DESCRIPTION AND EVALUATION OF SELECTED METHODS USED TO DELINEATE WELLHEAD-PROTECTION AREAS AROUND PUBLIC-SUPPLY WELLS NEAR MT. HOPE, KANSAS

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	*By*	*To obtain*
inch	2.54	centimeter
inch per year (in/yr)	2.54	centimeter per year
foot (ft)	0.3048	meter
mile	1.609	kilometer
foot per day (ft/d)	0.3048	meter per day
foot per year (ft/yr)	0.3048	meter per year
foot per mile (ft/mi)	0.1894	meter per kilometer
foot squared per day (ft^2/d)	0.0929	meter squared per day
foot squared per year (ft^2/yr)	0.0929	meter squared per year
gallon per minute (gal/min)	0.06309	liter per second
gallon per day	0.06309	liter per day
cubic foot per day (ft^3/d)	28.32	cubic meter per day
cubic foot per year (ft^3/yr)	28.32	cubic meter per year

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929-- a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

SYMBOLS USED IN REPORT

Symbol	Dimensions (L, distance M, mass T, time)	Explanation
B	L	Saturated or aquifer thickness.
C	ML^{-3}	Concentration of dissolved chemical species.
D	L^2T^{-1}	Coefficient of hydrodynamic dispersion.
H	L	Length of open or screened interval in well.
h	L	Total hydraulic head or altitude of water table.
i	([1])	Gradient of water table or potentiometric surface.
K	LT^{-1}	Hydraulic conductivity.
n	([1])	Porosity or effective porosity.
Q	L^3T^{-1}	Pumping rate.
q	LT^{-1}	Specific discharge or Darcian velocity.
R	LT^{-1}	Rate of natural recharge.
r	L	Radius or distance from well.
r_i	L	Radius of influence of well.
S	([1])	Storage coefficient or specific yield.
s	L	Drawdown.
T	L^2T^{-1}	Transmissivity.
t	T	Time.
u	([1])	Parameter from well-function table.
V	LT^{-1}	Seepage velocity.
W	LT^{-1}	Volume of flux per unit area.
$W(u)$	([1])	Well function.
x	L	Cartesian coordinate.
y	L	Cartesian coordinate.

[1]Dimensionless.

DEFINITION OF TERMS

Adsorption--The adhesion of an extremely thin layer of molecules (as of gases, solutes, or liquids) to the surface of solid bodies or liquids with which they are in contact.

Advection--The horizontal flow of a mass of water in an aquifer.

Aquifer--A formation, or group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs.

Aquifer test--A test made by pumping a well for a period of time and observing the change in hydraulic head in the aquifer. An aquifer test may be used to determine aquifer or well characteristics.

Assimilative capacity--The ability of the aquifer to attenuate the concentrations of contaminants to acceptable levels before they reach a well.

Capture zone--The volume of aquifer through which ground water flows to a pumped well during a given time of travel.

Chemical contamination--The introduction of organic or inorganic contaminants into a well from an aquifer.

Confined aquifer--An aquifer that contains water under pressure significantly greater than atmospheric. Its upper limit is the bottom of a bed of distinctly smaller hydraulic conductivity than that of the aquifer material itself.

Contaminant--An undesirable substance not normally present, or an unusually large concentration of a naturally occurring substance, in water, soil, or other environmental medium.

Diffusion--The process whereby particles of liquids, gases, or solids intermingle as the result of their spontaneous movement caused by thermal agitation and in dissolved substances move from a region of larger to one of smaller concentration.

Dilution--The action of diminishing the strength, flavor, or brilliance by mixing.

Direct contamination--The introduction of contaminants directly into a well by spilling or pouring the contaminants into or along the well casing.

Dispersion--The spreading and mixing of chemical constituents in ground water caused by diffusion and mixing due to microscopic variations in velocities within and between pores.

Drawdown--The extent to which well pumping lowers the water table of an unconfined aquifer, or the potentiometric surface of a confined aquifer.

Effective porosity--The amount of interconnected pore space available for fluid transmission. It is expressed as a percentage of the total volume occupied by the interconnecting interstices. It is similar to specific yield.

Flow boundary--Physical or hydrologic features that affect the flow of ground water.

Hydraulic conductivity--The volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Hydraulic gradient--Rate of change in hydraulic head per unit distance of flow in a given direction.

Hydraulic head--Height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point.

Hydrodynamic dispersion--Tendency for a solute to spread beyond the path determined strictly by convective flow in an aquifer. Hydrodynamic dispersion is caused by mechanical mixing and by diffusion.

Longitudinal dispersivity--Component of hydrodynamic dispersion parallel to the direction of flow in an aquifer.

Microbial contamination--The introduction of microorganisms in concentrations that are harmful to humans into a well from an aquifer.

Natural recharge--The infiltration of precipitation across the water table into the saturated zone in an aquifer that directly underlies the soil at land surface.

Null point--The stagnation point at the boundary of a well's zone of contribution or transport.

Porosity--A rock or soil's property of containing interstices or voids. It is usually expressed as the ratio of the volume of its interstices to its total volume.

Potentiometric surface--A surface that represents the levels to which water will rise in tightly cased wells that are open to the aquifer.

Radius of influence--The radial distance from the center of a well bore to the point where there is no lowering of the water table or potentiometric surface (the boundary of its zone of influence).

Retardation--The extent to which something is held back or slowed down.

Saturated thickness--The thickness of an aquifer that is below the water table.

Solid-solute interaction--The processes in which some amount of a particular dissolved chemical species may be added or removed from the ground water due to physical reactions between the water and the solid aquifer materials.

Solute--A dissolved substance.

Specific discharge--The rate of discharge of ground water per unit area of the porous medium measured at right angles to the direction of flow; also called bulk velocity or Darcian velocity.

Specific yield--The ratio of the volume of water that a rock or soil, after being saturated, will yield by gravity to the total volume of the rock or soil. Usually expressed as a percentage.

Steady state--Conditions remain constant through time.

Storage coefficient--The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in hydraulic head.

Time of travel--The time required for a contaminant to move in the saturated zone from a specific point to a well.

Transient state--Nonequilibrium conditions when hydraulic head and the volume of water in storage change significantly with time.

Transmissivity--The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of aquifer under a unit hydraulic gradient.

Transverse dispersivity--Component of hydrodynamic dispersion perpendicular to the direction of flow in the aquifer.

Unconfined aquifer--An aquifer that has a water table.

Water table--The surface in a ground-water body at which the water pressure is atmospheric.

Well yield--The volume of water discharged from a well.

Wellhead-protection area--The surface and subsurface area surrounding a water well or well field that supplies a public water-supply system and through which contaminants are reasonably likely to move toward and reach such water well or well field.

Zone of contribution--The area surrounding a pumped well that encompasses all areas or features that supply ground-water recharge to the well.

Zone of influence--The area surrounding a pumped well within which the water table or potentiometric surface has been changed due to ground-water withdrawal.

Zone of transport--The area surrounding a pumped well and bounded by a contour line of equal time or equal concentration through which a contaminant may travel and reach the well.

DESCRIPTION AND EVALUATION OF SELECTED METHODS USED TO DELINEATE WELLHEAD-PROTECTION AREAS AROUND PUBLIC-SUPPLY WELLS NEAR MT. HOPE, KANSAS

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ABSTRACT

Many different methods have been developed which can be used to delineate wellhead-protection areas that will provide safeguards against direct, microbial, and chemical contamination of ground water. However, these methods have not been evaluated for use under conditions common in the Midwest. Many communities in the Midwest, including Mt. Hope, Kansas, are situated in an agricultural setting and depend on extensive, unconfined, large-yielding aquifers for their water supplies. These aquifers typically are shallow, have sloping water tables, and are overlain by permeable materials. Mt. Hope's public-supply wells and the surrounding hydrologic conditions were used to evaluate some of the methods used to delineate wellhead-protection areas.

Methods in each of four categories--arbitrary fixed radius, calculated fixed radius, analytical models, and numerical flow and transport models--were evaluated on the basis of six technical considerations suggested by the U.S. Environmental Protection Agency. The categories of simplified variable shapes and hydrogeologic mapping were not used and could not be thoroughly evaluated. The six technical considerations were: (1) ease of application, (2) ease of quantification, (3) ease of onsite verification of a factor's threshold or limiting value, (4) ability to reflect variability of hydrologic conditions, (5) suitability for a given hydrologic setting, and (6) ability to incorporate physical and chemical processes.

Because they allow for a sloping water table, the analytical and numerical ground-water flow and transport models more closely reflect actual hydrologic conditions than the arbitrary and calculated fixed-radius methods. A numerical ground-water flow and transport model is the most hydrologically credible method to use to delineate wellhead-protection areas, but other methods that give similar results and are more efficient can be useful choices. If the radius is small enough, the arbitrary fixed-radius method might be the most efficient method for delineating areas to protect wellheads from direct contamination. The analytical models are easier to use than the numerical ground-water flow and transport model and can be useful choices with which to delineate areas to protect wells from microbial and chemical contamination if the areas delineated using the models are surrounded by buffer zones.

INTRODUCTION

Awareness and concern regarding ground-water contamination potential is increasing in areas where ground water is an important source of public supplies. Many communities in the Midwest depend on extensive, unconfined, large-yielding aquifers for their water supplies. These aquifers typically are quite shallow and are overlain by relatively permeable materials. This combination of hydrologic conditions and the agricultural setting of most of the Midwest make the aquifers particularly vulnerable to contamination from sources at or near land surface. Such conditions prevail near Mt. Hope, a small community in Sedgwick County, Kansas, that depends on shallow ground water for its public supplies.

The Safe Drinking Water Act (Public Law 99-339, 1986) requires States to adopt programs "***to protect wellhead areas***from contaminants that may have adverse affects on the health of persons." Wellhead-protection areas generally are designed to meet one of three goals (U.S. Environmental Protection Agency, 1987a). These goals are to: (1) provide a remedial-action zone around the well to protect it from unexpected contaminant releases; (2) provide a zone around the well in which concentrations of specific contaminants will be attenuated to acceptable levels by the time they reach the wellhead; or (3) provide a well-field management zone for all or part of a well's existing or potential recharge area (U.S. Environmental Protection Agency, 1987a). Many methods have been developed that are useful for delineating wellhead-protection areas (see U.S. Environmental Protection Agency, 1987a, for a partial listing), but these methods have not been evaluated for their appropriateness for use under hydrologic conditions common to the Midwest. In this study, which was conducted by the U.S. Geological Survey in cooperation with the U.S. Environmental Protection Agency during 1987-88, several different methods useful for delineating wellhead-protection areas were applied using the hydrologic conditions present in the Mt. Hope, Kansas, area.

Purpose and Scope

The purpose of this report is to present evaluations of several methods that can be used to delineate wellhead-protection areas. Others interested in delineating wellhead-protection areas for wells under hydrologic conditions similar to those near Mt. Hope, Kansas, can use these evaluations to assess (1) the appropriateness of each method for the hydrologic conditions and (2) the types of information needed to apply each method. These evaluations also may be used to facilitate the choice of method most suitable for the available resources.

Each method was evaluated using six technical considerations suggested by the U.S. Environmental Protection Agency (1987a). These six considerations were: (1) ease of application, (2) ease of quantification, (3) ease of onsite verification of a factor's threshold or limiting value, (4) ability to reflect variability of hydrologic conditions, (5) suitability for a given hydrologic setting, and (6) ability to incorporate physical and chemical processes. The processes of retardation, dilution, and dispersion are peculiar to each chemical contaminant and were not investigated in this study; only the process of advection was considered. Although none of the wellhead-protection areas delineated in this report were intended to meet any of the three design goals previously stated, the methods were evaluated as to how well they were able to simulate a well's existing or potential recharge area for 1- and 20-year times of travel.

Concepts and Terminology

The U.S. Environmental Protection Agency defines a wellhead-protection area as "***the surface and subsurface area surrounding a water well or well field, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or well field" (U.S. Environmental Protection Agency, 1987a). This definition indicates that if a wellhead-protection area is to have a scientific basis, it will be dependent on both the contaminant and the area that contributes water to the well or well field.

The type of contamination from which the well or well field needs protection will, in part, determine the size of the wellhead-protection area. In general, the types of ground-water contamination can be classified into three groups: (1) direct contamination, (2) microbial contamination, and (3) chemical contamination (U.S. Environmental Protection Agency, 1987a). A well can be protected from direct contamination, which is the introduction of contaminants directly into a well by spilling or pouring them into or along the well casing, by proper well construction and by removal of all possible sources of contamination from the immediate area surrounding the wellhead. It is more difficult to protect a well from microbial and chemical contamination because these types of contamination are not introduced directly into the wells but rather come from surface spills or underground leakage from point or nonpoint sources at some distance from the wells. The movement in ground water of these contaminants from the source to the well is affected by advection.

Biological, chemical, and physical processes also may affect the fate of microbial and chemical contaminants in ground water. Biological processes have a significant effect on microbial contamination. Bacteria and viruses can survive in ground water for periods approaching 1 year (U.S. Environmental Protection Agency, 1987a). Siting of a well in a location more than 1 year's ground-water time of travel from any source of bacteria or viruses (such as septic tanks or lagoons) can prevent microbial contamination. Larger areas commonly are needed to protect a well from chemical contaminants because chemicals are not living organisms with limited lifespans. Biological and chemical processes may remove or destroy chemical contaminants in the ground water, thereby retarding their movement or diluting their concentration. Dispersion, while decreasing the concentration of a chemical contaminant, may speed its movement.

The *zone of contribution* is the area surrounding a pumped well that includes all areas or features that supply ground-water recharge to the well (fig. 1). Where advection is the primary physical property involved in ground-water movement, the zone of contribution is dependent on the aquifer's potentiometric surface and the drawdown of this surface near the well. Drawdown of the potentiometric surface is caused by pumping the well. The area around the well that is affected by drawdown is called the *zone of influence* (fig. 1). If the water table is perfectly flat, the zone of contribution and the zone of influence will be identical. Most potentiometric surfaces are sloping rather than flat. Where the potentiometric surface slopes, the zone of contribution and the zone of influence do not coincide except near the well (fig. 1). The zone of contribution may be limited by physical boundaries, such as the extent of the aquifer or a ground-water divide (fig. 1). That part of the zone of contribution from which water would flow to the well during a particular time period (time of travel) is referred to as the *zone of transport* (fig. 1). As longer time periods are considered, the zone of transport and the zone of contribution become more similar, whereas the zone of transport and the zone of influence become less similar (fig. 1).

The type of contamination that a well is to be protected from is an important consideration when delineating the wellhead-protection area. An ideal wellhead-protection area would neither overprotect (include more area than necessary for adequate protection from a potential contaminant) nor underprotect (not include enough area). If a well is to be protected from direct contamination, only the area immediately around the well needs to be included in the wellhead-protection area. If the well is to be protected from microbial contamination, then an area equal to the 1-year zone of transport probably would be suitable because most pathogens in ground water do not survive beyond 1 year (U.S. Environmental Protection Agency, 1987a).

For protection from chemical contamination, the wellhead-protection area is much more difficult to define because the size of the area depends on the particular chemical, its concentration, whether it is from a point or nonpoint source, and the hydrologic conditions in the aquifer. Limited resources and knowledge prevent the delineation of wellhead-protection areas from all the possible combinations of factors involved in chemical contamination. A wellhead-protection area that includes the entire zone of contribution would protect a well from all chemical contaminants. Unfortunately, it generally is not economically possible to include the entire zone of contribution. Instead, a wellhead-protection area equal to the zone of transport, based on ground-water time of travel that would provide an adequate period to recognize and clean up most types of chemical contamination in the ground water before it reaches the well, is probably suitable. This time period may depend on which particular chemicals are viewed as potential contaminants in the area because the length of time that a chemical retains its potency can range from less than 1 year to more than 100 years (U.S. Environmental Protection Agency, 1987a) and the technologies to remove or eliminate chemicals from ground water vary.

In general, the size of the wellhead-protection area needed increases as the type of contamination changes from direct to microbial to chemical. A wellhead-protection area that is just large enough to protect a well from direct contamination will not be large enough to protect it from either microbial or chemical contamination. A wellhead-protection area that is just large enough to protect the well from microbial contamination will be large enough to protect it from direct contamination but probably will not be large enough to protect it from most chemical contamination. A wellhead-protection area that is large enough to protect a well from chemical contamination also will include the areas that will protect the well from direct and microbial contamination. For this reason, if only

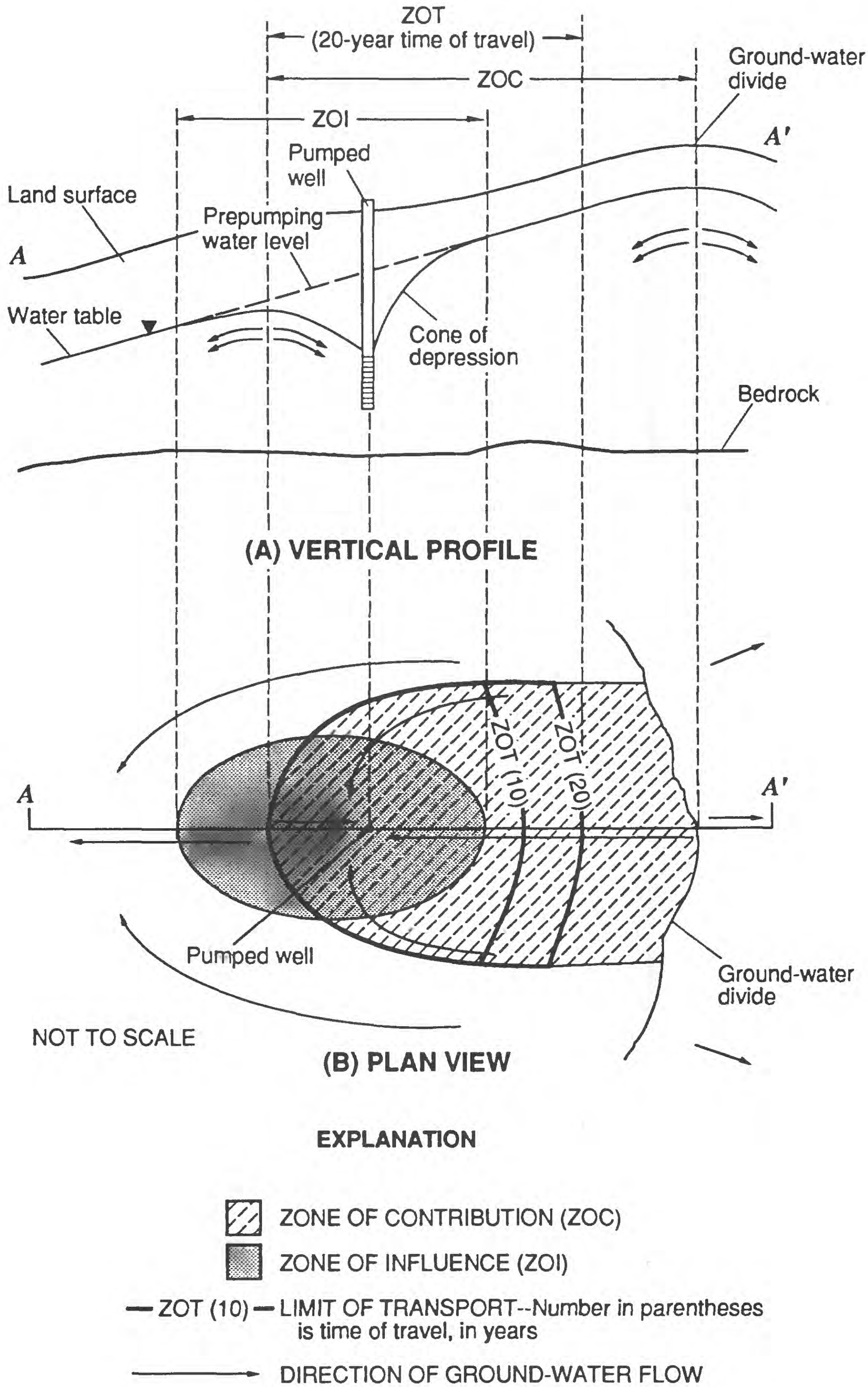

Figure 1. Zones of contribution, influence, and transport under sloping water-table conditions.

one wellhead-protection area is to be delineated, it probably would be most useful to delineate the area that will protect the wellhead from chemical contamination because this area also will protect the well from direct and microbial contamination.

Description of Study Area

The study area for this report is located in T. 25 S., R. 3 W., which contains the community of Mt. Hope in the northwest corner of Sedgwick County, south-central Kansas (fig. 2). The study area lies in the flat, smooth plain of the Great Bend Lowland (Hammond, 1964) and is drained by the Arkansas River to the north and Big Slough Creek to the south (fig. 2).

The study area is underlain at depth by the Lower Permian Wellington Formation, which contains the Hutchinson Salt Member. In this area, the salt in the Hutchinson Salt Member is dissolving; when the salt has dissolved, the overlying rocks collapse. This process has created a deep saline-water aquifer called the Wellington aquifer (Gogel, 1981). It also has created sinkholes at the surface, which can become wetlands. A wetland in the east-central part of the study area (fig. 2) was identified by Lane and Miller (1965) as one of these sinkholes. The Lower Permian Ninnescah Shale overlies the Wellington Formation and separates it from the *Equus* beds aquifer. The *Equus* beds aquifer consists of unconsolidated Quaternary terrace and alluvial deposits of silt, clay, and gravel. Soil in the area typically has a fine-to-loamy texture (Penner and Wehmueller, 1979).

The *Equus* beds aquifer is the easternmost part of the High Plains aquifer in Kansas, the largest and most extensively used aquifer in the State. The *Equus* beds aquifer is unconfined; the water table generally slopes downward from the northwest to the southeast across the study area (fig. 2) with a hydraulic gradient of about 0.001. Depth to water ranges from at or near land surface along streams and ponds to about 40 feet below land surface in the southwest part of the area and is about 20 feet below land surface at Mt. Hope. Saturated thickness of the *Equus* beds aquifer ranges from less than 20 feet in the southwest corner of the study area to more than 220 feet along the Arkansas River in the northwest part of the study area and averages about 100 feet (Bevans, 1989).

The amount of recharge an aquifer receives varies greatly spatially. Measurements of recharge from precipitation to the *Equus* beds aquifer range from 0.1 to 6 inches (Sophocleous and Perry, 1987), but estimates of areal average recharge to the *Equus* beds aquifer by other investigators (Lane and Miller, 1965; Spinazola and others, 1985; Hansen, in press) range from 2 to 4.5 inches. Recharge was estimated at 3 inches per year for this report.

Transmissivity was estimated from maps used by J.M. Spinazola (unpublished map, on file with U.S. Geological Survey, Lawrence, Kans.) in a previous ground-water modeling study of the *Equus* beds aquifer. Transmissivity ranges from less than 4,500 ft^2/d in the southwestern part of the study area to more than 30,000 ft^2/d in an area northwest of the Mt. Hope public-supply wells. Transmissivity is estimated at 29,000 ft^2/d for the Mt. Hope public-supply wells.

A value of 0.2 was chosen for both effective porosity and storage coefficient on the basis of a specific yield of 0.2 estimated for the *Equus* beds aquifer in this area by Bayne and Ward (1967). Where an aquifer is unconfined, values for storage coefficient, specific yield, and effective porosity of the aquifer are approximately the same and can be used as estimates of each other.

Hydraulic conductivity was estimated by Spinazola and others (1985) to range from less than 25 ft/d in the southwestern part of the study area to 750 ft/d in the northwestern part. For this study, hydraulic conductivity was estimated at 290 ft/d in the area surrounding the Mt. Hope public- supply wells.

The *Equus* beds aquifer is the principal source of ground water for public-supply wells in Wichita and many other communities in south-central Kansas, including Mt. Hope. Water from the *Equus* beds aquifer is generally of better quality than that from either the Arkansas River or the Wellington aquifer. Some wells that are completed in the *Equus* beds aquifer in the study area have yielded water having dissolved-solids and chloride concentrations that increased through time (Bevans, 1989), including one of the Mt. Hope public-supply wells (Chris

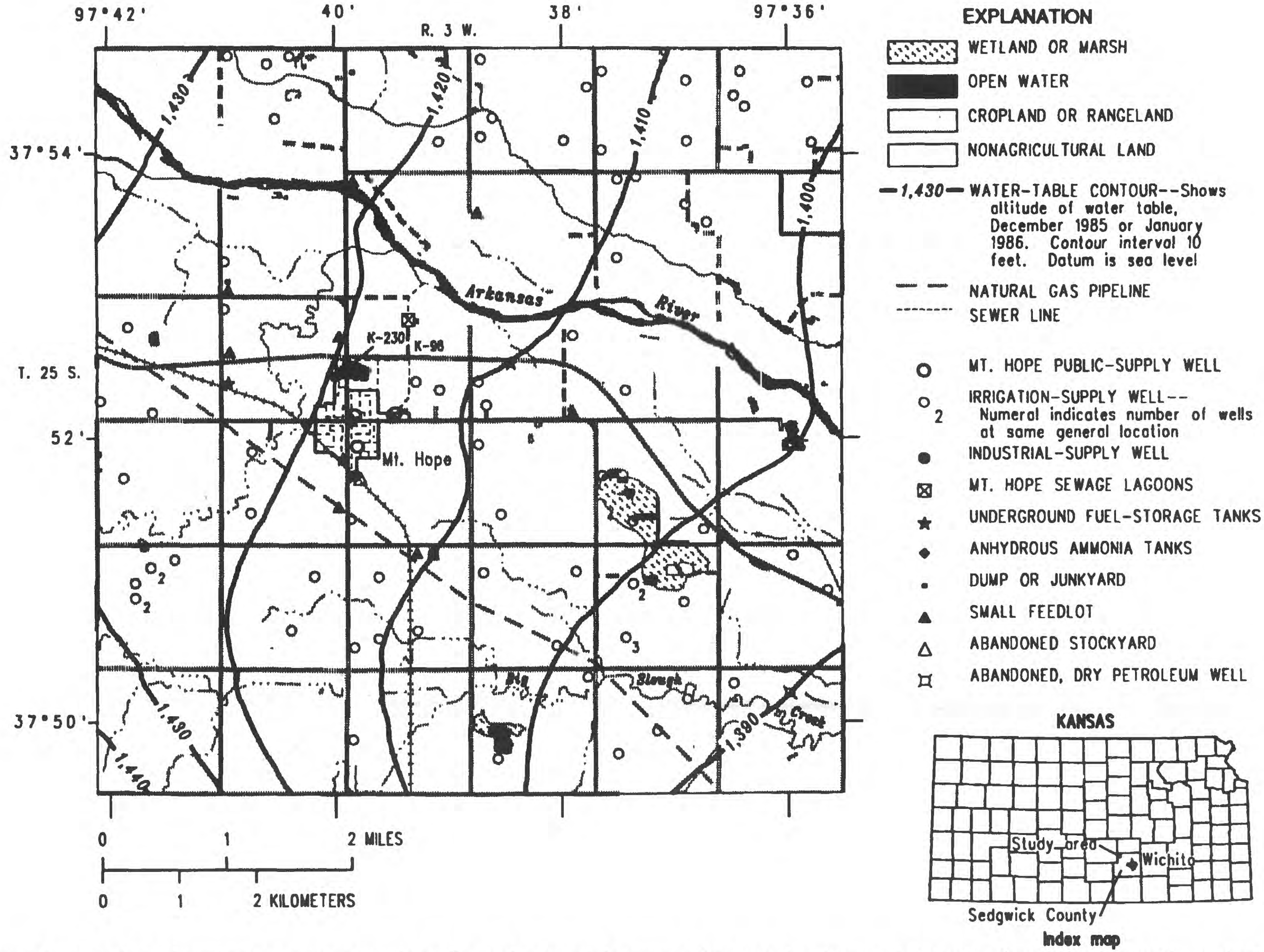

Figure 2. Location of study area, water-supply wells, and potential sources of contamination, and altitude of water table in *Equus* beds aquifer.

Rasmussen, Mt. Hope City Engineer, oral commun., 1988). The source of this mineralized water is not presently known but possibly is due to induced infiltration from the Arkansas River caused by pumped irrigation wells (J.B Gillespie, U.S. Geological Survey, oral commun., 1988). In 1986, trihalomethanes were detected in the public-water-supply system of Mt. Hope. The concentration (3.2 µg/L, micrograms per liter) was considerably less than the State and Federal Maximum Contaminant Level (100 µg/L) and was thought to have formed when natural organic compounds in the ground water reacted with the chlorine used as a disinfectant (Kansas Department of Health and Environment, written commun., 1986).

The Mt. Hope water supply is obtained from three wells in or near the city (fig. 2). Each well is 100 feet deep and is pumped at irregular intervals. Because delineation of wellhead-protection areas considers long-term, approximately steady-state conditions, the actual pumping rate was adjusted during method evaluations to a value that would correspond to a constant rate producing the same annual volume. This rate is 28.33 gal/min for each of the three wells. The pumpage of the Mt. Hope public-supply wells is small when compared to pumpage of the 76 irrigation wells in the study area, some of which are authorized by the Division of Water Resources (Kansas State Board of Agriculture) to pump as much as 185 gal/min at a constant rate or as much as 2,000 gal/min for short periods.

Mt. Hope's population (about 780 in 1985, files of the Kansas Department of Health and Environment) and location in an area where agriculture is the dominant industry make it typical of many small communities in the Midwest. It does not have the many potential point-sources of contamination that are associated with more populous or industrialized areas. Most of the land in the study area (fig. 2) is cropland or pasture, except along the Arkansas River and within the Mt. Hope city limits (U.S. Geological Survey, 1979). Agricultural chemicals (herbicides, insecticides, and fertilizers) are used extensively on the cropland, which make the land a potential source of nonpoint chemical contamination. Small feedlots and sewer lines and lagoons are potential point sources of microbial contamination. The major possible point sources of chemical contamination (fig. 2) appear to be underground fuel-storage tanks, dumps and junkyards, and the salt applied as a deicing agent during winter to State highway K-96 and to about 1/4-mile of State highway K-230 between K-96 and the Mt. Hope city limits. Although the oil and gas industry is important in much of south-central Kansas, there are no active petroleum wells in the study area. A plugged, dry, abandoned petroleum well is located in the southeast corner of the area (fig. 2); the Kansas Corporation Commission (Topeka) has no records of other abandoned wells. No spills of hazardous materials have been reported in the study area since 1980 when the U.S. Environmental Protection Agency began keeping records of this type.

Previous Work

The U.S. Environmental Protection Agency has compiled an extensive list of wellhead-protection methods and criteria (U.S. Environmental Protection Agency, 1987a) used in other studies throughout the world. Other methods evaluated by this study are described by Shafer (1987) and Woods and others (1987). Two studies have been completed on the geohydrology of Sedgwick County (Lane and Miller, 1965; Bevans, 1989). Studies also have been made of the *Equus* beds aquifer (for example, Williams and Lohman, 1949; Spinazola and others, 1985), which is the source of public supply for Mt. Hope.

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DESCRIPTION AND RESULTS OF WELLHEAD-PROTECTION METHODS

The U.S. Environmental Protection Agency (1987a) has identified six primary categories of wellhead-protection methods. These categories are: arbitrary fixed radius, calculated fixed radius, simplified variable shapes, analytical models, hydrogeologic mapping, and numerical flow and transport models. On the basis of available information, the appropriateness of each category for the Mt. Hope area was determined, and where the category was deemed appropriate, at least one method was used.

Most methods used to delineate wellhead-protection areas depend on the use of one or more of the following factors or criteria: (1) distance, (2) drawdown, (3) time of travel, (4) flow boundaries, and (5) assimilative capacity (U.S. Environmental Protection Agency, 1987a).

Distance is a factor based on a particular radius or dimension measured from a pumped well to a point of concern (U.S. Environmental Protection Agency, 1987a). Wellhead-protection areas delineated using a method dependent on the distance factor generally do not represent the zones of contribution, influence, or transport because the hydrologic conditions surrounding the well are ignored.

Drawdown is a factor based on the extent to which well pumping lowers the water table of an unconfined aquifer or the potentiometric surface of a confined aquifer (U.S. Environmental Protection Agency, 1987a). Wellhead-protection areas delineated using a method dependent on the drawdown factor generally correspond to the zone of influence.

Time of travel is a factor based on the maximum time for a ground-water contaminant to reach a well (U.S. Environmental Protection Agency, 1987a). Wellhead-protection areas delineated using a method dependent on time of travel generally correspond to the zone of transport.

Flow boundaries are factors based on physical or hydrologic features that affect ground-water flow (U.S. Environmental Protection Agency, 1987a). Most physical flow boundaries, such as a geologic contact between an aquifer and a relatively impermeable rock unit, generally do not change location or lose their effect over time or with changes in stress on the ground-water flow system (increased pumping of ground water, for example). Hydrologic flow boundaries, including ground-water divides, interfaces between fresh and saline water, and lakes or streams, may either change location or gain or lose their effect as the stress on the ground-water flow system changes. Some hydrologic flow boundaries, such as regional ground-water divides, large fractures or solution channels in otherwise relatively impermeable rock, or very large streams or lakes, may seem like physical flow boundaries because they generally do not change location or lose their effect over time or with changes in stress on the ground-water flow system. Wellhead-protection areas delineated using a method dependent on flow boundaries generally correspond to the zone of contribution.

Assimilative capacity is a factor based on the ability of the saturated and unsaturated zones of a formation to attenuate concentrations of contaminants to acceptable levels before they reach a pumped well (U.S. Environmental Protection Agency, 1987a). Wellhead-protection areas delineated using a method dependent on assimilative capacity generally correspond to the zone of transport.

Each of these factors requires the user to choose an acceptable limiting or threshold value. The threshold value may be based on hydrologic conditions or professional judgment. In general, the more of these factors a method includes, the more useful the method will be under a variety of conditions.

Arbitrary Fixed-Radius Method

The arbitrary fixed-radius method is based on the distance factor only (length of radius in table 1) and can be used to delineate a wellhead-protection area around a well that is a circle of fixed radius. It is called "arbitrary" because the radius does not have any hydrologic basis for its selection. The wellhead-protection areas delineated using the arbitrary fixed-radius method are not designed to correspond to the zones of contribution, influence, or transport.

Table 1. *Data requirements for selected wellhead-protection methods*

[X, information needed; --, information not needed; G, information needed, gridded format required; and O, information needed, gridded format optional]

Method	Data requirements												
	Length of radius	Time of tra-vel	Pump-ing rate	Satur-ated thick-ness or screen length	Effec-tive poro-sity	Storage coef-ficient or specific yield	Transmis-sivity or hy-draulic conduct-ivity	Re-charge rate	Hydraulic-head dis-tribution or ground-water flow direction and gradient	Hydro-logic or flow bound-aries	Mapping coor-dinates	Aqui-fer test	Concen-tration of contam-inant or solute
Arbitrary fixed radius:	X	--	--	--	--	--	--	--	--	--	--	--	--
Calculated fixed radius:													
Radius of influence	--	--	X	X	--	X	X	--	--	--	--	X	--
Rate of recharge	--	--	X	--	--	--	--	X	--	--	--	--	--
Volumetric	--	X	X	X	X	--	--	--	--	--	--	--	--
Analytical models:													
CAPZONE	--	X	X	X	X	--	X	--	X	--	X	--	--
PATH	--	X	X	X	X	--	X	--	X	--	X	--	--
GWPATH	--	X	--	--	O	--	O	--	G	--	G	--	--
Numerical flow and transport models:													
MOC	--	X	X	O	X	X	O	O	O	G	G	--	O

Several agencies have used the arbitrary fixed-radius method because of its simplicity. The State of Kansas has a wellhead-protection guideline of a 100-foot radius (Kansas Department of Health and Environment, 1984); Nebraska uses a 1,000-foot radius (U.S. Environmental Protection Agency, 1987a); and the U.S. Environmental Protection Agency (1987a) suggests a minimum radius of 2 miles as an initial guideline for wellhead-protection areas.

The wellhead-protection areas for the Mt. Hope public-supply wells delineated using these arbitrary fixed radii are shown in figures 3 and 4. The wellhead-protection areas delineated using the 100-foot arbitrary fixed radius used by the State of Kansas include several Mt. Hope city sewer lines as known potential sources of contamination (fig. 3). The wellhead-protection area delineated using the 1,000-foot radius used by the State of Nebraska includes two locations with underground fuel-storage tanks and the Mt. Hope city sewer lines as known potential sources of contamination (fig. 3). It also includes a small amount of land outside the city limits that could be a nonpoint source of contamination from agricultural chemicals. Figure 4 shows the wellhead-protection area delineated using the 2-mile radius suggested by the U.S. Environmental Protection Agency (1987a); the area includes four locations with underground fuel-storage tanks, nine small active feedlots and one abandoned stockyard, one dump and one junkyard, three city sewage lagoons, all of the Mt. Hope city sewer lines, and the parts of State highways K-96 and K-230 that are salted for deicing. It also includes large areas of cropland that may be nonpoint sources of agricultural chemicals.

Calculated Fixed-Radius Methods

The calculated fixed-radius methods are used to delineate a circular wellhead-protection area around a well. The radius (and therefore the size of the wellhead-protection area) may change as the variables in the equations are changed to reflect conditions in the hydrologic system. Depending on the method used, the resulting wellhead-protection area corresponds to either the zone of contribution, the zone of influence, or the zone of transport. Three calculated fixed-radius methods evaluated by this study are the radius-of-influence, rate-of-recharge, and volumetric methods. Both the radius-of-influence method and the rate-of-recharge method do not allow for a time-of-travel factor; they can be used to delineate only one wellhead-protection area for each well. For the radius-of-influence method, the wellhead-protection area corresponds to the zone of influence; for the rate-of-recharge method, it corresponds to the zone of contribution. The volumetric method allows for wellhead-protection areas of different sizes, depending on the length of the time-of-travel factor, and the resulting wellhead-protection areas correspond to the zone of transport.

Radius-of-Influence Method

The radius-of-influence method can be used to delineate the area around a well where a specified (threshold) drawdown could be expected to occur. As drawdown decreases away from the well, the smaller the specified drawdown, the more closely the wellhead-protection area will approximate the zone of influence (fig. 1). An example of this method is the one used by the Vermont Department of Water Resources and Environmental Engineering (1983). The equations used to determine the radius (r) of area where drawdown is greater than or equal to the specified drawdown (s) are based on the Theis (1935) nonequilibrium equation:

$$W(u) = \frac{4\pi Ts}{Q}, \text{ and } r = \sqrt{\frac{u4Tt,}{S}} \quad (1)$$

where

$W(u)$ = well function, dimensionless;

T = transmissivity of the aquifer;

s = drawdown (0.05 foot is specified by Vermont Department of Water Resources and Environmental Engineering);

Q = pumping rate of well during aquifer test;

t = time to reach steady-state conditions at the pumped well;

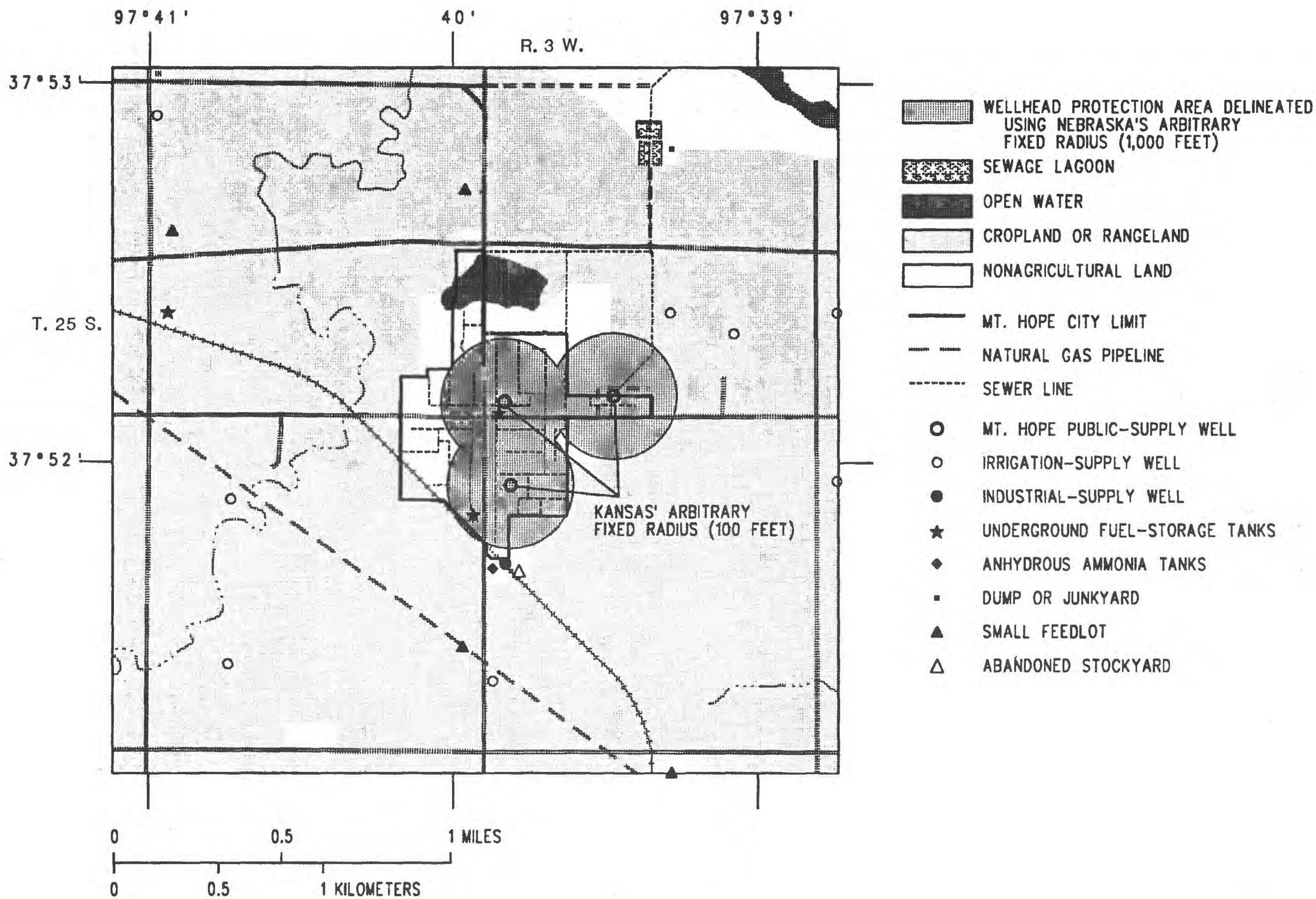

Figure 3. Wellhead-protection areas delineated using arbitrary fixed-radii guidelines of Kansas and Nebraska.

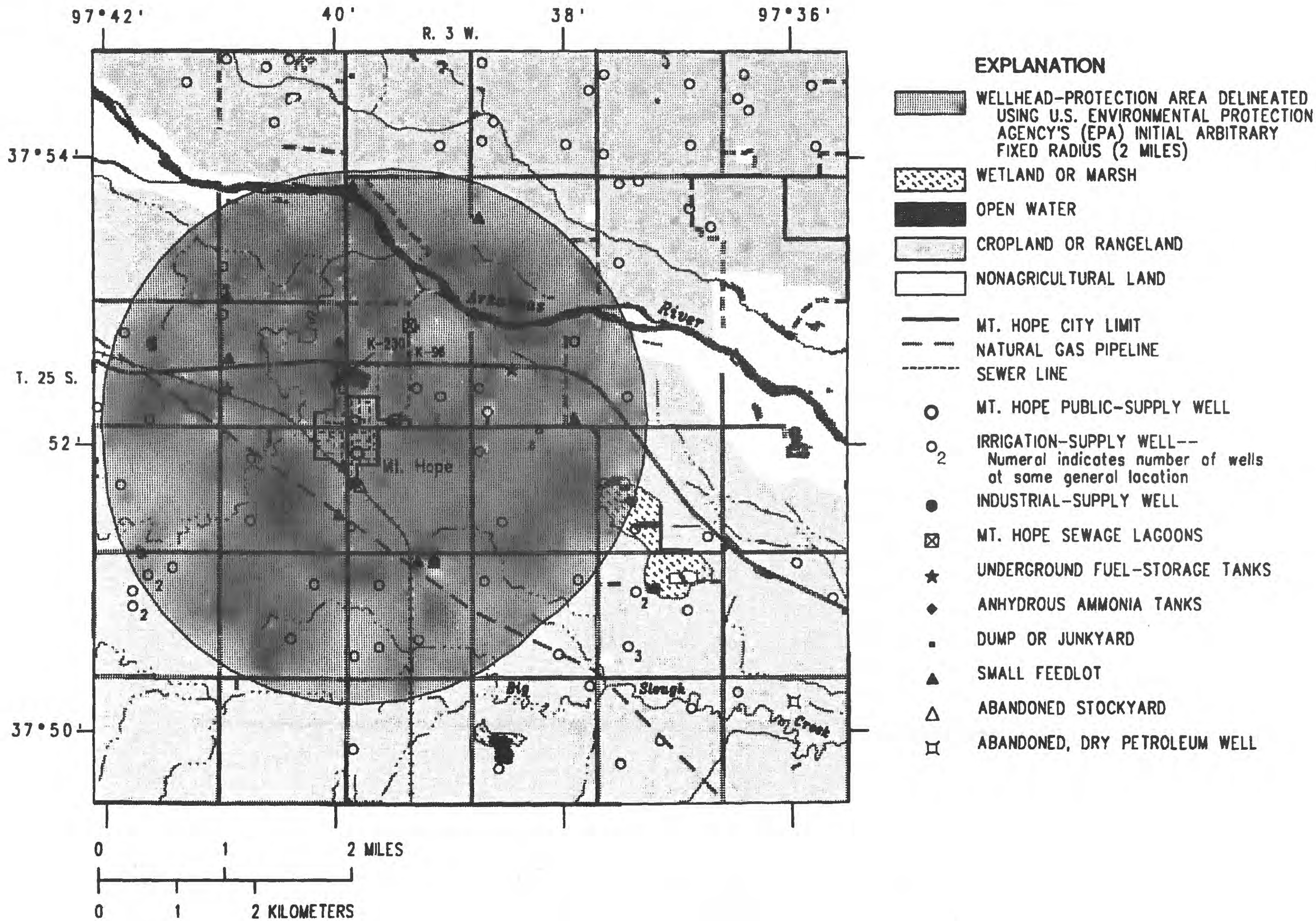

Figure 4. Wellhead-protection areas delinated using initial arbitrary fixed-radius guideline suggested by U.S. Environmental Protection Agency.

u = variable of integration read from well-function table after $W(u)$ is determined; and

S = storage coefficient or specific yield of aquifer.

Data requirements

The radius-of-influence method requires that the results of an aquifer test be available for the well (table 1). Ideally, during the aquifer test, the well should be pumped at its maximum designed-discharge rate until drawdown at the well stabilizes. From the aquifer test, t and Q are known; T can be determined by standard aquifer-test analysis methods; and s is some small value close to zero. If the aquifer test includes measurements from an observation well, S can be determined; otherwise previously made estimates of S, which are commonly available, can be used. The radius of the wellhead-protection area then can be determined by use of these variables and a table of well-function values.

Results and discussion

The wellhead-protection areas delineated for the Mt. Hope public-supply wells using the radius-of-influence method are shown in figure 5. All three areas include city sewer lines as possible point sources of contamination, and one area includes underground fuel-storage tanks.

Aquifer tests were not available for the wells Mt. Hope used in 1988 for its public-water supply. However, an aquifer test was available for a well Mt. Hope once used as a public-water supply well. The results of this test were applied to the present Mt. Hope public-supply wells and are probably similar to what could be expected from aquifer tests for any of the present wells:

$$T = 11{,}900 \text{ ft}^2\text{/d from the method outlined by Theis (1963).} \quad (2)$$

$$W(u) = \frac{4\pi Ts}{Q} = \frac{4\,(3.14159)\,(11{,}900 \text{ ft}^2\text{/d})\,(0.05 \text{ ft})}{32{,}920 \text{ ft}^3\text{/d}} \quad (3)$$

$$= 0.2271, \text{ and}$$

from the well-function table (Ferris and others, 1962, p. 96),

$$u = 0.9795, \text{ and}$$

$$r = \sqrt{\frac{u4Tt}{S}} = \sqrt{\frac{(0.9795)\,(4)\,(11{,}900 \text{ ft}^2\text{/d})\,(1.5 \text{ days})}{0.2}} \quad (4)$$

$$= 591 \text{ feet.}$$

Values for drawdown (s) do not vary greatly because investigators should choose a value close to zero; neither will values of specific yield (S) for any one aquifer. However, the size of r will vary inversely with S. As is seen in the example calculation, transmissivity (T) and pumping rate (Q) are both comparatively large values. These values were determined from the aquifer test, and their effect on the size of the radius is moderated by the use of u. This is especially true for T because u does not vary directly with T.

Rate-of-Recharge Method

The rate-of-recharge method was developed for this study by John Helgesen of the U.S. Geological Survey (written commun., 1987). The rate-of-recharge method is based on the assumption that all water pumped from a well comes from direct natural recharge. This method is only applicable to unconfined aquifers. If both the rate of pumpage and rate of recharge are known, the size and radius of the recharge area can be delineated:

$$r = \sqrt{\frac{Q}{R\pi}}, \quad (5)$$

where Q = pumping rate of well; and

R = rate of natural recharge.

Data requirements

The rate of recharge method requires both the pumping rate (Q) and some estimate of the rate of natural recharge (R) (table 1). The pumping rate generally is available from well records. Estimates of the rate of recharge are not always available, and even if they are available, they may differ considerably.

Results and discussion

The wellhead-protection area delineated for the Mt. Hope public-supply wells using the rate-of-recharge method is shown in figure 5. This area includes two locations with

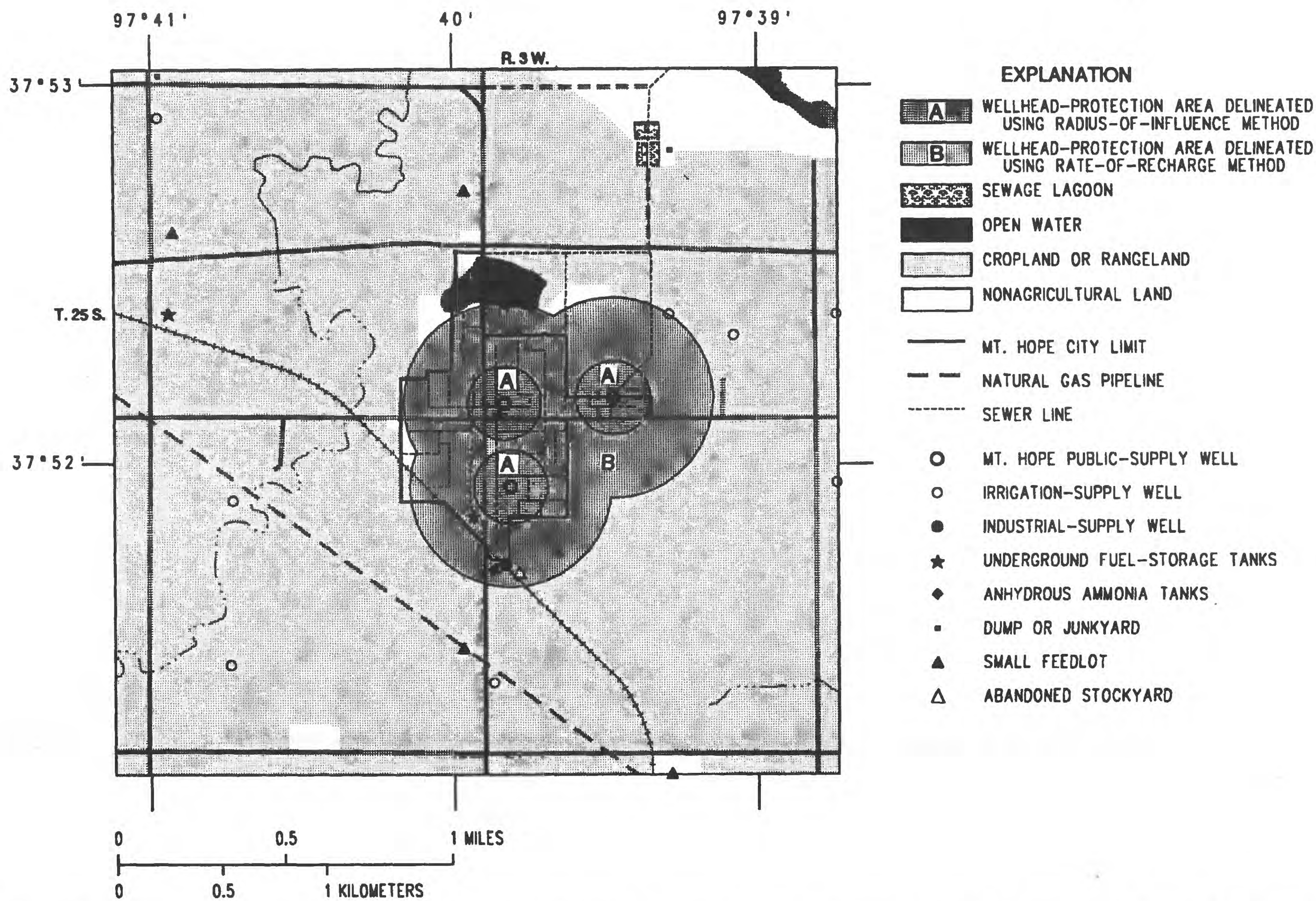

Figure 5. Wellhead-protection areas delineated using calculated fixed-radius methods--(A) radius-of-influence and (B) rate-of-recharge methods.

underground fuel-storage tanks, an abandoned stockyard, and city sewer lines as potential point sources of contamination (fig. 5). It also includes some cropland that might be a potential nonpoint source of contamination from agricultural chemicals. The calculation used to determine the radius of the wellhead-protection area for the rate-of-recharge method is given below:

$$r = \sqrt{\frac{Q}{R\pi}} = \sqrt{\frac{1{,}990{,}675 \text{ ft}^3/\text{yr}}{(0.25 \text{ ft/yr})\ (3.1459)}} = 1{,}592 \text{ feet}. \quad (6)$$

Values for the pumping rate (Q) and rate of natural recharge (R) can be varied to fit the hydrologic conditions. In general, R will not vary much in any one area, but Q can vary considerably. As a result, the computed radius of the wellhead-protection area depends to a large degree on the pumping rate. If Q is large enough, the wellhead-protection areas of wells near each other will overlap and result in a single, large area (fig. 5). This would imply that the rate of recharge (R) in the areas of of overlap is much greater than that used in the equation.

Volumetric Method

Volumetric methods used for delineating wellhead-protection areas are based on determining the radius of the volume of aquifer that is contributing water to the well. The method used in this study was developed by the U.S. Environmental Protection Agency (1987a) from the volumetric flow equation and incorporates the time-of-travel factor:

$$r = \sqrt{\frac{Q}{\pi n H}}\ , \quad (7)$$

where Q = pumping rate of well;

t = time of travel;

n = effective porosity of aquifer; and

H = length of open or screened interval in the well.

A similar equation is used by the Florida Department of Environmental Regulations in which H is defined as the "***distance from the top of the producing aquifer to the bottom of the hole." The U.S. Environmental Protection Agency recommends the definition of H used in this study (Marilyn Ginsberg, U.S. Environmental Protection Agency, Washington, D.C., oral commun., 1990).

Data requirements

The pumping rate and length of open or screened interval in the well can be obtained from well records (table 1). If estimates of effective porosity are not available, estimates of specific yield, which are generally available, may be used instead. The time of travel is chosen by the investigator.

Results and discussion

The wellhead-protection areas delineated for the Mt. Hope public-supply wells using the volumetric calculated fixed-radius method for 1- and 20-year times of travel are shown in figure 6. All the delineated areas include city sewer lines as potential point sources of contamination. In addition, all the areas that include the northwest public-supply well also include a location with underground fuel-storage tanks. The 20-year wellhead-protection area includes another location with underground fuel-storage tanks, an abandoned stockyard, and a part of K-230 that is salted for deicing. Some cropland is also included as a potential nonpoint source of agricultural chemicals.

The following is an example calculation of the volumetric method:

$$r_{1\ \text{year}} = \sqrt{\frac{Qt}{\pi n H}} = \sqrt{\frac{(1{,}990{,}675 \text{ ft}^3/\text{yr})\ (1 \text{ yr})}{(3.1459)\ (0.2)\ (15 \text{ ft})}}$$
$$= 460 \text{ feet; and}$$
$$r_{20\ \text{year}} = 2{,}055 \text{ feet.} \quad (8)$$

The variables--pumping rate (Q), time of travel (t), effective porosity (n), and length of open or screened interval (H)--may be adjusted to fit the hydrologic conditions. In general, n and H will not vary greatly in any one aquifer; Q and t are more likely to vary. For a particular well, Q will tend to stay within a relatively narrow range. Unlike the previous methods, it is possible, by adjusting t, to delineate more than one wellhead-protection area for each well while holding the hydrologic variables constant. The wellhead-protection areas of wells near each other will overlap and result in a single, large area if Q or t

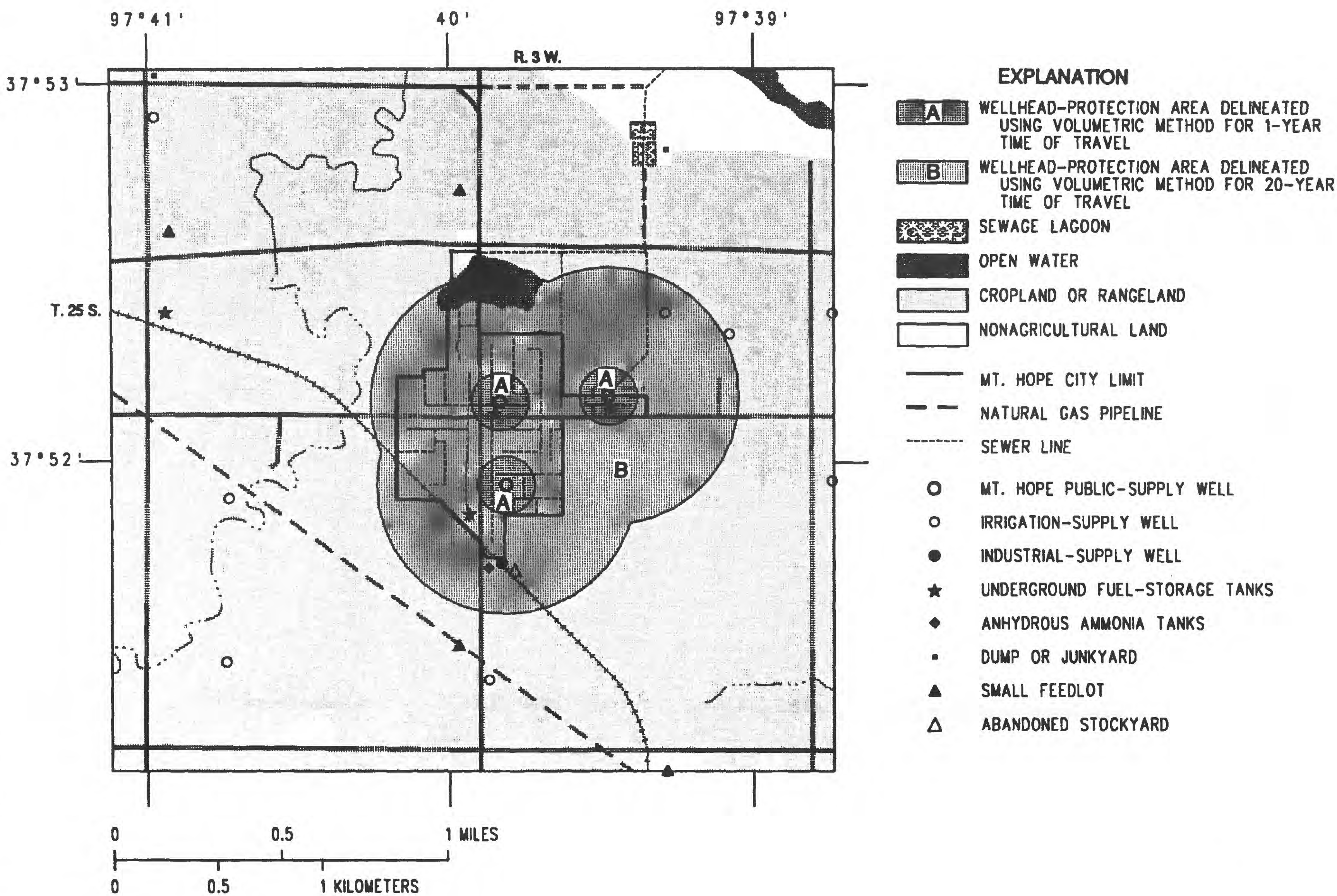

Figure 6. Wellhead-protection areas delineated using volumetric calculated fixed-radius method for (A) 1- and (B) 20-year times of travel.

are large enough (fig. 6). This would imply that the effective porosity (n) in the areas of overlap is much greater than that used in the equation.

Simplified Variable-Shapes Method

The simplified variable-shapes method is based primarily on the time-of-travel factor, and the area delineated by this method corresponds to the zone of transport. The method utilizes a set of simplified variable shapes, which were previously developed using an analytical model to delineate zones of transport for the entire range of well and aquifer properties found in the region. These zones have been grouped by sets of well and aquifer properties and then generalized into groups of simplified shapes. The well and aquifer properties for which ranges must be determined will depend on which analytical model is used to develop the set of shapes. In addition to time of travel, information generally needed for each aquifer in the region includes ranges in the properties of saturated or aquifer thickness, effective porosity, hydraulic conductivity, slope of the water table, and pumping rate of wells.

To use the simplified variable-shapes method, the investigator selects the appropriate shape from the available set of simplified variable shapes, based on known or estimated properties of the well and the aquifer it penetrates. The investigator then orients the shape properly with respect to the location of the well and direction of ground-water movement and delineates the wellhead-protection area by tracing the shape.

The simplifed variable-shapes method was not used for the Mt. Hope area because a previously developed set of shapes was not available. The size of the Mt. Hope study area and its limited range of hydrologic conditions did not warrant development of a set of simplified variable shapes. Instead, analytical models were run for the particular conditions present at Mt. Hope (see section on "Analytical Models").

Analytical Models

The analytical models evaluated in this study are based on the time-of-travel factor. Time of travel is used by the models as they calculate particle motion in a reverse direction; that is, from the well to the point where the particle was at the beginning of the time-of-travel period. To calculate the motion of the particles, each model uses several variables to represent the properties of the hydrologic system, including the magnitude and direction of the slope of the water table. With these data and the time-of-travel factor, the model can be used to delineate a wellhead-protection area that is similar in size, shape, and location to the zone of transport (fig. 1).

The three analytical models evaluated by this study were CAPZONE, PATH, and GWPATH. The analytical models CAPZONE and PATH assume uniform ground-water flow and aquifer conditions, whereas GWPATH allows for nonuniform ground-water flow and areally variable aquifer conditions. All three models assume steady-state conditions. These models all require the use of a computer. The results from these models are referenced geographically and passed to a geographic information system in order to show the wellhead-protection areas.

CAPZONE Model

The analytical model CAPZONE was developed by the Kansas Geological Survey to compute the "capture zone" of a well (Martinko and others, 1987). A capture zone is the volume of aquifer through which ground water flows to a pumped well during a given time of travel. The areal expression of the capture zone is the wellhead-protection area for the given time of travel. This area is delineated using the "capture-zone curve." The equation for the capture-zone curve was derived by Bear and Jacobs (1965) and, as explained by Martinko and others (1987, p. 17-19 and appendix IV, p. 6-7), is as follows:

$$e^{(x'-t')} = \cos(y') + (x'/y')\sin(y') \qquad (9)$$

where

$$t' = [2q^2B/(nQ)]t\,; \qquad (10)$$

$$x' = (2qB/Q)x\,; \qquad (11)$$

$$y' = (2qB/Q)y\,; \qquad (12)$$

and

q = specific discharge or Darcian velocity;

B = saturated or aquifer thickness;

n = effective porosity of aquifer;

Q = pumping rate of well;

t = time of travel;

x = distance in x-direction; and

y = distance in y-direction.

For each value of x', the value of y' is determined by the method of successive approximations and three different arrangements of equation 9. Each arrangement of equation 9 is applicable (converges) in a specific region of x', y', and t' values. The relative Cartesian coordinates x and y are computed from equations 11 and 12. These relative Cartesian coordinates then are rotated by the directional angle relative to north of the hydraulic gradient, translated by a distance equal to the well's positional coordinates, and converted to longitude and latitude pairs. These longitude and latitude pairs can be plotted and connected by hand but were designed to be used by a geographic information system to generate a line that can be used to delineate the wellhead-protection area.

Data requirements

The CAPZONE model requires average areal estimates of saturated or aquifer thickness, effective porosity, hydraulic conductivity, and direction and gradient of the water table (table 1). The model also requires the user to provide the longitude and latitude locations of the origin of the area being modeled and of the wells for which the wellhead-protection areas are being computed, the pumping rate of these wells, and the time of travel. If maps of saturated thickness are not available, estimates of saturated thickness may be determined from maps of depth to the water table and depth to the base of the aquifer or from maps of altitude of the water table and altitude of the base of the aquifer. Maps of aquifer thickness may be used for confined aquifers. Where estimates of effective porosity are not available, estimates of specific yield may be used instead. Estimates of hydraulic conductivity may be obtained from aquifer tests, estimates of other investigators, examination of well logs, or tables of ranges of expected values of hydraulic conductivity for selected types of deposits (for example, Heath, 1983, p. 13). The direction and gradient of ground-water flow may be determined from maps of water-table altitude. Longitude and latitude can be determined from U.S. Geological Survey 7.5-minute topographic quadrangles. Pumping rates should be available from records of the wells. The time of travel is determined by the user.

Results and discussion

The wellhead-protection areas delineated for the Mt. Hope public-supply wells using the CAPZONE model, a saturated thickness of 100 feet, a hydraulic conductivity of 290 ft/d, an effective porosity of 0.2, a hydraulic gradient of about 5.45 ft/mi at N. 116° E., and times of travel of 1 and 20 years are shown in figures 7 and 8. The only potential sources of contamination in the wellhead-protection areas delineated using the CAPZONE model for a 1-year time of travel are Mt. Hope's sewer lines (fig. 7). The wellhead-protection areas for a 20-year time of travel include these same sources, plus cropland that may be a nonpoint source of agricultural chemicals (fig. 8). The 20-year time-of-travel areas for all three wells extend across State highway K-96, a potential source of pollution from salt used for deicing. The 20-year time-of-travel area for the northwest public-supply well has a small feedlot along its northern edge; the 20-year time-of-travel area for the southwest public-supply well has a location with underground fuel-storage tanks along its northern edge.

The narrow, elongated wellhead-protection areas all extend upgradient of the Mt. Hope public-supply wells. The narrowness of these areas is of concern because the location of the wellhead-protection areas may change significantly if there is any error in the simulation of the water table. If the water table is not accurately represented, the error in the location of the wellhead-protection area will increase with increasing distance from the well.

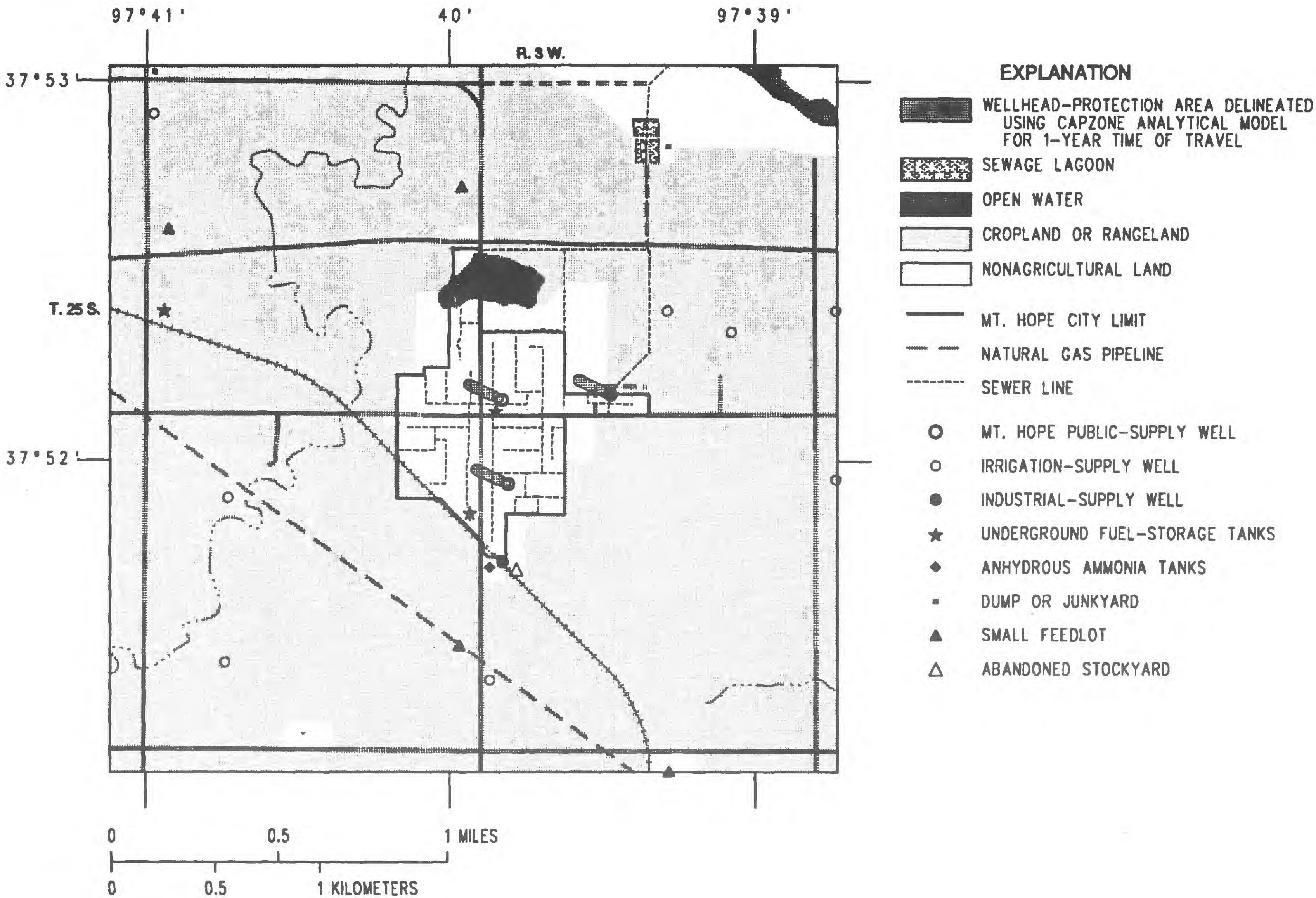

Figure 7. Wellhead-protection areas delineated using CAPZONE analytical model for 1-year time of travel.

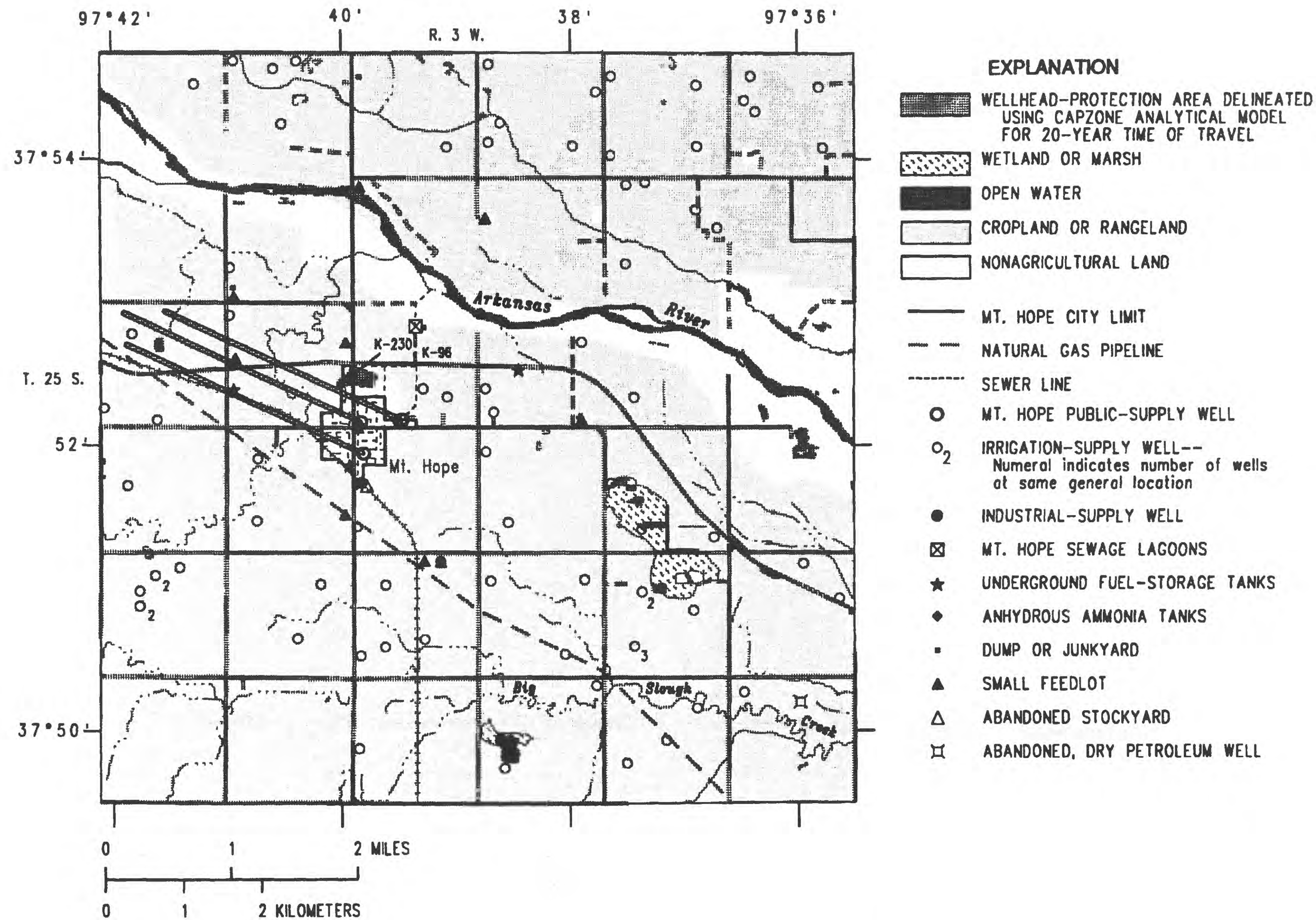

Figure 8. Wellhead-protection areas delineated using CAPZONE analytical model for 20-year time of travel.

For this reason, it may be desirable to add buffer zones around the wellhead-protection areas delineated with the CAPZONE model. The buffer zone probably should be wedge shaped, with the narrow end slightly downgradient of the well and the wide end oriented upgradient. An example of a method used by the U.S. Geological Survey to determine buffer zones for a study in Colorado is discussed by the U.S. Environmental Protection Agency (1987a).

Larger values of specific discharge (q) (which varies directly with hydraulic conductivity), saturated thickness (B), and time of travel (t) result in longer and narrower wellhead-protection areas, whereas larger values of effective porosity (n) and pumping rate (Q) result in more circular areas. For example, if q, B, and t are held constant and n and Q are increased, the resulting wellhead-protection area will not be longer, but it will be larger because it is wider. If the pumping rates (Q) are large enough, the wellhead-protection areas of wells near each other will overlap and result in a single, large area. This would imply that B in the areas of overlap is much greater than that used in the model.

PATH Model

A computer program, referred to as the PATH model throughout this report, was developed by A.T. Rutledge of the U.S. Geological Survey (written commun., 1988) to calculate, in reverse, the flow line that a particle would follow from its starting point to a well for a given time of travel. A collection of these flow lines about a well can be used to delineate a wellhead-protection area around the well. The PATH model was developed for use only in this study to serve as an example of an analytical model; therefore, it has not been formally documented. However, the analytical methods implemented in the PATH model are documented in detail in Appendix A so that the computations performed by the computer program can be reproduced by the reader if desired.

Data requirements

The PATH model requires average areal estimates of saturated or aquifer thickness, effective porosity, and hydraulic conductivity (table 1). The model calculates the direction and magnitude of the gradient of the water table, but it needs the location and hydraulic head at three points that will define this surface. The model also requires the radius for an estimated zone of influence, the time of travel, the pumping rate of these wells, and the longitude and latitude location of the origin of the area being modeled and of the wells for which the wellhead-protection areas are being delineated. Estimates of time of travel, pumping rates of wells, saturated or aquifer thickness, hydraulic conductivity, and longitude and latitude of points may be determined as described in the CAPZONE "Data requirements" section of this report. The radius for an estimated zone of influence is selected by the user to be any large distance. Estimates of hydraulic head at three points to define the water table can be determined from a map of the water table.

Results and discussion

A hydraulic conductivity of 290 ft/d, a saturated thickness of 100 feet, an effective porosity of 0.2, and the hydraulic-head values at three points representing the water table were used as input to the PATH model to delineate wellhead-protection areas for the Mt. Hope public-supply wells for 1- and 20-year times of travel (figs. 9 and 10). The Mt. Hope sewer lines are potential sources of contamination within the wellhead-protection areas delineated using the PATH model for the 1-year time of travel. The 20-year time-of-travel areas include Mt. Hope sewer lines, cropland, and State highway K-96, which may be a potential source of contamination due to the salt used as a deicing agent. The 20-year time-of-travel area for the northwest public-supply well also extends across a small feedlot, a potential source of contamination; for the southwest public-supply well, the 20-year time-of-travel area also includes a location with underground fuel-storage tanks.

Unlike the previous methods, the results of the PATH model cannot be used to outline the wellhead-protection area, rather they can be used to determine the length and location of flow lines within it. When these flow lines are spaced closely, the extent of the wellhead-protection area is easily seen. The wellhead-protection areas delineated for the Mt. Hope public-supply

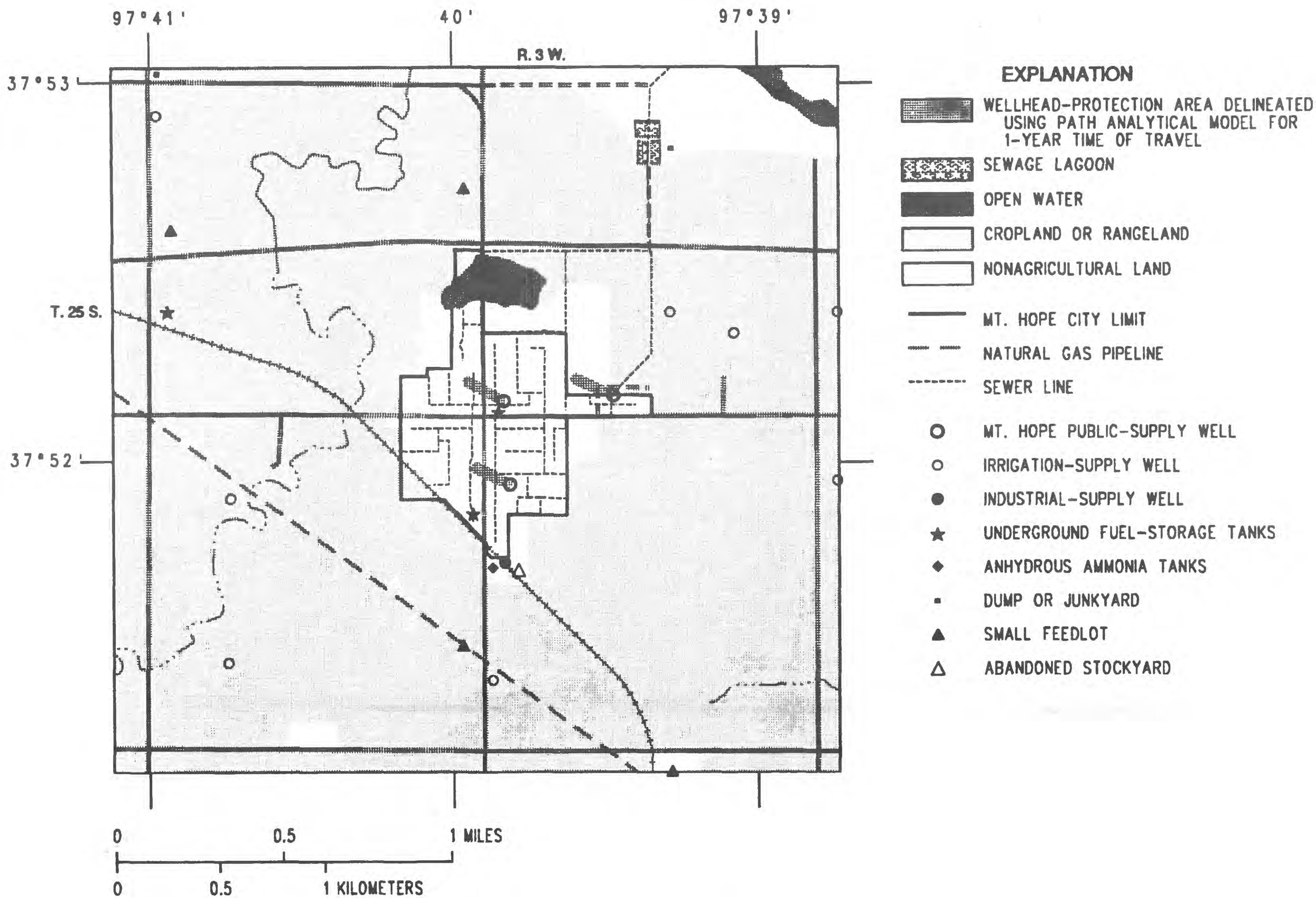

Figure 9. Wellhead-protection areas delineated using PATH analytical model for 1-year time of travel.

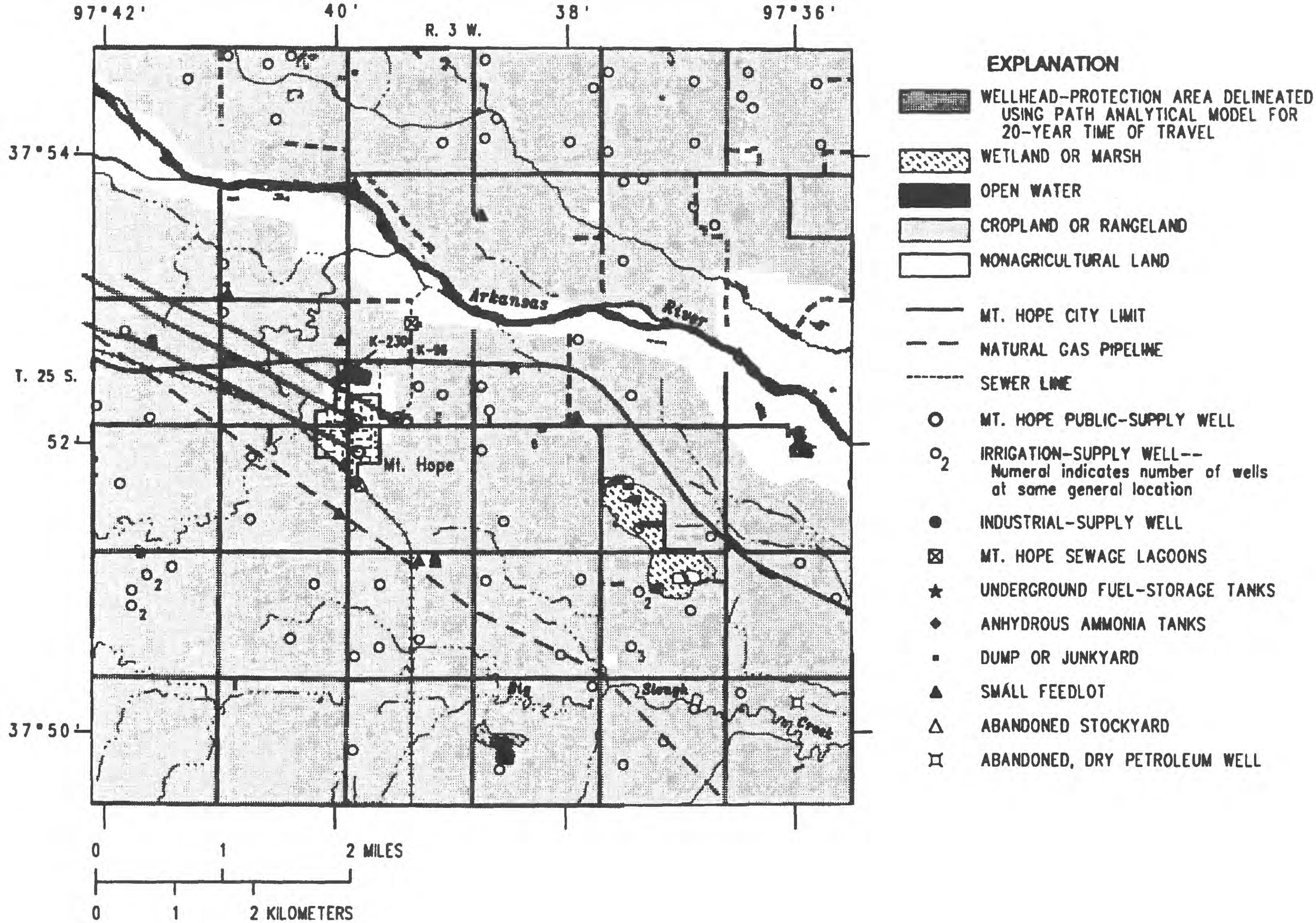

Figure 10. Wellhead-protection areas delineated using PATH analytical model for 20-year time of travel.

wells all extend upgradient and are narrow and elongated. The narrowness of these areas is of concern because the location of the wellhead-protection areas may change significantly if there is any error in the representation of the water table. If the water table is not accurately represented, the error in location of the wellhead-protection area will tend to increase with increasing distance from the well. For this reason, it may be desirable to add buffer zones around the wellhead-protection areas delineated using the PATH model. The buffer zone probably should be wedge shaped, with the narrow end slightly downgradient of the well and the wide end oriented upgradient. An example of a method used by the U.S. Geological Survey to determine buffer zones for a study in Colorado is discussed by the U.S. Environmental Protection Agency (1987a).

Increasing values for time of travel result in longer areas that remain the same width; increasing values of pumping rate result in wellhead-protection areas that are both longer and wider; increasing values of saturated thickness result in slightly shorter and narrower areas; increasing values of effective porosity result in shorter areas that remain the same width; and increasing values of hydraulic conductivity result in longer but narrower areas. The largest wellhead-protection areas would be those delineated using larger values of time of travel, pumping rate, and hydraulic conductivity and smaller values of effective porosity; whereas the smallest area would be delineated using larger values of porosity and smaller values of time of travel, pumping rate, and hydraulic conductivity. Time of travel and pumping rate seem to be the most important variables because the other variables are more likely to be restricted to a smaller range of values in any one area. The PATH model is capable of determining the null points between adjacent wells with large pumping rates. This allows the PATH model to be used to delineate wellhead-protection areas without overlap.

GWPATH Model

The computer model GWPATH was developed by the Illinois State Water Survey to be used to delineate 20-year wellhead-protection areas for public-supply wells as part of the Illinois ground-water-protection plan (Shafer, 1986). The GWPATH model can calculate flow lines in both forward (downgradient) and reverse (upgradient) directions. Like PATH, the collection of reverse flow lines about a well can be used to delineate the wellhead-protection area. An abbreviated version of Shafer's (1987) discussion about the governing equations of the GWPATH model follows.

The equations for fluid flow lines are derived from Darcy's law and can be written as:

$$v = \left(\frac{K}{n}\right) \operatorname{grad} h \qquad (13)$$

where

$\underline{v}$ = $\left(\frac{q}{n}\right)$ = average linear velocity vector;

q = Darcian velocity vector;

n = effective porosity;

K = hydraulic conductivity; and

h = total hydraulic head.

The individual components of $\underline{v}$ in the x and y directions can be expressed as:

$$v_x = \frac{dx}{dt}, \text{ and } v_y = \frac{dy}{dt}; \qquad (14)$$

where

x,y = two-dimensional horizontal components; and

t = time.

From these equations and using an approach developed by Prickett and others (1981), the flow velocity can be computed for any point within a continuous flow-velocity field that is approximated by a grid of values. To determine the trajectory of a particle through this field, a fourth-order Runge-Kutta numerical integration technique, as described by Daly and Morel-Seytoux (1980) is used. The flow lines are computed for the user-specified time of travel.

Data requirements

The GWPATH model requires a regular grid of values for hydraulic head and the dimensions of the grid (table 1). This is most easily obtained by first running a ground-water flow model; the ground-water flow model must be run for the same period as the time of travel and must include pumping rates of the wells. The GWPATH model can use either gridded or areal average estimates of effective porosity and hydraulic conductivity. The same gridded values used by the ground-water flow model can be used by the GWPATH model, or areal averages may be determined as described under CAPZONE data requirements. The GWPATH model, like the other analytical models, requires the user to specify the time of travel and to define the location of the origin of the grid and any wells. The same methods used to determine these values for the other analytical models may be used for the GWPATH model.

Results and Discussion

The GWPATH model did not provide satisfactory results for the Mt. Hope application. Like the PATH model, the GWPATH model can be used to delineate the wellhead-protection area as a set of closely spaced flow lines distributed about the well. GWPATH, as a result of the equations it uses, must have the flow lines begin a small distance from the well because the flow lines must emanate from a sink of finite size rather than a single point (Shafer, 1987). If the radius for the circle about the well from which the flow lines will start is too small, the downgradient flow lines will not delineate a reasonable ground-water flow pattern. As a result, unless the pumping rates of the public-supply wells are much larger than those used for the Mt. Hope public-supply wells, the radius required to compute reasonable flow lines may be larger than the width of the probable wellhead-protection area. The GWPATH model also is sensitive to the resolution of the grid; if the resolution is not fine enough, the flow lines may not be smooth. These factors appear to be significant in preventing valid results in the Mt. Hope application.

Hydrogeologic-Mapping Method

Hydrogeologic mapping is based on the identification of ground-water flow boundaries as the primary and commonly the only factor used to delineate wellhead-protection areas. These flow boundaries can be rivers, ground-water divides, and geologic contacts. This method can be used to delineate the entire zone of contribution (fig. 1). This method was not used to delineate wellhead-protection areas for the Mt. Hope public-supply wells because most of the flow boundaries were outside the study area and beyond the distance where they would affect the wells in a reasonable length of time.

Numerical Flow and Transport Model

Most or all of the following factors can be used with a numerical flow and transport model to delineate a wellhead-protection area: drawdown, time of travel, ground-water flow boundaries, and assimilative capacity. This type of model can be used to delineate the zone of contribution, or if the time of travel is one of the factors included, the zone of transport (fig. 1).

MOC Model

The method of characteristics (MOC) model is a two-dimensional, finite-difference, solute-transport and dispersion model developed by the U.S. Geological Survey to simulate the movement of solutes in a ground-water flow system. The MOC model does not directly define a wellhead-protection area because it cannot calculate the flow line of a particle in the reverse direction. It can simulate dispersion and dilution but cannot simulate reactive substances. A complete description of the equations and the model documentation can be found in Konikow and Bredehoeft (1978). They describe the workings of the model in this way (Konikow and Bredehoeft, 1978, p. 1):

> "The model couples the ground-water flow equation with the solute-transport equation. The digital computer program uses an alternating-direction implicit procedure to solve a finite-difference approximation to the ground-water flow equation, and it uses the method of characteristics to solve the solute-transport equation. The latter uses a particle-tracking procedure to represent convective transport and a two-step

explicit procedure to solve a finite-difference equation that describes the effects of hydrodynamic dispersion, fluid sources and sinks, and divergence of velocity."

The equation Konikow and Bredehoeft (1978, p. 2) use to describe areal flow in the MOC model is:

$$\frac{\partial}{\partial x_i}\left(T_{ij}\frac{\partial h}{\partial x_j}\right) = S\frac{\partial h}{\partial t} + W \qquad i,j = 1,2 \qquad (15)$$

where T_{ij} = transmissivity tensor;

h = hydraulic head;

S = storage coefficient;

t = time;

W = $W(x,y,t)$ = volume flux per unit area (positive sign for outflow and negative for inflow); and

x_i and x_j = cartesian coordinates.

The equation used by the MOC model to describe solute transport and dispersion (Konikow and Bredehoeft, 1978, p. 3) is:

$$\frac{\partial(CB)}{\partial t} = \frac{\partial}{\partial x_i} = \left(BD_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(BCV_i) - \frac{C'W}{n} \qquad i,j = 1,2 \qquad (16)$$

where C = concentration of the dissolved chemical species;

D_{ij} = coefficient of hydrodynamic dispersion (a second-order tensor);

B = saturated thickness of the aquifer;

C' = concentration of the dissolved chemical in a source or sink fluid;

V_i = seepage velocity in the direction of x_i;

n = effective porosity of the aquifer;

t = time; and

x_i and x_j = cartesian coordinates.

The MOC model requires a number of assumptions be made about the ground-water flow system and the solute in order to apply the model (Konikow and Bredehoeft, 1978). These assumptions are:

(1) Darcy's law is valid, and hydraulic-head gradients are the only significant driving mechanism for fluid flow.

(2) The porosity and hydraulic conductivity of the aquifer are constant with time, and porosity is uniform in space.

(3) Gradients of fluid density, viscosity, and temperature do not affect the velocity distribution.

(4) No chemical reactions occur that affect the concentration of the solute, the fluid properties, or the aquifer properties.

(5) Ionic and molecular diffusion are negligible contributors to the total dispersive flux.

(6) Vertical variations in hydraulic head and concentration are negligible.

(7) The aquifer is homogeneous and isotropic with respect to the coefficient of longitudinal and transverse dispersivity.

The parts of the MOC model that deal with dispersion and dilution were not tested because those processes are beyond the scope of this study. Only the parts of the model dealing with advection and particle tracking were used. No attempt was made during this study to change the results of the MOC model to link them directly to a geographic information system for display purposes.

Data requirements

The MOC model allows the use of gridded (areally variable) data (table 1). To use gridded data, the grid must have uniform dimensions. It is possible to avoid gridding most data, but that would defeat the purpose of using a numerical model. The data the MOC model can use in a gridded form include saturated or aquifer thickness, transmissivity, recharge rate, initial hydraulic head, and initial concentrations of solute. The model requires gridded information on the location of the origin of the grid, pumped wells, flow boundaries, and beginning position of the solute that will be tracked. Values for effective porosity and storage coefficient also are required but are not gridded. Some estimates of these data may be determined as described previously in "Description of Study Area" and in the "Data requirements" sections of "Analytical Models." Other required information is the length and number of pumping periods (the product of which is the time of travel) and (if these parts of the model are used) values related to retardation and dispersion.

Results and discussion

A two-dimensional model was considered appropriate for the Mt. Hope area because the *Equus* beds aquifer is neither overlain by nor contains a confining layer and the properties of the aquifer are generally homogeneous. The area modeled with the MOC model in this study does not coincide with the study area (fig. 11). The model grid extends 1 7/8 miles west and 1/8 mile north of the study area to minimize boundary effects; also, the model grid eliminates 1 7/8 miles along the east edge and 1 mile along the south edge of the study area to avoid inclusion of unaffected areas in the model.

The model area is divided into a grid of cells that are 660 feet (1/8 mile) on a side. The model specifies the first and last rows and columns of the model grid to be no-flow boundaries. The active area of the model is reduced further to an area bounded by constant-flux boundaries approximately parallel to the water-table contours (fig. 11) in the northwest and southeast, a constant-head boundary along the Arkansas River in the northeast, and a no-flow boundary perpendicular to the water-table contours in the southwest (fig. 11). Injection wells were placed in the grid cells along the northwest constant-flux boundary and pumped wells in the grid cells along the southeast constant-flux boundary to simulate flow into and out of the modelled area. Pumped wells in the appropriate constant-flux grid cells represent the three public-supply, one industrial-supply, and the 21 irrigation-supply wells in the active model area (fig. 11).

The model first was used to simulate steady-state conditions. On the basis of results from the steady-state model and the water-table contours, the pumping rate of the wells representing flow across part of the southeast constant-flux boundary was reduced to decrease the amount of drawdown in that part of the model area. Further calibration of the model was beyond the scope of this study.

Gridded values for saturated thickness, transmissivity, initial hydraulic head, and initial concentration of solute and an effective porosity of 0.2, a storage coefficient of 0.2, and a recharge rate of 3 in/yr were used in the MOC model to delineate the wellhead-protection areas for the Mt. Hope public-supply wells for 1- and 20-year times of travel (fig. 12). For the 1-year time of travel, the wellhead-protection area includes the Mt. Hope sewer lines, a location with underground fuel-storage tanks, plus cropland that may be a potential nonpoint source of contamination from agricultural chemicals. The 20-year time-of-travel area includes the previously mentioned potential sources of contamination, more cropland, parts of State highways K-96 and K-230, which are potential sources of contamination due to the salt used for deicing, three small feedlots, and a junkyard.

Wellhead-protection areas are delineated as the grid cells through which the solute passes during the time of travel. For areas with pumping rates as small as those in Mt. Hope (an average of 28.33 gal/min), this grid size was so large that the drawdown at each node containing one of the Mt. Hope public-supply wells was less than the gradient of the water table across the node. As a result, solute would not be "captured" by the nodes containing these wells but would continue to flow downgradient as the time of travel increased.

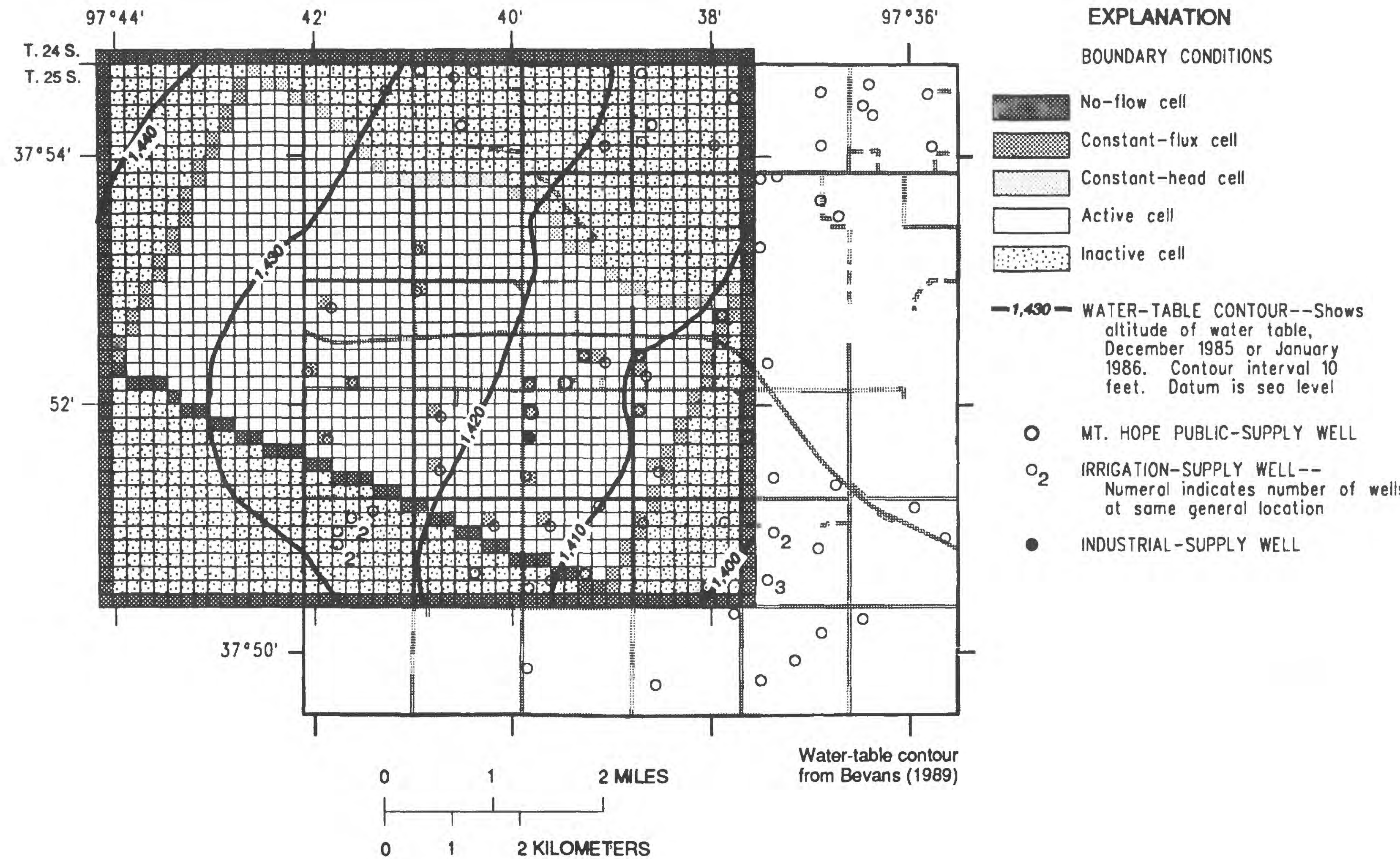

Figure 11. Location of study area and MOC model grid, boundary conditions, and altitude of water table in *Equus* beds aquifer.

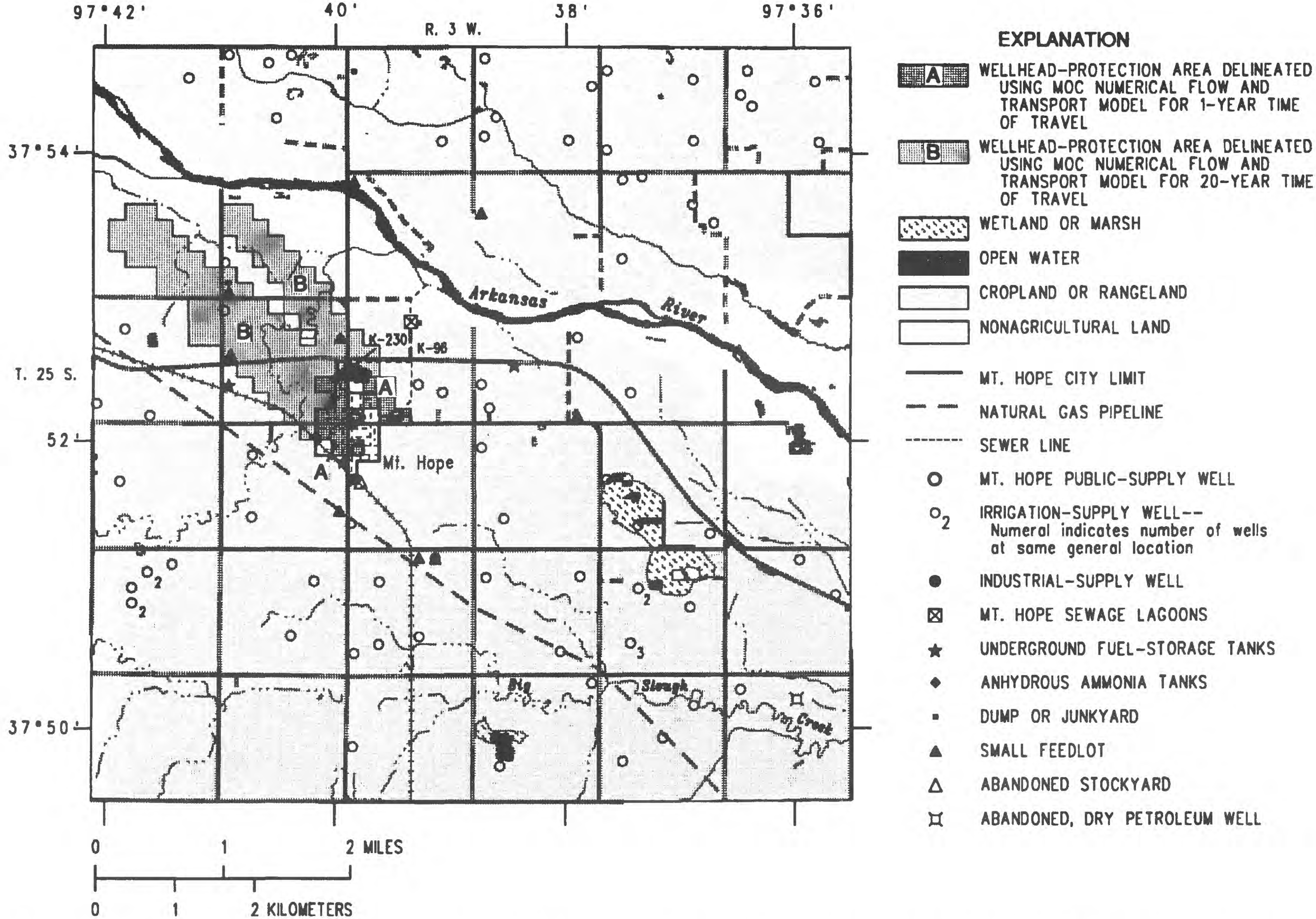

Figure 12. Wellhead-protection areas delineated using MOC numerical flow and transport model for (A) 1- and (B) 20-year times of travel.

EVALUATION OF METHODS

The U.S. Environmental Protection Agency (1987a) suggests that the following technical considerations be used when evaluating each method:

(1) ease of application;

(2) ease of quantification;

(3) ease of onsite verification of a factor's threshold or limiting value;

(4) ability to reflect variability of hydrologic conditions;

(5) suitability for a given hydrologic setting;

(6) ability to incorporate physical and chemical processes (advection, dispersion, and solid-solute interaction); and

(7) ability to reflect water-quality standards.

The amount of weight given to each technical consideration may vary depending on what the user thinks is most important. Technical considerations (1), (2), and (3) are important for the user's ease; considerations (4), (5), and (6) are important for hydrologic credibility; and consideration (7) is important for determining if the concentration of the contaminant will be within health limits when it reaches the well. The first six technical considerations were used to evaluate each category and method discussed in this report for the hydrologic conditions present in the study area.

Evaluations of each method for each of the first six technical considerations are summarized in table 2. The seventh technical consideration, the ability to reflect water-quality standards, was not evaluated because consideration of all the existing standards was beyond the scope of this study. The wellhead-protection area delineated using the method that best satisfies technical considerations 4, 5 and 6 (hydrologic credibility) for the conditions surrounding a particular public-supply well will correspond better to the zone of contribution or transport than those wellhead-protection areas delineated using methods with less hydrologic credibility. Although the results discussed in this report apply only to the Mt. Hope public-supply wells, some generalizations can be made about each of the methods that may be useful for other communitites with hydrologic conditions similar to those at Mt. Hope.

The arbitrary fixed-radius method sacrifices hydrologic credibility for ease of use, quantification, and onsite verification. This method is the simplest method to apply, to quantify, and to verify onsite. However, it does not consider any variations in conditions from site to site, properties of the hydrologic system, or incorporate any physical properties. The lack of hydrologic credibility may limit the use of this method.

The calculated fixed-radius methods differ in ease of application and ease of quantification of needed data. The requirement of some hydrologic training to determine the values needed for the radius-of-influence equations makes it the most difficult to apply of the calculated fixed-radius methods. Both the radius-of-influence and rate-of-recharge methods generally cannot be applied because the data needed (aquifer properties derived from the results of an aquifer test for the well and a reliable estimate of natural recharge, respectively) commonly are not available. Information needed for the volumetric method generally is more easily obtained than for the other calculated fixed-radius methods. Onsite verification of the factors used by the calculated fixed-radius methods commonly is difficult. One would need to verify the drawdown at the outer edge of the wellhead-protection area when using the radius-of-influence method. Tracer-test analyses could be used to verify the recharge and time-of-travel rates for the rate-of-recharge and volumetric methods, respectively.

The calculated fixed-radius methods do have the ability to reflect some variability in actual conditions but are limited to site-specific data or to areal averages. For example, if the radius-of-influence method was used and the pumping rate of the public-supply well increases beyond that of the aquifer test, the wellhead-protection area would no longer be valid. Also,

Table 2. *Technical considerations used in evaluation of selected methods used to delineate wellhead-protection areas for hydrologic conditions present in the Mt. Hope study area*

[Ranking (1-5): 1 is least apt, and 5 is most apt; N/A = Not applicable]

Method	Technical considerations[1]					
	Ease of application (1)	Ease of data quantification (2)	Ease of on-site verification (3)	Reflects variability of hydrologic conditions (4)	Suitability for hydrologic setting (5)	Incorporation of physical and chemical processes (6)
Arbitrary fixed radius	5	5	5	N/A	1	N/A
Calculated fixed radius:						
Radius of influence	3	1-3	2	1-3	1-2	2
Rate of recharge	3-4	1-3	1	1	1	2
Volumetric	3-4	3-4	1	1-3	1-2	2
Analytical models:						
CAPZONE	3	3	1	3-4	3	3
PATH	3	3	1	3-4	4	3
GWPATH	2	1	1	4	1	3
Numerical flow and transport models:						
MOC	1	1	1	5	3-5	3-5

[1]U.S. Environmental Protection Agency (1987a).

the estimates of recharge used by the rate-of-recharge method generally are averages for large areas and, as Sophocleous and Perry (1987) have shown, may not accurately reflect the rate of recharge in the wellhead-protection area. The calculated fixed-radius methods do not account for interference between pumped wells, which will cause overlapping wellhead-protection areas where the combined radii of the wellhead-protection areas of any two wells are longer than the distance between the two wells, as in the examples of the rate-of-recharge and 20-year volumetric methods (figs. 5 and 6). None of the calculated fixed-radius methods used in this study are suitable for the hydrologic setting of the Mt. Hope study area because they lack provisions for a sloping water table, transient conditions, and well interference. The calculated fixed-radius methods described in this study do not incorporate any physical or chemical processes other than advection.

The simplified variable-shapes method was not used in the Mt. Hope study area. This method might be useful if a set of simplified variable shapes already exists for the area of interest or if a large enough area is under study to warrant development of a set of simplified variable shapes. Because this method depends on analytical models to determine the shapes, the evaluation of this method is identical to that for analytical models except that the simplified variable-shapes method would be easier for the end user to apply.

The analytical models differ in their ease of application and data quantification. Of the analytical models used in this study, GWPATH is the most difficult to apply and to quantify data because it requires results from a ground-water flow model. Onsite verification of the time-of-travel factor used by the analytical models may be accomplished by tracer-test analyses, but generally this is difficult.

The ability of analytical models to reflect the variability of hydrologic conditions differs. The CAPZONE and PATH models depend on areal averages for all the hydrologic variables; GWPATH requires areally variable (gridded) data for hydraulic head and allows it for effective porosity and hydraulic conductivity (table 1). Analytical models do include provisions for a sloping water table, which make them more suitable for the hydrologic setting of the Mt. Hope study area than the fixed-radius methods, but they all include the assumption of steady-state conditions, which prevent them from being entirely suitable for the Mt. Hope study area. Both PATH and GWPATH account for interference between pumped wells, which makes them more suitable for the conditions in the Mt. Hope area than CAPZONE, which does not account for interference. The inability of the GWPATH model to simulate wells with small pumping rates prevents it from being suitable for the Mt. Hope public-supply wells. None of the analytical models described in this study incorporate any physical or chemical processes other than advection.

The hydrogeologic-mapping method is not appropriate for small study areas if the hydrologic conditions include a thick, areally extensive aquifer with diffuse ground-water flow, which is the case in the Mt. Hope study area. This method might be useful where the aquifer is much more limited in extent, such as some glacial or thin alluvial aquifers, or where ground-water flow is primarily through fractures or solution channels, such as fractured bedrock or karst.

A numerical flow and transport model is more difficult to apply than any of the previously described methods. Use of a numerical flow and transport model requires much more hydrologic training and judgment to determine whether the results are valid than the other methods described in this study. The MOC model is difficult to apply because a trial-and-error method of introducing a solute in each grid cell and determining if it reached but did not go beyond any of the public-supply wells during the time of travel needs to be used to delineate the location of the wellhead-protection areas. The MOC model contains no provisions for reverse calculation of particle motion. The MOC model requires areal variable (gridded) data, which makes data quantification more difficult for this model than for the other methods described in this study. The results of the MOC model may be verified by tracer-test analyses.

A numerical flow and transport model sacrifices ease of application and data quantification to gain increased flexibility in portraying the variability of hydrologic conditions. The MOC model allows for inclusion of more different types of data than the other methods described in this study and for areally variable data. Any numerical flow and transport model similar to the MOC model is more suitable for different hydrologic settings, including the Mt. Hope study area, than the other methods used in this study because the model includes provisions for a sloping water table, flow boundaries, areally variable conditions, and transient conditions. The MOC model is among those numerical flow and transport models that account for some physical and chemical processes other than advection by incorporating dispersion and retardation equations.

The results of the MOC model best reflect the actual hydrologic conditions in the Mt. Hope study area. If, however, the results of the other methods are similar to those of the MOC model, then they may be preferable for the user because they are easier to use and quantify. A comparison of the different wellhead-protection areas in figures 3-10 and 12 shows that the areas delineated for the Mt. Hope public-supply wells vary greatly in size and shape. The arbitrary and calculated fixed-radius methods result in circular areas of varying sizes, whereas the computer-dependent analytical and numerical flow and transport models result in elongated shapes of varying lengths. Generally, the analytical and numerical models are thought to more closely reflect actual hydrologic conditions because these models include the sloping water table in their calculations. Because the water table does slope from the northwest to the southeast in the study area, large parts of the areas delineated using the fixed-radius methods that are northeast, southeast, and southwest of each Mt. Hope public-supply well may not be contributing water to the wells and, therefore, may not need to be included in the wellhead-protection areas. Although it is often safer to use a wellhead-protection area that overprotects, inclusion of areas that do not contribute water to the well may be difficult to justify on a hydrologic basis.

For small wellhead-protection areas, the results of the fixed-radius methods and the analytical and numerical flow and transport models are similar in size (compare areas based on arbitrary fixed radius of Kansas, 1-year volumetric calculated fixed radius, and 1-year times of travel for CAPZONE, PATH, and MOC models, figs. 3, 6, 7, 9 and 12, respectively). To protect a well from direct contamination, only the area immediately surrounding the well needs to be included in the wellhead-protection area. Therefore, the arbitrary fixed-radius method used to delineate the smallest area probably would be the most efficient method to use to delineate the area needed to protect each wellhead from direct contamination. For the Mt. Hope public-supply wells, the arbitrary fixed radius of 100 feet probably is adequate for protection from direct contamination. The other methods used in this report could be used but probably would overprotect for this purpose.

To protect a well from microbial contamination the areas delineated using the analytical and numerical flow and transport models for a 1-year time of travel could be used. Although the fixed-radius methods that use a radius of similar extent may overprotect in the downgradient direction, the total area will not be large, and these methods are easier to apply and quanitify than the analytical and numerical models. Of the fixed-radius methods used with the Mt. Hope public-supply wells, the wellhead-protection area delineated using the radius-of-influence method most closely matches the results of the analytical and numerical flow and transport models in size, and the 1,000-foot radius can be used to delineate a slightly larger area. The wellhead-protection areas delineated using an arbitrary fixed radius of 100 feet and the calculated fixed radius from the volumetric method with a 1-year time of travel are smaller and would underprotect for microbial contamination. The wellhead-protection area delineated using the 2-mile arbitrary fixed radius is much larger than than necessary and would overprotect for this purpose.

To protect a well from most potential chemical contamination, whether it be from a point or nonpoint source, generally requires a much larger area than for protection from direct or microbial contamination. Assuming that 20 years would provide enough time to recognize and clean up any chemical contamination before it could reach the well, then the area delineated using the numerical flow and transport model for a 20-year time of travel would provide adequate protection. When this area is compared with those from the fixed-radius methods, it is obvious that all of the fixed-radius methods will underprotect in the upgradient direction, except the 2-mile arbitrary fixed radius suggested by the U.S. Environmental Protection Agency for initial wellhead-protection areas. The wellhead-protection areas delineated using the CAPZONE and PATH analytical models are similar in length and general shape to those of the MOC numerical flow and transport model. The CAPZONE and PATH models would be more hydrologically defensible if a method could be determined that would buffer the areas delineated using these methods such that the buffered areas would include all of the area delineated using the MOC model for the same time of travel. The wellhead-protection areas delineated using the CAPZONE and PATH models then would be more hydrologically defensible than the results of the 2-mile arbitrary fixed- radius method and easier to apply and quantify than the MOC model.

It is possible for a community to designate wellhead-protection areas for different types of contamination and to designate them in stages. The community might begin with a wellhead-protection area delineated using a large arbitrary fixed radius that will overprotect in all directions for all types of contamination. Later, as information and resources become available, methods with more hydrologic credibility could be used to refine the wellhead-protection area. If a community wished to use one of the computer-dependent models to delineate wellhead-protection areas but lacked the expertise or computer needed, many engineering consulting firms or State and Federal agencies with water-related responsibilities could assist them.

SUMMARY

The Mt. Hope, Kansas, community, like many others in the Midwest, depends on an aquifer that is particularly vulnerable to contamination from sources at or near the land surface for its public-water supplies. Implementation of a wellhead-protection area is one way of protecting a public-supply well from contamination. Many methods have been developed that are useful for delineating wellhead-protection areas, but before this study these methods had not been evaluated for their appropriateness under conditions that are present in the Mt. Hope area and common in many parts of the Midwest. The conditions in the Mt. Hope study area include an agricultural setting and a shallow, sloping water table in an extensive and large-yielding aquifer that is overlain by relatively permeable materials. Although the results discussed in this report apply to the Mt. Hope, Kansas, public-supply wells only, some generalizations can be made about each of the wellhead-protection methods that may be useful for other communities with hydrologic conditions that are similar to those at Mt. Hope.

Both the arbitrary fixed-radius and the calculated fixed-radius methods have relatively simple data requirements and are relatively easy to use, but the results may not be reasonable because they cannot simulate a sloping water table. Wellhead-protection areas delineated using most calculated fixed-radius methods will not provide adequate protection from chemical contamination. If large radii are used, they will tend to overprotect in the downgradient direction and may be difficult to justify on a hydrologic basis.

The simplified variable-shapes method might be useful if a set of shapes is available for the range of expected hydrologic conditions for an entire region. Once a set of shapes was available, results probably would be comparable to those from an analytical model, but with much smaller data requirements; therefore, the variable-shapes method would be easier to use.

If a method for defining an appropriate buffer zone around the wellhead-protection areas delineated using the analytical models can be determined, the analytical models might be a good compromise between the fixed-radius methods and the numerical flow and transport models. Although the PATH and CAPZONE analytical models are similar in data requirements and ease of use, PATH would seem to have an advantage over CAPZONE because it can determine the null points between wells, which prevents overlap of wellhead-protection areas of adjacent wells. The other analytical model, GWPATH, is more difficult to use because of its requirement for gridded data, some of which must be obtained from the results of a numerical flow model. Also, the results from GWPATH may be invalid for wells with small pumping rates. Although analytical models can be used to delineate areas to protect wellheads from direct, microbial, and chemical contamination, they probably will be most useful for delineating areas to protect wellheads from chemical contamination because they can be used to delineate the zones of transport of the wells.

The hydrogeologic-mapping method depends on identification of ground-water flow boundaries. How easy this method is to use depends on how easy it is to define the flow boundaries. This method was not suitable for the Mt. Hope study area because the flow boundaries are outside the study area. The hydrogeologic-mapping method could be useful for hydrologic conditions similar to those at Mt. Hope if the aquifer is more limited in extent or the study area is larger. Because the hydrogeologic-mapping method can be used to delineate the entire zone of contribution to the well, its most useful application probably would be for delineating areas to protect wellheads from chemical contamination.

Numerical flow and transport models are the most credible and flexible in simulating the hydrologic conditions and the most difficult to use because their requirements for data and hydrologic training are much greater than any of the other methods. With most applications of numerical flow and transport models, the grid-cell size probably will not be fine enough to allow delineation of areas to protect wellheads from direct contamination only. Numerical flow and transport models can be used to delineate areas to protect wellheads from microbial contamination but probably would be most useful for delineating areas to protect wellheads from chemical contamination because they can be used to delineate the zones of transport of the wells.

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APPENDIX A

Description of PATH Model

by A.T. Rutledge

The PATH model consists of (1) a mathematical scheme for defining the altitude of the water table at any point in the area of interest, (2) a method for calculating the ground-water gradient at any point in the system by calculating the altitude of the water table at three points surrounding the point of interest, and (3) a procedure that defines the shape and length of flow lines by backstepping from pumped wells, using Darcy's law, for a given period of time.

The mathematical expression for the altitude of the water table consists of a mathematical definition for the natural, prepumping hydraulic-head distribution minus the drawdown caused by pumped wells. In its simplest case (the method used here), the natural hydraulic-head distribution is conceptualized to have a uniform gradient. The head distribution thus is defined by the location of three points at which the natural altitude of the water table is known. The natural altitude of the water table is thus equal to the unique solution of a set of three equations:

$$Ex_1 + Fy_1 + G = h_1 \; ; \qquad (17)$$

$$Ex_2 + Fy_2 + G = h_2 \; ; \text{and} \qquad (18)$$

$$Ex_3 + Fy_3 + G = h_3 \; ; \qquad (19)$$

where x and y are the areal-location coordinates, and h is the hydraulic heads (altitude of the water table) at the three points, and the terms E, F, and G are to be solved for. The solution of equations 17-19 is an equation of the form:

$$h = Ex + Fy + G \; , \qquad (20)$$

where h equals the altitude of the water table at any point, and x and y are coordinates of the point. To arrive at the altitude of the water table at the point of interest, the "natural" altitude of the water table is calculated, then the drawdown at the point of interest caused by each pumped well is subtracted.

The drawdown at the point of interest is calculated from an adapted form of the Thiem equation:

$$s = \frac{Q \ln \left(\frac{r_i}{r}\right)}{2\pi T} \qquad (21)$$

where s = drawdown at the point of interest;

Q = pumping rate of the well;

r = distance from the pumped well;

r_i = radius of influence of the well; and

T = transmissivity of the aquifer.

The method for calculating the gradient at a point of interest utilizes three "scouting points" that are located around the point of interest a short distance from the central point (0.1 to 10 feet). At each point, the hydraulic head is calculated by the methods defined in the previous paragraph. Then, the same methodology of deriving a mathematical expression for the hydraulic head at the three scouting points is used. An equation of the form of equation 20 defines this localized-scale potentiometric-surface distribution surrounding the point of interest. The x and y components of the gradient of this hydraulic-head distribution are developed from differentiation of these equations:

$$\frac{dh}{dx} = E \quad \text{for the gradient in the x direction} \ , \tag{22}$$

and

$$\frac{dh}{dy} = F \quad \text{for the gradient in the y direction} \ . \tag{23}$$

For each pumped well, a user-specified number of lines of flow approaching the well are defined by the PATH model. The flow lines converge radially on the well every 5 degrees. Each flow line is defined as "starting" just outside the well. The methods just described are used to determine the gradient at the starting point of the flow line. From Darcy's law, the velocity of ground water at that point is:

$$v_x = \frac{K}{n} (E) \text{, and} \tag{24}$$

$$v_y = \frac{K}{n} (F) \text{,} \tag{25}$$

where

v_x = velocity in the x direction;

v_y = velocity in the y direction;

K = hydraulic conductivity; and

n = porosity.

From the starting point, the point of interest is moved out upgradient from the well in a direction determined by the gradient, to a new point, by a distance increment designated by the user. The program keeps track of the time it takes to move this increment. Subsequent movements from the new position are executed until the user-defined time period of interest is exceeded. This back-stepping procedure is followed for all flow lines.