An Ounce of Prevention: Wellhead Protection in Action

by Hans-Olaf Pfannkuch

Contamination or the threat of contamination of our water supply is all around us. Contamination of groundwater is most critical because it is out of sight and not easily observed, and when contamination occurs it takes a long time to detect and even longer to clean up, if clean up is even possible. Over 94 percent of Minnesota’s municipalities get their water supply from groundwater.

Wellhead protection is a strategy to prevent pollution of public water supplies. Its ultimate goal is to assure an adequate supply of safe drinking water. This is done by identifying sensitive aquifers and vulnerable wells or well fields, delineating protection zones around the wells, and restricting or regulating land use activities that might potentially pollute the aquifer and eventually the wells and the drinking water in them.

Evolution of Wellhead Protection

The concept of wellhead protection was introduced about forty years ago in Europe, where high population densities and previous experience with waterborne diseases had spurred concern about the movement of pathogens towards wells. Although one of the oldest regulations on the books is from the former USSR, most of the principles and methods for delineating protection zones that have been used as models were developed in Germany in the 1950s.

The former Federal Republic of Germany has very stringent regulations for its three protection zones. The innermost zone is essentially isolated and totally enclosed, while the following zones restrict farming methods, sewage treatment facilities, mining and manufacturing operations, transport, and storage and handling of hazardous substances, to name a few. The regulatory power of the state to bring land uses retroactively into compliance by way of eminent domain and dispossession is also strong. About 62 percent of all eligible public water supply systems in West Germany have been zoned as wellhead protection areas so far. They represent 10 percent of the total land area of the country. Essentially all countries belonging to the European Economic Community have some form of wellhead protection legislation in force.

In this country the idea of wellhead protection was picked up in the early 1980s by the United States Environmental Protection Agency. It derives its legal status from the Federal Safe Drinking Water Act.* The agency has left the initiative to develop specific wellhead protection programs to the states.

In Minnesota, the Minnesota Department of Health has been designated as the lead agency for developing a wellhead protection plan.** Working with ad hoc technical and policy work groups whose members constituted a representative cross section of state agency, scientific, professional, and private industry interests and points of view, the Department of Health has prepared its recommendations for “Wellhead Protection in Minnesota” that will be submitted to the Environmental Protection Agency for approval. In the years to come approximately 17,000 public water supplies in Minnesota will be included in the wellhead protection program.

How Contamination Occurs

The typical pathway of a contaminated particle released on the land is to infiltrate downward through the soil, continue downward through the partially saturated underground, the vadose zone, and then enter the aquifer through the water table. Once the particle is in the aquifer it moves horizontally with the natural flow of the groundwater. The particle can end up inside a pumping well if it follows the flow paths into the well (Figure 1). Very small amounts, parts per billion, of a virulent pollutant can effectively render a municipal groundwater supply useless. This was the case a few years ago, when a few gallons of spilled organic solvent, TCE, used for dry-cleaning, entered the groundwater supply of the city of Long Prairie, Minnesota.

The speed with which pollutants enter a city’s water supply will vary depending on the geology of the land, how saturated with water it is, and the volume of water being pumped from the aquifer each day. Rain recharges the aquifer, carrying contaminated particles with it as it percolates down through the soil to the water table. Coarser materials, like gravel or sand, ease the flow, while tighter soils, such as clays and glacial

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*Section 1429, as amended in 1988.
**This authority was granted in the Groundwater Protection Act, Chapter 326 of Minnesota Session Laws, 1988.

John Fraser Hart is a professor of geography at the University of Minnesota. This study is an outgrowth of his curiosity about population change in Minnesota’s small towns and villages. He wishes to acknowledge the help of Sue Johnson, Minnesota Center for Health Statistics, who provided unpublished data on numbers of births and deaths in 1989, and of Mui D. Le, who drafted the figures for this article.
til, cause resistance to flow and lower the risk of contamination reaching the aquifer.

Once a contaminant enters the aquifer, it will flow with the slope of the water table. When a well withdraws water from the aquifer, it creates a cone of depression in the water table which accelerates flow towards the well. The depth and reach of this cone depend on the discharge rate of the well. Most aquifers have appreciable natural background flow toward a natural discharge area, such as a stream or lake. A well pumping from such an aquifer superimposes its cone of depression on the background flow, producing a peculiar flow pattern, as shown in Figure 2. The shaded area designates the somewhat parabolic envelope of flowlines that contribute flow to the well. A contaminant entering anywhere within this envelope will eventually reach the well. This is the zone of potential contribution. Travel times to the well, however, will depend on where a particle enters this zone and how far it is from the well. Three time zones are shown in the figure. A particle entering along any of the broken lines indicating the circumference of the time zones will take one hundred days, one year, or two years to reach the well. These demarcation lines are the basis for delineating wellhead protection areas. Their shape and area depend on the natural flow rate in the aquifer and the pumping rate from the well.

Whether a contaminant represents a hazard for the water supply depends on the time it will take to travel to the well and the assimilative capacity of the geologic materials in the aquifer along the way, which may absorb or greatly reduce the concentration of the contaminant before it arrives at the well. In order to stay on the conservative side of estimates, and because the calculations would otherwise be extremely complex, most travel time calculations assume that contaminants do not react with geologic materials in the aquifer.

**Wellhead Protection Zones**

Guarding a municipal water supply against contamination can be done by establishing wellhead protection zones. The protection zones are areas arranged concentrically around a well based on the time it might take a contaminant to travel to the well. Usually three zones are created (Figure 2): Zone I, the smallest, innermost area, protects the immediate area around the wellhead from any kind of physical interference; Zone II, serves as protection against biological pathogens; and Zone III, the largest area, affords protection against chemical contaminants. Land use is then regulated within the zones so that activities that could pollute these areas are prevented. In Zone II, therefore, no structures or activities that release pathogenic organisms are permitted. The underlying idea is that restricting land use is less costly in the long run than paying for pollution abatement and cleanup after contamination has already occurred.

Methods for delineating wellhead protection zones range from simple to highly complex. At the simple end are radius methods that merely establish circular areas of a fixed radius around the well. More sophisticated methods establish areas of variable shape around the well, taking into account the groundwater flow direction and a variety of generic hydrogeologic conditions. These intermediate methods are easy to apply once they are established. Their drawback is that they may not realistically represent the actual areas of contribution around the well. The most complex methods are analytic. They calculate the actual zone of contribution in a naturally flowing aquifer, producing zones of contribution shaped like those in Figure 2, and they assess other hydrogeologic conditions as well.

Once a method has been chosen, the criteria that will be used to establish zones are selected. These might be the distance from the well, the drawdown of the cone of depression around the pumping well, the time it takes a contaminated particle to travel to the well, or the flow boundaries and assimilative capacity of the subsurface geologic materials. The most often used criteria are distance and time of travel. Threshold values are then chosen, such as ten meters for the radius of the innermost protection zone, and one kilometer or several miles for the next zones. Or, these values may be based on the time of travel. They might be fifty days for the biologic protection zone (assuming that pathogens die off after fifty days) and five, ten, or twenty years for subsequent zones. In many cases combinations of several criteria and threshold values have been used.
Time of travel is only defined and considered for horizontal flow within the aquifer. This neglects vertical travel through the soil and the vadose zone. One reason is that vertical travel depends on the degree of constantly changing water saturation and is therefore very difficult to assess. A protective layer between the soil surface and the aquifer that impedes downward flow, although not explicitly taken into account, can be considered as an additional safety factor in the assessment of a city’s water supply.

**Risk Management**

Wellhead protection, it becomes clear, is a form of risk management. The methods developed for risk assessment can be applied to geologic evaluations of the risk involved for public water supplies. A complete risk assessment process has three basic components: risk determination, risk evaluation, and risk management. It is in the first of these, risk determination, that the tools of the physical scientist and engineer can be used. The process of risk determination has two components: hazard identification and risk estimation.

In hazard identification, potential hazards to the water supply are inventoried, identified, and described. All processes that might contribute to their release into the environment are evaluated. The path that these pollutants might take into the public water supply is studied and measured. A causal string or probable chain of events can thus be created, providing a step-by-step model that shows how pollution of the water supply could occur. This model provides opportunities to design countermeasures and to intervene effectively in the casual string.

In risk estimation the probability of contamination of the public water supply is quantified and expressed in consistent units. Large uncertainties are introduced in estimating the risks. The concentration of contaminants, their duration and persistence, and the intensity of exposure people will have to them, and their sensitivity to the contaminants are all difficult to estimate with accuracy.

A complete risk determination for even a simple municipal water supply system would require tremendous efforts and monies for information gathering alone. Efforts of this nature would only be feasible for projects where the risk is very large or where severe consequences could affect large populations, as in the failure of nuclear installations.

In order to create workable risk assessments when a complete risk determination is not needed, semi-quantitative analysis of geologic vulnerability can be used. This creates an approximate assessment of the vulnerability of a public water supply. In place of a quantitative risk estimate, it relies on a relative ranking system where surrogate conditions are used, based on the type of geologic formation, to calculate time of travel and distance from pumping well, for example, for a pollutant that might enter the drinking water.

Wellhead protection can be formulated, based on the results of the risk determination and a separate risk evaluation analysis. The risk management functions included in the process are delineation of protection zones and identification of land use activities that can be allowed inside these zones.

**Proposed Methodology for Minnesota**

The ad hoc technical working group on wellhead protection in Minnesota has formulated a plan following this type of risk assessment. It proposes to establish different categories of public water supplies based on the number of people using each source and whether their use is long term and permanent or transient. Seven categories of geologic environments have been defined. Methods of delineating wellhead protection zones have been developed on a generic basis for each of these categories. The categories represent the most typical aquifer settings in Minnesota.

The choice of criteria, methods, and thresholds for the protection zones were made according to technical defensibility, implicit risk, and implicit ability to pay for complex studies. Smaller transient users and smaller communities (those with fewer than 3,000 persons) can use simpler methods, such as the fixed radius method.

Basically, two zones will be defined in addition to the immediate physical protection zone, where a physical barrier will prohibit access to the well itself. The first zone will be a fixed radius zone, based on the isolation distances as specified in the Minnesota Well Code. It will protect the well from contamination by pathogens. The second and outermost zone will be based on time of travel. It is not required for small or for transient water supplies. The minimum time of travel will be five years. This zone is designed to protect the well from chemical and radioactive contaminants and will provide reaction time for countering any known pollution incidents. Monitoring of wells is also included in the proposed requirements.

From a regulatory point of view, the state will start out to convince municipalities to comply voluntarily. This means that emphasis will be given to education and planning assistance for managers in the cooperating communities. Compulsory compliance will be expected when new wells are built.

**Field Study in Belle Plaine**

A wellhead protection study was carried out as a pilot project for the City of Belle Plaine, Minnesota. The city currently takes its water from two wells placed side-by-side in Prairie Park. Because peak water demand in the city sometimes exceeds the combined capacity of these wells and because a new well would be more efficient, Belle Plaine was looking for possible locations for a new municipal well that would become the main well for the city, leaving the existing wells as a backup system. The study was conducted by combining an analytical modeling method with geohydrologic research. An inventory of present and past land use in the city was used to assess potential pollution sources.

Belle Plaine, southwest of the Twin Cities metropolitan area, is situated on a river terrace deposit 850 feet above the Minnesota River. It is underlain by three quaternary units: an upper sand, about 50 feet thick; a middle gravel, about 100 feet thick; and a lower gravel, 150 feet thick.
A computer board manufacturer, car wash and auto body operations, stock yards, an industrial building, and a block and tile manufacturer. These potential pollutants were located on the city map and the areas of contribution for nine proposed well sites were also placed on the map.

A very simple rating method was used. The number of potential polluters, or point sources of pollution, that fell in the area of contribution for each proposed well site was counted. Those sites with the lowest number of point sources were ranked highest. Well A, for example, had no potential point sources of pollution. Three other proposed well sites had only a small number of point sources and were ranked as an intermediate group. The other five well sites and the existing city wells had ten to twelve point sources of pollution and were placed in a third group. Figure 4 shows how this process looked for the present city wells and for proposed site A. The city wells have no pollution sources, or point sources, in the fifty and one hundred day zones, but eleven point sources in the one-year through ten-year time zones. Of these, only one in each zone can be considered a potentially high impact source. These are service stations and the computer board manufacturer. Proposed Well A, located in a field outside of town, has no potential point sources of pollution.

The ranking is relative, it must be understood, and the quantitative differences between the three groups of potential well sites are probably very small. The counting of potential sources of pollution is also simplistic. A more accurate assessment would need to consider the potential intensity of each source—its volume, mass, and concentration, as well as the state of repair of its physical plant, and so on.

A further mitigating circumstance is the presence of the clayey till above the aquifer in Belle Plaine. This adds significantly to the travel time of potentially hazardous substances released at the surface. Because of this clay shield, even locations in the third group of possible well sites are feasible. Analysis of water in the city wells indicates that none of the more common contaminants have yet reached the city water supply.

A measure of the ease with which water can flow through an aquifer.
- The city should inventory all existing wells, and especially those in the area of its prospective well field, and be sure that any abandoned wells are properly sealed. These may otherwise become prime conduits for the rapid contamination of the aquifer.

- The city should carry out a detailed inventory of business and industrial activities in the proposed well field area so that a more accurate assessment can be made of the potential hazards.

- The city should educate the people who generate potentially hazardous wastes about the dangers involved and find ways for them to voluntarily minimize these risks.

- Because any spill or accident along U.S. Highway 169 within the well field area will affect all of the existing or proposed well sites except Well A, a contingency plan should be developed in case such an accidental spill should occur.

In Conclusion

Minnesota state government has shown initiative and expediency in developing rules and regulations for creating a program of wellhead protection. The recommendations are based on sound hydrogeologic and technical principles. Now in draft form, they will soon be submitted to the United States Environmental Protection Agency for review. Thirty-two states have already submitted their plans, and twenty-one of these plans have been accepted by the various regions of the Environmental Protection Agency.

The same state legislation that promoted wellhead protection, the Groundwater Protection Bill of 1989, also mandates that state agencies, in this case the Minnesota Department of Natural Resources, assess the sensitivity of Minnesota’s groundwater resources to contamination. Guidelines for the determination of geologic sensitivity have already been developed. The sensitivity assessment, as now defined, only takes into account the vertical travel time of contaminants from the surface to the aquifer. In the wellhead protection plans, as we have seen here, only horizontal travel times within the aquifer are considered.

An ideal methodology for safeguarding the groundwaters of Minnesota would be to merge these two approaches for planning purposes. When new well fields need to be sited, the approach would be to first consult the state sensitivity maps which are to be prepared on a county-level scale. These maps will be part of the ongoing Geologic County Atlas Program jointly carried out by the Minnesota Department of Natural Resources and the Minnesota Geological Survey. This would direct the search to the least vulnerable areas which then would have to have individual wellhead protection assessment studies performed. This combined method would eliminate highly unsuitable sites from the start of investigations and thus materially reduce the effort to design and implement a viable wellhead protection program.

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league from St. Petersburg are conducting theoretical studies of delineating wellhead protection zones under variable and unsteady state pumping rates.

Pfannkuch received an interactive research grant from CURA and the Office of the Vice President for Academic Affairs at the University of Minnesota to begin his study of wellhead protection. The grant led to his increasing involvement in the problems of protecting groundwaters from pollution. Interactive research grants have been created to encourage University faculty to carry out research projects that involve significant issues of public policy for the state and that include interaction with community groups, agencies, or organizations in Minnesota. These grants are available to regular faculty members at the University of Minnesota and are awarded annually on a competitive basis.

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Project Awards

In an attempt to keep our readers more up to date about CURA projects, we are adding this new feature. In each issue of the CURA Reporter we will provide a few capsule descriptions of projects currently underway at CURA. The projects listed this time represent research that is made possible through CURA’s Community University Personnel Grants. These grants are awarded twice a year on a competitive basis. They are designed to serve minority communities—especially American Indians, African Americans, Hispanics, and Asian Americans—by offering short-term help to nonprofit agencies and organizations based in Minnesota communities. If a grant is awarded, CURA supports the extra personnel needed, usually an advanced graduate student, who works directly with the agency receiving the award. Projects range from staff development to research to evaluation to short-term technical assistance. During the past two years eighty-seven such projects have received CURA support.

* Indian AIDS Survey. A graduate student is analyzing data and writing a report based on a survey of sexual and drug use behavior of American Indian adolescents for the Minnesota American Indian AIDS Task Force in Minneapolis.

* Evaluation of Elder Programs. Three agencies, staffed primarily by Southeast Asians, sponsor active Elder Programs and collaborate on a number of components in their programs. These are the Refugee and Immigrant Resource Center, Vietnamese Social Services, and Women’s Association of Hmong and Lao in St. Paul. They are using a graduate student to prepare a written evaluation of their programs with special attention to the collaborative components.

* Conflict Mediation on School Buses. In an effort to reduce conflicts on school buses, Olson Contemporary School in North Minneapolis has created a Bus Mediation Project. A graduate student is training students and parents as mediators and convening liaison sessions with teachers, parents, and students.

* Survey of Women Who Have Been in Jail. A graduate student is conducting a survey of women who have been in jail to explore sexual abuse and other possible causes for their incarceration. The survey was designed for W.H.I.S.P.E.R., a nonprofit organization in St. Paul that educates the public about prostitution as a system of exploitation and abuse and that advocates for the expansion of services to women and girls escaping the sex industry.

* Housing in the Payne-Phalen Area of St. Paul. A graduate student is working with the East Side Neighborhood Development Company to complete research for the second stage of a strategic housing plan in the Payne-Phalen neighborhood.

* Marketing and Economic Development Plans for North Minneapolis. Working with a citizen’s group primarily from near-north neighborhoods, a graduate student is helping gather data and conducting preliminary research for plans that will be presented to the Minneapolis City Council. The project is sponsored by the Northside Residents Redevelopment Council.

* Information for Prospective Buyers. A graduate student is helping residents prepare information on housing codes, rehabilitation, and financing for prospective buyers of turn-of-the-century homes in the old Highland Neighborhood of Near-North Minneapolis.

* Multiculturalism at Neighborhood House in West St. Paul. Using assessment tools prepared by a previous student, a graduate student is evaluating multiculturalism at the Neighborhood House Association. This is a decades-old multi-service social service agency that provides day care, crisis intervention, community organizing, and other services in a neighborhood of great diversity on St. Paul’s West Side.

* Collaboration for a Southeast Asian Housing Development. Working with the Powderhorn Residents Group in Minneapolis, a graduate student is preparing a documented report on the collaborative process that resulted in New Village—a renovated housing development for low income Cambodians and Laotians. The residents of the development worked with Powderhorn Residents Group and the Cambodian Mutual Assistance Association to create this housing project.

* Minority Networks and a Survey of Minority-Owned Businesses. The minority population in the North End of St. Paul has increased from 3 percent in the early 1970s to 24 percent today. The North End News will be using a graduate student to survey minority businesses in the area and create a network of minority people to provide regular local news coverage of minority concerns.