MICHIGAN DEPARTMENT OF ENVIRONMENT, GREAT LAKES, AND ENERGY
DRINKING WATER AND ENVIRONMENTAL HEALTH DIVISION

WELLHEAD PROTECTION AREA DELINEATION GUIDANCE

OVERVIEW OF THE WHPA DELINEATION PROCESS

The State of Michigan, Wellhead Protection Program requirements for delineation of a Wellhead Protection Area (WHPA*)* necessitate completion of a hydrogeologic study. The hydrogeologic study includes an initial compiling of readily available information, the completion of fieldwork to obtain a better understanding of the hydrogeologic system, and groundwater modeling to identify the WHPA.

Readily available information may include water well records, aquifer test reports, hydrogeologic studies from local sites of environmental contamination, water-use records, geologic maps, topographic maps, and other related information. Sources of information include the Michigan Department of Environment, Great Lakes, and Energy, the Michigan Department of Natural Resources, local health departments, and public water supply system records. Additional investigation may be warranted to uncover potentially useful hydrogeologic information available as historical or archived records. Available information is normally sufficient to develop a rudimentary conceptualization of the hydrogeologic system and identify areas requiring additional acquisition of information and data.

Fieldwork is completed to fill voids in the available information, confirm or modify the rudimentary conceptualization, and provide the information base necessary for groundwater flow modeling to delineate the WHPA. The available information and information collected through fieldwork is used to develop a final conceptualization of the hydrogeologic system. The final hydrogeologic conceptualization is incorporated into a groundwater flow model that is used to identify the WHPA.

FIELD WORK

Groundwater flow models require as input, at a minimum, an estimate of the following parameters: 1) aquifer transmissivity, 2) groundwater flow direction, 3) hydraulic gradient, 4) effective porosity, 5) pumping rates for all wells, and 6) aquifer thickness. The requirements for fieldwork are meant to provide an aquifer transmissivity, a groundwater flow direction, and the hydraulic gradient. These three parameters exert the greatest influence on the areal extent and configuration of the WHPA.

Aquifer Tests

An aquifer test provides a quantitative and qualitative evaluation of the water-yielding capacity and hydraulic properties of an aquifer. At a minimum, the test provides an estimate of the aquifer’s transmissivity and storage coefficient. Transmissivity is a product of the aquifer material's hydraulic conductivity and the aquifer thickness and provides a measure of how easily groundwater moves in the aquifer. The storage coefficient reflects the volume of water available in the aquifer. Together they influence the areal extent of the WHPA by defining the radius of influence of a well as a function of the pumping rate and the duration of pumping.

The aquifer test can also provide a useful characterization of the aquifer. When properly conducted and the data appropriately analyzed, information may be obtained on the aquifer conditions (i.e., confined, leaky-confined, and unconfined). This qualitative characterization can be used to confirm area geology, aid in the conceptualization of the aquifer system, and provide insight relative to the vulnerability of the aquifer, which is useful in development of a groundwater flow model. Other quantitative information may be obtained from a properly conducted aquifer test such as the vertical hydraulic conductivity of an overlying confining unit, or the vertical component of hydraulic conductivity within an aquifer.

All aquifer tests completed as part of a wellhead protection area delineation must meet the requirements of EGLE policy ODWMA-399-003 Aquifer Test Requirements for Public Water Supply Wells.

Groundwater Flow Direction, Hydraulic Gradient, and SWL Elevations

The single most important aspect of a WHPA delineation is determination of the groundwater flow direction and hydraulic gradient. These two parameters exert considerable influence on the upgradient shape and areal extent of the WHPA. Groundwater flow direction and hydraulic gradient are determined by the collection of static water level (SWL) elevations. Depending on the modeling approach, SWL elevations may be used to confirm groundwater flow direction and hydraulic gradient information, directly determine the groundwater flow direction and gradient, or as "calibration targets" in more complex groundwater modeling and groundwater flow simulation efforts.

To grasp the importance of SWL elevations, it is important to understand the concept of the "potentiometric surface." Groundwater moves from areas of high energy (high elevation) to areas of low energy (low elevation). A single static water elevation reflects the energy of the groundwater at a specific location in the groundwater system. Multiple SWL elevations reflect the energy at multiple locations and may be used to develop a potentiometric surface. Once developed, the potentiometric surface depicts, in two dimensions, the spatial distribution of energy within the groundwater system. The direction of maximum change in the potentiometric surface defines the groundwater flow direction, and the magnitude of the change defines the hydraulic gradient.

Because SWL elevations in groundwater systems may vary little over long distances, it is important that SWL elevations be obtained while maintaining good vertical control. Static water level elevations must be provided relative to the National Geodetic Vertical Datum of 1929, or the North American Vertical Datum of 1988. All SWL elevations must be determined by surveying relative to a known vertical control point, such as a survey "benchmark," and determined to an accuracy of 0.01 feet.

DELINEATION APPROACHES

There are three widely accepted approaches for delineation of a WHPA. The three approaches reflect an increase in the amount of fieldwork, an increase in the level of complexity of the groundwater flow model, or both. For the purpose of discussion the approaches will be referred to as follows:

1. Confirmation of Existing Information,
2. Direct Determination of Groundwater Flow Direction and Hydraulic Gradient,
3. Extensive Hydrogeologic Investigations.

A common denominator to the three approaches is the use of "reverse particle tracking" to identify the WHPA. Particle tracking may be described as "tracing the movement of an imaginary groundwater particle on the groundwater potentiometric surface." Thus, particle tracking identifies the path which groundwater takes in moving from areas of high energy to areas of low energy. In WHPA delineations it is more practical to perform the tracing of groundwater movement in reverse, or reverse particle tracking. Reverse particle tracking traces the movement of groundwater from areas of low energy to areas of high energy (i.e., from the pumping well back to the area of recharge). Reverse particle tracking eliminates the "trial-and-error" associated with forward particle tracking by eliminating areas of the potentiometric surface from which groundwater would not migrate to the well.

With any of these three delineation approaches, there must be an appropriate aquifer test conducted for the water supply well. If there is not a test which meets the requirements of EGLE policy, ODWMA-399-003 Aquifer Test Requirements for Public Water Supply Wells, an appropriate aquifer test will need to be performed.

Delineations That Confirm Existing Information

A delineation that confirms existing information is the least expensive. In this approach, an estimate of the groundwater potentiometric surface is obtained. The potentiometric surface is then confirmed by measurement of a minimal number of SWL elevations.

First, well log information is utilized to construct cross-sections representative of the local geology and to identify the discrete aquifer units present in the area. The well logs are further inspected to identify water wells that are completed in the same aquifer as the public water supply wells. The locations of an adequate number (approximately 15 or greater) of water wells completed in the same aquifer are identified on a map in a manner to provide a distribution of wells in the area surrounding a public water supply well. Where a water well in the same aquifer has been located, an estimate of the land surface elevation is made from topographic maps and other elevation data. Water level data, which is generally reported on well logs as a depth below the land surface, is obtained. The estimate of the land surface elevation and the depth of the groundwater below the land surface reported on the well log are used to estimate the SWL elevation at individual well locations. Collectively, the estimated SWL elevations from the multiple well locations are then used to develop a potentiometric surface map of the groundwater system.

It should be apparent from the preceding discussion that, in this approach, the potentiometric surface map is developed from existing well log and topographic information. This information is often of poor quality, insufficient in both spatial and vertical control to provide a true and accurate representation of the potentiometric surface. Error is introduced because of a lack of resolution in the estimate of land surface elevations, or because the water level information is inaccurate (plus or minus 5 feet). Also, seasonal differences relative to the time of well construction when the information was recorded can impart error to the water level information. As a result, the potentiometric surface developed from existing well log and topographic information must be confirmed. Confirmation is provided by the determination of SWL elevations in a minimal number of water wells (~4-6) completed in the same aquifer. If the SWL elevations confirm the potentiometric surface, a simple groundwater flow model is constructed and reverse particle tracking is completed to identify the WHPA.

Direct Determination of GW Flow Direction and Hydraulic Gradient

Delineations that involve direct determination of the groundwater flow direction and hydraulic gradient place a much greater emphasis on fieldwork. In this approach considerable emphasis is placed on fieldwork to provide a greater number of actual SWL elevation measurements for development of the potentiometric surface.

As in the previous approach, well logs are screened to identify an adequate number of water wells (approximately 15 or more) completed in the same aquifer as the public water supply wells. The locations of selected water wells are placed on a map in a manner to provide a distribution of wells in the area surrounding a public water supply well. It is important that an emphasis be placed on wells in the area projected as upgradient of the public water supply well. As in the previous approach, the wells are utilized in the development of cross-sections to characterize the area geology. The selected wells are then further screened to identify the wells from which a SWL measurement can be easily obtained. This generally involves the elimination of wells equipped with a shallow or deep well jet, and small diameter wells. An emphasis is placed on locating wells 4-inches in diameter or greater, as they provide the easiest access. An elevation for the top of casing on selected wells is obtained by surveying, and the SWL in all wells is the measured distance below the top of casing. The SWL elevation of the groundwater is then determined as the difference between the top of casing elevation and the distance to the SWL. The process provides actual SWL elevations from multiple well locations, which are than used to develop a potentiometric surface map of the groundwater system. As in the previous approach, a simple groundwater flow model is used in conjunction with reverse particle tracking to identify the WHPA.

Complex Hydrogeologic Investigations

Delineations may also be obtained by conducting a complex hydrogeologic investigation, which is by far the most expensive approach. This approach includes extensive compiling of existing information and a preliminary characterization of the hydrogeologic system. Information sources may include water well records, aquifer test reports, hydrogeologic studies from local sites of environmental contamination, water-use records, geologic maps, topographic maps, stream flow data, rainfall data, and other available hydrologic information. Fieldwork is then directed at addressing inconsistencies in the available information or providing more detailed information in areas where the available information is limited. The fieldwork may include geologic borings, installation of observation or monitoring wells, determination of SWL elevations, aquifer tests, geophysical tests and isotope analysis. The combined set of existing information and newly acquired data is used to develop a conceptual model of the groundwater system that is reproduced mathematically as a groundwater flow model.

The mathematical duplication of the conceptual model may be completed using a sophisticated analytical groundwater model program or a numerical groundwater model program. The model programs are used to develop a mathematical representation of the groundwater flow system that can mimic the movement of groundwater in the hydrogeologic system. The mathematical representation in its simplest form depicts the hydrologic system in 2-dimensions incorporating boundary conditions and aquifer hydraulic characteristics (transmissivity, hydraulic conductivity, and aquifer thickness). Other hydrogeologic features, which may control the movement of groundwater, are frequently incorporated into the model. These features can include the effect of pumping wells, "positive" boundaries (i.e., lakes, streams and rivers), negative boundaries (i.e., presence of impermeable materials, pinching out of the aquifer), recharge to the groundwater system, and evapotranspiration. Depending upon the degree of complexity in the groundwater system, the vertical movement of groundwater may be incorporated into the model resulting in a model that is 3-dimensional. The vertical movement of groundwater may be necessary to simulate the movement of groundwater between aquifers or the dewatering of an unconfined aquifer.

Once the conceptual model has been mathematically duplicated, the mathematical model is used to simulate the movement of groundwater in the groundwater system. Output from the simulation includes, at a minimum, potentiometric surface information that defines how groundwater moves in the hydrogeologic system, and information on the distribution of groundwater discharges in the system. The output from the simulation is compared, or calibrated, against known SWL elevations and discharge information to determine a "goodness of fit." A close match between the observed information and simulation output indicates the model provides an accurate mathematical representation of the groundwater flow system. The model may than be used to evaluate different resource development scenarios and identify the wellhead protection area. As with the previous approaches, reverse particle tracking is used to identify the WHPA.

Summary of Delineation Approaches

Regardless of the approach that is used, simplifying assumptions relative to the hydrogeologic system must be made to complete a WHPA delineation. In the succession of approaches discussed above, the accumulation of additional reliable information results in a successive reduction in the potential impact of the simplifying assumptions. Generally, the simplifying assumptions are handled in a manner so as to insure a "conservative" delineation of the WHPA.

Delineations based on existing information are characterized by an emphasis on available data and a minimal amount of fieldwork. The direct determination of the groundwater flow direction and hydraulic gradient also relies on existing data, although much greater emphasis is placed on the acquisition of SWL elevation data and the development of the potentiometric surface. Both approaches are characterized by the use of elementary groundwater flow models. The models are analytical solutions to a complex problem that describe the groundwater system in two dimensions. Although highly recommended and appropriate for the delineation of a WHPA, a clear understanding of the assumptions and limitations of the two approaches is essential. The two approaches tend to provide a delineation which, although frequently accurate, may provide a conservative over-estimate of the "actual" WHPA. This means that the WHPA area may be larger than it needs to be, making management of the area a more difficult task.

Complex hydrogeologic studies necessitate the acquisition of more specific information. The approach entails the use of sophisticated groundwater flow models that allow for the incorporation of many more hydrogeologic subtleties. The approach tends to rely to a lesser extent on coarse simplifying assumptions resulting in a groundwater flow model that better mimics the hydrogeologic system. As a result, the complex approach frequently provides a more concise, smaller, and defensible WHPA. The groundwater flow model that is developed may also be useful in assessing various groundwater resource development scenarios for which the previous approaches are not amenable. Unfortunately, this approach requires a much greater investment of time and resources to complete the delineation.

SELECTING A DELINEATION APPROACH

Delineations based on existing information may be performed for as little as $15,000, while complex hydrogeologic studies can cost in excess of $100,000. The cost is highly dependent on the number of municipal wells and the hydrogeologic complexity of the groundwater system. A community must weigh the options relative to their goals, economics, and long-term planning objectives related to the local wellhead protection program to evaluate which delineation approach is most appropriate. The delineation approach should meet the wellhead protection goals and objectives of the community.

An important factor to remember when applying any delineation approach is that the WHPA may change with time. The WHPA must be reevaluated as changes in the community alter the operational parameters of the public water supply system. Changes in the public water supply system such as the construction of a new well, an increase in the rate of groundwater withdrawal, or shifts in pumpage from one well field to another are actions that would necessitate a reassessment of the WHPA.

Summary of Groundwater Flow Model Programs

Following are examples of groundwater flow model programs that may be used to complete a WHPA delineation. The list is not all-inclusive and other model codes are available that may be appropriate. The list is provided to emphasize the diversity of model codes available.

<u>MODEL</u> **<u>TYPE: ANALYTICAL, ANALYTIC ELEMENT OR NUMERICAL</u>**

WHPA **Analytical (2-dimensional)**
Developed by the U.S. Environmental Protection Agency (U.S. EPA), Office of Groundwater Protection. An integrated program of analytical and semi-analytical solutions to the groundwater flow equation coupled with particle tracking. Very easy to use, although limited in the scope of information it accepts

and ability to simulate hydrogeologic complexities. Semi-analytical GPTRAC Numeric option has been widely used for delineation of WHPAs.

CAPZONE/GWPATH **Analytical (2-dimensional)**
An analytical flow model for simulating confined, leaky confined or unconfined flow to wells with superposition of regional water levels and particle tracking. Requires interface with SURFER, a computer contouring program. Able to incorporate some hydrogeologic complexities but restricted by limiting assumptions incorporated into methodology. Provides model head output that allows for "calibration" of the model.

QUICK FLOW **Analytic Element (2-dimensional)**
An interactive analytical element model that simulates 2-dimensional steady-state and transient groundwater flow. Steady-state model simulates flow in horizontal plane using analytical functions. Model generates streamlines, particle traces and head contours. Easy to use, menu driven, able to incorporate some hydrogeologic complexities, but restricted by limiting assumptions incorporated into the methodology.

WINFLOW **Analytic Element (2-dimensional)**
This program was developed by the same author as **QUICK FLOW.** This model is an enhanced, Windows-based, version of **QUICK FLOW.**

GFLOW **Analytic Element (2-dimensional)**
A flexible model used to simulate regional flow systems. Able to incorporate wells, area inhomogeneities, and some hydrogeologic complexities which can account for the vertical movement of water through localized interconnections (infiltration/discharge from lakes, drains and rivers). A flexible model incorporating greater field diversities by virtue of the analytic element method. Modeled head output and limited discharge information is obtained for "calibration" of the model.

CZAEM **Analytic Element (2-dimensional)**
Developed by the U.S. EPA. Similar in application to GFLOW, although unable to incorporate the full range of hydrogeologic complexities. Designed for elementary capture zone analysis.

WhAEM **Analytical (2-dimensional)**
Developed by Indiana University for the U.S. EPA, Office of Groundwater Protection. Includes an analytic element model that superposes many analytic solutions to generate a solution to the groundwater flow equation. The model uses two programs, a preprocessor GAEP and the flow model CZAEM. The model is easy to use and can handle fairly realistic boundary conditions such as streams, lakes and aquifer recharge due to precipitation unlike most analytical models.

MODFLOW **Numerical (2- or 3-dimensional)**
Finite difference model for the simulation of 2-dimensional, quasi-3-dimensional or fully 3-dimensional steady-state and transient groundwater flow. Model incorporates virtually all hydrologic complexities including wells, recharge, evapotranspiration and movement of groundwater into and out of drains, rivers and lakes. A complex groundwater flow model that was previously difficult to use.

Various pre- and post-processors are now available. Most widely used numerical model, well documented for modeling simple or complex hydrogeologic settings. Provides model head and discharge as output for calibration of the model.

Suggested Questions

Hydrogeologic studies involve special knowledge, skills, and services that often necessitate the assistance of a consulting firm. It is important that the consultant have experience providing services in the area of hydrogeologic investigations and/or water supply development. A list of general questions which you may ask, of yourself or a potential consultant, include the following:

1) What experience does the consultant or investigator (if not a consulting firm) have in performing WHPA delineation?

2) What is to be accomplished by the WHPA delineation?

3) What is the minimum amount of data required to obtain a reasonably accurate delineation?

4) Are there additional information sources that would be beneficial? If yes, how costly is it to obtain this information?

5) How does the consultant intend to obtain the required information to be used as input to the model?

6) Can any part of the data collection process be conducted and maintained "in house" by city/township/village staff?

7) Can the consultant provide a work plan describing the various tasks that need to be completed and the time and cost required to complete each task?

8) Will the consultant need to obtain the services of a licensed water well driller?

9) Who will obtain access to existing water wells? What precautions need to be taken to protect these wells? Who is responsible for any problems that arise?

10) What groundwater flow model will be used and why? Does the chosen model have particular strengths applicable to your specific geologic setting?

11) Are there other advantages or disadvantages to using the selected model?

12) Can a similar answer be obtained with other models that are less complex and require less input information?

13) Is the groundwater model easily updated? How much will it cost to maintain or update the model? How often will it need to be updated?