. Calculation of travel time along a flow line to a well in the southwestern part of the study area during the summer of 1990 indicated that it takes about 11 years for ground water to move about 2 miles under these pumping conditions.

Ginsberg, M. 1995. Applicability of wellhead protection area delineation to domestic wells: a case study. EPA-813-B-95-007, 13 pp.

Wellhead protection for a community supplied by numerous private wells requires a different approach than that for wellhead protection of PWS wells. The higher density of private wells within a community may cause wellhead protection areas to overlap where hydrogeology is not sufficiently known and long ground water travel times are needed to meet protection goals.

Golder Associates Inc., Oregon, and W.E. Nork. Nevada. 1992. Draft wellhead delineation demonstration project for Conger Wellfield. Klamath Falls, Oregon.

A wellhead protection demonstration project was conducted at the Conger Wellfield in Klamath Falls, Oregon. It is a prototype for determining if the State of Oregon Draft Guidance Document for Wellhead Protection Area Delineation is adequate for determining WHPAs where the ground water source is a deep, fractured-rock aquifer.

Golder Associates Inc. 1992. Demonstration of wellhead protection area delineation methods applied to the Weyerhaeuser Wellfield Springfield, Oregon.

Using the Draft Guidance Document for Wellhead Protection Area Delineation developed by the Oregon Department of Environmental Quality, the Springfield Utility Board in Springfield, Oregon, defined a wellhead protection area at the Weyerhauser Wellfield. This wellfield supplies one third of the ground water supply providing drinking water to Springfield area residents.

Hansen, C.V. 1991. Description and evaluation of selected methods used to delineate wellhead-protection areas around public-supply wells near Mt. Hope, Kansas; Water Resources Investigation. USGS Report USGS/WRI-90-4102.

The purpose of the report is to present evaluations of several methods that can be used to delineate wellhead-protection areas. Others interested in delineating wellhead protection areas for wells under hydrologic conditions similar to those near Mt. Hope, Kansas, can use these evaluations to assess (1) the appropriateness of each method for the hydrologic conditions and (2) the types of information needed to apply each method. These evaluations also may be used to facilitate the choice of method most suitable for the available resources.

Heath, Douglas L. 1995. Delineation of a refined wellhead protection area for bedrock public supply wells, Charlestown, Rhode Island. USEPA.

This report describes the refined delineation of the WHPA of a wellfield of five public supply wells installed in granitic bedrock in Charlestown, Rhode Island, approximately 32 miles southwest of Providence, Rhode Island. The supply wells range in depth from 125 to 500 feet and pump from 6.6 to 40 gallons per minute.

Refined delineation of the 1992 Rhode Island Department of Environmental Management (RIDEM) WHPA was performed using the 10-Step Method, which describes well location, regional and local flow patterns, well discharge, aquifer properties, and conceptual and computer models. Because the wellfield aquifer is shallow, medium-grained granite, in which ground water flows in discrete fracture sets, various diagnostic tests from available information were made to determine its behavior as an equivalent porous medium, so that standard analytic-element modeling and particle tracking could be applied for approximate capture-zone simulation of lateral and downgradient flow boundaries.

The revised WHPA for the wellfield was delineated in four stages: (1) Analyses of well discharge, drawdown/recovery, and ground water quality data suggested that the Narragansett Pier Granite aquifer behaves as an equivalent porous medium at the wellfield's scale of investigation; (2) performing transient capture-zone modeling on all five supply wells to determine distances from the wells to downgradient and lateral boundaries; (3) comparing these boundaries to the 200-foot radius circles of existing sanitary protection areas mandated by the Rhode Island Department of Health, all lateral and downgradient capture zone boundaries were less than 200 feet from the supply wells; and (4) extending streamline flow boundaries upgradient from these areas and normal to water-table altitude contours to the regional ground water divide, as determined by the U.S. Geological Survey. Therefore, the final WHPA is delineated by the arbitrary fixed radius and hydrogeological mapping methods and supported by distance and flow boundary criteria.

Based on the best available information, the refined wellhead protection area is approximately one-tenth the size of that delineated by the RIDEM. In addition, despite this modified size, a portion of the waste cell of the Charlestown Municipal Landfill apparently still lies within the refined WHPA. Other potential sources of contamination are several individual septic disposal systems at residences upgradient of the wellfield.

Heath, Douglas L. 1993. The Wilton, N.H. wellhead protection area pilot project. USEPA.

This report describes the delineation of the WHPA of two municipal supply wells in Wilton, New Hampshire. The size of the WHPA is approximately 0.52 square miles. The wellfield is located within the watershed of the Souhegan River, a tributary of the Merrimack River. It consists of two gravel-packed supply wells pumping from an unconfined, stratified-drift aquifer at a combined rate of approximately 8 million gallons per month. The aquifer, which is bounded on the east and west by till and bedrock uplands up to 1,000 feet in altitude, consists predominantly of fine sand to coarse cobbles and boulders laid down by the retreat of the Wisconsinan ice sheet. Finer-grained deposits of silt and clay deposited by glacial ice or as lake deposits also occur locally. These valley-fill materials are recharged by ground water inflow from surrounding highlands and also from infiltration originating as precipitation or as surface water, especially near pumping wells.

The delineation criteria, criteria thresholds, and methods applied in the wellhead protection area meet or exceed the requirements of the New Hampshire Department of Environmental Services

(NHDES) Phase I Delineation Guidelines of the NHDES Wellhead Protection Program. These criteria are distance and flow boundaries, used in conjunction with the following combined methods: arbitrary-fixed radius, analytical modeling, and hydrogeological mapping. One of the supply wells was also investigated for its potential to induce infiltration and water-borne pathogens (including enteric viruses) from the Souhegan River, located 91 feet away from the wellhead.

The information and techniques used to delineate the wellhead protection area are outlined as a ten-step process performed in sequential order. This approach was found to be effective given New Hampshire's well-developed hydrogeological data base and the specific requirements of the selected delineation methods.

Landmeyer, J.E. 1994. Description and application of capture zone delineation for a wellfield at Hilton Head Island, South Carolina. USGS Water-Resources Investigation Report. USGS Report 94-4012, 33 pp.

Numerical and analytical ground water models were used for delineating capture zone boundaries for individual pumping wells in a confined aquifer. Two-dimensional capture zone boundaries representing the extent of the contribution of ground water to a pumped well were delineated by all the models used. Capture zones were then evaluated on the ability of each model to represent realistically the portion of the ground water flow system that contributes water to the pumped well. The fixed radius method is the basis for the analytical models. Also included in the analytical models is the arbitrary radius model, the calculated fixed radius model based on the volumetric flow equation with a time-of-travel criterion, and a calculated fixed radius method with drawdown criterion derived from the Theis model. Two-dimensional, finite difference models RESSQC and MWCAP were used for the numerical models. The Theis analytical model and the arbitrary radius method both delineated capture zone boundaries that compared least favorably with the capture zones delineated using both numerical models and the volumetric-flow analytical model. More reasonable capture zones, parallel to the regional flow direction, were produced by the numerical models than the volumetric-flow equation. The numerical model RESSQC computed more realistic capture zones than the numerical model MWCAP by considering the effects of multiple-well interference. Capture zones predicted by both numerical and analytical models indicate that the current 100-foot radius of protection around a wellhead in South Carolina is much smaller than the ground water capture for pumping wells in this particular wellfield in the Upper Floridan. The arbitrary fixed radius of 100 feet underestimated the upgradient contribution of ground water flow to a pumped well.

Moore, Beth A. 1993. Case studies in wellhead protection area delineation and monitoring. USEPA Report 600/R-93/107.

A methodology for planning and implementing a wellhead protection monitoring program is formulated and demonstrated at unique case study sites. This methodology emphasizes saturated zone monitoring and is intended to serve as a guide for wellhead protection program implementors. Careful implementation of this methodology will enable managers and scientists to establish technically defensible, reliable, and effective ground water monitoring programs for wellhead protection.

Basic hydrogeology concepts and equations are discussed as they pertain to ground water systems and flow, conceptual hydrogeologic models and flow nets, and accurate delineation and monitoring in different hydrogeologic settings. The spectrum of unconfined to confined aquifers is discussed in relation to porous, granular aquifers; fractured-bedrock aquifers; and karst aquifers.

Physical and chemical parameter monitoring apply to wellhead protection. Three types of ground water monitoring are useful in managing wellhead protection areas--ambient trend, source assessment, and early-warning detection monitoring. Ambient trend monitoring detects the temporal and spatial trends in physical and chemical quality of the ground water system. Source assessment monitoring evaluates the existing or potential impacts on the physical or chemical ground water system from a proposed, active, or abandoned contaminant source. Early-warning detection monitoring is conducted upgradient from the wellhead, based on known travel times, to trigger a contingency response to prevent public exposure to contaminants in aquifers; they should not be mistaken as preventative or remedial measures.

Noake, K.D. 1989. Fox (Borough) guarding the aquifer coop: local control at work. Protecting Ground Water from the Bottom Up: Local Responses to Wellhead Protection. Proceedings of the Conference, October 2-3, 1989. Danvers, Massachusetts. Underground Injection Practices Council, Oklahoma City, Oklahoma, pp. 71-101. 8 fig, 2 tab, 13 ref.

Responding to local needs, the Town of Foxborough, Massachusetts wellhead protection strategy evolved over a five year period. To delineate a wellhead protection area, one must know the hydrogeologic characteristics of the aquifer, pumping rates of wells, and the recharge the aquifer receives. When Foxborough delineated its wellhead protection areas, it also adopted a Water Resource Protection District bylaw in 1984. To update the 1984 bylaw and redefine the wellhead protection areas to follow the guidelines for delineating primary (Zone II) and secondary (Zone III) aquifer recharge areas, a consultant was retained. A defensible wellhead protection strategy was the goal. The recharge areas for 11 existing wells and 6 proven well sites were performed using different approaches. Pumping tests were performed at the town's pumping stations using an automated data gathering and processing system. This database was used in a aquifer simulation model using MODFLOW which delineated the 17 wells' recharge areas. Computer programs were used to check the existing data in the database. To determine nitrate loading in Zone II areas under maximum build-out conditions, a mass balance nitrate loading model was utilized.

Osborne, T.J., J.L. Sorenson, M.R. Knaack, D.J. Mechenich, and M.J. Travis. Designs for wellhead protection in central Wisconsin: Case studies of the town of Weston and City of Wisconsin Rapids. (Internet download, 1997)

These were the first studies to monitor wellhead protection areas in Wisconsin. Wellhead protection areas of the City of Wisconsin Rapids and Town of Weston were examined specifically for defining zones of contribution (ZOC), mapping and acknowledging potential contaminant sources, and beginning management strategy plans for use in implementing wellhead protection programs. Application of the uniform flow equation, taking into consideration boundaries and the relationship between pumping rate and natural recharge, defined the zones of contribution of the wellfields. Time of travel zones, inside the ZOC, were determined to present time of travel of ground water from an area to the well. The ground water supply of Weston is in an alluvial sand and gravel aquifer contaminated by hazardous material spills and underground fuel storage tanks. Numerous sources of contamination in the zones of contribution exist in the municipal wells for both Weston and Wisconsin Rapids.

Rheineck, Bruce D. 1995. River-ground water interactions and implications for wellhead protection at Black River Falls, Wisconsin. University of Wisconsin-Madison. Madison, Wisconsin, 133 pp.

Two municipal wells for the city of Black River Falls are located along the Black River, which flooded in June 1993. Unsafe levels of coliform and fecal coliform were detected in the drinking water under the municipal wells. This study investigates potential sources of contamination using ground water and surface water interactions. The objectives of this study were to: (1) identify sources of ground water and their contributions to the municipal wells, and (2) determine distances from municipal wells based on travel time. A numerical ground water model was calibrated using field and existing data from the municipal wellfield. Hydraulic conductivity of the Quaternary sand and gravel aquifer was determined using slug tests, aquifer tests, and grain-size analysis. Cambrian sandstone hydraulic conductivity was determined using specific capacity test data. The aquifer at the site was thought to be above an impermeable basal silt unit of Precambrian granite and Archean gneiss. After calibrating a steady-state flow model, the resulting steady-state parameters were used to calibrate a transient model by varying storage parameters. Using travel time analysis from PATH3D, the water takes approximately six months to travel from the Black River to the supply wells. There are three explanations for the bacteria contamination: the flood waters were contaminated, the flood waters pushed contamination from the unsaturated zone to the aquifer, or the contamination from an unknown location happened to coincide with the flood. This study points to the first explanation, which would explain the detection of bacteria after the flood and detection over time. Under the assumption of purely advective transport, the contamination will continue until the supply wells are receiving water from areas other than the flood area. Analysis of travel time indicates that this will take about five years.

Risser, D.W. and T.M. Madden. 1994. Evaluation of methods for delineating areas that contribute water to wells completed in valley-fill aquifers in Pennsylvania. USGS/92- 635, 82 pp.

Valley-fill aquifers in Pennsylvania are the source of drinking water for many wells in the glaciated parts of the State and along major river valleys. These aquifers are subject to contamination because of their shallow water-table depth and highly transmissive sediments. The possibility for contamination of water-supply wells in valley-fill aquifers can be minimized by excluding activities that could contaminate areas that contribute water to supply wells. An area that contributes water to a well is identified in this report as either an area of diversion, time-of-travel area, or contributing area. The area of diversion is a projection to land surface of the valley-fill aquifer volume through which water is diverted to a well. The time-of-travel area is that fraction of the area of diversion through which water moves to the well in a specified time. The contributing area, the largest of the three areas, includes the area of diversion but also incorporates bedrock uplands and other areas that contribute water. Methods for delineating areas of diversion and contributing areas in valley-fill aquifers, described and compared in order of increasing complexity, include fixed radius, uniform flow, analytical, semi-analytical, and numerical modeling. Delineated areas are considered approximations because the hydraulic properties and boundary conditions of the real ground water system are simplified even in the most complex numerical methods. Successful application of any of these methods depends on the investigator's understanding of the hydrologic system in and near the wellfield and the limitations of the method. The hydrologic system includes not only the valley-fill aquifer but also the regional surface-water and ground water

flow systems within which the valley is situated. As shown by numerical flow simulations of a wellfield in a valley-fill aquifer along Marsh Creek Valley near Asaph, PA, water from upland bedrock sources can provide nearly all the water contributed to the wells.

Robinson, J.L. 1995. Hydrogeology and results of tracer tests at the Old Tampa Well Field in Hillsborough County, with implications for wellhead protection strategies in West-Central Florida. Water Resources Investigation. USGS Report 93-4171, 63 pp.

Using the old Tampa wellfield in northeastern Hillsborough County, Florida as a test site, evaluation of wellhead-protection strategies was done for the Upper Floridan aquifer of west-central Florida. The upper 400 feet of the Upper Floridan responded to pumping with discharge rates of 450 to 1,000 gallons per minute. Storage coefficient and transmissivity values of the Upper Floridan aquifer are 0.0001 and 23,000 feet squared per day, respectively. Effective porosity values, determined from rock cores, ranges from 21 to 46 percent. A fluorescent dye was used for the tracer tests. The tracer test results determined an effective porosity of 25 percent and a longitudinal dispersivity of 1.3 feet for the aquifer. Using the fluorescent dye to measure ground water travel time, a particle tracking program was used to simulate ground water flow. Simulation of areas of contribution was done for different wellhead protection strategies using the particle tracking program. Due to the heterogeneity of the Upper Floridan aquifer, the use of uniform porosity models to delineate time-related areas of wellhead-protection in the Upper Floridan karst aquifer is not appropriate. Movement of ground water in the aquifer can be determined using these same uniform porosity models.

Schmidt, R.G., M.S. Beljin, R. Ritz, A. Field, and A. Zahradnik. 1991 Wellhead management modeling project, final report project 661428, Montgomery County Phase III. The Center for Ground Water Management, Wright State University, Dayton, Ohio.

This report incorporates data from a three phase wellfield management study to develop a ground water flow system model for use in Montgomery County. Hydrogeologic data were gathered from government agencies and the private sector and entered into a dBase III program for use in developing the model. The ground water flow model is considered useful in predicting travel times of contaminants and definition of one and three year wellhead protection areas.

USEPA. 1995. Tribal wellhead protection demonstration projects. EPA Report 813/R-95/001, Office of Water, 141 pp.

These case studies illustrate Tribal wellhead protection activities and highlight several concerns Tribes may have in implementing wellhead protection. These concerns include: ground water recharge or wellhead protection areas that are located outside the boundaries of Tribal reservations, interrelationship between ground and surface water within the reservation, and difficulties in implementing or enforcing a program in the absence of a Tribal judicial body.

USEPA. 1992. Development of a map and image processing system as decision support tool to local wellhead protection. EPA Report 813/R-92/001, Office of Water, 117 pp.

The report documents the development and use of enhanced Geographic Information System (GIS) technology to assemble a wide range of data for the protection of municipal public supply wellheads in Carroll County, Maryland.

Walden, R. Ground water protection efforts in four New England states; Technical Report. 1988. EPA Report EPA/600/9-89/084. Office of Cooperative Environmental Management, 154 pp.

The study evaluates local ground water and wellhead protection strategies in representative, but progressive communities, in New England: Springfield, Vermont; Topsham, Maine; Merrimack, New Hampshire; North Kingstown, Rhode Island. The case study method is employed on the premise that the lessons drawn from the four communities will be useful to EPA and State agencies in providing guidance to other communities in the region.

Land Use/Mapping/Geographic Information Systems (GIS)

Baker, Carol P., M.D. Bradley, and S.M.K. Bobiak. 1993. Wellhead protection area delineation: Linking flow model with GIS. Journal of Water Resources Planning Management, v. 119, no. 2, pp. 275-287.

An important part of the RIDEM ground water protection plan is the protection of areas contributing water to public wells, also known as wellhead protection areas or WHPAs. The first step in wellhead protection is WHPA delineation. A Uniform Flow analytical model is used with hydrogeologic mapping by RIDEM for WHPA delineation around large supply wells in stratified drift. Variables for input into the model are calculated using a geographic information system, which transforms the data into geographically referenced layers and provides mylar overlays for the final hydrogeologic mapping of the WHPAs. WHPA maps and other hydrogeologic data will be available to the communities and water suppliers and will be used by the Rhode Island Wellhead Protection Program as the basis for planning of local wellhead protection.

Barnett, Christopher, Y. Zhou, S. Vance, and C. Fulcher. Wellhead protection area delineation for identifying potential contamination sources. (Internet download, 1997).

This paper investigates using GIS to delineate WHPAs and identify contaminant sources. For this pilot project, twenty-five wellheads are used for WHPA delineation. A GIS layer is generated for each WHPA, using orthophotos which have a very limited set of land use categories. Base maps are produced for persons in each community to use for ground surveys. At the local level, very highly detailed information is gathered and placed on the maps. The GIS layers will be updated using these maps. Then, potential threats to public drinking water within the area are determined using the GIS layer.

Freethey, G.W., L.E. Spangler, and W.J. Monheiser. 1994. Determination of hydrologic properties needed to calculate average linear velocity and travel time of ground water in the principal aquifer underlying the southeastern part of Salt Lake Valley. USGS Water Resources Investigations Report: 92-4085.

A 48-square-mile area in the southeastern part of the Salt Lake Valley, Utah, was studied to determine if generalized information obtained from geologic maps, water-level maps, and drillers' logs could be used to estimate hydraulic conductivity, porosity, and the slope of the potentiometric surface: the three properties needed to calculate average linear velocity of ground water. Estimated values of these properties could be used by water management and regulatory agencies to compute values of average linear velocity, which could be further used to estimate travel time of ground water along selected flow lines, and thus to determine wellhead protection areas around public-supply wells. The methods used to estimate the three properties are based on assumptions about the drillers' descriptions, the depositional history of the sediments, and the boundary conditions of the hydrologic system. These assumptions were based on geologic and hydrologic information determined from previous investigations. The reliability of the estimated values for hydrologic properties and average linear velocity depends on the accuracy of these assumptions.

Hydraulic conductivity of the principal aquifer was estimated by calculating the thickness-weighted average of values assigned to different drillers' descriptions of material penetrated during the construction of 98 wells. Using these 98 control points, the study area was divided into zones representing approximate hydraulic-conductivity values of 20, 60, 100, 140, 180, 220, and 250 feet per day. This range of values is about the same range of values used in developing a ground water flow model of the principal aquifer in the early 1980s. Porosity of the principal aquifer was estimated by compiling the range of porosity values determined or estimated during previous investigations of basin-fill sediments, and then using five different values ranging from 15 to 35 percent to delineate zones in the study area that were assumed to be underlain by similar deposits. Delineation of the zones was based on depositional history of the area and the distribution of sediments shown on a surficial geologic map. Water levels in wells were measured twice in 1990, during late winter when ground water withdrawals were the least and water levels the highest, and again in late summer, when ground water withdrawals were the greatest and water levels the lowest. These water levels were used to construct potentiometric-contour maps and subsequently to determine the variability of the slope in the potentiometric surface in the area.

Values for the three properties, derived from the described sources of information, were used to produce a map showing the general distribution of average linear velocity of ground water moving through the principal aquifer of the study area. Velocity derived ranged from 0.06 to 144 feet per day with a median of about 3 feet per day. Values were slightly faster for late summer 1990 than for the later winter 1990, mainly because increased withdrawal of water during the summer created slightly steeper hydraulic-head gradients between the recharge area near the mountain front and the wellfields farther to the west. The fastest average linear-velocity values were located at the mouth of Little Cottonwood Canyon and south of Dry Creek near the mountain front, where the hydraulic conductivity was estimated to be the largest because the drillers described the sediments to be predominantly clean and coarse grained. Both of these areas also had steep slopes in the potentiometric surface. Other areas where average linear velocity was fast included small areas near pumping wells where the slope in the potentiometric surface was locally steepened. No apparent relation between average linear velocity and porosity could be seen in the mapped distributions of

these two properties. Calculation of travel time along a flow line to a well in the southwestern part of the study area during the summer of 1990 indicated that it takes about 11 years for ground water to move about 2 miles under these pumping conditions.

Hendricks, Laurel Ann. 1992. Implementation of a wellhead protection program utilizing a Geographic Information System. Rice University. Masters Thesis. Environmental Science. Also available through UMI *Masters Abstracts International*, v. 31-01, p. 0256, 274 pp.

This report describes a research project in Harris County, Texas to develop a database for the City of Houston's proposed wellhead protection program. GIS data were inputted from local, state, and federal agency sources and linked with existing ground water models in order to delineate a wellhead protection area.

Kilborn, K., H.S. Rifai, and P.B. Bedient. The integration of ground water models with GIS. 1991. In: Technical papers ACSM-ASPRS annual convention, Baltimore, Maryland, 1991. Publ. ACSM/ASPRS, pp. 150-159.

Presented in this paper is the development of an interface between a GIS database of ground water characteristics in Houston, Texas and a WHPA model. The WHPA model calculates potential pollution source zones which must be managed and monitored. The user can delineate wellhead protection areas for any geographic boundary in Houston. First, the user updates the model with all information needed in the model input file. Next, the user puts additional parameters in the model if needed. Finally, the geographic results from the model are put in the database. This process is more efficient and effective than using paper maps and overlays.

Muttiah, Ranjan Samuel. 1992. Neural networks in agriculture and natural resources: its application to the wellhead protection area problem using GIS (Indiana, Vermont). Purdue University. Dissertation Abstracts International, v. 54-01B, 224 pp.

The general objective of this research was finding the system characteristics of agriculture and natural resources that allow them to be easily studied using neural networks. Delineation of WHPAs using neural networks was the specific objective. A new method, introduced in this research, delineates WHPAs based on numerical simulations of a non-point source model. This model accounts for surface factors, as well as subsurface conditions through saturated-flow-and-transport finite-element models. The simulations were performed for an area known as the Indian Pine in Tippecanoe County, Indiana. Nitrogen concentration in the runoff volume leaving a cell was determined using the non-point source surface model. Predictions of drawdown and contaminant concentrations in the area near the water well were done using the saturated zone models for different pumping and contaminant discharge rates. Using the numerical solutions, the WHPAs were delineated. Manually delineated WHPAs were determined using a cascade-correlation neural network with Gaussian hidden units. The network accurately remembered the WHPAs used in training.

Olimpio, J. C., E.C. Flynn, S. Tso, and P.A. Steeves. 1990. Use of a Geographic Information System to assess risk to ground water quality at public supply wells, Cape Cod, Massachusetts. Water Resources Investigation. USGS Report, 52 pp.

Ground water in the sole-source, sand and gravel aquifer on Cape Cod, Massachusetts, is plentiful and of chemical quality suitable for public supply. However, the water quality is vulnerable to changing land use, particularly the rapid conversion of undeveloped land to residential and commercial uses. Considerable efforts have been made to delineate wellhead protection areas around the approximately 60 public water supply wells on Cape Cod and to assess risk to ground water quality from current and potential sources of contamination. This report presents the results of a project that demonstrates GIS methods for assessing the risk to water quality of public supply wells on Cape Cod, Massachusetts. Other project goals included the development of a large scale computer data base at the establishment of a step-by-step approach for assessing risk, the delivery of a set of specified GIS map products, and the establishment of a regional GIS data base for future use.

Rifai, H.S., L.A. Hendricks, K. Kilborn, and P.B. Bedient. 1993. GIS user interface for delineating wellhead protection areas. Groundwater. v. 31, no. 3, pp. 480-488.

This paper presents a GIS modeling users' interface for delineating WHPAs around public supply wells. Necessary information can be extracted from the built-in GIS database. The delineated WHPAs can then be stored in the GIS database for future use. This interface provides local agencies with a tool for managing WHPAs more efficiently and effectively, as is shown in a wellhead protection study for the city of Houston. This modeling interface was used to delineate WHPAs for 202 public water supply wells. Sensitivity analysis was performed to determine the effect of model parameter uncertainty on delineated WHPAs. Sources of contamination within the delineated WHPAs were identified using the GIS database. Although GIS is a useful tool, GIS requires a large investment in financial and human resources.

Analytical

Bair, E.S., C.M. Safreed, and E.A. Stasny. 1991. A Monte Carlo-based approach for determining traveltime-related capture zones of wells using convex hulls as confidence regions. Groundwater. v. 29, no.6, pp. 849-855.

Designation of wellhead protection areas may be too hasty in cases in which determination of traveltime-related capture zones of wells is made with a lack of site-specific values or there is a heterogeneous nature to the area. This uncertainty in hydraulic and geologic parameters is used by a Monte Carlo simulation of the traveltime-related capture zones. Traditional deterministic flow models do not take these parameters into account. One-year capture zones, using percentile confidence regions from reverse tracked flowpaths from a well in a leaky-confined aquifer in North Canton, Ohio, were determined from 100 randomly generated hydraulic conductivity and effective porosity values in a Monte Carlo simulation. The mean of the lognormal distribution of hydraulic conductivity was 3.89 ft/d while the average value from an aquifer test in log scale and the standard deviation were both 1.0 ft/d. The effective porosity, using a normal distribution, had a mean value of 25% and standard deviation of 3.5%. An analytical flow model was used in conjunction with a particle-tracking program to obtain 100 sets of endpoints for 36 reverse particle-tracked flowpaths emanating from the well. Using a distribution of 3,600 endpoints, wellhead protection areas were determined based on the 90th-percentile and 75th-percentile confidence regions by deleting the 10 and 25 outlier endpoints. Determination of the convex hull of the remaining endpoints was determined for delineation of wellhead-protection areas. The placement of the remaining endpoints around the well and determination of likely flowpaths were used to analyze the best locations of wells used to detect contaminants flowing toward the well.

Bolt, Walter Joseph. 1995. Delineation of a wellhead protection area for the village of Chelsea, Michigan, using two dimensional steady-state MODFLOW. Eastern Michigan University. Masters Abstracts International, v. 34-02, 191 pp.

For the village of Chelsea's municipal wellfield, four separate wellhead protection areas were delineated for 1, 5, 10, and 20 year time-of-travel distances with MODFLOW-MODPATH. The municipal wells for Chelsea are within a leaky confined glacial drift aquifer which contains considerable amounts of coarse sand and gravel. From the ground surface to about 20 feet below grade, geologic materials consist of silty clay till. From 20 to 40 feet below grade, the composition of the geologic materials is sand and gravel. Silty clay is below the confined aquifer. A two-dimensional steady-state MODFLOW model was developed using hydrogeologic data and water levels from 21 residential wells. The particle tracking program MODPATH was then used to process the calibrated MODFLOW model. Using 1, 5, 10, and 20 year time-of-travel distances for the wellhead protection areas resulted in delineated areas of approximately 0.44, 1.71, 2.84, and 3.37 square miles, respectively.

Bradbury, K.R. and M.A. Muldoon. 1994. Effects of fracture density and anisotropy on delineation of wellhead protection areas in fractured-rock aquifers. Applied Hydrogeology. v. 2, no. 3, pp. 17-23.

Many wellhead protection investigations in fractured-rock aquifers assume that the aquifer approximates a porous medium at the same scale as the wellhead protection area. Theoretical explanations and criteria have been used for determining when to employ the porous media approximation. However, most of these criteria require extensive field work for validation. To test when it is appropriate to delineate the capture zone of a well drilled in fractured rock, using the assumption of porous media equivalence, experiments were conducted with Rouleau's two-dimensional discrete fracture flow model coupled with a particle-tracking code focusing on the effects of anisotropy and fracture density on capture zone delineation. Even in densely fractured aquifers, the zone of contribution calculated by the fracture-flow model is much larger than the capture zone predicted by the porous-media-based models.

Cole, Bryce Evan. 1996. Impact of hydraulic conductivity uncertainty on capture zone delineation (wellhead protection, contaminant transport). University of Notre Dame. UMI, Doctoral Abstracts International, v. 56-07B, 185 pp.

Delineating capture zones, assuming a homogeneous hydraulic conductivity field, does not take into account the accurate definition of the area supplying water to a well in a set time period needed for pump-and-treat systems and wellhead protection plans. A Monte Carlo simulation of the hydraulic conductivity distribution is used, in this study, to determine time-related capture zones and the variability of regional gradient estimates. Identification of capture zone boundaries is accomplished using the steady-state flow model MODFLOW and a fourth order Runge-Kutta integration along with reverse particle tracking. The pumping scenarios include both regional flow domination and flow conditions dominated by pumping. Observations included: (1) estimation of the regional hydraulic gradient using a 3-point scheme showed high uncertainty in the heterogeneous conductivity field; (2) the flow lines did not generally follow the mean regional gradient to passive wells or even straight line flow paths to the well under pure pumping conditions; (3) those correlation directions not aligned with the mean of the regional gradient resulted in deviations in the orientation of average flow paths using a mean regional gradient; (4) travel time variation from a few areas exceeded two orders of magnitude; and (5) with greater distances to the well, a decrease in the probability that points upgradient of the well would be included in the capture zone was determined. The Monte Carlo analysis results indicate that heterogeneous hydraulic conductivity fields complicate wellhead protection programs or plans for sampling networks. Future characterization to reduce uncertainty would, in most cases, be prohibitive in cost. It is suggested that safety factors be considered for estimating travel time to a wellhead or delineation of a capture zone area. Using the results of this study, safety factors greater than ten may be good enough for most cases.

Edson, D.F. 1989. Aquifer protection through large scale computer modeling. Protecting Ground Water from the Bottom Up: Local Responses to Wellhead Protection. Proceedings of the Conference, October 2-3, 1989, Danvers, Massachusetts. Underground Injection Practices Council, Oklahoma City, Oklahoma, pp. 119-121.

One of the largest aquifers in central and western Massachusetts is the Barnes Aquifer which covers the eastern area of the City of Westerfield. The City developed a wellhead protection program and a series of bylaws aimed at protecting the aquifer based on topography and surficial geology in 1985. In 1989, a more thorough approach to delineating wellhead protection areas was enacted using large scale hydrogeologic computer modeling. MODFLOW, a three-dimensional finite difference model developed by the U.S. Geologic Survey, was used for detailing wellhead protection areas. The modeled area was 14,000 feet by 32,000 feet represented by a 33 by 70 grid. The node spacing was between 400 and 900 feet. Characteristics of the aquifer incorporated into the model included: saturated thickness, aquifer permeability, initial head distribution, storativity, till barrier boundaries, induced infiltration from surface water bodies, and pumping well withdrawals. A USGS resources investigation of the area and City well testing records served as sources for the data. Development of wellhead protection districts were done using criteria for Zone II in Massachusetts. Zone II state guidelines include 180 days of continuous pumping with no recharge from precipitation.

Grubb, S. 1993. Analytical model for estimation of steady-state capture zones of pumping wells in confined and unconfined aquifers. Groundwater. v. 31, no. 1, pp. 27-32.

Capture zone analysis is a useful tool when designing pumping systems and wellhead protection programs. By using discharge potentials, equations were derived for application to confined, unconfined, or combined confined and unconfined aquifers. These transient equations can not be solved explicitly. Steady-state equations, on the other hand, have been formulated and can be solved. The equations define an area in which, in theory, all the water in the aquifer eventually reaches the pumping well. However, these equations fail to account for effects of hydrodynamic dispersion. Also, equations were formulated for finding the stagnation point, upgradient divide, and dividing stream line. These equations were applied to an example problem. The capture zones were similar when the calculations of both a confined and an unconfined aquifer were compared. The formulated equations are useful for a fast analysis of a pumping system and the properties in the aquifer even though they do not take into account hydrodynamic dispersion. Although many of the assumptions restrict its application to many sites, solving of small geohydrologic problems could be a benefit of the analysis presented here.

Haitjema, H.M., J. Wittman, V. Kelson, and N. Bauch. 1994. Wellhead Analytic Element Model (WhAEM): program documentation for the wellhead analytic element model. EPA Report /600/R-94/210, 131 pp.

The WhAEM demonstrates a new technique for the definition of time-of-travel capture zones in relatively simple geohydrologic settings. The WhAEM package includes an analytic element model that uses superposition of (many) analytic solutions to generate a ground water flow solution. WhAEM consists of two executables: the preprocessor Geographical Analytic Element Preprocessor (GAEP), and the flow model Capture Zone Analytic Element Model (CZAEM). WhAEM differs from existing analytical models in that it can handle fairly realistic boundary conditions such as streams, lakes, and aquifer recharge due to precipitation. The preprocessor GAEP is designed to simplify input data preparation; specifically, it facilitates the interactive process of ground water flow modeling that precedes capture zone delineation. The flow model CZAEM is equipped with a novel algorithm to accurately define capture zone boundaries by first determining all stagnation points and dividing streamlines in the flow domain. No models currently in use for wellhead protection contain such an algorithm.

Hall, J.C. 1989. Use of time of travel in zone of contribution delineation and aquifer contamination warning. Protecting Ground Water from the Bottom Up: Local Responses to Wellhead Protection. Proceedings of the Conference, October 2-3, 1989. Danvers, Massachusetts. Underground Injection Practices Council, Oklahoma City, Oklahoma, pp. 137-143.

Determining the zone of contribution for water supply wells has typically depended on using specified drawdown data. Advances in computer modeling allow for the determination of both drawdown and travel time also. It is more advantageous to use travel time determination instead of drawdown due to the freedom from sloping piezometric surfaces, accounting for high permeability strata in the aquifer, proper inclusion of recharge from nearby low-permeability areas, and delineation of where monitoring should take place. The model must account, at each node, for all significant strata and permeabilities. This is of particular importance for glacial sediments. There are two-dimensional models available regarding head field output that can accept differences in stratigraphy at every node. This is preferable to the strictly two-dimensional models, such as PLASM, or three-dimensional models requiring too many layers. If possible, the grid should cover the entire watershed of the aquifer. In calibrating time of travel models, permeability should be adjusted only to levels consistent with geologic data. Errors in geologic interpretation often signal problems with calibration. For most cases in time of travel modeling, more input is required than in simple flow modeling.

Harmsen, E.W., J.C. Converse, M.P. Anderson, and J.A. Hoopes. 1991. A model for evaluating the three-dimensional ground water dividing pathline between a contaminant source and a partially penetrating water-supply well. Journal of Contaminant Hydrology. v. 8, no. 1, pp. 71-90.

Degradation of ground water quality results when effluent from septic tank drainfields encroaches on ground water and contaminates water supplies. Development of a model was undertaken to assist planners in the unsewered area of central Wisconsin to reduce the risks of contamination of water supplies from septic systems. The model can handle three-dimensional transient flow in an unconfined homogeneous aquifer of infinite areal extent with a regional horizontal gradient. Results of the model are in good agreement with other numerical and analytical models. Due to the applicability to larger scale problems, this model could be a welcome addition to the U.S. Environmental Protection Agency's Wellhead Protection Program.

Kraemer, S.R., H.M. Haitjema, and O.D.L. Strack. 1994. Capture zone modeling using the WhAEM. EPA Report /600/A-94/109, 9 pp.

A new computer modeling package has been developed through a cooperative agreement between Indiana University, the University of Minnesota, and the U.S. Environmental Protection Agency for the determination of time-of-travel capture zones in relatively simple geohydrological settings. The WHAEM package includes an analytic element model that uses superposition of (many) closed form analytical solutions to generate a ground water flow solution. WhAEM consists of two executables: the preprocessor GAEP and the flow model CZAEM. WHAEM distinguishes itself from existing analytical models in that it can handle fairly realistic boundary conditions such as streams, lakes, and aquifer recharge due to precipitation. GAEP is designed to simplify input data preparation, specifically to facilitate the interactive process of ground water flow modeling that supports capture zone delineation. CZAEM is equipped with a novel algorithm to accurately define capture zone boundaries by determining all stagnation points and dividing streamlines in the flow domain.

Morrice, Joseph Nathan. 1997. Wellhead protection area delineation: evaluation of an analytic solution under parameter uncertainty. University of Nevada. Masters Thesis. UMI Masters Abstracts International, v. 35-04, 86 pp.

Time dependent capture zone analysis is commonly used in determining wellhead protection areas. One method used for delineating capture zones is a two-dimensional analytic solution for a pumping well in a homogeneous aquifer with a regional gradient. This method requires true estimates of the representative mean values for hydraulic parameters. A probabilistic approach to capture zone delineation has been developed by incorporating uncertainties in the hydraulic parameter estimates into the analytic solution. To evaluate the effectiveness of this method, three comparisons were undertaken: the first involved analyzing capture zones resulting from different input statistics, the second used Monte Carlo simulations, and the third involved a capture zone delineated in practice using three data sets based on published data. It was determined that there was a reliance on the uncertainty in transmissivity and the direction of regional flow. By including uncertainty, the calculated capture zone overlayed most or all of the field capture zone using two data sets, whereas the capture zones determined without using uncertainty in the analytical solution did not detect large parts of the field capture zone.

Noake, K.D. 1989. Fox (Borough) guarding the aquifer coop: local control at work. Protecting Ground Water from the Bottom Up: Local Responses to Wellhead Protection. Proceedings of the Conference, October 2-3, 1989. Danvers, Massachusetts. Underground Injection Practices Council, Oklahoma City, Oklahoma, pp. 71-101. 8 fig, 2 tab, 13 ref.

Responding to local needs, the Town of Foxborough, Massachusetts wellhead protection strategy evolved over a five year period. To delineate a wellhead protection area, one must know the hydrogeologic characteristics of the aquifer, pumping rates of wells, and the recharge the aquifer receives. When Foxborough delineated its wellhead protection areas, it also adopted a Water Resource Protection District bylaw in 1984. To update the 1984 bylaw and redefine the wellhead protection areas to follow the guidelines for delineating primary (Zone II) and secondary (Zone III) aquifer recharge areas, a consultant was retained. A defensible wellhead protection strategy was the goal. The recharge areas for 11 existing wells and 6 proven well sites were performed using different approaches. Pumping tests were performed at the town's pumping stations, using an automated data gathering and processing system. This database was used in an aquifer simulation model using MODFLOW which delineated the 17 wells' recharge areas. Computer programs were used to check the existing data in the database. To determine nitrate loading in Zone II areas under maximum build-out conditions, a mass balance nitrate loading model was utilized.

Ramanarayanan, T.S., D.E. Storm, and M.D. Smolen. 1995. Seasonal pumping variation effects on wellhead protection area delineation. Water Resources Bulletin. v. 31, no. 3, pp. 421-430.

The main feature of the wellhead protection programs for drinking water supplies is the delineation of WHPAs. Very often, WHPAs are delineated using idealized steady-state assumptions, leading to an incorrect estimation of area and geometry. Results presented in this paper compare a commonly used steady-state method with a more complex transient assumption allowing seasonal variations in pumping rates. A transient procedure is also introduced for time-related capture zone delineation using a numerical flow and transport model. A ten year time-of-travel assumption is employed for examining wellhead delineation for two municipal wells in Tipton, Oklahoma. GPTRAQ, a semi-analytical model, was used assuming constant pumping rates, for the steady-state procedure along with MOC, a numerical model. The capture zone estimated by GPTRAQ has the same shape as the capture zone estimated by MOC but they are of different sizes due to the different solution schemes. MOC was used for the transient method incorporating seasonal variations in pumping rates. The capture zones delineated by the steady-state procedure were much smaller than those predicted by the transient procedure using the same model. Also, the transient procedure predicted higher drawdown than the steady-state procedure which explains the larger capture zones.

Sahl, Barbara L. 1994. A comparison of wellhead protection area delineation methods at Larimore, North Dakota. Masters Thesis. University of North Dakota. Grand Forks, ND, 177 pp.

Shallow aquifers provide many communities in North Dakota with water which is susceptible to contamination. Delineation of WHPAs is one of the strategies to protect the ground water supplies. Five delineation methods were evaluated in Larimore, North Dakota. All five methods were tested for sensitivity to recharge, hydraulic conductivity, specific yield, and porosity. Circular WHPAs are produced using arbitrary (AFR) and calculated fixed radius (CFR) methods. The CFR varies only with porosity and the AFR uses no site-specific data. RESSQC and GPTRAC, semi-analytical models, generate WHPAs using well and aquifer data and particle tracking. MODFLOW/SURFER/GWPATH (MSG) connects a numerical flow model (M), with a contouring program (S), and a particle-tracking program (G). The head distribution from a cone of depression generated from MODFLOW is combined with a digital map for input into GWPATH. MSG produced the closest representation of the aquifer/well system and was assumed to produce the most accurate WHPAs. Neither of the fixed radius methods was accurate for the Larimore site. RESSQC and GPTRAC, without recharge, generated WHPAs that were too large. With recharge, GPTRAC generated WHPAs most similar to those produced by MSG and is probably accurate for the simple aquifer system at Larimore.

Shafer, J.M. and M.D. Varljen. 1992. Coupled simulation-optimization approach to wellhead protection area delineation to minimize contamination of public ground water supplies. In: The 20th Anniversary Conference on Water Management in the '90s, Seattle, Washington, May 5, 1992 . Reprinted in Water Resources Planning and Management and Urban Water Resources, 1993. Publ. ASCE, New York, NY, pp. 567-570.

A determination of the steady-state pumping rates for individual wells (in a wellfield containing multiple wells) that results in the fewest number of potential contaminant sources in the wells' time-period capture zones was done using a loosely coupled simulation-optimization procedure. In order for the total wellfield pumping rate to meet the wellfield demand, the nonlinear, unconstrained optimization problem is solved with a conjugate direction search algorithm.

USEPA. 1993. Wellhead protection in confined, semi-confined, fractured and karst aquifer settings. EPA Report /810/K-93/0012, 10 pp.

Protection areas around wells producing from confined, fractured, and karst aquifers are, because of their complex hydrogeology, more difficult to define than protection areas for wells in porous media settings. The document provides background information explaining the need to define protection areas for wells that draw public drinking water from several complex hydrogeologic settings: confined, semi-confined, fractured, and karst aquifers. These settings include aquifers in which the ground water is not open to the atmosphere, or the aquifer does not consist of unconsolidated porous media. Several figures illustrate these settings in a general way.

van der Heijke, P. and M.S. Beljin. 1988. Model assessment for delineating wellhead protection areas. Final Report. EPA Report /440/6-88/002, 271 pp.

The document offers a compilation of ground water computer flow models potentially applicable to wellhead protection area delineation. It contributes information on existing ground water flow and contaminant transport and fate models that may be considered for use in these delineations. Each of the 64 personal computer models described was rated with respect to applied quality assurance, user-friendliness, accessibility, portability, and modificability.

Varljen, M.D. and J.M. Shafer. 1993. Coupled simulation-optimization modeling for municipal ground water supply protection. Groundwater. v. 31, no. 3, pp. 401-409.

A technique has been developed to protect municipal water supplies from potential contamination through capture zone management using a numerical ground water flow model and unconstrained nonlinear optimization. This technique combines nonlinear programming with finite difference ground water flow modeling and travel time calculations. The reason for using this method is to determine pumping rates for wells in a wellfield that will minimize the potential risks of contamination while maintaining the total output of water from the wellfield. Features of this technique include the incorporation of realistic boundary conditions, the treatment of complicated aquifer configurations, and the use of spatially varying aquifer properties depending on the availability of site-specific data. This method improves upon the conventional wellhead protection and delineation approaches by achieving a greater level of protection. Protection improvement is achieved through essentially nullifying the effects of potential contaminant sources in capture zone analysis, instead of reducing the threat of these sources. This technique was tested at a site in Pekin, Illinois and in a hypothetical ground water system.

Varljen, M.D. and J.M. Shafer. 1991. Assessment of uncertainty in time-related capture zones using conditional simulation of hydraulic conductivity. Groundwater. v. 29, no. 5, pp. 737-748.

Presented is a time-related, steady-state, stochastic capture zone analysis based on conditional simulation of hydraulic conductivity. A conditional simulation of hydraulic conductivity preserves the measured and spatial correlation of the hydraulic conductivity field while presenting the most representative results by optimization of the use of available data. A test problem, with a water supply well, was formulated to find, using stochastic analysis, the uncertainty in the one year and ten year capture zones of the well. The influence of hydraulic conductivity values on the 'zone of uncertainty' of the capture zone as a function of time of travel and direction of regional flow is demonstrated in the results. Monte Carlo techniques are used to determine uncertainty in the delineation of time-related capture zones based on uncertainty in hydraulic conductivity. This method makes optimum use of the available data by using not only the data values but also their corresponding spatial attributes. The problems associated with implementing the conditional analysis have been answered by testing this technique on a hypothetical ground water flow domain with a simulated pumping well. Using this demonstration, estimates of ranges in uncertainty in the sizes and layouts of time-related capture zones that arise from incomplete knowledge of hydraulic conductivity can be estimated adequately using this technique.

Wilson, J. and G. Achmad. 1995. Delineation of wellhead protection areas using particle tracking analysis and hydrogeologic mapping, northern Anne Arundel County, Maryland. Report of Investigations - Maryland Geological Survey, v. 61, 121 pp.

The report compares two computer modeling techniques used to delineate WHPAs for the public supply wells of northern Anne Arundel County. The first technique involves using the U.S. Geological Survey MODFLOW program along with the 1989 version of the U.S. Geological Survey MODPATH program, a particle tracking code. The alternative technique is performing particle tracking using the semi-analytical module called GPTRAC in the WHPA code (version 2.1) from

the U.S. Environmental Protection Agency. Using hydrogeologic mapping, an 'aquifer vulnerability map' is developed. Although the overall water quality of the Lower Patapsco aquifer is good, contaminants are present in the more vulnerable regions of the aquifer. Without remediation, upgradient sources of contamination pose a threat to the presently unused Glendale and Sawmill wellfields.

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

Delineation of wellhead protection areas was done using the Analytic Element Method of ground water modeling for proposed and existing wells in Brooklyn Park, Minnesota. This was accomplished by simulating steady-state flow in the Franconia-Ironton-Galesville aquifer and the water table aquifer. Delineation was performed using ground water time-of-travel as the delineation criterion. The solution produced by the Analytic Element Method includes local scale and regional scale features in the same solution. This allowed for simulation of the city wells in relation to the regional flow field. The Single Layer Analytic Element Model (SLAEM) was used for developing and calibrating separate models. Each of these separate models was linked together using the Multi-Layer Analytic Element Model (MLAEM). Wellhead protection areas and ground water travel time zones were delineated using reverse particle tracking for the existing wells.

Yeh, G.T., S. Sharp-Hansen, B. Lester, and Strobl. 1992. Three-Dimensional Finite Element Model of Water Flow Through Saturated-Unsaturated Media (3DFEMWATER)/Three-Dimensional Lagrangian-Eulerian Finite Element Model of Waste Transport Through Saturated-Unsaturated Media (3DLEWASTE): numerical codes for delineating wellhead protection areas in agricultural regions based on the assimilative capacity criterion. EPA Report /600/R-92/223, 254 pp.

Two related numerical codes, 3DFEMWATER/3DLEWASTE, are presented that can be used to delineate wellhead protection areas in agricultural regions using the assimilative capacity criterion. 3DFEMWATER (Three-dimensional Finite Element Model of Water Flow Through Saturated-Unsaturated Media) simulates subsurface flows, whereas 3DLEWASTE (Hybrid Three-dimensional Lagrangian-Eulerian Finite Element Model of Waste Transport Through Saturated-Unsaturated Media) models contaminant transport. Both codes treat heterogeneous and anisotropic media consisting of as many geologic formations as desired, consider both distributed and point sources/sinks that are spatially and temporally dependent, and accept four types of boundary conditions--i.e., Dirichlet (fixed-head or concentration), specified-flux, Neumann (specified-pressure-head gradient or specified-dispersive flux), and variable. The variable boundary condition in 3DFEMWATER simulates evaporation/infiltration/seepage at the soil-air interface, and, in 3DLEWASTE, simulates mass infiltration into or advection out of the system. 3DLEWASTE contains options to model adsorption using a linear, Fruendlich, or Langmuir isotherm, plus dispersion, and first-order decay.

Numerical/Modeling

Banton, O., P. Lafrance, and J.P. Villeneuve. 1992. Delineation of wellhead protection area in an agricultural zone by using solute transport modeling. Rev. Sci. EAU. v. 5, no. 2, pp. 211-227.

When delineating wellhead protection areas, certain ideas need to be considered: zones of influence encircling the well, recharge areas, flow paths, transport velocities, sources of contamination, types of contamination, and travel times. For site-specific examples of wellhead protection areas, a defined analytic method must be employed. When using quantitative criteria, mathematical simulation models are often used as the only method capable of defining wellhead protection areas.

Guiger, N. and T. Franz. 1991. Development and application of a wellhead protection area delineation computer program. Water Science and Technology. v. 24, no. 11, pp. 51-62.

A ground water flow code with pathline analysis is FLOWPATH, which can calculate hydraulic head distributions, pathlines, travel times, and velocities using a steady-state flow simulation. Time-related capture zones and pumping well drawdown distributions also are calculated. Case studies were performed on the Vega Alta Superfund Site in Puerto Rico, and for a town in Massachusetts. FLOWPATH was used to determine that proposed capture zones of remediation wells would not be sufficient to contain the future migration of significant amounts of trichloroethylene in Puerto Rico. At the Massachusetts site, it was determined that contaminants released within the watershed of a nearby pond would eventually contaminate the wellhead.

Harmsen, E.W., J.C. Converse, and M.P. Anderson. 1991. Application of the Monte Carlo simulation procedure to estimate water-supply well/septic tank-drainfield separation distances in the Central Wisconsin Sand Plain. Journal of Contaminant Hydrology JCOHE6. v. 8, no. 1, pp. 91-109.

A three-dimensional groundwater contaminant tracking model was used to estimate the mean and standard deviations of both the necessary separation distances and the minimum well depth between a water supply well and a septic tank drainfield, based on conditions found in the Central Wisconsin sand plain. Sensitivity analysis of Monte Carlo simulations identified horizontal hydraulic conductivity, anistrophy ratio, and horizontal regional gradient as the most important factors.

Johanson, Mary Giglio. 1992. Delineation of time-related capture zones with estimates of uncertainty using conditional simulation of hydraulic conductivity and numerical modeling. University of New Orleans. Masters Thesis. New Orleans, LA, 163 pp.

The most reliable method for defining wellhead protection areas is using particle tracking analysis to determine numerical time-related capture zones. Aquifer parameter estimates, required by this method, can be sources of error in capture zone delineation. This study uses a stochastic approach to calculate the one-year, five-year, and ten-year capture zones around a municipal wellfield with estimates of capture zone configuration and extent. Variogram analysis was used to assess the spatial distribution of the hydraulic conductivity field. Uncertainty of capture zone delineation was determined using statistical analysis of model results. This study concluded that the technique outlined can be used to estimate time-related capture zones around a municipal wellfield.

Outlaw, James. 1995. A ground water flow analysis of the Memphis Sand Aquifer in the Memphis, Tennessee Area. Ground Water Institute: The University of Memphis. (Internet download, 1997).

The towns of Arlington and Collierville in Shelby County along with the cities of Memphis, Germantown, Millington, and Bartlett in Tennessee depend completely on ground water for their drinking water. An important part of the protection process of the ground water supply is understanding the aquifer system in West Tennessee. A flow model of the primary aquifer in the Memphis area known as the Memphis Sand aquifer, was developed using the USGS model, MODFLOW. An earlier regional-scale flow model developed by the Ground Water Institute at the University of Memphis served as the basis for this model. The final model was calibrated using December, 1991 conditions and verified using information from 1992 and 1993. Leakage from the surficial aquifer was estimated using the model. The flow model, already calibrated, was run to a steady-state solution, and capture zones within the municipal wellfields in Shelby County were delineated using the USGS model MODPATH. EPA WHPA model results were compared to the capture zones predicted by MODFLOW and MODPATH. Approximately 31% of the total pumping from the Memphis Sand aquifer, predicted by the model, could possibly be attributed to leakage originating in the surficial aquifer. About 19% is taken from storage, especially in the eastern and southeastern portion of the county where the Memphis Sand aquifer should be treated as an unconfined unit. The Memphis Sand aquifer recharge area to the east (and lesser amounts from other directions) provides the source of the remaining water that enters the Memphis area. Also, the model indicates more information is needed about the flow system in the Memphis area to fully understand it.

USEPA. 1997. Numerical codes for delineating wellhead protection areas in agricultural regions based on the assimilative capacity criterion. EPA Report /600/R-92-223.

The 3DFEMWATER/3DLEWASTE are related numerical codes that can be used together to model flow and transport in three-dimensional, variably-saturated porous media under transient conditions with multiple distributed and point sources/sinks. Thus, these models can be used to apply the assimilative capacity criterion to the development of wellhead protection areas, as each state in the U.S. is required to do under the 1986 Amendments to the Safe Drinking Water Act. The complexity of the 3DFEMWATER/3DLEWASTE numerical models requires that they be used by experienced numerical modelers with a strong background in hydrogeology.

Hydrogeologic/Geologic Analysis

Bhatt, K. 1993. Uncertainty in wellhead protection area delineation due to uncertainty in aquifer parameter values. Journal of Hydrology. v. 149, no. 4, pp. 1-8.

Studies have been done on the importance of modeling in hydrogeologic investigations. A parameter analysis is essential to determining whether a model is applicable to the hydrogeologic setting. A parametric analysis was performed to determine the effect of data uncertainty on delineation of WHPAs. The most important factor in WHPA delineation is the precision of aquifer parameter values and their relationship to the model itself. To test effects of different values in a wellfield model, a modified version of the time-related analytical ground water flow model RESSQC was used to determine capture zone boundaries and delineate contaminant fronts for injection wells. Aquifer parameters, measured in a shallow aquifer, were used in this analysis.

Caswell, B. 1990. River Recharge. Water Well Journal. v. 44, no. 11, pp. 34-37.

Delineation of WHPAs and determination of the connection between ground water and surface water were the major issues for a Vermont community that decided to replace an existing municipal well. A geohydrologic investigation of the aquifer was required by state regulations as a part of constructing a new well. Using test boring and test pumping information, the results showed that the nearby Connecticut River provides significant recharge to the ground water source, but a brook adjacent to the well site does not. This determination requires small amounts of land purchase or land use zoning by the community due to the high transmissivity of the glacial stream aquifer and the coupling of the aquifer with the Connecticut River. However, river water quality should be addressed at the state level.

Frederick, William T. 1991. Hydrogeology of the Onondaga Limestone and Marcellus Shale in Central New York's Finger Lake region with emphasis in well-head protection and pollution potential. State University of New York. Buffalo, NY. Masters Thesis. p. 212.

To implement wellhead protection , the New York State Health Department will mandate the delineation of three zones around municipal wellfields: ZOC, zone of influence (ZOI), and the watershed tributary to the ZOC. The unconfined, fractured Onondaga Limestone and the Marcellus Shale aquifer system serve as the main water supply for the Village of Shortsville, New York. These ground water sources are contaminated by the community they supply. A MODFLOW simulation is performed to help develop protection plans. Fractures, horizontal bedding plains, joints, vertical fractures and joints, slumpfold induced fractures, pop-up induced fractures, and Paleo-ground water surface fluctuations serve as the sources of the secondary permeability within the Onondaga Limestone and Marcellus Shale. In some areas, the Pleistocene deposits overlie the bedrock and in other areas lie within the saturated thickness of the aquifer. It is these deposits, made up of outwash, alluvium, kame deposits, variably textured tills, and moraines, that define the rates at which pollutants migrate to the bedrock aquifer. Wellhead protection zones around the Village wellfield are delineated. A regional ground water protection plan can be implemented by incorporating (1) point source locations of contamination, (2) hydrogeologic properties of these sites, and (3) locations of point sources of contamination in relation to wellhead protection zones. Such a plan includes ground water pollution potential maps showing areas with low pollution potential and high hydrologic efficiency.

Gadt, Jeff W. 1994. Hydrogeology and hydrochemistry of the east-central portion of the Salt Lake Valley, Utah, as applied to wellhead protection in a confined to semiconfined aquifer. Utah State University. Logan, Utah, 151 pp.

Numerical and analytical methods are used to delineate drinking water source protection zones Two and Three, which are based on hydrogeologic time-of-travel data and recharge data acquired through the use of hydrogeochemical and hydrogeologic techniques. The findings of this research are: (1) the hydrogeology is much more complex than previously thought. This was determined through the use of fence diagrams and hydrostratigraphic diagrams; (2) horizontal ground water flow velocities are low at the site, which is indicated by the recovery rate of water in the monitoring wells due to pumping of the target well; (3) the deepest of the three water-bearing zones is not well connected to the upper two zones as indicated by interpretation of major ions relative to the depth of the highest open interval on various sample wells; (4) the chemical makeup of the westernmost of three flowpaths indicates there is a change from calcium bicarbonate to sodium-sulfate water; (5) total-dissolved-solids contents from samples of water recharged from the southern Wasatch mountains are lower than in those samples of water recharged from the northern Wasatch mountains; (6) sources of recharged water must be evaluated on an individual basis with regards to the sample wells; (7) wells located farthest into the valley have the lowest tritium values; (8) determined through Carbon 14 dating, the ground water is between 1,300 and 1,500 years old; and (9) the risk of contamination of the target well site is low in terms of the 15-year travel time.

Jost, Donald J. 1994. Hydrogeology and pollution potential of aquifers, Doylestown, Wayne County, Ohio. University of Akron. Masters Thesis, 177 pp.

A primary wellhead protection program was designed for the municipal wellfield in Doylestown using the geologic and hydrogeologic data of northeastern Wayne County. The wellfield, on top of Pennsylvanian Sharon Sandstone, is just west of the village. This formation provides drinking water for some homes in the area but the aquifer providing the bulk of the water is the Rittman Sandstone/Armstrong Siltstone of the Mississippian Cuyahoga Formation. Approximately 2.5 miles south of Doylestown is Chippewa Creek, underlain by a buried valley. This buried valley contains permeable sand and gravel that may be a future ground water source for the village. Four hydrogeologic settings are within the Glaciated Central Region (DRASTIC designation) where Doylestown is located: (7Aa) glacial till over bedded sedimentary rocks, (7Ad) glacial till over sandstone, (7Ac) glacial till over shale, and (7D) buried valley. Using pumping tests, the average transmissivity of bedrock aquifers is determined to be about 3500 gpd/ft. Pennsylvanian sandstones have moderate conductivities (2.1-21 gpd/ft), and conductivities of the Cuyahoga Formation are low to moderate (0.021-2.1 gpd/ft). The Bradbury-Rothschild computer program compared well with these hydraulic parameters. Also, wellhead protection areas were delineated for 1 yr, 2 yr, 5 yr, 10 yr, and 20 yr times-of-travel using the fixed-radius method. DRASTIC indexes from 74 to 163 and pesticide indexes between 88 and 184 were determined using the DRASTIC system.

Paillet, F.L.and W.H. Pedler. 1996. Integrated borehole logging methods for wellhead protection. The 1993 36th Annual Meeting of the Association of Engineering Geologists, San Antonio, TX. Engineering Geologists, v. 42, no. 2-3, pp. 155-165.

Models depend on accurate descriptions of the aquifer so reliable contaminant travel times can be determined in order to define a protection area. Applications of multiple geophysical measurements to ground water flow in the wellhead protection area are adapted to alluvial, fractured sedimentary, and fractured crystalline rock aquifers. Obtaining data from a single test well cannot indicate large-scale flow paths. A number of observation boreholes, with geophysical and hydraulic measurements, can indicate large-scale flow paths, and are also very useful in defining aquifer properties for wellhead protection studies.

Pesti, Geza. 1993. Geoelectrics and geostatistics for characterizing ground water protection zones (Kriging, Aquifer protection). University of Nebraska. Doctoral Abstracts International, v. 54-04B, 160 pp.

A series of tools are presented in this dissertation for characterization of the protection and yield of ground water reservoirs. Traditional measuring techniques, such as well logs, specific capacity, and pump tests, are supplemented with geophysical observations. There are four main sections to the dissertation. In the first section, a method is presented for defining aquifer properties of low conductivity subsurface layers. Mapping of the thickness of a protective clay layer is achieved using cokriging of data estimated from electrical resistivity data and well data. In the second section, a procedure is presented for mapping travel times to existing wellhead protection areas. A fixed protection zone is assumed around each well for travel time calculations. The third section describes a method for delineation of areas for new wells using the yield of the wells and protection zone effectiveness as criteria. This method is developed for leaky aquifer settings. The protection zone effectiveness is best characterized by corresponding travel times. Composite programming, a multi-criteria decision making technique, is used to determine the most sensible well locations. Section four discusses selecting the most optimal water supply well locations in an area using observation network design. This method uses measurement network alternatives which combine wells and geoelectric measurements. All the methods are presented using actual data.

Quinlan, J.F., J.A. Ray, and G.M. Schindel. 1995. Intrinsic limitations of standard criteria and methods for delineation of ground water-source protection areas (springhead and wellhead protection areas) in carbonate terrains: critical review, technically-sound resolution of limitations, and case study in a Kentucky karst. In: Karst geohazards: engineering and environmental problems in karst terrain. Proceedings 5th conference, Gatlinburg, pp. 525-537. Beck, B.F. Editor.

A Ground Water Source Protection Area in Mississippian limestones is delineated with the use of tracer-test results in this case study. The study illustrates the necessity of tracer-test results for delineating a Ground Water Source Protection Area in the karst over and above the use of computer modeling.

Teutsch, G. and B. Hofmann. 1990. The delineation of ground water protection zones using forced gradient tracer tests: a model validation case study. In: Calibration and reliability in ground water modeling, The Hague, pp. 351-360.

The study compared direct measurements observed from a gradient test covering the ZONE II area and delineation of the ZONE II area as calculated from a large scale hydraulic test. The case study examines a new waterworks which is planned for the Rhine Valley near Karlsruhe in the city of Southwest Germany. A two dimensional regional model was linked with a local scale three dimensional model to determine ground water flow and transport. Depending on the type of data used, examples include tracer or hydraulic test data, the ZONE II area estimates can differ by more than 100%.

Violette, P. 1987. Surface geophysical techniques for aquifer and wellhead protection area delineation. Technical Report. Final. EPA Report /440/12-87/106, 63 pp.

Surface geophysical techniques developed by the petroleum and minerals industries are applicable to ground water investigations. The document examines some of these techniques to aid in the delineation of aquifers as part of the delineation of wellhead protection areas. Techniques reviewed include seismic, electrical, electromagnetic induction, very low frequency (VLF) resistivity, ground penetrating radar, gravity, and magnetic geophysical techniques, and their applicability to aquifer delineation. The theory and methodology of these are discussed, along with costs as of early 1987. Also briefly discussed is the delineation of wellhead protection areas.

Welhan, J. and C. Meehan. 1994. Hydrogeology of the Pocatello Aquifer: implications for wellhead protection strategies. In: Hydrogeology, waste disposal, science and politics. Proceedings of 30th symposium on engineering geology and geotechnical engineering, Idaho, pp. 1-18.

The southern wellfield is located on a shallow strip aquifer (1:6 width:length aspect ratio) comprised of sorted fluvial gravels. The wellfield is also bounded by low permeability regions laterally. The linear velocities range from 6 to 60 ft/day and the transmissivities range from 0.1-10 ft/day. Longer pumping well capture zones are a result of high ground water flow velocities with ground water time of travel over a one year period on the order of kilometers. Design of wells to intercept the ground water flow is assisted by the rapid linear migration of ground water.

Miscellaneous

Jacobson, E., R. Andricevic, and T. Hultin. 1994. Wellhead protection area delineation under uncertainty. U.S. Department of Energy. Nevada Field Office, 81 pp.

The Nevada Test Site (NTS) is currently using 14 water supply wells. Of the 14 wells, 11 are being used as potable water supplies and the three additional wells are used strictly for construction purposes. This study estimates WHPAs for each water-supply well at the NTS. Since there was limited information about the hydraulic properties used for estimating WHPAs, a plan for considering the uncertainty in estimating the hydraulic properties was created and used.

Pesti, G., I. Bogardi, and W.E. Kelly. 1994. Risk-based wellfield design combining different source of data. Future Ground Water Resources at Risk, pp. 255-270.

Hydraulic conductivities and layer thicknesses, measured from well-logs and well-performance tests, are predicted and mapped for determination of well yield and travel times. Layer thicknesses, hydraulic conductivities, and total travel times, in conjunction with estimated yields, are treated as spatially random variables. Simulated hydraulic conductivities and thicknesses are used to determine expected value maps of specified reliability for yield and total travel-time. Combinations of yield and travel time maps, developed using composite programming, are determined using trade-off maps. The trade-off relationship incorporates the methodology of well yield versus wellhead protection. The incorporation of this method is enacted at an area close to Ashland, Nebraska.

Ramanarayanan, Tharacad Subramanian. 1995. Evaluation of existing wellhead protection strategies for controlling nonpoint source nitrate pollution. Oklahoma State University. Doctoral Abstracts International, v. 56-09B, 232 pp.

The purpose of this research is to study nonpoint source pollution to ground water due to leaching of nitrate from agricultural fields. To control agricultural nonpoint source nitrate pollution, existing time-of-travel and assimilative capacity criteria are used for WHPA delineation. The study area was Tipton, Oklahoma. Delineation of a ten year capture zone was performed using a transient ground water flow and transport model. A volume mass balance was used to study the effectiveness of the WHPA. Water flux in the saturated zone was determined using a numerical flow model. In the root zone, nitrate and water fluxes were approximated using a root zone hydrologic-water quality model. The WHPA for the Tipton municipal wells was updated using a different method of delineating WHPAs which encompasses nonpoint source pollution. The conclusions are that the existing wellhead protection criteria do not effectively account for the nitrate pollution. Even after implimentation of best management practices and elimination of agriculture within the WHPA, the Tipton WHPA did not meet the drinking water standards. In the Tipton WHPA, the resultant nitrate concentration using the alternative procedure meets the drinking water quality standards.