NATURAL RESOURCES

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Wellhead Protection: An Overview

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Groundwater, the source for wells and springs, supplies drinking water to more than half of the people in this country and more than 90 percent of the residents in rural areas. Of the population served by public water supplies, close to 40 percent rely on groundwater.

Although traditionally groundwater has been assumed to be free from contamination, numerous discoveries in recent years of toxic chemicals in well water have proven this assumption to be false. Groundwater contamination from chemical dump sites tends to attract the greatest public attention, but contamination from other sources such as septic systems, pesticides, and underground storage tanks also can be significant.

The 1986 Amendments to the Safe Drinking Water Act established a federal program to protect the quality of groundwater used in public water supply systems. This program, called the Wellhead Protection Program, is designed to protect the surface and underground areas through which contaminants are likely to pass before reaching a public water system well or wellfield (a group of wells within a common geographic location). The goal of the program is to delineate the wellhead protection area for each public water supply well, identify sources of contaminants within these areas, and develop management strategies to prevent well water contamination.

There are many ways to define a wellhead protection area. This must be done, however, with the understanding that wellhead protection does not end with the definition of a boundary. To protect the quality of well water supplies, careful thought and planning must be devoted to identifying and controlling contaminants within the wellhead protection area boundaries.

Wellhead protection requires the consideration of three factors:

1. the nature of potential contaminant sources,
2. the geographic location of potential sources in relation to the well, and
3. the appropriate management options.

Sources with the greatest potential for groundwater degradation should be subject to the most stringent controls. Similarly, the geographic areas most vulnerable to well water contamination should be managed more restrictively than areas at lower risk.

Before developing a wellhead protection program, local officials and water suppliers should familiarize themselves with the existing state regulations and programs for groundwater protection. These may include programs related to water quality, solid wastes, hazardous materials, mineral resources, and many others. Following an assessment of existing programs and a determination of local goals and needs, a preliminary conceptual plan can be drawn up for the types and forms of possible new local management efforts. This plan can help save both time and money by basing wellhead protection area delineation and management on an assessment of the local needs and the appropriate degree of technical sophistication.

A Few Definitions

Water percolates through the soil to become groundwater in a process called **recharge**. The amount of water recharged in any particular location depends on a number of factors, including climate, land use, topography, and geological conditions.

Groundwater moves through the ground, below the place where it first enters the soil to the area where it later resurfaces (fig. 1). Flow rates typically are measured in inches or feet per day, although they can be much faster in coarse gravel or in bedrock with large openings or crevices. Groundwater tends to move in parallel paths, with little vertical mixing between layers (fig.1). Geological formations that yield significant amounts of groundwater are called **aquifers**.

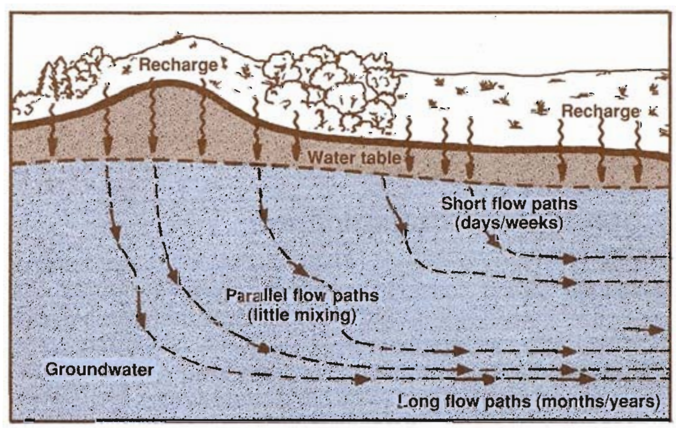

Fig. 1. Groundwater moves through the ground along flow paths. The water table is the top of the groundwater layer.

Aquifers can be divided into two basic types. **Unconfined aquifers** have an upper water surface that is free to rise and fall depending on the volume of groundwater present. The groundwater surface in an unconfined aquifer is called the **water table**. The level of water in a well tapping an unconfined aquifer is the same as that of the surrounding water table (fig. 2). **Confined** or **artesian aquifers** contain groundwater that is trapped under a layer of impermeable material such as clay. Hydraulic pressure causes water in an artesian well to rise above the top of the aquifer (fig. 3).

Some aquifers consist of porous media such as sand and gravel. Others occur where groundwater fills cracks and openings in bedrock or where groundwater has dissolved caverns in limestone or gypsum bedrock. These aquifers may have high

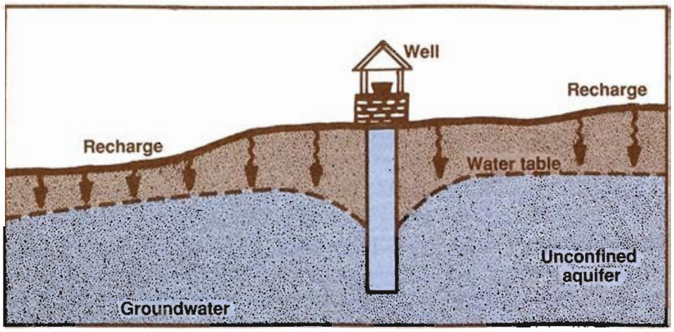

Fig. 2. Unconfined aquifers have no upper confining layer, so the water table rises and falls depending on the climate and the amounts of groundwater removed at wells.

rates of flow and little filtering of contaminants compared with aquifers in porous media.

Groundwater movement is affected by the pumping of wells. When water is withdrawn from a well, the water table around the well is lowered, and groundwater from surrounding areas flows toward the well to compensate. The lowered water table around a well is called the **cone of depression** (fig. 4). The size and shape of the cone of depression depend on many factors, including the rate and duration of pumping, the rate of groundwater recharge, and the geology of the aquifer.

The area at the land surface lying directly over the cone of depression is called the **zone of influence** (fig. 4). Although the zone of influence indicates the area in which the water table elevation is affected by a well, it does not necessarily coincide with the land area contributing recharge water to the well. This area, called the **zone of contribution**, usually is larger than the zone of influence. It may include parts of the zone of influence or extend miles from the well location, depending on the type of aquifer being tapped.

Groundwater Contamination

Whether well water is taken from individual wells or large community wellfields, the concepts behind its protection remain the same. The concept of utmost importance is that groundwater originates at the earth's surface, so its quality is determined by land uses and chemical management practices such as fertilization, chemical waste disposal, or petroleum storage. Groundwater contamination typically results from activity on, or just below, the land surface. As water percolates through the soil, it may pick up contaminants and carry them downward to groundwater.

Most human-caused groundwater contamination results from the interaction of recharge water with chemicals at or just below the land surface. Chemicals may be deliberately placed in or on the soil for a specific reason; for example, pesticides are sprayed to protect crops, and gasoline is stored in underground tanks for later use. Waste chemicals may be inadvertently spilled or deliberately applied to land for disposal.

Soluble chemicals, which readily dissolve in water, move with groundwater as it flows. Insoluble chemicals do not mix fully with groundwater, and their flow patterns depend on their densities relative to water. The rates of movement and degradation of the compounds depend on a variety of chemical, physical, and biological processes.

Knowledge of groundwater flow patterns is important in preventing the contamination of zones of groundwater tapped by water supply wells. Tracing groundwater flow backward (upgradient) from a well to its recharge area on the land surface makes it possible to identify and prevent potential contamination problems.

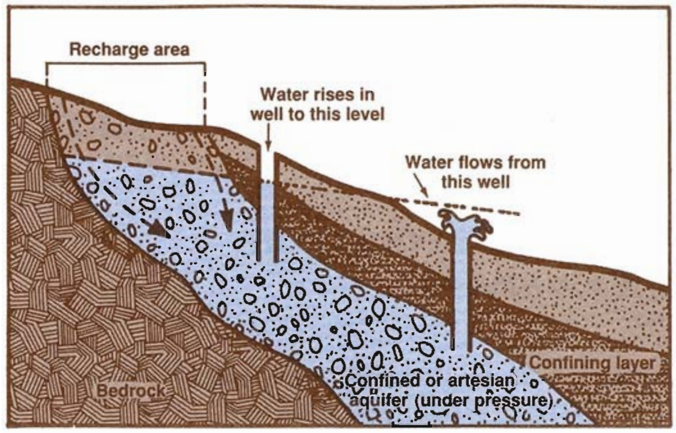

Fig. 3. Confined or artesian aquifers contain groundwater that is trapped under a confining layer of impermeable material. The groundwater therefore may be under pressure, causing water in wells to rise above the aquifer level.

Delineation of Wellhead Protection Areas

Wellhead protection means the protection of the land area around a well. The Safe Drinking Water Act defines a wellhead protection area as the surface and subsurface area through which contaminants are likely to pass before reaching a well or group of wells used for public water supplies.

A wellhead protection area can be divided into zones to allow for varying degrees of management relative to the sensitivity of each zone to groundwater contamination. For example, the outer boundaries might be drawn to protect all recharge water to a particular well, based on the zone of contribution (fig. 4). Within these outer boundaries, inner zones could be delineated using any of various methods, criteria, or thresholds for wellhead protection. The zone requiring the most restrictive management, for example, could be designated as the area immediately surrounding the well or the area from which groundwater is expected to reach the well within a relatively short time.

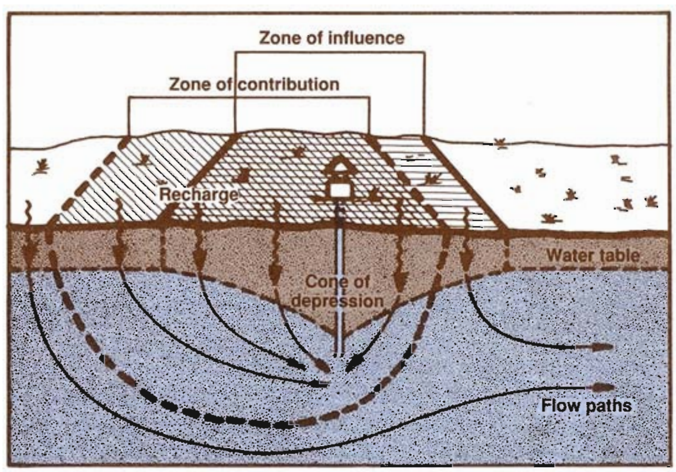

Fig. 4. The zone of contribution represents the land area contributing recharge to a well. It usually overlaps with but is larger than the zone of influence, the land area overlying the cone of depression caused by well pumping.

The criteria used to delineate wellhead protection areas depend on the type of aquifer and the degree of protection desired. Criteria commonly used include

- distance from the well,
- drawdown of the water table,
- flow boundaries,
- time of travel, and
- assimilative capacity.

Each of these delineation techniques is discussed below. Other considerations also are important, including the existing degree of development, the local goals for groundwater protection, and the existing regulatory system for controlling potential contaminants.

Distance from the Well

The simplest method of delineating an area for wellhead protection involves drawing a circle around the well, with the idea that the land area closest to the well is in greatest need of protection. The radius of such a circle typically extends up to several thousand feet from a well.

Depending on the properties of the well and the contributing aquifer, the land immediately surrounding a well may or may not be part of the area from which the well's recharge is derived. Even in the case of a distant recharge area, however, protection of the land surrounding a well can help prevent well water contamination. If well casings are not properly sealed, for example, contaminants introduced at the land surface could leak into the aquifer along the well casing.

Drawdown of the Water Table

A slightly more sophisticated approach to protecting the land surrounding a well is to delineate the zone of influence, or the land area under which the water table is lowered by well pumping (fig. 4). Drawdown of the water table is greatest at the well and diminishes with increasing distance.

Although protection of the area immediately surrounding a well will help prevent contamination from bacteria and viruses, it is unlikely to provide complete protection from chemical contaminants. Since many chemicals can be transported long distances underground without being filtered out or degraded, keeping them out of well water requires keeping them out of any recharge water that will eventually reach the well.

Delineation of wellhead protection areas based on distance from the well or on drawdown of the water table is most appropriate for shallow wells in unconfined aquifers. For artesian wells or wells tapping deep aquifers, a different approach may be required because the recharge areas may extend far from the well location. Even in such cases, however, protection of the land surrounding the well may help prevent problems such as the penetration of contaminants down the well casing.

Flow Boundaries

For the most thorough protection of a particular well, the wellhead protection area should encompass all the land from which recharge water is derived (the zone of contribution, fig. 4). All water recharging the aquifer within the zone of contribution is eventually drawn to the well by pumping. If the rate or duration of pumping changes, then the size of the zone of contribution changes as well. Weather conditions also may affect the zone of contribution. During a drought, for example, the rate of recharge diminishes, so the area drawn upon by a well increases.

In some cases the wellhead protection area is expanded to include land areas that are not directly within the recharge area of a well, but which send overland runoff into the recharge area. Some of this runoff may seep into the ground in the recharge area, along with any contaminants that have been carried along.

Time of Travel

Another approach to designating wellhead protection areas is to base the boundaries on the estimated time of travel of groundwater or contaminants to the well. For example, a line can be drawn around the area from which groundwater is expected to reach the well within a month, a year, or any other chosen period. Since the rate of contaminant travel is likely to be equal to or lower than that of groundwater, using groundwater travel times provides a conservative estimate of contaminant travel times as well.

Assimilative Capacity

Wellhead protection areas can also be designated based on assimilative capacity, the degree to which contaminants are degraded or diluted as they travel to and through groundwater. The idea is to protect a sufficiently large area around a well so that any contaminants entering with recharge water will be diminished to acceptable concentrations by the time the groundwater reaches the well. An example of well protection based on assimilative capacity is the use of density criteria for planning houses with septic systems.

Because the rate at which groundwater contaminant concentrations will diminish depends on the contaminant, the soil type, and groundwater flow conditions, assimilative capacity must depend both on the specific site conditions and on the properties of the specified contaminants. This approach therefore has limited use, confined to areas in which relevant data are available.

Aquifer Protection

All the above methods delineate wellhead protection areas based on providing protection to specific identified wells. In New York State, a broader definition of wellhead protection areas is used. Because state law calls for a level of protection that ensures groundwater meets drinking water standards, the wellhead protection areas encompass entire aquifers or aquifer segments rather than recharge areas for specific wells. In this way, protection also is provided for future, as yet undetermined, well sites. Within these broadly defined wellhead protection areas, smaller areas are delineated for extra protection of individual public water supply wells.

In upstate New York, most of the highly productive aquifers consist of relatively thin layers of glacial deposits in river valleys that are generally less than one or two miles wide (fig. 5). The state has defined the wellhead protection areas to encompass these

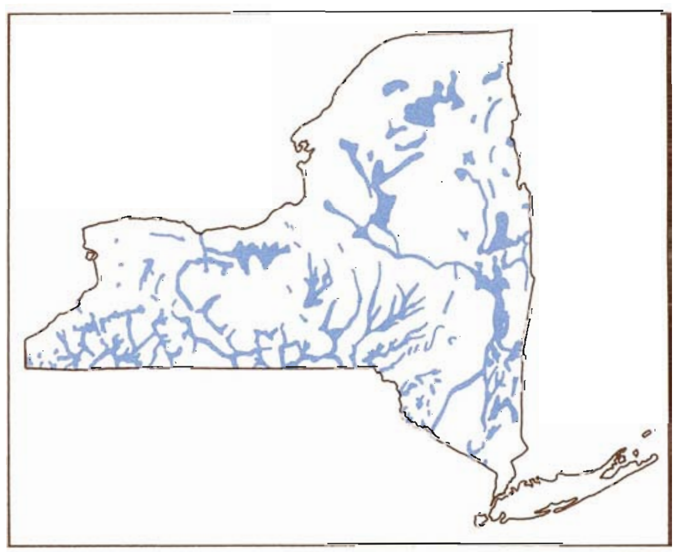

Fig. 5. Sand and gravel aquifers in upstate New York.

aquifers in entirety, with smaller areas to be delineated for additional protection to the land surrounding each public water supply well.

On Long Island, the deep-lying Magothy and Lloyd aquifers underlie the entire island and supply a large number of wells, some of which are far removed from the recharge areas (fig. 6). The shallower Upper Glacial aquifer also is tapped by many wells, both public and private. Wellhead protection on Long Island therefore has two goals: protection of the land that provides recharge water to the two deep aquifers, and protection of the area immediately surrounding each public water supply well. (For further information on wellhead protection in New York State, contact the Groundwater Management Section, New York State Department of Environmental Conservation, Room 201, 50 Wolf Road, Albany, NY 12233-3508.)

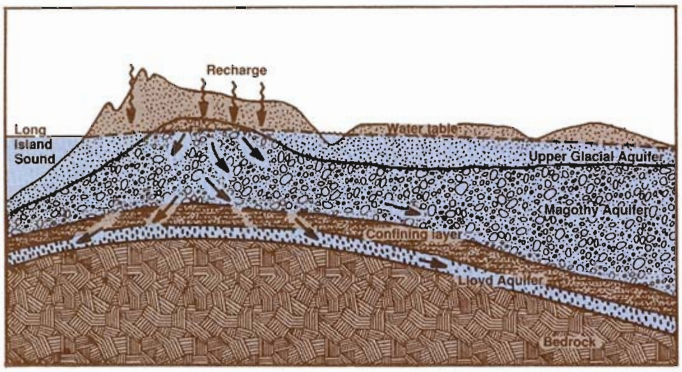

Fig. 6. On Long Island, the deep-lying Magothy and Lloyd aquifers supply a large number of wells, some far removed from the recharge areas.

Protection Techniques

As part of the process of delineating wellhead protection areas, decisions need to be made about how these areas will be protected. Based on a determination of local goals for groundwater protection and an evaluation of existing mechanisms for controlling potential contaminant sources, local officials can decide what additional management or enforcement is needed.

Tables 1 and 2 outline some of the regulatory, nonregulatory, and legislative approaches to wellhead protection. Options vary greatly in the level of protection attained. The highest level of protection is provided by public purchase of the recharge area so that the land can be kept in its natural state. In many cases this is infeasible, either because of prohibitive expense or because the area already has been developed. Then the choice becomes one of how to control contaminants from existing, historical, and expected future land uses.

An inventory of potential contaminant sources should include ongoing sources, sources from the past, and expected sources from projected land uses. It should also include a review of existing regulatory programs that might address such sources.

Mapping existing land uses and taking an inventory of chemical disposal practices provide information about current contaminant sources. Protective measures might include the exclusion, containment, or treatment of selected potential contaminants, depending on the properties of the site, the existing regulatory framework, and the chemical characteristics of the contaminants of concern.

Table 1. Regulatory Techniques for Wellhead Protection [1]

Regulatory Technique	*Description*
ZONING ORDINANCES	
Down-zoning	For land that is zoned for intensive use but not yet developed, "down-zoning" can ensure a less intensive eventual use.
Phase-ins	If existing development is incompatible with wellhead protection, new zoning requirements may be "phased in" over time.
Large-lot zoning	In residential areas with septic systems, large-lot zoning preserves open spaces and provides dilution for the effects of septic system leachate on groundwater.
Conditional zoning	Certain land uses are allowed, while others are allowed only under specified conditions (often used in conjunction with Site Plan Review).
Floating zones	Floating zones are defined by specified land conditions, not necessarily delineated on a zoning map. Developers must demonstrate that proposed projects conform to whatever specifications are required.
Cluster zoning	Zoning density requirements are altered to allow residential planned unit development to cluster into one section of the site, leaving the remainder as open space.
Incentive or bonus zoning	Clustered zones are promoted by allowing extra development in the clustered area in exchange for preserving the remainder of the site as open space.
Overlay zoning	An existing zoning map is overlaid with additional zoning, which imposes special regulations for wellhead protection areas.
SUBDIVISION ORDINANCES	Subdivision ordinances apply when a land parcel is divided into lots for sale or development. They may be included in zoning or used where no zoning ordinance is in effect.
SITE PLAN REVIEW	Proposed development projects are reviewed by a local authority for compatibility with existing land uses and environmental considerations.
DESIGN OR OPERATING STANDARDS	Standards covering features such as drainage, recharge basins, or chemical storage facilities can be imposed on the design and operation of new development projects.
SOURCE PROHIBITIONS	The storage or use of dangerous materials is prohibited from a defined area.

[1] More information on these techniques can be found in *Wellhead Protection Programs: Tools for Local Governments* (U.S. Environmental Protection Agency, 1989).

Because most groundwater moves very slowly, a contaminant may not appear in a well until many years after it enters groundwater with recharge water. For this reason, an inventory of potential contaminant sources must also include historical information. From an analysis of historical aerial photographs taken at intervals through the years, professionals can identify potential problem areas such as

- abandoned dumps or landfills,
- pits or lagoons used for chemical disposal,
- stockpiles of barrels or other hazardous waste containers,
- fuel or chemical storage tanks, or
- prior industrial sites.

If potential contaminant sources such as these are found, remedial measures can be devised for containment or treatment.

Future contaminant sources can be analyzed by asking what would happen if the land within the wellhead protection area were developed to the maximum extent allowed by existing zoning or other regulatory statutes. One common contaminant used for planning purposes is nitrate, which is added to groundwater by septic systems and by the leaching of fertilizers. By determining the sources and fates of nitrogen at a specific site, decisions can be made about which land uses and fertilization practices will be able to attain specified water quality goals. For example, various densities of unsewered residential development can be analyzed to determine which will provide acceptable levels of nitrate in groundwater recharge (see, for example, Hughs and Pacenka 1985, Hughes and Porter 1983, Hughes et al. 1985, Pacenka et al. 1984, or Trautmann et al. 1983). The limitation of this approach is that it does not take into account other contaminants, many of which do not act in the same manner as nitrate.

Within a wellhead protection area, some land areas may be given higher priority than others because of their greater vulnerability to groundwater contamination. Using overlay maps of soil type, permeability, and depth to groundwater, the land areas in greatest need of protection can be identified. Maps can be drawn identifying zones such as these:

1. the land immediately surrounding each public water supply well,
2. the area supplying recharge water to each public well, and
3. the recharge area for the entire aquifer, or the part of the aquifer located within the community's boundaries.

Land use regulations and ordinances can then be tailored to the specific vulnerability of each site. Zoning ordinances, for example, can be used to direct new development primarily to areas outside the wellhead protection boundaries. If zoning already is in place, additional wellhead protection zones can be superimposed using overlay zoning, in which special restrictions are applied to development in key areas. Cluster zoning can be used to cluster developments beyond wellhead protection area boundaries, reserving the prime recharge areas for open space uses.

Another means of limiting development in key areas is through the restriction of major capital improvements such as roads, sewers, and water mains, which are essential for intensive development. In some cases, however, sewers carrying wastewater away from the wellhead protection area make more sense than septic systems within its boundaries.

Educational programs are a key to community understanding of and support for groundwater protection programs. One topic of primary concern is the proper handling of hazardous materials, by homeowners as well as commercial and industrial establishments. Communities can facilitate the voluntary use of proper disposal practices by providing lists of acceptable disposal methods for various chemicals and reputable hazardous waste haulers. (See, for example, *Disposal of Hazardous Waste,* a fact sheet produced by Cornell Cooperative Extension, New York State College of Human Ecology, and available from the Distribution Center, 7 Cornell Business and Technology Park, Ithaca, NY 14850.)

Table 2. Nonregulatory and Legislative Techniques for Wellhead Protection [1]

Technique	*Description*
NONREGULATORY	
PURCHASE OF PROPERTY OR DEVELOPMENT RIGHTS	
Acquisition of fee simple	Fullest control over land uses is achieved by public interests acquisition. Publicly owned wellhead protection areas can be restricted to public access or used for park land.
Acquisition of partial interests	Communities can purchase development rights, conservation easements, or restrictive covenants limiting what uses can be applied to the land.
GROUNDWATER MONITORING	Developers may be required to monitor groundwater quality downgradient from their development.
HAZARDOUS WASTE COLLECTION	To promote safe disposal of household hazardous waste materials, communities can sponsor hazardous waste collection days.
PUBLIC EDUCATION	Communities can sponsor public education relating groundwater quality to topics such as the proper handling and disposal of household hazardous waste, septic system maintenance, or fertilization and pesticide application practices.
LEGISLATIVE	
REGIONAL WELLHEAD PROTECTION AREA DISTRICTS	For protection of regional aquifer systems, states can create legislative districts to transcend existing jurisdictional boundaries.
LAND BANKING	State governments can empower local governments to impose a tax on land sales, with the revenues to be used to acquire and protect land within wellhead protection areas.

[1] More information on these techniques can be found in *Wellhead Protection Programs: Tools for Local Governments* (U.S. Environmental Protection Agency, 1989).

Conclusion

The traditional assumption that groundwater provides a source of pure water is not valid unless deliberate steps are taken to ensure the quality of this supply. Groundwater contaminants typically are invisible, often tasteless, and may take years to travel from their source to a water supply well. Once it has occurred, groundwater contamination may be infeasible to clean up, and expensive alternative water supply measures may be required. Primary emphasis, therefore, must be on preventing contamination at its source rather than on treating the problem after contaminants are discovered in public water supply wells.

Groundwater originates from water seeping downward through the soil from the land surface. Groundwater quality, therefore, is determined by land uses and chemical management practices, and efforts to protect groundwater supplies must rely on keeping contaminants out of the recharge water.

Wellhead protection areas can be designated using maps of groundwater flow to wells, and site-specific management plans can be developed designating the most appropriate protective measures for each wellhead area. These protective measures vary widely, ranging from community education about proper chemical use and disposal to public acquisition and management of critical recharge areas.

Land development and the use of toxic chemicals are steadily increasing in this country, as is our reliance on groundwater supplies. Clearly, protective measures will become ever more critical to ensure the availability of high-quality groundwater for both present and future uses.

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