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Groundwater Quality—Emerging Challenges

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ABSTRACT: This paper presents the groundwater contamination issues from various sources and how to protect the quality of groundwater. Wellhead protection is used for point source pollutants environment. Also included in the paper and presentation are landfill siting, radioactive waste disposal and deepwell injection of liquid waste.

INTRODUCTION

Groundwater contamination is a widespread problem. The problem of groundwater contamination can be prevented if the source of the contamination is known and managed. There are two different sources of groundwater contamination. There are point sources and non-point sources. Point sources are contamination sources that are confined and apparent. Several examples of point sources of groundwater contamination include landfills, deep injection wells, pipelines, storage tanks and containers, septic tanks, and concentrated animal feeding operation. Non-point sources are dispersed sources. Non-point sources include runoff from excess pesticide and fertilizer applications, construction sites, crop and forest lands, and eroding streambanks.

In the following sections, several techniques used to manage point and non-point sources of groundwater contamination will be discussed and illustrated. The non-point sources addressed include the agricultural application of pesticides. The point sources addressed in the following sections include landfills, deep injection wells, and radioactive waste disposal sites. The delineation of wellhead protection areas to detect and prevent contamination to the public water supply will also be discussed at the time of presentation.

WELLHEAD PROTECTION DELINEATION METHODS

Wellhead protection is the management of an area of land to prevent the groundwater source from being contaminated. Groundwater is a key source of drinking water for many communities. Almost half of the United States population uses groundwater [EPA, 1993a]. In 1986, amendments were made to the Safe Drinking Water Act (SDWA) focusing on the prevention of groundwater contamination. The Wellhead Protection Program (WHPP) is a voluntary program developed for the states to protect groundwater from contamination. Every state is required to develop and execute a WHPP that is approved by the Environmental Protection Agency (EPA). As of 1999, 49 states and territories have implemented Wellhead Protection Programs [EPA, 1999]. The EPA is informed every two years of each state’s progress towards wellhead protection. When a state is implementing a WHPP, EPA often provides technical assistance. Several EPA publications including *Wellhead Protection: A Guide for Small Communities* and *Handbook: Ground Water and Wellhead Protection* are helpful resources for states organizing a plan for wellhead protection. EPA sets guidelines for communities and states to follow when implementing a WHPP. One of the most difficult steps in developing a WHPP is the delineation of wellhead protection areas (WHPA). In the following sections, the steps involved in implementing a WHPP and methods used to delineate WHPA will be discussed.

WHPP IMPLEMENTATION

According to the EPA, there are five steps to implementing a Wellhead Protection Program. These are the formation of a planning team, delineation of the wellhead protection area, source identification, source management, and contingency planning.

Planning Team

The community planning team implements the wellhead protection program. By including members of diverse backgrounds within the community, the planning team can be more efficient. The team’s purpose is to define goals for implementing the WHPP and carry out the next four steps. A few short-term goals as defined by the EPA include:

- determining whether the state has a wellhead protection program in place
- determining the geology of the community; and
- locating wells and developing knowledge of the drinking water supply system.

Another important duty of the planning team is educating the community about the wellhead protection program establishment. Public support of the project is helpful in implementing the WHPP [EPA, 1993a].

Delineation

The wellhead protection area must be delineated in order to define the area that needs to be protected. Methods for delineating the wellhead protection area are discussed later. Delineation involves determining the zone of contribution or area that recharges the well and the zone of influence or area affected by pumping the well. In order to start the delineation process, information about the geologic and hydrologic nature of the groundwater area should be obtained. Aquifer and flow characteristics are needed to determine the method of delineation used. A map of the community's water resources and public supply wells should be made. The map should also include geologic features of the community. There are several different types of maps that can provide useful data. These include topographic maps, geologic maps, soil maps, aerial photography maps, and satellite imagery [EPA, 1993a].

Source Identification

There are several different objectives the planning team needs to accomplish to identify potential and current sources of contamination, which are summarized below [EPA, 1993a].

- Determining the areas of different land use on the maps created in the delineation step. Locating the residential, commercial, and industrial zones in the community. Also, locating current and past waste disposal sites.
- Listing potential or current sources of contamination which may include naturally-occurring sources, agricultural sources, residential sources, municipal sources, commercial sources, industrial sources, and industrial processes. Identifying point sources as well as non-point sources, which are more difficult to locate.
- Determining activities that could be sources of contamination in the wellhead protection area.
- Plotting the potential sources of contamination on the community map. The map should show potential and current sources of contamination.
- Assigning risk values to each of the contaminant sources. The sources with the greater risk should be managed first.

The EPA has several different checklists to facilitate the identification of contaminant sources.

Source Management

There are several non-regulatory and regulatory management methods. Public education is important to increase the awareness of groundwater contamination and its effects. Water conservation and proper disposal of wastes should be encouraged. Other non-regulatory methods include acquiring the land in the wellhead protection area and using monitoring wells. Regulatory management methods include zoning the wellhead protection area to preclude activities that could result in groundwater contamination or requiring wellhead monitoring. A community could also develop health regulations that help prevent groundwater contamination such as limiting the use of septic tank systems. There are many other options of managing the sources of contamination. The choice of management options depends on the characteristics of the wellhead protection area [EPA, 1993a].

Contingency Planning

The community should review the WHPP established by the planning team annually to ensure that the plan is effective and make any changes necessary to handle any new information and activities. The planning team should also consider plans for future water-supply wells needed to serve a growing population, as well as develop plans that could introduce new potential sources of contamination. Long-term development plans for the area should be determined. Also, in case of an emergency, plans for an alternate water supply should be made. A plan of action should be drafted so that the community knows what to do in case of an emergency [EPA, 1993a].

METHODOLOGY FOR WELLHEAD PROTECTION AREA DELINEATION

Several methods are available for delineating wellhead protection areas. Geometric methods include the arbitrary fixed radius, calculated fixed radius, and simplified variable shapes. Analytical methods include time of travel and drawdown methods. Other methods include hydrogeologic mapping and computer modeling.

Arbitrary Fixed Radius

This method uses only a distance defined by time of travel or drawdown for a generalized aquifer similar to the aquifer being protected. An arbitrary fixed radius is useful when an area needs to be determined on a provisional basis, proving some protection while allowing a more complex and accurate wellhead protection area delineation to be performed [EPA, 1994a]. Figure 1(a) shows the wellhead protection area boundary at a fixed radius.

Calculated Fixed Radius

This method is best if used for a highly confined aquifer. The calculated fixed radius is based on time of travel based on hydrology and source locations of contaminants and the pumping rate of the well. The radius can be found using the equation,

$$r = \sqrt{\frac{Qt}{\pi n H}} \qquad \ldots (1)$$

where r = fixed radius, Q = pumping rate of well, t = time of travel threshold, n = aquifer porosity, and H = length of well screen [EPA, 1994a]. Figure 1(b) shows the volume of ground water being pumped when the calculated fixed radius method is used. Once the fixed radius is calculated, the area can be drawn on the map with the well in center.

Simplified Variable Shapes

The variable shape method is based on standardized shapes used for different aquifers with varying pumping levels. Time of travel and drawdown information can also be used to determine the shape. Different combinations can be used for an aquifer with varying characteristics [EPA, 1994a]. Figure 1(c) shows an example of possible shapes of the wellhead protection area that could be applied to an aquifer with similar characteristics as an aquifer that has already had wellhead protection area delineation. The upgradient extent is determined by time of travel and the zone of contribution of the well while the downgradient extent is determined assuming uniform flow [EPA, 1993a]. The shape can also depend on the direction of the movement of groundwater and hydraulic gradient. The transmissivity is also a factor as well as boundaries formed by streams or other topographic divides [NCDENR, 2001].

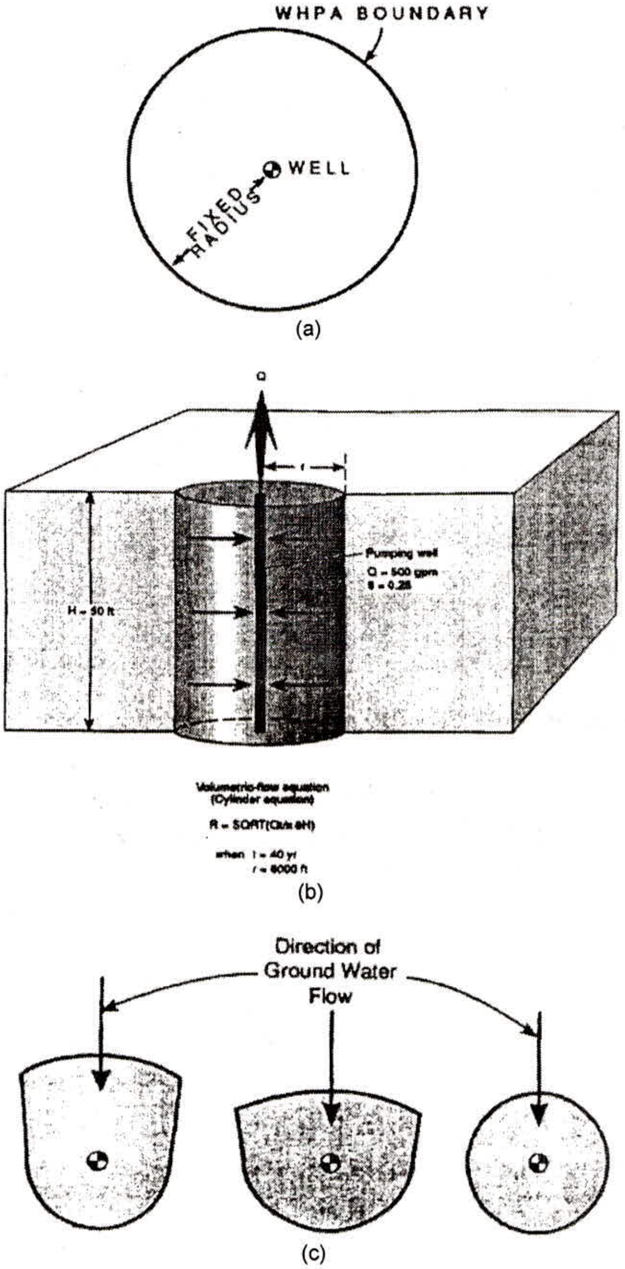

Fig. 1: WHPA delineation using geometric methods: (a) arbitrary fixed radius; (b) cylinder method; and (c) simplified variable shapes

Time of Travel

A time of travel should be chosen that provides ample time to detect contamination of the groundwater. Darcy's law can be used to determine the distance from the well to the time of travel using the equation,

$$v = \frac{Ki}{n} \qquad \ldots (2)$$

where v = average linear velocity, K = hydraulic conductivity, i = hydraulic gradient, and n = porosity [EPA, 1994a]. The distance can then be calculated by,

$$d = vt \qquad \ldots (3)$$

where d = distance from the well to the time of travel boundary and t = specified time of travel [EPA, 1994a].

In the situation where there may be steep hydraulic gradients in the vicinity of the pumping well, equation 4 from McLane (1990) may be used,

$$t = \frac{rn}{Ki} \qquad \ldots (4)$$

The cone of depression, r, must be determined accurately to obtain reasonable estimates of the time of travel [EPA, 1994a]. For an asymmetric cone of depression, an equation from Kreitler and Senger (1991) can be used,

$$t_x = \frac{n}{Ki\left[r_x - \left(\frac{Q}{2\pi Kbi}\right)\ln\left\{1 + \frac{2\pi Kbi}{Q}\right\}r_x\right]} \qquad \ldots (5)$$

where t_x = travel time from point x to a pumping well, n = porosity, K = hydraulic conductivity, i = hydraulic gradient, r_x = distance ground water travels in t_x, Q = flow rate, and b = aquifer thickness [EPA, 1994a].

Time of travel can also be determined through interaquifer flow or leakage from one aquifer to another through Darcy's law as,

$$Q_l = \left(\frac{K_v}{m}\right)AH \qquad \ldots (6)$$

where Q_l = quantity of leakage, K_v = vertical hydraulic conductivity of confining bed, m = thickness of confining bed, A = cross-sectional area, and H = difference in head between two wells [EPA, 1994a]. Kreitler and Senger (1991) give an equation for the time of travel for this situation as,

$$t_v = \frac{nmx}{K_v H} \qquad \ldots (7)$$

where t_v = vertical time of travel and x = travel distance across confining bed [EPA, 1994a].

Drawdown

Drawdown deals with the analysis of the cone of depression. The groundwater captured by a well withdrawing water from a confined aquifer may be determined using potential flow theory. In this case, the location of the zone of contribution may be obtained from,

$$-\frac{y}{x} = \tan\left[\left(\frac{2\pi Kbi}{Q}\right)y\right] \qquad \ldots (8)$$

where the origin of coordinates coincides with the well. The downgradient extent of the zone of contribution is defined by,

$$x_l = -\frac{Q}{2\pi Kbi} \qquad \ldots (9)$$

while the cross-gradient extent is given by,

$$y_l = \pm\frac{Q}{2Kbi} \qquad \ldots (10)$$

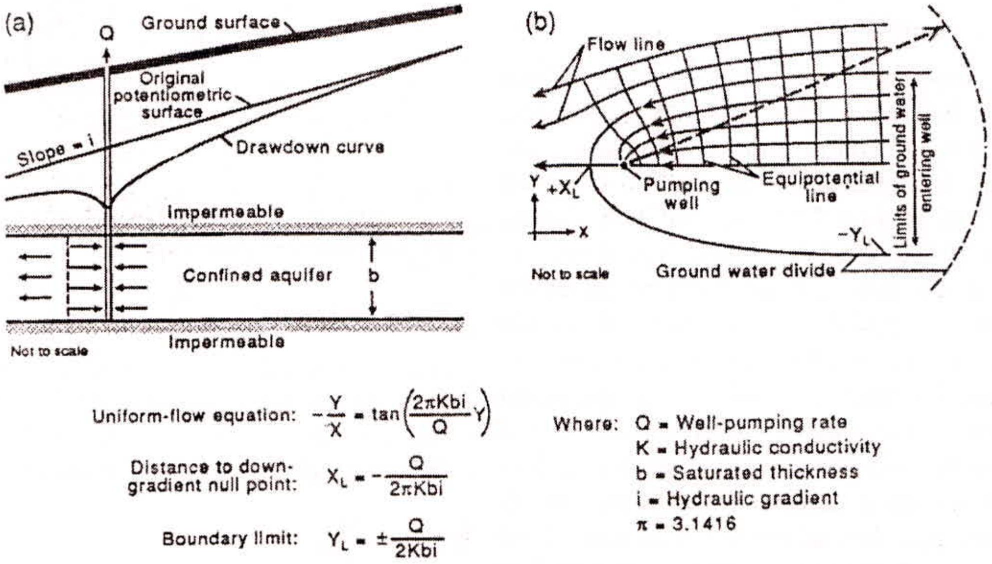

Fig. 2: A well penetrating a confined aquifer with a sloping potentiometric surface

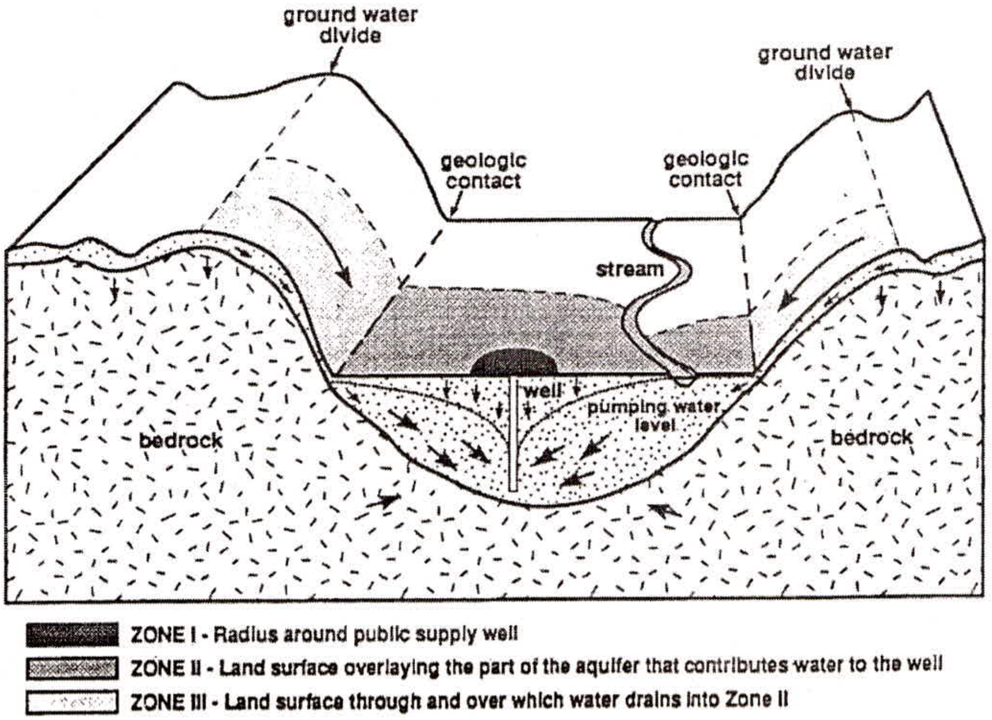

Fig. 3: Wellhead protection delineation using hydrogeologic boundaries

where x_l = distance to the downgradient null point and y_l = boundary limits [EPA, 1994a]. Figure 2 illustrates the application of this method.

There are several other equations for particular situations such as the Theis equation for unsteady flow, the Theis equilibrium equation, as well as unconfined aquifers, leaky aquifers, and partial penetrating wells. One should choose the best equation for the physical situation.

Hydrogeologic Mapping

Flow boundaries and time of travel may be determined by using geological and geophysical methods. Data that should be included on a hydrogeologic map include soil and geomorphic data, geologic and hydrologic data [EPA, 1994a]. The zone of contribution to the well may then be determined through hydrogeological interpretation of these data. Wellhead protection areas can be determined for karst aquifers or for areas of rapid ground water flow by using hydrogeologic mapping. Aerial photographs can also be used in hydrogeologic mapping and are relatively inexpensive. Field data collection may also be needed but can become expensive [EPA, 1993a]. In combination with analytical methods, aquifer boundaries can be mapped. It is also helpful to map the type of aquifer. A Geographic Information System (GIS) is a good tool to create and store data for hydrogeologic mapping [EPA, 1994a]. Figure 3 shows an example of the hydrogeologic mapping.

Computer Modeling

Groundwater flow and particle tracking models may be used to delineate wellhead protection areas when accuracy is required. There are several flow model programs available which are described below [MDEQ, 1998]:

- WHPA was developed by the EPA and uses analytical and semi-analytical solutions.
- CAPZONE and GWPATH are recommended to be used together to simulate confined or leaky aquifers.
- WINFLOW simulates flow in the horizontal plane using a steady-state model.
- GFLOW can simulate regional flow systems.
- CZAEM was developed by the EPA and is similar to GFLOW. Elementary capture zone analysis can be simulated.
- WhAEM was developed for the EPA and handles many boundary conditions.
- MODFLOW is a common numerical analysis program and can model most all hydrologic complexities [MDEQ, 1998].

Several numerical programs other than MODFLOW include FLOWPATH, PLASM and many others. The choice of program used depends on the hydrogeologic setting and availability of data.

CASE STUDIES FOR DELINEATION APPROACHES

The type of aquifer delineated, the delineation method, and any criteria used in the calculations of the wellhead protection area will be discussed for each case.

Enid, Oklahoma

The soils around the Cleo Springs wellfield in Enid include consolidated shale and sandstone, alluvial deposits, and terrace deposits. Computer methods, MODFLOW and MODPATH, were used to help delineate the wellhead protection area after semi-analytical methods were applied. The team working on the delineation used one and ten year time of travel parameters. There are several oil companies in the area and the team specified that the companies outside of the ten year wellhead protection area were allowed to inject salt water into their wells while those companies inside the ten year area could only inject fresh water [EPA, 1993a]. Figure 4 shows the wellhead protection areas calculated for Cleo Springs.

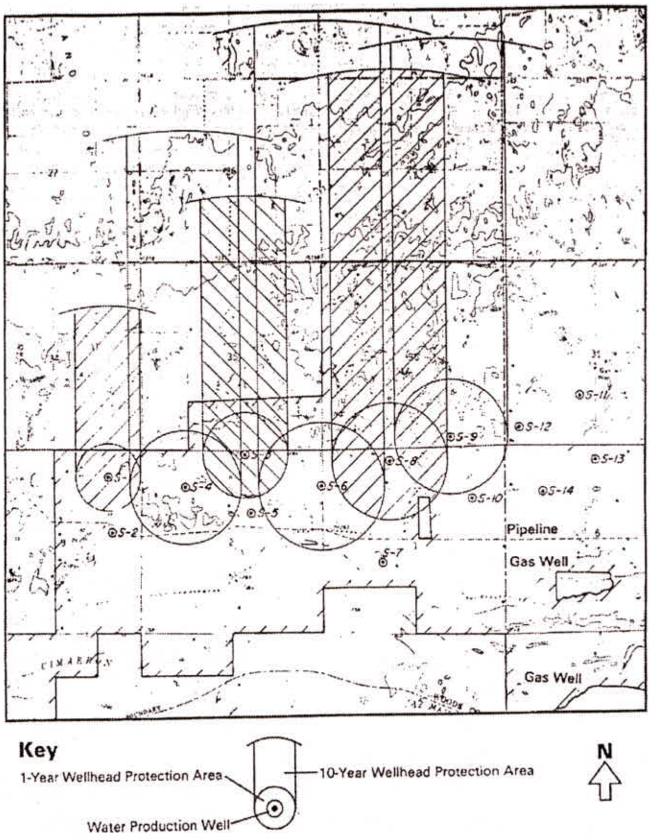

Fig. 4: Wellhead delineations for Cleo Springs wellfield

Descanso Community Water District, California

The Descanso Community Water District is located in San Diego County where the aquifer is a thin layer of weathered bedrock. Under the weathered bedrock lies metamorphic and granite bedrock. The wellhead protection area was calculated using the Theis equations as mentioned in the methodology section. The criteria used were a pumping rate of 75 gal/min, a transmissivity of 360 ft^2/day and a storage capacity of 0.02. The time of travel parameters used were one and five years [EPA, 1993a]. Figure 5 shows the wellhead protection areas for Descanso.

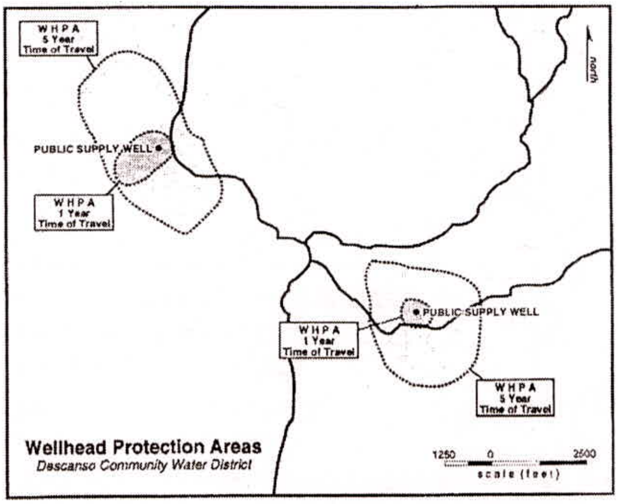

Fig. 5: Wellhead delineated for Descanso's drinking water

Palm Beach County, Florida

The aquifer where Palm Beach County obtains most of its drinking water is comprised of sand and is shallow and unconfined. The method used to delineate the wellhead protection area was MODFLOW, as used by the city of Enid also. The criteria used were 30 day, 210 day, and 500 day time of travel. Also determined was the area where one-foot drawdown occurred [EPA, 1994a].

Mt. Hope, Kansas

This aquifer contains alluvial and terrace deposits, clay, and gravel and is unconfined. The team delineating the wellhead protection areas found that the numerical models represented the aquifer parameters and hydrologic conditions in the best manner. The methods of characteristics model was used. The criteria used were 1 and 20 year time of travel. A recharge rate of 3 in/year, an effective porosity of 0.2, and a storage capacity of 0.2 were used in the model [USGS, 1991]. The wellhead protection areas for Mt. Hope, Kansas are shown in Figure 6. Analytical computer models, CAPZONE, PATH, and GWPATH, were carried out as well [USGS, 1991].

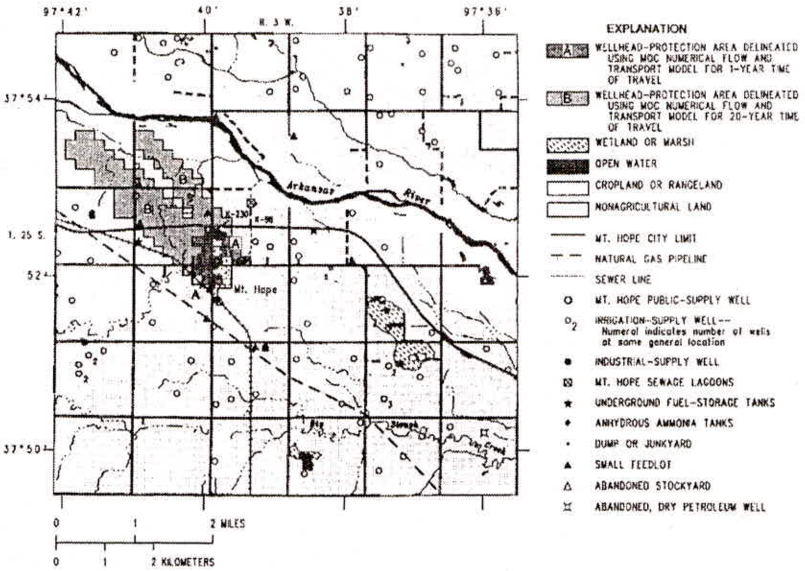

Fig. 6: Wellhead-protection areas delineated using MOC model for (D) 1 year and 20 year time of travel

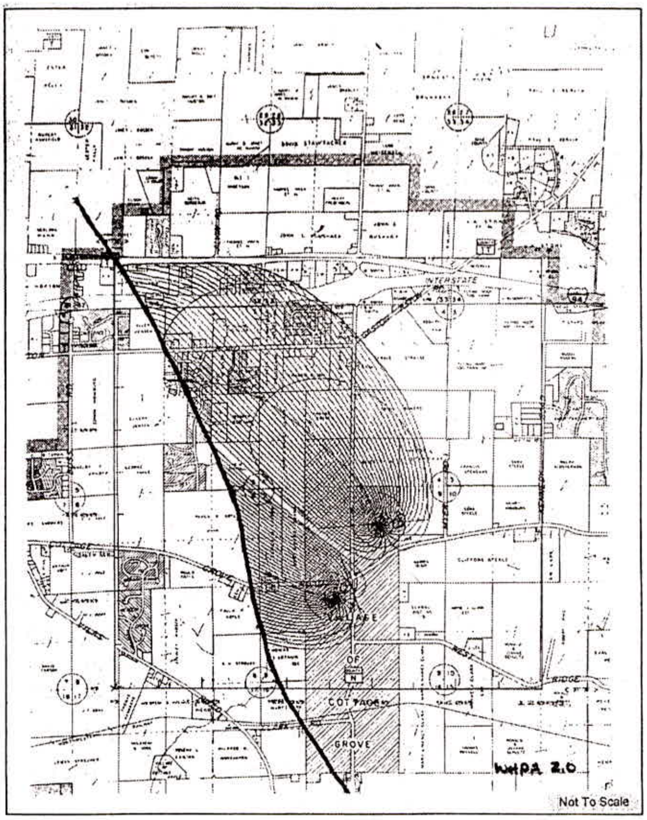

Fig. 7: Wellhead delineation of Cottage Grove using WHPA model

Cottage Grove, Wisconsin

The aquifer used in Cottage Grove is composed of sandstone. The wells were delineated using the WHPA program. The criteria used were 1, 5, 50, and 100 year time of travel [EPA, 1993a]. Figure 7 shows the delineation of wellhead protection areas using WHPA computer program.

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