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METHODS TO DETERMINE WELLHEAD PROTECTION AREAS

FOR PUBLIC SUPPLY WELLS IN CLARK COUNTY, WASHINGTON

Intergovernmental Resource Center

Rodney D. Swanson

February 1992

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CONTENTS

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LIST OF FIGURES

Page

APPENDICES

Appendix A.	*Wellhead Protection Area Delineation Report* Battle Ground Wells 1 and 2
Appendix B.	*Wellhead Protection Area Delineation Report* Camas and Washougal Supply Wells
Appendix C.	*Wellhead Protection Area Delineation Report* Clark Public Utilities Well 8.1
Appendix D.	*Wellhead Protection Area Delineation Report* Clark Public Utilities Well 14
Appendix E.	*Wellhead Protection Area Delineation Report* Clark Public Utilities Well 16.1
Appendix F.	*Wellhead Protection Area Delineation Report* Clark Public Utilities Well 19
Appendix G.	*Wellhead Protection Area Delineation Report* LaCenter Wells
Appendix H.	*Wellhead Protection Area Delineation Report* Meadow Glade Darling Well
Appendix I.	*Wellhead Protection Area Delineation Report* Ridgefield Wells 7, 8, and 9
Appendix J.	*Wellhead Protection Area Delineation Report* Vancouver Well Stations 1, 3, and 4
Appendix K.	*Wellhead Protection Area Delineation Report* Vancouver Well 7.1
Appendix L.	*Wellhead Protection Area Delineation Report* Vancouver Well 7.2, the Ellsworth Springs Well & State Hatchery Wells
Appendix M.	*Wellhead Protection Area Delineation Report* Vancouver Well Station 8
Appendix N.	*Wellhead Protection Area Delineation Report* Vancouver Well Station 9
Appendix O.	*Wellhead Protection Area Delineation Report* Vancouver Well Station 14
Appendix P.	*Wellhead Protection Area Delineation Report* Vancouver Well Station 15
Appendix Q.	*Wellhead Protection Area Delineation Report* Yacolt Wells 3, 4, and 6
Appendix R.	Change of 150 percent in Pumpage Rate at Vancouver Well Station 15
Appendix S.	Vancouver Area Two-Dimensional Finite Difference Numerical Model Report
Appendix T.	US Geological Survey Three-Dimensional Regional MODFLOW/ MODPATH Delineation Report

Introduction

Amendments to the Federal Safe Drinking Water Act in 1986 require states to develop wellhead protection programs to prevent public drinking water sources from contaminants that have adverse human effects (EPA, June, 1987). The designating of wellhead protection areas is one of the required wellhead protection program elements defined by the Safe Drinking Water Act.

The Safe Drinking Water Act also requires EPA (the US Environmental Protection Agency) to provide technical guidance to the states. The EPA technical guidance document Guidelines for Delineation of Wellhead Protection Areas (EPA, June, 1987) was produced to provide general guidance to states in selecting means to delineate wellhead protection areas.

A wellhead protection area is the surface and subsurface area through which contaminants are reasonably likely to move toward and reach a well or well station supplying a public supply system. Springs may also be included in wellhead protection. The boundaries of a wellhead protection area can be based on a determination of the area contributing water to the well (zone of contribution) or more arbitrary considerations such as drawing a circle around the well. A wellhead protection area boundary is by definition a jurisdictional or management area boundary.

The designation of a wellhead protection area can be based on variety of methods that range in technical sophistication from simply drawing arbitrarily defined circles around wells to multi-layer numerical models that simulate ground water flow and contaminant transport.

Determining a zone of contribution requires some consideration of hydrologic and hydrogeologic factors. Figure 1 is a diagram showing a hypothetical zone of influence and zone of contribution for a pumping well. The zone of influence is the area where the pumping well influences water levels. The zone of influence will not normally correspond to the area contributing water to the well, the zone of contribution, because normally, ground water flow from areas upgradient of the zone of influence will be captured by the zone of influence. Conversely, parts of the zone of influence may not contribute to the well because effects of aquifer gradient are greater than the effect of pumping.

In Washington, the Department of Health has responsibility for developing and implementing a state wellhead protection program. The Department of Health established policy and technical advisory committees to help assure that the wellhead protection program is appropriate for conditions in Washington. These committees are referred to as the Wellhead Policy Advisory Committee and the Wellhead Technical Advisory Committee.

Terminology for Wellhead Protection Area Delineation (Hypothetical Pumping Well in Porous Media)

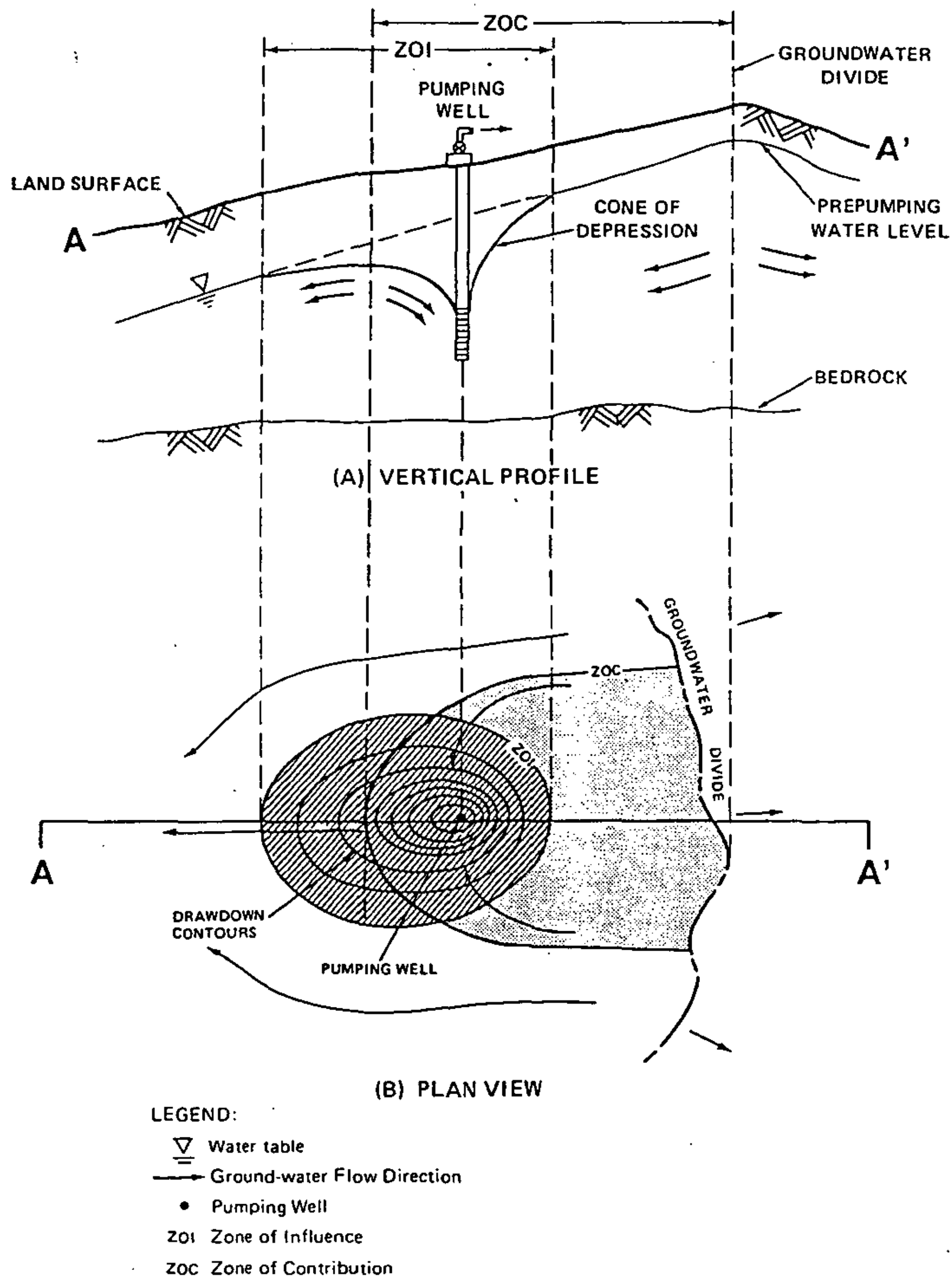


Figure 1. Zone of Influence (ZOI) and Zone of Contribution (ZOC) to a pumping well (EPA, June 1987)

The Technical Advisory Committee is responsible for recommending appropriate means to delineate wellhead protection areas and is the recipient of this report. The Policy Advisory Committee will incorporate Technical committee recommendations into the state wellhead protection program.

This report was completed by the Intergovernmental Resource Center under Washington Department of Ecology Centennial Grant TAX 91075 to support State efforts to develop an effective wellhead protection program. The US Geological Survey cooperated in this project by defining time-related zones of contribution for Clark County Public supply wells using the Portland Basin ground water flow model. Additional support was provided by funding from the City of Vancouver.

Purpose

This project was undertaken to assess the standard methods of wellhead zone of contribution defined by EPA (June, 1987) to assist Department of Health efforts to determine the most appropriate wellhead protection area delineation methods for conditions in Washington. These results are presented to the Washington Wellhead Program Technical Advisory Committee who will make recommendations to the Department of Health. A second goal is to provide wellhead zone of contribution maps for the principal public supply wells in Clark County, Washington.

Scope

This report describes wellhead protection area zone of contribution delineation methodologies used on a set of Clark County area public supply wells by the Intergovernmental Resource Center. A determination of the most appropriate method is made using a qualitative assessment of data requirements, applicability and level of confidence, and cost of each reviewed delineation method.

There are two main parts to this report. The first is a summary section that describes the preferred delineation methods and the reasons for the selection of these methods. The summary section also includes a general description of the standard EPA (June, 1987) delineation methods applied in Clark County. The remaining part of this document is appendices with reports describing the application of the EPA delineation methods to public supply wells in Clark County. This includes a series of brief reports with map figures showing delineation results using hydrogeologic mapping, analytical models, calculated fixed radius, and arbitral fixed radius. Two appendix sections describe the two-dimensional and three-dimensional numerical model derived delineations.

Delineation analysis consisted of applying the EPA defined methods to a set of public supply wells and noting the level of effort, data requirements, and general accuracy of the methods to incorporate local hydrogeologic factors. The six general delineation methodologies evaluated are described by the EPA guidelines document (EPA, June 1987). They are:

- Arbitrary Fixed Radius
- Calculated Fixed Radius
- Simplified Variable Shapes
- Analytical Models
- Hydrogeologic Mapping
- Numerical Flow/Transport Models

In general, there is an increase in complexity and cost from the top to bottom of the list, with arbitrary fixed radius lowest and numerical modeling highest. Along with increasing cost and complexity there is generally an increase in accuracy.

Some modifications were made to the EPA basic delineation method list during this project. Two separate numerical modeling methods were applied; both are finite difference models. Output from the regional three-dimensional Portland Basin model (Morgan and McFarland, 1992) using MODFLOW (McDonald and Harbaugh, 1988) was used with MODPATH (Pollack, 1989) to delineate zones of contribution for about forty public supply wells. Two models of the Vancouver area aquifer were constructed at the Intergovernmental Resource Center using a CAD-assisted two-dimensional finite-difference model (FLOWPATH, Franz and Guiguier, 1989).

An additional method was added by defining a method as Combined Hydrogeologic Mapping and Analytical Models. This method combines analytical models and hydrogeologic mapping of aquifer boundaries and variations in gradient and flow direction. This method is included in the Hydrogeologic Methods section of the delineation report appendices, but is described separately in the summary section.

Only methods that define zones of contribution in terms of time of travel were included in the analysis. Alternative approaches use drawdown criteria, aquifer boundaries, and assimilative capacity to define wellhead protection areas. The desire of the state program was to use a time of travel based delineation method. The state program is currently considering requiring zones of contribution for travel times of five to ten years. The Clark County delineations were done for 1, 5, 10, 20, and 50 years where hydrogeologic conditions permitted.

Limitations of Reviewed Delineation Methods

Except for three dimensional models, delineation methods used in this project only consider travel time of ground water to a well within the aquifer of interest. No consideration is given to the time required for water to travel from land surface to the aquifer. Contaminant behavior within the ground water system is not considered; contaminants are assumed to be conservative, or move at the rate of ground water.

This simplification results from two considerations. First, it is recognized that data and resources are rarely available to perform the analysis required for more detailed description of ground water and contaminant flow. Secondly, a conservative policy is in place to protect the aquifer through its extent based on the assumption that contaminants can enter the aquifer through vertical conduits such as abandoned wells and naturally occurring holes in overlaying low permeability zones.

Also, it should be stressed that all of the methods used here are simplified models of the natural system. The ability of each method to simulate the actual contributing area of a well is dependent upon the degree to which the simplifying assumptions of the model match actual hydrogeologic conditions. Most models, especially widely applied simple two-dimensional models, only incorporate the most basic elements of the natural system.

All of the delineations in this document could be characterized as a first approximation of the true zone of contribution. In many cases this will be adequate, but in areas where there is a larger risk to ground water or a need to carefully manage pumping to prevent contamination, a more sophisticated delineation process incorporating data collection and monitoring may be warranted.

Criteria For Preferred Method Selection

A qualitative comparison of delineation methods applied in Clark County was made using these criteria: level of accuracy or confidence, level of effort required, and cost.

Delineation methods to fit into two general groups: methods that can be applied with little or no collection or interpretation of hydrogeologic data and methods that require hydrogeologic data and interpretation by ground water professionals. Many hydrogeologic settings require delineations that incorporate hydrogeologic data collection and interpretation to generate reasonably accurate delineations.

The methods that do not require hydrogeologic data or very limited data are:

- Arbitrary Fixed Radius
- Calculated Fixed Radius

The methods that require hydrogeologic data and interpretation are:

- Simplified Variable Shapes
- Analytical Models
- Hydrogeologic Mapping
- Numerical Flow/Transport Models

Preferred method not requiring hydrogeologic data interpretation

If the overriding consideration is a lack of financial resources or hydrogeologic data, the most appropriate method is one that requires little or no data. Here, the calculated fixed radius or arbitrary fixed radius are the best option. Ideally the calculated fixed radius method can be applied using information that should be readily available at each public supply system.

The calculated fixed radius delineation can be determined in a few hours using well construction information from the system water well reports and records of pumping or an estimate of pumping based on average per capita consumption. Also, once the method is understood and data is assembled, additional delineation calculations can be completed in several minutes. Some interpretation is required to determine screen interval, aquifer porosity, and when to combine more than one well into a single delineation, but simple guidelines could be provided to assure that reasonable parameters are used.

The principal drawback to using the calculated fixed radius method is severely limiting assumptions that do not consider common hydrogeologic characteristics such as ground water flow gradient and possible aquifer boundaries. The calculated fixed radius is most appropriate in aquifers that approach truly confined conditions where little water moves vertically through the aquifer and the potentiometric surface gradient is low. Alternatively, the method could be applied to unconfined settings with flat water level surfaces or low ground water flow rates.

Where these basic assumption conditions are not met, it is likely that the zone of contribution will not be circular or centered over the well. The use of calculated fixed radius should include some method to establish when another more sophisticated method should be used. This might include some analysis of ambient ground water velocity and proximity to hydrogeologic boundaries.

Preferred methods requiring hydrogeologic interpretation

These methods offer diversity in level of effort and ability to characterize complex hydrogeologic settings. In some cases, a simple analytical model may provide a good approximation of the zone of contribution. However, in settings with important aquifer boundaries and non-uniform hydrogeologic characteristics more sophisticated methods such as detailed hydrogeologic investigation or three-dimensional computer modeling may be warranted. These methods also have limitations in simulating real field conditions such as non-steady state flow, and vertical flow through aquifers. In practice, the data required to accurately simulate these conditions is rarely available.

When general hydrogeologic data availability and amount of effort that can be expended on delineations is considered, the preferred method is a combination of hydrogeologic mapping and computerized analytical models. This method can make a good first approximation of the zone of contribution using available hydrogeologic information. This method can produce two dimensional delineations incorporating some aquifer non-uniformity, irregular boundaries, water level irregularities, and an estimate for time of travel zones of contribution to a pumping well.

The combined hydrogeologic and analytical method has the advantage of providing a framework for assembling available information describing hydrogeologic setting, well station design, and pumping rates.

Description of EPA Delineation Methods Used in Clark County

Arbitrary Fixed Radius

Arbitrary fixed radius delineation uses a specified radius distance to draw a circular boundary around the protected well. The radius distance is usually specified by the managing agency. The current Department of Health 100 foot sanitary setback is an example of an arbitrary fixed radius wellhead protection zone currently in use.

Radius distance determination can be based on hydrogeologic analysis or policy considerations such as the perceived size of a manageable wellhead protection area. Once the radius distance is specified, it is very simple to use the method at individual wells.

Some latitude can be built into an arbitrary fixed radius delineation system by basing radius size on pumping rates, system size, or hydrogeologic setting. Varying the radius size with pumping rate or system size will help to balance minimum zone of contribution size requirements for adequate protection with the need to keep zones of contribution small enough to effectively manage.

The radius used by IRC was determined using average values for aquifer properties and pumping from the 20 delineated wells and well stations to calculate a ten year time of travel radius with a RESSQC model (EPA, March 1991).

Data Requirements

Arbitrary fixed radius is simpler to implement than any other method because little or no site specific data is required to draw the delineation boundary. The only requirements are accurate well location mapping and an understanding of map scales.

Applicability and Confidence Level

From a technical standpoint the arbitrary fixed radius method is most applicable where hydrogeologic conditions approximate a flat lying tabular aquifer. In practice the arbitrary fixed radius method is used as a simple means to implement of drawing a wellhead protection area boundary. This is most desirable where resources are in short supply or there is an imperative to designate protection areas without taking the time to perform more technically rigorous delineations. Arbitrary fixed radius delineations are compatible with the concept of "phasing," where more sophisticated delineation methods are applied as local wellhead protection programs evolve.

The arbitrary fixed radius method often fails to accurately define the zone of contribution because it doesn't consider site specific hydrogeologic conditions such as gradient, boundaries, and aquifer hydraulic properties. This can be a particularly significant concern in Washington where hydrogeologic conditions often do not dictate circular zones of contribution, especially for travel times longer than one year or wells with low pumping rates. This leads to the tendency of the arbitrary fixed radius method to both over protect and under protect at the same site.

Cost

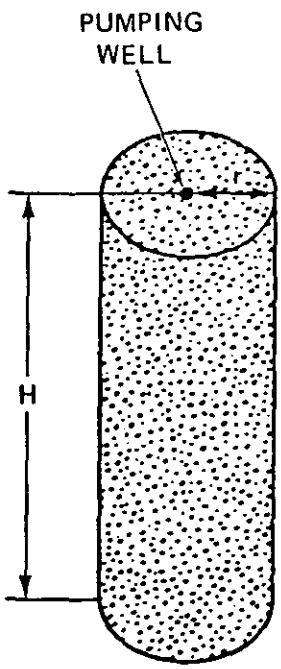
Arbitrary fixed radius is an inexpensive method to implement. Most of the cost is in the time required to make the scale base map and correctly locate the wells that are to be delineated. Drawing the delineation should only take a few minutes. At the state program level some time will be required to determine a radius or set of radii, and describe the rationale for each.

Calculated Fixed Radius

Calculated fixed radius delineations draw a circular protection area for a specified time of travel threshold. A simple volumetric flow equation is used to calculate the radius. A good description of how to use the volumetric flow equation is included in EPA (June, 1987) and is shown in Figure 2.

The calculated fixed radius calculations were performed by a planner using the EPA guidance document (June 1987) as an instruction guide. The basic data included well records for all the wells and pumpage data to determine annual withdrawal. A spread sheet program was used to make the calculations. Assistance was required to determine the best way to interpret well open intervals, multiple well stations, and porosity.

WHPA Delineation Using FDER Volumetric Flow Equation for Well in Florida



$$r = \sqrt{\frac{Q\,t}{\pi\,n\,H}} = 1138 \text{ ft}$$

WHERE
Q = Pumping Rate of Well = 694.4 gpm = 48,793,668 ft^3/yr
n = Aquifer Porosity = 0.2
H = Open Interval or Length of Well Screen = 300 ft
t = Travel Time to Well (5 Years)

(Any consistent system of units may be used.)

$$\underbrace{Q\,t}_{\text{VOLUME PUMPED}} = \underbrace{n\,\pi\,H\,r^2}_{\text{VOLUME OF CYLINDER}}$$

Figure 2. Volumetric flow equation (EPA, June 1987)

Data Requirements

The volumetric flow equation referenced by EPA (June 1987) requires pumping rate, screened interval length, porosity, and specified travel time to calculate a protection area boundary radius. Pumping rate may be available from well pump meter readings or can be estimated from the number of people or hookups served. Screened interval is taken from well construction records and requires some interpretation. Porosity is rarely known, and is often estimated from aquifer rock type using standard tables. This may require specification of appropriate porosity values by the state.

Applicability and Confidence level

Generally, if well construction records and clear instructions are available, most people with some technical training or experience should be able to perform the volumetric flow equation calculations.

The basic assumptions of the method are that the water bearing zone has uniform porosity and has no regional gradient, allowing a circular area to contribute to the well, and that there is no recharge to the aquifer. The method is most applicable where these conditions are nearly met: Settings with confined low flow rate aquifers or settings with flat lying unconfined or semiconfined aquifers with low rates of recharge.

The use of well-specific data describing pumping rate and unit thickness increases the level of accuracy over the arbitrary fixed radius method. However, the inability of this method to incorporate hydrogeologic heterogeneity leads to the likelihood of both over protect and under protect non circular contributing areas.

Cost

Calculated fixed radius delineations are slightly more costly to perform than arbitrary fixed radius delineation because some analysis is required. However, if well records, and pumping rates are readily available the delineation calculations should take a few minutes to perform and document for each well. This makes it possible to do a large set in one or two days. If well construction and pumping data has to be assembled another few hours or so can be added to the analysis time. Cost for an engineering consultant to do the job should be under a $1000, and would depend on the number of wells and amount of time spent compiling data.

Simplified Variable Shapes

The simplified variable shapes method uses a set of standardized wellhead protection area shapes or forms that are drawn to incorporate analysis of hydrogeologic settings and pumping rates. The method has been used in England where a large number of standard forms were generated for the chalk aquifer (EPA, June 1987). The forms vary in shape from circles to elongated parabolas. Larger pumping rates give wider forms. Higher ground water flow rates produce longer parabolas. The process of designating a protection area involves selection of the appropriate standard form matching well pumping rate and regional ground water flow rate. Then orienting the form according to ground water flow direction. In the English example, standard forms were generated using the analytical methods based on the uniform flow equation.

Data Requirements

Information needed to construct the standard shapes includes general hydrogeologic setting information such gradient, aquifer type, aquifer thickness, aquifer hydraulic properties, simple aquifer boundaries, and possibly recharge rates. Shapes are generated for a variety of pumping rates and water level gradients or ground water flow velocities for each setting type. The data required to correctly place a standard shape at a well include pumping rate, aquifer type or hydraulic properties, aquifer water level gradient or flow velocity, and flow direction.

Applicability and Level of Confidence

The method depends on the ability to construct a reasonable set of forms and then select and orient them properly. Areas most suited to this process should have relatively uniform hydrogeologic conditions and a group of ground water professionals that can uniformly implement the delineation program.

Simplified variable shapes are not being considered as a delineation alternative because the level of effort to develop and correctly orient the forms could be as great as generating individual analytical method delineations for each well. The method requires a level of data collection and hydrogeologic interpretation similar to simple analytical models. Also, the great variety of hydrogeologic settings in Washington suggests that producing a set of standard forms for the state would be a large task.

If the method is carefully implemented, it could give results that may be nearly as good as applying simple analytical models to each well. Accuracy depends to a large extent on the ability of individual selecting and orienting the form at the well. An error in characterizing the hydrogeologic setting could result in selection of an inappropriate form or orienting the form in a direction that does not correspond to the actual ground water flow direction.

Cost

The cost of implementation includes the expense to the state of developing the sets of shapes and the expense to water systems of selecting and orienting the appropriate shape. Development and documentation of a set of shapes could take a ground water professional several months due to the number of different hydrogeologic regions in the state and the great diversity of the principal hydrogeologic parameter values within these hydrogeologic regions. Making a proper shape selection and orienting it would probably take almost the same amount of effort as doing a simple analytical model. It is conceivable that the complexity of diverse shapes could make selection of the appropriate shape more time consuming than constructing a simple analytical model.

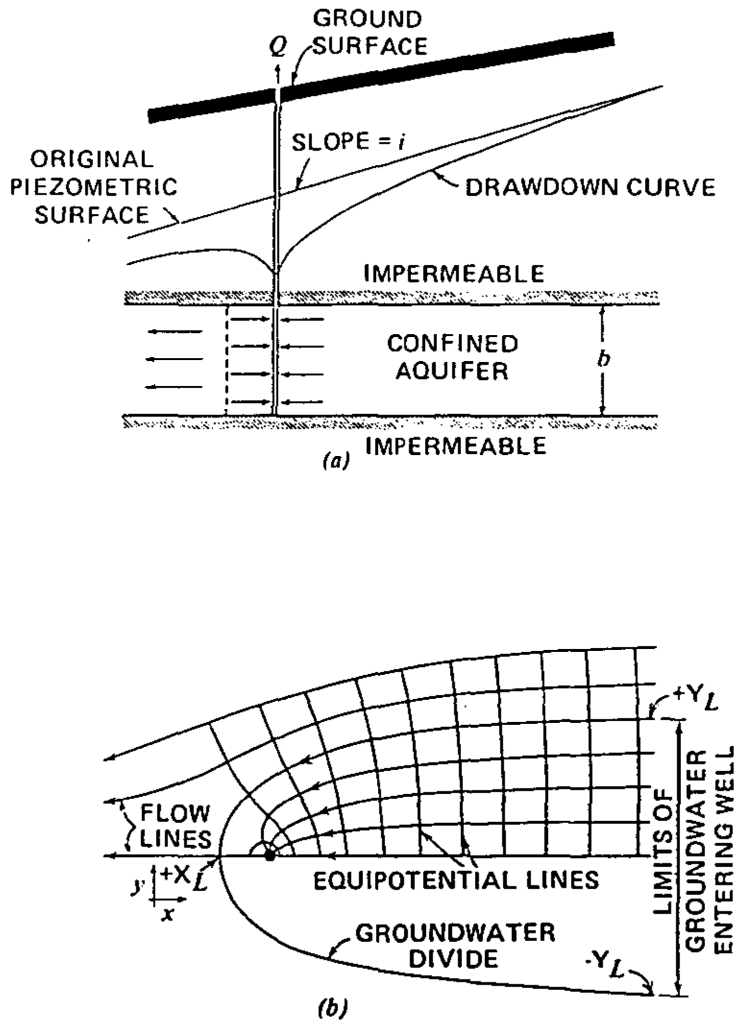
Analytical Methods

Analytical methods can include simple mathematical calculations and graphical methods to delineate wellhead zones of contribution (EPA, June 1987) or simple analytical solution based computerized ground water flow models. Figure 3 shows a simple method to determine a steady state zone of contribution using the uniform flow equation. The International Ground Water Modeling Center is compiling a revised bibliography of ground water flow models that should include all the currently available computerized analytical models.

The general description of computerized analytical models includes two groups. One group, described as analytical models includes models such as DREAM (Bonn and Rounds, 1990) that superposition calculated well drawdown on to uniform flow fields. The other group, semi-analytical models, is characterized by the EPA WHPA models (EPA, March 1991) and the RESSQ model (Javandel and others, 1984). These models are based on the uniform flow equation and use numerical solution and the Darcy velocity equation to calculate flow path lines and travel time. The EPA WHPA models are probably the most widely used semi-analytical models and are based on the RESSQ model.

This project used the EPA WHPA semi-analytical computer models for time of travel zone of contribution delineations due to the ease of use, general applicability, and widespread use of the EPA WHPA models and earlier RESSQ model. The EPA models are generally easy to use. Menu driven input forms set up models and control graphic display of model results. Output can be directed to common graphics and print formats at map scales that correspond to common USGS quadrangle scales. The models produce time related zone of contribution that can match the times commonly used in wellhead protection area delineation. The public domain model has been distributed by EPA at evaluation workshops and is available though the International Ground Water Modeling Center.

WHPA Delineation Using the Uniform Flow Analytical Model



$$-\frac{Y}{X} = \tan\left(\frac{2\pi Kbi}{Q} Y\right)$$

UNIFORM-FLOW EQUATION

$$X_L = -\frac{Q}{2\pi Kbi}$$

DISTANCE TO DOWN-GRADIENT NULL POINT

$$Y_L = \pm \frac{Q}{2Kbi}$$

BOUNDARY LIMIT

LEGEND:

- ● Pumping Well

Where:
Q = Well Pumping Rate
K = Hydraulic Conductivity
b = Saturated Thickness
i = Hydraulic Gradient
π = 3.1416

Figure 3. Uniform flow equation (EPA, June 1987)

Data Requirements

Morrissey (1989) describes the data necessary to correctly use an analytical model. Each model or method will have specific requirements that may expand upon these basic data needs. The data include: 1) a water level map for pre-pumping conditions, 2) presence and position of lateral aquifer boundaries, these can be idealized as no-flow barrier boundaries or fully penetrating stream boundaries, 3) well construction description, well pumping rate and schedule to determine an average pumping rate, 4) average aquifer hydraulic properties including transmissivity and porosity, and in some models 5) information describing leaky or unconfined conditions.

Applicability and Level of Confidence

The EPA WHPA models and other computerized semi-analytical and analytical models allow more sophisticated delineation than the use of the uniform flow equations and graphical analysis of drawdown superimposed on water level slope. The principal advantage of the computerized models is that they can provide time of travel delineations that incorporate a number of boundary conditions such as multiple pumping and injection wells, stream and barrier aquifer boundaries, and recharge of leakage into an analytical solution of gradient around the delineated well.

The EPA WHPA models are recognized as an appropriate method to delineate wellhead zones of contribution when sufficient hydrogeologic data is available. The principal advantages of those models include ease of use by ground water professionals and ability to incorporate some site specific hydrogeologic characteristics. Analytical model delineations can also be used in conjunction with hydrogeologic mapping to incorporate more complex aquifer boundaries and gradient characteristics than is possible solely with the models.

However, there are serious limitations to analytical models that result from the required simplification of actual conditions and limitations of the superpositional analysis. These include the inability to model leaky boundaries, inability to model partially penetrating wells, and an inability to account for variation in aquifer hydraulic properties.

Analytical models generally consider only two-dimensional flow. This may result travel pathlines that continue past the actual extent of recharge to the well. Another limitation of two dimensional models noted by Morrissey (1989) is that they do not consider differences between horizontal and vertical hydraulic conductivity. In layered aquifers, where vertical hydraulic conductivity is often much lower than horizontal hydraulic conductivity, this can result in smaller zones of influence than would be modeled considering vertical anisotropy.

In many settings analytical models are probably best suited for examining conditions near a pumping well where deviations from basic assumptions are least likely to be violated by boundary conditions and varying aquifer properties, and simulated pumping effects are greatest.

Some consideration should be given to the degree of conservatism (delineating the largest possible area) that is being incorporated into a specific model. Using the best estimate for each parameter is one option. Using the most conservative value estimate for each parameter is an alternative approach that assures a conservative delineation. In cases where a large potential range of parameter values exists, some sensitivity analysis may be useful. Another approach that can be useful in dealing with uncertain parameter values is the EPA WHPA MONTEC module (EPA, March 1991), which uses the Monte Carlo approach to incorporate uncertainty into zone of contribution delineations.

With careful application, using good hydrogeologic data, analytical models can give moderate levels of accuracy. Approaches can be developed to simulate boundaries using image wells, well interference can be incorporated, and semi-confined or unconfined conditions can be approximated, resulting in zone of contribution simulations that may approach real world conditions. Aquifer heterogeneity, irregular boundaries, and irregular gradient and flow direction are not normally accounted for in simple analytical models.

Cost

Cost for delineations using analytical models is expected to be between $5,000 and $25,000 for a group of wells. This estimate is approximate and includes compilation of existing hydrogeologic data, modeling and report preparation.

Hydrogeologic Mapping Methods

Hydrogeologic mapping delineation methods are loosely defined by EPA (June 1987) as geologic, geophysical, and dye tracing methods that can be used to define zones of contribution, flow boundaries, and time of travel. One of the principal uses of hydrogeologic mapping in existing wellhead protection programs has been to map the extent of small alluvial aquifers. In Washington, where hydrogeologic and geologic information often is either regional in scope on non-existent, hydrogeologic mapping is often required to characterizing aquifer properties, ground water flow directions, and aquifer boundaries as a prelude to analytical or numerical modeling.

Hydrogeologic mapping methods can be useful tools where hydrogeologic conditions preclude application of simple analytical models. Examples of settings where geologic features exert strong control over ground water flow direction and rates are fractured rock settings, karst, small valley fill deposits, and irregular river or barrier boundaries.

Basic hydrogeologic mapping steps should include 1) acquiring or producing a water level map for the delineated aquifer; 2) establishing and mapping aquifer boundaries including confining layers; 3) description of well pumping rate and well field construction; 4) description of aquifer hydraulic properties; 5) determining the vertical direction of flow and recharge rate. The water level map is probably the single most important piece of hydrogeologic information because it determines direction and gradient of ground water flow.

Field hydrogeologic methods that can be applied to track ground water flow or mapping aquifer boundaries include: geologic mapping, multiple well pump tests, tracer tests, geophysical methods, and age dating using tritium or fluorocarbons. Each of these field methods can be costly and should be used after analysis of all existing hydrogeologic data. Age dating may be an especially useful and cost effective tool for assessing the degree to which "confined" aquifers are separated from leakage from above. Multi-well pumping tests have been used to identify areas that are influenced by pumping in complex hydrogeologic settings. One example is to map the interconnected fracture zones by observed drawdown in monitoring wells.

Combining analytical modeling with hydrogeologic mapping was identified as an effective means to combine mathematical simulations of pumping effects with observed hydrogeologic boundaries to produce zone of contribution delineations that are enhanced beyond the capability of either single method.

Data Requirements

Hydrogeologic methods are data compilation and interpretation processes. The basic data that needs to be assembled for a hydrogeologic interpretation to determine zone of contribution includes geologic maps, aquifer water level mapping, pump test data, hydrogeologic reports, and well reports.

Basic well and hydrogeologic information is often compiled for water system reports, source characterization reports, regional hydrogeologic investigations, and geologic map reports. Principal data sources are existing geologic reports, hydrogeologic reports, water system plans, water purveyor engineering reports and records, and Department of Ecology water well reports. Other information that can be useful includes river stage measurements, rainfall data, and water quality analyses. Good sources for information include the US Geological Survey, local water purveyors, the Department of Natural Resources library, and water system reports prepared for the Department of Health.

Applicability and Level of Confidence

One of the principle benefits of using hydrogeologic mapping as a component of, or basis for wellhead protection area delineations is the incorporation of existing geologic data to make a more hydrogeologically sensible delineation. In some cases, such as fractured rock or karst, hydrogeologic methods may be the only valid approach to identifying flow directions.

One drawback to simple hydrogeologic mapping methods is that while these methods produce good definition of the total zone of contribution based on aquifer boundaries and geometry, time of travel zones of contribution require additional analysis to evaluate the movement of ground water under the influence of pumping wells.

Hydrogeologic methods require a high level of professional expertise in hydrogeologic mapping or the use of specific geophysical or tracer methods.

Hydrogeologic methods have a high level of confidence in shallow aquifer systems, where easy to define, near surface boundaries exist.

Cost

Cost can increase rapidly as investigations move from office analysis of to field investigations. A minimum of several hours of hydrogeologic data compilation and site characterization should be included in any delineation more sophisticated than calculated fixed radius. More elaborate characterizations that include interpretation of well data, drawing water level maps, cross-sections, and geologic maps can take from one week to several weeks and cost from $5,000 to $20,000. When work moves to the field, costs can escalate into the tens of thousands of dollars for work that includes aquifer pumping tests, geophysics, water level monitoring and tracer analysis.

<u>Combined Hydrogeologic Mapping and Analytical Models</u>

This method was used on several wells where there was a need to combine pumping well effects on the zone of contribution and incorporate important hydrogelogic features. Combining analytical models with hydrogeologic mapping served as a means to produce more accurate delineations than either individual method. In this case, hydrogeologic mapping refers to basic characterization of aquifer geometry, boundaries, aquifer properties, and ground water flow direction. Analytical models are the EPA WHPA semi-analytical models (March 1991). Use of analytical models enhances hydrogeologic mapping delineations by calculating time of travel related zones of contribution in the area of directly effected by well pumping. Hydrogeologic mapping-derived information such as changes in gradient and flow direction, and position of aquifer boundaries can enhance analytical model zones of contribution by adding these difficult to model heterogeneities.

The method combining hydrogeologic mapping and analytical models was included in the hydrogeologic methods sections of the Clark County wellhead delineation reports (Appendices A through Q).

The methodology is three stepped. A hydrogeologic mapping compilation is performed to characterize the aquifer and well field setting. Once suitable information is developed, the EPA WHPA models, or another suitable model is used to simulate the time related zone of contribution to the pumping well. The hydrogeologic mapping data and model results are then compiled onto one map.

Basic hydrogeologic mapping steps should include 1) acquiring or producing a water level map for the delineated aquifer; 2) establishing and mapping aquifer boundaries including confining layers; 3) description of well pumping rate and well field construction; 4) description of aquifer hydraulic properties; 5) determining the vertical direction of flow and recharge rate. The water level map is probably the single most important piece of hydrogeologic information because it determines direction and gradient of ground water flow.

Once hydrogeologic information is assembled an appropriate analytical model can be selected and used. The method of modeling will depend largely on the aquifer boundaries proximity, and the variability of gradient, flow direction and aquifer properties.

The final step of integrating the hydrogeologic mapping and analytical model results produces a wellhead protection area delineation map for the desired time period and hydrogeologic boundaries. The modeled zone of contribution is integrated, as well as possible, with the hydrogeologic mapping. Care must be taken to assure that assumptions incorporated into the model are reasonably matched to the hydrogeologic mapping.

The simplest type of delineation using this method would be for a uniform and continuous aquifer with a slight variation in flow direct or ground water divide up gradient from the delineated well. In settings where boundaries are present or gradient changes significantly require more careful integration of basic hydrogeologic data and flow rate analysis.

Data requirements

Hydrogeologic methods are data compilation and interpretation processes. The basic data that needs to be assembled for a hydrogeologic interpretation to determine zone of contribution includes geologic maps, aquifer water level mapping, pump test data, hydrogeologic reports, and well reports.

Basic well and hydrogeologic information is often compiled for water system reports, source characterization reports, regional hydrogeologic investigations, and geologic map reports. Principal data sources are existing geologic reports, hydrogeologic reports, water system plans, water purveyor engineering reports and records, and Department of Ecology water well reports. Other information that can be useful includes river stage measurements, rainfall data, and water quality analyses. Good sources for information include the US Geological Survey, local water purveyors, the Department of Natural Resources library, and water system reports prepared for the Department of Health.

Applicability and Level of Confidence

This method is applicable anywhere that hydrogeologic mapping methods are used. The method is most applicable in areas where hydrogeologic conditions are sufficiently non-uniform enough to merit the extra effort to combine the two methods. For instance, a confined aquifer with little variation in water level gradient and no apparent near well boundaries is less likely to benefit from this method. However, a large capacity well in a setting with large transmissivity, steep gradient, and changing flow direction would be an ideal situation to apply this method. Another example where the method could be used is a setting where a stream or barrier boundary is modeled as a straight line paralleling a more irregular mapped hydrogeologic boundary. In such a case, the model and the mapped boundary could both be transferred to a single map preserving the detail of the hydrogeologic map and using the model results.

This method may be applicable in many areas of the West were large basins contain extensive alluvial aquifer systems. In these basins hydrogeologic boundaries are often very distant from wells and complex depositional and tectonic histories produce non-uniform aquifer properties and water level surfaces near wells.

The level of confidence for this method is similar to both the hydrogeologic mapping method and the analytical model methods. Careful application of the method should produce more accurate delineations than simply using hydrogeologic mapping or analytical models. As is the case with hydrogeologic mapping and analytical models, an experienced hydrogeologic professional is required to perform the analysis.

Cost

Cost should be higher than either simple hydrogeologic mapping or analytical models because more work is required. The cost to incorporate analytical models into hydrogeologic mapping based analysis should be equivalent to an additional several days of work; depending on the complexity of the setting and number of wells, one to three days is a good estimate. A total effort could be measured in days or a few weeks depending on complexity and scope.

Numerical Modeling

Numerical ground water flow models with particle tracking or transport models are generally recognized as a technically superior means to delineate wellhead zones of contribution where sufficient hydrogeologic data can be assembled. Numerical models can incorporate complex boundary conditions, aquifer heterogeneity, and multiple aquifer settings. Solute or contaminant transport models can include parameters describing movement of specific compounds through aquifer materials. Models are generally grouped as two dimensional and three dimensional. A good short discussion of the various types of models and capabilities of specific model codes is presented in van der Heijde and Beljin (1987).

Many models are available that can be run on personal computers. Also, commercial pre- and post-processors for standard models such as USGS MODFLOW (McDonald and Harbaugh 1988) and MODPATH (Pollack, 1989) use computer assisted drafting systems to greatly ease the time consuming process of entering data into the model. The International Ground Water Modeling Center has compiled lists of models suitable for wellhead protection area delineation. One listing is included in EPA guidance document (June, 1987). A more complete annotated bibliography describing ground water flow models is published by the International Ground Water Modeling Center (1987). The Center reports that an updated version of the 1987 annotated bibliography should be available soon.

Models can simulate either steady state equilibrium conditions or transient conditions. Steady state models are more widely used and require less information to calibrate. Transient models can be used to simulate the effects varied pumping rates or other hydraulic changes will have on zone of contribution size and shape in non-equilibrium conditions.

Usually, numerical model based delineations follow two step process. A ground water flow model is constructed to simulate the observed aquifer water level distribution and in may cases estimated flux rates. Then a particle tracking or contaminant transport model is added to calculate the zone of contribution.

Data Requirements

Data requirements for numerical modeling are similar to hydrogeologic mapping and analytical models. However, the numerical model is able to incorporate much more of this information. Basic data needs for a numerical model include: 1) an aquifer water level map, 2) aquifer boundary conditions, 3) well field design criteria, 4) aquifer hydraulic properties, and 5) recharge rates. Other information that is likely to be needed to produce a good model includes hydraulic properties of bounding units and measurements and estimates of model boundary flux rates.

Applicability and Level of Confidence

Numerical models are especially appropriate in areas where complex hydrogeologic conditions exist or a variety of management alternatives need to be evaluated. Since modeling can be an expensive, clear goals need to be established to guide model development and data collection. Numerical modeling projects are most applicable where there is need and support for an ongoing management tool.

Numerical modeling should be used following hydrogeologic data collection and formation of a hydrogeologic model. Ongoing data collection should be performed to assure that the model is accurate and provide a basis for further model refinement.

A well calibrated numerical model, using good hydrogeologic data and an accurate approximation of boundary conditions can have a high level of accuracy. The confidence in a particular model simulation is determined, to a large extent by how well the model simulates observed heads and observed or estimated boundary fluxes.

Two-dimensional models with particle tracking will produce different results of than three dimensional models with particle tracking. Three dimensional models, can simulate vertical flow, allowing reverse flow paths to exit the aquifer at the point of recharge. This is not the case with a two dimensional model, where flow paths extend to the lateral edges of the model.

Cost

Model development costs can be high and depend on many factors that influence the level of effort. Minimum costs for a simple modeling effort could be about $20,000, while complex models that incorporate many types of data, require additional data collection, and require careful calibration can cost several hundred thousand dollars to complete and will require continuing support.

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GLOSSARY

The purpose of this Glossary is to provide a list of terms commonly used by hydrogeologists, as well as some specific terms used in ground-water contamination assessments and wellhead protection. The definitions provided in this glossary are not necessarily endorsed by EPA nor are they to be viewed as suggested language for regulatory purposes. Not all of these terms appear in this document. Numbers in parentheses indicate the reference sources for most of the hydrogeologic terms; the major source was (1). Some adaptations of the definitions in these published references is included.

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GLOSSARY

Absorption. The process by which substances in gaseous, liquid, or solid form dissolve or mix with other substances (6).

Adsorption. Adherence of ions or molecules in solution to the surface of solids (1). The assimilation of gas, vapor, or dissolved matter by the surface of a solid (2). The

Capillary fringe. The zone at the bottom of the vadose zone where ground water is drawn upward by capillary force (2). The zone immediately above the water table, where water is drawn upward by capillary action (3).

Capillary rise. The height above a free water surface to which water will rise by capillary action (1).

Capillary water. Water held in the soil above the phreatic surface by capillary forces; or soil water above hydroscopic moisture and below the field capacity (1).

Carbonate. A sediment formed by the organic or inorganic precipitation from aqueous solution of carbonates of calcium, magnesium, or iron (2).

Carbonate rocks. A rock consisting chiefly of carbonate minerals, such as limestone and dolomite (2).

Clastic. Pertaining to a rock or sediment composed principally of broken fragments that are derived from pre-existing rocks or minerals and that have been transported some distance from their places of origin (2).

Coefficient of storage. The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head (2).

Coefficient of transmissivity. See transmissivity (2).

Colloid. Extremely small solid particles, 0.0001 to 1 micron in size, which will not settle out of a solution; intermediate between a true dissolved particle and a suspended solid, which will settle out of solution (2).

Cone of depression (COD). A depression in the ground-water table or potentiometric surface that has the shape of an inverted cone and develops around a well from which water is being withdrawn. It defines (in cross-section) the area of influence of a well. Also called pumping cone and cone of drawdown (COD) (1,2).

Confined aquifer. An aquifer bounded above and below by confining units of distinctly lower permeability than the aquifer media; or one containing confined ground water (1). An aquifer in which ground water is under pressure significantly greater than atmospheric and its upper limit is the bottom of a bed of distinctly lower hyraulic conductivity than that of the aquifer itself.

Confining unit. A hydrogeologic unit of relatively impermeable material, bounding one or more aquifers. This is a general term that has replaced aquitard, aquifuge, and aquiclude and is synonymous with confining bed (1). A body of material of low hydraulic conductivity that is stratigraphically adjacent to one or more aquifers. It may lie above or below the aquifer (3).

Connate water. Ground water entrapped in the interstices of a sedimentary or extrusive igneous rock at the time of its deposition (1).

Consolidated aquifer. An aquifer made up of consolidated rock that has undergone solidification or lithification.

Contaminant. An undesirable substance not normally present, or an usually high concentration of a naturally occurring substance, in water, soil, or other environmental medium (1).

Contamination. The degradation of natural water quality as a result of man's activities. There is no implication of any specific limits, since the degree of permissible contamination depends upon the intended end use, or uses, of the water (2).

Convective transport. The component of movement of heat or mass induced by thermal gradients in ground water (see advection).

Criteria, WHPA. Conceptual standards that form the basis for WHPA delineation. WHPA criteria can include distance, drawdown, time of travel, assimilative capacity, and flow boundaries.

Critical Aquifer Protection Area (CAPA). As defined in the Safe Drinking Water Act, is (1) all or part of an area located within an area for which an application of designation as a sole or principal source aquifer (pursuant to Section 1424(e)) has been submitted and approved by the Administrator not later than 24 months after the date of enactment and which satisfies the criteria established by the Administrator; and (2) all or part of an area that is within an aquifer designated as a sole source aquifer (SSA), as of the date of enactment of the Safe Drinking Water Act Amendments of 1986, and for which an areawide ground-water protection plan has been approved under Section 208 of the Clean Water Act prior to such enactment.

Darcy's law. An empirically derived equation for the flow of fluids through porous media. It is based on the assumptions that flow is laminar and inertia can be neglected, and states that velocity of flow is directly proportional to hydraulic gradient (see specific discharge).

Delay time. Duration of time for contaminant or water to move from point of concern to the well; analogous to time-of-travel.

Density. Matter measured as mass per unit volume expressed in pounds per gallon (lb/gal), pounds per cubic foot (lb/ft^3), and kilograms per cubic meter (kg/m^3) (2). The mass of quantity of a substance per unit volume. Units are kilograms per cubic meter or grams per cubic centimeter (3).

Desorption. See sorption, which is the reverse process.

Diffusion coefficient. See molecular diffusion.

Diffusivity, soil water. The hydraulic conductivity divided by the differential water capacity, or the flux of water per unit gradient of moisture content in the absence of other force fields (1).

Direct precipitation. Water that falls directly into a lake or stream without passing through any land phase of the runoff cycle (3).

Discharge area. An area in which ground water is discharged to the land surface, surface water, or atmosphere (1). An area in which there are upward components of hydraulic head in the aquifer. Ground water is flowing toward the surface in a discharge area and may escape as a spring, seep, or base flow, or by evaporation and transpiration (3).

Discharge velocity. An apparent velocity, calculated by Darcy's law, which represents the flow rate at which water would move through an aquifer if the aquifer were an open conduit. Also called specific discharge (3).

Dispersion. The spreading and mixing of chemical constituents in ground water caused by diffusion and mixing due to microscopic variations in velocities within and between pores (2).

Dispersion coefficient. A measure of the spreading of a flowing substance due to the nature of the porous medium (and specific substance or fluid properties), with interconnected channels distributed at random in all directions. Also the sum of the coefficients of mechanical dispersion and molecular diffusion in a porous medium (1).

Dispersivity. A property of a porous medium (and the specific substance or fluid) that determines the dispersion characteristics of the contaminant in that medium by relating the components of pore velocity to the dispersion coefficient (1).

Distribution coefficient. The quantity of a solute sorbed per unit weight of a solid divided by the quantity dissolved in water per unit volume of water (1).

Drainage basin. The land area from which surface runoff drains into a stream system (3).

Drawdown. The vertical distance ground-water elevation is lowered, or the amount pressure head is reduced, due to the removal of ground water. Also the decline in potentiometric surface caused by the withdrawal of water from a hydrogeologic unit (1). The distance between the static water level and the surface of the cone of depression (2). A lowering of the water table of an unconfined aquifer or the potentiometric surface of a confined aquifer caused by pumping of ground water from wells (3).

Dynamic equilibrium. A condition of which the amount of recharge to an aquifer equals the amount of natural discharge (3).

Effective porosity. The amount of interconnected pore space through which fluids can pass, expressed as a percent of bulk volume. Part of the total porosity will be occupied by static fluid being held to the mineral surface by surface tension, so effective porosity will be less than total porosity (3).

Effluent stream. See gaining stream.

Equipotential line. Surface (or line) along which the potential is constant (1). A contour line on the water table or potentiometric surface; a line along which the pressure head of ground water in an aquifer is the same. Fluid flow is normal to these lines in the direction of decreasing fluid potential (2). A line in a two-dimensional ground-water flow field such that the total hydraulic head is the same for all points along the line (3).

Equipotential surface (line). A surface (or line) in a three-dimensional ground-water flow field such that the total hydraulic head is the same everywhere on the surface (3).

Evapotranspiration. Combined loss of water from a land area, during a specified period of time, through evaporation from the soil and transpiration of plants (2). The sum of evaporation plus transpiration (3).

Evapotranspiration, actual. The evaporation that actually occurs under given climatic and soil-moisture conditions (3).

Evapotranspiration, potential. The evapotranspiration that would occur under given climatic conditions if there were unlimited soil moisture (3).

Exchange capacity. Amount of exchangeable ions, measured in milliequivalents per 100 grams of solid material at a given pH. The total ionic charge of the adsorption complex active in the adsorption of ions (see cation exchange) (1).

Fissure. A surface of a fracture or crack in a rock along which there is a distinct separation (4).

Flow line. The general path that a particle of water follows under laminar flow conditions (1). Line indicating the direction followed by ground water toward points of discharge. Flow lines are perpendicular to equipotential lines (2).

Flow model. A digital computer model that calculates a hydraulic head field for the modeling domain using numerical methods to arrive at an approximate solution to the differential equation of ground-water flow.

Flow net. A graphical representation of flow lines and equipotential lines for two-dimensional, steady-state ground-water flow (1).

Flow path. Subsurface course a water molecule or solute would follow in a given ground-water velocity field (1).

Flow, steady. A characteristic of a flow system, where the magnitude and direction of specific discharge are constant in time at any point (1).

Flow, uniform. A characteristic of a flow system where specific discharge has the same magnitude and direction at any point (1).

Flow, unsteady (nonsteady). A characteristic of a flow system where the magnitude and/or direction of the specific discharge changes with time (1).

Flow velocity. See specific discharge.

Fluid potential. Mechanical energy per unit mass of a fluid at any given point in space and time, with regard to an arbitrary state and datum (1).

Flux. See specific discharge.

Formation. A body of rock of considerable thickness that has characteristics making it distinguishable from adjacent rock unit.

Fracture. A general term for any breakin a rock, which includes cracks, joints and faults (4).

Gaining stream. A stream or reach of a stream, the flow of which is being increased by inflow of ground water. Also known as an effluent stream (3).

Glacial drift. A general term for unconsolidated sediment transported by glaciers and deposited directly on land or in the sea (2).

GPD. Gallons per day, a measure of the withdrawal rate of a well.

Gravitational head. Component of total hydraulic head related to the position of a given mass of water relative to an arbitrary datum (1).

Gravitational water. Water that moves into, through, or out of a soil or rock mass under the influence of gravity (1).

Ground water. That part of the subsurface water that is in the saturated zone (1). The water contained in interconnected pores located below the water table in an unconfined aquifer or located in a confined aquifer (3).

Ground-water barrier. Rock or artificial material with a relatively low permeability that occurs (or is placed) below ground surface, where it impedes the movement of ground water and thus causes a pronounced difference in the heads on opposite sides of the barrier (1).

Ground-water basin. General term used to define a ground-water flow system that has defined boundaries and may include more than one aquifer underlain by permeable materials that are capable of storing or furnishing a significant water supply. The basin includes both the surface area and the permeable materials beneath it (1). A rather vague designation pertaining to a ground-water reservoir that is more or less separate from neighboring ground-water reservoirs. A ground-water basin could be separated from adjacent basins by geologic boundaries or by hydrologic boundaries (3).

Ground water, confined. Ground water within an aquifer that underlies a confining unit.

Ground-water discharge. Flow of water released from the zone of saturation (1).

Ground-water divide. Ridge in the water table, or potentiometric surface, from which ground water moves away at right angles in both directions (1). Line of highest hydraulic head in the water table or potentiometric surface.

Ground-water flow. The movement of water through openings in sediment and rock that occurs in the zone of saturation (1).

Ground-water model. A simplified conceptual or mathematical image of a ground-water system, describing the feature essential to the purpose for which the model was developed and including various assumptions pertinent to the system. Mathematical ground-water models can include numerical and analytical models.

Influent stream. See losing stream.

Interference. The result of two or more pumping wells, the drawdown cones of which intercept. At a given location, the total well interference is the sum of the drawdowns due to each individual well (3). The condition occurring when the area of influence of a water well comes into contact with or overlaps that of a neighboring well, as when two wells are pumping from the same aquifer or are located near each other (2).

Interstice. An opening or space in rock or soil that may be occupied by air, water, or other fluid; synonymous with void or pore (1).

Intrinsic permeability. Pertaining to the relative ease with which a porous medium can transmit a liquid under a hydraulic or potential gradient. It is a property of the porous medium and is independent of the nature of the liquid or the potential field (3).

Ion. Any element or compound that has gained or lost an electron, so that it is no longer neutral electrically, but carries a charge (2).

Isochrone. Plotted line graphically connecting all points having the same time of travel for contaminants to move through the saturated zone and reach a well.

Isoconcentration. Graphic plot of points having the same contaminant concentration levels.

Isotropy. The condition in which the properties of interest (generally hydraulic properties of the aquifer) are the same in all directions (1).

Karst topography. A type of terrain that is formed on limestone, gypsum, and other rocks by dissolution, and is characterized by sinkholes, caves, and underground drainage (1).

Kinematic viscosity. The ratio of dynamic viscosity to mass density. It is obtained by dividing dynamic viscosity by the fluid density. Units of kinematic viscosity are square meters per second (2).

Laminar flow. Fluid flow in which the head loss is proportional to the first power of the velocity; synonymous with streamline flow and viscous flow. The stream lines remain distinct and the flow directions at every point remain unchanged with time. It is characteristic of the movement of ground water (1). Type of flow in which the fluid particles follow paths that are smooth, straight, and parallel to the channel walls. In laminar flow, the viscosity of the fluid damps out turbulent motion. Compare with turbulent flow (2).

Leaching. Removal of materials in solution from rock, soil, or waste; separation or dissolving out of soluble constituents from a porous medium by percolation of water (1).

Leakage. Flow of water from one hydrogeologic unit to another. This may be natural, as through a somewhat permeable confining layer, or anthropogenic, as through an uncased well. It may also be the natural loss of water from artificial structures, as a result of hydrostatic pressure (1).

Leaky aquifer. An artesian or water table aquifer that loses or gains water through adjacent semipermeable confining units (1).

Limestone. A sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite (1).

Losing stream. A stream or reach of a stream that is losing water by seepage into the ground. Also known as an influent stream (3).

Matrix. Solid framework of a porous material or system (1).

Maximum Contaminant Level (MCL). Maximum permissible level of a contaminant in water that is delivered to the users of a public water system. MCL is defined more explicitly in SDWA regulations (40 CFR Section 141.2).

MCL. See Maximum Contaminant Level.

Mechanical dispersion. Process whereby solutes are mechanically mixed during advective transport, caused by the velocity variations at the microscopic level; synonymous with hydraulic dispersion (1). The coefficient of mechanical dispersion is the component of mass transport flux of solutes caused by velocity variations at the microscopic level (1).

MGD. Million gallons per day, a measure of the withdrawal rate of a well.

Miscible. Chemical characteristic of two or more liquids or phases, making them able to mix and dissolve in each other, or form one phase (1).

Miscible displacement. Mutual mixing and movement of two fluids that are soluble in each other; synonymous with miscible-phase displacement (1).

Molecular diffusion. Process in which solutes are transported at the microscopic level due to variations in the solute concentrations within the fluid phases (1). Dispersion of a chemical caused by the kinetic activity of the ionic or molecular constituents (2).

Nonpoint source. A source discharging pollutants into the environment that is not a single point (1).

Observation well. A well drilled in a selected location for the purpose of observing parameters such as water levels and pressure changes (2). A nonpumping well used to observe the elevation of the water table or the potentiometric surface. An observation well is generally of larger diameter than a piezometer and typically is screened or slotted throughout the thickness of the aquifer (3).

Parameter. See hydrogeologic parameter.

Partial penetration. When the intake portion of the well is less than the full thickness of the aquifer (2). A well constructed in such a way that it draws water directly from a fractional part of the total thickness of the aquifer. The fractional part may be located at the top, the bottom, or anywhere else in the aquifer (3).

Particulate transport. Movement of undissolved particles in subsurface water (1).

Peclet number. Relationship between the advective and diffusive components of solute transport; expressed as the ratio of the product of the average interstitial velocity and the characteristic length, divided by the coefficient of molecular diffusion. Small values indicate diffusion dominates; large values indicate advection dominates (1).

Perched water. Unconfined ground water separated from an underlying main body of ground water by an unsaturated zone (2).

Percolation. Downward movement of water through the unsaturated zone; also defined as the downward flow of water in saturated or nearly saturated porous media at hydraulic gradients of 1.0 or less (1). The act of water seeping or filtering through the soil without a definite channel (2).

Permeability. Ability of a porous medium to transmit fluids under a hydraulic gradient (1). The property or capacity of a porous rock, sediment, or soil for transmitting a fluid; it is a measure of the relative ease of fluid flow under unequal pressure (2).

Permeability coefficient. Rate of flow of water through a unit cross-sectional area under a unit hydraulic gradient at the prevailing temperature (field permeability coefficient), or adjusted to 15 degrees C (1).

Permeability, effective. Observed permeability of a porous medium to one fluid phase, under conditions of physical interaction between the phase and other fluid phases present (1).

Permeability, intrinsic. Relative ease with which porous medium can transmit a fluid under a potential gradient, as a property of the medium itself. Property of a medium expressing the relative ease with which fluids can pass through it (1).

pH. A measure of the acidity or alkalinity of a solution, numerically equal to 7 for neutral solutions, increasing with increasing alkalinity and decreasing with increasing acidity. Originally stood for "potential of hydrogen" (2).

Phreatic water. See saturated zone.

Piezometric surface. See potentiometric surface.

Point source. Any discernible, confined, or discrete conveyance from which pollutants are or may be discharged, including (but not limited to) pipes, ditches, channels, tunnels, conduits, wells, containers, rolling stock, concentrated animal feeding operations, or vessels (1).

Pollutant. Any solute or cause of change in physical properties that renders water unfit for a given use (3).

Pollution. When the contamination concentration levels restrict the potential use of ground water (2).

Pore. See interstice.

Pore space. Total space in an aquifer medium not occupied by solid soil or rock particles (1).

Porosity (n). Ratio of the total volume of voids available for fluid transmission to the total volume of a porous medium. Also the ratio of the volume of the voids of a soil or rock mass that can be drained by gravity to the total volume of the mass (1). The percentage of the bulk volume of a rock or soil that is occupied by interstices, whether isolated or connected (2). The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment (3). Porosity may be primary, formed during deposition or cementation of the material, or secondary, formed after deposition or cementation, such as fractures.

Potable water. Suitable for human consumption as drinking water (1).

Potential. Any of several scalar variables, each involving energy as a function of position or condition; of relevance here is the fluid potential of ground water (1).

Potential drop. Difference in total head between two equipotential lines (1).

Potentiometric surface. A surface that represents the level to which water will rise in tightly cased wells. If the head varies significantly with depth in the aquifer, then there may be more than one potentiometric surface. The water table is a particular potentiometric surface for an unconfined aquifer (3).

Pressure head. Hydrostatic pressure expressed as the height (above a measurement point) of a column of water that the pressure can support (1).

Pressure, static. Pressure exerted by a fluid at rest (1).

Public water supply system. System for provision to the public of piped water for human consumption, if such system has at least 15 service connections or regularly serves at least 25 individuals daily or at least 60 days out of the year. The term includes any collection, treatment, storage, and distribution facilities under control of the operator of such system and used primarily in connection with the system, and any collection or pretreatment storage facilities not under such control that are used primarily in connection with the system.

Pumping test. A test that is conducted to determine aquifer or well characteristics (1). A test made by pumping a well for a period of time and observing the change in hydraulic head in the aquifer. A pump test may be used to determine the capacity of the well and the hydraulic characteristics of the aquifer. Also called aquifer test (3).

Radial flow. The flow of water in an aquifer toward a vertically oriented well (3).

Radius of influence. The radial distance from the center of a well bore to the point where there is no lowering of the water table or potentiometric surface (the edge of its cone of depression) (2).

Recharge (r). The addition of water to the zone of saturation; also, the amount of water added. Can be expressed as a rate (i.e., in/yr) or a volume (2).

Recharge area. Area in which water reaches the zone of saturation by surface infiltration (1). An area in which there are downward components of hydraulic head in the aquifer. Infiltration moves downward into the deeper parts of an aquifer in a recharge area (3).

Recharge basin. A basin or pit excavated to provide a means of allowing water to soak into the ground at rates exceeding those that would occur naturally (2).

Recharge boundary. An aquifer system boundary that adds water to the aquifer. Streams and lakes are typical recharge boundaries (2).

Runoff. That part of precipitation flowing to surface streams (1). The total amount of water flowing in a stream. It includes overland flow, return flow, interflow, and baseflow (2).

Saturated zone. Portion of the subsurface environment in which all voids are ideally filled with water under pressure greater than atmospheric (1). The zone in which the voids in the rock or soil are filled with water at a pressure greater than atmospheric. The water table is the top of the saturated zone in an unconfined aquifer (3). Also called the phreatic zone.

SDWA. Safe Drinking Water Act.

Semiconfined. An aquifer that has a "leaky" confining unit and displays characteristics of both confined and unconfined aquifers (see leaky aquifer) (1).

Sole Source Aquifer (SSA). An aquifer that is the sole or principal source of drinking water, as established under Section 1424(e) of the SDWA.

Solute transport. Net flux of solute through a hydrogeologic unit, controlled by the flow of subsurface water and transport mechanisms (1).

Solute transport model. Mathematical model used to predict the movement of solutes (generally contaminants) in an aquifer through time.

Solution channel. Tubular or planar channel formed by solution in carbonate-rock terrains, usually along joints and bedding planes (4).

Sorption. Processes that remove solutes from the fluid phase and concentrate them on the solid phase of a medium; used to encompass absorption and adsorption (1).

Specific discharge. The volume of water flowing through a unit cross-sectional area of an aquifer (1).

Specific yield. The ratio of the volume of water that a given mass of saturated rock or soil will yield by gravity to the volume of that mass. This ratio is stated as a percentage (1).

Spring. Discrete place where ground water flows naturally from rock or soil onto the land surface or into a surface-water body (1).

SSA. See Sole Source Aquifer.

Stagnation point. A place in a ground-water flow field at which the ground water is not moving. The magnitude of vectors of hydraulic head at the point are equal but opposite in direction (3).

Static head. See head, static.

State. Includes, in addition to the several States, only the District of Columbia, Guam, the Commonwealth of Puerto Rico, the Northern Mariana Islands, the Virgin Islands, American Samoa, and the Trust Territory of the Pacific Islands.

State Wellhead Protection Program. Program to protect wellhead protection areas within a State's jurisdiction from contaminants that may have any adverse effects on the health of persons (SDWA, subsection 1428(a)).

Static water level. The level of water in a well that is not being affected by withdrawal of ground water (2).

Storage coefficient. Volume of water an aquifer releases from or takes into storage per unit surface (or subsurface) area per unit change in head (1).

Storage, specific. The amount of water released from or taken into storage per unit volume of a porous medium per unit change in head (3).

Storativity (s). A dimensionless term representing the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. It is equal to the product of specific storage and aquifer thickness. In an unconfined aquifer, the storativity is equivalent to the specific yield. Also called storage coefficient (3).

Time of travel (TOT). The time required for a contaminant to move in the saturated zone from a specific point to a well.

TOT. See time of travel.

Transmissivity (t). Rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It is equal to an integration of the hydraulic conductivities across the saturated part of the aquifer perpendicular to the flow paths (1). The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Transmissivity values are given in gallons per minute through a vertical section of an aquifer 1 foot wide and extending the full saturated height of an aquifer under a hydraulic gradient of one in the English Engineering system; in the Standard International System, transmissivity is given in cubic meters per day through a vertical section of an aquifer 1 meter wide and extending the full saturated height of an aquifer under a hydraulic gradient of one (2). It is a function of properties of the liquid, the porous media, and the thickness of the porous media (3).

Transport. Conveyance of solutes and particles in flow systems (1).

Turbulent flow. Water flow in which the flow lines are confused and heterogeneously mixed. It is typical of flow in surface water bodies (2). That type of flow in which the fluid particles move along very irregular paths. Momentum can be exchanged between one portion of the fluid and another. Compare with laminar flow (3).

UIC. See Underground Injection Control.

Unconfined. Conditions in which the upper surface of the zone of saturation forms a water table under atmospheric pressure (1).

Unconsolidated aquifer. An aquifer made up of loose material, such as sand or gravel, that has not undergone lithification.

Underground Injection Control (UIC). The regulations for injection wells. The program provides grants to States under Section 1443(b) of SDWA.

Unsaturated flow. Movement of water in a porous medium in which the pore spaces are not filled with water (1).

Unsaturated zone. The zone between the land surface and the deepest or regional water table. It includes the root zone, intermediate zone, and capillary fringe. The pore spaces contain water, as well as air and other gases at less than atmospheric pressure. Saturated bodies, such as perched ground water, may exist in the unsaturated zone, and water pressure within these may be greater than atmospheric (1). Same as vadose zone.

Vadose zone. See unsaturated zone.

Velocity, average interstitial (v). Average rate of ground-water flow in interstices, expressed as the product of hydraulic conductivity and hydraulic gradient divided by the effective porosity. It is synonymous with average linear ground-water velocity or effective velocity (1).

Water budget. An evaluation of all the sources of supply and the corresponding discharges with respect to an aquifer or a drainage basin (3).

Water table. Upper surface of a zone of saturation, where that surface is not formed by a confining unit; water pressure in the porous medium is equal to atmospheric pressure (1). The surface between the vadose zone and the ground water; that surface of a body of unconfined ground water at which the pressure is equal to that of the atmosphere (2). The surface in an unconfined aquifer or confining bed at which the pore water pressure is atmospheric. It can be measured by installing shallow wells extending a few feet into the zone of saturation and then measuring the water level in those wells (3).

Well field. An area containing two or more wells supplying a public water supply system.

Wellfield. Synonymous with well field.

Well, fully penetrating. A well drilled to the bottom of an aquifer, constructed in such a way that it withdraws water from the entire thickness of the aquifer (3).

Wellhead. The physical structure, facility, or device at the land surface from or through which ground water flows or is pumped from subsurface, water-bearing formations.

Wellhead Protection Area (WHPA). The surface and subsurface area surrounding a water well or well field, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or well field.

Well interference. See interference.

Well screen. A filtering device used to keep sediment from entering a water well (2).

Well yield. The volume of water discharged from a well in gallons per minute or cubic meters per day (2).

WHPA. See Wellhead Protection Area.

ZOC. See zone of contribution.

ZOI. See zone of influence.

Zone of Contribution (ZOC). The area surrounding a pumping well that encompasses all areas or features that supply ground-water recharge to the well.

Zone of Influence (ZOI). The area surrounding a pumping well within which the water table or potentiometric surfaces have been changed due to ground-water withdrawal.

Zone of Transport (ZOT). The area surrounding a pumping well, bounded by an isochrone and/or isoconcentration contour, through which a contaminant may travel and reach the well.

ZOT. See zone of transport.