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DELINEATION OF WELLHEAD PROTECTION AREAS IN FRACTURED ROCKS

Wisconsin Geological and Natural History Survey

Ground-Water Protection Division
Office of Ground Water and Drinking Water
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DISCLAIMER

This report is the result of an investigation supported by the U.S. Environmental Protection Agency's Office of Ground-Water Protection, as part of its efforts to provide technical assistance to state, tribal, and local governments on the implementation of the Wellhead Protection Program. The specific methods and approaches contained in this document have been peer reviewed but do not constitute official Agency endorsement or policy recommendations. The Office of Ground-Water Protection provides this information to help solve complex technical problems related to the delineation of wellhead protection areas in fractured-aquifer settings. Further assistance is available from the Office of Ground-Water Protection in Washington, D.C. and from the ground-water offices in the ten EPA regions.

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DELINEATION OF WELLHEAD PROTECTION AREAS IN FRACTURED ROCKS

ABSTRACT

In 1987 the U.S. Environmental Protection Agency (EPA) published guidelines for delineation of wellhead protection areas (WHPA) to meet the requirements of the 1986 Amendments of the Safe Drinking Water Act of 1974. In the document, EPA concentrated on WHPA delineation in common types of aquifers--granular, porous aquifers under unconfined conditions. In 1989 the Wisconsin Geological and Natural History Survey prepared this report, under an agreement with EPA to evaluate methods for WHPA delineation in unconfined fractured-rock aquifers.

Two fractured-rock settings were selected for the study: Precambrian crystalline rocks in central Wisconsin and Silurian dolomite in northeastern Wisconsin. In both situations, densely fractured rocks behaved as uniform, porous media at the scale of field tests. Potential methods for WHPA delineation were tested using a full range of hydrogeologic investigations, including water-table mapping, collection and analysis of water samples, geophysical logging, monitoring, and numerical modeling.

The methods tested ranged from simple "cookie-cutter" approaches to complex computer models, including the fixed radius methods, flow-system and vulnerability mapping methods, residence-time methods, and numerical flow/transport models. The evaluation of these methods indicated that flow-system mapping (combined either with time of travel criterion or calculations using the uniform flow equation) and numerical modeling are the two most viable approaches to wellhead protection in fractured rocks that act as porous media at the WHPA scale. Flow-system mapping is especially useful when a ground-water divide is relatively close to the protected well, and it offers reasonable accuracy at the least cost. Numerical modeling (the most expensive method) provides increased precision and a better three-dimensional picture, which may justify the increased costs, especially in complicated settings.

Four WHPA delineation approaches are suggested for unconfined fractured-rock aquifers that do not behave as porous media. Vulnerability mapping combined with the arbitrary fixed radius method or the simplified variable shape method produces a WHPA that includes most of the areas near the well that are susceptible to ground-water contamination. Hydrogeologic mapping can be used to determine ground-water basin boundaries and in some cases, the ground-water basin may function as the ZOC for a given well. The geochemical approach may be used to provide information on relative ground-water ages and source areas. Numerical ground-water flow/transport models, used carefully, may be able to simulate flow in discrete fractures or fracture zones. Even though the models are based upon porous-media assumptions, careful discretization can allow one to incorporate a few high-permeability fractures or fracture zones into the model design.

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EXECUTIVE SUMMARY

Background

The 1986 Amendments to the Safe Drinking Water Act (SDWA) of 1974 established a nationwide program to prevent contamination of ground-water sources tapped by public water supply wells--the Wellhead Protection Program. The U.S. Environmental Protection Agency (EPA) was required to provide technical guidance to help state, tribal, and local agencies implement the hydrogeologic aspects of the program. In 1987 EPA published "Guidelines for Delineation of Wellhead Protection Areas" to meet this requirement. The guidelines provided a summary of criteria and methods for delineating wellhead protection areas (WHPAs). The document concentrated on WHPA delineation in one common type of aquifer--the porous, granular aquifer existing under unconfined conditions. Given the lack of attention by the states at that point to delineating specific WHPAs in confined aquifers and less common fractured-rock aquifers, the guidance provided limited information on such settings.

This report, "Delineation of Wellhead Protection Areas in Fractured Rocks," was prepared by the Wisconsin Geological and Natural History Survey (WGNHS), under an agreement with the EPA Office of Ground-Water Protection, to evaluate approaches to delineating WHPAs in unconfined fractured-rock aquifers that would be applicable to fractured-rock settings in Wisconsin and in similar settings elsewhere in the United States.

Hydrogeologic Setting

Two fractured-rock settings were selected for the study: Precambrian crystalline rocks in central Wisconsin and Silurian dolomite in northeastern Wisconsin. The first test site is typical of terrains where crystalline rocks are at or near the land surface and covered only by residual soil or a thin layer of unlithified deposits, and where fractured crystalline rocks are the sole source of community water supplies. The second test site is typical of fractured sedimentary carbonate-rock aquifers either exposed at the land surface or covered by thin soils, where potential for ground-water contamination is very high. Due to abundant fractures, the fractured rocks at both sites behaved as porous media at the scale of field tests. The porous-media assumption implies that the hydraulic properties of the individual fractures are not important and that the aquifer can be treated as a continuum when the problem scale is large enough.

Approaches Used

Methods to delineate WHPAs were tested using a full range of hydrogeologic investigations, including water-table mapping, collection and analysis of water samples, geophysical logging, aquifer testing, and numerical modeling. Four approaches to WHPA delineation were tested at the two test sites. The overall goal of each approach was to delineate the zone of influence (ZOI) or the zone of contribution (ZOC) of a well in an unconfined fractured-rock aquifer.

Four main approaches were used for testing WHPA delineation methods. The first approach included calculating the ZOI of a well by standard well and ground-water hydraulics equations. These equations are based on the assumption that a large body of fractured rock with closely spaced fractures acts hydraulically similar to a porous, granular medium. The second approach involved mapping hydrologic and geologic boundaries, as well as identifying areas of the landscape particularly vulnerable to ground-water contamination. The third approach utilized geochemical and isotopic indicators to estimate the age and source of water produced by a well. The isotopic results can be used to verify the validity of the ZOC estimates based on hydraulic considerations alone. The fourth, and most sophisticated approach, was the construction and calibration of a detailed, three-dimensional numerical ground-water flow/transport model of each study area.

WHPA Delineation Criteria

WHPA delineation is based upon the analysis of criteria, thresholds, and delineation methods. The criteria and thresholds incorporate the general technical basis of the WHPA. The WHPA delineation methods are techniques by which criteria and thresholds are translated into on-the-ground or on-the-map WHPA boundaries.

Criteria used for the WHPA delineation at the two test sites in Wisconsin were adopted from the 1987 EPA guidelines and included

1) distance from the well,
2) drawdown around the well,
3) time of travel (TOT) to the well, and
4) ground-water flow system boundaries.

Some combinations of these criteria will work better than others in establishing a wellhead protection program in fractured rocks. For example, the distance criterion would not work well by itself because it does not account for any site-specific hydrogeologic characteristics. The drawdown criterion leads to the delineation of a ZOI only, which is not a good basis for a WHPA in fractured rocks for two reasons. First, the dimensions of the drawdown cone may be too small for the porous-media assumption to be valid. Second, unless the water table is nearly horizontal, the zone of influence will seriously underestimate the true ZOC. A more protective WHPA is probably based on the flow-system boundary criterion. Delineation of ground-water divides and flow lines is done at a large enough scale that the assumption that fractured rock behaves as a uniform porous medium is likely to be valid. Even if the porous-media assumption is not completely valid, flow-system mapping may delineate zones of conduit fracture flow, which can often be simulated numerically.

WHPA Delineation Methods

Following selection of WHPA delineation criteria, six methods were tested for WHPA delineation at the two test sites in Wisconsin. The methods, in order of increasing complexity include

1) arbitrary fixed radius,
2) calculated fixed radius,
3) vulnerability mapping,
4) flow-system mapping,
    - with TOT calculations,
    - with analytical equations,
5) residence-time approach, and
6) numerical flow/transport modeling.

The first two methods are not recommended for WHPA delineation in fractured rocks. The arbitrary fixed radius method does not incorporate any hydrogeologic considerations, and the estimates of the radius are more difficult to make in complex fractured-rock conditions than in porous media. The calculated fixed radius method resulted in unrealistic radii around the protected well, probably because the errors associated with aquifer parameter estimates and with estimates of the time required for the aquifer to reach steady state are larger in fractured rocks than in porous media.

Vulnerability mapping can be applied to any type of hydrogeologic setting. This method does not delineate a ZOC for a well; rather, it identifies areas particularly vulnerable to ground-water contamination. A WHPA that includes most of the areas near the well that are susceptible to contamination can be delineated by combining vulnerability mapping with the arbitrary fixed radius method or the simplified variable shapes method.

The flow-system mapping method utilizes flow-system boundaries, and it is a very efficient method for delineating ZOCs in fractured-rock settings, especially where the flow-system boundaries are close to the well. A water-table map can be compiled with a minimum of field work if enough water-level data are available from agencies' water-well files and if water-level fluctuations in the area are relatively small. In general, flow-system mapping requires the assumption that the fractured rock behaves as a porous medium at the scale of the problem. However, in cases where the aquifer does not behave as a porous medium, the flow-system mapping technique may be useful for delineating fracture conduits or zones of high hydraulic conductivity. The WHPA for the well should then take such zones into account.

Combining the flow-system mapping method with calculations of the time of travel or with calculations using the uniform flow equation may lead to a more accurate ZOC for relatively little additional cost. These combination methods offer reasonably accurate and efficient protection for wells in many fractured-rock settings, but they may not be adequate if the fractured rock does not act as a porous medium.

The residence-time approach utilizes water chemistry and isotopes to identify ground-water flow paths and to provide information on relative ground-water ages and source areas. This approach does not assume that the fractured rock behaves as a uniform porous medium. The residence-time approach does not delineate a ZOC and is therefore only useful when used in combination with other WHPA delineation methods, especially with the flow-system mapping and numerical models. The method can identify those hydrogeologic settings where recent recharge indicates vulnerability to potential contamination.

Numerical models use mathematical approximations of ground-water flow and/or contaminant transport equations that can take into account a variety of hydrogeologic and contamination conditions and do not necessarily require that aquifers behave as porous media. The flexibility of computer models allows for handling features such as conductive fracture zones in some relatively simple settings. These models possibly offer the most accurate ZOC delineation, but at considerable cost, which may be justified in complex settings or when great accuracy is required.

The study of two fractured-rock settings in Wisconsin demonstrated that standard ground-water flow equations and field techniques developed for porous media can be used for the delineation of WHPAs protection areas in fractured rocks. Even so, both sites were complex enough that methods less sophisticated than flow-system mapping did not encompass enough of the site characteristics to result in an adequate WHPA. The aquifers at both sites were heterogeneous and anisotropic, and numerical modeling was the only method able to take the heterogeneity and anisotropy into account. Both sites were located near ground-water divides, which limited the size of the ZOCs for each site. Due to the presence of these ground-water divides, the numerical models produced ZOCs that were not much different from ZOCs produced by flow-system mapping. However, at both sites the TOT estimates produced by modeling were more accurate than TOT estimates from other methods. At sites far from hydrogeologic boundaries, numerical modeling will probably be the only method that can delineate an accurate WHPA of reasonable size.

For a fractured-rock aquifer that does not act as a porous medium, WHPA delineation can be accomplished by a combination of vulnerability mapping, hydrogeologic mapping, the residence-time approach, tracer tests, and numerical modeling. Flow in such aquifers can occur mainly through discrete fracture conduits. It is particularly important to identify possible areas where such conduits intersect either the land surface or the well to be protected because such conduits can offer direct and rapid pathways for contamination to travel from the land surface to the well.

WHPA Implementation

The WHPA delineation methods tested in Wisconsin can be applied to similar settings elsewhere in the United States. Unconfined crystalline-rock and carbonate-rock aquifers are common throughout much of the eastern United States and western mountain ranges and in many places in the midcontinental section. Even though similar aquifers are quite common, there are some limitations to the transferability of the results. The recommended methods were tested only in one type of the fractured-rock environment--aquifers with closely spaced fractures, which were the geological conditions found at both Wisconsin test sites. Under these conditions fractured rocks behave as uniform, porous media at the scale of field tests. Fortunately, we can expect that the size of WHPAs in other parts of the United States would be large enough that the porous-media approach to WHPA delineation will be adequate for many, if not most, densely fractured rocks. In any case, vulnerability mapping, hydrogeologic mapping, and the residence-time approach do not require the porous-media assumption and flow-system mapping and numerical modeling could work well or moderately well even when the porous-media assumption is not completely justified.

Chapter I

INTRODUCTION

Project Background

The 1986 Amendments to the Safe Drinking Water Act (SDWA) of 1974 established a nationwide program to protect ground-water resources tapped by public supply wells from a wide range of potential threats. A major provision of the Amendments was the establishment of the Wellhead Protection Program. This program differs from previous federal ground-water protection efforts in that it approaches the assessment and management of ground-water quality from a more comprehensive perspective. Rather that focusing on individual contamination sources, the program focuses on preventing contamination of the actual resource--ground water.

The Wellhead Protection Program seeks to accomplish this goal by the establishment of wellhead protection areas (WHPAs), within which potential contamination sources are differentially managed. A WHPA is defined in the 1986 Amendments as "the surface or subsurface area surrounding a water well or wellfield, supplying a public water system, an area through which contaminants are reasonably likely to move toward and reach such water well or wellfield." The land surface within a WHPA or adjoining a WHPA may be managed using a more protective, focused approach. Thus, WHPAs are created as a means to reduce the potential for contamination of public water supplies.

The Wellhead Protection Program requires the participation of all levels of government. Individual states must develop and implement wellhead protection programs to meet the requirements of the SDWA Amendments. The federal government is responsible for approving state wellhead protection programs and for providing technical support to state and local governments. Because of this, the U.S. Environmental Protection Agency (EPA) was required to provide technical guidance to help state and local agencies implement the hydrogeologic aspects of the wellhead protection program. In 1987, EPA published "Guidelines for Delineation of Wellhead Protection Areas" as part of this requirement (U.S. EPA, 1987). The guidelines provided a summary of criteria and methods for delineating WHPAs. The document, however, concentrated on WHPA delineation in one common type of aquifer--the porous, granular aquifer existing under unconfined conditions--with more limited attention to delineating WHPAs in confined aquifers and less common fractured-rock aquifers.

Staff of the Wisconsin Geological and Natural History Survey (WGNHS) prepared this report under Federal Assistance Agreement No. CX-815386-01-0 with the U.S. EPA Office of Ground-Water Protection, Washington, D.C., with Marilyn Ginsberg as EPA Project Officer and Alexander Zaporozec as Project Manager. Parts of the report were contributed by Bruce

Brown and Ronald Hennings of WGNHS, and by William McCabe of EPA. The project period was October 1, 1988 - December 31, 1989.

Purpose and Scope

The purpose of the project was to investigate methods for delineating WHPAs that would be applicable to fractured-rock settings in Wisconsin and to similar settings elsewhere in the United States. This document was prepared to assist planners, managers, and administrators of state, county, or municipal governments in the task of protecting their water supplies against contamination.

The main objectives of the project were

1) to study the patterns of ground-water flow in fractured crystalline rock in central Wisconsin and in fractured dolomite in northeastern Wisconsin;
2) to develop methods for estimating hydraulic properties and time of travel (TOT) in these two rock types;
3) to identify, on the basis of the results of the studies, criteria and the range of methods that can be used for delineating WHPA in fractured-rock aquifers;
4) to examine implementation limitations that may influence the applicability and usefulness of the recommended methods;
5) to evaluate the applicability and transferability of the recommended methods to similar hydrogeologic settings elsewhere in the United States.

The scope of the project included investigation of several methods thought by the investigators to be applicable to solving the technical problems of delineating WHPAs in fractured rocks. These methods range from simple "cookie-cutter" approaches to complex computer models; they include the fixed radius methods, flow-system and vulnerability mapping methods, analytical methods, residence-time methods, and numerical flow/transport modeling.

The investigation of the study areas was carried out in two steps. The first step involved the collection of background data about the geology and hydrogeology of each site. The second step included testing WHPA methods using different approaches. The background investigations led to the assumption that the fractured rock at both sites contained enough closely spaced fractures to function hydraulically similar to a porous, granular medium. Our field investigations confirmed this assumption.

Four main approaches were used for testing WHPA delineation methods. The first approach included calculating the zone of influence (ZOI) of a well by standard well and ground-water hydraulics equations. The second approach involved mapping hydrologic and geologic boundaries, as well as identifying areas of the landscape particularly vulnerable to ground-water contamination. The third approach utilized geochemical and isotopic indicators to estimate the age and source of water produced by a well. This approach can be used to verify the validity of the zone of contribution (ZOC) estimates made on the basis of hydraulic considerations alone. The fourth, most sophisticated approach, was the construction and calibration of a detailed, three-dimensional numerical ground-water flow/transport model of each study area.

The study also included the evaluation of criteria used to establish the extent of a WHPA and a comparison of each method in terms of advantages, disadvantages, skill requirements, and costs. The last chapter of the report analyzes limitations of methods and their applicability to other parts of the United States and suggests potential tools for managing WHPAs. The implementation possibilities were discussed at meetings with local elected officials in the study areas.

Description of Study Areas

Two different fractured-rock settings were selected for the project: one in central Wisconsin (at the Village of Junction City) in a complex of Precambrian crystalline rock and one in the Door Peninsula of northeastern Wisconsin (in the Town of Sevastopol), where the aquifer is composed of fractured Silurian dolomite.

Junction City Study Area

This site was selected to represent areas where small communities rely on ground water produced by one or more wells in fractured crystalline rocks. The site is located at the western edge of the Village of Junction City (fig. 1), a small community (population 525) 12 miles northwest of Stevens Point, Portage County. The village is supplied with water from a drilled well, 321 ft deep, developed in Precambrian metavolcanic rock. Average daily pumpage is about 40,000 gallons.

Junction City is located at the southern, exposed edge of the Precambrian shield--a geologically stable region, consisting of metamorphic and igneous rocks more than 600 million years old (fig. 2). The crystalline rocks are covered by a thin layer of Pleistocene deposits, and locally by outliers of Cambrian sandstone. The Precambrian rocks were subjected to intense deformation during a long and complex history. A detailed description of the geological setting is included in Appendix A.

The Precambrian rock is the main source of water supply in this otherwise water-poor area (Zaporozec and Cotter, 1985). Most domestic wells produce less than 10 gallons per minute (gpm); some municipal wells may yield between 50 and 100 gpm. Yields depend on the degree and depth of weathering and on the size and interconnection of fractures. Bell and Sherrill (1974) note that the degree and depth of weathering of the crystalline rock vary considerably; generally, weathering is greater in valleys than on hillsides and ridges. Fractures are numerous and well developed in the upper portion of the aquifer and they

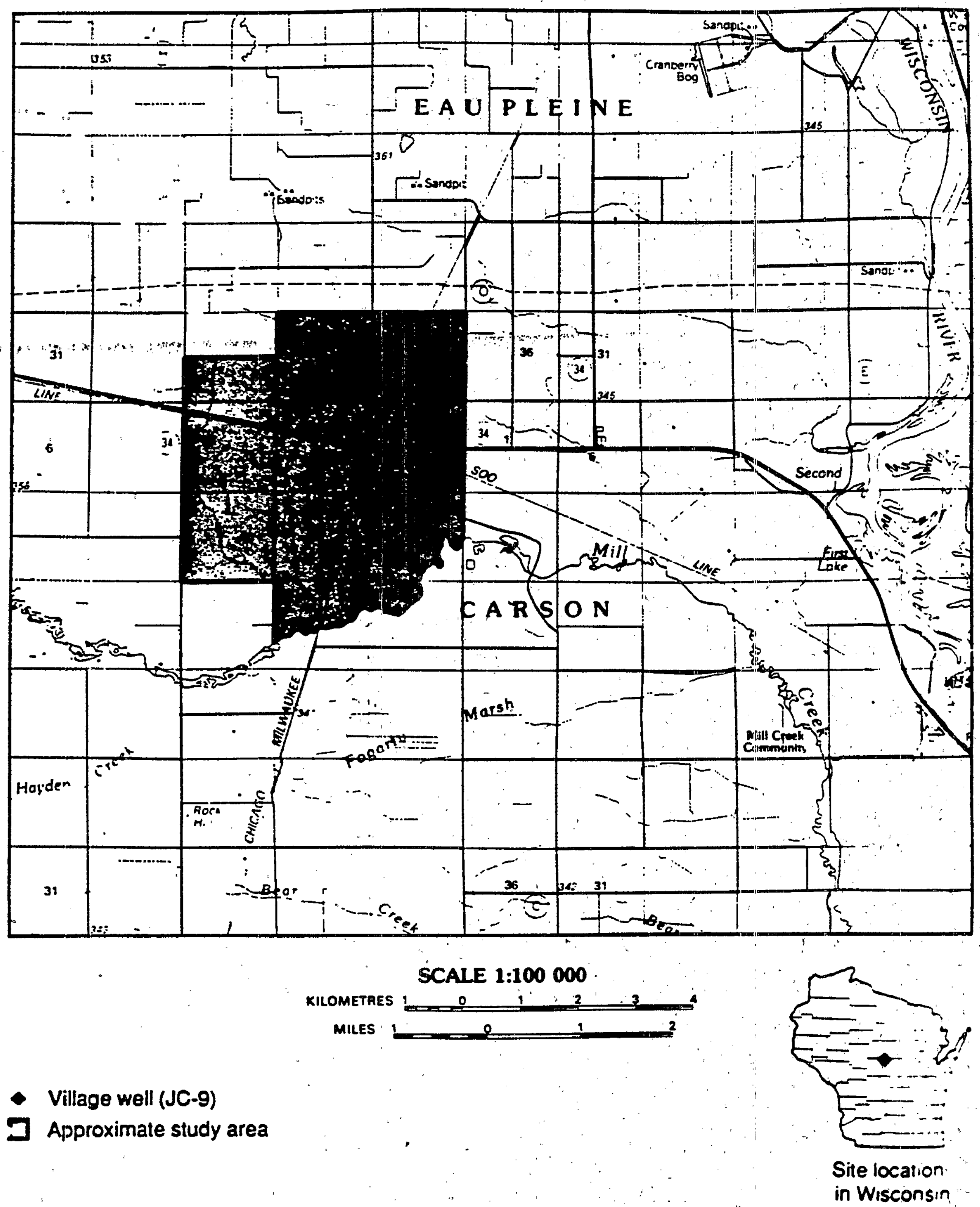

Figure 1. Junction City study area, Portage County, Wisconsin.

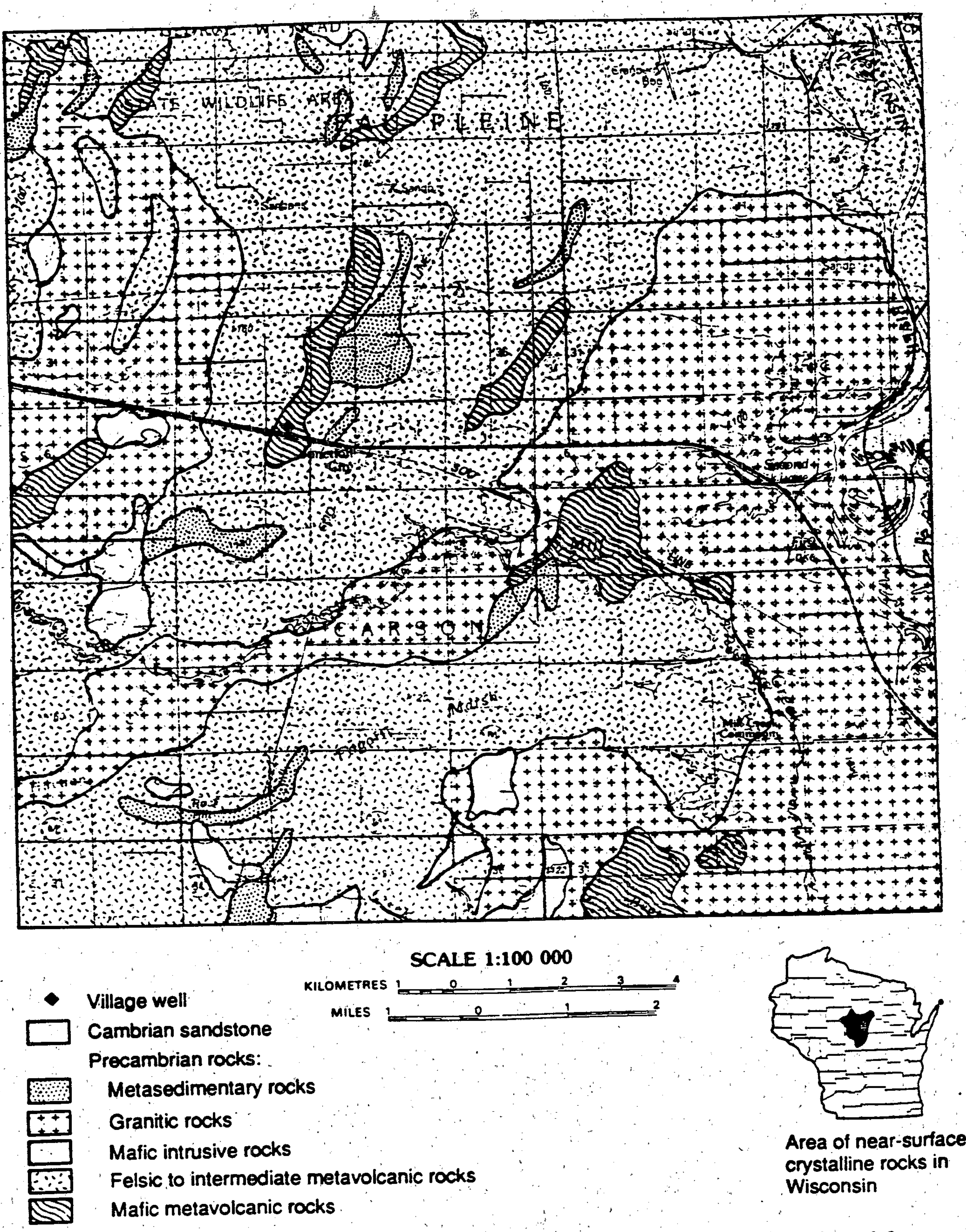

Figure 2. Generalized bedrock geology of the Junction City area, Wisconsin (adapted from Greenberg and Brown, 1986).

decrease in size and number with depth. Recent investigations indicate that the surficial materials are hydraulically connected to the bedrock system (Hutasoit and Davidson, 1989).

Junction City is located in the part of Wisconsin that was glaciated prior to the late Wisconsin glacial period. Surficial materials in the area consist of highly weathered, older glacial deposits mixed with younger clayey, silty sand derived from weathering of the bedrock and reworked by hillslope processes. Occasional erratic boulders mixed with the bedrock residuum are the only evidence of pre-Wisconsin glaciation (Clayton, 1986). The surficial materials are thin and discontinuous and are generally inadequate for domestic and community water supplies (Zaporozec and Cotter, 1985).

The general area of the test site is a relatively smooth upland plain with gently sloping topography. The land surface ranges between 1140 and 1180 ft above mean sea level. The area receives about 31.5 in. of precipitation annually and is drained by small intermittent tributaries of Mill Creek (fig. 1), a tributary of the Wisconsin River.

The village well is situated 100 ft from U.S. Highway 10, a major thoroughfare, and 250 ft from a railroad, which pose potential contamination threats to the well. The well was used as a pumping well for tests conducted during the study. Ten piezometers were installed at seven sites upgradient and one 6-in. observation well was installed downgradient of the village well (for locations, see Appendix A).

Sevastopol Study Area

The study focus in this area was on wellhead protection in rural settings underlain by fractured dolomite either exposed at the land surface or covered by thin soils, where potential for ground-water contamination is great. The test site is located about 9 miles north of Sturgeon Bay, Door County (fig. 3). The site contains a cluster of 17 piezometers installed in seven wells within a 100-ft radius of each other on farm land near a small patch of woods. Seven additional piezometers are located at a barnyard about 1 mile northeast of the test site (for locations, see Appendix B).

The Door Peninsula is a narrow (7 to 20 miles wide) peninsula that rises more than 200 ft above Green Bay and Lake Michigan (fig. 4). Bedrock is dolomite of Silurian age (approximately 400 million years old), a thick (400 to 600 ft), resistant formation, which forms the prominent Niagara escarpment in eastern Wisconsin (Sherrill, 1975). The west-facing escarpment descends abruptly to Green Bay. The site lies on the back slope of the escarpment (fig. 4), which dips southeastward under Lake Michigan into the Michigan basin. The dolomite is a major aquifer in eastern Wisconsin and extends from the northern tip of Door County south into Illinois. Well yields range from 10 to 500 gpm (Zaporozec and Cotter, 1985). Pleistocene deposits are thin or absent in the area, and do not form a productive aquifer. The Silurian dolomite is exposed at the land surface or covered by a thin layer of soil. It is densely fractured; horizontal fractures occur on the order of every 1 to 10

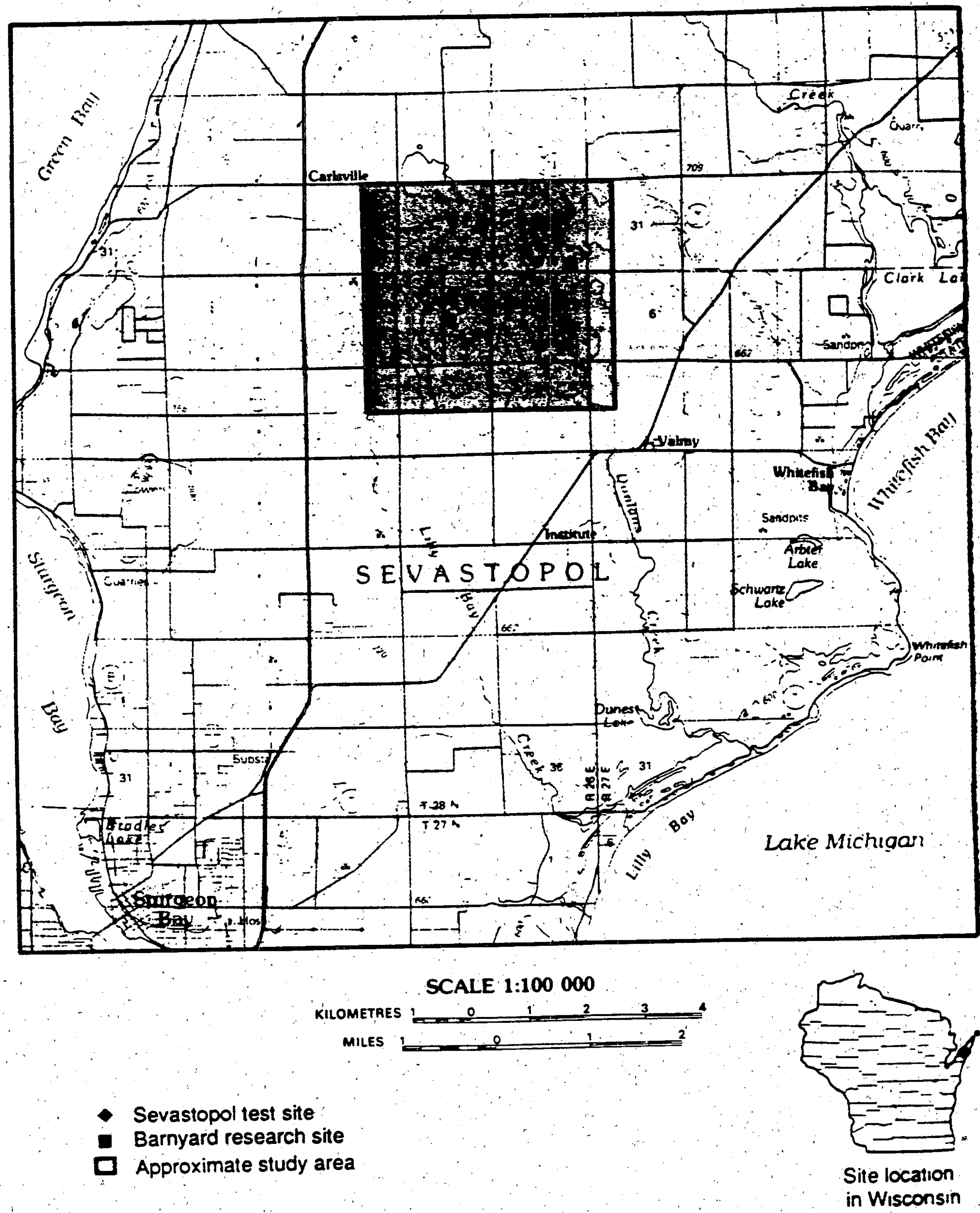

Figure 3. Sevastopol study area, Door County, Wisconsin.

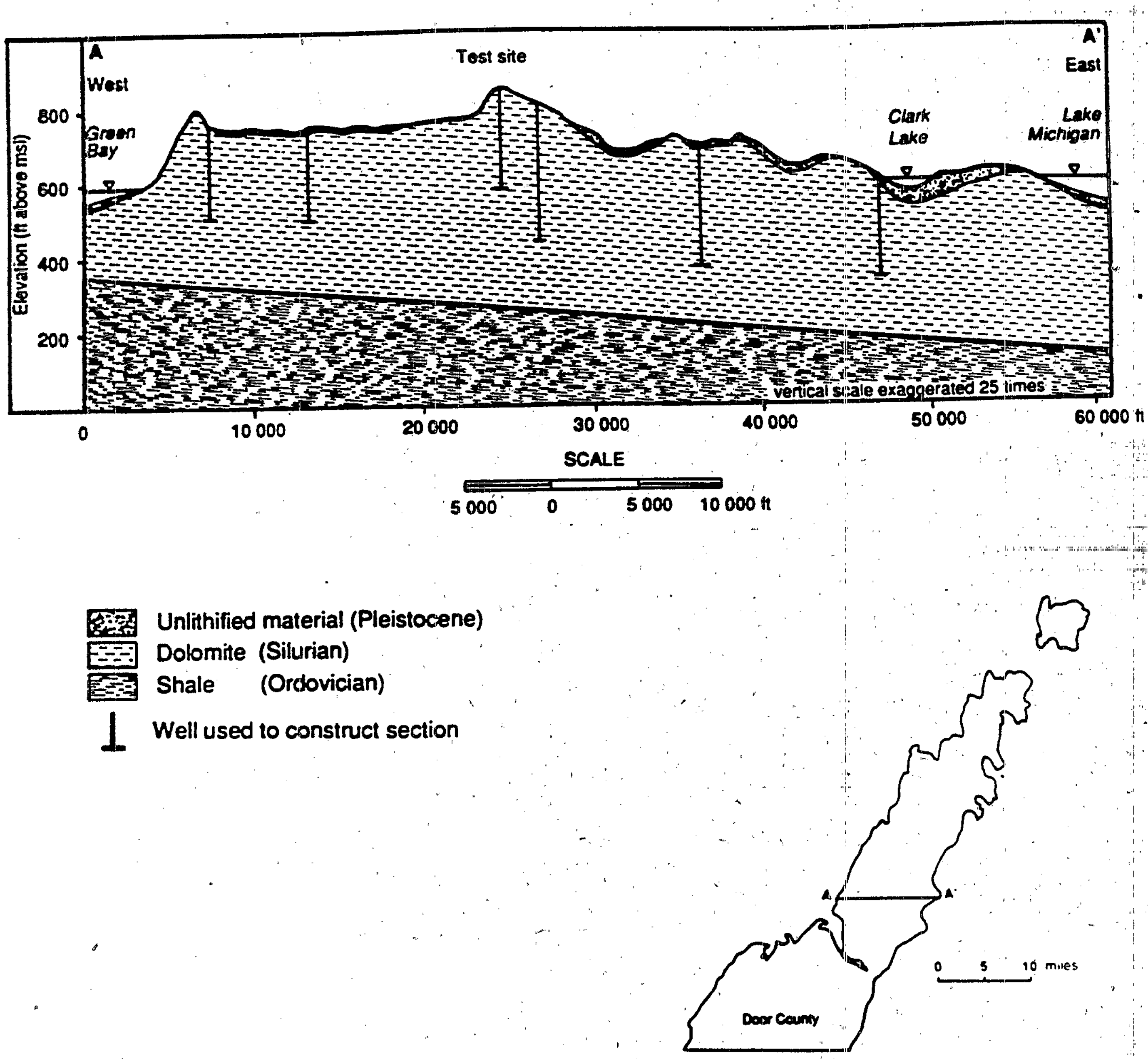

Figure 4. Generalized geologic cross section of the Door Peninsula, Wisconsin.

ft, and vertical fractures form a more or less regular pattern (fig. B2, Appendix B) clearly visible in cropped fields and pastures during the growing season. A detailed description of the geological setting is included in Appendix B.

The test site is located on a local topographic divide between Donlans and Lilly Bay Creeks, which drain southeast to Lake Michigan. Topography is of very moderate relief and slopes very gently in all directions from the site. The land surface is between 790 and 810 ft above mean sea level (msl). Average annual precipitation is 30 in. Land use at the site, typical of central Door County, consists of pasture, corn and hay crops, and maple syrup production.

Previous Studies

The concept of wellhead protection zones is relatively new in the United States. Attempts at establishing WHPAs in the U.S. have been scattered and not as advanced as in Europe, especially in West Germany, where the concept originated (Headworth, 1986). Generally, WHPAs have been delineated only for porous, granular media; the authors' literature search did not locate any publications on delineating WHPAs in fractured rocks.

Acknowledgments

Appreciation is given to land owners in the two study areas who allowed access to their land to measure water levels in wells and to take water samples. Special appreciation is given to the Village of Junction City Board for its support of the study and permission to use the village well for pumping tests. David Haupt, of Haupt Well and Pump Co., Inc., registered well driller from Auburndale, provided information on the test holes for the Village of Junction City well and other wells in the area.

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The editorial, cartographic, and administrative staff of the Wisconsin Geological and Natural History Survey have all contributed to the successful completion of this project; their patience and assistance are greatly appreciated.

Chapter II

HYDROGEOLOGY OF FRACTURED ROCKS

Basic Characteristics of Fractured Rocks

Definitions and Terminology

Fractures can occur in almost all geologic materials, from unlithified surficial materials to deeply buried rocks. The term "fracture" can have many definitions. In this report, a fracture is defined as follows:

> Fracture: A general term for any break in a rock, whether or not it causes displacement, due to mechanical failure by stress. Fractures include cracks, joints, and faults (Bates and Jackson, 1980).

A crack is a partial or incomplete fracture; a joint is a parting in a rock along which no movement occurred; a fault is a fracture or a fracture zone along which movement occurred. Although the last two categories of fractures form in very different ways, their effect on ground-water flow is similar.

Fracture zones consist of closely spaced and highly connected discrete fractures (Gale, 1982). Related terms often used in discussions of fractures include bedding planes--discontinuities in the depositional form of sedimentary rocks; fracture traces--small-scale (hundreds of feet) linear features visible on the land surface above buried fractures; and lineaments--large-scale (miles) linear features related to major fractures extending to great depths and visible on aerial photographs. No discussion of fractures is complete without mentioning karst, a carbonate-rock terrain where fractures in soluble rocks have been enlarged by chemical solution or physical erosion.

Origin and Examples of Fractures

Although the origin of fractures is not always clear, fracturing is usually attributed to one or more of the following geologic processes:

- tectonic forces, geologic uplift, mechanical folding;
- magma movement;
- thermal processes, stress relief associated with heating or cooling;
- glacial or erosional loading or unloading;
- earth tides.

Rock types most susceptible to fracturing include

- crystalline plutonic rocks (granite, gabbro, diorite, etc.);

- other igneous and metavolcanic rocks (basalt, rhyolite);
- metamorphic rocks (schist, gneiss, quartzite);
- carbonate sedimentary rocks (limestone, dolomite).

Such rocks generally are not ductile, and thus are subject to failure and fracture formation under applied stress. However, these are not the only rock types in which fractures occur. Some sandstones, especially when well cemented, are also highly fractured. Stephenson and others (1988) discuss the formation and importance of fractures in unlithified clayey till units in central North America. Fractures are also important in shales and other low-permeability argillaceous rocks, but little research has been done on fractures in these materials (Gale, 1982).

General Characteristics of Fractured-Rock Aquifers

Although fractures can be important to ground-water movement through almost any geologic material, this report is concerned with the hydrogeologic properties of aquifers in which water moves primarily through fractures. Fractured-rock aquifers differ from porous, granular aquifers in several important ways, summarized in table 1.

Table 1. Differences between porous-media and fractured-media aquifers.

Aquifer Characteristics	Porous Media	Fractured Media
Porosity	Mostly primary	Mostly secondary
Flow	Slow, laminar	Possibly fast and turbulent
Isotropy	More isotropic	Less isotropic
Homogeneity	More homogeneous	Less homogeneous
Flow predictions	Darcy's law applies	Darcy's law may not apply

Porosity refers to the ratio between the volume of voids and volume of solids in a given volume of rock mass, and it is related to the storage and transmission characteristics of an aquifer. Type of porosity is probably the single most important difference between fractured-rock and granular aquifers. Primary porosity is the volume of original pores between rock or mineral grains and is usually a function of the packing of the grains. Secondary porosity refers to the pore volume related to spaces created within a rock after its deposition or emplacement, through fracturing or diagenetic processes such as dolomitization and dissolution of primary cements. Primary porosity is relatively predictable and easy to measure; secondary porosity can be unpredictable and difficult to measure.

Anisotropy refers to the variability of hydraulic conductivity or transmissivity with direction. Fractured-rock aquifers can be highly anisotropic in three dimensions (Snow, 1969); hydraulic conductivity and ground-water velocity can vary by several orders of magnitude depending on the direction of ground-water movement. Figure 5A shows the effects of fracture anisotropy on regional ground-water movement. Ground water in anisotropic media may not move perpendicularly to the hydraulic gradient, but at some angle to it.

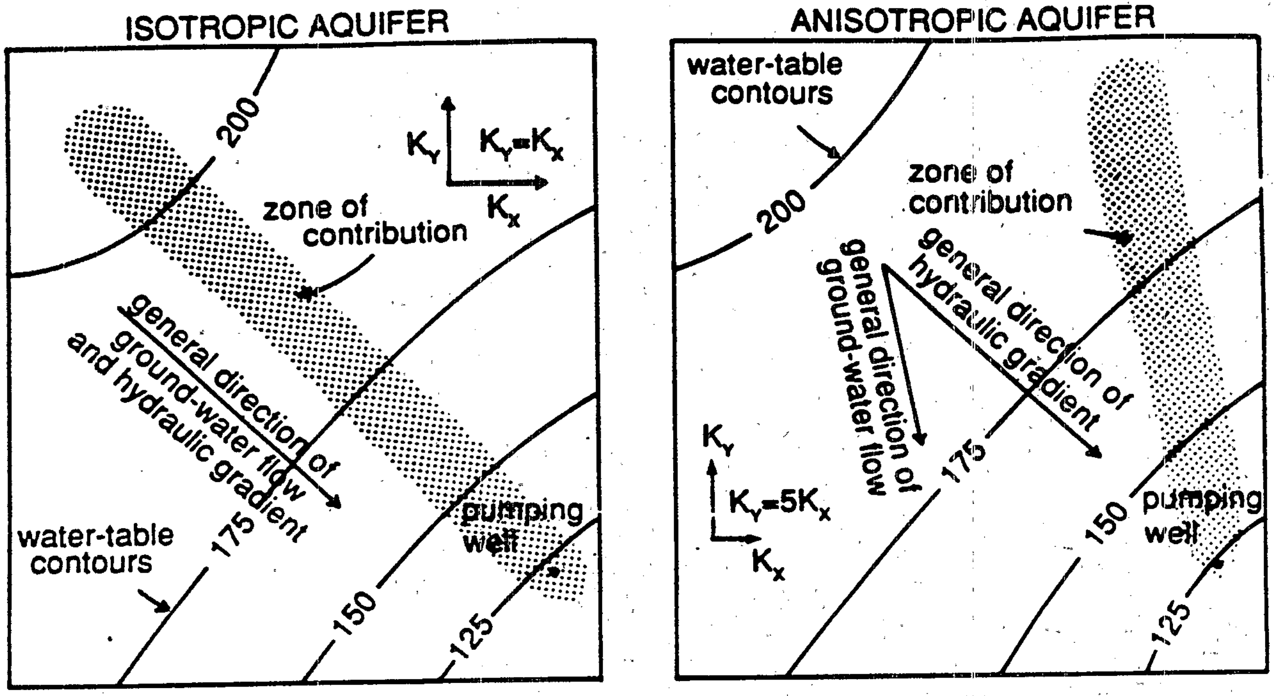
Fractured rocks tend to be less homogeneous (more heterogeneous) than porous, granular rocks. Heterogeneity, the variation of hydrogeologic properties (hydraulic conductivity, porosity) from place to place within the aquifer, is frequently large in fractured-rock settings due to the discrete and linear nature of many fracture systems. Figure 5B shows how near-vertical fracture zones can short-circuit a regional ground-water flow system in crystalline rock.

The equations of flow in porous media, generally based on Darcy's law, usually require that ground-water flow be laminar and of low velocity. In some fractured systems, particularly in areas where fractures become enlarged by solution, ground-water flow may become turbulent and fast, and the classic ground-water flow equations may no longer apply (Freeze and Cherry, 1979, p. 73-74). Although turbulent flow can be modeled, the complex equations and enormous amounts of data required make analysis of turbulent ground-water flow impractical for most wellhead protection studies.

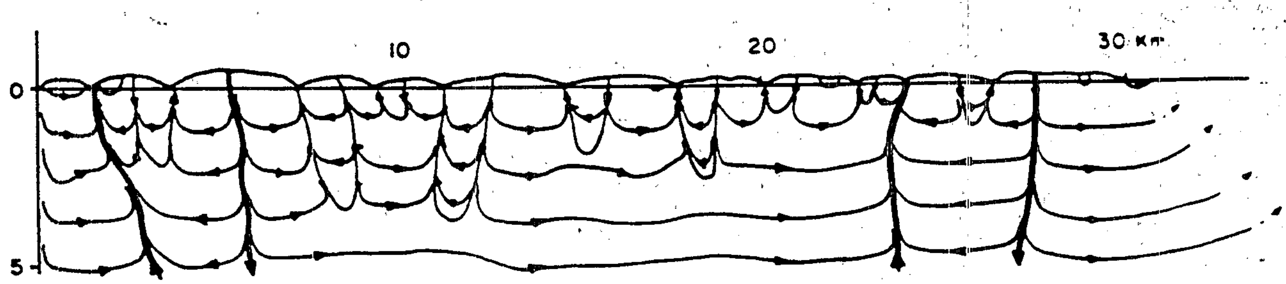
Hydrogeologic Characterization of Fractured-Rock Aquifers

Discrete versus Continuum Approaches

Hydrogeologic investigations in fractured-rock terranes usually fall somewhere between two very different approaches to fracture characterization. The discrete approach considers each fracture individually. Careful measurement of such fracture properties as length, orientation, width, aperture, wall roughness, and connectivity provide the parameters necessary for detailed study of ground-water movement in each fracture. The discrete



A. Effect of fracture anisotropy on the orientation of the zone of contribution.



B. Numerical simulation of regional flow paths in fractured crystalline rock, showing "short-circuiting" along vertical fracture features (from: Gale, 1982).

Figure 5. Effect of fractures on ground-water movement.

approach can potentially provide great detail on ground-water movement. However, the data and computational requirements of this approach are so great as to make the approach impractical for all but relatively small volumes of rock in the most simple field situations.

At the opposite end of the spectrum, the continuum approach assumes that the fractured medium approximates a porous medium at some working scale. In this approach, the properties of individual fractures are not as important as the properties of large regions or volumes of fractured material. The continuum approach offers the advantage of requiring manageable amounts of data, but cannot resolve as much detail about the flow system as is possible with the discrete approach.

Most field-scale hydrogeologic investigations of fractured-rock aquifers, and therefore, most wellhead protection studies in fractured rock, fall somewhere between these two approaches. Although detailed examination of all fractures present in the field is usually impossible, some details, such as the orientation and length of major fractures or fracture zones, can be incorporated into analyses based on the continuum approach and porous-media assumption.

The Problem of Scale and the Porous-Media Assumption

The use of standard ground-water flow equations, such as Darcy's law, in fractured-rock settings requires the assumption that the fractured rocks behave as porous media at the scale of the problem. Knowledge of the problem scale therefore becomes critical in field studies of wellhead protection because "major" fractures at the scale of a few inches or feet can become "minor" fractures in the area at the scale of thousands of feet or miles. "Major" fractures in an otherwise uniform flow system can short-circuit the system, causing ground water to move in unexpected directions (fig. 5B). The size of observable fractures usually depends on the observation technique. For example, aerial photographs might identify large bedrock fractures, observations in vertical boreholes might identify smaller fractures, and microscope studies of laboratory samples might identify even smaller fractures.

The porous-media assumption implies that the classical equations of ground-water movement hold at the problem scale, that knowledge of the hydraulic properties of individual fractures is not important, and that the fractured-rock mass can be characterized by field and laboratory techniques developed for porous media. Long and others (1982) provide theoretical criteria for determining when fractured systems behave as porous media. They suggest that "fracture systems behave more like porous media when (1) fracture density is increased, (2) apertures are constant rather than distributed, (3) orientations are distributed rather than constant, and (4) larger sample sizes are tested" (Long and others, 1982, p. 645). However, rigorous testing of these criteria for field situations is difficult and expensive. For most wellhead protection studies investigators could use a combination of subjective criteria to determine whether the fractured-rock aquifer can be treated as a porous medium. The criteria listed below are subjective because fractured-rock aquifers fall on a continuum between true porous-media and conduit systems, and the decision whether to use the porous-media model will always require professional judgment and experience. Treating the aquifer as a porous medium at the wellhead protection scale should never imply that the porous-media assumption is valid at smaller scales or for site-specific problems.

Although the porous-media assumption may often be justified, critical errors can result if the assumption is incorrectly applied in situations where it does not hold. The porous-media assumption is usually not justified in conduit karst environments, where ground water can move under turbulent flow through networks of cave systems. Ground-water investigations in such areas can require detailed analyses of cave systems, including cave mapping and tracer studies (Quinlan and Ewers, 1985).

Determining Whether Fractured-Rock Aquifers Behave as Porous Media

Subjective criteria for determining whether fractured rock can be treated as a porous medium for the purposes of wellhead protection include pumping test responses, configuration of the water-table surface, the ratio of fracture scale to problem scale, distribution of hydraulic conductivity, and variations in water chemistry and water quality.

Pumping test responses.--There are three main criteria for determining whether a fractured-rock aquifer approximates a porous medium using an aquifer pumping test.

1) The drawdown in observation wells should increase linearly with increases in the discharge rate of the pumped well. Hickey (1984) suggests conducting a series of 1-hour pumping tests with incrementally increased discharge rates. A plot of drawdown at 1 hour versus pumping rate for the series of tests should approximate a straight line in porous-media-equivalent settings (fig. 6A).
2) Time-drawdown curves for observation wells located in two or more different directions from the pumped well should be similar in shape and should not show sharp inflections, which could indicate hydraulic boundaries (fig. 6B).
3) A plotted drawdown cone from a pumping test using multiple observation wells should be either circular or elliptical. Linear or very irregular cones can indicate a failure of the porous-media assumption (fig. 6C).

Water-table surface configuration.--For porous-media-equivalent fractured aquifers a water-table map should show a smooth and continuous water-table surface without areas of rapidly changing or anomalous water levels. In particular, the water table should not have the "stair-step" appearance that can occur in sparsely fractured rocks with large contrasts in hydraulic conductivity between blocks and fractures. Although a "stair-step" water table clearly indicates a failure of the porous-media assumption, a smooth water-table map does not prove a porous-media-equivalent setting. Detection of irregularities in the water table may require more closely spaced monitoring wells than are available for most wellhead protection studies.

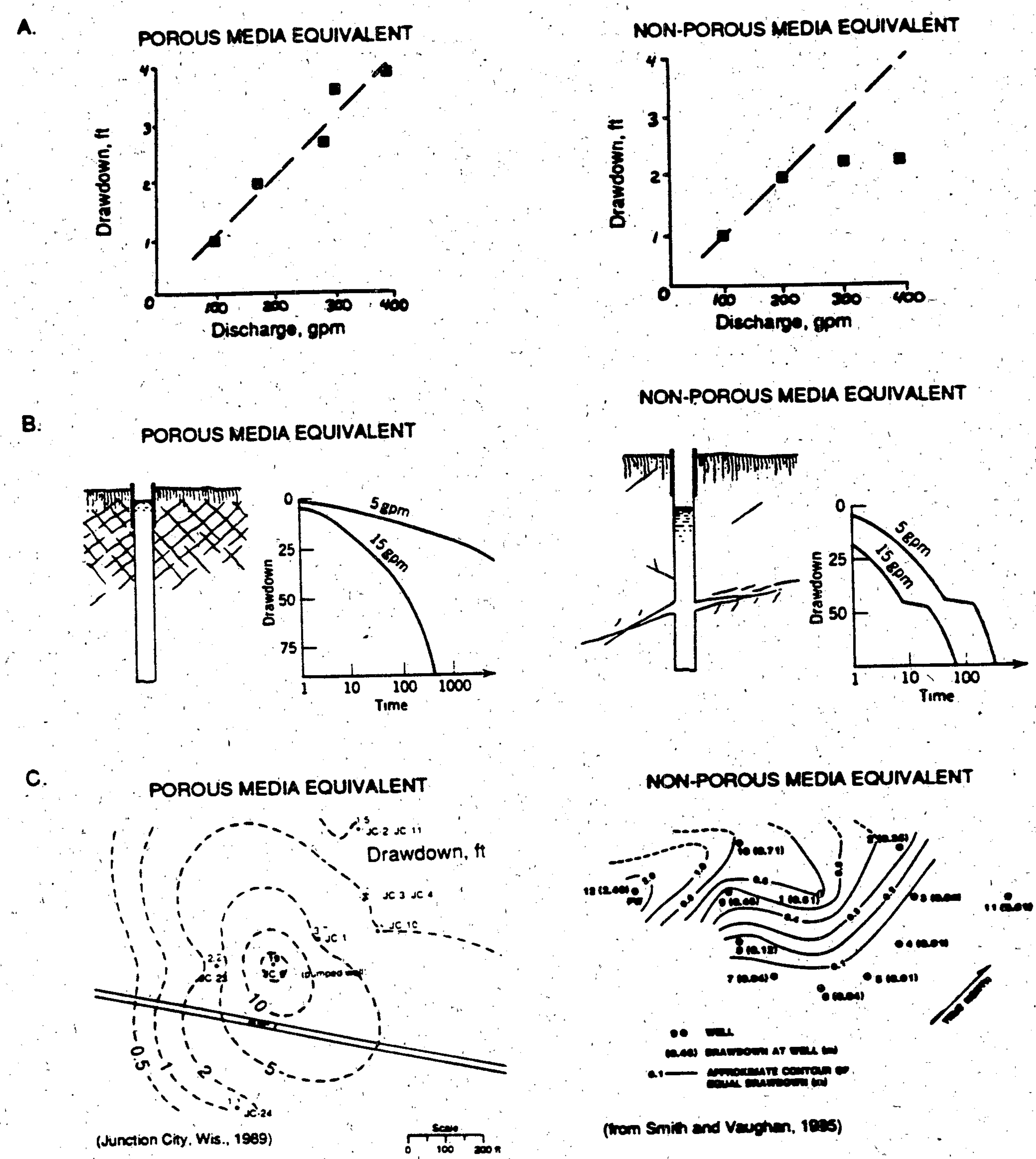


Figure 6. Pumping test responses in settings where the porous-media assumption does and does not apply. **A.** Discharge-drawdown plots (after Hickey, 1984). **B.** Time-drawdown curves (from Davis and DeWiest, 1966). **C.** Areal drawdown distribution.

Ratio of fracture scale to problem scale.--For porous-media-equivalent aquifers, the observed vertical and horizontal fractures should be numerous and the scale of fracturing should be much smaller than the scale of the wellhead protection problem. As a rule of thumb, the minimum dimension of the WHPA should be at least 100 times the average fracture spacing. For example, at the Junction City and the Sevastopol test sites, bedrock fractures are numerous and occur on a scale of a few feet or tens of feet, but the potential WHPAs at both sites cover several square miles.

Hydraulic conductivity distribution.--In porous-media-equivalent settings the distribution of hydraulic conductivity, as estimated from piezometer slug tests or from specific capacity analyses (Bradbury and Rothschild, 1985), should be approximately log-normal. In aquifers where the hydraulic conductivity distribution is strongly bimodal, the porous-media assumption is probably not valid.

Variations in water chemistry.--Overall variations in ground-water chemistry have been shown to be useful in determining whether fractured aquifers behave as diffuse-flow (porous-media) systems or as conduit (discrete-fracture) systems. In conduit systems, variations in ground-water chemistry can be significant from place to place and through time. Water moving through conduits usually has less contact time with mineral surfaces and so can be lower in total dissolved solids and have lower mineral saturation indices than water moving through a diffuse-flow aquifer having similar mineralogy. Ground water in diffuse-flow fractured aquifers will usually have relatively uniform chemical composition through time and from place to place within the aquifer. For example, Shuster and White (1971) examined water chemistry and temperature of several springs in Pennsylvania and showed that water chemistry in conduit-flow springs varied greatly with time, but the water chemistry of diffuse-flow springs did not (fig. 7). Municipal wells are sampled on a regular basis for such parameters as temperature, pH, hardness, turbidity, and bacteria. The variation in these parameters can help determine whether a fractured-rock aquifer behaves as a porous medium. For example, ground water high in turbidity and bacteria is more often a result of conduit flow rather than diffuse flow. If a production well never has a turbidity or bacteria problem, it is probably not connected to significant conduits intersecting the land surface.

Evaluation of Fractured-Rock Aquifers for Wellhead Protection Studies

Wellhead protection studies in fractured rocks usually require an evaluation of the hydrogeologic setting and properties of the potential WHPA. Essential data for wellhead protection studies in fractured rocks can include

1) characterization of fracture patterns and locations,
2) determination of hydraulic head distribution, and
3) determination of aquifer characteristics.

The amount of effort required to characterize fractured-rock aquifers varies with the complexity of the aquifer and the scope of the wellhead protection study. For example, use

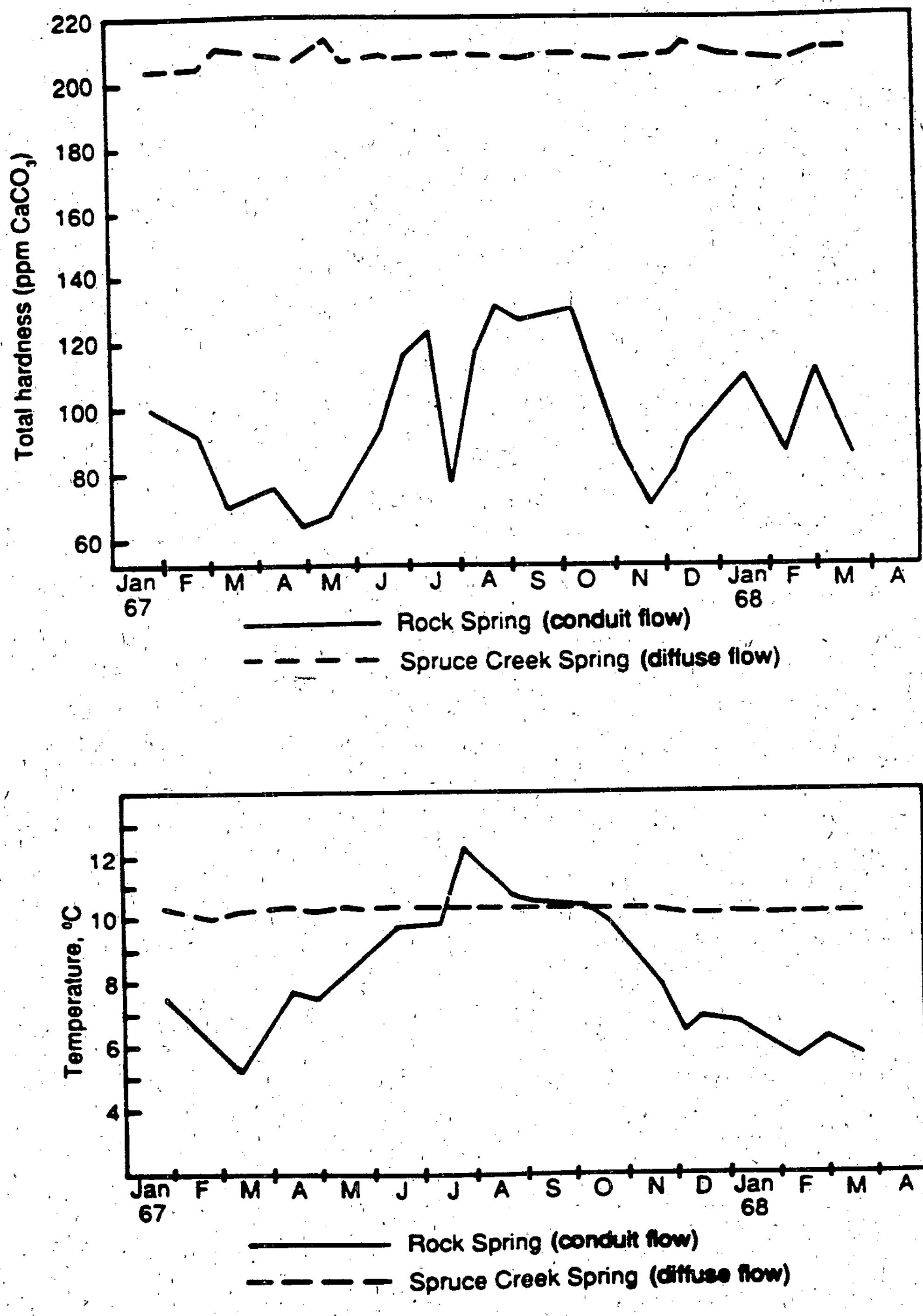


Figure 7. Examples of water chemistry and temperature variations with time in diffuse-flow and conduit-flow aquifers (after Shuster and White, 1971).

of the arbitrary fixed radius method requires little or no aquifer characterization; numerical models require extensive data sets. The following discussion is intended as a guide to some of the techniques that could be used in wellhead protection studies in fractured rocks.

Characterization of Fracture Patterns and Locations

The first step in characterizing fractured-rock aquifers usually involves determining the spacing, orientation, depth, and length of fractures present in the field, which is important for determining whether the porous-media approximation is applicable or not. The methods employed to gain this information depend on the surface or outcrop expression of fractures, type of material, depth of unlithified material over the aquifer, and fracture orientation (vertical and horizontal).

In areas where unlithified surficial materials are thin or absent, bedrock fracture patterns can be mapped from aerial photographs or from detailed measurements on the ground. Figure B2 (Appendix B) shows surface expression of fractures in dolomite beneath thin soil in Door County, Wisconsin. Although such mapping methods provide good detail on fracture strike and density, they give little information about the distribution of fractures at depth and provide only a two-dimensional measure of a three-dimensional system. Description of fractures and measurement of fracture dip and strike in vertical outcrops can help provide an understanding of the three-dimensional fracture system. Surface and borehole geophysical methods can help characterize subsurface fractures in areas where there is little visual fracture expression. Although most surface geophysical methods have the advantage of relatively rapid data acquisition over large areas, the acquired data generally provide a depth-averaged measure of some geophysical property over a large volume of subsurface material. Surface methods can provide good delineation of zones of fractured rock, but detailed data on individual fractures are difficult to obtain. Borehole geophysical methods provide detailed information about rock properties along borehole walls and are particularly valuable for investigations of fractured-rock aquifers.

Drilling is usually the most accurate way to locate fractures in the subsurface, and is also required prior to the use of borehole geophysical methods. Core drilling and recovery is the preferred method for obtaining a good record of subsurface fractures. Figure A4 (Appendix A) shows the log, with interpretations of fractures and fracture zones, of a core obtained in fractured crystalline rock at Junction City. Because vertical boreholes provide little information about vertical fractures, angle drilling is sometimes used to characterize vertical and near-vertical fracture systems.

Determination of Hydraulic Head Distribution

In any wellhead protection study, determination of the three-dimensional distribution of hydraulic head in the subsurface provides critical information for the prediction of ground-water flow paths and rates. In fractured systems, where hydraulic conductivity can vary significantly in space, a detailed three-dimensional analysis of the head distribution is particularly important.

Frequently, in fractured-rock aquifers, total hydraulic head varies significantly with depth. Such variations are particularly important in wellhead protection studies because knowledge of vertical hydraulic gradients is required for vertical flow calculations. Measurement of the vertical distribution of hydraulic head generally requires "nests" of closely spaced piezometers screened at several different depths. Existing domestic wells with long open intervals are usually inappropriate for measurement of vertical hydraulic gradients. Figure B5 (Appendix B) shows how hydraulic head varies with depth at the Sevastopol test site.

Hydraulic heads in fractured-rock settings can vary significantly in response to precipitation, snowmelt, nearby pumping, surface-water fluctuations, and other phenomena. An understanding of such variations is important to some wellhead protection studies because extreme hydraulic head variations can lead to variations in ground-water flow rates and directions at various times of the year. Determination of water-level fluctuations requires periodic measurement of water levels in monitoring wells. Modern measuring and recording equipment, such as pressure transducers and digital data loggers, has greatly simplified the acquisition and processing of such data. Such elaborate data collection would be necessary only for more complete WHPA delineation methods.

Determination of Aquifer Characteristics

Knowledge of aquifer parameters, including aquifer thickness, porosity, hydraulic conductivity, and specific yield, is essential for the analyses of ground-water flow to wells required in more complex WHPA delineation methods. In most cases, the standard testing methods developed for porous, granular aquifers can be applied to fractured-rock aquifers with little modification. However, use of these methods in fractured rock requires some special considerations, outlined below.

Aquifer thickness is an important parameter in most standard equations of ground-water flow to wells. In porous-media settings, where aquifers are bounded by confining beds, the aquifer thickness is usually obvious and easy to measure. In fractured-rock settings, however, aquifer thickness can be problematic. An example is the crystalline rock aquifer at Junction City, Wisconsin (Appendix A). This aquifer is formed in the upper part of the Precambrian basement rocks of central Wisconsin, the lower stratigraphic boundary of which is unknown. In fact, as in many non-plutonic basement rocks, the original depositional (bedding) planes are now vertical or steeply dipping. For the purpose of this report, the aquifer boundary was defined as the depth at which significant fractures, as measured by borehole logging and observed in a core sample, disappear.

Porosity is an important value in wellhead protection studies because it has a large influence on time of travel calculations. Porosities of fractured rocks are generally less than porosities of non-fractured rocks, as shown in table 2.

Table 2. Range of values of porosity (from Freeze and Cherry, 1979).

Material	n(%)
Unconsolidated deposits	
Gravel	25-40
Sand	25-50
Silt	35-50
Clay	40-70
Rocks	
Fractured basalt	5-50
Karst limestone	5-50
Sandstone	5-30
Limestone, dolomite	0-20
Shale	0-10
Fractured crystalline rock	0-10
Dense crystalline rock	0-5

In general, porosities of unconfined fractured aquifers can be estimated from the specific yield values obtained during aquifer pumping tests. More accurate porosity measurements are sometimes obtained using field tracer experiments, but such field tests are often complex and beyond the scope of most wellhead protection studies.

Methods for determining basic aquifer parameters for wellhead protection studies include
- use of "textbook" values,
- use of specific capacity data,
- piezometer slug tests,
- single-well pumping tests,
- multiple-well pumping tests, and
- packer tests.

Many widely available hydrogeology texts (Davis and DeWiest, 1966; Freeze and Cherry, 1979) list typical values of hydraulic conductivity and storage coefficient for a variety of fractured-rock settings, and such values can be used as a starting point in wellhead protection studies. However, location-specific data would be required for more complex wellhead protection studies.

The specific capacity of a well refers to the drawdown occurring for a given pumping rate at a pseudo-steady state. Well constructors commonly report specific capacity data to government agencies upon the completion of many domestic and industrial wells. Appendices A and B provide examples of the use of specific-capacity data to estimate transmissivity and hydraulic conductivity in fractured-rock settings. For site-specific studies, the piezometer rate-of-rise or "slug" test (Freeze and Cherry, 1979) provides an estimate of the hydraulic conductivity around the piezometer tip. Tables A2 and B2 (Appendices A and B) give examples of slug-test data at the test sites in Wisconsin.

Full-scale pumping tests involving several monitoring wells probably provide the most reliable measure of aquifer parameters for wellhead protection studies. Such tests can provide data averaged over a large fractured-rock mass and can be used to measure the vertical and horizontal anisotropy of the fractured-rock mass (Hsieh and others, 1985; Papadopoulos, 1965). Hickey (1984) used a pumping test to test the Darcian flow assumption for fractured limestone in Florida. Although often a preferred method of data acquisition, pumping tests in fractured-rock systems can be expensive to conduct and complex to analyze. Appendices A and B discuss the results of pumping tests in fractured rock at two test sites in Wisconsin.

Packer tests, in which inflatable packers are used to isolate specific parts of a borehole, are a variation of the standard pumping test. Packer tests have particular application to fractured-rock aquifers. By isolating particular fractures or fracture zones, the specific properties of these zones can be tested. For example, Shapiro and Nicholas (1989) used packer testing and analyses in fractured dolomite in northern Illinois to estimate fracture properties.

Chapter III

WELLHEAD PROTECTION AREA DELINEATION

Zones Used for WHPA Delineation

The purpose of wellhead protection area (WHPA) delineation is to approximate the area through which water flows to a well so that management decisions regarding the control of contamination sources in that area can be implemented. The area through which water recharges a well is the zone of contribution, or ZOC (fig. 8). In contrast, the zone of influence, or ZOI, is the area affected by a pumping well, and coincides with the areal extent of the cone of depression. The ZOI extends outward from the pumping well to the point of negligible drawdown (fig. 8). Field measurements of drawdown resulting from well pumpage give the most accurate determination of the ZOI.

In a homogeneous, isotropic aquifer with a horizontal water table, the ZOI is a circle and only water within that circle flows to the pumping well. In such an aquifer, the ZOI is equivalent to a ZOC. In the more common case of a sloping water table, however, the ZOI and the ZOC can be quite different (fig. 8). Water upgradient of a well will flow toward the well even if it is outside the well's cone of depression. Likewise, some areas might be within the ZOI and yet not be drawn down enough to reverse the natural hydraulic gradient. Water within such areas will flow away from the well.

This chapter describes the criteria commonly used in the WHPA delineation process and examines various methods for determination of the ZOC in fractured rocks. Example applications of the various methods are given for two test sites in different geologic settings. The aquifer at the Junction City site is developed in highly fractured metamorphic rock. The aquifer at the Sevastopol site is developed in fractured dolomite.

Although fractures are abundant at both sites, the characteristics of the fractures and the sites are quite different, as described in Appendices A and B. At the Junction City site, the aquifer is covered by up to 55 ft of silt and clay. Fractures in the igneous and metamorphic rocks are most abundant near the bedrock surface, and decrease in size and frequency with depth. They have narrow apertures (typically less than 0.01 in.), frequently contain fillings of calcite or other minerals, and probably are short (typically less than 30 ft). Fracture spacings are irregular, ranging from a few tenths of an inch to several feet. Fractures are frequently vertical, especially between 130 and 160 ft below the land surface.

In contrast, at the Sevastopol site, the dolomite is either exposed at the land surface or is covered by soil less than 5 ft thick. Fracture apertures range from a fraction of an inch to several inches. Some fractures have been widened by solution, and minor karst features occur in the area. However, these karst features are infrequent and isolated. Fractures in the dolomite tend to be regularly spaced and can be traced across the landscape for hundreds or

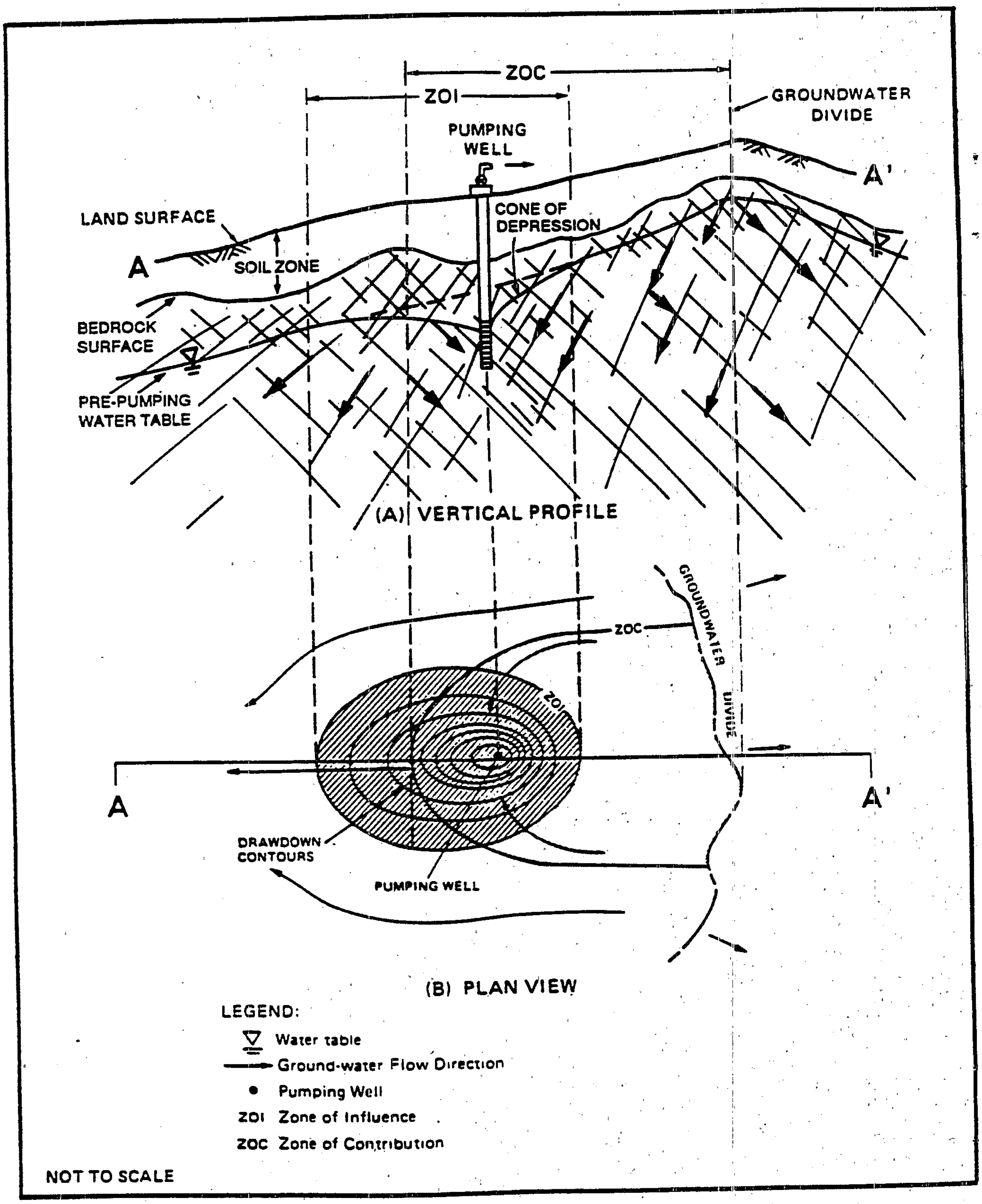


Figure 8. Terminology for WHPA delineation in fractured rocks (adapted from U.S. EPA, 1987).

thousands of feet. Although fractures occur throughout the dolomite aquifer, horizontal zones of interconnected fractures with high hydraulic conductivity occur at several different depths.

Common Delineation Criteria

Five common criteria considered in delineating a WHPA are: 1) distance from the well, 2) drawdown around the well, 3) time of travel (TOT) to the well, 4) physical boundaries to the ground-water system, and 5) capacity of the subsurface environment to assimilate contamination (U.S. EPA, 1987). This report assesses various combinations of these criteria in delineating WHPAs in fractured rocks.

Distance

The most basic criterion for WHPA delineation is distance from the well without regard for the ground-water flow direction. The distance criterion delineates a WHPA by placing a circle of fixed radius around the well. The radius can be arbitrarily chosen or calculated using an analytical equation usually involving a specific travel-time threshold.

Drawdown

The drawdown criterion defines the areal extent of the cone of depression (ZOI) of a well. In areas where the water table is essentially flat, the ZOI coincides with the well's zone of contribution; however, such cases are rare in practice. Delineation of a WHPA based on drawdown requires estimations of transmissivity and storativity, and selection of a drawdown limit (for example, 0.05 ft), beyond which the drawdown is considered negligible.

Time of Travel (TOT)

The TOT criterion bases WHPA delineation on the amount of time it takes ground water to travel from a recharge point at the land surface to a well, and theoretically incorporates all the processes involved in contaminant transport. Practically, however, the TOT criterion usually incorporates advection only. Incorporation of contaminant dispersion, diffusion, or retardation is difficult given the available information on these processes for a given compound. In addition, it would render the TOT delineations too compound-specific. The use of TOT/distance calculations based on the average linear velocity of the ground water is a particularly feasible approach for a generalized wellhead protection program. Limiting the contaminant transport processes to advection only is most valid where ground-water flow velocities are relatively high, as often occurs in fractured rocks.

A TOT limit (for example, 10 or 20 years) can be chosen in various ways. One method, based on chemical degradation rates, sets the limit at the point where contaminant residues are no longer considered a threat to water quality. Alternatively, the TOT limit can be based on the time required to contain contamination of an aquifer. The TOT limit chosen can vary considerably depending on the nature of the main contamination risk. Delineating a WHPA with a TOT criterion implies that the TOT is translated into a distance from the well through determination of ground-water velocity. Delineating WHPAs based on the TOT criterion therefore requires more technical input than either the distance or the drawdown criterion. Required information includes an estimate of aquifer hydraulic conductivity, an estimate of aquifer porosity, and determination of the magnitude and direction of the hydraulic gradient.

Flow-System Boundaries

The flow-boundary criterion uses ground-water divides, surface-water bodies, or other hydrologic/physical features to delineate a WHPA. For a localized flow system, the WHPA often corresponds to a ZOC, and water entering the ground-water system inside the ZOC is assumed to eventually reach the well. The flow-system-boundary criterion therefore provides the maximum protection for a given well, but implementation of a WHPA based on hydrogeologic boundaries may be impractical if the defined area is too large. The flow-boundary criterion is most useful for aquifer systems where the boundaries are easily defined and the distances from the boundaries to the well are relatively short.

Assimilative Capacity

The assimilative-capacity criterion is used in combination with the TOT criterion with the assumption that contaminant attenuation will take place within the unsaturated and/or saturated flow system. Non-toxic concentration levels and the time it takes to reach those levels must be determined to delineate a WHPA on the basis of this criterion. Such a designation is compound-specific and the processes involved in attenuation are often not well understood and not easily quantified; and this is particularly true in fractured rocks. This criterion was not used in WHPA delineation at the two test sites in Wisconsin.

Evaluation of Criteria

Some combinations of the above criteria will work better than others in establishing a wellhead protection program in fractured rocks. The choice of criteria depends on the availability of existing hydrogeologic information, the personnel and financial resources available, and the complexity of the fractured-rock setting. Some generalizations regarding these criteria can be made. The distance criterion alone gives a very poor measure of the ZOC because it does not account for any hydrogeologic site characteristics. Drawdown is a useful criterion if the pre-pumping water table is relatively flat and if there is information regarding the well pumpage and accurate aquifer parameter estimates. The TOT criterion is useful for establishing practical WHPA boundaries in situations where ground-water flow is mostly horizontal and existing hydrogeologic boundaries are far from the protected well. However, the TOT criterion can be misleading and difficult to establish in sparsely fractured rock where highly conductive fracture-conduits occur and where significant vertical flow occurs. The assimilative-capacity criterion is useful, but it is difficult to implement due to the lack of information regarding the fate of contaminants in the saturated zone. This criterion cannot stand alone because TOT considerations are necessary to translate a time of concern into a distance on a map. The best criterion probably is the flow-system-boundary criterion. A WHPA based on this criterion might also be less sensitive to the porous-media assumption in the fractured-rock environment than WHPAs based on other criteria. Delineation of ground-water divides and general flow directions is carried out over a large enough area that the assumption that fractured rock behaves as a uniform porous medium is likely to be valid.

WHPA Delineation Methods for Fractured Rocks

Many methods have been recommended for the delineation of WHPAs. This study tested six methods for delineating WHPAs using various combinations of the criteria listed above. The methods tested, in order of increasing complexity, were

1) arbitrary fixed radius,
2) calculated fixed radius,
3) vulnerability mapping,
4) flow-system mapping,
   - with TOT criterion,
   - with analytical equations,
5) residence-time approach, and
6) numerical flow/transport models.

The first two methods are not particularly suitable for the accurate delineation of WHPAs in fractured rocks. The arbitrary fixed radius method does not incorporate any hydrogeologic or contaminant transport considerations, and can best be used as a first-step approach. When the radius is large enough, the true ZOC will be included within the WHPA delineated by methods 1 and 2 and will be protected. However, large areas outside the ZOC will also be protected. The application of analytical flow equations to calculate a fixed radius brings an improvement over the arbitrary fixed radius method, but may not give acceptable results in unconfined fractured-rock settings because it fails to account for heterogeneity, anisotropy, ground-water recharge, and vertical components of flow, all of which can occur in fractured-rock settings. For example, at the two Wisconsin test sites, the Theis nonequilibrium equation (Theis, 1935) gives unrealistic radii around the protected well. The circles calculated by this method are too large and encompass so much area that implementation of an appropriate WHPA would be difficult. One problem with the Theis nonequilibrium equation approach stems from the estimation of the time to reach steady state. The final radius is highly sensitive to this parameter that is difficult to estimate. Unless the time can be somewhat accurately determined, this approach will have significant limitations for fractured-rock aquifer analyses.

Vulnerability mapping uses geologic maps, soils maps, water-table maps, aerial photographs, and mapping of surficial features to identify areas of the landscape particularly vulnerable to ground-water contamination. Vulnerability mapping does not produce a ZOC for a given well; however, it does identify significant fractures near the well that may contribute to ground-water contamination. Vulnerability mapping combined with the arbitrary fixed radius method or the simplified variable shapes method (U.S. EPA, 1987) can be used to delineate a WHPA in fractured rocks that do not approximate porous media.

The remaining three methods--flow-system mapping and flow-system mapping combined with TOT criterion or with analytical equations, the residence-time approach, and numerical modeling--were found suitable for ZOC delineation in unconfined fractured rocks that behave as porous media at the WHPA scale. The following sections describe each of these methods in detail.

Four WHPA delineation approaches are suggested for unconfined fractured-rock aquifers that do not behave as porous media. These methods include vulnerability mapping combined with the arbitrary fixed radius method or the simplified variable shapes method; hydrogeologic mapping; the residence-time approach; and numerical ground-water flow/transport modeling. These methods are discussed in more detail in the following sections.

Vulnerability Mapping

Description.--Vulnerability mapping uses geologic maps, soils maps, water-table maps, aerial photographs, and mapping of surface features to identify areas particularly vulnerable to ground-water contamination. Such areas include shallow or exposed bedrock, permeable soils, open surface fractures, and sinkholes. This method is excellent for assessing the overall susceptibility of an area to ground-water contamination from surface sources in any hydrogeologic setting, whether it be porous-media or fractured-rock aquifers.

Vulnerability mapping does not produce a ZOC for a given well; however, it does identify significant fractures near the well that may contribute to ground-water contamination, and it can be used in combination with some methods recommended in EPA guidelines (U.S. EPA, 1987). Once the recharge areas and/or vulnerable surface areas are delineated, a WHPA can be defined either by choosing the arbitrary fixed radius method or the simplified variable shapes method (U.S. EPA, 1987) that would include the surface areas from which recharge could enter the subsurface through fracture conduits as well as the majority of the areas most susceptible to contamination. Tracer tests are often useful for proving a connection between fractures exposed at the land surface and water discharged to a well or spring. Mapping of areas particularly susceptible to ground-water contamination could be conducted as part of the data collection for other methods.

Advantages of vulnerability mapping are
1) the assumption of a uniform porous medium is not necessary;
2) the method does not require detailed measurements of aquifer parameters;
3) the method uses a variety of data, ranging from office-available maps to field-measured surface features.

Disadvantages of vulnerability mapping are
1) the method does not delineate a ZOC for the well;
2) the results are somewhat subjective.

Example from the Sevastopol site.--Schuster and others (1989) constructed a map of exposed bedrock and shallow soils for northern Door County, Wisconsin, including the area around the Sevastopol test site. This map considered fracture traces, areas of exposed bedrock, solution features, closed topographic depressions, and soil attenuation potential. Areas of the landscape containing these features and having low soil attenuation potential have the highest potential for ground-water contamination. As shown on figure 9, the areas susceptible to contamination are irregular and not centered on the well to be protected. A WHPA for the well might be circular, using an arbitrary fixed radius of 4000 ft, or could be delineated using a simplified variable shape (U.S. EPA, 1987) oriented around the well according to the regional ground-water flow direction.

Flow-System Mapping

Description.--Hydrogeologic mapping (U.S. EPA, 1987) identifies the physical and hydrologic features that control ground-water flow. Physical boundaries to ground-water flow can include the geologic contacts that form the limits of the aquifer, structural features such as fault-block walls or zones of fracturing, and topographic features that may function as ground-water divides. Hydrologic features, including rivers, canals, and lakes, can function as flow-system boundaries. The flow-system mapping method, a subset of the hydrogeologic mapping method, uses ground-water divides and flow-system boundaries derived from a water-table map to delineate the ZOC for a given well.

Flow-system mapping assumes that hydrogeologic boundaries, particularly potentiometric boundaries, are stationary through time. In aquifers where water levels fluctuate seasonally or where well drawdowns approach potentiometric divides, caution must be used when delineating boundaries for ZOC analysis.

Flow-system mapping requires detailed mapping of the configuration of the water table. Ideally, investigators should use field measurements in properly constructed monitoring wells and nested piezometers for construction of such maps. In practice, funding and time

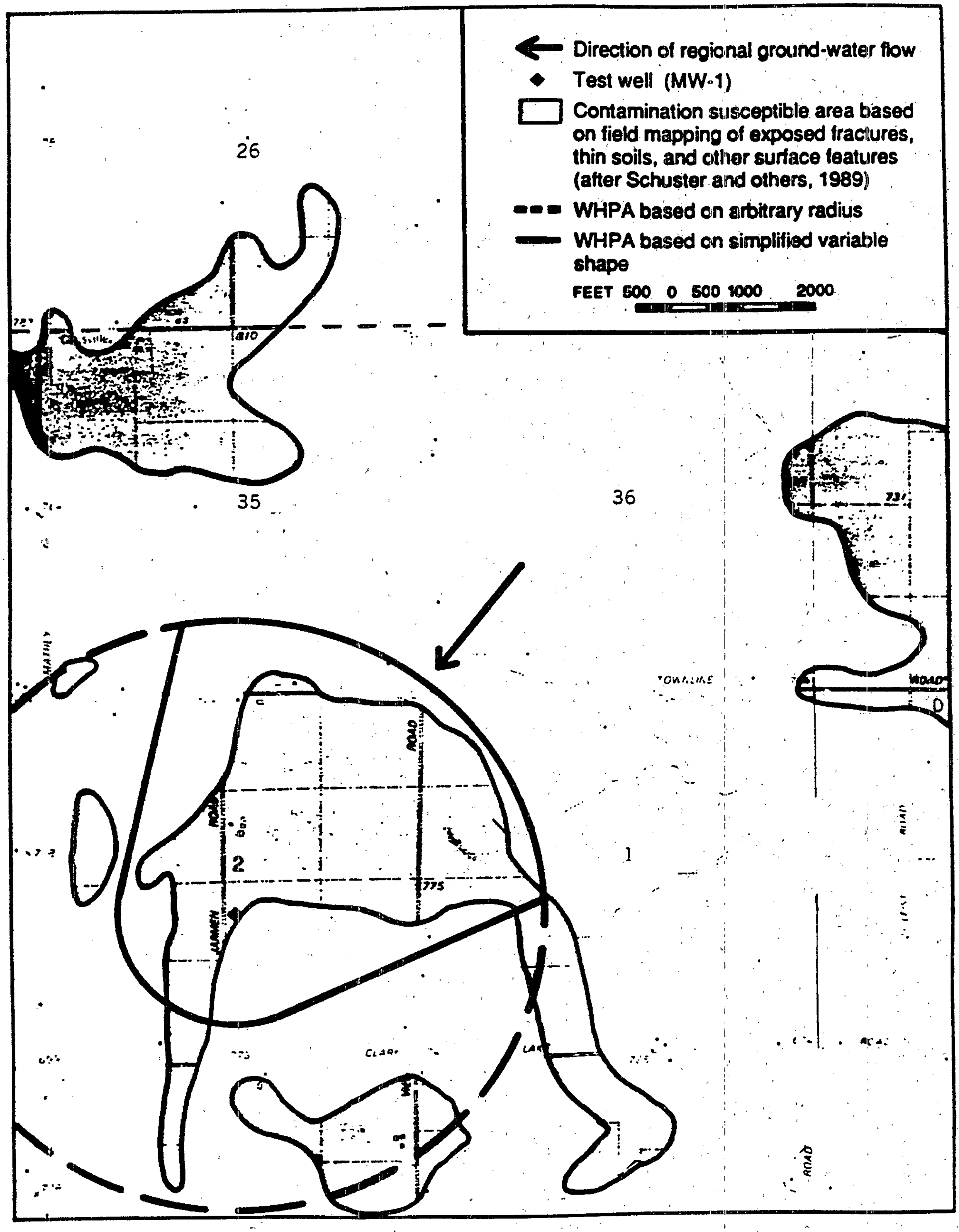


Figure 9. WHPAs based on vulnerability mapping at the Sevastopol site.

considerations can rule out such detailed field work. In some situations, available office data, in the form of water levels on well constructors' reports, previous hydrogeologic studies, and surface-water features on topographic maps, can produce acceptable water-table maps (Blanchard and Bradbury, 1987). Field measurements of water levels in existing domestic and industrial wells can supplement these data. Appendices A and B (figs. A8 and B4) provide examples of water-table maps in fractured-rock settings from the two study areas in Wisconsin.

Once a water-table map is constructed, flow lines are drawn perpendicular to the water-table elevation lines. These flow lines begin at the well and extend upgradient to the ground-water divide. Using a water-table map to determine ground-water flow lines assumes an isotropic aquifer, which is not always the case in fractured-rock settings. In simple hydrogeologic settings (without major faults, facies changes, etc.), the ZOC delineated by the flow-system mapping method takes into account the ground-water flow system geometry. It neither includes downgradient areas that do not contribute water to the well nor excludes upgradient areas that do contribute water to the well. This method tends to be conservative in the sense that it usually overestimates the true ZOC for a given well.

Advantages of the flow-system mapping method are
1) the method is simple and requires only limited training in hydrogeology;
2) the method can be used with various types of data ranging from office data to detailed field data;
3) the method uses mappable hydrogeologic boundaries.

Disadvantages of the flow-system mapping method are
1) the method assumes a uniform, two-dimensional aquifer that approximates a uniform porous medium;
2) the method can produce unacceptably large ZOC estimates if the protected well is located far from a ground-water divide;
3) errors in the water-table map can cause large errors in ZOC delineation.

Results of the application of the flow-system mapping method at the Junction City and Sevastopol sites are discussed below together with the results of the flow-system/TOT method, and shown in figures 10, 11, and 12.

Flow-System Mapping with Time of Travel Calculations

A water-table map can be used to estimate the horizontal hydraulic gradient. Using the gradient in combination with estimates of hydraulic conductivity and aquifer porosity, ground-water velocity can be calculated according to:

$$\bar{v} = K\, i/n \qquad (1)$$

where $\overline{v}$ is the average linear velocity of the ground water, K is the horizontal hydraulic conductivity, i is the horizontal hydraulic gradient, and n is the porosity. The velocity, in combination with a specified time of travel, can be used to limit the WHPA to that portion of the ZOC that will contribute water to the well within a specified amount of time. Determination of the position of the TOT line incorporates the assumption that contaminants in ground water will move in the same direction and at the same velocity as the ground water.

Calculation of the TOT boundary is based on:

$$d = \overline{v}\, t \tag{2}$$

where d is the upgradient distance from the well to the TOT line, $\overline{v}$ is the average linear velocity across the ZOC (calculated using Eq. 1 above), and t is the desired time of travel. Note that the hydraulic gradient, i, in Eq. 1, is calculated as the total change in water-table elevation from the upgradient ZOC boundary to the well divided by the horizontal distance from the upgradient ZOC boundary to the well. This is clearly a simplification of reality because, in most cases, i will not be uniform over the basin. However, in most cases, the error in the location of the TOT line will be small.

Advantages of combining flow-system mapping with the TOT criterion are
1) the TOT criterion provides a way to limit the WHPA in areas where the ZOC delineated from flow-system boundaries is unacceptably large;
2) adding the TOT criterion requires little additional work once the flow-system method has been completed;
3) the method requires only elementary mathematics.

Disadvantages of combining flow-system mapping with the TOT criterion are
1) errors in estimates of porosity or hydraulic conductivity can cause large errors in the TOT calculation and thus in WHPA delineation;
2) the method assumes a uniform, two-dimensional aquifer that approximates a uniform porous medium;
3) the presence of a highly conductive fracture zone could cause very large errors in the TOT calculation and in the resulting WHPA.

Application of the flow-system/TOT method is shown with examples from the Junction City and Sevastopol sites. The examples use only the most accurate aquifer parameter estimates derived from pumping tests. The use of the flow-system mapping method at both sites required the assumption that the fractured rock behaves as a uniform porous medium at the WHPA scale.

Example 1: Junction City site.--Detailed site investigation conducted at the Junction City well field provided a water-table map that clearly indicated a cone of depression around the village well (hatchured contours, fig. 10). The cone creates ground-water divides between

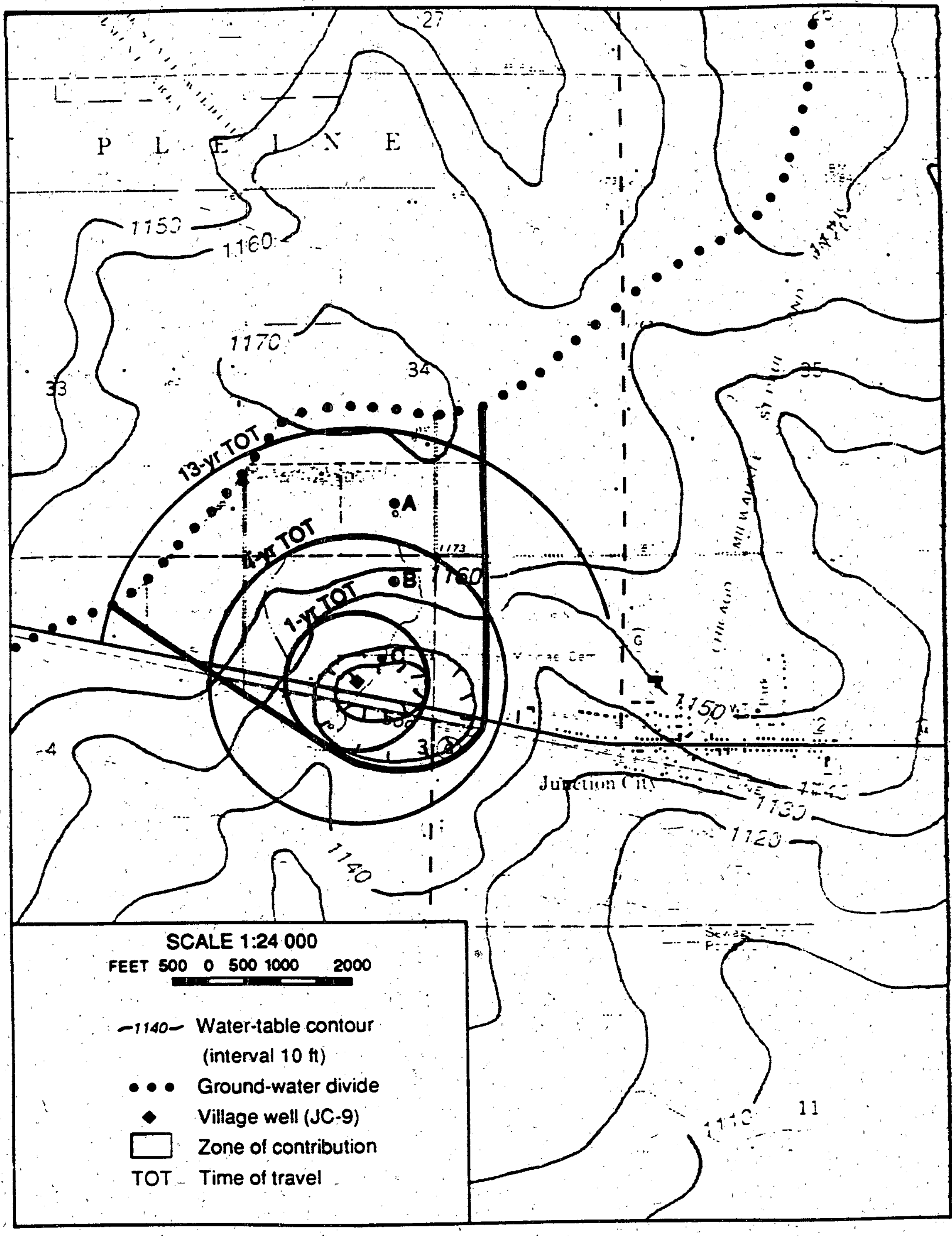


Figure 10. ZOC delineation in crystalline rocks using a field-measured water-table map. A, B, and C are points where hydraulic gradients and ground-water velocities were calculated. Velocities were calculated using the hydraulic conductivity determined from the pumping test.

flow lines reaching the village well and flow lines bypassing it. Outlining these ground-water divides and extending the divides upgradient to the regional water-table divide produces the ZOC shown in figure 10.

Once the ZOC has been delineated, Eq. 1 can be used to estimate ground-water flow velocities needed to delineate that portion of the ZOC within a specific TOT threshold. The horizontal hydraulic gradient (*i* in Eq. 1) represents the decrease in total hydraulic head over a horizontal distance. The hydraulic gradients at points A, B, and C on figure 10 are, respectively, 0.0063, 0.013, and 0.05. Hydraulic conductivity estimated from a pumping test of the village well (Appendix A) was 8.3×10^{-5} ft/sec (about an order of magnitude higher than that estimated from slug tests and specific capacity data). Using Eq. 1, with a fractured-rock porosity of 0.10 (Freeze and Cherry, 1979), calculated ground-water velocities at points A, B, and C are about 165, 340, and 1300 ft/yr. Note that ground-water velocities increase significantly near the village well as the ground-water flow paths converge to enter the well. Because of the variability of ground-water velocities over the study area, TOT lines based on this analysis are only approximate. Figure 10 shows approximate TOT distances for 1 year, 4 years, and 13 years.

Example 2: Sevastopol site.--The Sevastopol site example demonstrates use of the flow-system mapping method at a site where the production well is not yet in use and no mappable cone of depression yet exists. In addition, water-level measurements at multilevel piezometer nests revealed that the ground-water system at the Sevastopol site was more complex than that at Junction City and required a three-dimensional analysis. The system can be best characterized by two separate flow systems, one shallow and one deep, which correspond to zones of intense fracturing, separated by zones of less-fractured dolomite. The water-table map for the shallow system and the potentiometric-surface map for the deep system and their respective ZOCs are shown in figures 11 and 12, respectively. Because no cone of depression exists around test well MW1, the downgradient boundaries of the ZOCs were squared off and flow lines were started arbitrarily 500 ft on either side of the well for the shallow system (fig. 11) and 1000 ft on either side of the well for the deep system (fig. 12). The flow lines were then drawn upgradient to the ground-water divide.

From the perspective of implementation, there is a significant problem with a narrow WHPA, as shown by the shaded zone in figure 12. In such areas, the delineation of the ZOC depends on the position of the potentiometric contours, and a relatively small error in the potentiometric map can result in a major shift in the ZOC. This problem is most critical when the ZOC is long and narrow.

One method to help insure that the WHPA covers the actual ZOC in such areas is to delineate a buffer zone around the mapped ZOC (U.S. EPA, 1987). In figure 12, the buffer zone was extended outward from the mapped ZOC boundary by 250 ft for every 1000 ft of distance upgradient from the well.

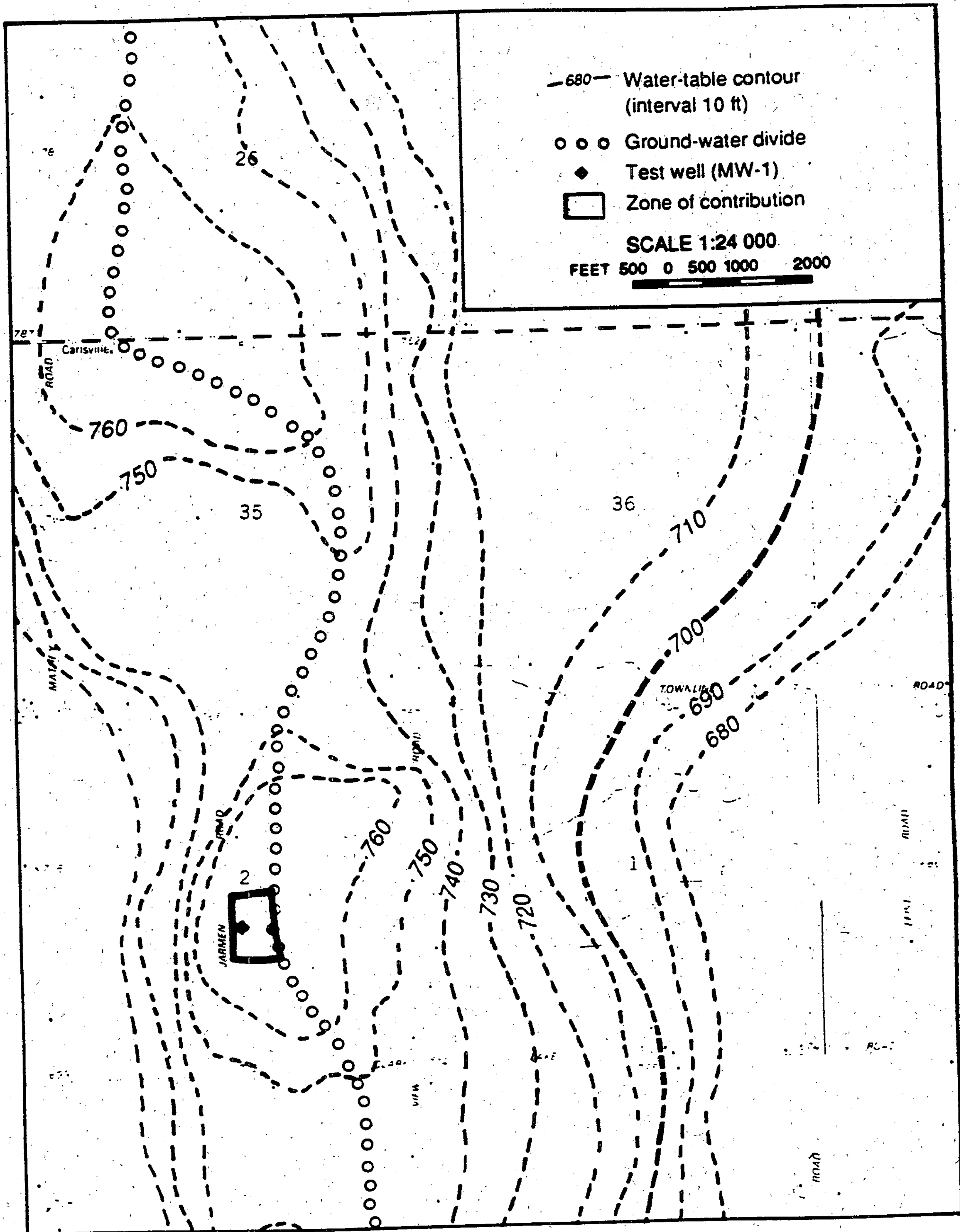


Figure 11. ZOC delineation in a shallow ground-water system in dolomite using a water-table map.

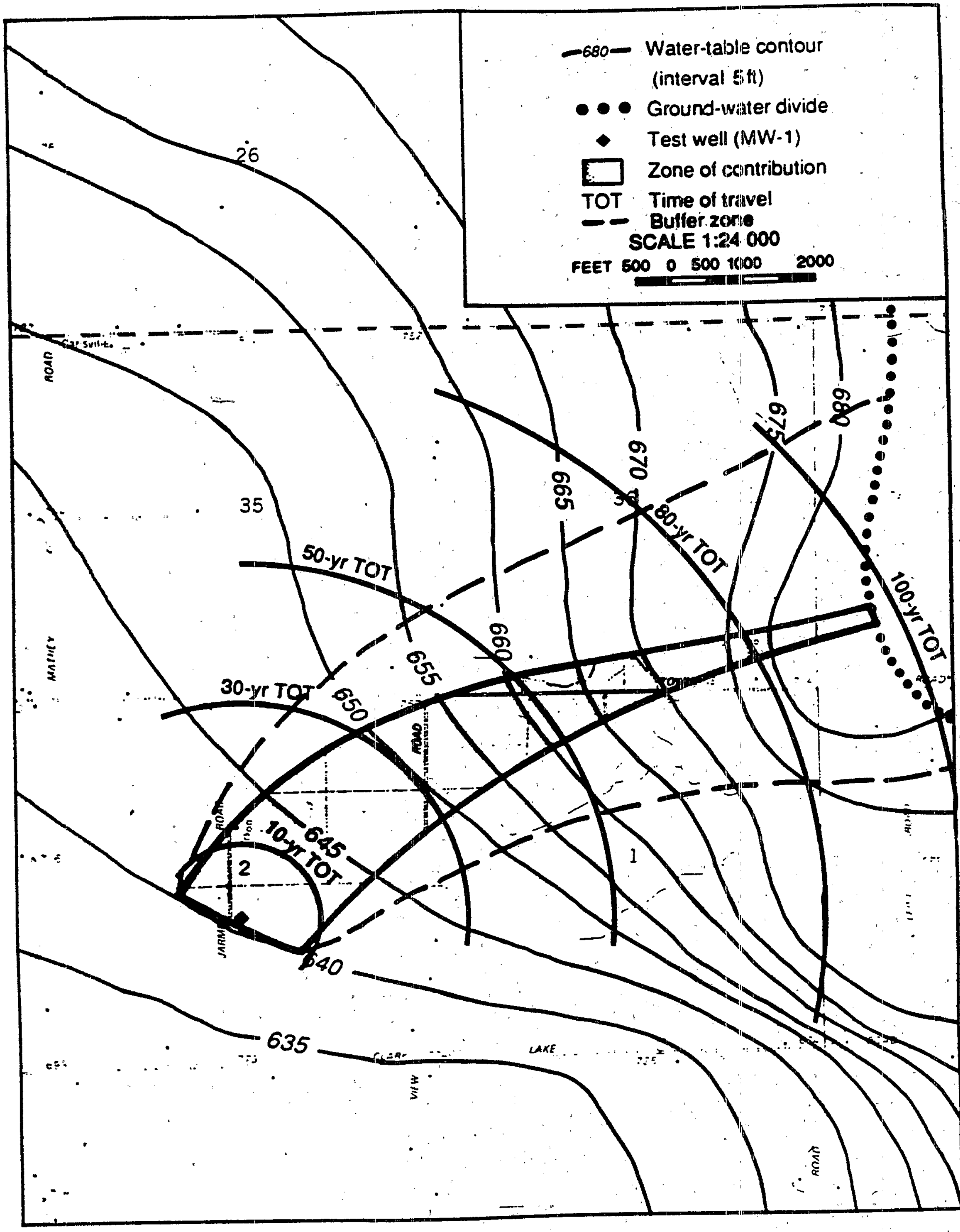


Figure 12. ZOC delineation in a deep ground-water system in dolomite using a potentiometric-surface map.

In the area of the test well, the hydraulic gradient of the shallow system is about 0.0060 (derived from the water-table map). Using this gradient, a hydraulic conductivity of 1.4×10^{-4} ft/sec, and a porosity value of 0.2, the ground-water velocity is about 4.2×10^{-6} ft/sec (130 ft/yr), and the TOT from the ground-water divide to the well (a distance of about 650 ft) is about 5 years. For the deep system, the average gradient from the well to the ground-water divide is about 0.0046. Using the same conductivity and porosity, the average ground-water velocity of the deep system is 3.2×10^{-6} ft/sec (100 ft/yr). Based on this velocity, TOT lines have been drawn on figure 12.

Delineating an adequate ZOC at the Sevastopol site required combining the shallow and deep system ZOCs into one overall ZOC. A conservative assumption for the purpose of combining the ZOCs is that vertical leakage from the shallow system to the deep system can occur anywhere. Therefore, not only does the land surface directly above the shallow and deep ZOCs have to be protected, but so does the land surface above that part of the shallow system that might contribute flow to the deep system ZOC. Figure 13 illustrates the combined ZOC.

The combined ZOC was drawn by first overlaying the individual ZOCs from the shallow and deep systems, and then adding an additional area where water from the shallow system could move and to enter the ZOC of the deep system. Points A and B on figure 13 illustrate the directions of ground-water movement in this combined ZOC. Point A lies in the ZOC for the deep system. Water entering the deep system at point A will follow the indicated path to the well. Point B does not lie in the ZOC for the deep system, but it does lie in that part of the shallow system that could contribute to the deep system ZOC. Water entering the shallow system at point B could move southeast through the shallow system, downward to the deep system, then southwest through the deep system to the well.

Flow-System Mapping with Uniform Flow Equation

Description.--The construction of a water-table map allows the application of the uniform flow equation (Todd, 1980) to define the ZOC to a pumping well in a sloping water table (fig. 14). The input requirements are the same as for combining flow-system mapping with the TOT criterion. The uniform flow equation assumes a uniform porous medium and can be expressed as:

$$-Y/X = \tan(2\pi KbiY/Q) \qquad (3)$$

where Y is the distance from the well parallel to the pre-pumping equipotential lines, X is the distance from the well perpendicular to the pre-pumping equipotential lines, K is the hydraulic conductivity, b is the saturated thickness of an aquifer, i is the pre-pumping hydraulic

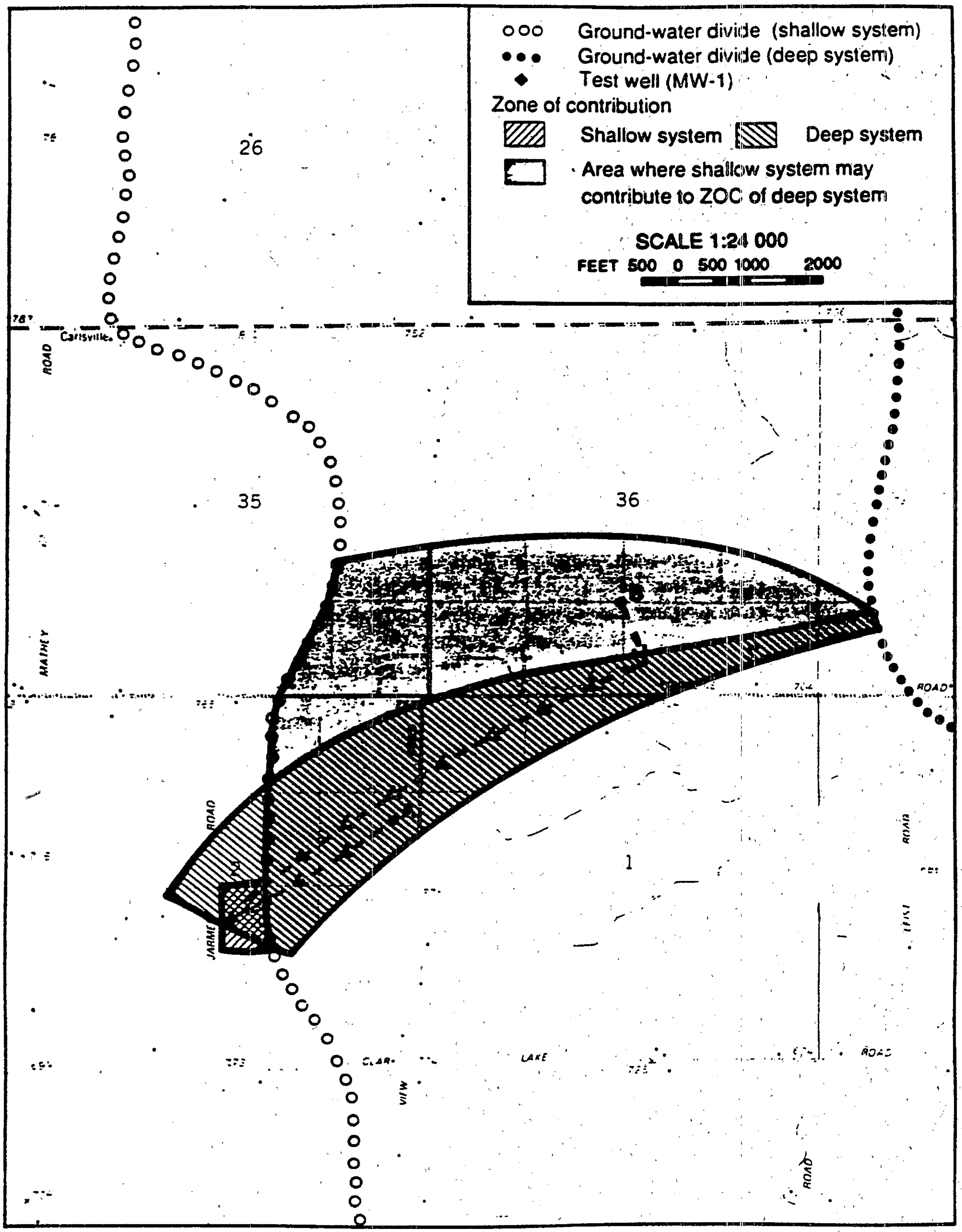
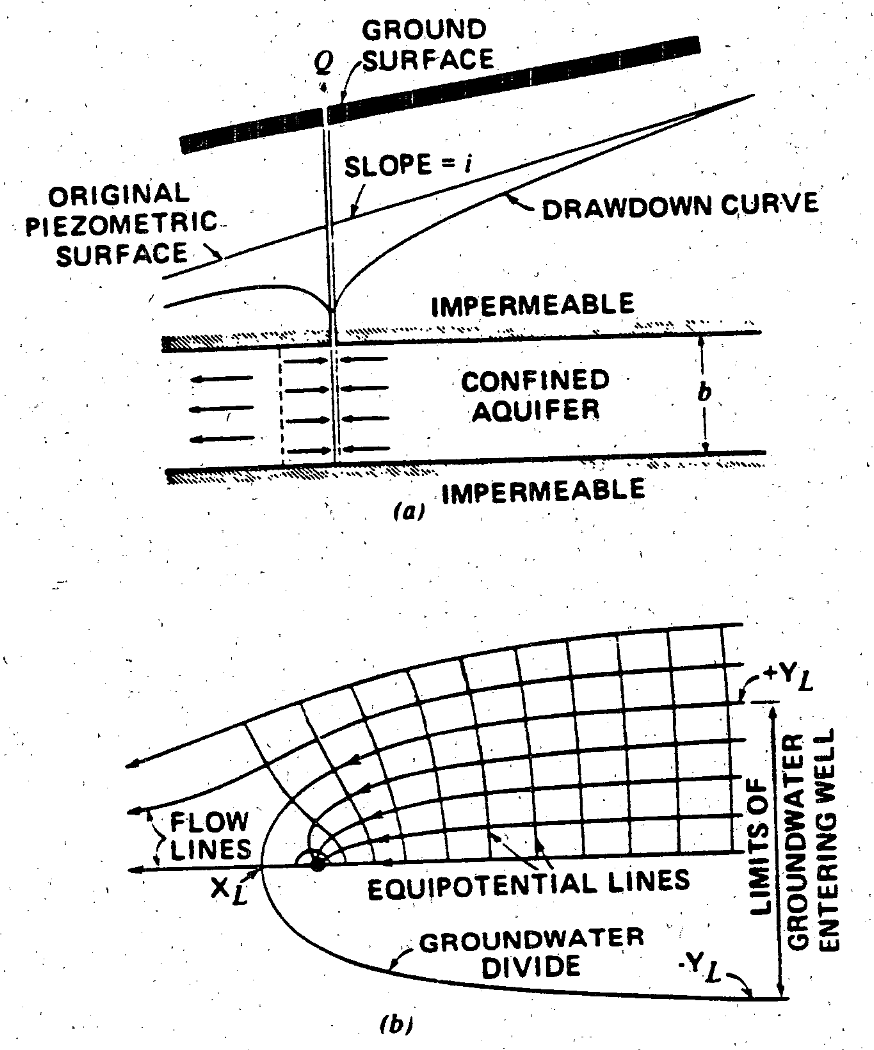


Figure 13. ZOC delineation in dolomite using water-table and potentiometric-surface maps. Arrows show hypothetical travel paths for water particles originating in the deep system (Point A) and in the shallow system (Point B).



$$-\frac{Y}{X} = \tan\left(\frac{2\pi K b i}{Q} Y\right)$$

UNIFORM-FLOW EQUATION

$$X_L = -\frac{Q}{2\pi K b i}$$

DISTANCE TO DOWN-GRADIENT NULL POINT

$$Y_L = \pm \frac{Q}{2Kbi}$$

BOUNDARY LIMIT

LEGEND:

● Pumping Well

Where:
Q = Well Pumping Rate
K = Hydraulic Conductivity
b = Saturated Thickness
i = Hydraulic Gradient
π = 3.1416

NOT TO SCALE

Figure 14. ZOC delineation using the uniform flow equation.

gradient, and Q is the well pumping rate. This equation leads to two equations that delineate the ZOC of a well:

$$X_L = -Q/(2\pi Kbi) \quad (4)$$

and

$$Y_L = \pm Q/(2Kbi) \quad (5)$$

where X_L is the distance from the well to the pre-pumping downgradient null or stagnation point, and Y_L is the distance to the transverse boundary limits from the upgradient boundary center (fig. 14).

Advantages of this method are
1) the method accounts for some of the effects of pumping on the ZOC without detailed mapping of a cone of depression, which reduces the amount of required field work;
2) the method is simple and requires only limited training in hydrogeology;
3) the method uses data derived from a water-table map.

Disadvantages of this method are
1) the method assumes a uniform, two-dimensional aquifer that approximates a uniform porous medium;
2) the method ignores the effects of hydrologic boundaries (except ground-water divides), aquifer heterogeneities, and non-uniform recharge;
3) the method can produce unacceptably large ZOC estimates if the protected well is located far from the ground-water divide;
4) errors in the water-table map or in estimates of porosity or hydraulic conductivity can cause large errors in ZOC delineation.

Example 1: Junction City site.--Using the water-table map and the hydraulic conductivity estimate based on the pumping test, the following values were assigned to the variables in the uniform flow equation:

$$K = 8.3 \times 10^{-5} \text{ ft/sec},$$
$$b = 160 \text{ ft},$$
$$i = 0.0047,$$
$$Q = 0.072 \text{ ft}^3\text{/sec}.$$

These values resulted in a downgradient null point (X_L) of -180 ft and a transverse null point (Y_L) of $\pm$580 ft (fig. 15). The ZOC extending to the ground-water divide in this example is narrower than the ZOC delineated from the water-table map (fig. 10), because the mapped cone of depression is larger than would be predicted by using the uniform flow equation.

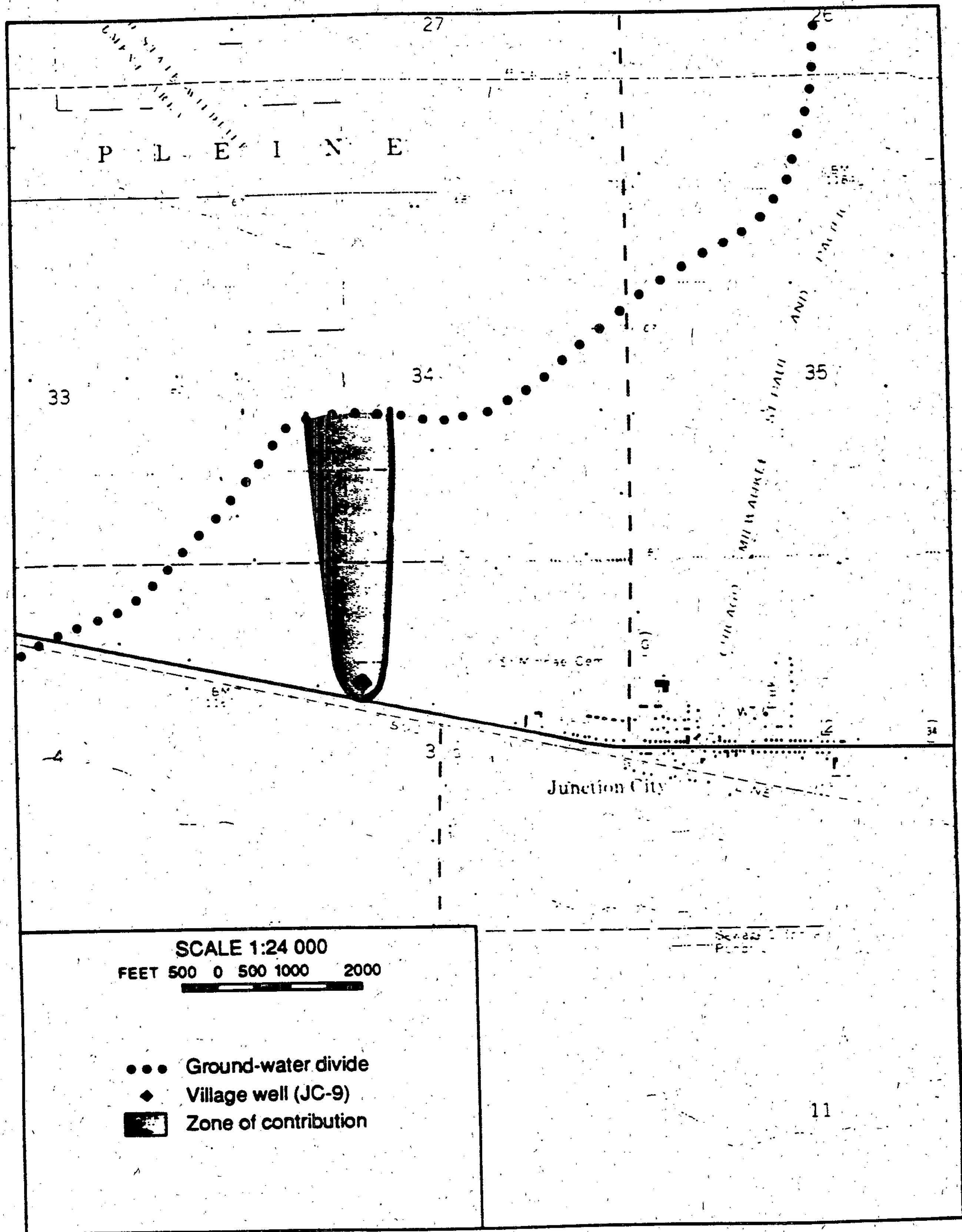


Figure 15. ZOC delineation in crystalline rocks using the uniform flow equation.

Example 2: Sevastopol site.--On the basis of aquifer evaluation, geophysical logging, and the potentiometric-surface map of the deep system (see Appendix B), the following parameters were assigned to the deep aquifer system:

$$K = 1.4 \times 10^{-4} \text{ ft/sec},$$
$$b = 410 \text{ ft},$$
$$i = 0.0046,$$
$$Q = 100 \text{ gpm } (0.22 \text{ ft}^3/\text{sec}).$$

The calculated X_L and Y_L are -130 ft and $\pm$420 ft for the hypothetical municipal well. The ZOC drawn with these limits is shown in figure 16. Note that the ZOC has been curved to follow the regional direction of ground-water flow.

Residence-Time Approach

Description.--The residence-time approach utilizes water chemistry and isotopes to identify ground-water travel paths and flow rates. Geochemical parameters (for example, mineral concentrations and saturation indices) can help indicate the source area of ground water. Environmental isotopes (tritium, oxygen-18) in ground water can be used to estimate a minimum age of water produced by a well. Such analyses are relevant to ZOC and TOT analyses in three ways. First, relative age determinations can provide a check on travel-time estimates obtained by the hydraulic approaches described above. Second, in areas where the water produced by a well can be shown to be hundreds or thousands of years old, the potential ZOC of a well might be so large that local wellhead protection might not be appropriate or effective. Third, in areas where the geochemical and isotopic signatures of ground water vary radically from place to place, these variations can be used to differentiate zones of rapid recharge from zones of less rapid recharge. For example, a well located near a river that produces water having geochemical and isotopic contents similar to the river water might be directly connected to the river through the fracture network; a well adjacent to a river that produces water with a different geochemical and isotopic content might not be directly connected to the river.

Tritium (^3H) is a radioactive isotope of hydrogen that is naturally present at low levels in the earth's atmosphere, but tritium in the atmosphere increased dramatically following atmospheric atomic weapons testing from 1952 to the mid-1960s. During this time, all recharging ground water was enriched with tritium, and ground water that has entered aquifers since 1952 generally contains elevated tritium levels. The half-life of tritium (12.3 years) is relatively short, making it an excellent indicator of recent ground-water recharge and relative ground-water age (Egboka and others, 1983; Knott and Olimpio, 1986), where age is defined as the time since the water was in contact with the atmosphere. Hendry (1988) summarized the general qualitative interpretations of ground-water age on the basis of tritium in ground-water (table 3). Tritium analyses are reported in tritium units--a ratio of tritium atoms (^3H) to the much more common ^1H atoms. One tritium unit, or TU, represents one tritium atom per 10^{18} hydrogen atoms.

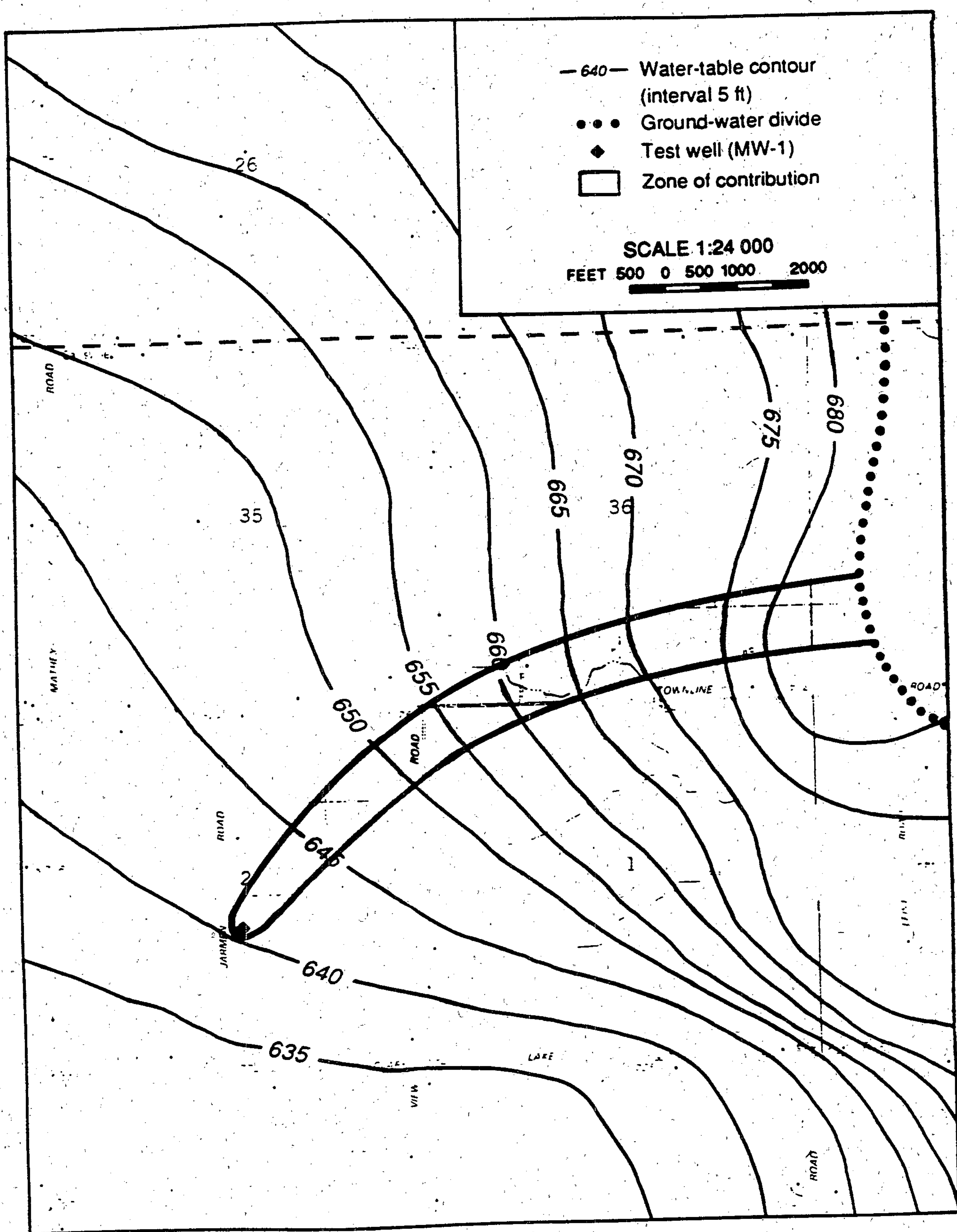


Figure 16. ZOC delineation in a deep ground-water system in dolomite using the uniform flow equation.

Table 3. Qualitative interpretations of tritium concentrations in ground water (from Hendry, 1988).

Concentration (TU)	Interpretation
> 100	Average ground water likely recharged during thermonuclear testing between 1960 and 1965.
10-100	Average ground water less than 35 years old.
2-10	Average ground water at least 20 years old.
< 2.0	Average ground water older than 30 years.
< 0.2	Average ground water older than 50 years.

Oxygen-18 (^{18}O) is a naturally occurring isotope of oxygen present at low concentrations in air and water. The ratio of ^{18}O to the more common ^{16}O is a function of climate, season, latitude, and weather patterns. In general, the $^{18}O/^{16}O$ ratio becomes lower in more northerly latitudes and colder climates, and so the ^{18}O content of ground water has been used as an indicator of the climate at the time the water recharged. Bradbury (1985) and Desaulniers and others (1981) have used the ^{18}O content of ground water in clayey fractured tills in Wisconsin and Ontario, respectively, to suggest that the ground water recharged in a colder climate than present, possibly as much as 10,000 years ago. In addition, the $^{18}O/^{16}O$ ratio in precipitation varies seasonally, and variations in the ratio are often used to distinguish ground water originating from different recharge areas. As with tritium, ^{18}O values are reported as a ratio deviation from a standard. For ^{18}O the standard is known as Standard Mean Ocean Water (SMOW); results are reported as per mil deviations from this standard.

The residence-time approach requires the collection of high-quality ground-water samples from pumping wells, monitoring wells, and discharge points such as springs and streams. These samples are tested for a full range of inorganic cations and anions as well as such field parameters as pH, conductivity, dissolved oxygen, and temperature. In addition, the water should be analyzed for ^{3}H and ^{18}O. This method also requires information about the mineralogy and geochemistry of rocks supplying water to the well.

Advantages of the residence-time approach are
1) the assumption of a uniform porous medium is not necessary;
2) the method can give information about relative ground-water age, which can be

useful in determining the appropriateness of WHPA delineation;

3) the method helps confirm TOT estimates made by other techniques;
4) the method does not require detailed measurements of aquifer parameters, although knowledge of such parameters increases the method's usefulness.

Disadvantages of the residence-time approach are

1) the method requires skill and experience in geochemical and isotopic interpretation;
2) the method is not applicable to all settings, and results are sometimes ambiguous;
3) geochemical and isotopic analyses can be expensive;
4) the method may not produce a mappable ZOC, but it can help confirm a ZOC and TOTs delineated by some other method.

Example 1: Junction City site.--Ground-water samples were collected from 14 wells and piezometers in and around the Junction City well field between October 1988 and June 1989 (fig. 17). The samples were analyzed for all major cations and anions and for ^{3}H and ^{18}O. Analytical results are presented in Appendix A (tables A4 and A5).

Using the qualitative tritium interpretations in table 3, ground water currently produced by the village well contains about 21 TU and is therefore less than 35 years old. This is relatively young ground water, which indicates that ground-water flow paths from the recharge area to the village well are relatively short.

Most other bedrock wells and piezometers near the village well also produced water less than 35 years old, with three exceptions. Shallow piezometer JC5, bedrock well JC12, and deep piezometer JC23A contain, respectively, 5.4, 3.4, and 7.7 TU (see inset map fig. 17; table A5, Appendix A), and ground water at these locations is older than in the other wells. Piezometer JC5 is finished in the thickest section (greater than 50 ft) of unlithified silty clay present in the well field. Ground water at JC5 has taken at least 20 years to move less than 50 ft downward, implying that the bedrock aquifer probably receives very little recharge in the vicinity of JC5. Well JC12 is several thousand feet west of the village well and is outside the cone of depression. The tritium data confirm that JC12 is outside the ZOC of the village well (fig. 17). Finally, piezometer JC23A is finished deep in the poorly fractured section of the bedrock aquifer. Even though the village well (JC9) extends to an equal depth as JC23A (fig. 17), the discrepancy in tritium values between JC9 and JC23A indicates that the deep, poorly fractured part of the aquifer probably contributes little or no water to the village well. This finding implies that the ZOC for the well may be small, and that the well receives little or no water from a regional flow system.

The ^{18}O values for the Junction City area range from -9.6 to -11.6 per mil (table A5, Appendix A), which is about the range of variation expected for ^{18}O in recent precipitation in central Wisconsin. The oxygen data are thus consistent with the tritium data (ground water less than 35 years old), and the small variations between wells in the study area are probably not significant.

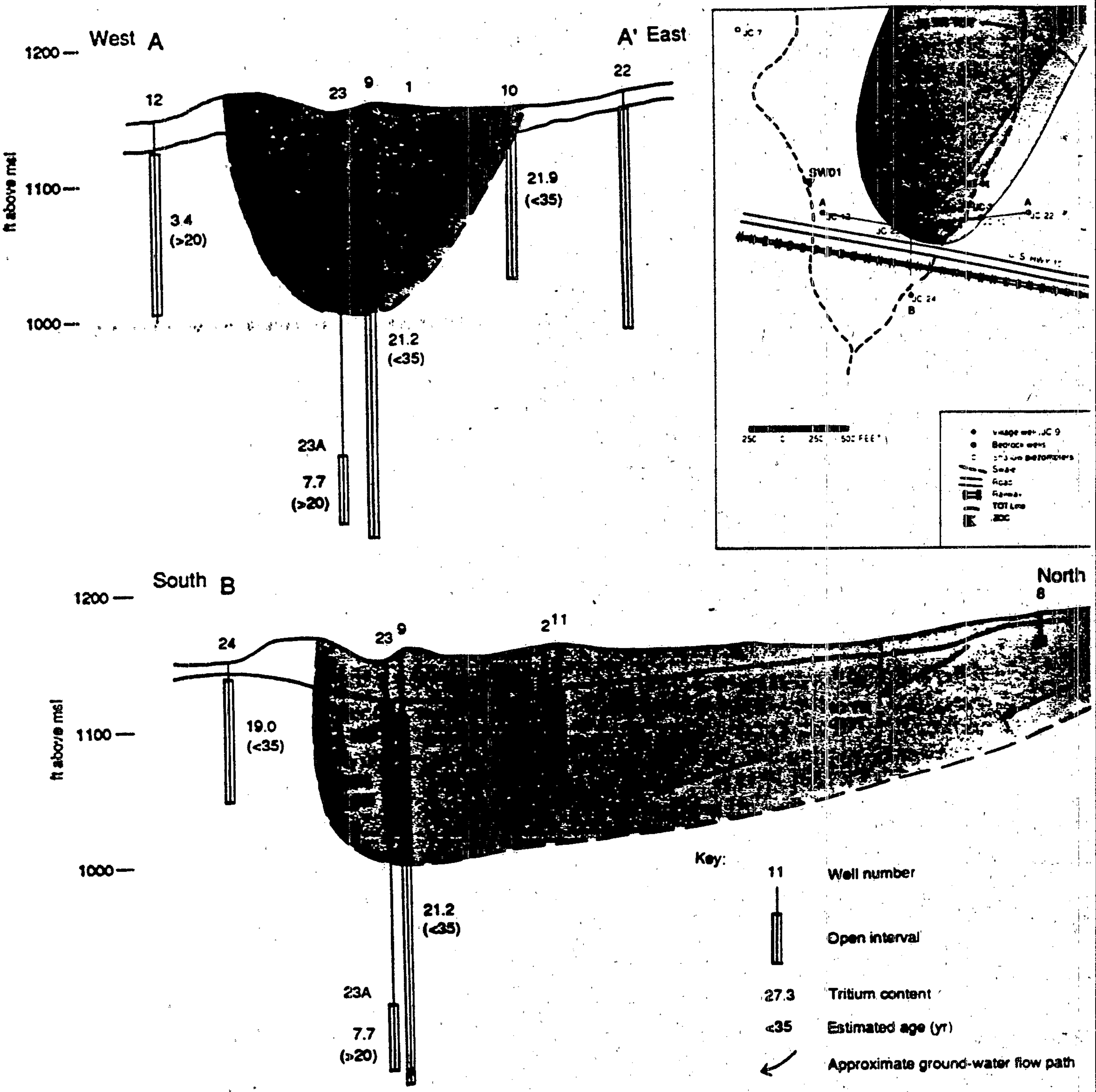


Figure 17. ZOC verification using tritium data at Junction City, Wisconsin.

Results of chemical analyses (table A4, Appendix A) lead to these conclusions about ground-water flow to the village well.

1) Because the chemistry of the village well (JC9, 325 ft deep) is very similar to the chemistry of surrounding test wells (JC10, JC11, and JC24, about 100 ft deep) and is not similar to the chemistry of piezometer JC23A (300 ft deep), it seems likely that most of the water produced by the village well moves into the well from the upper, highly fractured bedrock. The lower part of the bedrock supplies little water to the village well.
2) The village well chemistry is different from the chemistry of a surface-water sample collected from the swale west of the village well (SW01). This suggests that there is no direct conduit carrying surface water to the village well through the fracture system.
3) The village well chemistry is clearly different from water chemistry in the vicinity of piezometer JC5, screened at the base of a thick layer of unlithified materials. Apparently, little recharge enters the aquifer from areas of thick, clayey surficial materials.
4) Water quality in the upper, fractured bedrock is relatively uniform, supporting the concept of a diffuse-flow system (porous medium) rather than conduit-flow system for this aquifer.

Taken together, the isotope and chemical data suggest that water produced by the village well is well-mixed, flows mainly through the upper fractured zone, and has a residence time of less than 35 years. These results suggest that wellhead protection measures based on the porous-media assumption will be effective at Junction City.

Example 2: Sevastopol site.--Ground-water samples were collected from 16 wells and piezometers during November 1988, and analyzed for major ions and for ^{3}H and ^{18}O. Analytical results are presented in Appendix B (tables B4 and B5).

As with the Junction City example, the residence time of ground water in the fractured dolomite of the Sevastopol site is generally less than 35 years based on qualitative tritium interpretations. The ^{18}O data are consistent with this age interpretation (table B5, Appendix B). Isotopically "young" water is expected in Door County because of the high degree of fracturing of the dolomite and the thin soil cover, which allow rapid recharge. The similarity of isotope results from all piezometers is consistent with the assumption of porous-media behavior for the dolomite aquifer.

Major-ion ground-water chemistry is uniform with depth and position at the Sevastopol site. The homogeneity of bedrock at the Sevastopol site probably masks any subtle chemical changes associated with varying source areas. The lack of major variations in major-ion concentrations, electrical conductivity, mineral-saturation indices, and other parameters supports the assumption that the dolomite aquifer behaves as a porous medium (diffuse-flow system) at the WHPA scale.

Numerical Flow/Transport Models

Description.--A WHPA can be delineated using computer models that approximate ground-water and/or solute transport equations numerically. Such delineation is usually a two-step process: simulating a flow system followed by calculation of contaminant flow paths within that system. Where the hydrogeologic setting is complex, models can be particularly useful because they allow simulation of a wide variety of conditions and ground-water flow boundaries. Modeling of a flow system involves discretization of either a two- or three-dimensional problem domain into nodes. Such discretization can account for spatial variability of aquifer parameters, thus enabling the inclusion of aquifer heterogeneity and anisotropy in the model simulation. Most ground-water flow models also allow for temporal variation of many parameters. The flexibility of computer models allows for variation of recharge rates, pumping rates, thickness of aquifer layers, storativity, and hydraulic conductivity. Models such as the widely-used U.S. Geological Survey (USGS) Modular Three-Dimensional Finite-Difference Ground-Water Flow Model (McDonald and Harbaugh, 1988) are able to simulate pumping wells, rivers, drains, recharge, and evapotranspiration.

Most numerical models in the public domain at the present time (1989) simulate ground-water flow using the governing equations of porous-media flow. Such models are adequate for wellhead protection studies in fractured-rock aquifers if the aquifer behaves as a porous medium at the scale of the study. Although models that can simulate flow through fracture networks using the governing equations for fracture flow exist, few, if any, such models are currently in the public domain. In addition, the enormous data requirements for such models limit their use to very sophisticated studies.

Once a flow-system model is calibrated so that the simulated head distribution approximates the field heads, transport computer programs can simulate the probable flow paths that contaminants may follow and the TOTs of these contaminants. A ZOC can be delineated by starting these paths at various locations within the flow system and noting which flow paths terminate at the pumping well. Model-produced TOTs along these travel paths can further refine the ZOC using the TOT criterion.

Model simulations are only as reliable as their input parameter values. The cost and technical expertise needed for adequate data collection can be quite high and such collection can require substantial field investigations. Input parameters requiring some degree of field measurement can include aquifer transmissivity, porosity, and the thickness of various layers. Characterization of these layers requires a high degree of geological background and skill. Building, running, and calibrating the model are also complex tasks requiring skilled personnel and a large time investment. In general, if the modeled system is an accurate portrayal of the real system, the resulting ZOC represents the most accurate delineation possible. Changes in the ZOC delineation resulting from natural or man-made effects can also be predicted. The accuracy and adaptability of the model to so many types of hydrogeologic settings make this method desirable, but it is usually the most costly method to implement in terms of time, money, and personnel. Numerical modeling is probably best applicable to those situations where the accuracy required or the flow system complexities warrant such a costly approach.

Advantages of numerical simulation are
1) commonly available numerical models can simulate aquifers in three dimensions and can include most of the inhomogeneity, anisotropy, and transient behavior observed in the field;
2) if properly discretized, numerical models can simulate discrete fracture zones;
3) because numerical models give an integrated solution over the model domain, ground-water flow paths and travel times can be determined with much greater precision than with other methods;
4) adequate numerical codes are widely available.

Disadvantages of numerical simulation are
1) most practical models require a porous-medium assumption at some scale;
2) models require significant amounts of data for proper calibration, verification, and prediction;
3) modeling is often very expensive and time-consuming because it requires substantial amounts of data and expertise.

Example 1: Junction City site.--Modeling of the Junction City area was performed using the USGS modular model (McDonald and Harbaugh, 1988). Field work performed for model parameter estimation consisted of borehole drilling and logging, piezometer installation, piezometer and deep well slug tests, a pumping test, surveying, water-level measurements, and characterizing bedrock exposures for lithology and fracture-trace orientation (Appendix A). Using the information from the field investigations, the flow system was divided into layers, assigned hydrologic boundaries, spatially discretized, and assigned appropriate aquifer parameter values. Details of the modeling are given in Appendix A.

Once the head distribution was adequately simulated, PATH3D, a three-dimensional particle-tracking program (Zheng and others, in press), was used to delineate a ZOC for the village well. PATH3D uses the model-produced head distribution to predict the path of hypothetical particles of water within a flow system; it deals only with the process of advection and ignores the effects of contaminant dispersion and diffusion. By using the steady-state model simulation, particles can be tracked backward from any specified point to the particle origin in the ground-water system. The easiest way to delineate a ZOC is to place the particles in a small circle surrounding the pumping well and track their paths backwards to either the water table or a ground-water flow divide. PATH3D was also used to find the downgradient extent of the ZOC. Trial-and-error placement of particles at the water table near the village well was used to establish the downgradient null point (the divide between the water escaping the well's influence and the water moving backward toward the well). Model results indicated that particles beginning 310 or more feet downgradient (pre-pumping) of the village well continued to move away from the well. Particles beginning less than 305 ft downgradient of the village well were within the ZOC of the well. The final ZOC and approximate TOTs predicted by numerical modeling are shown in figure 18.

Exdmple 2: Sevastopol site.--Numerical modeling of the Sevastopol site was performed similarly to the Junction City modeling, requiring a similar intensity of field work (Appendix B). The modeling and calibration of the Sevastopol site was more complex, however, due to the existence of the shallow and deep flow systems, greater aquifer anisotropy and heterogeneity, and greater head fluctuations associated with seasonal or recharge events.

PATH3D was again used to delineate a ZOC. Hypothetical particles were placed around the pumping well and their paths were tracked backward until they emerged at the water table. The particle paths delineate a thin elliptical ZOC for the well shown in figure 19. Calculated TOTs are also shown. The model predicts small TOTs relative to estimates from other methods due to the incorporation in the model of a thin but highly conductive fracture zone about 180 ft below the land surface. The ability of the model to simulate such a fracture zone makes it superior to previously discussed methods that assume a homogeneous aquifer.

WHPA Delineation Methods for Fractured Rocks That Do Not Behave As Porous Media

Fractured-rock aquifers that do not behave as porous-media aquifers generally fall into two categories. The first category includes aquifers with numerous interconnected fractures. These aquifers contain discrete zones or regions of intense fracturing, large fracture apertures, or fractures widened by solution that are significantly more permeable than the surrounding fractured rock. The second category of fractured-rock aquifers that do not behave as porous-media includes rocks with very sparse and poorly connected fractures in a low-permeability matrix. Such situations are probably most common in structurally homogeneous igneous and metamorphic rocks such as granite and quartzite. In such aquifers, obtaining adequate yield for production wells can be difficult and usually involves completing the well to intersect one or two major water-bearing fractures that act as conduits and storage reservoirs for ground water.

In both cases, ZOCs based on well hydraulics or the uniform flow equation will be incorrect because they ignore the system heterogeneity. However, porous-media-based numerical models may be able to simulate some of these systems by treating the permeable fractured zones as permeable model layers or a series of nodes in a less-permeable matrix. The model at the Sevastopol test site (Appendix B) demonstrated this method by simulating a high permeability horizontal fracture zone in the dolomite aquifer. The model showed that the presence of this zone had a profound effect on ground-water flow paths and travel times in the WHPA.

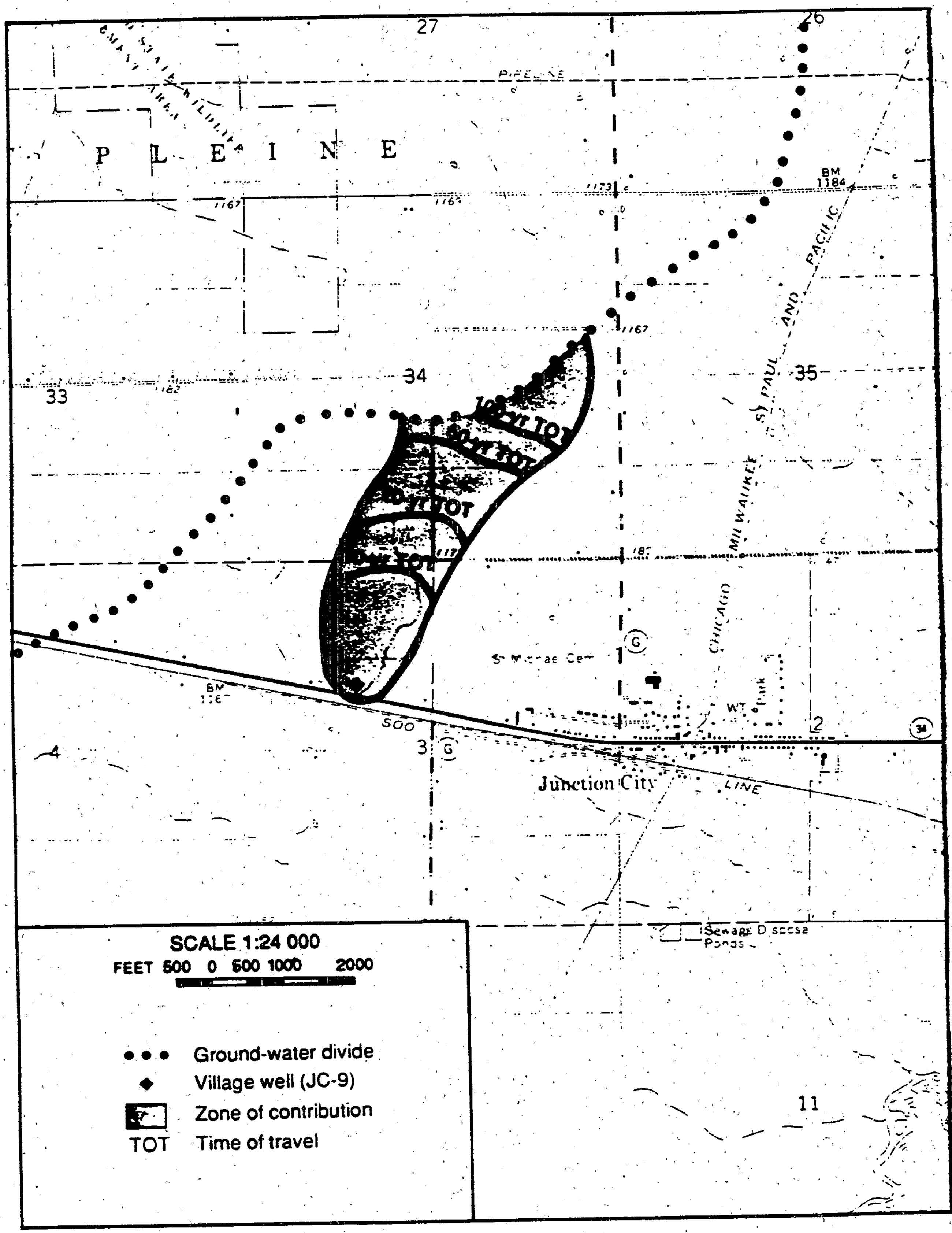


Figure 18. ZOC predicted by numerical modeling for a well in crystalline rocks.

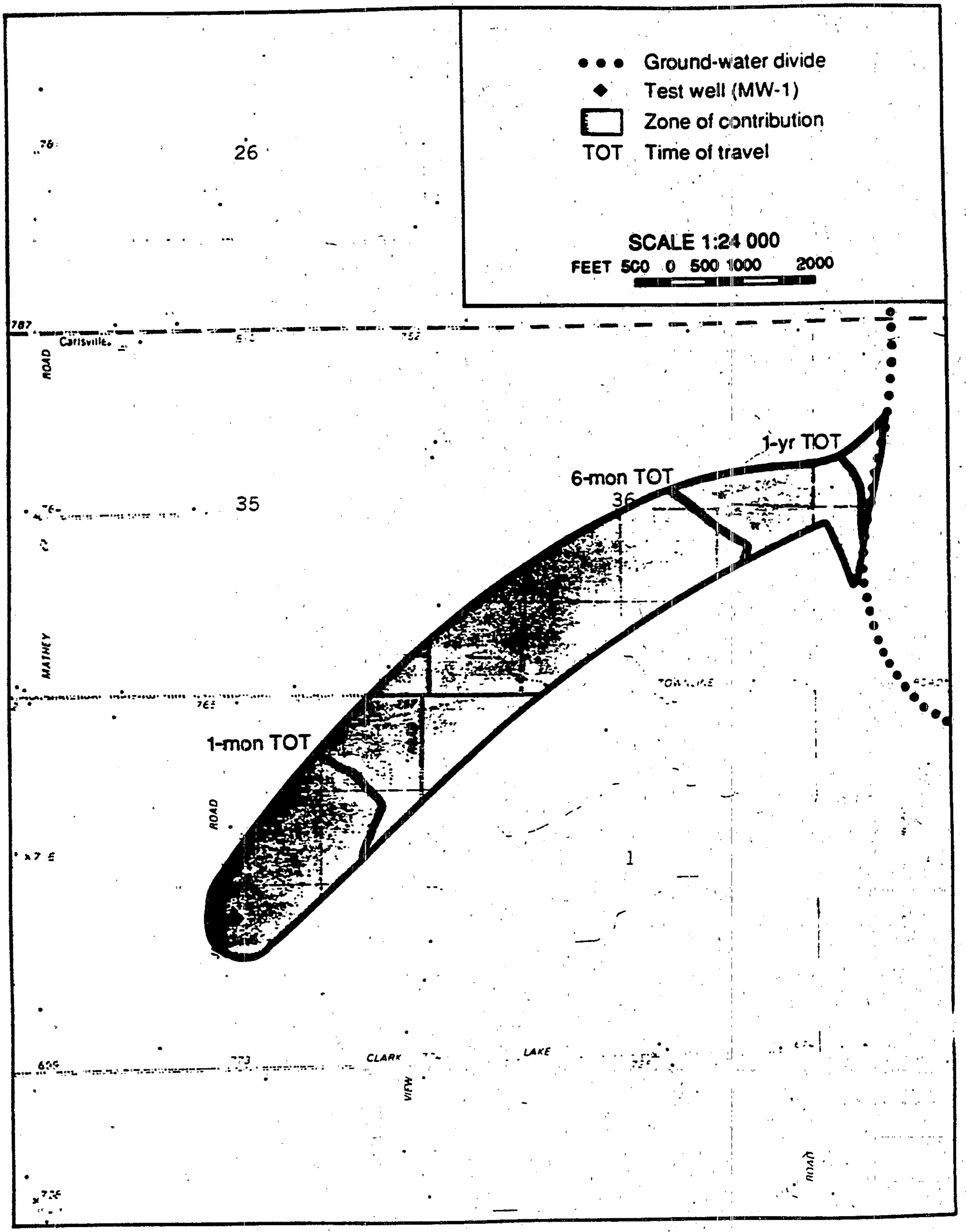


Figure 19. ZOC predicted by numerical modeling for a well in dolomite.

Vulnerability mapping and hydrogeologic mapping are also possible methods for fractured-rock aquifers that do not behave as porous media. Vulnerability mapping may be used to identify areas particularly vulnerable to ground-water contamination, and these areas could form the basis for the delineation of a WHPA using the arbitrary fixed radius method or the simplified variable shapes method (U.S. EPA, 1987). Hydrogeologic mapping (U.S. EPA, 1987) uses geologic contacts, structural features, and water-table maps to determine ground-water basin boundaries. In some cases, the ground-water basin may function as the ZOC for a given well; in cases where the basin is small enough, the entire basin could be delineated as the WHPA.

The residence-time approach is useful in settings where the porous-media assumption does not hold. This approach can be used to establish the age and geochemical origin of water produced by the well to be protected. The residence-time approach alone cannot be used to determine a WHPA and it should be used in combination with the hydrogeologic mapping method or the vulnerability mapping method.

WHPA Comparative Analysis

Cost Analysis

Exact prediction of the costs inherent in each of the methods is difficult because the amount of field work required for each method depends on how much information is already available, the complexity of the problem area, and the degree of accuracy desired by the wellhead protection program. For example, the work required for aquifer parameter estimation can range from the least costly and least accurate method of simply citing the average values of parameters (such as hydraulic conductivity or porosity) found in literature to the most costly and most accurate method of performing a pumping test. The latter requires extensive field work and many hours of technical data analysis. The parameters necessary for each ZOC delineation method are included in table 4. Table 5 summarizes some of the work, time, skill, and approximate cost requirements of performing the individual tasks for each of the methods.

The cost estimates are primarily based on an hourly rate that represents the actual salary to an individual at a particular skill level. It does not include general overhead, benefits, taxes, profit, or the amortization of equipment. If a consultant were employed to perform the same tasks, s/he would usually charge three times the hourly costs that are listed in table 5. Six ground-water consultants or consulting firms in Wisconsin were contacted regarding typical costs for this type of work. They would charge $40 to $100/hr for tasks with skill levels IV, V, and VI. The cost of the flow-system mapping method with calculations (but without drilling or monitoring-well installation) probably would be between $10,000 and $20,000.

Table 4. Data requirements for WHPA delineation methods for fractured crystalline and dolomitic rocks.

Method	Data Requirements									
	K	V	Q	n	i	b	S	R	Hydrologic Boundaries	Aquifer Geometries
Vulnerability Mapping	Geologic, soils, and water-table maps Field mapping of surficial features									
Flow-System Mapping									X	X
Flow-System Mapping with TOT	X			X	X				X	X
Flow-System Mapping with Uniform Flow Equation	X		X	X	X	X			X	X
Residence Time	Water sampling and analyses									
Numerical Flow/Transport Model	X	X	X	X		X	X	X	X	X

Explanation:

K - hydraulic conductivity
V - vertical leakance
Q - well pumping rate
n - porosity
i - hydraulic gradient
b - aquifer thickness
S - storativity
R - recharge rate

Assessment, Comparison, and Selection of Methods

In deciding which of the ZOC delineation methods is most appropriate for a given wellhead protection program, many factors need to be considered. These include relative accuracy, level of technical expertise needed, and costs. Although the best method might differ from one setting to another, a comparison of the results from the Junction City and

Table 5. Estimated work, time, skill, and cost requirements for selected WHPA delineation methods.

Method	Work Requirements	Approx. Time Requirement[1]	Skill Level[2]	Approx. Costs ($)[3]
Vulnerability Mapping	Field			
	- Location of measurable wells	2 days	I	300
	- Depth to ground water measurements	several days	IV	600
	- Location of bedrock outcrops	several days	III, IV	1500
				2400
	Office			
	- Interpretation of soil surveys	several days	soils expert	500
	- Constructing depth to ground water map	2 days	III	400
	- Constructing depth to bedrock map	2 days	III	400
	- Map compilation	2 days	III	400
				1700
				4100
Flow-System Mapping	Field			
	- Location of measurable wells	2 days	I	100
	- Surveying well elevations	3 days	IV	400
	- Piezometer installations	3 days	IV, III	2000
	- Water-level measurements	1 day	IV	120
				2620
	Office			
	- Collection and plotting of well logs	2-3 days	III	240
	- Hand contouring of maps	2 days	III	160
	- Computer contouring	2 days	V	800
	- ZOC delineation	4 hrs	IV	60
				1260
				3880
Flow-System Mapping with TOT calculations	All work listed under flow-system mapping method plus:			3880
	Field			
	- Aquifer parameter estimation	2-3 days	IV, III	1000
	Office			
	- Interpretation of hydraulic gradients	1 hr	II	20

Method	Work Requirements	Approx. Time Requirement[1]	Skill Level[2]	Approx. Costs ($)[3]
	- Hydraulic conductivity estimates (from literature, specific capacity estimates, analysis of field data)	2-3 days	VI	1500
	- Application of ground-water velocity equation to establish TOTs	5 hrs	IV, III	50
				1570
				6450
Flow-System Mapping with Uniform Flow Equation	All work listed under flow-system mapping method plus:			3880
	Field - Aquifer parameter estimation	2-3 days	IV, III	1000
	Office - Interpretation of hydraulic gradients	1 hr	II	20
	- Hydraulic conductivity estimates	2-3 days	VI	1500
	- Application of uniform flow equations	4 hr	II	60
				1580
				6460
Residence-Time Approach	Field - Water sampling	2 days	IV	300
	Laboratory - Sample analyses	--	chem lab	3000
	Office - Data interpretation	2 days	VI	1200
				4500
Numerical Modeling	Field Might include:			
	- Location of measurable wells	2 days	I	100
	- Surveying well elevations	3 days	IV	400
	- Water level measurements	several days	IV	500
	- Piezometer installation	3 days	IV, III	2000
	- Borehole drilling and logging	1 week	IV, III	15000
	- Geophysical logging	several days	IV, III	5000
	- Video logging	1 day	IV	1000
	- Slug tests	1-2 weeks	IV	1500
	- Aquifer pumping test	2 days	IV, III	2000
	- Location of bedrock outcrops	2 days	IV, III	500
				28000

Method	Work Requirements	Approx. Time Requirement[1]	Skill Level[2]	Approx. Costs ($)[3]
	<u>Office</u>			
	- Water-table mapping	1 week	III	500
	- Bedrock surface elevation mapping	2 days	III	200
	- Analysis of field data:	2-3 weeks		5000
	-Slug tests		VI	
	-Geophysical logs		III	
	-Pumping test		VI	
	-Borehole drilling		III	
	- Initial model construction:	3 weeks	VI	9000
	-Parameter selection			
	-Boundaries			
	-Spatial discretization (horizontal and vertical)			
	-Data management			
	- Model calibration	2 weeks	VI	6000
	- Transient simulations	1 week	VI	3000
	- Application of particle tracking program to delineate ZOC	2 weeks	VI	6000
	- Prepartion of graphic output	1 week	V	2000
				31700
				59700

[1] Time requirements depend on the scale and complexity of the problem.

[2] Skill Level:

Skill Level	Hourly Rate ($)
I - Little or no technical expertise required	5
II - Some knowledge of hydrogeology helpful	7.50
III - Training in hydrogeology and/or mapping required	10
IV - Training in hydrogeologic field methods required	15
V - Computer expertise required	50
VI - Requires combination of computer and hydrogeologic expertise	75

[3] Costs do not include overhead, equipment, travel expense, and other administrative charges.

Sevastopol sites is illustrative of some of the advantages and disadvantages of each method and of which methods are the most likely candidates for wellhead protection programs in fractured-rock settings.

The various WHPA delineation methods applied in this study resulted in areas of greatly varying size and shape and in TOTs of greatly varying lengths. For the purpose of comparison, it is assumed that the ZOCs delineated by numerical modeling, as shown in figures 18 and 19, are the most accurate because they incorporated the greatest amount of site-specific field data. The ZOCs delineated with the flow-system mapping, the flow-system mapping with the uniform flow equation, and the numerical modeling methods at the Junction City and Sevastopol sites are compared in figures 20 and 21, respectively.

With the exceptions of vulnerability mapping and the residence-time approach, the WHPA delineation methods tested require the assumption that the fractured-rock aquifer behaves similarly to a porous medium at the scale of the wellhead protection effort. However, numerical models, when carefully discretized, may be able to simulate some high-hydraulic conductivity fracture zones. Although the porous-media assumption can introduce some error, it will be reasonable in many, if not most, fractured-rock settings.

Assuming that porous-media models can accurately simulate fractured-rock aquifers in WHPA studies, wellhead protection analyses in fractured rocks differ from analyses in porous media in several important respects. First, fractured-rock aquifers tend to be highly anisotropic. Second, fractured-rock aquifers tend to be heterogeneous in three dimensions. Third, production wells in fractured-rock aquifers are often constructed with long open-hole intervals. Pumping of such wells draws water from long vertical sections of the aquifer and tends to result in larger ZOCs. For all three reasons, WHPA determinations in fractured-rock aquifers usually require a more sophisticated analysis than in porous media. Numerical modeling is currently the only practical means of carrying out this type of sophisticated analysis, incorporating anisotropy, heterogeneity, and three-dimensional flow. More sophisticated methods of analysis, such as discrete fracture models, fractal analysis, and stochastic models, offer promise but are currently in the research stage and are not viable options for community wellhead protection projects at this time.

Vulnerability mapping.--Vulnerability mapping can help delineate land surface areas most susceptible to contamination including open fractures, exposed or shallow bedrock, and permeable soils. In addition, if fracture conduits can be identified in the subsurface (for example, by using geophysical logs), well casing should be placed so that it isolates the well from major conduits. The results of vulnerability mapping can be used for WHPA delineation using either the arbitrary fixed radius method or simplified variable shapes methods (fig. 9). In areas where the aquifer does not behave as a porous medium, vulnerability mapping offers a relatively cost-effective basis for delineating a WHPA. If geologic, soils, and water-table maps are available for the site in question; the only field work necessary is field mapping of surficial fractures.

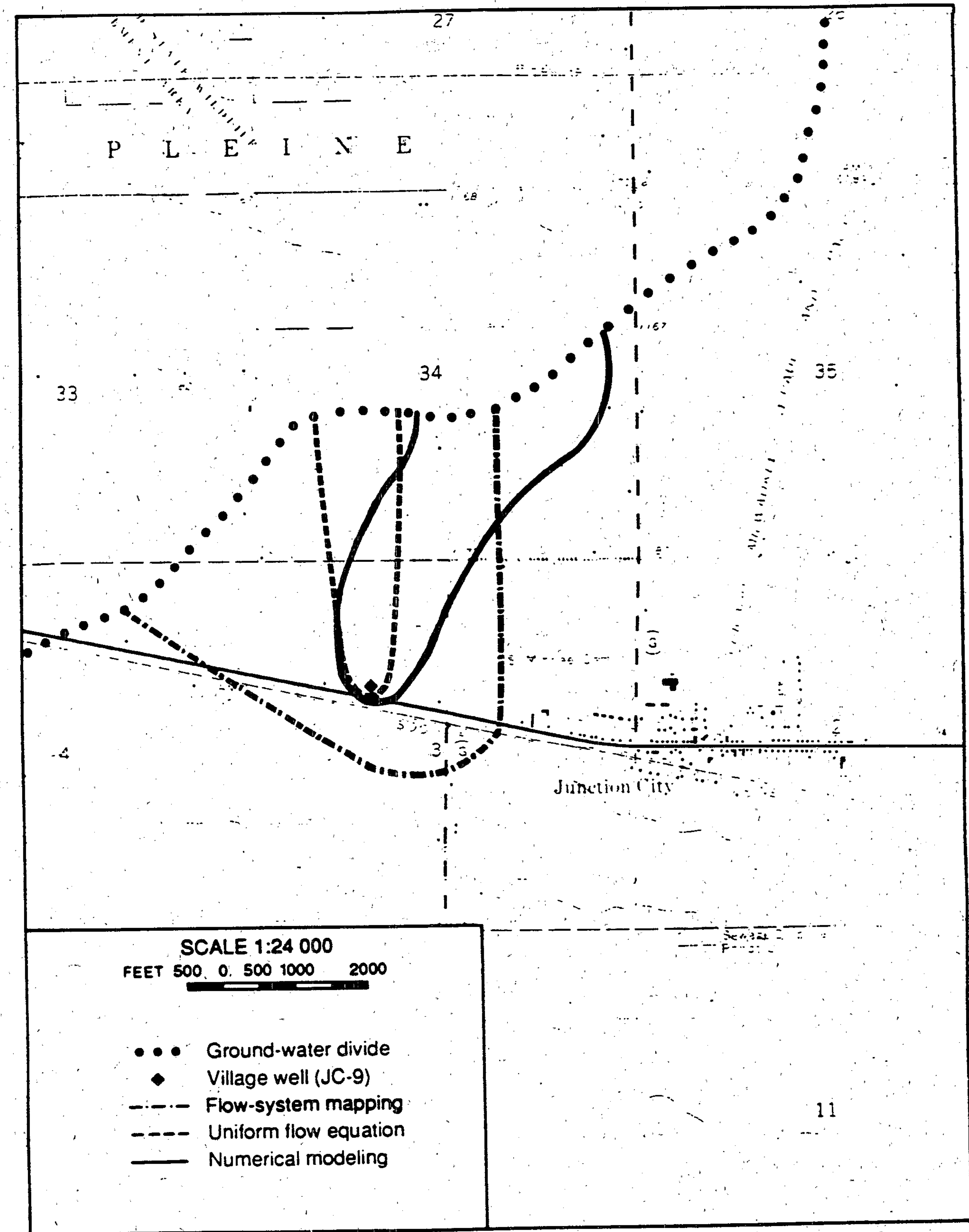


Figure 20. ZOC comparative analysis for a well in crystalline rocks.

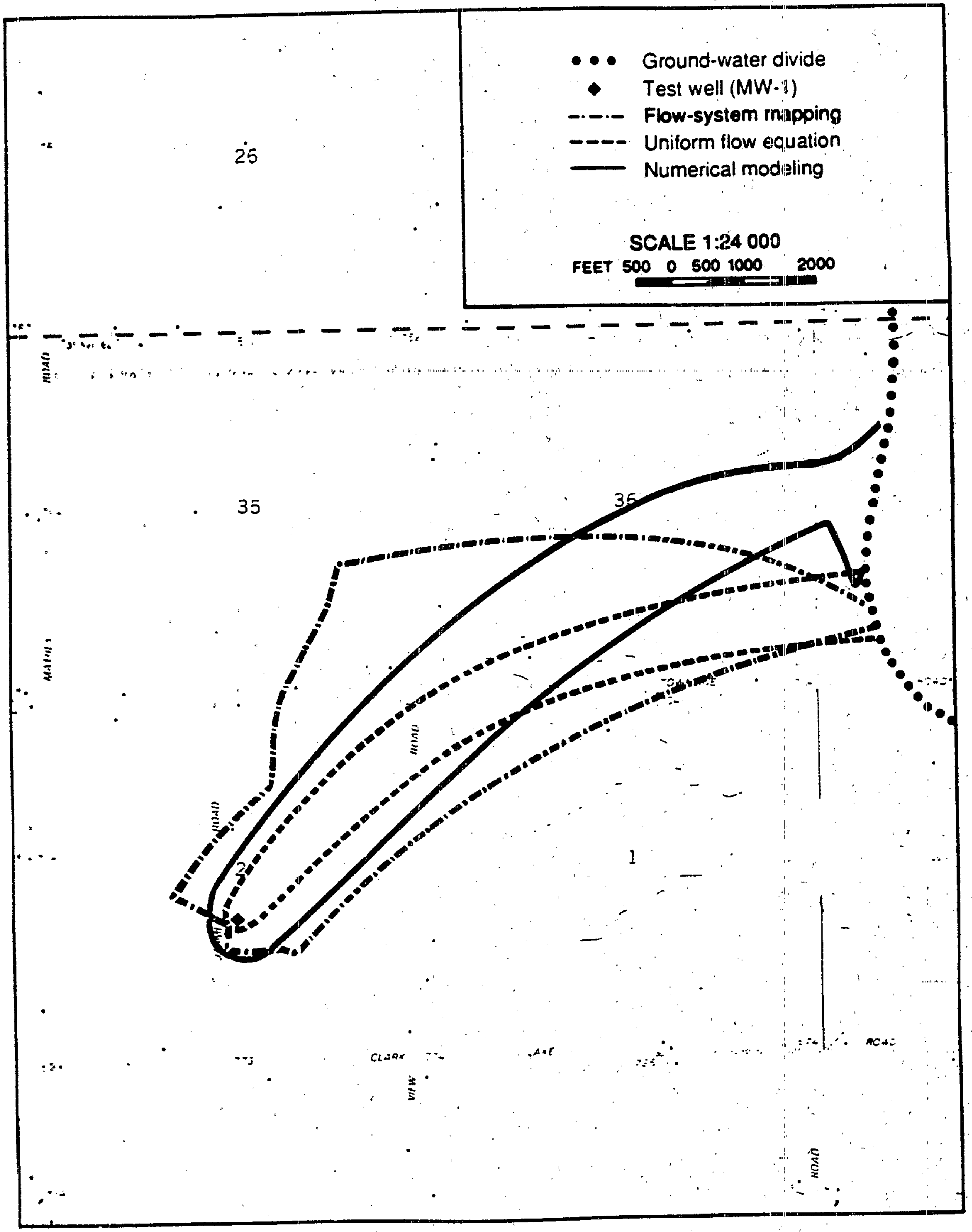


Figure 21. ZOC comparative analysis for a well in dolomite.

Flow-system mapping and flow-system mapping combined with TOT criterion.--At both sites, flow-system mapping produced the largest ZOC estimates and included the majority ofthe ZOC area delineated by numerical modeling. General similarity between the flow-system mapping and the computer-modeled ZOCs is expected because the hydraulic-head distributions generated by the computer simulations are calibrated against the water-table maps. Differences between the ZOCs occur in part due to the consideration of heterogeneity and anisotropy by the modeling method but also due to less than perfect model calibration. Flow-system mapping therefore might offer the most protection for the least cost. In general, the amount of field work involved in flow-system mapping depends on how many water-table measuring points exist in the well vicinity. If no additional wells are needed, the only field work required is measuring water levels in existing wells and surveying the elevations of those wells. Using data from existing well logs saves substantial amounts of time and should suffice outside the area immediately surrounding the production well.

The flow-system mapping approach is especially useful when the ground-water flow boundaries are close to the well. In the case of the Junction City well, the ground-water divide is only about 1 mile away. At the Sevastopol site, the shallow system ground-water divide is only about 1000 ft from the well; the deep system ground-water divide is about 1.5 miles from the well. In cases where ground-water flow boundaries are farther from the well, the resulting ZOC can be extremely large and the TOT criterion can be used to limit the WHPA to that portion of the ZOC that will contribute water to the well within a specified length of time.

Using various estimates of hydraulic conductivity at the Junction City site resulted in different TOT estimates. The most accurate method for measuring hydraulic conductivity (the pumping test) resulted in the shortest TOT estimates (fig. 10). These TOT estimates suggest that the whole ZOC be used as the WHPA unless dealing with contaminants that degrade to non-toxic levels in less than 5 years. It should be noted, however, that the ZOC and TOT estimates from this estimate differ from those calculated by the numerical modeling. The computer-delineated ZOC was smaller and extended farther east than the water-table map ZOC (fig. 20). The difference in TOTs occurred in part because the computer model simulates flow paths in three dimensions and accounts for flow paths through deeper zones of varying hydraulic conductivity.

At the Sevastopol site, the flow-system mapping approach was more complicated due to the existence of shallow and deep ground-water systems, but the results were more compatible with the results of numerical modeling than at the Junction City site. At the Sevastopol site, the flow-system mapping ZOC is slightly larger than the computer-delineated ZOC (fig. 21) and only a small area of the computer-delineated ZOC is not included in the flow-system mapping ZOC. The TOT estimates based on the potentiometric-surface map (fig. 12) were much longer (100 years compared to 1 year) than those predicted by numerical modeling (fig. 19). The modeling TOTs were short because the model accounted for a very thin but very conductive zone about 180 ft below the land surface.

Disadvantages of using the flow-system mapping method in fractured-rock settings are that the method does not account for three-dimensional flow and for the heterogeneity and anisotropy inherent in many fractured-aquifer systems. At the Junction City site, the hydraulic conductivity decreases dramatically with depth as the number of water-transmitting fractures diminishes. At the Sevastopol site, a highly fractured conductive zone dramatically reduces travel times.

Flow-system mapping with analytical equations.--Applying the uniform flow equations after a water-table map is constructed requires little additional time or cost and provides a good analytical basis for ZOC delineation. It is recommended that the uniform flow equations be added to any ZOC delineation made from flow-system mapping. The two methods used in tandem can serve as checks on one another's accuracy. The uniform flow equation ZOCs, calculated with the hydraulic conductivities measured during the pumping tests, were the smallest of the three ZOCs compared in figures 20 and 21. At the Junction City site, the size of the cone of depression of the village well (fig. 10) indicates that the uniform flow equation ZOC (fig. 20) is probably too small to adequately protect the village water supply. At the Sevastopol site, the ZOC delineated with the uniform flow equation corresponds closely with the flow-system mapping and the numerical modeling ZOCs, but it is still the smallest (fig. 21).

Residence-time approach.--The residence-time approach by itself does not delineate a ZOC and is therefore only useful when used in combination with one of the other approaches. It serves as a useful check on the TOTs estimated by the other methods because TOTs based on the residence-time approach do not depend on measurements of aquifer parameters. Because it requires no assumptions about the aquifer, it is useful in providing TOTs for the flow-system mapping method and can be used in conjunction with this method for WHPA delineation. It is also useful in verifying modeling results and in model calibration.

The residence-time approach will be helpful in settings where the fractured-rock aquifer does not behave as a porous medium. In some areas, the pattern of fracture conduits is so complex that delineation of individual conduits will not be possible, and ground-water flow paths will be unpredictable. In such settings, isotopic and geochemical information can be useful for delineating ground-water ages, travel times to the well, and recharge areas. Occasionally, isotopic data will show that water reaching the well to be protected is hundreds or thousands of years old. In such situations, wellhead protection practices might not be practical because the ZOC for the well could be extremely large and the effect of wellhead protection practices would not be seen for hundreds of years. In other areas, the residence-time approach might indicate particular bedrock types or areas of the landscape most likely to contribute water to the well.

Numerical modeling.--Numerical modeling requires substantially more time and expertise than the other methods considered (table 5), but it produces smaller, more accurate ZOCs. Being able to delineate a smaller area might be very important in some settings. The amount of effort and resources required might also be justified where there is need for a high degree of accuracy. In areas where the ground-water flow system and hydrologic boundaries are complex, numerical models might provide a significant improvement over other methods. Although numerical models are based on analytical equations that assume a uniform porous medium, they can take into account heterogeneities and anisotropy that are frequently inherent in a fractured-rock aquifer. The magnitude of improvement that numerical modeling brings to ZOC delineation will vary from site to site. Greatest improvement will occur at more complex sites. The following site characteristics may justify the added expense and time required for numerical modeling:

1) significant discrete fractures or fracture zones,
2) significant anisotropy,
3) significant spatial variations in various hydrogeologic parameters (T, K, recharge, etc.),
4) significant vertical movement of water and/or significant variation in total hydraulic head with depth,
5) significant changes in water levels seasonally or through time.

Numerical modeling is potentially the most accurate WHPA delineation method even in settings that do not behave as porous media. Although most widely available numerical codes are based on porous-media physics, these codes can often simulate flow in fracture conduits and can capture the spatial variability and anisotropy often present in fractured-rock aquifers. For example, the numerical model of the Sevastopol site (Appendix B) adequately simulates a highly conductive horizontal fracture zone and shows that this zone has a significant influence on ground-water movement toward the well to be protected.

At the Junction City site, the numerical model produced a ZOC that is smaller than the flow-system mapping ZOC (fig. 20). Increased precision of the numerical model method, due to inclusion of heterogeneities and anisotropy, probably accounts for the difference, although the lack of perfect model calibration may also play a role. Part of the computer-delineated ZOC extends beyond the eastern boundary of the flow-system mapping ZOC. This area might be the result of a less-than perfect model calibration at the site. Using the ZOC delineation as the sole criterion, the logical conclusion would be that the modeling produced only marginal improvement considering the time requirements and complexity of the task. However, the TOT lines resulting from the particle-tracking program (fig. 18) were substantially different from those resulting from the flow-system mapping approach (fig. 10). Whereas modeling predicted that water moving from the ground-water divide to the village well might take 50 to 100 years, the mapping approach predicted a TOT of less than 13 years. The order-of-magnitude difference occurred mostly because the model considers a three-dimensional path through a nonhomogeneous system; the other methods assume a homogeneous, two-dimensional system.

The hydrogeologic setting at the Sevastopol site was somewhat more complex than at the Junction City site. The existence of a shallow and a deep ground-water system and the existence of a thin, highly conductive fractured layer make this site a much more likely candidate for numerical modeling. The TOTs predicted with numerical modeling (fig. 19) were quite different from those calculated using the potentiometric-surface map (fig. 12). The numerical modeling ZOC, however, was only somewhat smaller than the ZOC predicted with the flow-system mapping method (fig. 21).

In some cases, numerical models may produce ZOCs significantly different from those produced by flow-system mapping. These differences are usually due to details of anisotropy, heterogeneity, and a three-dimensional system that are included in the model but not included in the simpler flow-system mapping method. In such cases, the model-produced ZOC is more reliable. In general, numerical modeling will be required when the aquifer is extremely anisotropic or heterogeneous, or when the aquifer exhibits significant changes in hydraulic head over short periods of time.

Conclusions

At the Junction City site and the Sevastopol site, methods less sophisticated than flow-system mapping clearly did not encompass enough of the site characteristics to result in an accurate ZOC determination. The flow-system mapping approach was sufficient for conservative (more protective) estimates of the ZOC. With the adequate field data obtained from the piezometers and existing wells, numerical modeling was not warranted for ZOC delineation but contributed more accurate TOT estimates. At both sites, the TOT estimates were more sensitive to the various delineation methods than was the ZOC delineation itself. When possible, the entire ZOC should be used as a WHPA. However, in some situations the resulting ZOC will be extremely large and in these cases the TOT criterion may be used to limit the size of the WHPA if implementation concerns arise.

At each of the two test sites in Wisconsin, the fractured-rock aquifers behaved as porous media at the wellhead protection scale. For a fractured-rock aquifer that does not act as a porous medium, WHPA delineation may be accomplished by a combination of vulnerability mapping, hydrogeologic mapping, the residence-time approach, tracer tests, or numerical modeling. Flow in such aquifers can occur mainly through discrete fracture conduits. It is particularly important to identify areas where such conduits intersect either the land surface or the production well because such conduits can offer direct and rapid pathways for contamination to travel from the land surface to the well.

Chapter IV

IMPLEMENTATION POSSIBILITIES

Applicability and Usefulness of Selected Methods

The study of two fractured-rock settings in Wisconsin demonstrated that the standard ground-water flow equations and field techniques developed for porous media can be used for the delineation of WHPAs in fractured rocks, provided the observed vertical and horizontal fractures are numerous and the scale of fracturing is much smaller than the scale of the wellhead protection area. For example, for the porous-media equivalent to be applicable, the minimum dimension of a WHPA should be at least 100 times the average spacing between fractures. In addition, other criteria should document that fractured rock approximates a porous medium, such as the response to pumping tests, configuration of the water table, log-normal distribution of hydraulic conductivity, and no dramatic fluctuations of water levels or water chemistry.

The evaluation of methods analyzed for possible delineation of WHPAs in fractured rocks indicated that flow-system mapping (in combination with the TOT criterion or uniform flow equation) and numerical modeling are the most accurate methods under such conditions. The residence-time approach can be used to verify the ZOCs and TOTs determined by these methods. The flow-system mapping method offered the most accuracy for the least cost. In general, the cost of this method will depend on the number of existing wells available for measuring water-table elevations in the area of study. If additional wells need to be drilled, costs may be high. Applying the uniform flow equations after a water-table map is constructed requires little additional time or cost and improves the results gained by mapping alone.

The residence-time approach using isotope and water-chemistry analyses provides information on recharge areas and ground-water flow paths. It does not define a specific ZOC for a well but it can verify ZOCs and TOTs determined by other methods. The relatively good agreement between TOT estimates using analytical methods and TOT estimates using the residence-time approach shows that the porous-media methods were adequate for WHPA delineation at the two test sites in Wisconsin.

Numerical modeling requires substantially more time and expertise than the other methods considered, but it offers the highest degree of accuracy. At both test sites, the ZOCs resulting from the modeling were generally smaller and not much different than the ZOCs resulting from flow-system mapping, but the TOTs differed significantly. Numerical modeling provided increased precision and an accurate, three-dimensional picture of ground-water flow patterns, which may justify the increased costs in more complex situations.

The evaluation of WHPA delineation methods addressed the question of the degree of technical sophistication necessary for WHPA delineation in fractured rocks. The least sophisticated and least expensive, fixed radii methods are clearly inadequate for accurately delineating WHPAs and would generally be considered primarily as a first step in a wellhead protection program. On the other hand, the most sophisticated and also the most expensive method, the computer-based numerical model, cannot eliminate all uncertainties, and the improved accuracy in WHPA boundaries may be minimal in some settings. In addition, numerical modeling is generally beyond the means of local governments. Therefore, the best methods for a wellhead protection program in fractured rocks are fairly simple approaches producing reasonable results, such as the flow-system mapping method and the residence-time approach.

The limitation of this study is that the selected methods were tested only in one type of fractured-rock environment--aquifers with closely spaced fractures, the geological condition found at both test sites. The fractured crystalline aquifer consisted of 35 ft of extensively weathered rock underlain by 90 ft of competent rock with vertical fractures spaced every 0.5 to 2 ft. In the fractured dolomite, horizontal fractures occurred on the order of every 1 to 10 ft and prominent vertical fractures were spaced approximately 10 to 20 ft apart. Under these conditions, the fractured rocks behaved as uniform, porous media at the scale of field tests. In general, the size of most ZOCs would be large enough that the porous-media approach may be adequate for WHPA delineation in many areas.

For fractured rocks that do not behave as porous media, the following techniques and methods may be applicable:

1) hydrogeologic mapping;
2) mapping of areas vulnerable to contamination, in combination with arbitrary fixed radius or a simplified variable shape;
3) residence-time approach; and
4) numerical flow/transport models.

Management Strategies for WHPAs

Even though management implications of WHPA delineation were not in the scope of this study, it seems appropriate to at least mention the main problems communities may face in delineating WHPAs and give references to publications that can help communities select appropriate management tools and strategies. These very questions were the ones most often asked at public meetings conducted during the study at the two sites.

The ZOC determined by hydrogeologic analysis can be used as the basis for the areal delineation of a WHPA, in which potentially contaminating uses and practices are limited and protection measures implemented. Ideally, the area within the WHPA would include the entire ZOC--all of the ground-water flow system that contributes to a well or wellfield. However, no matter how important hydrogeologic factors are in delineating WHPAs, other non-hydrogeologic concerns can influence--and in some cases determine--the establishment and ultimate configuration of the final WHPA. In reality, WHPA boundaries may have to relate to political and administrative boundaries and physical factors, as well as hydrogeologic factors. This means "squaring up" the WHPA boundaries using a large-scale topographic map or aerial photographs so that the WHPA follows boundaries that can be easily traced on the ground (roads, water bodies, fence lines, and similar features). Political boundaries were considered by local officials at the public meetings as a major threat for implementing WHPAs because difficulties may arise if the WHPA crosses two or more governmental units.

The establishment of WHPAs generally will be a compromise between the desirable and the feasible--a compromise between the socioeconomic and public health interest. WHPA regulations could have adverse economic effects on a community if an undue amount of land were placed into a wellhead protection district. On the other hand, if the delineated area is too small, under-protection may occur. This dilemma is difficult to solve, and requires patient negotiations between the opponents. Even in Europe, where wellhead protection has been practiced for more than 15 years, this problem remains to be solved. European countries use this general "rule" for determining the extent of wellhead protection districts: "on economic and planning grounds the protection zones must be as small as possible, while on public health grounds they should be as large as possible" (Headworth, 1986).

Once a community decides to implement a wellhead protection program, they must decide which management techniques will be effective. Techniques that can be used in local programs can be categorized as regulatory and nonregulatory, although in practice, most programs are a mix of these (Born and others, 1987).

Regulatory approaches involve placing a system of legal constraints on land uses or on particular activities that have a potential to contaminate the ground water. The delineation of a WHPA does not take place in a vacuum. Every state has a number of regulatory and management programs intended to control potential contaminating activities and sources of contamination; these can be used for implementing protection measures within the WHPA. Therefore, wellhead protection programs always should be considered in the context of existing state or local ground-water management programs.

In addition to regulatory tools, there are numerous nonregulatory tools that can complement regulations and government efforts to curb ground-water contamination. Nonregulatory approaches include activities such as public education, voluntary best management practices (BMPs), governmental coordination, inspection and training programs, emergency spill response plans, and monitoring to identify water-quality problems.

Some of the regulatory and nonregulatory tools are summarized in table 6. More details on the listed tools and other examples can be found in Born and others (1987), Jackson and others (1987), U.S. Environmental Protection Agency (1989), Yanggen and Amrhein (1989), and Zaporozec (1985).

Table 6. Potential management tools for wellhead protection (source; Born and others, 1987; U.S. EPA, 1989).

Regulatory	Nonregulatory
Zoning Ordinances. Zoning ordinances typically are comprehensive land-use requirements designed to direct the development of an area. Many local governments have used zoning to restrict or regulate certain land uses within wellhead protection areas.	**Purchase of Property or Development Rights.** The purchase of property or development rights is a tool used by some localities to ensure complete control of land uses in or surrounding a wellhead area. This tool may be preferable if regulatory restrictions on land use are not politically feasible and the land purchase is affordable.
Subdivision Ordinances. Subdivision ordinances are applied to land that is divided into two or more subunits for sale or development. Local governments use this tool to protect wellhead areas in which ongoing development is causing contamination.	**Public Education.** Public education often consists of brochures, pamphlets, or seminars designed to present wellhead area problems and protection efforts to the public in an understandable fashion. This tool promotes the use of voluntary protection efforts and builds public support for a community protection program.
Site Plan Review. Site plan reviews are regulations requiring developers to submit for approval plans for development occurring within a given area. This tool ensures compliance with regulations or other requirements made within a wellhead protection area.	**Waste Reduction.** Residential hazardous waste management programs can be designed to reduce the quantity of household hazardous waste being disposed of improperly. This program has been used in localities where municipal landfills potentially threaten ground water due to improper household waste disposal in the wellhead area.
Design Standards. Design standards typically are regulations that apply to the design and construction of buildings or structures. This tool can be used to ensure that new buildings or structures placed within a wellhead protection area are designed so as not to pose a threat to the water supply.	**Best Management Practices.** BMPs are voluntary actions that have a long tradition of being used, especially in agriculture. Technical assistance for farmers wishing to apply them is available from local Extension and SCS offices.
Operating Standards. Operating standards are regulations that apply to ongoing land-use activities to promote safety or environmental protection. Such standards can minimize the threat to the wellhead area from ongoing activities such as the application of agricultural chemicals or the storage and use of hazardous substances.	**Training and Demonstration.** These programs can complement many regulations. For example training underground storage tank inspectors and local emergency response teams or demonstration of agricultural BMPs.
Source Prohibitions. Source prohibitions are regulations that prohibit the presence or use of chemicals or hazardous activities within a given area. Local governments can use restrictions on the storage or handling of large quantities of hazardous materials within a wellhead protection area.	**Ground-Water Monitoring.** Ground-water monitoring generally consists of sinking a series of test wells and developing an ongoing water quality testing program. This tool provides for monitoring the quality of the ground-water supply or the movement of a contaminant plume.
Inspection and Testing. Local governments can use their statutory home rule power to require more stringent control of contamination sources within wellhead protection areas than given in federal or state rules.	**Contingency Planning.** Local governments can develop their own contingency plans for emergency response to spills and for alternative water supply in case of contamination of the existing supply.

Transferability of Results
(by William J. McCabe, U.S. EPA)

Introduction

The WHPA delineation methods tested in Wisconsin can be applied to similar settings elsewhere in the United States. Unconfined crystalline-rock and carbonate-rock aquifers are common throughout much of the United States. This section identifies the approximate geographic location and extent of the significant unconfined fractured-rock aquifer areas in the United States and its possessions. The text and figures 22 and 23 give a general indication of where the techniques discussed in this document may be applicable. Because this document was based on field work performed in shallow aquifers, application of the recommended techniques may not be appropriate for all fractured-rock aquifers at greater depth (more than about 300 ft below land surface) (table 7).

Furthermore, the techniques have not been tested in fractured sandstones, in karst, and in cavernous volcanic settings; they probably will not be applicable in such settings.

Acknowledgments

The author thanks the numerous scientists who orally provided information for this section. Any errors, or misinterpretations that appear here, however, are those of the author. The scientists contacted during the preparation of this section were from the U.S. Geological Survey (USGS) District Offices and Environmental Protection Agency (EPA) Regional Offices. The USGS scientists are Charles Avery, Allen Bewsher, Stephen Blumer, David Brown, Robert Buchmiller, Marvin Crist, Dan Davis, Jeffrey Deroche, Patrick Emmons, Robert Faust, Ector Gann, Joseph Gates, Michael Gaydos, Roy Glass, Robert Graves, Theodor Greemen, James Harrill, John Havens, John Helgesen, Jeff Imes, Patrick Hollyday, Kenneth Hollett, William Horak, Ivan James, Ron Kobel, James Krohelski, Larry Land, Robert MacNish, Angel Martin, John Miller, Joseph Moreland, Kathy Peter, John Powell, Stanley Robson, Michael Shulters, Jeffrey Stoner, Donald Vaupel, John Vecchioli, Richard Whitehead, John Williams, and Allen Zack. The EPA scientists are Kenneth Wenz and Mike Wireman.

Mapping Criteria

On the basis of geologic characteristics, the area of the United States and its possessions was classified into three categories: 1) unconfined, fractured, nonvolcanic aquifer areas; 2) unconfined, fractured, volcanic aquifer areas; and 3) other. The techniques described in this document are applicable in most of category 1 and 2. In category 1, techniques may not be

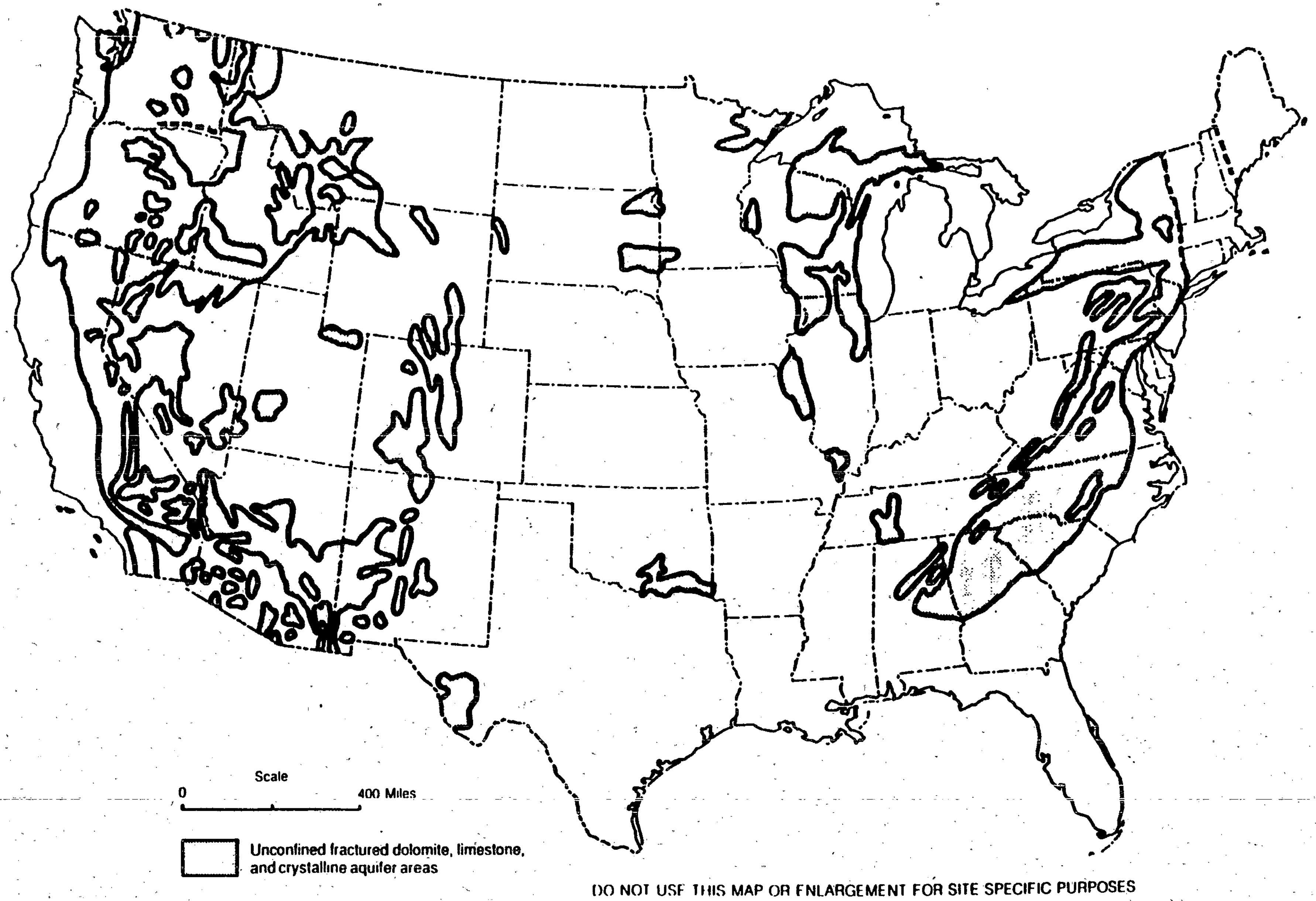


Figure 22. Areas of unconfined fractured rock aquifers in the contiguous United States (compiled by W.J. McCabe, U.S. EPA, 1989).

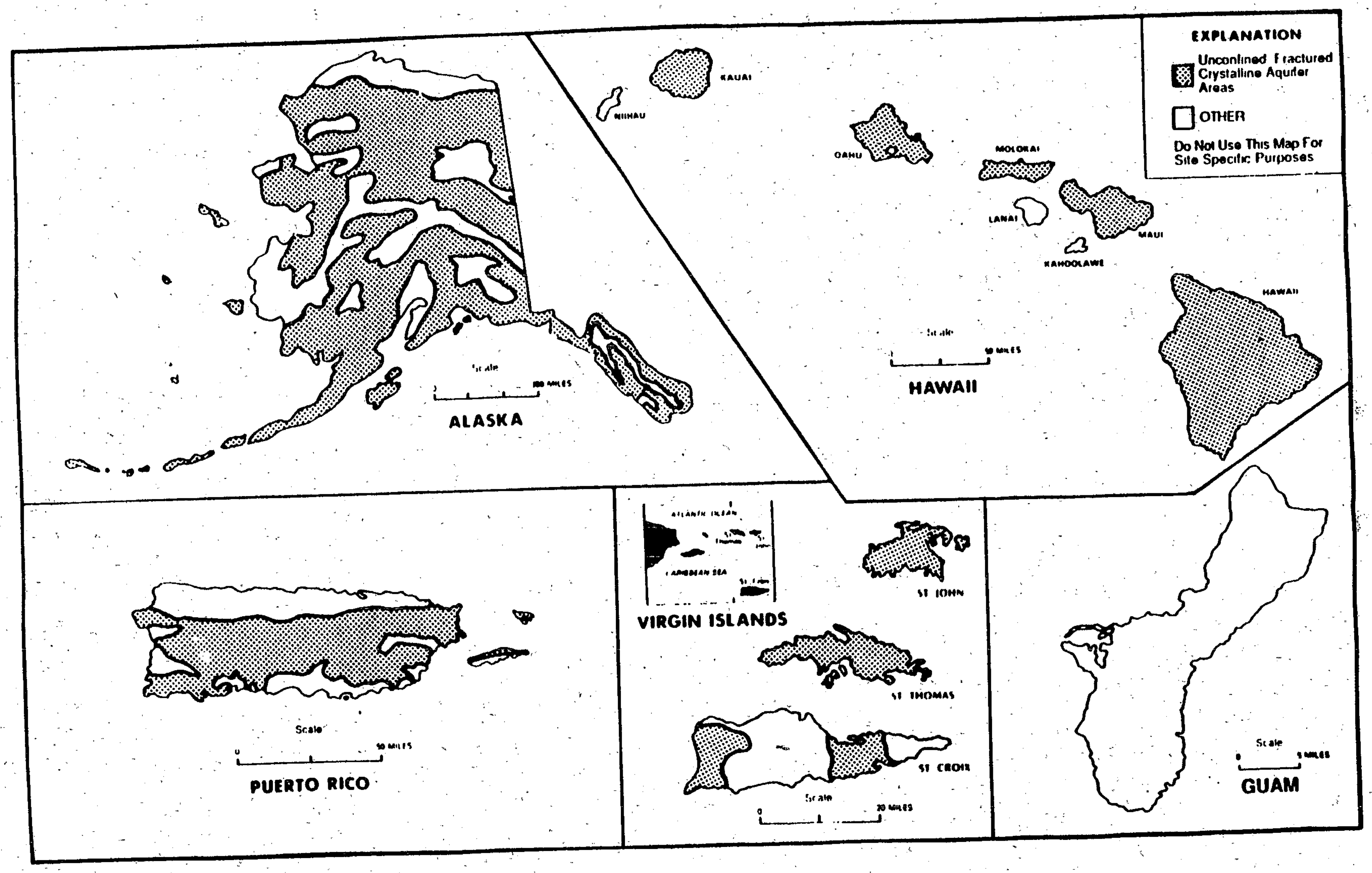


Figure 23. Areas of unconfined fractured-rock aquifers in Alaska, Hawaii, Puerto Rico, U.S. Virgin Islands, and Guam (after Moody and others, 1985).

Table 7. Common depth ranges of unconfined fractured-rock aquifers in the United States and its possessions (data from Moody and others, 1985).

State	Depth to Top of Aquifer (ft)	State	Depth to Top of Aquifer (ft)
ALABAMA	N/D	MISSOURI	N/D
ALASKA	50-500	MONTANA	100-300
ARIZONA	50-1000	NEBRASKA	N/A
ARKANSAS	N/D	NEVADA	100-1200
CALIFORNIA - volcanics	75-200	NEW HAMPSHIRE	N/A
- mountains & foothills	50-300	NEW JERSEY	35-800
COLORADO - foothills	100-250	NEW YORK	10-300
CONNECTICUT	N/A	NEW MEXICO	N/D
DELAWARE	40-100	NORTH CAROLINA	70-200
FLORIDA	N/A	NORTH DAKOTA	N/A
GEORGIA	40-600	OHIO	N/A
GUAM	N/A	OKLAHOMA - southeast	50-400
HAWAII - Hawaii	20-900	OREGON	100-600
- Kauai	100-1100	PENNSYLVANIA	75-150
- Maui	90-500	PUERTO RICO	N/D
- Oahu	30-1100	RHODE ISLAND	N/A
IDAHO	100-3000	SOUTH CAROLINA	50-300
ILLINOIS	50-500	SOUTH DAKOTA	N/D
INDIANA	N/A	TENNESSEE	50-150
IOWA	50-500	TEXAS	N/D
KANSAS	N/A	UTAH	N/D
KENTUCKY	N/A	VERMONT	N/A
LOUISIANA	N/A	VIRGINIA	50-300
MAINE	20-800	VIRGIN ISLANDS (all)	100-150
MARYLAND & DC	30-400	WASHINGTON - north	20-200
MASSACHUSETTS	N/A	- south	50-750
MICHIGAN	25-200	WEST VIRGINIA	N/D
MINNESOTA	120-1300	WISCONSIN	50-180
MISSISSIPPI	N/A	WYOMING	50-250

Explanation:
N/A = Not applicable.
N/D = Not determined.

applicable in regions of porous limestone. In category 2, techniques may not be applicable in areas of pseudokarst volcanics.

The first category, unconfined fractured-rock aquifers, typically includes igneous rocks, metamorphic rocks, sedimentary carbonate rocks, and, less frequently, shales. No areas of fractured shale aquifers were significant enough to be depicted on figures 22 or 23. Volcanic rocks of the Columbia Lava Plateau, the Western Mountain Ranges (Heath, 1984), and the Hawaiian and Caribbean islands were included in category 2 but they are not differentiated on figures 22 and 23. Basaltic volcanic flows (as are found, e.g., in the Hawaiian Islands) often exhibit vertical contraction joints, lava tubes, unconsolidated material between flows, and vesicles, with joints and fractures at the base of the flows. Such features provide high enough permeability for volcanics in these areas to be considered aquifers.

Only aquifers of drinking-, stock-, or irrigation-water quality are mapped on figures 22 and 23. Dashed lines represent an approximately located boundary. In some areas, such a boundary follows state borders because interpretations of geologic formations change at state boundaries as the result of different stratigraphic definitions being used by researchers in adjoining states, or because aquifer characteristics vary over space such that strata serving as a significant aquifer in one state may not be considered a significant aquifer in an adjoining state. It should be noted that in mountainous areas, such as the sparsely populated lands of the West and of Appalachia, no extensive water-well drilling programs, which would help better define aquifer boundaries and quality, have taken place.

Areas Where Techniques of This Document May Be Applicable

For ease of discussion, aquifers of the continental United States are grouped into four general physiographic regions (fig. 24): 1) the Atlantic Coastal Plain from Massachusetts to Florida, and the Gulf of Mexico Coastal Plain from Florida to Mexico; 2) the Appalachian Highlands from Maine to central Alabama, including the geologically similar Laurentian Uplands of the northern midcontinent states of Minnesota, Wisconsin, and Michigan; 3) the midcontinent section, consisting of the Interior Plains with mature basins and dissected plains and Interior Highlands with uplifts and folded eroded strata; and 4) the western portion of the United States, consisting of the Rocky and Pacific Mountain systems and Intermontane Plateaus and Basins (Fenneman, 1946).

Physiographic Region 1.--The geologically recent unlithified clastic and/or limestone deposits of the Atlantic and Gulf of Mexico coastal plains are unconfined but do not exhibit fracturing at shallow or moderate depths.

Physiographic Region 2.--Unconfined fractured-rock aquifers are present in northeastern Minnesota, northern Wisconsin, western Upper Peninsula of Michigan, Maine, New York, eastern Pennsylvania, northern New Jersey, Maryland, Virginia, parts of Tennessee, western North and South Carolinas, and northern Georgia and Alabama (fig. 22). The aquifers are

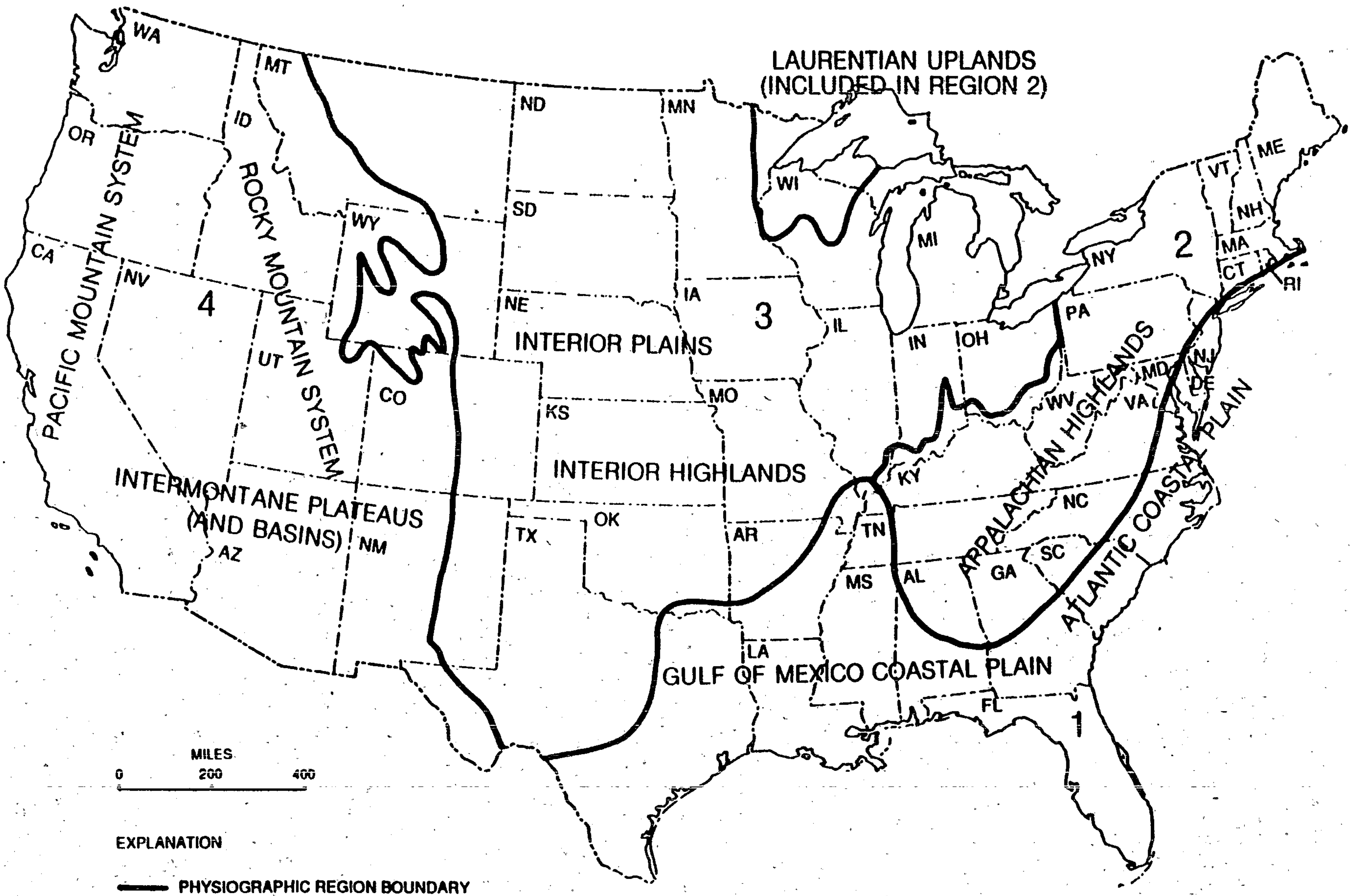


Figure 24. Major physiographic regions of the continental United States (based on Fenneman, 1946).

composed of folded, faulted, and fractured igneous and metamorphic rocks overlain by nonconfining unlithified material consisting either of glacial deposits or weathering residue. The thickness of the overburden ranges from a few feet to more than 200 ft (Heath, 1984).

Physiographic Region 3.--This area contains unconfined fractured-rock aquifers from the Upper Peninsula of Michigan through eastern and southern Wisconsin to northern Illinois and along the western border of Illinois with Iowa and Missouri (fig. 22). The Paleozoic limestone outcrop area in the Upper Peninsula of Michigan also contains, in part, unconfined fractured-rock aquifers (Moody and others, 1985).

Farther west, the domed area of the Black Hills of South Dakota contains exposed unconfined, fractured crystalline-rock aquifers (Fenneman, 1946). Other similar areas, too small to show on figure 22, occur in eastern Montana. Some of the crystalline areas of eastern South Dakota contain unconfined fractured-rock aquifers overlain by a thin regolith of nonconfining glacial material. Unconfined fractured-rock aquifer conditions may also extend into southwestern Minnesota.

In the Interior Highlands, nonconfining sediments overlie fractured, unconfined crystalline aquifers in southern and southeastern Oklahoma (Heath, 1984).

Physiographic Region 4.--Unconfined fractured-rock aquifers are found in the Front Range of the Rocky Mountain System from Idaho and Montana, through Wyoming, Colorado, and New Mexico, to southwestern Texas and in the western mountain ranges of Washington, Oregon, California, and Nevada. The unconfined fractured-rock aquifers of the Intermontane Basin area of southern California, Arizona, and New Mexico occur on the fractured crests of the block-mountain ranges and in volcanic rocks that characterize this region.

The volcanic lavas of the Columbia Lava Plateau contain alluvial valley deposits and unconfined river channel deposits. Volcanic rocks exhibit tectonic, erosional, and shrinkage fracturing and form unconfined aquifers. The lava-capped plateaus in northern California and other areas of the west are also areas of unconfined fractured-rock aquifers (Moody and others, 1985).

Alaska.--More than one half of the state contains unconfined fractured-rock aquifers and, except where permafrost conditions prevail, these aquifers provide the state with most of its municipal and domestic ground-water supplies. Four of Alaska's major cities, Anchorage, Fairbanks, Juneau, and Kodiak, obtain their drinking-water supplies from unconfined fractured-schist aquifers. These unconfined metamorphic bedrock aquifers are found over all the upland areas of Alaska (fig. 23).

Hawaii.--The four major islands of the state of Hawaii--Kauai, Oahu, Maui, and the big island of Hawaii (fig. 23)--are tops of shield volcanoes. Except where coastal sediments have been deposited, ground water is produced from unconfined fractured-lava aquifers. In some areas, lava contains tubes and crevasses, which were created at the time of lava deposition.

Such areas contain large volumes of ground water and, with respect to the storage and flow of ground water, are karst-like. The use of the techniques presented in this document is not appropriate in such areas.

U.S. possessions.--The indurated, fractured volcanic deposits of Puerto Rico's central core (fig. 23) serve as the island's minor aquifer (Heath, 1984). The volcanic rock aquifers are present on each of the Virgin Islands (Moody and others, 1985). On the islands of St. John and St. Thomas, the fractured lava flows serve as principal aquifers (fig. 23). On the island of St. Croix, unconfined, fractured volcanic rock aquifers occur in the western and mid-eastern sections (Moody and others, 1985). The lava flows in northern Guam have low permeability and no appreciable amounts of water (Moody and others, 1985).

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APPENDIX A

JUNCTION CITY SITE, PORTAGE COUNTY, WISCONSIN

SITE SELECTION

The first demonstration area for testing wellhead protection methods in a fractured-rock aquifer is located in central Wisconsin (see fig. 1). Crystalline rock of Precambrian age is at or near land surface throughout much of central Wisconsin. It is either exposed or covered by residual soil, a thin discontinuous layer of Pleistocene deposits, or small patches of Cambrian sandstone (Bell and Sherrill, 1974). Several communities in central Wisconsin rely on fractured Precambrian crystalline rock as their sole source of water supplies (Zaporozec and Cotter, 1985). In choosing a site for this study, we identified several municipal water supplies that were dependent on bedrock wells finished in crystalline rock. Utilizing published water-table maps (Lippelt and Hennings, 1981), we looked for a site in a simple hydrogeologic setting located near a ground-water divide. The Village of Junction City, located approximately 12 miles northwest of Stevens Point in Portage County, met these criteria. Additional advantages of this site included several existing test wells completed in the crystalline rock, which could be used in the study, as well as cooperative town officials and landowners.

INVESTIGATION METHODS

Preliminary site information was obtained from well constructors' reports on file at the Wisconsin Geological and Natural History Survey. Data from 45 existing wells were plotted on 1:24,000 topographic maps. The locations of the wells were digitized and entered into a computer database along with water-level, geologic, and specific-capacity data. Field checking identified 15 additional bedrock wells (JC9, the village well; JC10 - JC14; JC16 - JC19; JC22; and JC201 - JC204). The locations of the village well, the 14 existing bedrock wells, bedrock holes drilled as part of this study (JC23 - JC24), and well logs used to construct a geologic cross section are shown on figure A1.

Water-level measurements were taken on the 15 bedrock wells to assist in construction of a detailed water-table map. Well JC18 is an observation well included in the statewide water-level observation network under the number PT-82, for which water-level records are available from 1951. Geophysical logging was conducted on four of the existing bedrock wells (JC10, JC11, JC13, and JC14) as well as on core hole JC23 and test well JC24 (described below), which were specifically constructed for this project. Parameters measured included natural gamma radiation, resistivity, spontaneous potential, hole diameter, and temperature. A temperature log was also taken on the village well (JC9).

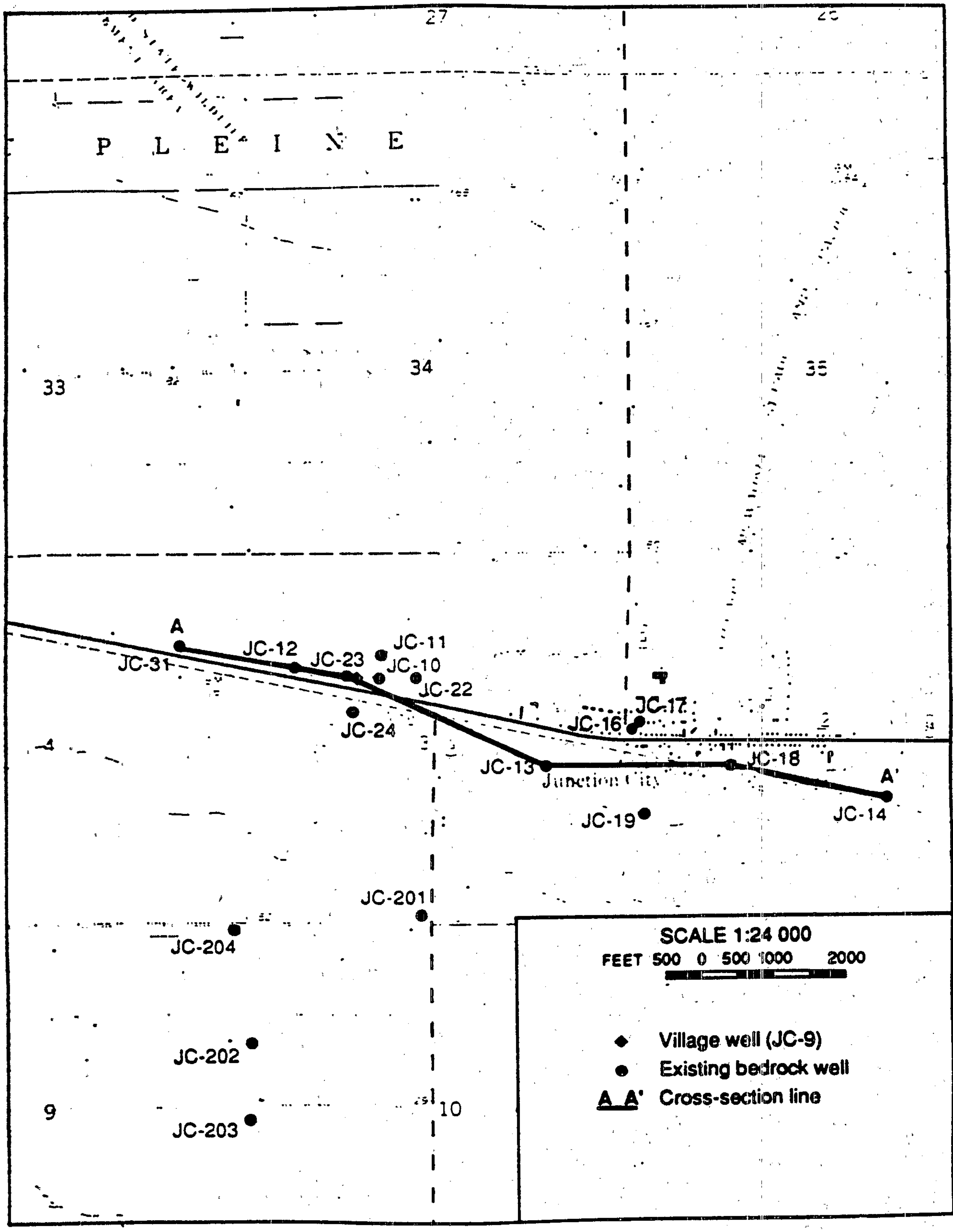


Figure A1. Location of wells in a portion of the Junction City study area, Portage County, Wisconsin.

To obtain more specific hydrogeologic data in the vicinity of the Junction City well field, eight piezometers (JC1 - JC8) were installed in the unlithified surficial deposits at six sites upgradient of the village supply well (fig. A2). Two of the sites (JC3 - JC4 and JC5 - JC6) contain vertically nested piezometers. All piezometers were installed by auger drilling, and drill cuttings were collected at 5-ft intervals. At each site, one of the boreholes was extended to the bedrock surface for accurate determination of bedrock depth. The depth of piezometers ranged from 10 to 60 ft. These piezometers were used to measure water-table elevation and vertical hydraulic gradients, to obtain water samples from the unlithified materials, and to conduct piezometer slug tests. Slug tests performed on wells JC10 - JC14, and JC22 provided estimates of bedrock hydraulic conductivity.

Two bedrock boreholes were installed near the village well. A core hole (JC23) was drilled 150 ft west of the village well to a depth of 300 ft (approximate depth of the village well) and a 100-ft observation well (JC24) was installed 440 ft south of the village well. For the core hole and the observation well, the casing was placed into the bedrock and the annular space was grouted. After installation of JC23 and JC24 natural gamma and temperature logs were run. Two piezometers were installed in the core hole (JC23A-deep, JC23B-shallow) to measure vertical hydraulic gradients within the fractured-rock aquifer.

A detailed site map (fig. A2) shows the location of the eight piezometers (JC1 - JC8), the village well (JC9), field-located bedrock test wells near the well field (JC10 - JC12, JC22), the core hole (JC23), and the bedrock observation well (JC24). Figure A2 also indicates two low-lying linear "swales" running north to south through the well field. Data on all wells and piezometers are included in table A1.

Ground-water samples were collected from ten piezometers (JC1 - JC8, JC23A, JC23B) and six wells (JC9 - JC13, JC24) in and around the Junction City well field and a surface-water sample (SW-01) was taken from the swale north of JC12 (fig. A2). These samples were tested for field parameters (temperature, specific conductance, and pH) and analyzed for major cations and anions as well as for environmental isotopes (tritium, oxygen-18).

A multi-well pumping test was performed to determine the transmissivity and specific yield of the fractured-bedrock aquifer and to study the heterogeneity and anisotropy of the aquifer. The village well was pumped for 24 hours at a rate of 74.1 gallons per minute (gpm); the water was discharged through a pipeline to the village water tower 1 mile away. Drawdowns were measured at 11 observation wells (JC1 - JC6, JC10, JC12, JC23A, JC23B, JC24) and in the pumped well (JC9).

HYDROGEOLOGIC SETTING

The clayey residuum forming the surficial deposits in the Junction City area ranges in thickness from 0 to 55 ft. On the basis of laboratory analyses of samples obtained during piezometer installation, this material contains from 0 to 15 percent gravel, 9 to 78 percent

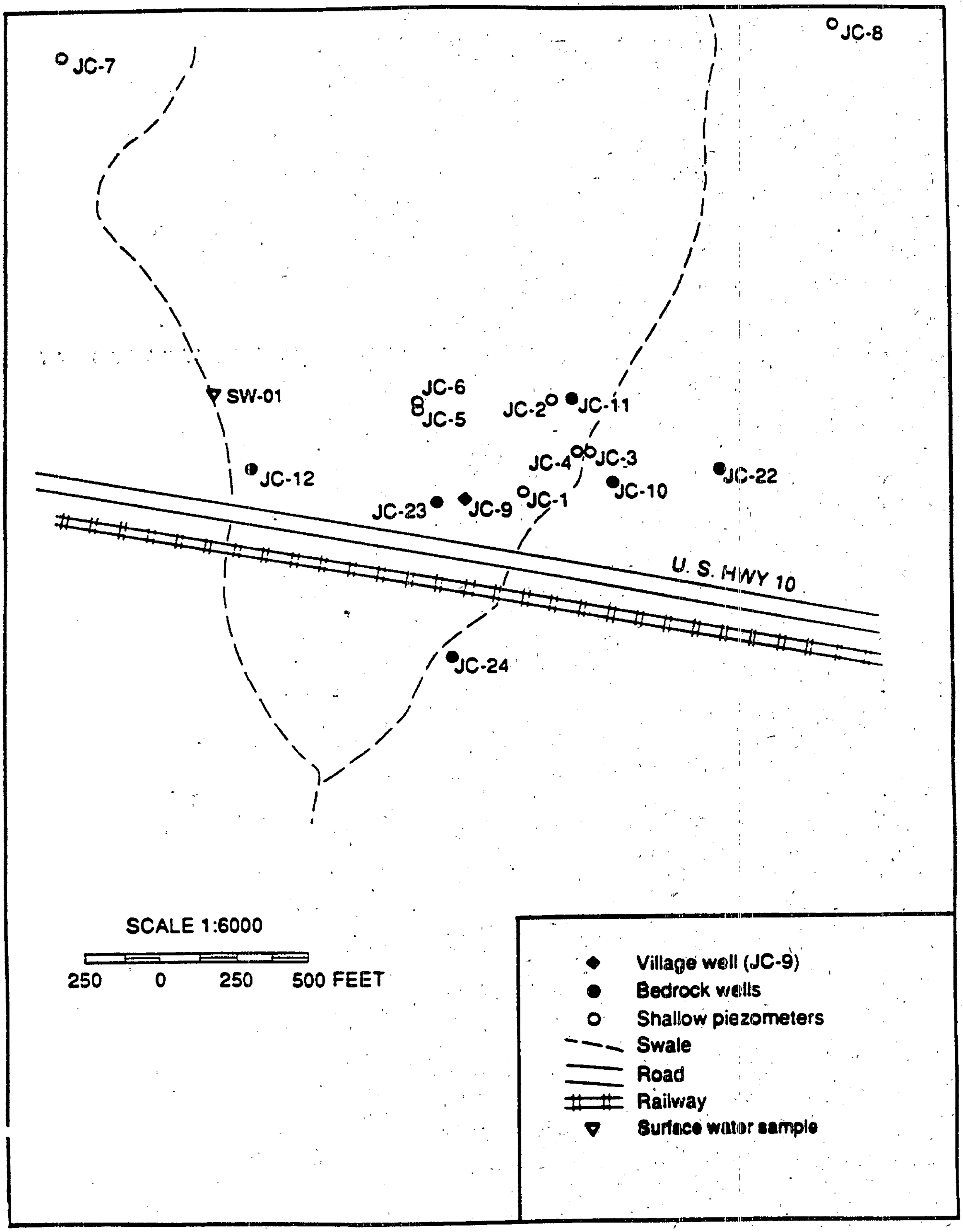


Figure A2. Location of wells and piezometers in the well field at Junction City.

Table A1. Well and piezometer data, Junction City study area, Portage County, Wisconsin.

Well No.	Well* Depth (feet below measuring point)	Open Interval (feet below measuring point)	Average Depth to Water (feet below measuring point)	Measuring Point** Elevation (feet above msl)
JC1	32	29-32	24.7	1153.5
JC2	30	27-30	23.9	1159.8
JC3	43	40-43	25.8	1154.4
JC4	30	27-30	23.7	1154.4
JC5	61	58-61	27.5	1167.9
JC6	35	32-35	28.4	1169.9
JC7	26	23-26	9.2	1172.8
JC8	18	15-18	10.6	1178.5
JC9	321	48-321	27.4	1159.4
JC10	128	18-128	21.0	1152.6
JC11	98	30-98	21.5	1157.8
JC12	143	21-143	3.7	1152.7
JC13	96	47-96	7.8	1147.5
JC14	162	30-162	7.3	1151.7
JC16	50	18-50	7.0	1149.1
JC17	130	40-130	7.5	1150.6
JC18	36	10-36	6.0	1151.0
JC19	21	10-21	4.5	1128.6
JC22	173	12-173	33.8	1164.8
JC23A	297	248-297	18.9	1151.5
JC23B	120	30-120	21.9	1151.5
JC24	100	10-100	4.9	1149.1
JC31	101	-	26.0	1183.0
JC201	-	-	24.0	1160.7
JC202	-	-	21.0	1151.2
JC203	186	-	27.9	1141.6
JC204	-	-	19.0	1151.7

* Numbers JC1 - JC8 are 1 1/4-in diameter PVC standpipe piezometers with 3-ft slotted screens. Numbers JC9 - JC204 are 6-in diameter wells cased into the bedrock and uncased below the bedrock surface.

** Measuring point elevations range from 1/2 to 3 ft above ground surface. All depths are reported relative to measuring point elevation which is measured in feet above mean sea level (msl).

\- Indicates well depth or open interval unknown.

sand, 7 to 63 percent silt, and 10 to 66 percent clay. A depth-to-bedrock map (fig. A3) was constructed with data from bedrock exposures, mineral exploration cores, well constructors' reports, and the eight piezometer boreholes installed as part of this study. The piezometer boreholes indicated that the bedrock surface is deeper or more deeply weathered below surface swales than in the areas between surface swales; resistivity surveys over the swales (Bebel, 1989) confirm this.

The bedrock geology in Portage County has been mapped by Greenberg and Brown (1986) and a detailed map of the Junction City area has been compiled by Brown for this project (see fig. 2). In the well field, the dominant lithology is a dark gray Precambrian mafic to intermediate metavolcanic rock. The rock consists of chlorite, quartz, and iron oxides. Some relict, highly weathered feldspar is visible in fresh rock at depth. Iron oxides and quartz partially fill fractures in the upper, weathered zone; calcite is the dominant fracture filling at depth. Continuous core recovered from JC23 (fig. A4) indicated that the top 35 ft of bedrock is extensively weathered and heavily fractured (shown as cross-hatches on log). The next 90 ft contained open, nearly vertical fractures spaced approximately 0.5 to 2 ft apart. Below a depth of approximately 155 ft, visible fractures were nearly absent in the core.

The presence of three distinct bedrock zones under the surficial deposits was corroborated by the natural gamma logs from JC10, JC11, JC12, JC23, and JC24. Figure A5 shows the correlation of the gamma logs for these holes. Zone 1 consists of clayey residuum and reworked hillslope deposits. Zone 2 is a highly weathered rock zone, approximately 20 to 40 ft thick. Zone 3 consists of rock with open fractures. The transition from a zone of open fractures (zone 3) to a zone with few to no fractures (zone 4) at a depth of about 165 ft is suggested by the gamma log from JC23 (fig. A5) and also by temperature logs from the village well (JC9) and JC23 (fig. A6). The temperature log for the village well indicates a change in temperature between 150 and 160 ft. (The temperature spike at 155 ft is caused by the motor of the submersible pump in this well.) The change in temperature occurs because little water enters the well below 160 ft; the zone of open fractures contributes significant amounts of water to the village well; the zone with few fractures contributes little. The temperature log of JC23 also shows a change at about 170 ft. Below this depth the borehole temperature is constant, indicating that little or no water enters the well in the lower zone.

Information from the geophysical logs was combined with data from existing well constructors' reports to generate a geologic cross section of the Junction City area (fig. A7).

RESULTS OF INVESTIGATIONS

Water-Table Mapping

A water-table map was essential for wellhead protection studies in the Junction City area. A preliminary water-table map was constructed using surface-water features and

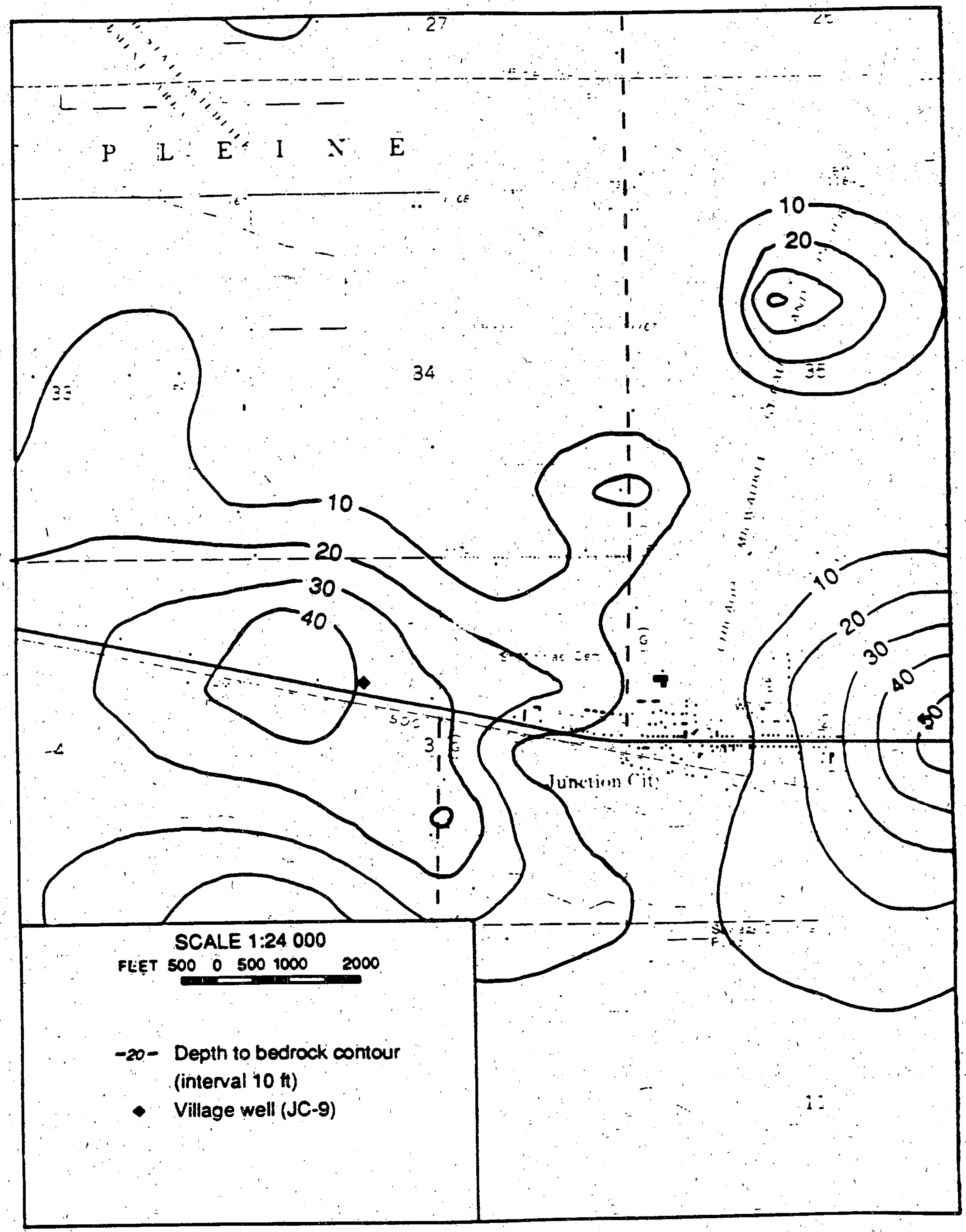


Figure A3. Depth to bedrock in the Junction City area.

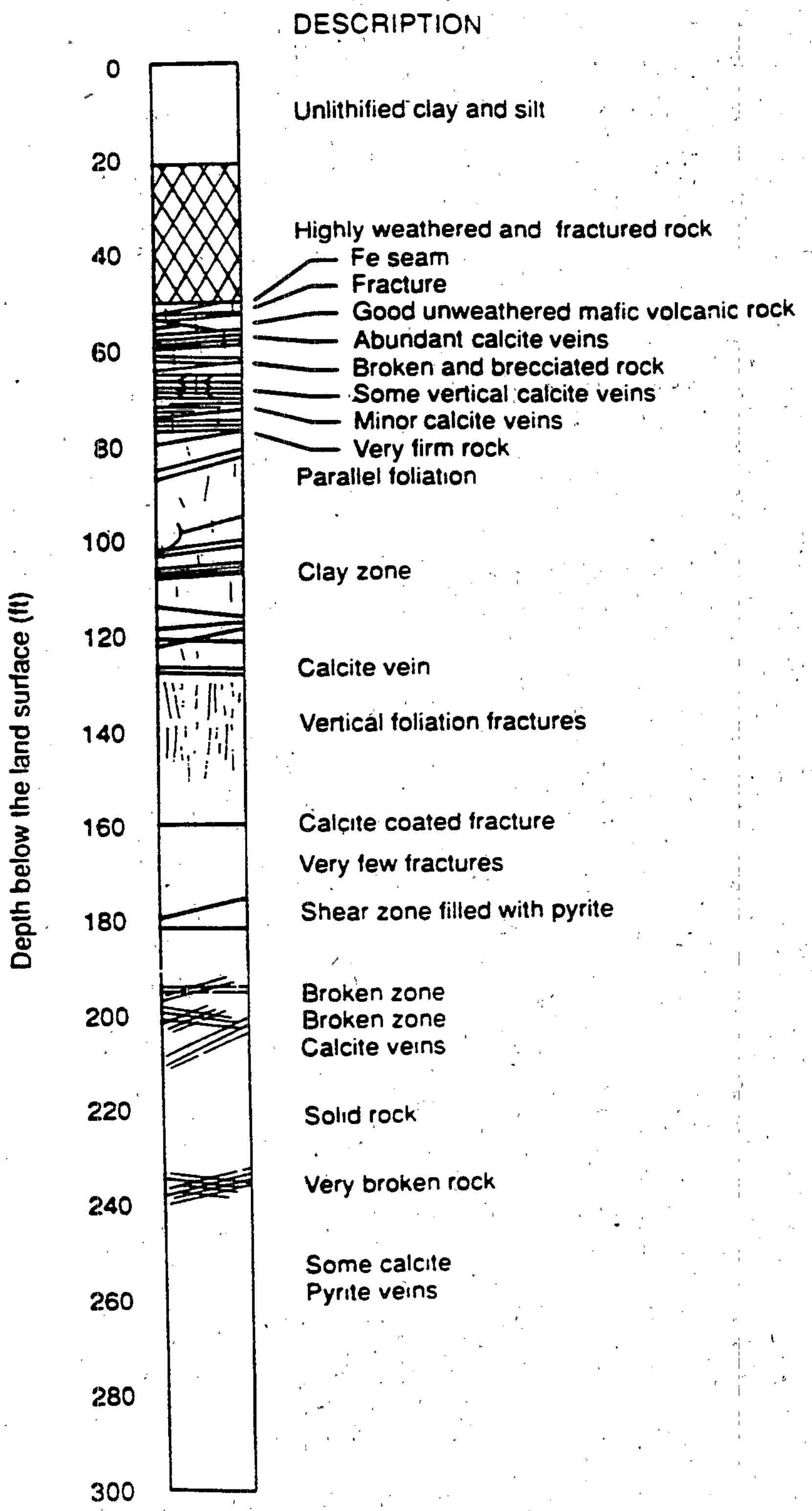


Figure A4. Geologic log for core hole JC23 at Junction City.

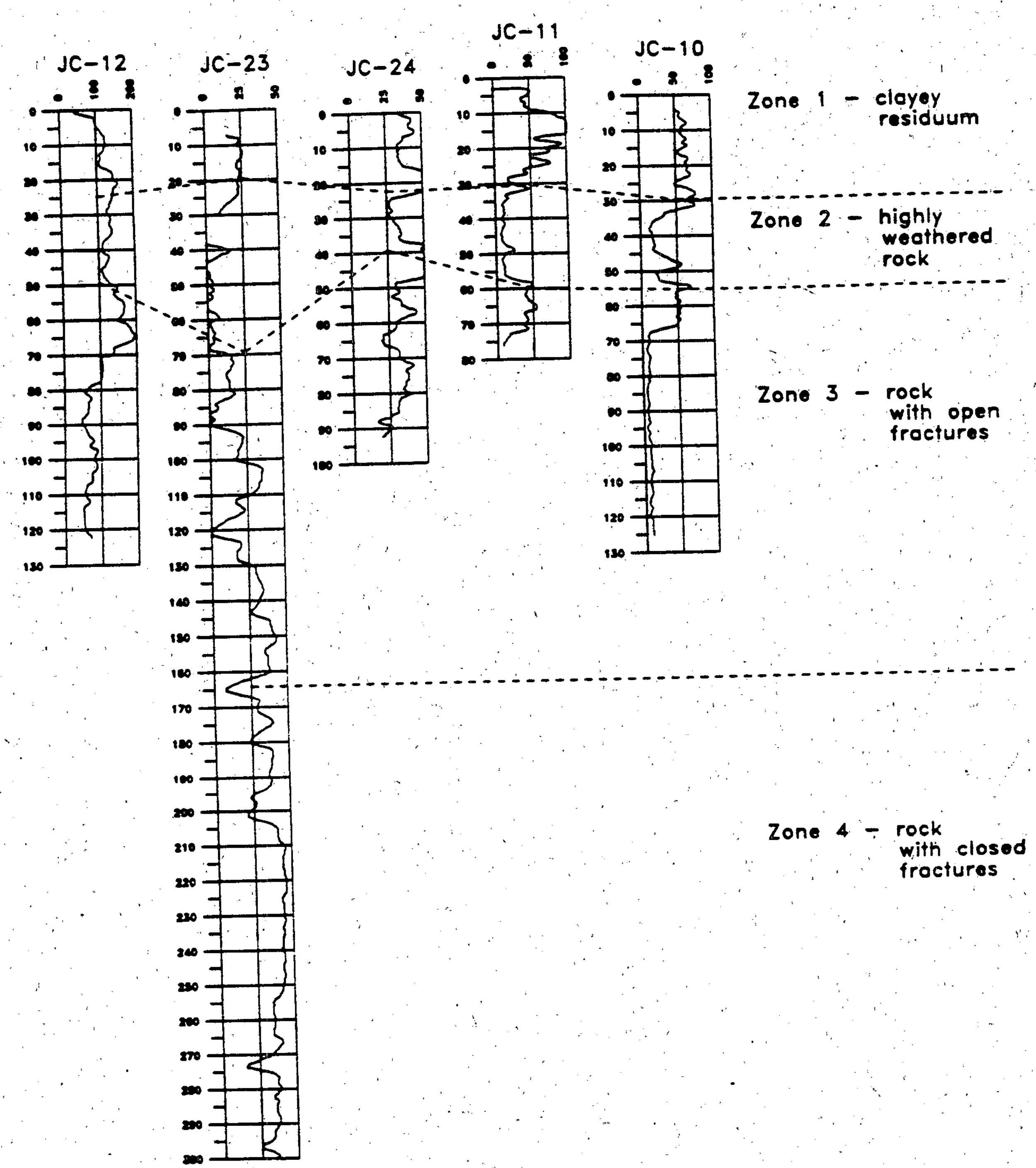


Figure A5. Correlation of natural gamma logs for wells in the Junction City area. For each log the horizontal axis is counts per second (note different scales) and the vertical axis is depth (ft from the land surface). Logs are slightly offset to correct for differing land surface elevations.

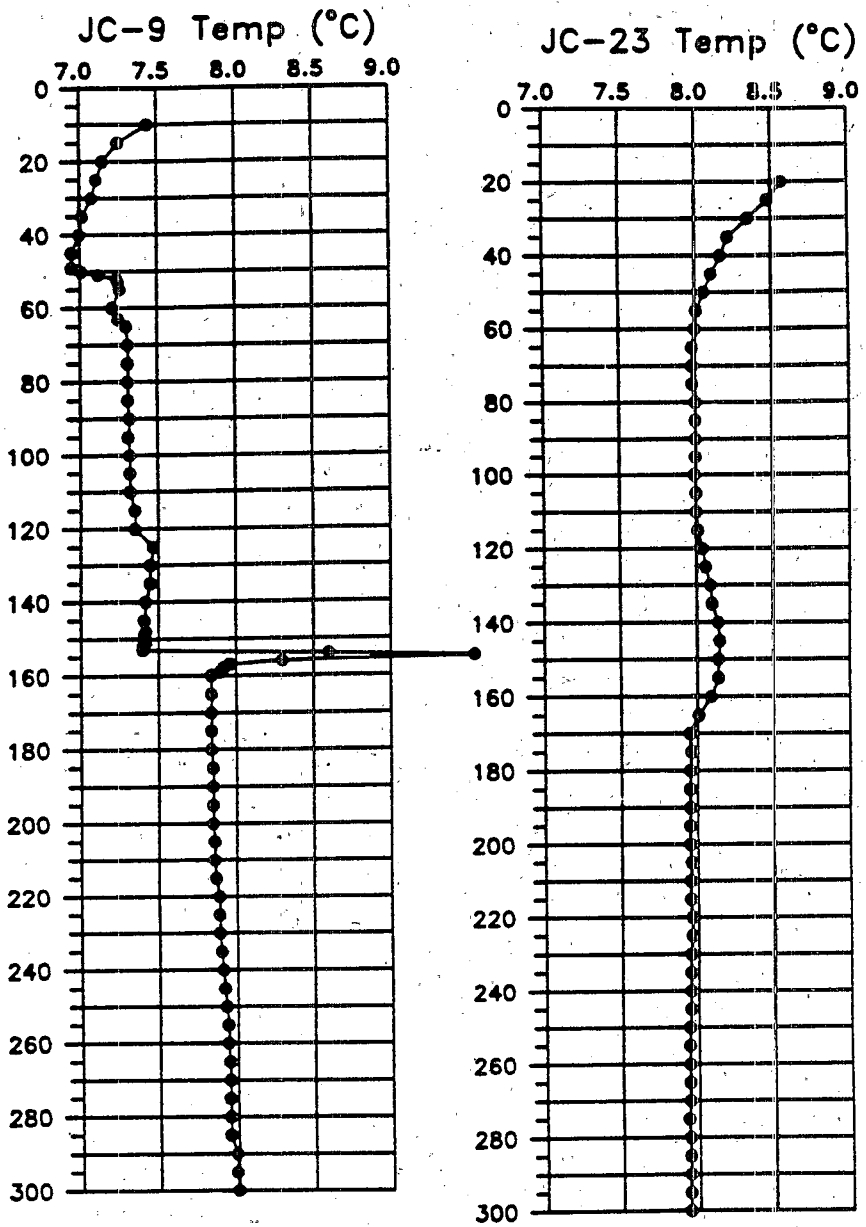
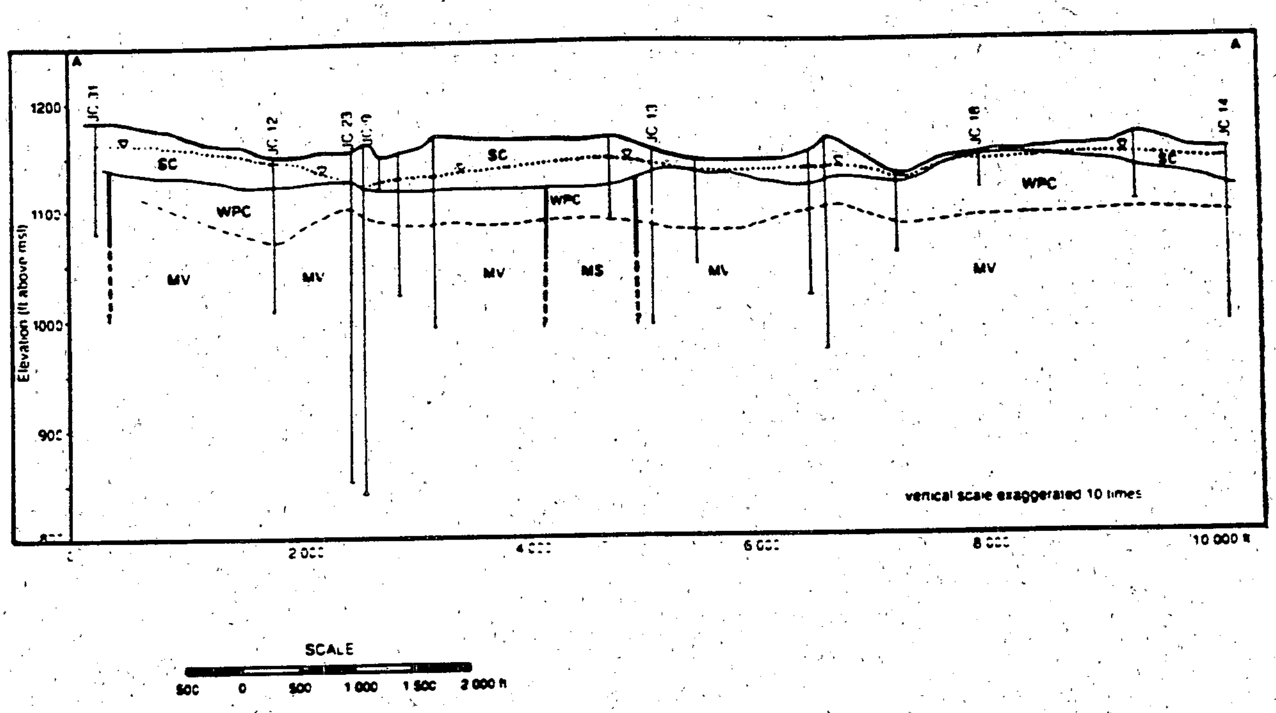


Figure A6. Temperature logs for the village well (JC9) and the nearby, deep core hole (JC23). Both logs were run while the wells were being pumped. The vertical axis is depth in ft from the land surface. Logs are slightly offset to correct for differing land surface elevations.



...∇...	Approximate water-table	
SC	Unlithified silty clay	
WPC	Weathered Precambrian	
MS	Metasedimentary rocks	Unweathered Precambrian
MV	Mafic volcanics	

Figure A7. Geologic cross section for the Junction City area.

depth-to-water data from well constructors' reports. The elevations of the surface-water features and the measuring point elevations of the wells were determined from 1:24,000 topographic maps. Due to sparse data in the vicinity of the well field, this office-derived map did not delineate a cone of depression around the village well.

The final water-table map (fig. A8) is based on the above data plus water levels from the 15 field-located bedrock (JC9, JC10 - JC14, JC16 - JC19, JC22, and JC201 - JC204) wells and the 8 piezometers (JC1 - JC8) measured in the spring of 1989. The elevations of these measuring points were determined by rod and level surveying from known benchmarks. The final water-table map depicts a clear cone of depression around the Junction City village well (hatchured contours, fig. A8).

Water-Level Measurements

Vertical Distribution of Hydraulic Head

Total hydraulic head decreases with depth in the Junction City well field, indicating that ground-water recharge occurs in the vicinity of the village well. Nested piezometers at four sites provided estimates of the vertical hydraulic gradients. Piezometer pairs JC3 and JC4, and JC5 and JC6 were finished in the unlithified surficial materials. At JC5 and JC6 hydraulic head decreased downward, with a gradient of 0.036, as calculated from water levels measured over a 6-month period. At piezometers JC3 and JC4, the gradient was 0.011 downward.

Piezometers (JC23A and JC23B) placed in the core hole indicated a relatively strong upward gradient of 0.016 between the deep portion of the bedrock and the upper zone with open fractures. Piezometer JC23A was open from 904 to 855 ft above msl (approximate depth of 250 to 300 ft below land surface) and piezometer JC23B was open from 1126.5 to 1051.5 ft above msl (approximate depth of 30 to 120 ft below land surface). The significant head difference between these two bedrock piezometers is probably due to shallow drawdown near the pumping village well.

Water-Level Fluctuations

Water levels were recorded approximately monthly in the 8 piezometers and in wells JC9 to JC13. Water levels in piezometers within the mapped cone of depression were influenced by pumping. Piezometers JC2 to JC4 exhibited fluctuations ranging from 9.6 ft for JC2, to 14.83 ft for JC3, and 13.83 ft for JC4. Wells JC10 and JC11, also located within the cone of depression, fluctuated 13.74 ft and 6.86 ft, respectively. The wells and piezometers outside the cone of depression exhibited smaller water-level fluctuations. Piezometers JC5 to JC8 all fluctuated less than 6 ft; wells JC12 and JC13 fluctuated 2 ft or less.

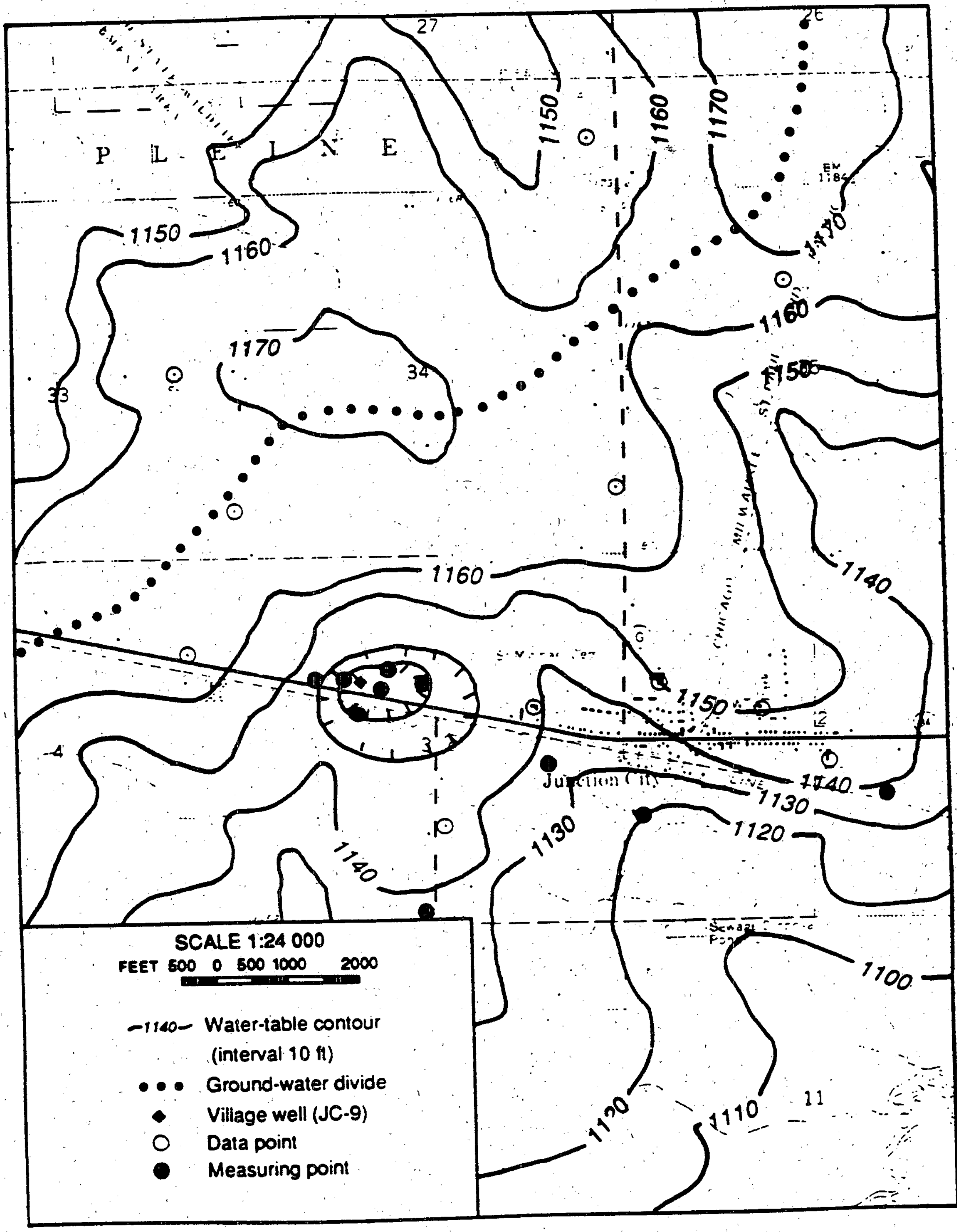


Figure A8. Portion of the water-table map of the Junction City area.

Aquifer Tests

A variety of methods was employed to determine the transmissivity (T) and hydraulic conductivity (K) distributions of the geologic materials in the Junction City area. These methods ranged from simple office calculations of hydraulic conductivity based on data available in well constructors' reports to a field-work intensive multi-well pumping test.

Specific Capacity Data

Specific capacity data from well constructors' reports were used to estimate the transmissivity and hydraulic conductivity distribution of the fractured rock using the computer program TGUESS (Bradbury and Rothschild, 1985). The calculated values for hydraulic conductivity ranged from $1.2x10^{-4}$ to $9.2x10^{-9}$ ft/sec and are approximately log-normally distributed. The geometric mean conductivity, which best represents the average conductivity of the log-normally distributed values, was $4.3x10^{-6}$ ft/sec. A computer-generated contour map of log hydraulic conductivity values for the Junction City area is shown in figure A9.

Slug Tests

Falling- and rising-head slug tests were conducted on the eight piezometers completed in the unlithified deposits and on six existing bedrock wells. Results were analyzed by the Hvorslev (1951) and the Cooper and others (1967) methods. Table A2 contains a summary of the slug test results. For each well, falling- and rising-head values were arithmetically averaged to obtain the values reported in table A2. The geometric mean hydraulic conductivity of the fractured crystalline rock based on slug tests was approximately $9.8x10^{-6}$ ft/sec. The hydraulic conductivity of the overlying silt and clay was approximately an order of magnitude lower, about $6.6x10^{-7}$ ft/sec.

Table A2. Results of slug tests at the Junction City site.

Piezometers	K (ft/sec)	Wells	K (ft/sec)
JC1	$1.9x10^{-7}$	JC10	$4.3x10^{-4}$
JC2	$5.7x10^{-6}$	JC11	$2.9x10^{-5}$
JC3	$3.4x10^{-7}$	JC12	$5.7x10^{-6}$
JC4	$6.2x10^{-5}$	JC13	$7.0x10^{-5}$
JC5	$1.4x10^{-7}$	JC14	$5.9x10^{-6}$
JC6	$1.3x10^{-6}$	JC22	$3.1x10^{-6}$
JC7	$2.0x10^{-7}$		
JC8	$4.0x10^{-7}$		

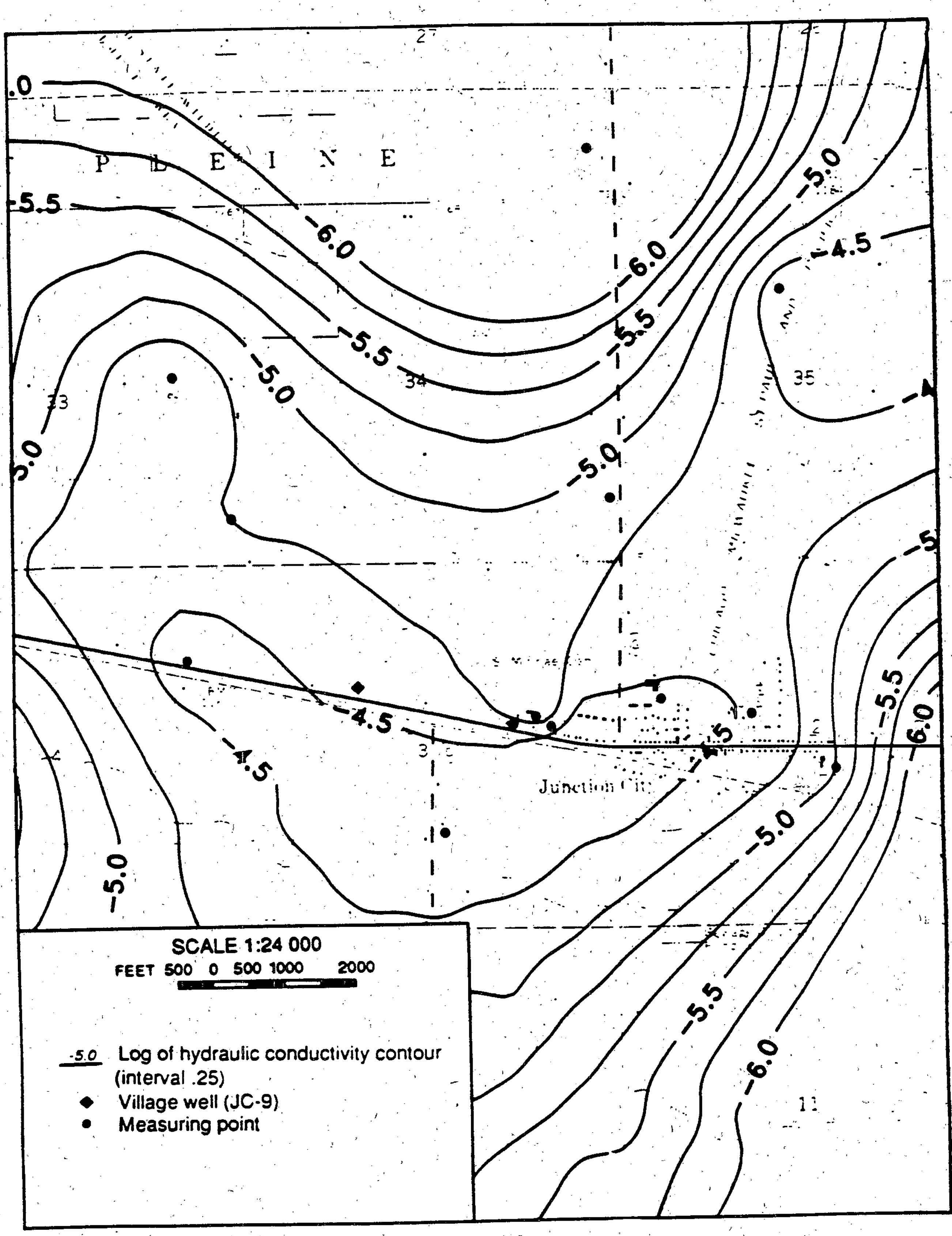


Figure A9. Computer-generated map of hydraulic conductivity values for the crystalline rocks at Junction City. Hydraulic conductivity values were determined from specific capacity data.

The installation of piezometers JC23A and JC23B and observation well JC24 allowed hydraulic testing of the upper and lower parts of the bedrock aquifer. Single-well tests were conducted on the core hole prior to piezometer installation and on the observation well. After piezometers JC23A and JC23B were installed in the core hole, a slug test was conducted on the deeper piezometer (JC23A). These results (summarized in table A3) show that the hydraulic conductivity of the upper part of the bedrock aquifer (represented by JC23B) is approximately four orders of magnitude greater than the hydraulic conductivity of the lower part of the aquifer (JC23A).

Table A3. Results of single-well tests on core hole piezometers at Junction City.

Well or Piezometer Tested	Method	Open Interval (ft below measuring pt.)	Open Interval (ft above mean sea level)	Hydraulic Conductivity (ft/sec)
JC23	Pumping	30 - 297	1122 - 855	1.6×10^{-5}
JC23A	Slug	248 - 297	904 - 855	1.0×10^{-8}
JC23B	Pumping	30 - 120	1122 - 1032	1.4×10^{-4}

Pumping Test

On June 1 and 2, 1989, a 24-hour pumping test was conducted in the village well field, using the village well (JC9) as the pumping well. During the multi-well pumping test most wells were hand-measured; however, the pumped well (JC9) and two piezometers (JC23A and JC23B) were measured using pressure transducers connected to a recording datalogger. Pressure transducer readings were calibrated using hand-measured water levels recorded throughout the pumping test. The village well was turned off for 24 hours prior to the test to allow water levels to stabilize. Pre-pumping water-level trends were measured and used to adjust the drawdowns recorded at each well. The corrected drawdowns at each observation point were analyzed using the Theis nonequilibrium method (Theis, 1935).

Measurable drawdowns ranged from 19 ft at the pumped well to about 1 ft at observation wells located approximately 450 ft away. Figure A10 shows the extent of the cone of depression at the conclusion of pumping. The cone is slightly elliptical, but the general uniformity of drawdown around the pumped well suggests that the fractured rock at Junction City behaves as a porous medium at the scale of the pump test.

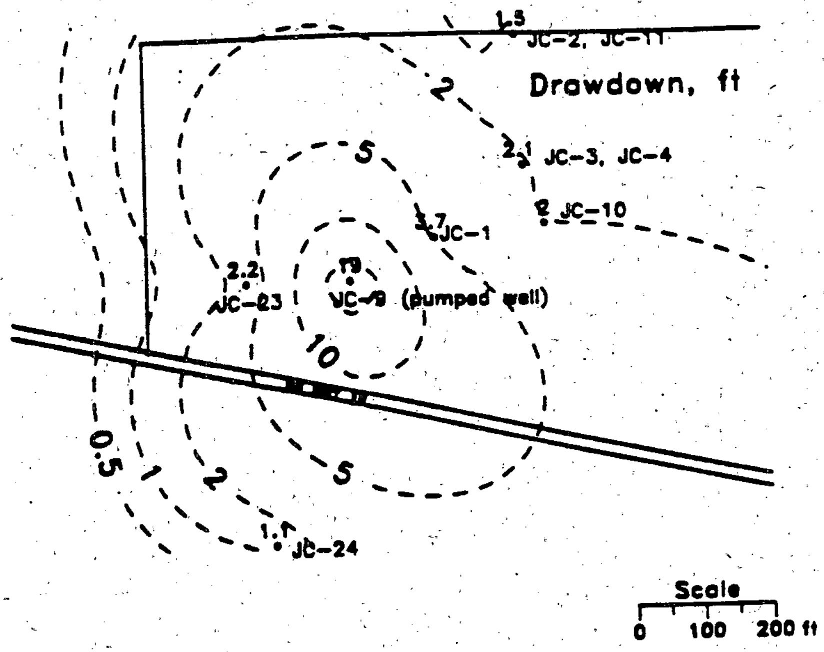


Figure A10. Drawdown for the Junction City pumping test.

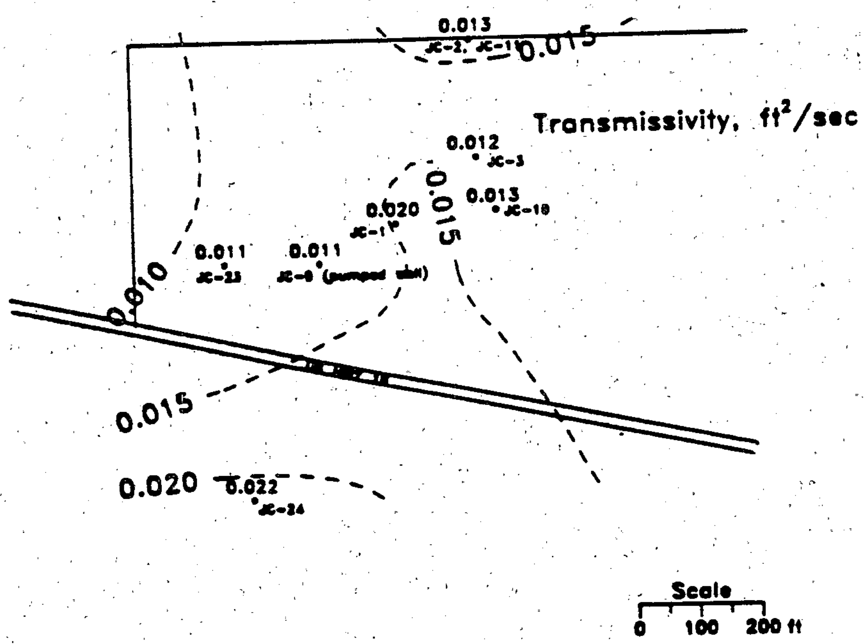


Figure A11. Transmissivity distribution in the Junction City wellfield based on the pumping test data.

On the basis of bedrock wells, transmissivity ranged from 0.011 to 0.022 ft^2/sec, with a geometric mean of approximately 0.013 ft^2/sec. The specific yield ranged from 0.003 to 0.019, with a geometric mean of 0.0049. The transmissivity map (fig. A11) shows a possible zone of higher conductivity east and south-southwest of the pumped well. This zone may correspond to swales in the landscape, and is consistent with previous observations that such swales may correspond to zones of bedrock fractures (Socha, 1983) or zones of more deeply weathered bedrock.

The method of Weeks (1969) was used to calculate the horizontal to vertical anisotropy ratio (K_h/K_v) of the bedrock aquifer. This method uses the principle that partially penetrating observation wells generally show less drawdown than fully penetrating wells during a pumping test in an anisotropic aquifer. The departure of the partially penetrating well from a predicted drawdown curve is related to the K_h/K_v ratio. Applying this method to the pumping test data yields a K_h/K_v ratio of 0.0006. This ratio seems anomalously low, but it is indeed possible that the aquifer might be more transmissive in the vertical than in the horizontal direction because the fractures and bedrock foliation are predominantly vertical.

Water Chemistry and Isotope Analyses

Water Chemistry

Ground water in the vicinity of the Junction City village well is currently of very good quality. As shown in table A4, concentrations of all constituents tested are relatively low and do not exceed drinking water quality standards. In particular, nitrate (NO_3^-), a common ground-water contaminant in agricultural regions, was not detected in any water samples.

Ground water at Junction City is chemically a calcium-magnesium-bicarbonate water. The chemistry of water produced by the village well (JC9) is similar to the chemistry of water from nearby piezometers, suggesting that the source of water for the village well is geochemically similar to shallow aquifer materials in the well field area. The deep piezometer (JC23A) finished at 297 ft below the surface produces water with significantly higher concentrations of HCO_3^- than the village well, suggesting that water produced by the village well enters the well near the upper part of the open interval.

Saturation indices for calcite and dolomite are negative for most water samples (table A4), indicating that the ground water is undersaturated with respect to these minerals, as would be expected for relatively young ground water in crystalline rocks. The deep core piezometer (JC23A) shows oversaturation with respect to these minerals, and ground water in the interval open to JC23A (248-297 ft deep) may be considerably older than the water currently produced by the well. Positive saturation indices at shallow piezometer JC1, located just downslope to the east of the village well, may be due to the use of road de-icing salt on

Table A4. Chemical analyses of Junction City samples (all values are in milligrams per liter unless otherwise indicated)

Sample ID	Sample Date	Temp. °C	Cond. umho	pH	Diss. Oxygen	Ca	Mg	Na	K	Fe	Mn	HCO_3	Cl	SO_4	NO_3	Ca/Mg	Saturation Index Calcite	Saturation Index Dolomite	Saturation Index PCO_2
JC 01	10/28/88	7.5	390.3	8.40	9.1	32.1	19.1	13.1	9.3	0.05	0.07	158.5	53.0	9.3	<0.5	1.68	0.41	0.66	3.33
JC 02	10/28/88	8.0	241.4	7.41	6.3	23.2	11.8	5.0	1.5	0.05	0.40	134.1	7.5	8.3	<0.6	1.97	-0.71	-1.63	-2.34
JC 03	10/28/88	7.8	197.3	8.92	5.6	16.1	8.5	7.0	12.3	0.06	0.03	97.5	12.0	4.7	<0.5	1.91	0.47	0.74	-4.02
JC 04	10/28/88	8.0	233.9	7.90	6.3	28.8	15.3	7.0	3.2	0.06	0.25	158.5	9.0	12.0	<0.5	1.89	-0.05	-0.30	-2.76
JC 05	10/28/88	7.3	215.5	8.17	5.3	14.3	15.4	2.5	3.9	0.07	0.04	121.9	6.5	0.9	<0.5	0.93	-0.20	-0.31	3.14
JC 06	10/28/88	8.0	513.0	7.80	8.7	44.5	29.4	12.6	7.5	0.06	0.20	128.0	15.0	126.5	<0.5	1.51	-0.19	-0.47	-2.81
JC 07	10/28/88	10.0	299.9	7.71	7.6	27.1	18.8	9.4	4.2	0.07	0.09	176.8	5.5	12.5	<0.5	1.44	-0.20	-0.44	-2.50
JC 08	10/28/88	9.0	278.8	7.06	9.9	23.7	13.3	11.4	4.9	0.04	0.43	109.7	29.0	20.5	<0.5	1.78	-1.18	-2.51	-2.12
JC 09	10/28/88	10.3	347.1	7.29	2.0	35.2	18.6	6.2	1.2	<0.01	0.28	164.6	25.0	11.4	<0.5	1.89	-0.54	-1.24	-2.12
JC 09	06/22/89	10.5	--	7.50	4.8	40.4	21.8	3.1	1.5	0.03	0.29	164.6	38.0	16.2	<0.5	1.86	-0.33	-0.80	-2.38
JC 11	10/28/88	7.5	40.3	6.88	7.0	25.9	12.3	4.5	0.9	0.04	0.05	128.0	7.5	8.1	<0.5	2.11	-1.31	-2.86	-1.92
JC 12	10/28/88	9.0	205.4	6.99	7.1	20.0	11.9	1.9	3.0	0.13	0.16	121.9	3.0	1.9	<0.5	1.68	-1.26	-2.64	-2.01
JC 13	10/28/88	9.5	246.1	6.90	2.0	20.1	14.3	4.5	2.4	0.21	0.10	128.0	10.5	6.5	<0.5	1.40	-1.36	-2.75	-1.95
JC 23A	07/06/89	8.2	--	8.15	--	30.5	16.9	30.1	3.6	<0.01	0.13	207.3	29.0	2.5	<0.5	1.81	0.25	0.35	-2.94
JC 24	06/22/89	13.0	--	7.40	3.8	23.5	12.1	1.2	0.8	0.74	0.07	97.5	16.0	6.2	<0.5	1.94	-0.81	-1.74	-2.48
SW 01	10/28/88	3.0	369.1	--	--	31.7	17.0	10.8	22.0	0.46	0.04	158.5	25.0	22.4	<0.5	1.86	-0.56	-1.40	-2.42

U.S. Highway. 10. Higher concentration of Cl^- in this piezometer is characteristic of road salt contamination.

Isotopes

Ground-water samples for tritium (^3H) and oxygen-18 (^{18}O) were collected from 15 wells and piezometers in and around the Junction City well field. Table A5 contains the isotope results.

As discussed in Chapter III, most of the ground water in the Junction City area contains between 20 and 30 tritium units and is thus less than about 35 years old, including water produced by the village well (JC9). One shallow piezometer (JC5), a deep well (JC12), and a deep piezometer (JC23A) yield water with significantly less tritium, and the ground water in the vicinity of these points is probably older.

Table A5. Isotope results for the Junction City area (estimated age is based on qualitative interpretations summarized in table 3, chapter III).

Well	Sample Date	Tritium (TU)	+/- Error (TU)	Estimated Age (yr)	^{18}O (per mil)
JC1	10/28/88	20.6	1.6	<35	-11.55
JC2	10/28/88	30.5	2.1	<35	-11.02
JC3	10/28/88	17.2	1.4	<35	-9.58
JC4	10/28/88	20.9	1.6	<35	-9.78
JC5	10/28/88	5.4	0.7	>20	-9.67
JC6	10/28/88	10.4	1.0	<35	-10.07
JC9	10/28/88	20.6	1.5	<35	-9.90
JC9	06/22/89	21.8	1.7	<35	-9.59
JC10	10/28/88	21.9	1.4	<35	-9.60
JC11	10/28/88	27.3	2.0	<35	-9.78
JC12	10/28/88	3.4	0.7	>20	-9.65
JC13	10/28/88	25.3	1.8	<35	-9.63
JC23A	07/07/89	7.7	0.9	>20	-9.75
JC23B	06/22/89	23.6	1.7	<35	-9.98
JC24	06/22/89	19.0	1.3	<35	--

NUMERICAL MODELING

Model Selection

The ground-water system at Junction City is nonhomogeneous, anisotropic, and three-dimensional. From the observations described above, bedrock fracturing and hydraulic conductivity decrease with depth, and transmissivity varies areally. A large number of near-vertical fractures contribute to significant differences between vertical and horizontal hydraulic conductivity. Simulation of these conditions required a three-dimensional numerical code. The Junction City area was modeled using the modular flow code of McDonald and Harbaugh (1988). This widely available code can simulate transient ground-water movement in three dimensions. The code is arranged in modules that correspond to various program options. Modules used for the Junction City simulations included SIP (strongly implicit numerical solver), recharge, and drains (representing intermittent streams), in addition to the basic model code and utility modules.

Conceptual Model

The first step in modeling any ground-water system is to construct a conceptual model characterizing the ground-water flow system. On the basis of the field-measured water-table map (fig. A8), a small ground-water basin can be delineated that includes the Junction City village well (fig. A12). A ground-water divide located at a topographic divide is the northwestern boundary of this ground-water basin. Mill Creek forms the southeastern edge of the basin. The northeastern and southwestern boundaries of the basin are streams, intermittent near the ground-water divide, but becoming perennial near Mill Creek. Precipitation recharges the aquifer after moving vertically through the unsaturated zone. Once having reached the water table, water moves mainly horizontally from the divide southeasterly towards Mill Creek.

The model boundaries correspond with the natural ground-water basin boundaries. The stream forming the northeastern basin boundary meets Mill Creek farther east than was convenient for modeling purposes. The east model boundary was therefore defined as roughly following the 1100 ft surface contour from Mill Creek to the northern basin boundary stream. This contour was modeled as a constant head boundary due to the presence of a marsh in that area. The streams forming the southwest and northeast boundaries were considered constant head boundaries near Mill Creek and as minor ground-water divides where the streams are only intermittent. Ground-water divides were modeled as no-flow nodes and streams were modeled as constant-head nodes and served as ground-water discharge points. Nonboundary intermittent streams were modeled as ground-water drains using the modular model's drain package.

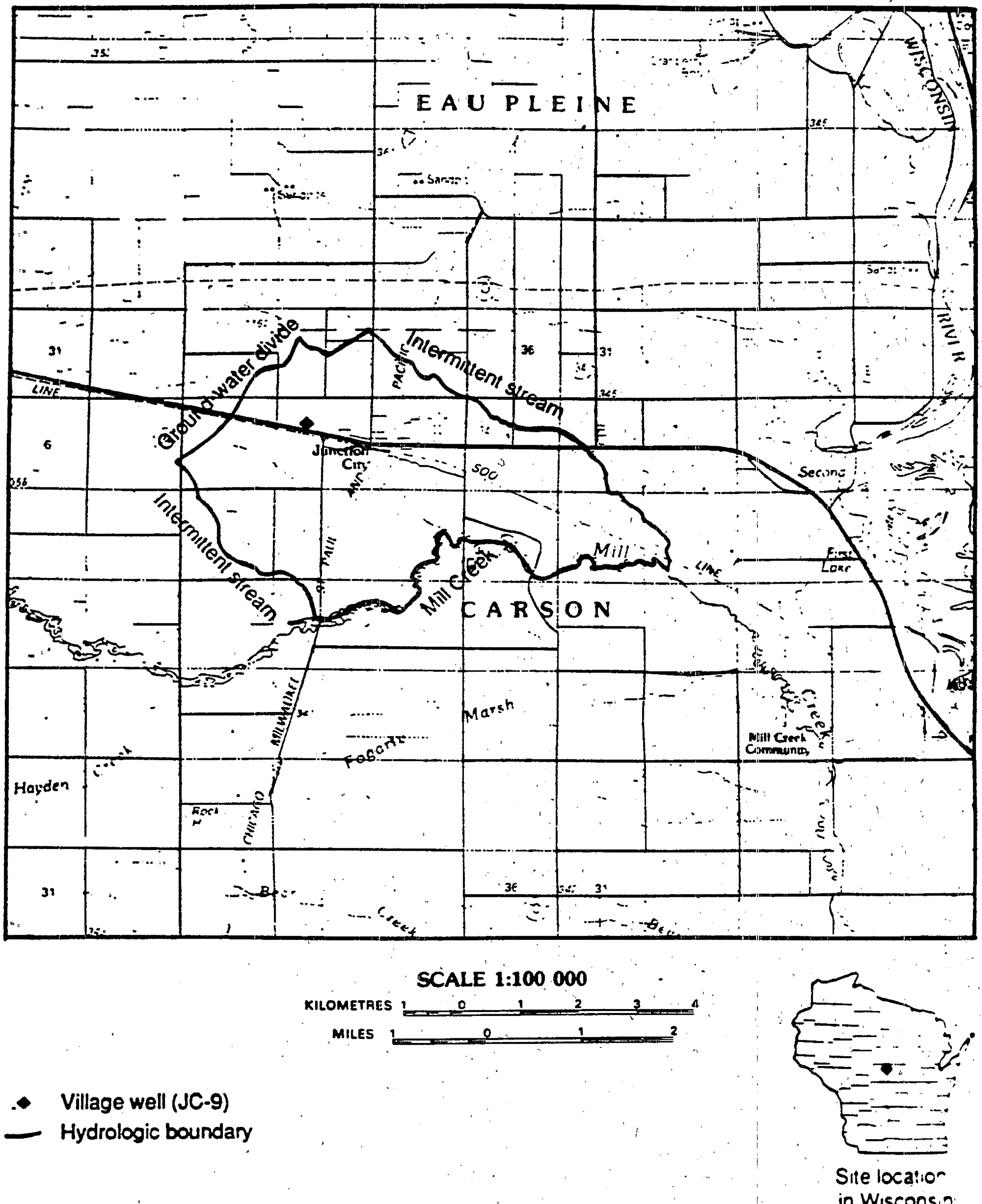


Figure A12. Hydrogeologic boundaries for the Junction City site.

Model Grid Design

The finite-difference grid was oriented in a northwest-southeast direction to parallel the dominant fracture orientation in the bedrock. The grid contains 27 columns, 22 rows, and 3 layers, for a total of 1782 nodes (fig. A13). Individual node spacings range from 250 to 1000 ft, with the smallest discretization near the village well.

The depth-to-bedrock map (fig. A3) indicates that 5 to 55 ft of unlithified material overlies the fractured crystalline bedrock. The upper 35 ft of the bedrock is highly weathered and overlies approximately 115 ft of bedrock with open fractures. Below this depth the bedrock contains few fractures. On the basis of these bedrock characteristics, the model was constructed with three layers: layer 1 represents the unlithified material and highly weathered bedrock; layer 2 represents bedrock with open fractures; and layer 3 represents bedrock with few to no fractures. Model layers are shown diagrammatically in figure A14 and table A6 lists the layer thicknesses and input parameters assigned to each layer.

Table A6. Layer characteristics for Junction City model.

Model Layer	Layer Type	Conceptual Representation	Thickness (ft)	K_H (ft/sec)	K_H:K_V Ratio	Average Porosity
1	Unconfined	Unlithified material and highly weathered bedrock	40-90	3.6×10^{-6} to 1.14×10^{-4}	1:1	0.10-0.27
2	Confined	Bedrock with open fractures	115	2.0×10^{-6} to 9.5×10^{-5}	1:1	0.05
3	Confined	Bedrock with few fractures	150	6.4×10^{-8}	1:1	0.03

Model Layer 1 - Unlithified Material and Highly Weathered Bedrock

Layer 1 is the uppermost layer in the model and represents unlithified material and highly weathered bedrock. Hydraulic conductivity values for this layer were determined at

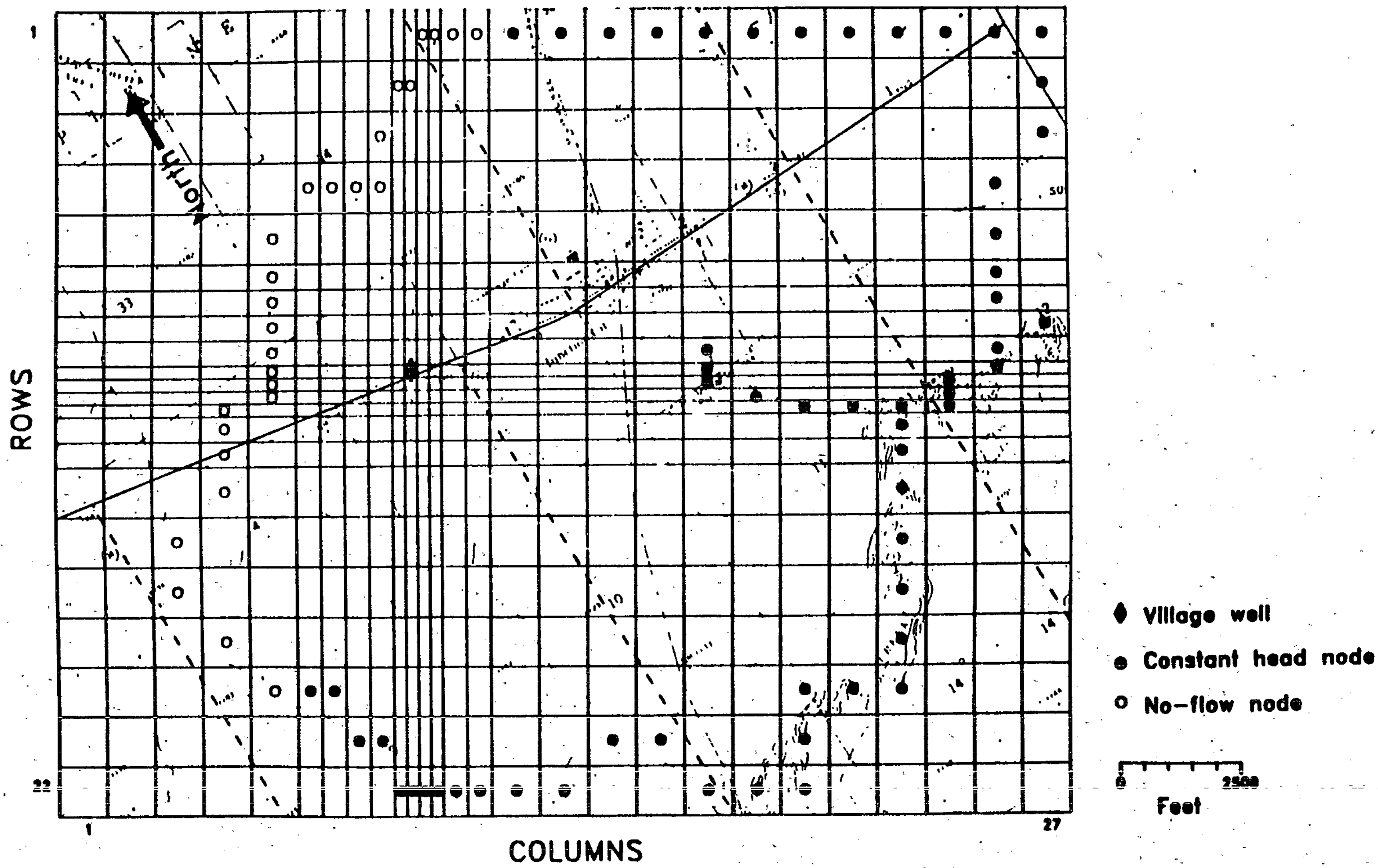


Figure A13. Areal view of grid and spatial discretization used in the numerical simulation of the Junction City ground-water flow system.

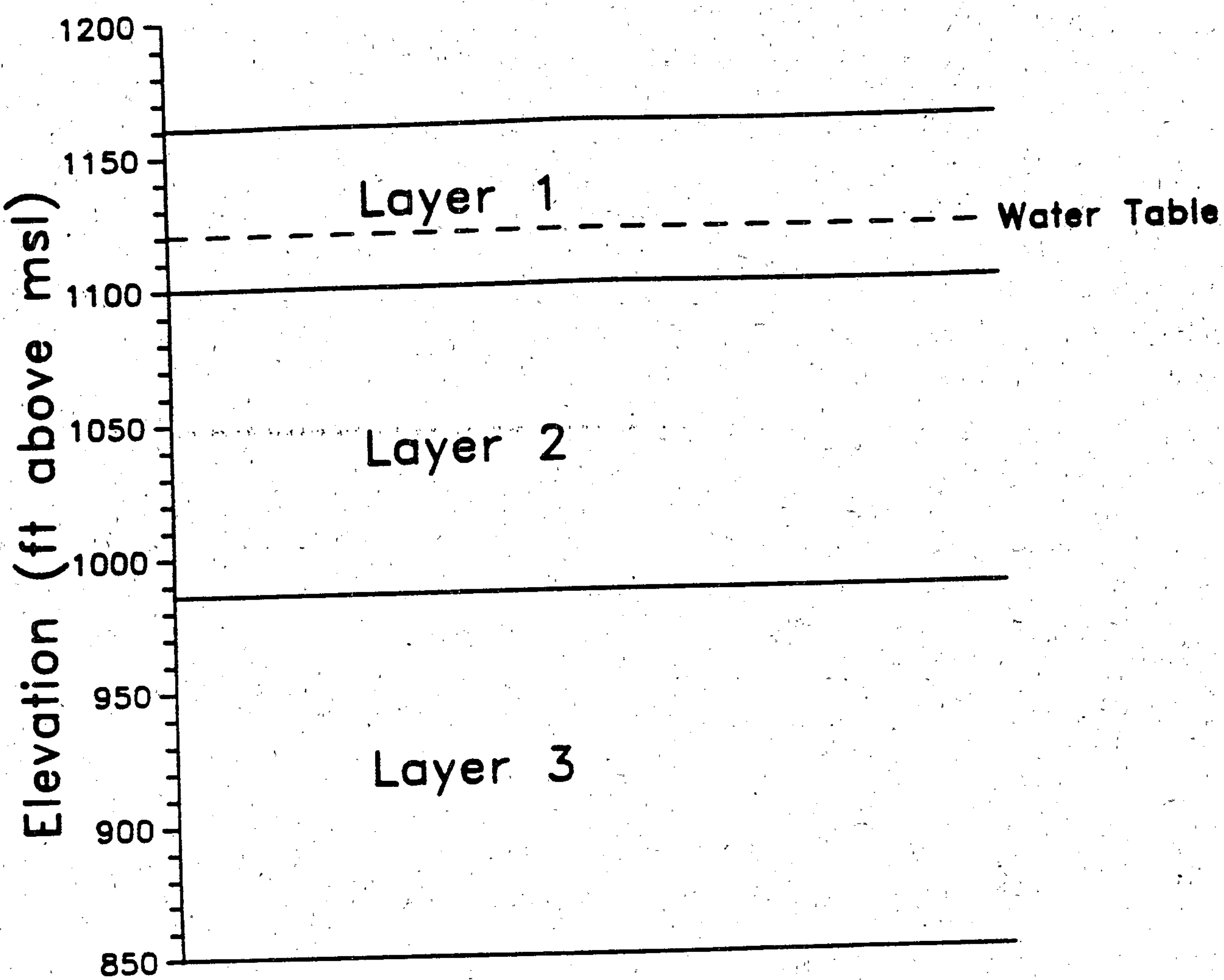


Figure A14. Configuration of model layers used in numerical model of ground-water flow at the Junction City site (represents area near the village well).

each node using saturated thickness-weighted averages of the conductivities of each of the two composing units (unlithified material and highly weathered bedrock).

Hydraulic conductivity of the unlithified material was based on shallow piezometer slug tests performed near the village well (table A2). Spatial variation of hydraulic conductivity throughout the rest of model area was based on the soil type given in the soil survey of Portage County, Wisconsin (Otter and Fiala, 1978). Piezometer drillholes suggest that the unlithified materials consist of Pleistocene hillslope deposits that grade into weathered Precambrian rock. In areas where no other data were available, the soil material was assumed to represent the composition of the entire thickness of unlithified sediment. Hydraulic conductivity values were adjusted according to soil type; values ranged from 4.6×10^{-7} ft/sec in the silty clay soils to 6.6×10^{-6} ft/sec in sandy soils.

Hydraulic conductivity of the highly weathered bedrock was based on aquifer transmissivity determined from the pumping test. Hydraulic conductivities along the swales near the well field were increased by a factor of 2.25 on the basis of the pumping test results. The swales are believed to correspond to areas of more highly weathered bedrock. Hydraulic conductivity away from the well field was adjusted relative to the hydraulic conductivities shown on the map generated from specific capacity data (fig. A9). Model conductivities varied spatially by as many as three orders of magnitude.

The elevation of the bottom of layer 1 was calculated for each grid node by subtracting the depth to bedrock plus 35 ft (thickness of the highly weathered bedrock) from the surface elevation. The drill core recovered from well JC23 contained numerous vertical fractures in the top 35 ft, suggesting that vertical hydraulic conductivity could be greater than horizontal. Because model calibration with vertical hydraulic conductivities greater than horizontal proved difficult, vertical hydraulic conductivity was set equal to the horizontal for model layer 1.

Model Layer 2 - Bedrock With Open Fractures

Layer 2 was simulated as a confined layer 115 ft thick, treated as unconfined if the water table were to drop below the top of layer. The pump test indicated that hydraulic conductivity of the upper bedrock was about 7.5×10^{-5} ft/sec. For best model calibration, the hydraulic conductivity of layer 2 was varied spatially from 2.0×10^{-6} to 9.5×10^{-5} ft/sec, and vertical conductivity was equal to the horizontal conductivity.

Model Layer 3 - Bedrock With Few Fractures

Layer 3 was simulated as a confined layer with a thickness of 150 ft. On the basis of slug test results from piezometer JC23A, the hydraulic conductivity of the lower bedrock layer was assumed to be much less than that of the upper bedrock layers and was lowered three orders of magnitude to 6.4×10^{-8} ft/sec. Transmissivity of layer 3 was therefore set at 9.5×10^{-6} ft²/sec, and vertical conductivity was set equal to horizontal conductivity.

Model Calibration

Recharge was used as a calibration parameter and was varied spatially on the basis of predicted recharge and discharge areas using a procedure described by Stoertz and Bradbury (1989). Recharge rates based on this distribution ranged from 0 in./yr in apparent discharge areas to 20 in./yr in high recharge areas. The average recharge rate over the entire model area was 5.2 in./yr, which is within 50 percent of the calculated recharge rate based on water-level fluctuations at a U.S. Geological Survey (USGS) long-term observation well just east of the study area (PT-82, which was numbered JC18 for this study).

The village well was simulated at the node of row 10, column 11, layer 2 (fig. A13). Although layer 1 was the most conductive, the well casing extends through most of it, and this layer probably supplies little water to the well. Layer 2, the zone of bedrock with open fractures, contributes most of the water produced by the well. The hydraulic conductivity of layer 3 was considered too low for that layer to yield substantial amounts of water to the well. The pumping rate based on 1988 village well pumpage records was 0.072 ft³/sec (32.2 gpm).

WHPA Simulations

Steady-State Flow Simulation

The model simulation produced a water-table map (fig. A15) that was a reasonable match of the one produced with field measurements (fig. A8). The only substantial discrepancy between the simulated and measured water-table elevations occurred in the vicinity of the village well where the model simulation did not predict as much drawdown in the cone of depression as observed, probably due to discretization effects.

Transient Flow Simulation

Simulation of transient ground-water conditions at Junction City required estimates of aquifer storaage coefficients for each model layer. In addition, recharge and well pumpage were varied according to realistic seasonal fluctuations.

Estimates of storage coefficient were based on pumping test results. The pumping test gave a bedrock storage coefficient of 0.0049. To account for the lower storage coefficient of the unlithified materials, the storage coefficient of the entire model layer 1 was set to 0.0013.

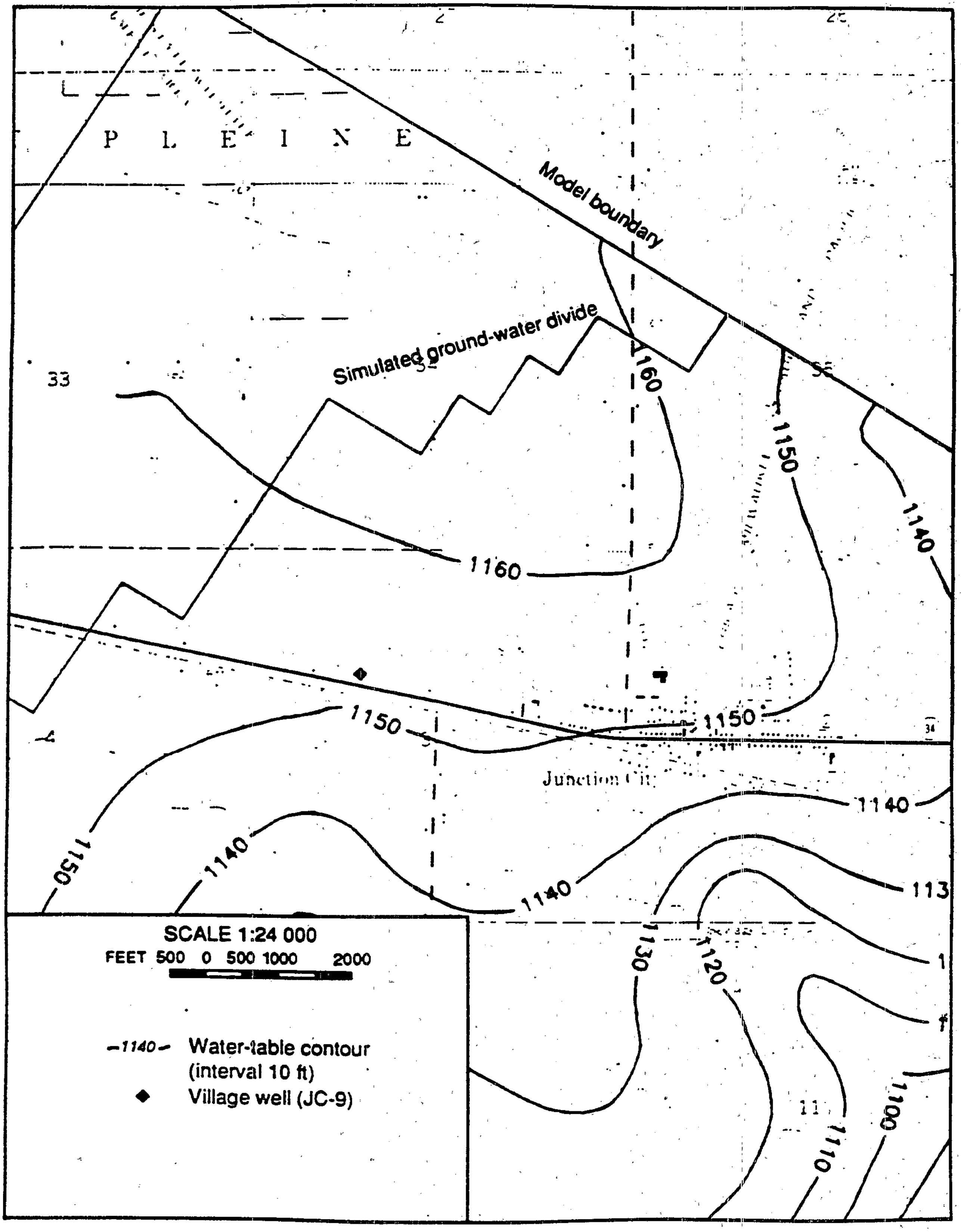


Figure A15. Simulated steady-state water-table elevations in the Junction City area.

The measured value of 0.0049 was used for layer 2. The storage coefficient should decrease with fracture density; therefore, an appropriate value for layer 3 was thought to be about 0.00001.

Records of water levels in a USGS long-term observation well (PT-82, numbered JC18 in this study) were examined to establish a typical yearly fluctuation in recharge rates. Recharge was varied on a monthly basis and transient simulation results at specific well nodes were compared against actual recorded fluctuations. Average recharge rates were varied in the simulation from 4.3 in./yr in February to 6.2 in./yr in May. Because a typical year, not a specific year, was being simulated, the recharge rates were calibrated by matching the magnitude rather than the timing of the water-level fluctuations.

Simulated pumping rates were varied according to the 1988 village well pumpage records. For each year simulated, the pumping rate ranged from 0.056 ft^3/sec in April to 0.098 ft^3/sec in June.

The transient simulation was run for a period of 10 years to provide a 10-yr period of head distributions with which to run PATH3D, the particle-tracking program. The transient simulation results differed little from the steady-state simulation results.

Particle-Tracking Simulations

PATH3D (Zheng and others, in press) is a particle-tracking program that makes use of head distribution created by a flow-model simulation. Ground-water velocities are computed for every node and every time-step and particle paths are based on these velocities. PATH3D tracks particle movement due to advection only; it ignores hydrodynamic dispersion, diffusion, retardation, and other chemical processes. If a steady-state model solution is used, PATH3D can trace a particle's movement backward as well as forward in time. This model capability allows ZOC delineation by placing hypothetical particles at the well in question and tracking them back to their origins in the ground-water system.

In addition to the files used for the modular model simulations, PATH3D also requires aquifer porosity for each model layer in order to calculate velocities. Porosity of the unlithified material of layer 1 was assumed to depend on soil type and was varied on the basis of the soil survey (Otter and Fiala, 1978) from 0.45 in silty clay soils to 0.35 in sandy soils. The porosity of the highly weathered portion of layer 1 was set at 0.10 based on the high end of the porosity range for fractured crystalline rock estimated by Freeze and Cherry (1979). The saturated thickness-weighted average for layer 1 varied spatially depending on the soil type and thickness of the unlithified material and ranged from 0.1 to 0.27. Porosity for layers 2 and 3 was set at 0.05 and 0.03, respectively (table A6).

Using the steady-state model simulation, particles at several depths were tracked backward in time from the well to delineate the upgradient ZOC. Figure A16 illustrates the

ZOC delineated when particles are placed at a depth of 53 ft (elevation of 1106 ft above msl), representing a point 5 ft below the bottom of the village well casing. The particles were tracked backwards through time until they reach the water table. The end points of the simulated paths therefore represent the origins in the ground-water system of particles that would eventually reach the village well at the specified depth. TOT lines shown in figure A16 are drawn to indicate the times involved for particles to travel from the water table to the well due to advection. A larger ZOC is created when the particles are started at a depth of 123 ft (approximately 75 ft below the bottom of the village well casing) at an elevation of 1036 ft above msl (fig. A17).

Because the ground-water flow system at Junction City is three-dimensional, TOT lines based on an assumption of horizontal flow can be misleading. Figure A18 shows five particle paths (1 - 5) in profile view, along with the total travel time of each particle. The farther upgradient a particle enters the water table, the deeper it sinks into the saturated zone before reaching the well (compare particle paths 1 and 5). Particles that were started in the zone of bedrock with few fractures (model layer 3) have much longer TOTs due to the substantially lower hydraulic conductivity of this zone.

Particles reaching the village well at a depth of 162 ft (elevation of 997 ft above msl) entered the water table near the ground-water divide. An elevation of 1000 ft was therefore used to delineate the largest predicted ZOC, extending almost from the ground-water divide to the well. Hypothetical particles were placed around the well at 1000 ft elevation and tracked backwards to the water table near the model boundary. The ZOC and associated TOTs are shown in figure A19. This is the most accurate ZOC for the well because it takes into account the full depth of the three-dimensional flow system terminating at the well.

PATH3D was also run with the 10-yr transient simulation. Particles were placed at points upgradient from the well along flow paths established in the steady-state runs. The paths tracked in the transient runs were identical to those in steady-state. When dealing with a site such as Junction City, in which the water-table fluctuations are relatively small, the transient simulations appear to be an unnecessary addition to the steady-state runs.

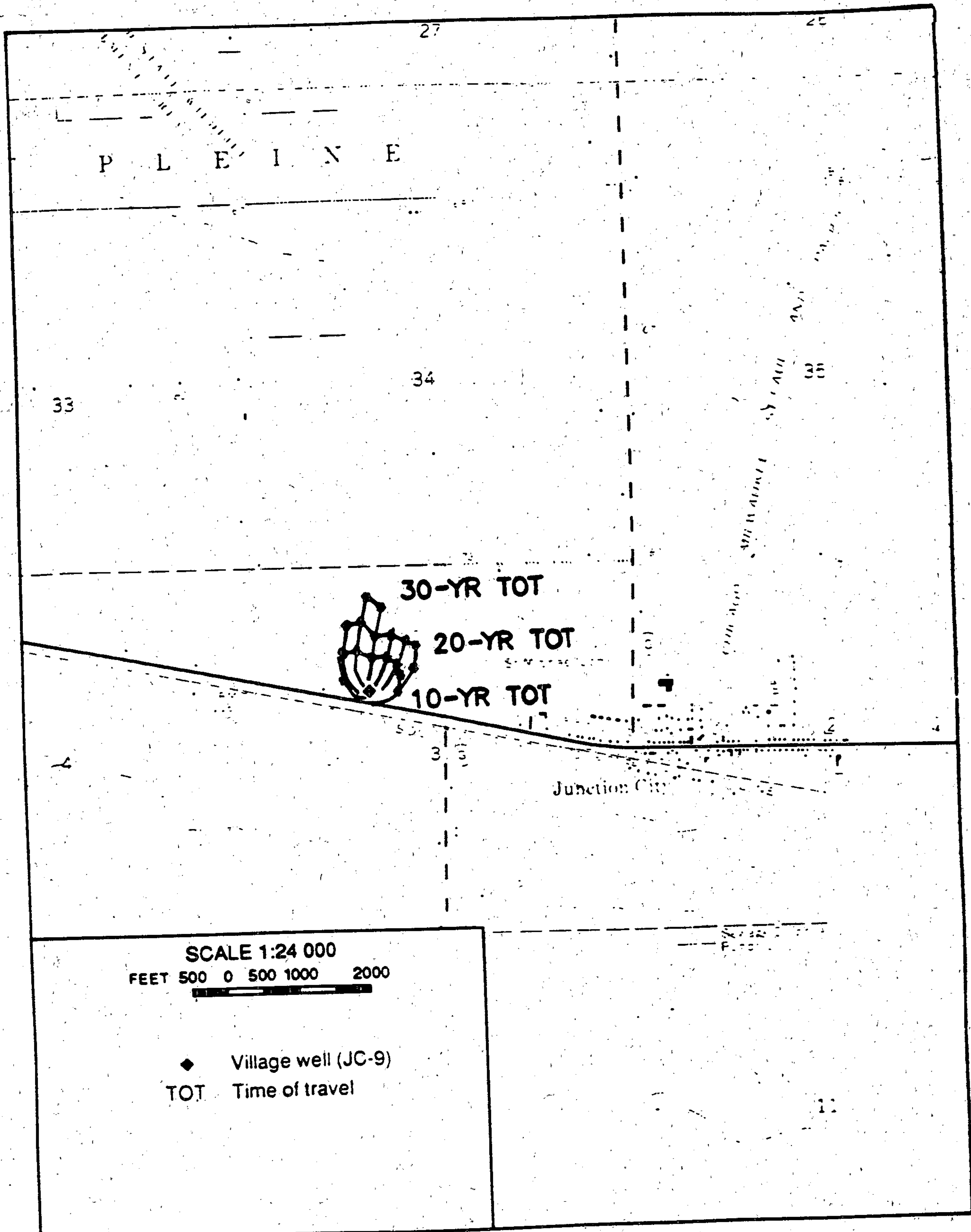


Figure A16. Travel paths and TOTs for particles reaching the Junction City village well at a depth of 53 ft below the land surface or 1106 ft above msl.

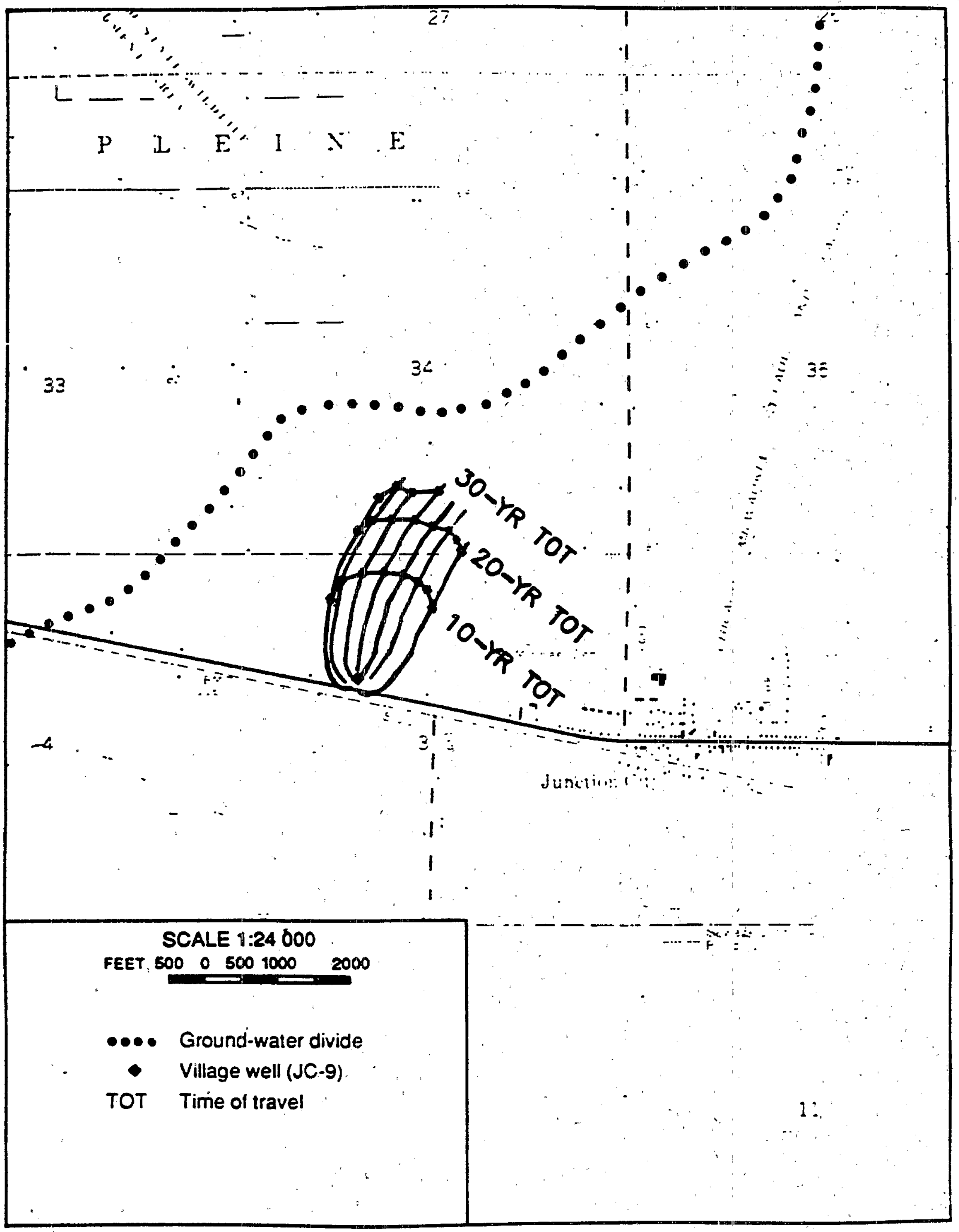


Figure A17. Travel paths and TOTs for particles reaching the Junction City village well at a depth of 123 ft below the land surface or 1036 ft above msl.

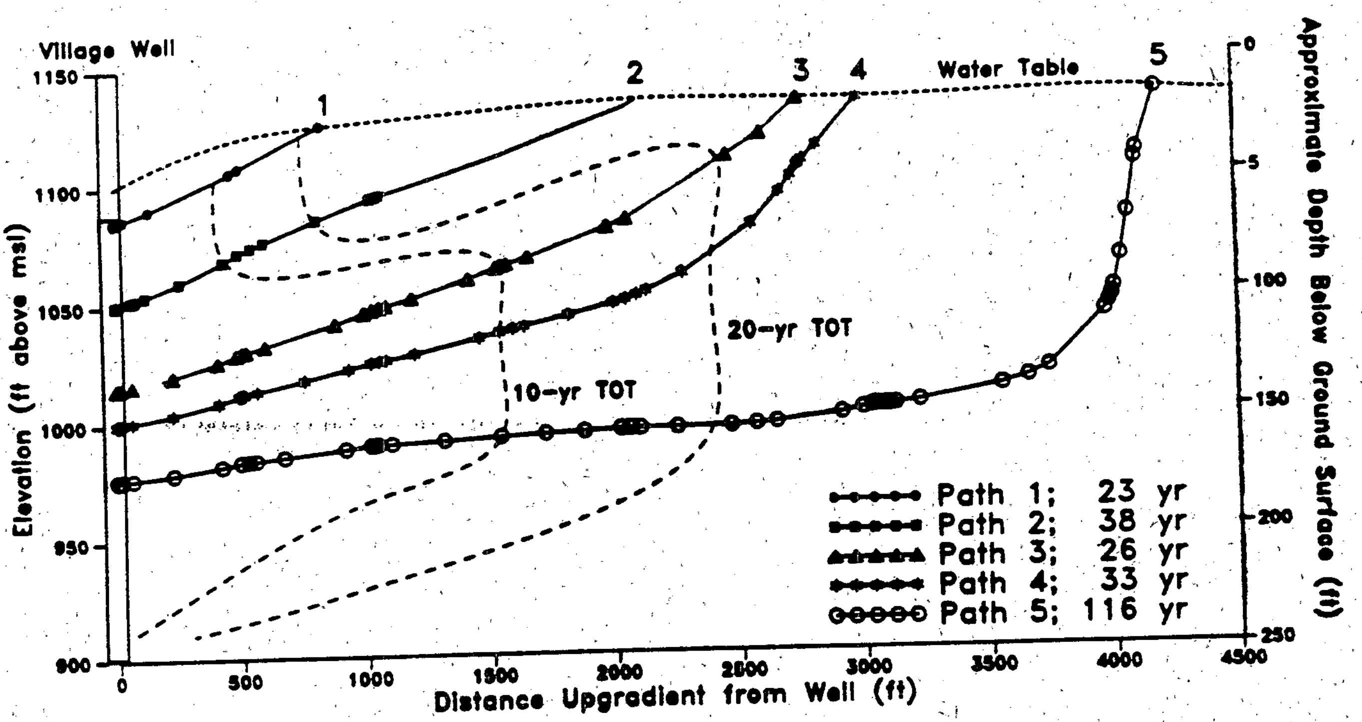


Figure A18. Profile view of travel paths and TOTs for hypothetical particles reaching the Junction City village well. Solid lines indicate particle travel paths; the time included at the end of each line is the total TOT for a given particle path. Dashed lines indicate the 10-yr and 20-yr TOTs.

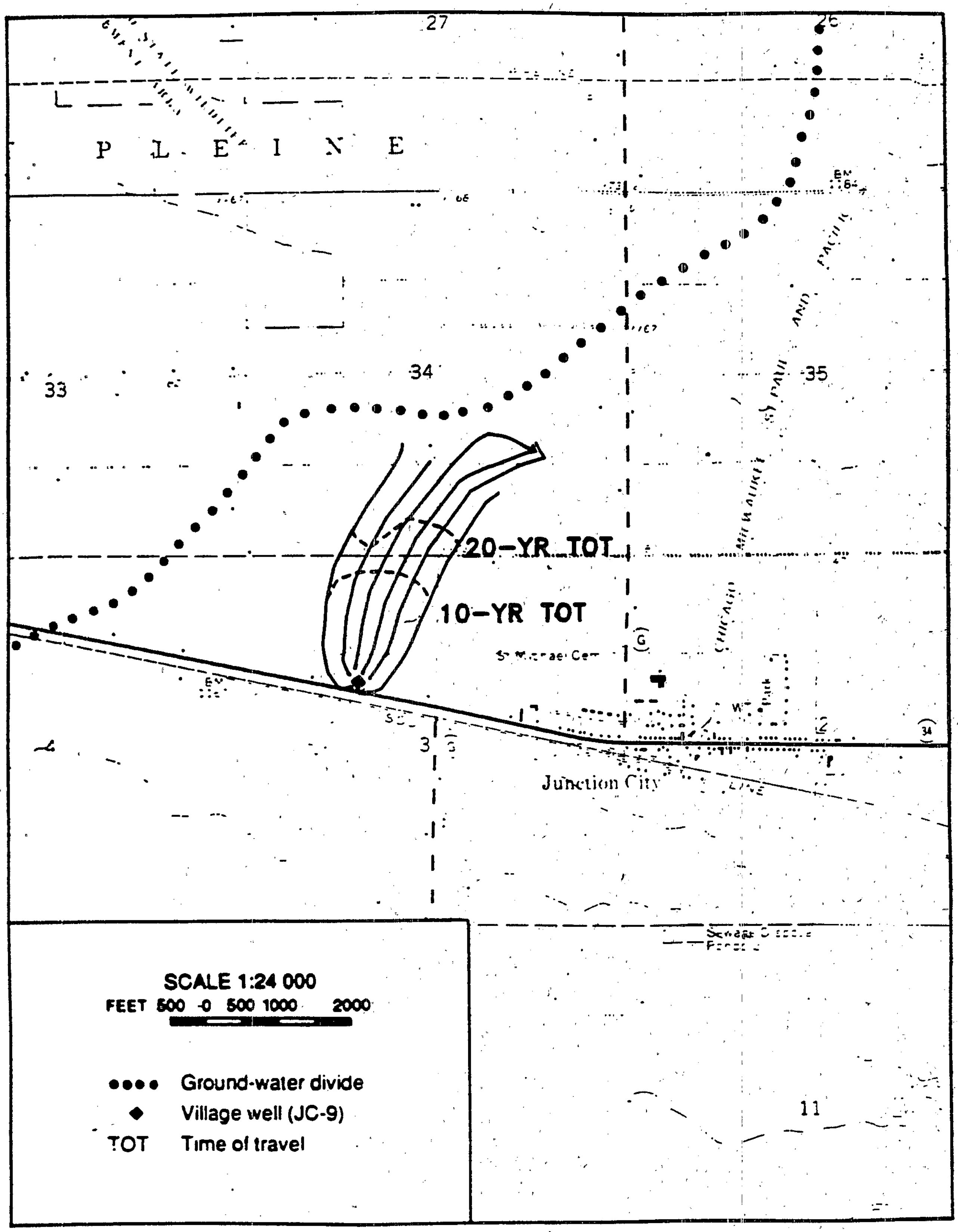


Figure A19. Travel paths and TOTs for particles reaching the Junction City village well at a depth of 162 ft below the land surface or 997 ft above msl.

APPENDIX B

SEVASTOPOL STUDY AREA, DOOR COUNTY, WISCONSIN

SITE SELECTION

The second demonstration area for testing wellhead protection methods in fractured-rock aquifers is in the central part of Door County (see fig. 3), which forms a peninsula between Lake Michigan and Green Bay in northeastern Wisconsin.

Door County is ideal for studies of fractured carbonate-rock aquifers for several reasons. First, the Silurian dolomite is highly fractured and provides the sole source of ground water for most county residents (Zaporozec and Cotter, 1985). Second, because there is only a thin veneer of soil covering the peninsula, the fractured rock is very near the land surface and is comparatively easy to study. Third, dolomites of Silurian age cover a large area of the northern midwest, extending south along the Lake Michigan shore to Chicago and wrapping around the Michigan Basin to occur in parts of Michigan, New York, and Ontario. Finally, a great deal of prior hydrogeologic research provides a good database for use in wellhead protection studies. Thwaites and Bertrand (1957) described the geology of the Door Peninsula, and Sherrill (1978) summarized the hydrogeology of the county. More recently, Bradbury (1982) and Nauta (1987) modeled ground-water flow in portions of the county. Schuster and others (1989) constructed detailed maps of soils and surficial features in part of the county, and rated the soils as to pollution attenuation potential.

This area has a history of elevated nitrate, chloride, bacteria, and occasionally, lead levels in ground-water samples collected from private and public wells (Blanchard, 1988; Wiersma and others, 1984). Such contamination is believed to be a direct result of agricultural and other land-use practices in areas where thin soils overlie the fractured dolomite.

Recent work by the WGNHS has focused on details of the hydrogeologic system at several research sites in the county. Blanchard (1988) and Bradbury and others (1988) instrumented two research sites near the center of the peninsula in the town of Sevastopol about 10 miles north of the city of Sturgeon Bay (see fig. 3, fig. B1). Existing test wells and piezometers at one of the sites, referred to as the Sevastopol test site, provided an excellent starting point for this wellhead protection study. Ongoing ground-water monitoring at another site, referred to as the barnyard research site, provided additional data points.

Door County is predominantly rural, and only two municipalities in the county are served by community wells. Neither of these communities was judged to be suitable as a research site due to complexities resulting from urbanization and proximity to surface-water bodies. Therefore, the wellhead protection methods demonstrated in Door County were applied to a

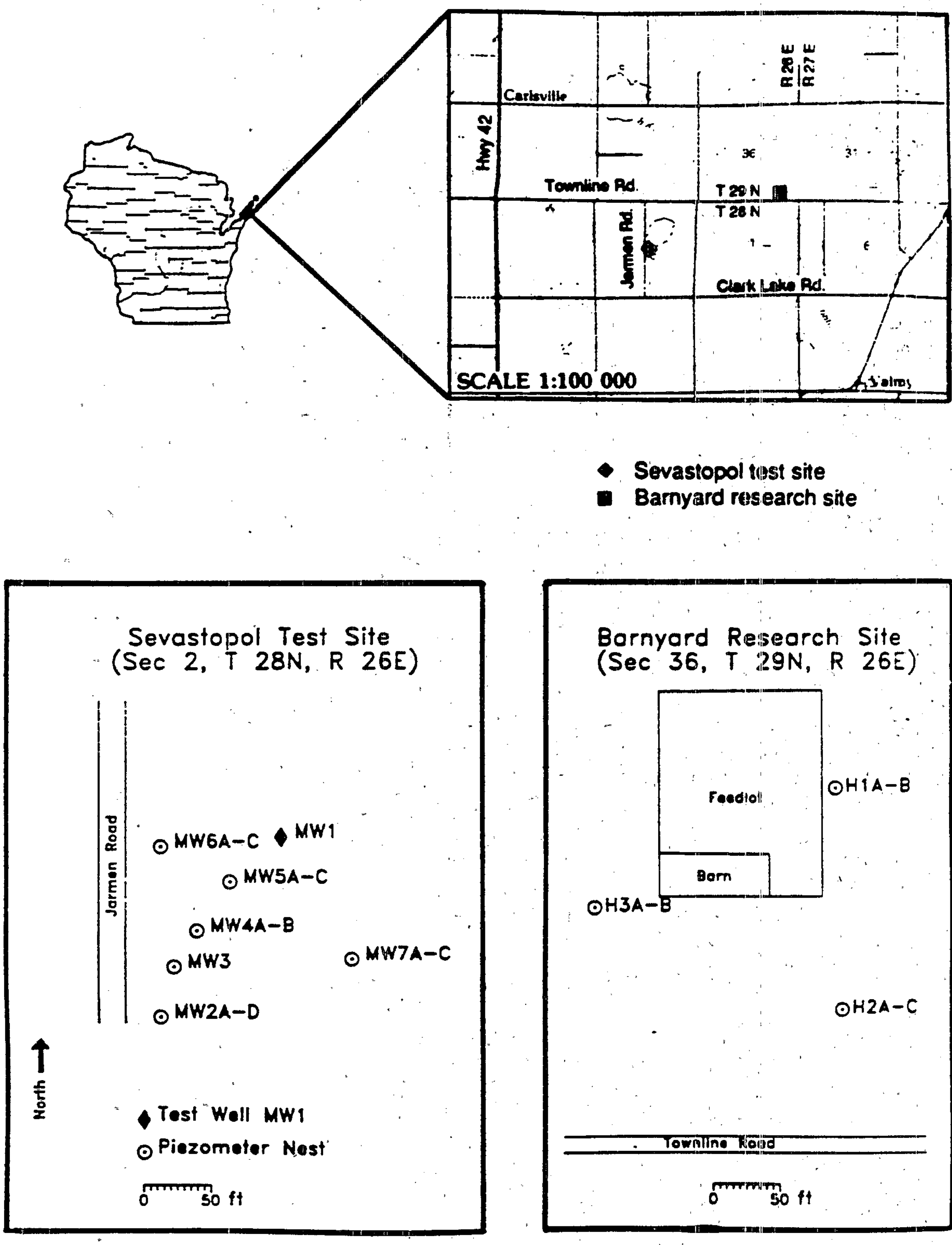


Figure B1. Research sites in Door County, Wisconsin. Generalized locations are shown in the top diagram. Detailed site diagrams are shown below.

test well located at the Sevastopol test site described above. The hydrogeologic setting of this site is characteristic of much of central Door County, and far more background data were available at this site than at other locations in the county.

INVESTIGATION METHODS

Hydrogeologic studies conducted at the Sevastopol test site from 1986 through 1989 examined, in detail, the vertical and horizontal movement of ground water through a small area of fractured dolomite, by determining the position of the water table, measuring vertical hydraulic gradients, measuring aquifer parameters, and sampling ground water at various depths below the surface in a ground-water recharge area. In addition, detailed borehole geophysical studies identified horizontal fracture zones within the bedrock.

Seven monitoring wells (MW1 - MW7) were installed at the Sevastopol test site (fig. B1) using air-rotary drilling. Piezometer nests were installed in five of the wells. Piezometers in each well are designated by the letters A, B, C, etc. Table B1 lists the construction details for all wells and piezometers. Five of the wells (MW1 - MW5) are oriented approximately along a ground-water flow line and also along a major fracture feature. Two of the wells (MW1 and MW2) reach a depth of approximately 240 ft, the common depth of newly constructed domestic wells in the area. Three shallow wells (MW3, MW4, and MW5) were installed on a line between the two deep wells (MW1 and MW2). Two additional wells (MW6 and MW7) are oriented at right angles to the line formed by MW1 through MW5. Piezometer nests installed in wells MW2, MW4, MW5, MW6, and MW7 were used to investigate changes in hydraulic head and water chemistry in relation to depth. The annular space between piezometers was sealed with a mixture of bentonite and cement grout, and the piezometers were developed using compressed air. The resulting array of 15 piezometers and two wells was used for measurements of the vertical distribution of hydraulic head in the dolomite, for slug tests, for two pumping tests, and for obtaining high-quality ground-water samples that were analyzed for major cations and anions as well as isotopes ^{3}H and ^{18}O. Seven additional piezometers (H1A-B, H2A-C, and H3A-B) at the barnyard research site, located approximately 1.5 miles northeast of the Sevastopol test site (fig. B1), provided additional hydrogeologic data. The construction of these piezometers was similar to the construction of piezometers at the Sevastopol test site. In addition, water levels were measured in approximately 50 domestic and irrigation wells in the area surrounding the sites.

Geophysical logs, including three-arm caliper, spontaneous potential, single-point and normal resistivity, natural gamma radiation, borehole temperature, and borehole fluid flow were obtained at most of the monitoring wells prior to casing installation. In addition, television logs provided a visual inspection of fractures and other features inside four boreholes. A ground-penetrating radar (GPR) survey of the site (Attig and others, 1987) gave details on depth to bedrock and delineated shallow fractures.

Table B1. Well data, Sevastopol Study Area, Door County, Wisconsin.

Well No.	Well Depth (feet below measuring point)	Open Interval (feet below measuring point)	Average Depth to Water (feet below measuring point)	Measuring Point Elevation (feet above msl)
Sevastopol Test Site				
MW1	240	40-240	140.9	798.2
MW2A	42	227-237	134.6	794.7
MW2B	161	152-157	123.0	794.7
MW2C	147	134-144	115.7	794.7
MW2D	78	70-75	70.8	794.7
MW3	60	20-60	36.5	794.8
MW4A	44	41-44	30.4	796.0
MW4B	31	27-30	17.7	796.0
MW5A	24	23-24	19.5	797.6
MW5B	21	20-21	17.4	797.5
MW5C	19	17-18	14.2	797.5
MW6A	61	56-61	48.2	794.9
MW6B	40	35-40	31.0	794.9
MW6C	20	13-18	16.2	794.9
MW7A	185	177-182	154.1	797.3
MW7B	153	145-150	137.0	797.3
MW7C	106	101-106	105.3	797.3
Barnyard Research Site				
H1A	62	56-61	36.6	720.2
H1B	37	31-36	29.8	720.2
H2A	63	58-63	37.1	715.2
H2B	50	44-49	32.5	715.2
H2C	29	23-28	25.1	715.2
H3A	63	58-63	38.8	719.9
H3B	37	31-36	30.3	719.9

HYDROGEOLOGIC SETTING

Dolomite of Silurian age lies beneath a thin cover of unlithified Pleistocene sediment, mostly clayey till on the uplands. The dolomite aquifer is a self-contained and easily studied unconfined aquifer system, covered only thinly by unlithified materials and bounded on all sides by surface water and beneath by the Ordovician Maquoketa shale, a regional confining bed (see fig.4)

Numerous vertical and horizontal fractures in the dolomite apparently control the hydraulic conductivity of the aquifer. Figure B2 shows near-vertical fracture expression in an alfalfa field across from the Sevastopol research site. The depth to bedrock in the field is approximately 6 in., as determined by ground-penetrating radar and by hand augering. Apparently, the near-vertical fractures are filled with fine-grained soil, which holds more moisture than surrounding rocks. The photo shows that fractures in the predominant joint set are spaced approximately 10 to 20 ft apart near the research site. Aerial photographs from other areas of the county indicate a similar frequency and regularity of fracture spacings. Rosen (1984) and Sherrill (1978) document principal joint azimuths over the entire county at about 25°, 70°, and 155°. At the Sevastopol site, major visible fractures are oriented approximately N30°E. Each fracture, if open, can provide a direct route for infiltrating water to recharge the ground-water system; however, most fractures are at least partially filled with clayey or silty sediment.

Direct evidence of fracture discontinuities observed during installation of well MW1 included loss of drilling fluids at elevations of 600 and 577 ft above mean sea level (msl) (198 and 221 ft below land surface) and voids at 582 and 577 ft above msl (221 and 216 ft below land surface). While drilling at MW2 and MW7, there was a loss of circulation and water erupted 40 ft above the ground at MW1. This shows a direct connection among wells MW1, MW2, and MW7, which are each over 200 ft apart. The loss of circulation occurred at a depth of 190 ft in both wells, and water eruption occurred when drilling at 190 ft in MW7 and 235 ft in MW2.

A suite of logs from the Sevastopol test site demonstrates how geophysical logs can be used to detect horizontal fracture zones. Figure B3 shows logs for well MW1; numbers on the left-hand axis of figure B3 are corrected elevations relative to mean sea level. Offsets appear in the temperature log at elevations of 648 ft and 563 ft above msl (depths of 150 and 235 ft). This log was run in the spring, when cold recharge water was entering the aquifer. Temperature increases at the offsets suggest that either the cold water was leaving or warmer water was entering the borehole through horizontal fractures or solution features at these elevations. Slight increases in borehole diameter occur at the same elevations, and also at other elevations where temperature changes were not observed.

The gamma log shows much variation over short vertical distances, suggesting small-scale variability in lithology. Highest gamma values generally should coincide with zones of clay or other fine-grained material. Television logs show fractures and vugs that

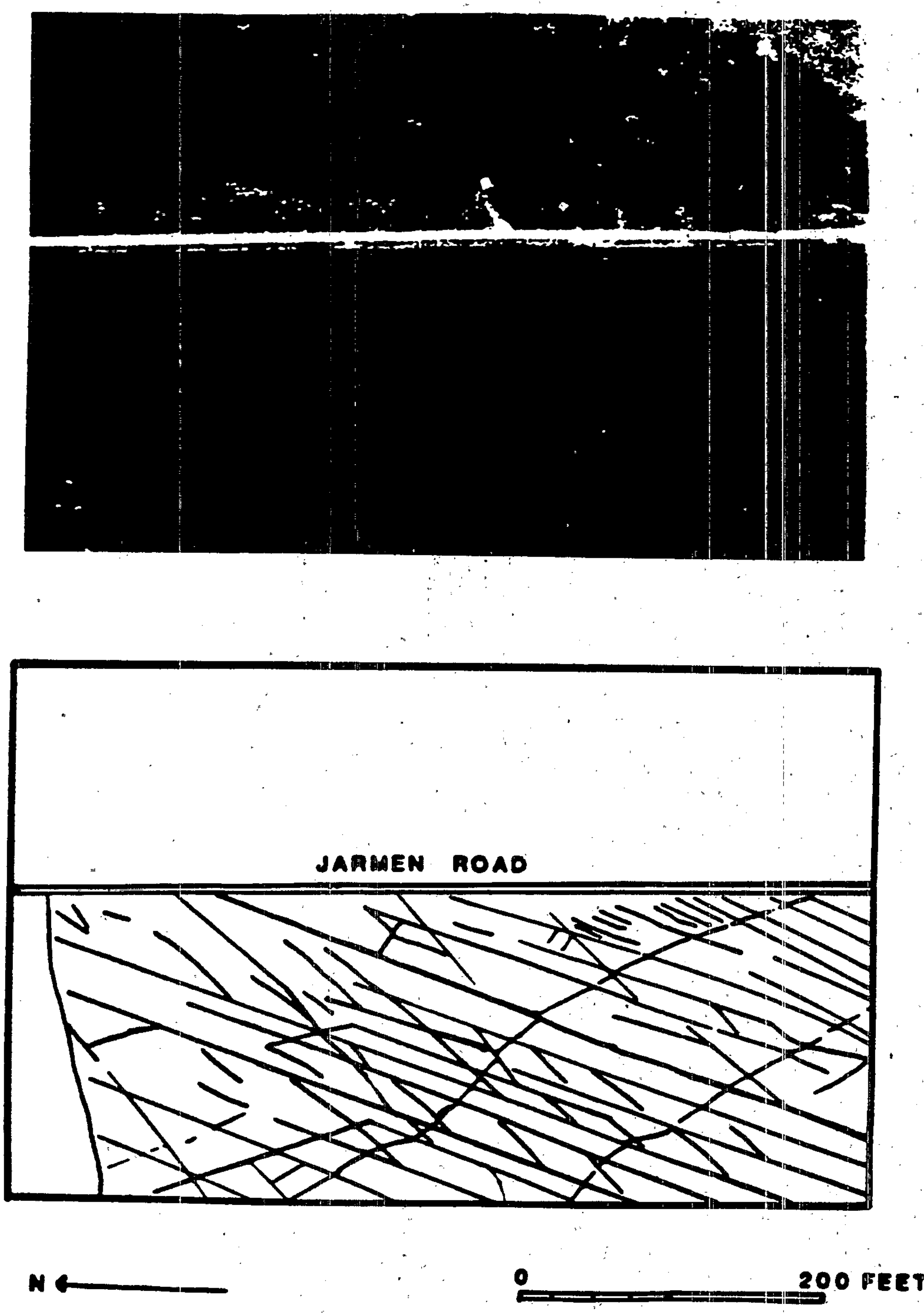


Figure B2. Expression of bedrock fractures in alfalfa field at the Sevastopol site, Door County, Wisconsin. **Top:** Oblique air photo showing vigorous alfalfa growth over fractures. **Bottom:** Highlighted locations of fracture traces.

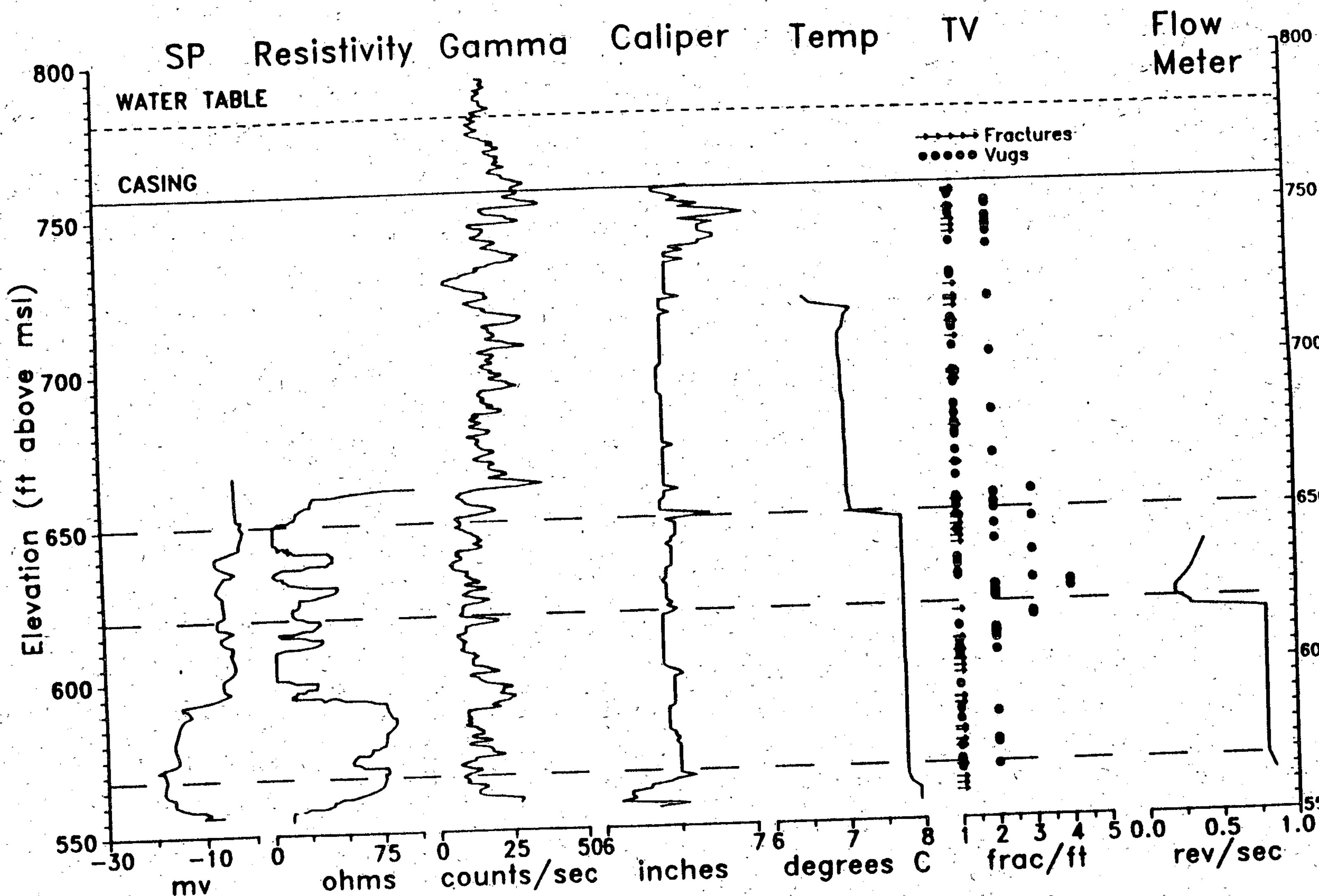


Figure B3. Geophysical logs for well MW1 at the Sevastopol site. Dashed horizontal lines indicate horizontal fracture zones.

have been enlarged by dissolution. The television log confirmed the presence of a permeable zone between 650 and 640 ft above msl (approximately 150 ft deep); this zone has a dissolved, "Swiss cheese" appearance rather than the appearance of a discrete fracture. The spinner flow meter detected significant borehole flow at an elevation of about 615 ft above msl, a place in which the television log showed numerous vugs. The spontaneous potential and resistivity logs can be easily correlated among boreholes at the site, and appear to be related more to lithologic changes than to fracture locations.

RESULTS OF INVESTIGATIONS

Water-Table Mapping

Wellhead protection studies require up-to-date water-table and potentiometric-surface maps for the ZOC delineation. Although detailed ground-water elevations were available at the Sevastopol test site, the construction of reliable water-table maps of the surrounding area required additional field measurements. During the summer of 1989, field personnel measured ground-water levels in approximately 50 domestic and irrigation wells in the area surrounding the site. After corrections for land-surface elevation, these data, in conjunction with piezometer data and surface-water elevations, allowed the construction of two contour maps of ground-water elevations (fig. B4). Note that the water table near the Sevastopol test site lies about 40 ft deep at an elevation of about 760 ft above msl (dashed contours, fig. B4), and the Sevastopol test site is just west of the ground-water divide for the shallow system. The potentiometric surface (solid contours, fig. B4) is more than 120 ft lower than the water table with a hydraulic head of about 640 ft above msl near the Sevastopol test site. The ground-water divide for the deep system lies about 2 miles northeast of the Sevastopol test site.

Water-Level Measurements

Vertical Distribution of Hydraulic Head

Vertical hydraulic gradients at the Sevastopol site are steeply downward and are much greater than horizontal gradients, suggesting that the aquifer is highly anisotropic. Figure B5 shows the distribution of total hydraulic head in the subsurface in March 1989. The water table at the Sevastopol site fluctuates over elevations of about 760 to 780 ft above msl, or about 20-40 ft below the land surface as shown by the heads in the shallow piezometers. The continuous presence of water in the shallow piezometers (MW5A-C and MW6A-C) was unexpected on the basis of previous research (Bradbury, 1982; Sherrill, 1978), which placed the water table in the area about 150 ft below the land surface. Below the water table, hydraulic heads decreased significantly with depth. A change in the vertical hydraulic

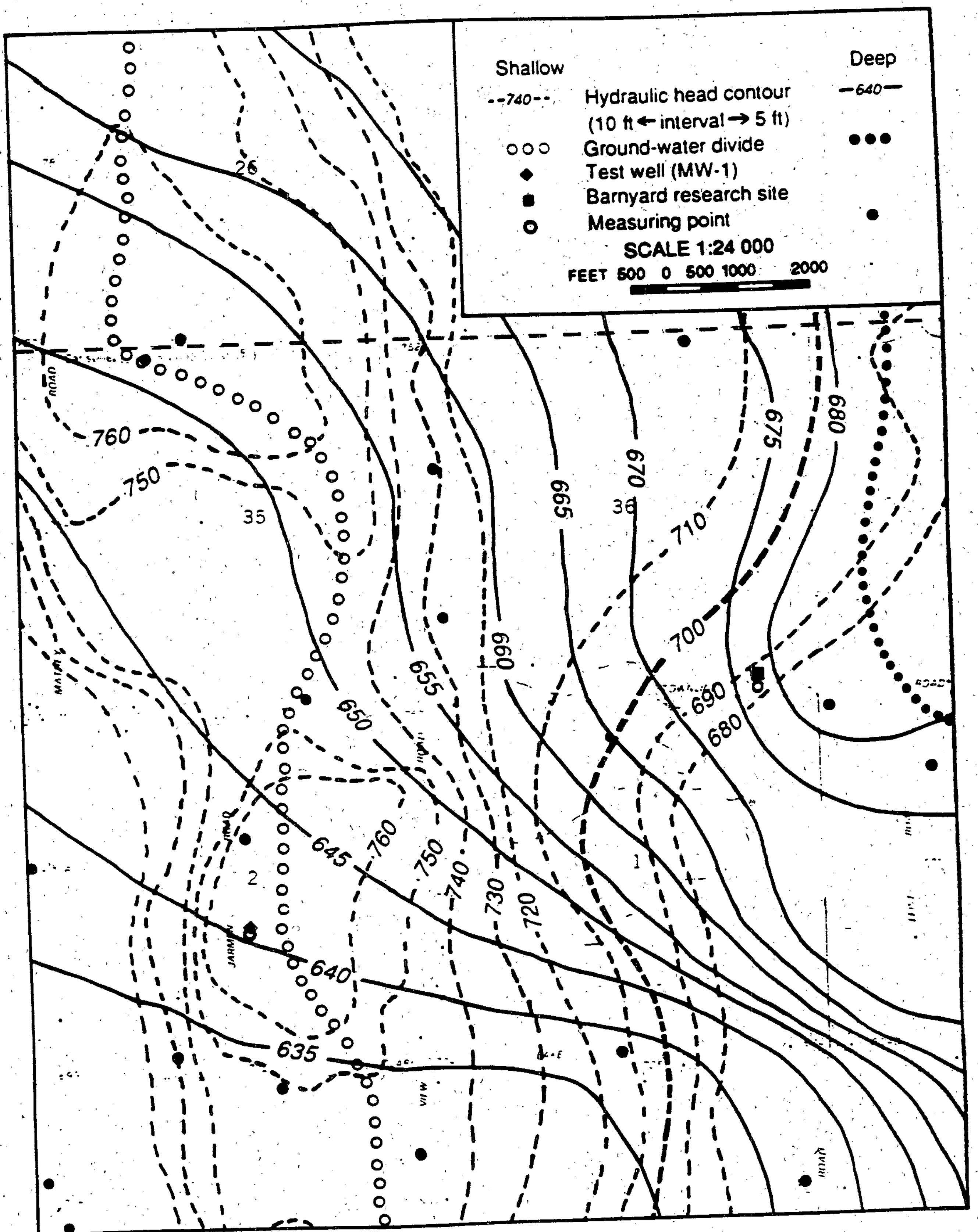


Figure B4. Distribution of hydraulic head in the shallow and deep ground-water systems in the Sevastopol study area, August 1989.

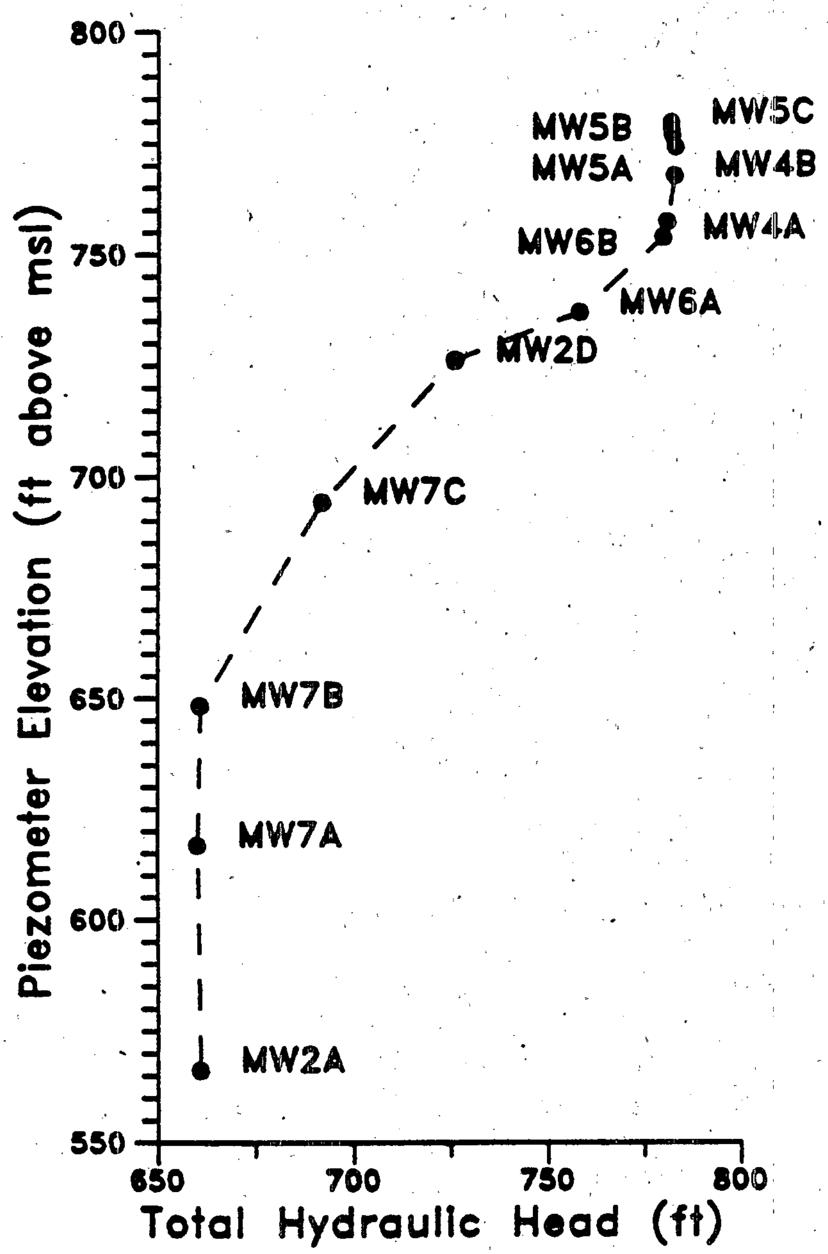


Figure B5. Profile of hydraulic head at the Sevastopol site in March 1989.

gradient occurred at about elevation 650 ft above msl, the approximate position of a prominent horizontal fracture zone.

A possible explanation for the large decrease in total hydraulic head with depth is a perched water table above a deeper unsaturated zone. Although during high water periods (March - May) there is no evidence of unsaturated conditions at depth at the site, unsaturated conditions at depth do occur during dry seasons. Piezometer MW7B, a piezometer of intermediate depth screened 100 ft below the surface (see table B1), was dry during much of the dry summer of 1989 even though shallower piezometers were continuously saturated. Apparently, previous "water-table" maps of the area, based on measurements in deeply cased domestic wells, incorrectly delineated a deeper potentiometric surface as the water table. Water levels in such deep wells are a function of the head differential, the hydraulic conductivity, and the rate of recharge to the system (Saines, 1981). Water-table measurements in shallow wells, combined with observed surface features such as wetlands and ponded water, show that a relatively shallow water table occurs at the site, in addition to the deeper potentiometric surface.

Water-Level Fluctuations

Significant temporal water-level fluctuations occurred at the Sevastopol test site, and water-level fluctuations in the deep zone are greater than in the shallow zone. Figure B6 is a hydrograph of water levels in MW3 and MW2A for the 1987-1989 period. Water levels in piezometer MW2A, finished in the deep system at 240 ft below the land surface, fluctuated by up to 95 ft in response to seasonal recharge during this period. The most significant water-level rises occurred just after snowmelt in March, 1988. Well MW3, finished about 60 ft below the surface in the shallow zone, fluctuated only about 45 ft during the observation period.

The rapid response of the shallow and deep piezometers to spring snowmelt suggests that both systems are directly connected to the land surface. The two systems respond differently during dry periods. The water level in MW3 (shallow system) drops sharply and then stabilizes at approximately 740 ft above sea level (depth 55 ft); the water level in MW2A (deep system) continues to drop steadily throughout the summer. The large and rapid water-level fluctuations in the deep system probably are caused by the presence of prominent conductive fracture zones not present in the shallow system.

Aquifer Tests

Specific capacity data, piezometer slug tests, and aquifer-pumping tests provided data on the distribution of transmissivity (T) and hydraulic conductivity (K) in the fractured dolomite. Additional data obtained from other ground-water monitoring projects in the area supplemented the Sevastopol test site measurements.

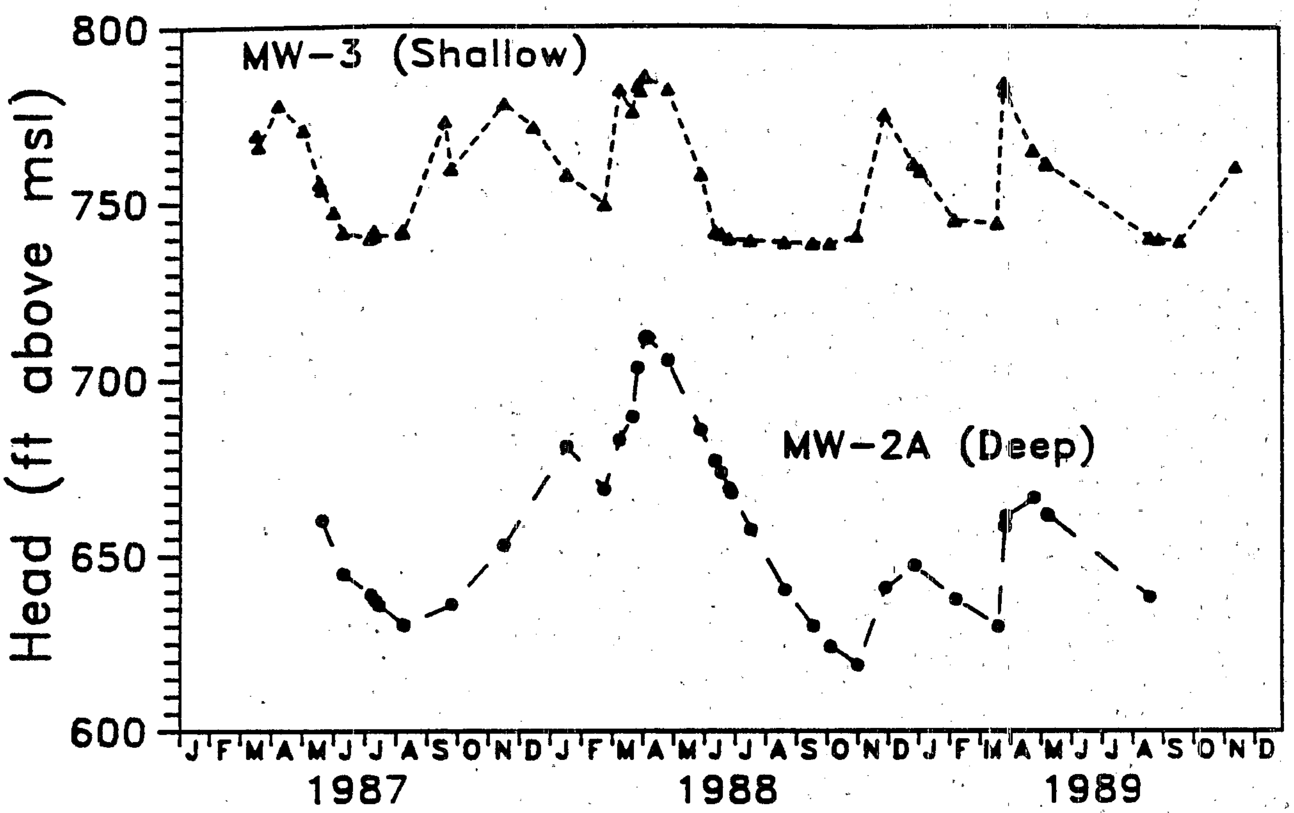


Figure B6. Hydrographs of water levels at the Sevastopol site.

Specific Capacity Data

Although detailed measurements of hydraulic properties of the dolomite were available at the Sevastopol site, construction of a numerical model (described below) required information about the distribution of hydraulic conductivity over a large area. Specific capacity data contained in well constructors' reports in the files of the WGNHS allowed regional estimates of hydraulic conductivity using the program TGUESS (Bradbury and Rothschild, 1985), which estimates transmissivity and hydraulic conductivity from information in well constructors' reports. On the basis of 249 well constructors' reports, the transmissivity of the dolomite varied from 1.6×10^{-8} ft/sec to 3.9×10^{-4} ft/sec. Because the hydraulic conductivity values were log-normally distributed, the geometric mean of 8.3×10^{-6} ft/sec is believed to represent the best estimate of the conductivity over the entire thickness of the aquifer (Bouwer, 1978).

Slug Tests

Results of 14 slug tests (table B2) gave the distribution of hydraulic conductivity in the dolomite. Slug tests consisted of instantaneously changing the water level in a well or piezometer by inserting or removing a solid slug of inert material and measuring water-level recovery using a recording datalogger. Slug tests were analyzed by the Hvorslev (1951) and Cooper and others (1967) methods. Hydraulic conductivities ranged from 3.2×10^{-9} ft/sec to 3.6×10^{-3} ft/sec, with a geometric mean of 3.2×10^{-6} ft/sec (table B2). The highest hydraulic conductivity, 3.6×10^{-3} ft/sec, was recorded in piezometer MW7A, which is screened across a fracture zone at an elevation of 617 ft above msl (depth 180 ft, see table B1). Very low hydraulic conductivities at piezometers H2B, MW5A, and MW6B suggest that these piezometers intersect very few fractures, and these results are probably characteristic of the hydraulic conductivity of unfractured dolomite blocks or massive units with few fractures.

Pumping Tests

Multi-well pumping tests suggested that the shallow and deep parts of the aquifer have different hydraulic properties. One test, on wells finished in the shallow zone, was conducted for 24 hours at a pumping rate of about 0.05 ft^3/sec (22 gpm); a second test, on wells finished in the deep zone, was conducted for 19 hours at a pumping rate of 0.079 ft^3/sec (35 gpm). Drawdowns were measured in adjacent wells and piezometers and in the pumped wells. Table B3 summarizes results of these tests. The pumping tests have three important results. First, the transmissivity of the shallow zone is significantly less than the transmissivity of the deeper zone. Second, the ability of the shallow part of the aquifer to sustain a 24-hour pumping test at the rate used is additional evidence that this upper zone contains significant quantities of ground water. Third, the aquifer is significantly anisotropic vertically and horizontally.

Table B2. Results of slug tests at the Sevastopol test site and Barnyard research site.

Well or Piezometer	K (ft/sec)
MW2A	1.6×10^{-4}
MW2B	1.0×10^{-5}
MW2D	4.1×10^{-6}
MW5A	6.9×10^{-9}
MW6A	4.3×10^{-5}
MW6B	5.5×10^{-8}
MW7A	3.6×10^{-3}
H1A	5.3×10^{-8}
H1B	1.8×10^{-6}
H2A	1.4×10^{-6}
H2B	3.2×10^{-9}
H2C	1.0×10^{-5}
H3A	2.9×10^{-6}
H3B	2.4×10^{-6}
Maximum	3.6×10^{-3}
Minimum	3.2×10^{-9}
Geometric Mean	3.5×10^{-6}

Table B3. Results of pumping tests at the Sevastopol site.

Test Zone:	Shallow, 0-60 ft	Deep, 150-240 ft
Date of Test:	March 1988	May 1989
Test Duration:	24 hours	19 hours
Pumped Well:	MW3	MW1
Pumping Rate:	0.05 ft^3/sec (22 gpm)	0.079 ft^3/sec (35 gpm)
Observation Wells:	MW4, MW5, MW2D	MW2A, MW7A
Transmissivity:	1.1×10^{-3} ft^2/sec	5.9×10^{-2} ft^2/sec
Storage Coefficient:	0.04	0.0014

An analysis of directional transmissivity using the method of Papadopoulos (1965) yielded the following values for the deep zone:

T_{xx}: 0.15 ft^2/sec; azimuth N33°E

T_{yy}: 0.037 ft^2/sec; azimuth N123°E

S: 0.0014

where T_{xx} and T_{yy} are the principal directions of the transmissivity tensor, and by definition are perpendicular to each other. This result is based on only two observation wells, so the transmissivity ellipse cannot be determined uniquely. However, this result is consistent with the assumption that for the Sevastopol site the principal directions of the transmissivity tensor are approximately parallel to the major fracture directions observed in the field. The horizontal anisotropy ratio is then T_{xx}/T_{yy} = 4.2. The ratio of horizontal to vertical conductivity could not be determined with the limited number of observation wells available at the site.

Water Chemistry and Isotope Analyses

Water Chemistry

Major-ion and isotopic results indicate little variation with depth or position at the Sevastopol site and suggest that the ground water is well mixed. Table B4 summarizes the results of the chemical analyses. As expected in a dolomite aquifer, ground water is of the calcium-magnesium-bicarbonate type. Dissolved calcium and magnesium ranged respectively from about 50 to 90 and 25 to 50 milligrams per liter (mg/l). The water is of good quality; nitrate content was consistently below the 10 mg/l drinking water standard.

Isotopes

Water samples for tritium (^3H) and oxygen-18 (^{18}O) were collected from 13 wells and piezometers in Door County during November 1988. Results are presented in table B5

Ground water in the fractured dolomite of Door County is generally less than 35 years of age based on qualitative tritium interpretations (see table 3, Chapter III). The ^{18}O data are consistent with this age interpretation. Isotopically "young" water is expected in Door County because of the high degree of fracturing of the dolomite and the thin soil cover that allow rapid recharge.

Table B4. Chemical analyses of Door County samples (all values are in milligrams per liter unless otherwise indicated)

Sample ID	Sample Date	Temp. °C	Cond. umho	pH	Diss. Oxygen	Ca	Mg	Na	K	Fe	Mn	HCO_3	Cl	SO_4	NO_3	Ca/Mg	Saturation Index Calcite	Saturation Index Dolomite	Saturation Index PCO_2
MW1	11/02/88	7.9	612.9	7.10	4.4	73.1	35.4	1.8	2.4	0.02	<0.00	329.2	12.0	17.5	5.0	2.07	-0.29	-0.82	-1.76
MW1	03/22/89	7.9	736.9	7.80	12.5	60.5	30.6	1.2	1.2	<0.01	<0.00	298.7	8.5	15.9	1.5	1.98	0.33	0.44	-2.44
MW2A	11/02/88	7.6	549.4	7.21	1.9	66.4	32.4	1.5	1.1	0.03	<0.00	310.9	8.0	14.9	2.0	2.05	-0.24	-0.71	-1.86
MW2A	03/22/89	7.6	531.1	6.95	3.5	59.5	27.6	3.3	2.8	<0.01	0.01	274.3	11.0	19.9	2.5	2.15	-0.56	-1.38	-1.62
MW2D	11/02/88	8.1	615.4	6.99	3.5	75.2	36.6	1.0	2.8	0.55	0.01	359.7	7.5	18.1	2.0	2.05	-0.33	-0.88	-1.56
MW2D	03/22/89	8.2	465.1	7.35	10.0	59.3	29.8	2.1	2.4	<0.01	0.01	280.4	12.5	19.2	2.5	1.99	-0.15	-0.51	-2.01
MW3	11/02/88	8.1	615.4	6.90	3.9	77.4	38.8	1.6	3.3	0.08	<0.00	359.7	7.0	17.2	3.0	1.99	-0.45	-1.12	-1.54
MW3	03/22/89	8.8	532.7	7.45	8.1	60.1	30.3	1.9	2.7	<0.01	<0.00	280.4	13.0	20.1	3.0	1.99	-0.03	-0.27	-2.11
MW4A	11/02/88	8.2	588.2	7.21	2.4	68.7	34.0	6.9	2.6	0.31	0.33	341.4	5.0	26.2	<0.5	2.02	-0.19	-0.59	-1.82
MW4A	03/22/89	8.4	578.9	7.20	3.0	64.6	33.3	7.7	1.2	0.10	0.15	347.5	5.0	--	0.0	1.94	--	--	--
MW6A	11/02/88	8.1	571.8	7.02	1.5	67.7	32.6	2.1	1.4	0.02	0.01	341.4	7.0	17.6	<0.5	2.08	-0.34	-0.92	-1.60
MW6A	03/22/89	8.2	664.7	7.55	5.5	57.1	27.1	1.5	1.8	<0.01	<0.00	268.2	9.5	17.3	2.5	2.10	0.02	-0.19	-2.23
MW6B	11/02/88	9.1	660.0	7.55	5.0	70.5	33.5	23.3	1.9	<0.01	<0.00	335.3	11.0	60.0	1.0	2.10	0.18	0.14	-2.14
MW6B	03/22/89	8.7	947.0	7.35	5.0	74.5	37.1	13.5	1.0	0.05	0.32	402.3	8.5	42.7	0.0	2.01	0.08	-0.05	-1.86
MW6C	03/22/89	5.8	1303.4	7.85	9.4	86.9	50.1	57.8	2.7	0.01	0.02	420.6	37.5	--	0.5	1.74	—	--	--
MW7A	11/02/88	7 8	607.0	7.05	1.5	72.6	35.0	3.3	2.9	0.06	<0.00	310.9	19.0	22.0	4.5	2.07	-0.38	-0.99	-1.72
MW7A	03/21/89	7.7	525.0	8.00	--	60.8	30.9	1.6	1.6	<0.01	<0.00	310.9	5.0	13.2	1.0	1.97	0.11	0.04	-2.08
H1A	11/02/88	8.5	683.0	7.91	2.4	65.2	35.6	20.8	7.1	0.14	0.03	353.6	13.5	27.9	<0.5	1.83	0.65	0.93	-2.08
H1A	03/20/89	8.3	927.7	7.40	6.3	71.8	39.6	20.0	5.8	0.01	0.05	390.2	32.0	29.3	0.0	1.81	0.09	0.02	-2.02
H1A	06/08/89	9.0	953.8	6.40	4.8	71.7	37.4	12.4	5.5	0.08	0.01	--	28.5	--	0.0	1.91	--	--	--
H1B	11/02/88	8.6	704.8	7.99	--	77.4	40.8	5.3	2.4	0.05	<0.00	396.2	19.0	34.8	<0.5	1.89	0.74	1.31	-1.93
H1B	03/20/89	8.3	912.7	7.15	7.8	75.8	42.8	3.2	2.4	<0.01	0.02	384.1	21.0	35.1	0.0	1.77	-0.14	-0.44	-1.92
H1B	06/08/89	7.7	928.3	6.50	2.8	86.1	47.3	3.6	4.1	1.54	0.20	--	21.0	--	0.0	1.82	--	--	--
H2A	11/02/88	8.2	718.7	7.10	--	70.7	36.5	7.4	2.7	0.08	0.02	359.7	15.5	31.4	<0.5	1.94	-0.29	-0.78	-1.98
H2A	06/08/89	8.5	1115.9	6.30	3.1	90.3	50.0	16.2	18.8	0.67	0.34	--	59.5	--	0.0	1.80	--	--	--
H2B	11/02/88	8.8	870.6	7.20	—	77.8	41.7	11.8	3.8	0.04	0.03	371.9	25.5	49.7	<0.5	1.87	-0.10	-0.38	-1.77
H2B	06/08/89	7.4	1105.2	6.30	2.9	78.7	43.6	52.3	15.4	0.38	0.59	--	54.5	--	0.0	1.81	--	--	—
H2C	11/02/88	10.1	726.4	7.10	--	82.1	43.7	6.5	3.5	0.24	0.07	371.9	25.5	47.5	<0.5	1.88	-0.17	-0.46	-1.77
H2C	06/08/89	6.9	1090.2	6.40	2.7	90.9	50.7	15.5	16.2	0.46	0.22	432.8	58.5	51.0	0.0	1.79	-0.81	-1.81	-1.72
H3A	11/02/88	8.3	481.8	7.60	--	49.7	25.5	3.9	1.4	0.08	0.01	298.7	1.5	11.3	<0.5	1.96	0.07	-0.06	-2.53
H3A	03/20/89	8.2	487.7	7.50	5.7	52.2	28.2	5.2	0.8	<0.01	<0.00	310.9	0.5	13.5	0.0	1.85	-0.00	-0.19	-2.43
H3A	06/08/89	10.7	476.6	6.20	6.4	49.5	26.5	20.0	1.7	0.06	0.01	--	3.5	--	0.0	1.87	—	--	--
H3B	11/02/88	9.1	1068.3	7.51	--	69.2	36.3	60.1	4.6	0.11	<0.00	359.7	18.5	128.1	<0.5	1.91	0.11	0.06	-1.45
H3B	03/20/89	8.0	950.6	7.15	8.3	88.6	49.6	10.0	3.2	<0.01	0.00	414.5	27.5	58.8	1.5	1.79	-0.07	-0.30	-1.66
H3B	06/08/89	7.9	1180.3	6.30	2.3	81.1	48.0	30.8	20.0	0.77	0.61	--	40.0	--	1.0	1.69	—	—	—

Table B5. Isotope results for Door County.

Well	Sample Date	Tritium (TU)	+/- Error (TU)	Estimated Age (yr)	^{18}O (per mil)
MW1	11/02/88	25	8	<35	-11.18
MW2A	11/02/88	17	8	<35	-11.19
MW2D	11/02/88	18	8	<35	-11.15
MW4A	11/02/88	13	8	<35	-9.58
MW5A	11/02/88	26	8	<35	-9.70
MW6A	11/02/88	23	8	<35	-11.23
H1A	11/02/88	30	8	<35	--
H1B	11/02/88	32	8	<35	--
H2A	11/02/88	29	8	<35	--
H2B	11/02/88	44	8	<35	--
H2C	11/02/88	41	8	<35	--
H3A	11/02/88	6	8	>20	--
H3B	11/02/88	40	8	<35	--

NUMERICAL MODELING

Justification and Code Selection

Numerical simulations of the ground-water system in the fractured dolomite aquifer of central Door County offer the best available analysis of the ground-water flow system and the best available delineation of the zone of contribution (ZOC) for a given well. Although commonly available numerical codes are based on the equations of ground-water movement through porous media and are not strictly applicable to fractured rocks, such models can successfully simulate ground-water movement through fractured aquifers as long as the scale of the problem is larger than the scale of fracturing. This is the case in Door County, where small fractures in the dolomite commonly occur at a spacing of a few inches or feet and the horizontal distance between major vertical fractures (visible in aerial photographs; see fig. B2) is usually less than 30 ft. In contrast, the area simulated by the model includes many square miles, and the model node spacings are much larger than the observed fracture spacings.

The wellhead protection modeling reported here builds on the results of several previous investigations that successfully simulated ground-water flow in parts of Door County using numerical codes. Bradbury (1982) simulated ground-water movement at a site in northern Door County using the two-dimensional parameter estimation inverse code of Cooley (1977) and a three-dimensional finite difference forward code (Trescott and Larson, 1976). Nauta (1987) extended this work to a three-dimensional model covering all mainland Door County. Both investigations focused on simulating ground-water discharge to Green Bay and Lake Michigan, and the models included only limited detail in the center of the county. Emmons (1987) included the fractured dolomite of Door County in a regional model simulating flow through the entire bedrock system in eastern Wisconsin, but his model was not detailed enough for wellhead protection studies.

The purpose of the numerical modeling study at the Sevastopol site is to simulate as accurately as possible the ground-water flow system at the site with the goal of delineating the ZOC for a hypothetical municipal well. The modular ground-water flow code of McDonald and Harbaugh (1988) provides for three-dimensional simulations incorporating vertical and areal anisotropy and heterogeneity. This is a widely available and generally accepted computer code, which is in the public domain and can be adapted to run on personal computers. The PATH3D particle-tracking code (Zheng and others, in press) links directly to the flow model and was the main tool used in ZOC delineation in this study.

Conceptual Model

The Door County model assumes a completely saturated three-dimensional ground-water system with hydrogeologic characteristics based on the results of field investigations in and around the Sevastopol study area. The observation of significant changes in total hydraulic head with depth, combined with the knowledge that extreme variations in hydraulic conductivity occur with depth, make a three-dimensional model essential for accurate simulation of ground-water flow paths from the land surface to a well. As previously described, an unsaturated zone occurs under certain conditions beneath the upper saturated zone at the test site. Because the flow model cannot simulate unsaturated flow, this zone was treated as completely saturated. The resulting simulations are thus probably overprotective for wellhead protection purposes because ground water moves more rapidly through a saturated system than through an unsaturated system.

Boundaries of the ground-water model are conceptually simple, and consist of constant heads where the dolomite aquifer intersects Green Bay on the western side and Lake Michigan on the eastern side of the county, constant heads along the Sturgeon Bay Ship Canal to the south, zero-flux boundaries along the ground-water divide north of the study area, and a zero-flux boundary at the base of the model where the underlying Maquoketa shale forms a regional aquitard. Additional constant-head boundaries occur where surface streams, such as Lilly Bay Creek and Donlans Creek, are in continual communication with the aquifer. The upper boundary of the aquifer is open to recharge, which varies spatially

Model Grid Design

The finite-difference grid used in the Door County model (fig. B7) consists of 24 rows, 23 columns, and 4 layers, for a total of 2208 nodes, of which approximately 75 percent are active. The node spacing is irregular, and ranges from 5000 ft at the model boundaries to 500 ft in the area of interest around the test site. The grid is oriented at an azimuth of N30°E so that the rows and columns in the model approximately parallel the principal directions of the transmissivity tensor estimated from the pumping test.

For modeling purposes the ground-water flow system is divided into four horizontal layers based on observed depth variations (fig. B8). The layers are numbered one to four, with layer 1 being the shallowest and layer 4 the deepest. In model simulations ground water can move only horizontally within layers and only vertically between layers. The layers cover increasingly larger areas of the finite-difference grid, with layer 1 covering the smallest area and layer 4 covering the largest area. Table B6 summarizes the layer thicknesses, characteristics, and input parameters. In all layers, a horizontal anisotropy of 4:1 was assumed between the northeast (along model columns) and northwest (along model rows), corresponding to the findings of the pumping test conducted at the test site.

Model Calibration

Steady-state model calibration consisted of adjusting model parameters until the model suitably reproduced the field-measured water-table and potentiometric-surface maps of late August 1989 (fig. B4). The model proved very sensitive to recharge rates and to the vertical

Table B6. Layer characteristics for Door County model.

Model Layer	Layer Type	Conceptual Representation	Thickness (ft)	K_{HMin} (ft/sec)	$K_{HMin}:K_v$ Ratio	Average Porosity
1	Unconfined	Upper system	0-75	1.8×10^{-5}	1:1	0.01
2	Semiconfined	Semiconfining bed	0-80	8.3×10^{-6}	10:1 to 1000:1	0.01
3	Semiconfined	Narrow fracture zone	0-5	1.5×10^{-2}	1:1	0.05
4	Semiconfined	Lower system	0-365	1.0×10^{-5} to 5.0×10^{-4}	1:1	0.05

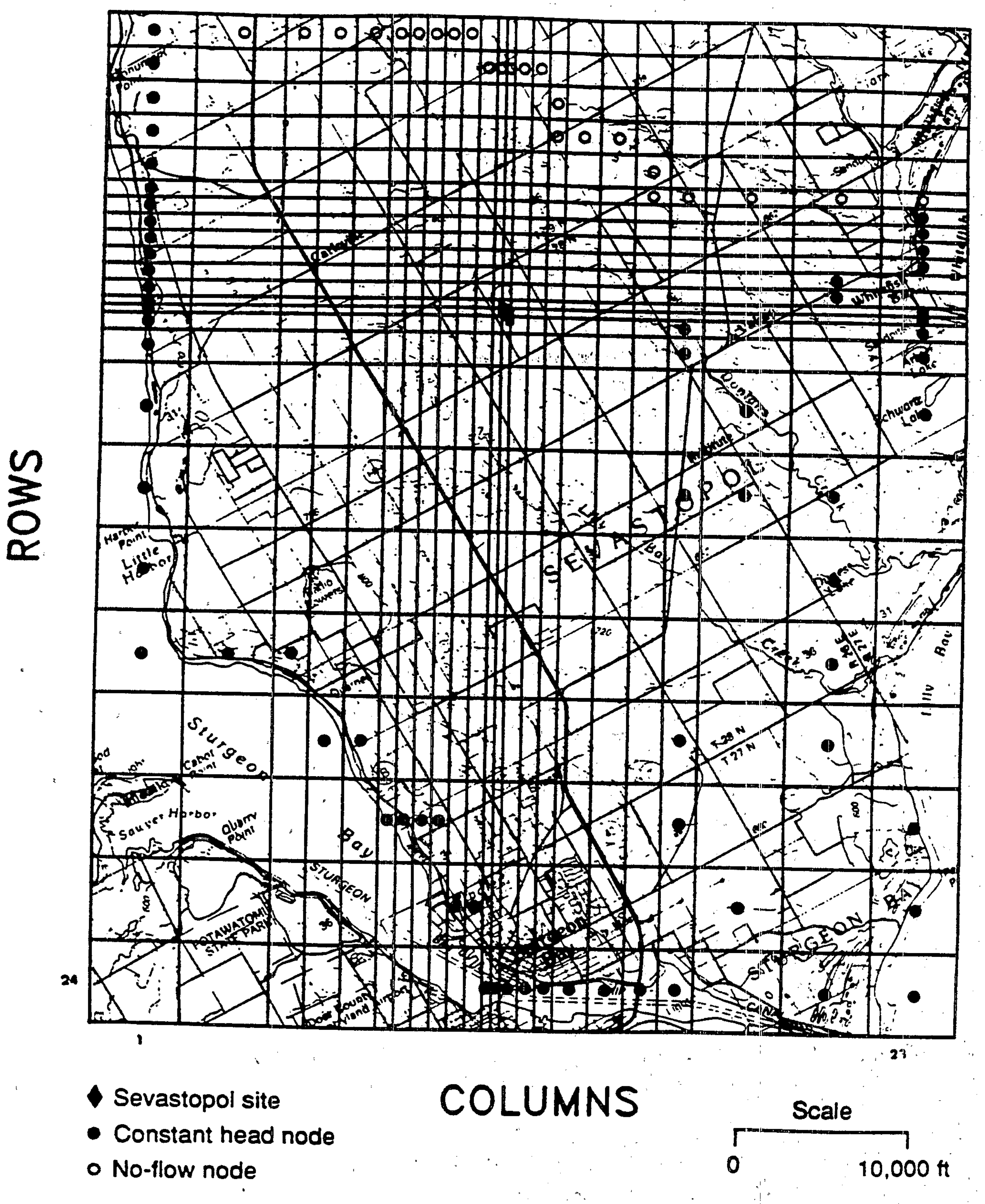


Figure B7. Finite-difference grid used in numerical model of ground-water flow at the Sevastopol site.

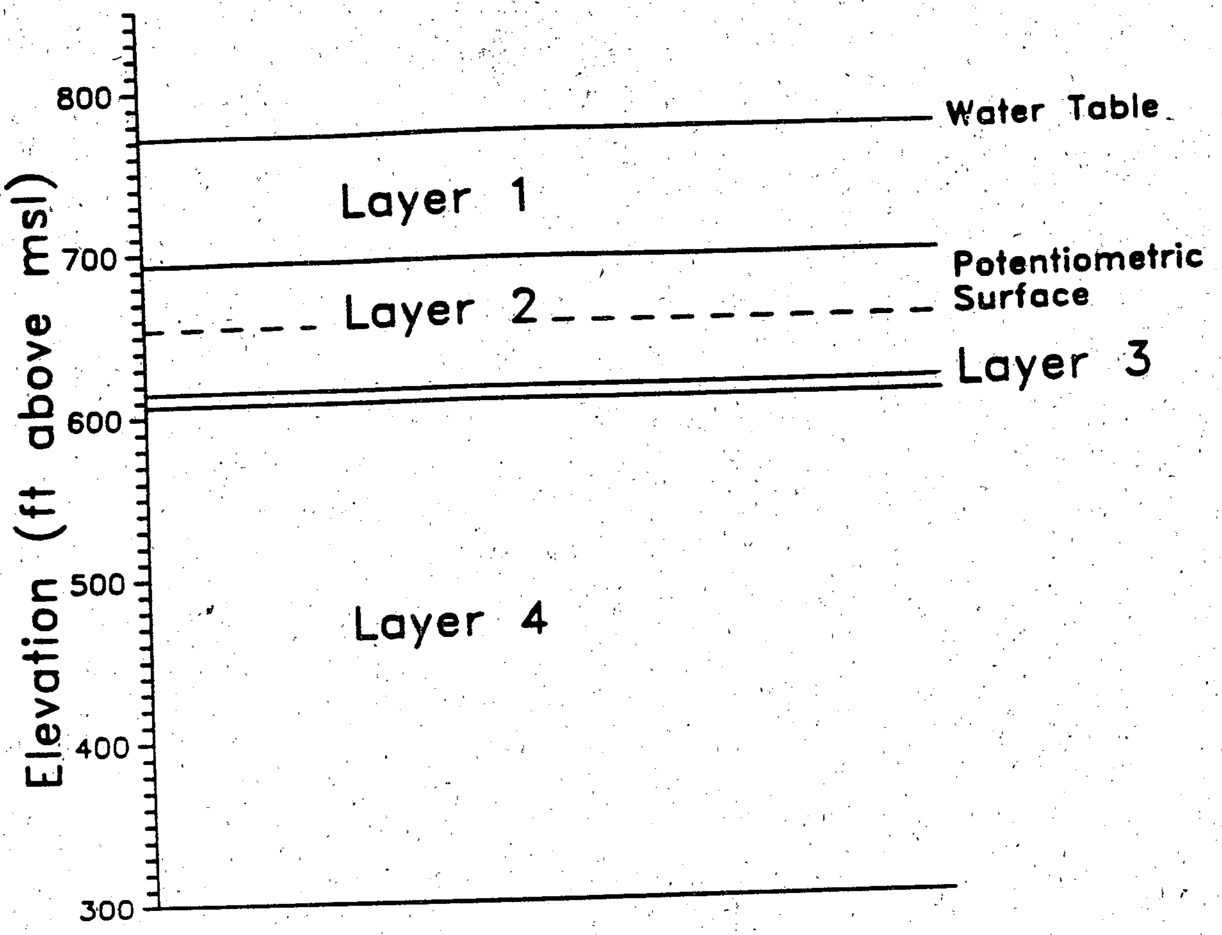


Figure B8. Configuration of model layers used in numerical model of ground-water flow at the Sevastopol site.

hydraulic conductivities of each layer. Previous models of Bradbury (1982) and Nauta (1987) provided baseline data for both these parameters. In the absence of detailed field data on the variability of recharge, an initial estimate of the recharge distribution was obtained using the inverse procedure of Stoertz and Bradbury (1989). Adjustment and smoothing of the resulting recharge matrix, using the surficial materials maps of Sherrill (1978) and Schuster and others (1989), gave the recharge distribution used in final model calibration.

Calibration to hydraulic heads alone generally does not yield a unique solution to a ground-water flow problem. Calibration of the Door County model considered four criteria for which field data were available:

1) reasonable match of the hydraulic head maps for the upper and lower layers,
2) accurate simulation of vertical hydraulic gradients measured at piezometer nests,
3) accurate simulation of the location of ground-water divides,
4) accurate simulation of the ground-water flux measured as base flow in surface streams.

Figure B9 shows simulated late-summer hydraulic heads for a "best-calibration" run in the area around the Sevastopol test site (compare to field data in fig. B4). Although differences exist between the simulated and measured heads, the match is considered acceptable for wellhead protection simulations.

WHPA Simulations

Steady-State Flow Simulation

A steady-state simulation produced the delineation of a reasonable ZOC at the Sevastopol test site. The simulation includes a hypothetical pumping well at node (13, 12), the location of the Sevastopol test site (fig. B7). Currently, only two communities in the county own wells, and most county residents obtain their water from individual private wells. Under current development pressure, however, more community wells may be installed in the county in the future. There is interest in ZOC delineation for public and private wells. Therefore, the simulation included a hypothetical community well pumping at 100 gpm. With current 170-ft well-casing restrictions, water enters the pumping node only in layers 3 and 4. Due to the high transmissivity of layers 3 and 4 and to the averaging of pumping stress over an entire node, the pumping simulation produced only a small cone of depression in the dolomite aquifer; such results are commonly observed in field pumping tests in the county.

Particle-Tracking Simulation

Coupling the PATH3D particle-tracking code (Zheng and others, in press) with the three-dimensional head distribution produced by the pumping simulation, gives a picture of

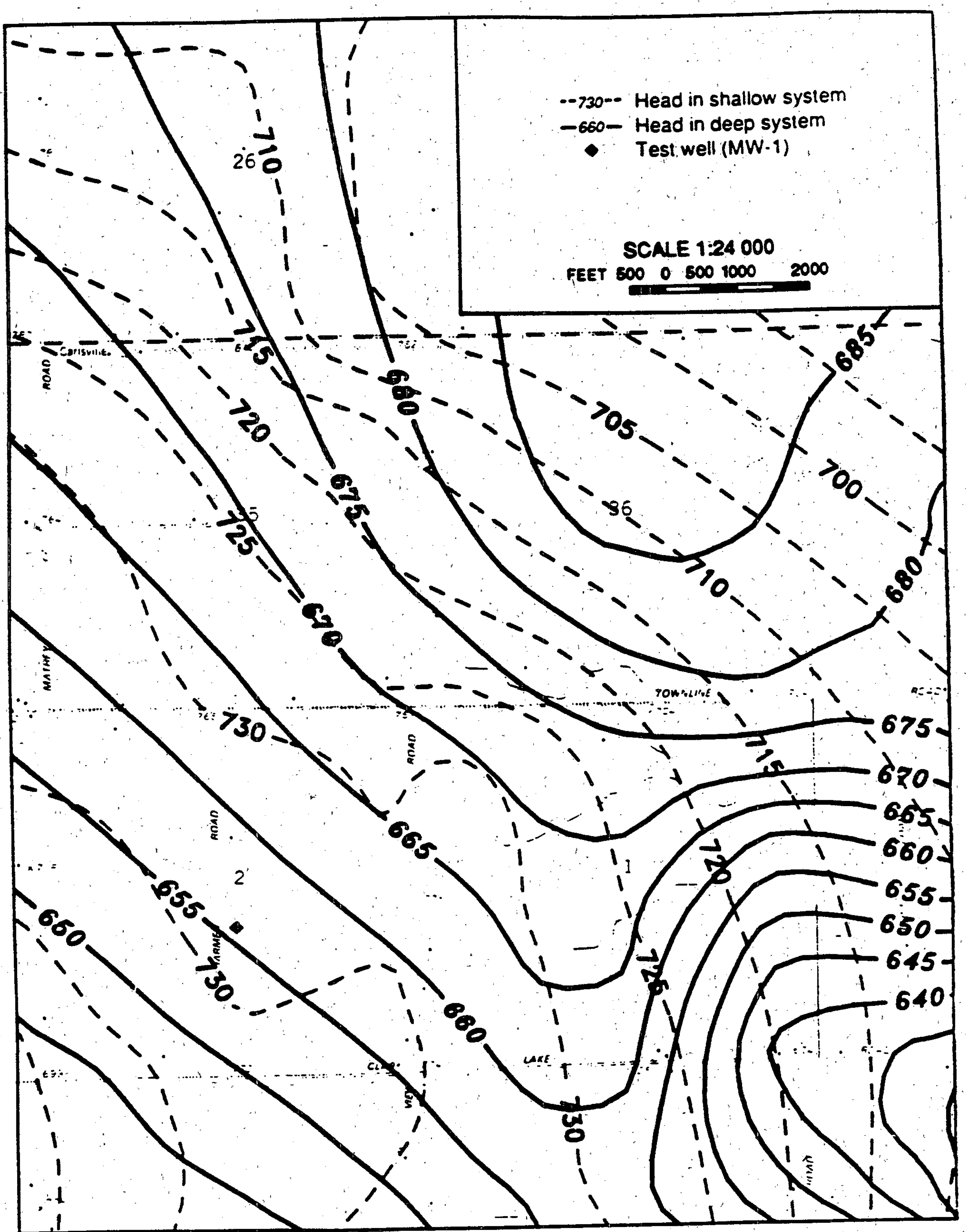


Figure B9. Simulated hydraulic head distribution at the Sevastopol site.

the three-dimensional ZOC for the hypothetical well under stressed conditions. In the steady-state simulations, PATH3D moves particles upgradient from the well until the particles emerge at the water table. The final particle distribution at the water table represents the land surface area where recharge eventually becomes ground water produced by the well; the particle paths represent three-dimensional ground-water flow paths.

Figure B10 shows the results of the PATH3D simulations in areal view. The simulation used eight particles arranged around the hypothetical well (pumping 100 gpm) in layer 3 (for clarity, fig. B10 shows only seven particle paths). The ZOC is narrow and elliptical, extending about 2 miles northeast of the hypothetical pumping well (see fig. 16). Figure B10 also shows simulated travel times from the recharge area to the hypothetical well.

The numerical model also provides a picture of ground-water movement in the vicinity of the hypothetical pumping well. Figure B11 is a cross-section through the ZOC for the hypothetical pumping well and shows how a thin, permeable fracture zone (at about 180 ft below the land surface) affects ground-water movement. In this figure, particles were started at various depths along the well casing and moved upgradient to their recharge points. Notice that the horizontal fracture zone is the main conduit for particle movement to the well. Ground water does not move with a constant velocity along the flow path but instead moves most rapidly in a horizontal direction in layer 3 (about 180 ft below the land surface) and much slower vertically between layers 1 and 2.

Figure B11 also shows how the depth of casing of the pumping well can affect the well's ZOC. Particles recharging farthest from the well enter the well bore at lower elevations than particles recharging near the well (path 4). Thus, the more deeply the well is cased, the larger the ZOC becomes.

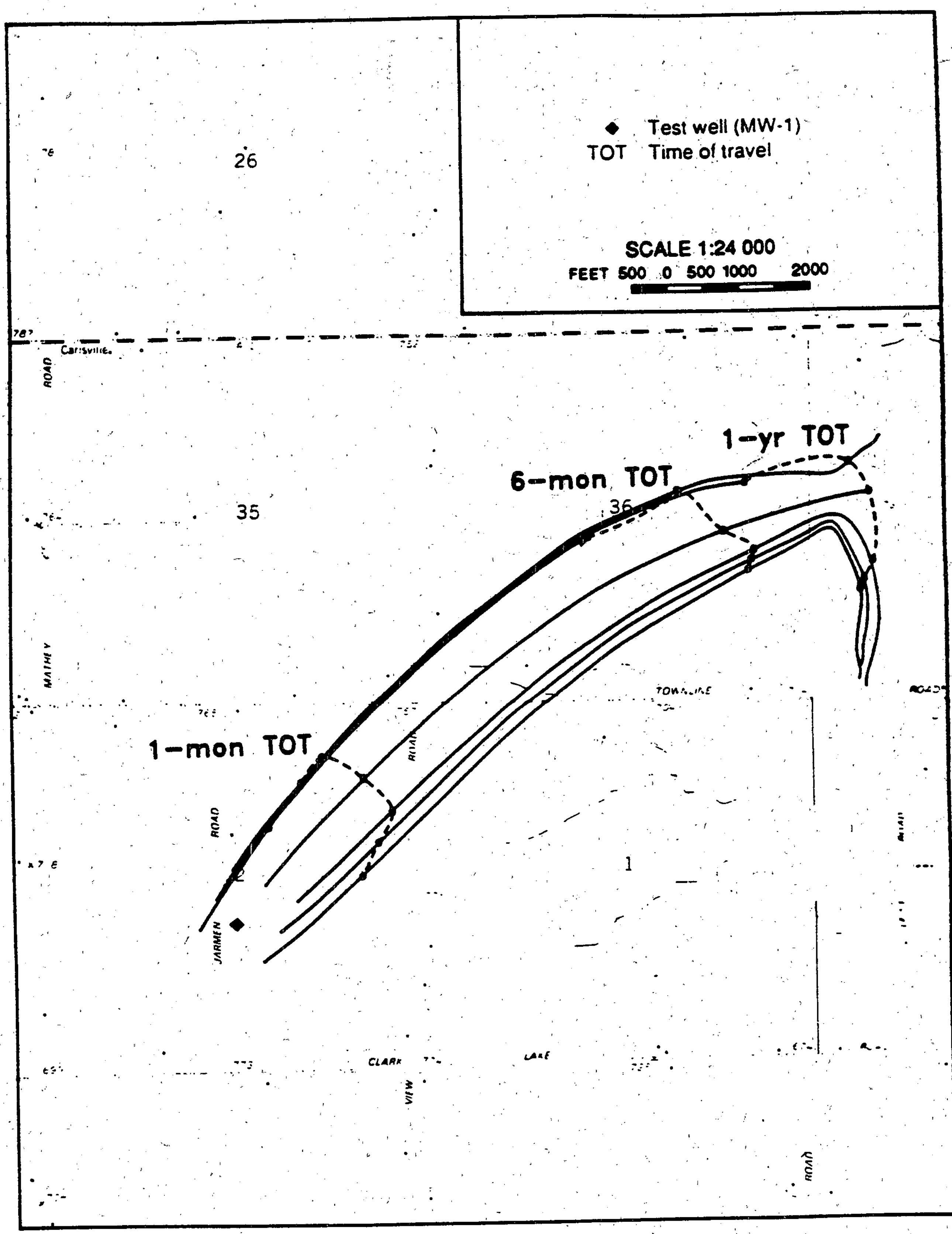


Figure B10. Simulated particle paths using the PATH3D code, Sevastopol site.

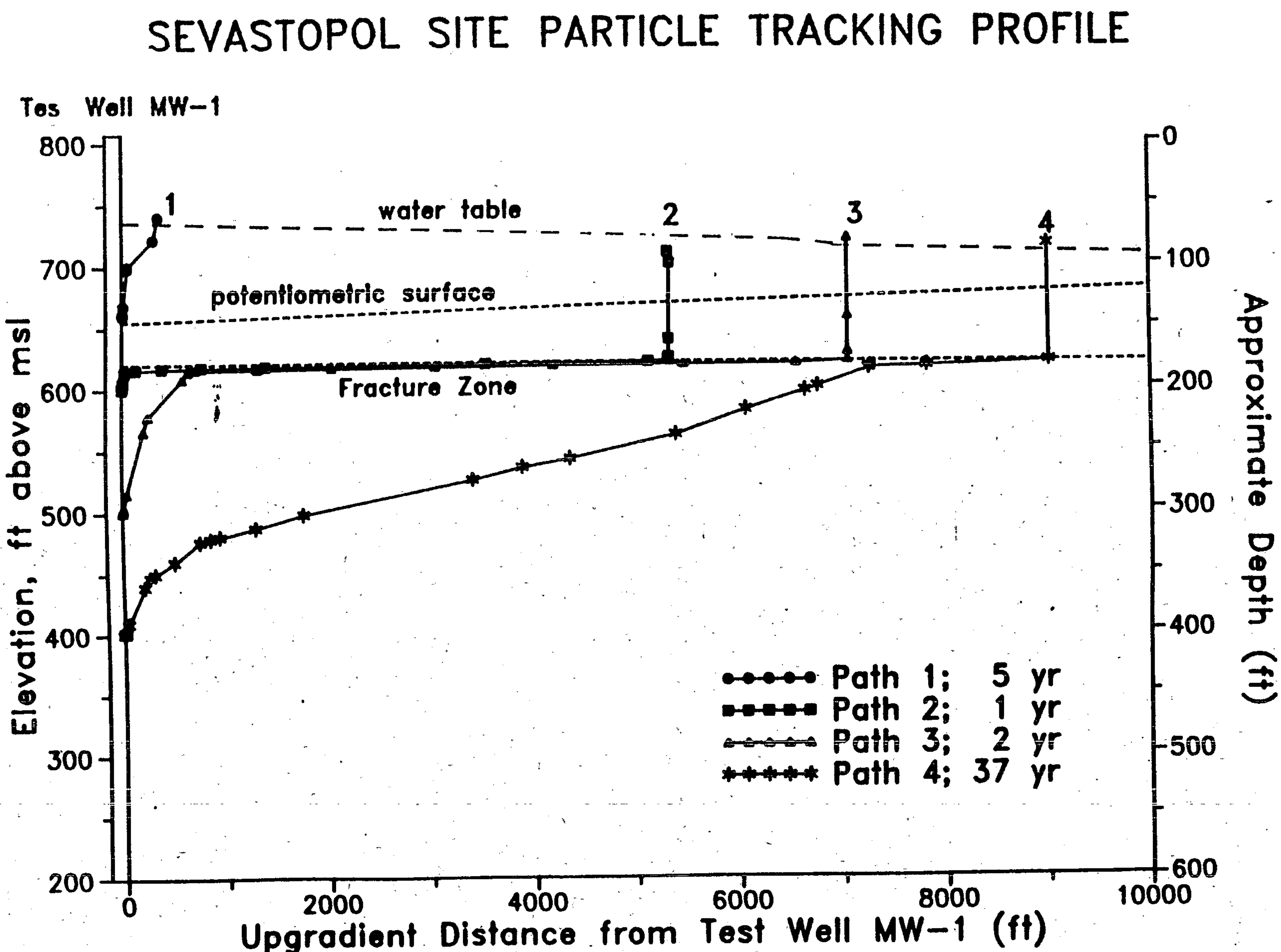


Figure B11. Cross section of the Sevastopol site showing vertical ground-water movement from the surface to various depths along a well casing.

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