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Project Summary

Case Studies in Wellhead Protection Area Delineation and Monitoring

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Groundwater monitoring is one of many management options for Wellhead Protection Program implementation. Groundwater parameters are monitored (1) to assess source-control measures, (2) to monitor compliance with drinking water standards at sites other than the wellhead, and (3) to provide advance warning of contaminants in ground water. Cooperative research was conducted with five municipalities to develop long-term monitoring programs for their existing wellhead protection areas. The product of this research is a technical assistance document which contains a methodology for planning and implementing a wellhead protection monitoring program. The methodology emphasizes source assessment, correct wellhead protection area delineation, and hydrogeologic characterization. Five case studies are included in the document to exemplify the monitoring methodology for different hydrogeologic and contaminant source settings.

The five case study research sites include Stevens Point, WI; Littleton, MA; Sioux Falls, SD; Dover, NH; and Springfield, MO. Three of these municipalities obtain their drinking water from unconfined aquifers; two aquifers receive significant recharge from a nearby pond and river. Two other case study sites are situated in fractured-bedrock and karst limestone aquifers. The document emphasizes a multi-disciplinary approach for hydrogeologic characterization, wellhead protection area delineation, and flowpath assessment. Hydrogeologic characterization techniques include: well installation, water quality sampling and assessment, geologic and structural-control mapping, aquifer testing, dye tracing, borehole geophysics, analytical solutions, and groundwater flow modeling. Long-term monitoring programs for wellhead protection include monitoring objectives, existing and new monitoring sites, guidance for monitoring site construction and installation, sampling protocol, optimal monitoring parameters and frequencies, and quality assurance and quality control considerations.

This Project Summary was developed by EPA's Environmental Monitoring Systems Laboratory, Las Vegas, NV, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The increasing contaminant threat to public water supply wells has created a new political and technical awareness of groundwater protection programs. Recognizing the need for conjunctive management of contaminant sources and public water supplies to prevent, or minimize, groundwater quality degradation, Congress amended the Safe Drinking Water Act in 1986 to include Section 1428. This section mandated the development of the Wellhead Protection Program (WHPP), which established a legal framework to protect public water supply wells, wellfields, and springs from contamination. An important technical element of WHPP implementation is wellhead protection area

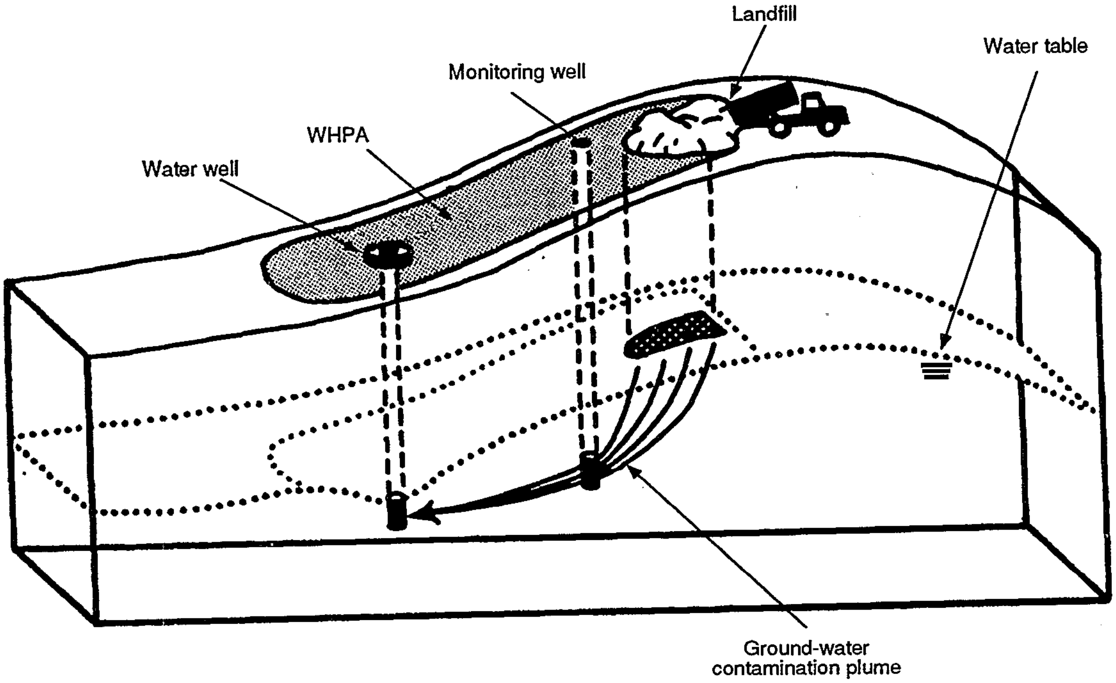

Figure 1. Conceptual wellhead protection area and monitoring scenario.

delineation. A wellhead protection area (WHPA) is defined as the surface and subsurface area surrounding a well, wellfield, or spring, through which contaminants may pass and reach the ground water contributing to the supply source (Figure 1). Criteria and methods for WHPA delineation are given in several U.S. Environmental Protection Agency (EPA) guidance documents.

Groundwater monitoring may enhance source characterization, WHPA delineation, and new water supply evaluation. This technical assistance document provides information to local, state, and tribal governments and the EPA Regions in their implementation of WHPPs. The primary goals of this document are to present a monitoring methodology for WHPAs and to exemplify this methodology in five unique case study settings.

Wellhead Protection Area Monitoring

In 1989, U.S. EPA's Environmental Monitoring Systems Laboratory (EMSL) at Las Vegas, NV, engaged in cooperative research with five carefully selected municipalities to develop proposed, long-term monitoring programs for their existing WHPAs. The product of the cooperative research contains two types of information:

(1) A recommended methodology for planning and implementing a wellhead protection monitoring program which emphasizes source assessment, correct WHPA delineation, and hydrogeologic characterization.

(2) Five case study narratives used to exemplify the monitoring methodology for different hydrogeologic and contaminant source settings (Table 1).

The monitoring methodology is intended to serve as a guide for WHPP implementors in establishing technically defensible, reliable, and effective groundwater monitoring programs for wellhead protection. This methodology emphasizes saturated zone monitoring. The first four case study narratives are presented in the document in order of increasing hydrogeologic complexity (aquifer heterogeneity). The exception to this organization is the Springfield, MO, case study, which is presented in abbreviated form in an appendix.

Basic hydrogeology concepts and equations are reviewed including: groundwater systems and flow, conceptual hydrogeologic models and flow nets, and accurate delineation and monitoring in different hydrogeologic settings. The spectrum of unconfined to confined aquifer conditions is discussed in relation to porous, granular aquifers; fractured-bedrock aquifers; and karst aquifers.

Physical and chemical parameter monitoring apply to wellhead protection. Three types of groundwater monitoring are useful in managing WHPAs: ambient trend, source assessment, and early-warning detection monitoring. Ambient trend monitoring detects the temporal and spatial trends in physical and chemical quality of the groundwater system. Source assessment monitoring evaluates the existing or potential impacts on the physical or chemical groundwater system from a proposed, active, or abandoned contaminant source. Early-warning detection monitoring is conducted upgradient from the wellhead, based on known travel times, to trigger a contingency response to prevent public exposure to contaminants. These types of monitoring are incorporated to measure or detect contaminants in aquifers, and should not be mistaken as preventative or remedial measures.

Table 1. Characteristics of the Case Study Research Sites.

Municipality	*Hydrogeologic setting*	*Characterization tasks*
Stevens Point, WI	*Unconfined aquifer*	*Flow system modeled with FLOWPATH (2-dimensional, steady state); point and nonpoint sources assessed*
Littleton, MA	*Unconfined aquifer, rehcarge from Spectacle Pond*	*Flow system modeled with FLOWPATH (2-dimensional, steady state); MODFLOW (3-dimensional, steady state); and FLOWCAD (2-dimensional, transient); Industrial and commercial point sources assessed*
Sioux Falls, SD	*Undonfined aquifer; recharge from the Big Sioux River*	*Flow system modeled with FLOWPATH (2-dimensional, steady state); Big Sioux River assessed as a line source; point and nonpoint sources present*
Dover, NH	*Fractured-bedrock aquifer, discrete flow system*	*Flow system characterized with lineament analysis, structural control mapping, aquifer testing, dye tracing, and borehole geophysics; a few commercial, point sources, and natural sources*
Springfield, MO	*Mature karst (porous limestone) aquifer, conduit flow system*	*Flow system determined by watershed boundaries, dye tracing, and flow analysis; point and nonpoint sources assessed*

Source assessment is a critical first step in designing an effective monitoring program. Target monitoring parameters for early-warning detection and source assessment are selected from a comprehensive list of known and suspected contaminants associated with land-use activities and practices. Optimal monitoring sites may be determined, reflecting prioritization of sources. An inventory of common sources of contamination within and in proximity to WHPAs is included.

The monitoring methodology is divided into three phases:

- Phase I: WHPP Elements and Scoping Tasks
- Phase II: Research Monitoring Program
- Phase III: Wellhead Protection Monitoring Program

Phase I WHPP elements and scoping tasks include: designating roles and a management framework, preliminary WHPA delineation, and source assessment. To support the research monitoring task, an initial information base of ancillary and monitoring data should be compiled and reviewed to determine data limitations and gaps. The strategy is to maximize information content; to define monitoring objectives; and to conduct field studies with the least, but still adequate number of monitoring points. Existing monitoring sites identified in this phase can be incorporated in the long-term monitoring network. Phase I generally requires a 3- to 6-month period for completion.

Phase II is aptly named the Research Monitoring Program, or the phase of acquiring information pertaining to how the subsurface system operates and of formulating interpretations. Research monitoring is conducted to improve, or verify, elements of the hydrogeologic conceptual model. A technically defensible conceptual flow model ensures a more protective and reliable monitoring program. Research monitoring for wellhead protection includes baseline water quality characterization, aquifer testing and characterization, refined or verified WHPA delineation, and groundwater flowpath determination to relate sources to the water supply well or spring. The product of research monitoring is a proposed long-term monitoring program that may be partly implemented in Phase II. Phase II may require 1 to 1.5 years for completion, depending on the complexity of the site hydrogeology and the quality of the initial information base.

The by-product of Phases I and II is a proposed wellhead protection monitoring program, Phase III. Generally, the program is submitted as a plan to be implemented in stages, as labor and financial resources become available. The plan should include an organization chart, a source assessment map and list, and a map depicting the WHPA and protective zones, as well as a description of the delineation criteria and method(s). General and specific objectives for ambient trend, source assessment, and early-warning detection monitoring should be detailed. Each objective should justify the selection of monitoring sites, parameters, and frequencies.

The locations of existing and recommended monitoring sites in the proposed network should be shown on a map. A formal identification system with a minimum set of data elements should be used to label each site. The integrity of the design and construction of each existing site should be considered prior to inclusion in the monitoring network to ensure data quality. New sites that require installation should be described in detail, concerning completion depth, open or screened interval, schematic design, and construction materials, as well as the methods of installation, development, and testing. Physical and chemical parameters to be monitored at select frequencies should be listed and technically justified. Monitoring site information should be stored in an automated data base for convenient and safe storage, update, and retrieval. Each monitoring program should formulate a minimum set of quality assurance and control objectives to match the objectives of the wellhead protection monitoring program.

A 15-step approach for the design of a wellhead protection monitoring program is depicted as a flowchart in Figure 2. The monitoring program should be reviewed and improved in an iterative process over the life span of the WHPP. The organization of the case studies research follows the logical outline of Phases I, II, and III.

Stevens Point, WI: Case Study

The city of Stevens Point is located in central Wisconsin and has a population of approximately 23,000. The source of the city water supply is from the Airport and Iverson wellfields. These wellfields pump an average of 5 million gallons of water per day from a shallow, unconfined aquifer. The aquifer is composed of coarse, unconsolidated sediments deposited by meltwater during the Wisconsin glaciation. The preliminary wellhead protection zones for the combined wellfields were based on estimates of the zone of influence, the 5-year time-of-travel (TOT) zone (analytically determined), and the recharge area. In the review process, the validity of the 5-year TOT calculation was questioned, and the WHPA was never promulgated.

An extensive, historical source assessment was conducted within the B Zone of the preliminary WHPA using aerial photographic interpretation techniques combined with conventional methods such as surveys of directories, local and state records, visual inspections, and monitoring data. Point and nonpoint sources were identified, ranked, and prioritized for management and regulation. Existing contaminant sources were given highest priority. Potential sources were then prioritized based on source type, quantity, hazard, and location.

A network of 55 monitoring sites (single monitoring wells, well nests, and a multilevel well) were used to measure water levels, to sample ground water, and to conduct aquifer tests in the unconfined aquifer. Of the total network, three single wells and four well nests represent new monitoring points installed for this research. Aquifer parameter results from slug, constant-discharge, and recovery tests indicate a range of hydraulic conductivity values for three distinct geologic settings: 820 to 1,700 ft per day (ft/d) for the buried valley, 220 to 240 ft/d for outwash plains, and 2 to 3 ft/d for bedrock highs.

Hydrochemical data indicate that nitrogen concentrations, a key indicator of contamination, have increased over time. Currently, nitrogen concentrations in the monitoring network range from less than 0.2 to 26.0 mg/L. Other indicators of groundwater degradation include iron and manganese from organic-rich soils located along the Plover River, chloride in proximity to roads where de-icing occurs, and previous volatile organic compound contamination at the Airport and several underground storage tanks.

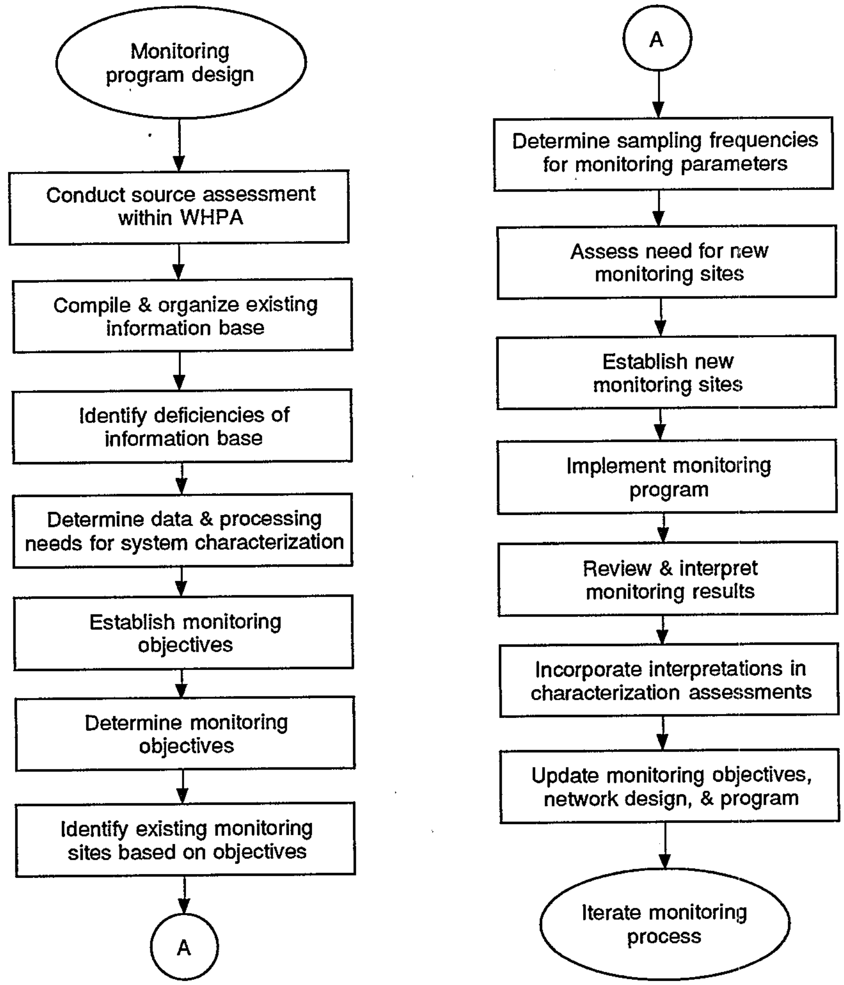

Figure 2. *Flowchart of the 15-step monitoring methodology for wellhead protection areas*

A two-dimensional, groundwater flow model (FLOWPATH) was used to delineate the 5- and 10-year TOT zones for the Airport and Iverson wellfields. In comparison, the previous, analytically derived B Zone is larger; however, the 5-year TOT zone from FLOWPATH extends farther to the east due to the effects of pumping at the Iverson wellfield and the presence of bedrock highs.

A long-term groundwater monitoring network is proposed for the Airport and Iverson wellfields consisting of 34 existing and proposed wells. Nine new well locations are proposed to fill data gaps in the existing network, primarily along the boundaries of the 5- and 10-year TOT zones. Wells in the long-term monitoring network should be sampled twice a year in April and September for indicator parameters. Water levels should be recorded each time a well is sampled. Compliance monitoring networks are recommended for point sources of highest priority.

The wellhead protection contingency plan consists of three components: (1) reaction to the early-warning detection system based on preventive action and state drinking water limits, (2) spill response, and (3) new water-supply development and implementation.

Littleton, MA: Case Study

The town of Littleton is located approximately 35 miles northwest of Boston in northeastern Massachusetts. The daily water demand for the town's population of 7,300 is from 800,000 to 1,500,000 gallons per day from four production wells. Techniques for refined delineation and long-term monitoring of the WHPA surrounding Production Well Number 5 (PW-5) are discussed. Production Well Number 5 is completed at a depth of 167 ft within saturated, stratified valley-fill deposits. The aquifer is unconfined and receives significant surface-water recharge (20 to 25%) from nearby Spectacle Pond and Bennetts Brook.

Land-use activities within the WHPA cover a range of commercial, industrial, and to a lesser degree, agricultural operations. Collectively, these land-use activities pose potential contamination threats to the aquifer, including heavy metals, volatile organic compounds, pesticides, and nutrients. Baseline monitoring results indicate that groundwater quality within the capture zone of PW-5 is currently unaffected by source operations. Sodium is the only exception. Slightly elevated levels of sodium in surface water and the shallow aquifer are attributed to roadway de-icing. Manganese and iron concentrations are elevated throughout the recharge area of PW-5, primarily because of their occurrence in wetland sediments and glacial deposits. The levels of these parameters have increased at PW-5 for several years and may warrant treatment in the future.

The PW-5 WHPA consists of three protection zones delineated using a combination of numerical groundwater flow models (FLOWPATH, FLOWCAD, and MODFLOW) and hydrogeologic mapping. Zone I is the 400-foot sanitary protective radius mandated by the State of Massachusetts. Zone II is the most critical management area and was delineated conservatively as the union of three numerical capture zone solutions. These numerical solutions incorporate two- and three-dimensional flow, as well as steady-state and transient flow conditions. Local and regional groundwater flow simulations are based on the results of short- and long-term aquifer testing.

Zone II generally represents the steady-state capture zone for PW-5 that corresponds approximately to the 400-day travel-time contour. Flowpath simulations indicate that Zone II extends to the bottom of the aquifer and is constrained by bedrock and glacial till. Within Zone II, three existing wells and two new wells are proposed for inclusion in the monitoring network for early-warning detection and source assessment purposes. These wells lie along either the 150-day or the 300-day travel-time contours. Screened intervals for the new monitoring wells were chosen based on results from MODPATH computer flow simulations. Monitoring parameter groups for these wells include general water quality, site-specific, and physical parameters. Recommended monitoring frequencies for these parameter groups vary from quarterly to annually, depending on the travel-time distance from the monitoring well to PW-5 and the monitoring well depth.

Zone III is defined as the upgradient area of the aquifer that contributes to Zone II and extends to the watershed boundary. Zone III is monitored at two surface-water locations, one at the inflow and one at the outflow of Spectacle Pond. In addition, Zone III is monitored biannually at existing compliance networks around waste management and industrial sites. Monitoring parameters for the compliance wells include general water quality, site-specific, and physical parameter groups.

The Littleton WHPP incorporates contingency planning. Catastrophic releases initiate a spill-response plan that involves many departments and agencies. In the event of contamination of PW-5 or another production well, Littleton has sited a new production well. The proposed well site is approved by the State, and protection Zones I, II, and III are delineated. The adjacent town of Boxborough shares the recharge area to the proposed well. Boxborough has adopted complementary strategies with Littleton to ensure its water quality protection.

Sioux Falls, SD: Case Study

The city of Sioux Falls is located in the southeast corner of South Dakota. The Big Sioux aquifer is the primary source of water for about 125,000 persons in the Sioux Falls metropolitan area. One of the municipal wells in the Big Sioux aquifer, the airport wellfield, is underlain by surficial, glacial outwash deposits. The Big Sioux River is located directly west of the airport wellfield and flows south over and through the outwash, draining approximately 4,000 square miles of upstream land.

The city's wells pump most of their water directly from the aquifer and a small quantity from the Big Sioux River. However, the river is hydraulically connected to the aquifer, and recharge from the river in the airport wellfield area is significant. In 1988, approximately 79% of the recharge to the airport wellfield aquifer was induced from the river due to wells pumping. Induced flow from the river to the aquifer is demonstrated by decreased flow in the river during low recharge periods.

This research was conducted to evaluate (1) the hydraulic connection between the Big Sioux River and the adjacent aquifer, and (2) the potential impact of the river on aquifer water quality. In the broader perspective, additional goals included refined delineation of the wellfield protection area and design of a long-term water quality monitoring program.

Drilling logs indicate that the thickness of the aquifer in the wellfield area ranges from 20 to 50 ft. Aquifer testing results yield an average hydraulic conductivity value of 800 ft/d and a transmissivity value of approximately 21,000 ft^2/d for the aquifer.

Many potential point sources of contamination exist in the study area. These include: industrial and commercial areas, the South Dakota Air National Guard facility, a petroleum pipeline, the Sioux Falls Regional Airport, and a decommissioned municipal landfill. The threat of contamination from these sources is underscored by the recent history of contaminant releases in the area.

To estimate groundwater travel times in the study area, aquifer testing, dye tracing, and groundwater modeling were employed. During aquifer testing, two dye injections were made. The first dye was injected in a well approximately 40 ft north of the pumping well. Detectable dye concentrations first arrived at the pumped well after about 12 hours. The second dye was injected in a well near the edge of the river, approximately 140 ft north of the pumping well. Detectable dye concentrations from the second injection site first arrived at the pumped well in 7 to 9 days. Aquifer testing and dye-tracing results indicate that a contaminant could travel from the river to the wellfield in less than 9 days.

A two-dimensional, steady-state model (FLOWPATH) was used to generate time-related capture zones for the municipal wells and to simulate contaminant travel times. One-, two-, and five-year capture zones were calculated for each of the municipal wells in the airport wellfield. Modeling of simulated spill sites from several of the potential point-source contamination areas indicates that contaminants entering the aquifer at areas to the north and south of the well field could reach the municipal wells in 1 to 2 years.

The City of Sioux Falls and Minnehaha County have delineated wellhead protection areas by using the hydrogeologic-mapping method. Wellhead protection ordinances are designed to impose guidelines and restrictions on new land uses, or proposed changes in existing use, in order to protect the aquifer water quality.

A wellhead protection monitoring program at the airport wellfield is proposed to document ambient water quality conditions and to serve as an early-warning detection system. Line-source monitoring is proposed to monitor the Big Sioux aquifer and the diversion canal for contaminants that could potentially enter the aquifer. Point-source and nonpoint-source monitoring are proposed to monitor water quality between the airport wellfield and potential sources. The categories of parameters for monitoring are general water quality, volatile organic compounds, trace metals, pesticides, and nutrients. Sampling frequencies for each of the categories were selected as a function of the type of source to be monitored.

Contingency planning is warranted to establish emergency responses to contaminant releases at the surface of the aquifer and in the river. Alternative water supply development must also be continued as part of the contingency planning effort.

Dover, NH: Case Study

Dover is a city of 26,000 people located in the seacoast region of New Hampshire. To meet the increasing water supply demands of the future, the city embarked on a water exploration effort in a fractured-bedrock aquifer at the Blackwater Brook site. A test well was installed to a depth of 400 ft in the bedrock aquifer as part of the groundwater exploration program. A wellhead protection area and groundwater monitoring strategy were established for the test well. This study describes how the conceptual hydrogeologic model for the site was developed and refined.

The bedrock aquifer consists primarily of quartz monzonite and metasedimentary rocks that interfinger along a fractured, faulted contact zone trending north 60 degrees east (N60°E). A N5-10°W trending lineament and fracture zone intersects the N60°E zone at the site. The bedrock aquifer is directly overlain by Pleistocene-age sands and gravels. These sediments are overlain by low-permeability marine clay and lodgement till. It is estimated that 20% of the water produced from the bedrock aquifer is derived from overburden sediments in the watershed area.

Four overburden and bedrock well pairs constitute the present monitoring network for the test well. Two well pairs lie along the N60°E faulted contact zone, and two well pairs lie along the perpendicular N30°W trend. The test well and four of five bedrock wells airlift in excess of 150 gal/min. Few contaminant threats exist near the site. Baseline sampling indicates that minor, elevated levels of iron, manganese, and radon pose the only water quality problems at present.

Test drilling and borehole surveys (caliper, video camera, acoustic televiewer, thermal-pulse flowmeter, and hydrophysical logging) indicate that fracturing and groundwater flow are highly discrete. Flow occurs at isolated, definable depths rather than uniformly along the length of the borehole. Hydrophysical logging indicates that the borehole water is distinctly layered with respect to the fluid electrical conductivity parameter. Most borehole water is produced by moderately to steeply dipping fractures and fracture zones that intersect the wells.

Aquifer testing and dye-trace results indicate that the N30°W and N60°E directions have higher aquifer transmissivities relative to the surrounding bedrock matrix. Drawdown contours are elongate about the N30°W well alignment, suggesting preferred flow in this direction. Dye-trace results indicate more rapid travel of injected dye along the N30°W direction than the N60°E direction. Dye traveled 152 ft in 130 minutes (the time of first arrival of the dye) from injection in a bedrock monitoring well along the N30°W trend to the test well, which was pumped at 200 gal/min. This represents a velocity of 1,680 ft/d. Dye injected in a bedrock monitoring well located 596 ft from the test well arrived there in 148 hours, indicating a velocity of 96 ft/d along the N60°E direction.

Flowmeter and acoustic televiewer surveys indicate that a moderately west-dipping fracture zone provides interconnection between the test well and bedrock well R2 along the N30°W trend. Lacking discrete flow information beyond the test well and well R2, statistical fracture descriptions become good approximations of flowpaths at increasing distances from the site. Therefore, prominent fracture peaks along the N5-10°W and N60°E trends represent the most probable flow directions within the bedrock fracture system at Blackwater Brook. The N60°E trend is substantiated by the existence of the faulted, fractured contact zone along this strike. Evidence to suggest preferred flow along the N5-10°W direction is structural and hydrogeologic. Structural control is inferred by strong expression of the lineament on several platforms of photography and in outcrop fracture trends. Enhanced transmissivity along the N30°W direction is attributed to the proximity and similar orientation of the N5-10°W fracture zone.

A quadratic equation is derived from accepted hydrogeologic relationships (Darcy's Law and the Thiem equation). In this equation, groundwater travel time (determined using the time of first arrival of dye at the test well) is directly proportional to the square root of distance from the test well. Constants of proportionality for the quadratic relationship are calculated for the N30°W and the N60°E directions based on dye-trace velocities. Distances for the 200-day and 1,000-day TOT thresholds are then calculated for the two fracture zone directions: N5-10°W and N60°E.

Three wellhead protection zones are delineated within the recharge area for the test well using a variety of criteria and methods. Zone I is the state-mandated 400-foot sanitary radius. Zone IIA consists of two 1,000-foot-wide "arms" along the N5-10°W and N60°E directions, extending to the 200-day TOT distances. Zone IIB is the area within a smooth curve connecting the outer boundaries of Zone IIA, producing an oval shape. Zone III is the upgradient area contributing to the 1,000-day TOT distance modified by hydrogeologic features. Recommended regulation of the wellhead protection zones varies from complete control and restriction of activities in Zone I to public education in Zone III.

A major component of wellhead protection program management is long-term groundwater monitoring. Under present conditions, monitoring of the test well and existing monitoring wells will focus on a moderate effort to assess ambient water quality and physical parameters. After the production well is developed, the monitoring frequency and list of monitoring parameters increases. Proposed frequencies, parameters, and new sites for monitoring derive from technical and management goals. Action levels are proposed to trigger contingency responses.

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The complete report, entitled "Case Studies in Wellhead Protection Area Delineation and Monitoring," (Order No. PB93-213510AS; Cost: $61.00, subject to change) will be available only from:

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