WELLHEAD PROTECTION STRATEGIES FOR CONFINED-AQUIFER SETTINGS

Charles W. Kreitler
Rainer K. Senger

Bureau of Economic Geology
The University of Texas at Austin
Austin, Texas 78713-7508

Marilyn Ginsberg
Project Manager

Ground-Water Protection Division
Office of Ground Water and Drinking Water
U.S. Environmental Protection Agency
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CONTENTS

Figures

EXECUTIVE SUMMARY

Improper management of contamination sources has resulted in numerous cases of ground-water contamination of public water supply wells. One approach toward preventing contamination of public water supplies is to protect the areas that recharge precipitation and surface water to the aquifer near the wells. This zone of protection is referred to as a wellhead protection area (WHPA). The potential for contamination is typically less in a confined aquifer than in an unconfined aquifer. Nevertheless, contamination of confined aquifers has occurred. Wellhead protection areas should be developed for all aquifer settings.

A confined aquifer is an aquifer overlain by low-permeability strata. The presence of the low permeability material reduces the risk of a surface contaminant reaching a producing well. The potential for contamination of a confined aquifer is controlled by two factors: (1) The presence of permeable pathways (for example, faults, fractures, permeable sands, or unplugged abandoned boreholes) that permit contaminant migration and (2) the existence of appropriate hydrologic conditions (for example, downward flow) that cause contaminants to migrate through the low-permeability strata.

Confined aquifers occur pervasively from coast to coast in the United States. The coastal plain aquifers along the Atlantic Ocean and Gulf of Mexico represent some of the largest confined aquifer systems in the United States. There are numerous other smaller aquifers which exhibit confined conditions.

Degree of Confinement

Before a wellhead protection area can be delineated, the degree of confinement of the aquifer setting must be determined. Aquifers can be unconfined or confined. Confined aquifers can be subdivided into semiconfined and highly confined aquifers. A semiconfined aquifer is an aquifer overlain by strata that have relatively low permeability compared to the aquifer. However, the permeability of these overlying strata may be high enough to allow significant leakage through the strata. A fractured till is a good example of a relatively low-permeability stratum with significant leakage. In such a setting, it is inferred that the leakage is areally distributed. In a highly confining strata, leakage is negligible. If leakage does occur, it is probably restricted to localized zones such as discrete faults or artificial penetrations such as wells, and abandoned or improperly plugged boreholes. A semiconfined aquifer is more susceptible to contamination than a highly confined aquifer because of the potential for significant leakage through the overlying confining strata.

There are several approaches for differentiating confined from unconfined aquifers. These approaches can be considered as (1) geologic, (2) hydrologic, and (3) hydrochemical. Geologic approaches include (a) classic geologic mapping, (b) environmental geologic and hydrogeologic mapping, and (c) construction of geologic cross sections. Hydrologic approaches include evaluations of (a) water-level elevation in wells, (b) potentiometric surface maps, (c) storativity, (d) leakage, (e) continual water-level responses in wells, and (f) numerical models. Hydrochemical approaches involve the evaluation of (a) general water chemistry, (b) tritium and (c) carbon-14 data. Tritium is the radioactive isotope of hydrogen that has been introduced into the atmosphere in the last 40 yr by atmospheric nuclear testing. It is now in the recently recharged ground water in measurable but nonharmful concentrations. Carbon-14 is the radioactive isotope of carbon that can be used to estimate the age of ground waters that may be hundreds to thousands of years old.

Though several techniques differentiate confined from unconfined aquifers, only a few approaches can be used to quantitatively differentiate semiconfined from highly confined aquifers. A 40-yr time of travel (TOT) approach is recommended for making this differentiation (that is, 40 yr is considered to be a reasonable "rule of thumb" to distinguish between semiconfined and highly confined conditions). This 40-yr time of travel from the recharge area at the ground surface to the well in the aquifer can be calculated by hydrologic methods or inferred from tritium analyses. Using the time of travel equation plus leakage values calculated from a pump test, the rate of vertical leakage through a low-permeability strata can be estimated. If the calculated time of travel is less than 40 yr the aquifer is considered semiconfined. If the time of travel is greater than 40 yr then the aquifer is considered highly confined. Similarly, if the tritium concentrations in the aquifer are less than 1 to 2 tritium units (TU), the lower level of detection for many tritium analyses, then the water is older than 40 yr. This is approximately the amount of time since tritium was first introduced in the hydrosphere by atmospheric nuclear testing. If the water contains tritium concentrations above 1 to 2 tritium units, then the confined aquifer has been recharged within the last 40 yr, either by horizontal flow or by vertical leakage. If horizontal flow cannot explain the presence of tritium, then the tritium must result from vertical leakage and the aquifer should be considered semiconfined.

It is important to differentiate between semiconfined and highly confined aquifers because, as previously Stated, semiconfined aquifers are subject to pervasive leakage through the overlying low-permeability strata, whereas potential leakage to a highly confined aquifer is limited to localized and discrete permeability pathways. Different types of wellhead protection strategies are needed for the semiconfined and highly confined aquifers.

Delineating Wellhead Protection Areas

Determining a wellhead protection area for a well or well field in a confined aquifer setting requires delineating a general area for protection based on hydrodynamic approaches. Subsequently, critical zones within the general area are defined by identifying potential high-permeability pathways for downward migration of contaminants through the low-permeability strata overlying the aquifer.

The hydrodynamically delineated wellhead protection area can be based on either a cone of depression (COD) (as referred to as zone of influence [ZOI]) approach or a zone of transport (ZOT) (also referred to as the time of travel [TOT]) approach. The time of travel approach is recommended in preference to the zone of influence approach.

The cone of depression approach uses the lateral pumping extent of a cone of depression as the wellhead protection area and, in an area where the prepumping gradient of the piezometric surface is negligible, cone of depression represents the area for which there is a potential for downward vertical and lateral flow towards a producing well. The zone of influence approach is one method recommended for defining the wellhead protection area in unconfined aquifers. However, this approach may not be appropriate for confined aquifers. As the confining strata become more impermeable, the lateral extent of a cone of depression in a confined aquifer may become unrealistically large. For example, the radius of a cone of depression for a semiconfined aquifer may be a few hundred feet, but for a highly confined setting it may extend more than 10,000 ft. The highly confined aquifer, which is less sensitive to potential contamination, will have a cone of depression area significantly larger than one for semiconfined and unconfined aquifers. This increase in lateral extent of the cone of depression is due to the fact that a pumping well in a confined aquifer must draw more of its ground water from lateral sources because less water is available from vertical leakage. Therefore, for highly confined aquifers wellhead protection areas based on cones of depressions may be unreasonably large.

A time of travel approach provides a more realistic estimate of a wellhead protection area for a confined aquifer. The time of travel approach provides a protection area defined by the lateral distance that ground water flows for a defined period of time and can be defined by an equal-time contour line. Inside that contour line, ground water will flow to a pumping well in less than the specified period of time. Outside that contour, it takes water longer than the specified time to flow to the producing well. There are two basic methods for calculating a time of travel: (1) A volumetric-flow equation, which is a modification of Darcy's law, provides the distance of flow over a given period of time. The volumetric-flow equation calculates the radius of a cylinder from which all ground water is pumped. The wellhead protection area calculated using time of travel may be too large, because it assumes that there is no vertical leakage and, therefore, that all ground water discharged results from lateral flow. (2) A second method is to use a time of travel calculation based on the hydraulic gradient of the cone of depression. The second method, the cone of depression/time of travel, is a more realistic estimate of time of travel, because it incorporates any vertical leakage into the calculation.

The distance of a time of travel contour from the pumping well for a leaky confined aquifer might be, for example, a few hundred feet, whereas for a highly confined setting the travel time distance for the same period of time might extend to thousands of feet. The cone of depression for the leaky system stabilizes with a much smaller radius than that for the more confined setting, because in the leaky setting vertical leakage supplies water to the pumping well, which otherwise has to be supplied by lateral flow. The more confined an aquifer, the more it approaches the condition of receiving no vertical leakage, and the closer the time of travel calculated with the cone of depression/time of travel method approaches the time of travel calculated by the volumetric-flow equation. In general, the wellhead protection area calculated with time of travel will be smaller than a wellhead protection area calculated with a cone of depression.

A forty-year time of travel threshold is a reasonable "rule of thumb" for distinguishing between semiconfined and highly confined aquifers. Forty years is the time frame for which tritium has been introduced into the atmosphere and therefore into ground water. Well water with no tritium indicates that it took ground water a minimum of 40 yr to flow horizontally and/or vertically from a point of recharge to the well. Conversely, well water with tritium indicates ground water that has been recharged within the last 40 yr; thus, the particular well or aquifer is relatively sensitive to aquifer contamination.

The shape and size of a wellhead protection area can be affected by the gradient of the regional potentiometric surface. Nonnegligible gradients cause a wellhead protection area to have a noncircular shape. The exact shape depends on the rate of pumpage, the transmissivity of the aquifer, and the regional gradient.

After a general wellhead protection area has been determined using hydrologic criteria, the permeability pathways through the confining strata should be considered. For a semiconfined aquifer, permeability pathways such as fractures are considered to be common and evenly distributed and, therefore, the entire wellhead protection area should be considered highly sensitive to potential contamination, as is the wellhead protection area for an unconfined aquifer. In contrast, for a highly confined aquifer, the pathways for contaminant migration probably are limited to a few discrete breaches of the confining strata. These breaches in confinement might be abandoned boreholes or faults and should be given a higher level of protection from the rest of the area. In a highly confined aquifer setting two levels of protection should be developed. The general hydrodynamic area should be given one level of protection and the immediate vicinity of discrete pathways, where leakage could occur, should be given a higher level of protection.

Examples of Wellhead Protection Areas in Confined Aquifers

Wellhead protection areas were determined for two confined aquifer settings in Texas. The first field case setting was in Bastrop, Texas, where the highly productive Wilcox aquifer crops out. Before the study it was not known whether the well field would be in the confined or unconfined part of the aquifer because of its location in the outcrop of the aquifer. The second field case setting was in Wharton, Texas, where the Gulf Coast aquifer was presumed to be highly confined beneath the Beaumont Clay. Field studies first evaluated the presence and degree of confinement and then wellhead protection areas were delineated for municipal well fields in both communities.

In Bastrop, Texas, the Wilcox aquifer was found to be highly confined even though it was located in the outcrop. The degree of confinement was tested with five techniques, which include (1) evaluating the regional hydrogeologic setting; (2) conducting a pumping test; (3) monitoring of continuous water levels; (4) assessing the general hydrochemistry; and (5) determining tritium and carbon-14 concentrations in the well water. The results of the investigations indicate a high degree of confinement and old waters with ages greater than 4,000 yr. The radius of the wellhead protection area ranged from 3,000 to 18,000 ft, based on the different hydrodynamic approaches. The regional gradient affected the shape of the wellhead protection area. A wellhead protection area of 3,000 to 7,000 ft in the downstream and upstream direction, respectively, was considered the most realistic. The most critical pathways for potential contamination of the ground water are artificial penetrations such as wells and abandoned boreholes.

In Wharton, Texas, the Gulf Coast aquifer was found to be highly confined. The regional hydrogeology was investigated, in addition to the evaluation of pumping tests, general hydrochemistry, and tritium and carbon-14 measurements. The results of the investigations indicate a high degree of confinement and old waters with ages greater than 15,000 yr. A pump test indicated extensive leakage, but it appears that this leakage results from ground-water draining from interbedded sands within the overlying thick aquitard and not from a shallow aquifer. The calculated radii of the wellhead protection area based on the different hydrodynamic approaches ranged from 300 to 4,000 ft. The negligible regional gradient of the potentiometric surface did not affect the shape of the wellhead protection area. A wellhead protection area of 1,000 ft is considered the most realistic. The most critical pathways for potential ground-water contamination are artificial penetrations such as wells and abandoned boreholes.

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CHAPTER 1. INTRODUCTION

Nearly half the population of the United States uses ground water as its drinking water supply. Improper management of contamination sources has resulted in numerous cases of ground-water supply contamination. One approach toward preventing contamination of these water supplies is to protect the areas that provide recharge to supply wells.

The 1986 Amendments to the Safe Drinking Water Act created the Wellhead Protection Program. Through this program, the U.S. Environmental Protection Agency (EPA) assists States in protecting areas surrounding public drinking water supply wells against contamination. The technical assistance document, "Guidelines for Wellhead Protection Area Delineation for Confined Aquifer Settings," was developed to provide technical information to the States in their implementation of wellhead protection programs.

Confined Aquifers: Why Be Concerned?

Confined aquifers, by definition, are overlain by low-permeability strata. Confined aquifers are typically less sensitive to surface contamination than water-table (unconfined) aquifers. However, ground-water contamination has occurred in confined aquifers, demonstrating the need to protect these sources of ground water.

In general, more confined aquifers are less sensitive to contamination than less confined or unconfined aquifers, and less restrictive wellhead protection strategies may be appropriate. Unless the degree of confinement of a well field is known, the potential for contamination is unknown. In some areas an entire region can be generally characterized because hydrogeologic conditions are relatively uniform. In other areas, however, it may be necessary to characterize the degree of confinement near each well or well field.

Some confined aquifers have become contaminated. Confining strata are not impervious to ground-water movement and to contaminant migration. Long-term pump tests have shown vertical flow through confining strata (Neuman and Witherspoon, 1972; Grisak and Cherry, 1975). Much of this leakage may be attributable to fractures through clay and silt strata (Williams and Farvolden, 1967; Gera and Chapman, 1988). Different types of contaminants have also been shown to migrate through confining layers that consist of clays, silts, and glacial till (Schwartz and others, 1982; Dorhofer and Fritz, 1988; Jackson and Patterson, 1989; Herzog and others, 1989). Downward migration of contamination through confining layers can also occur along monitoring-well casings (Meiri, 1989) and in naturally occurring faults (Keller and others, 1987). In Texas, Thompson and Hayes (1979) identified a fluorocarbon plume in the confined limestone Edwards aquifer.

Purpose of Document

The purpose of this technical document is two-fold. (1) To provide a methodology to define the sensitivity of an aquifer to contamination. This is accomplished first by determining the degree of confinement of an aquifer, that is, whether an aquifer is unconfined, semiconfined, or highly confined, because the more confined the aquifer, the lower the probability for its contamination. (2) To provide approaches for delineating wellhead protection areas (WHPA's) for highly confined and semiconfined aquifers.

Chapter 1 defines confinement. Chapter 2 explains the basic mechanics of ground-water flow in a confined aquifer. Chapter 3 provides methods for characterizing confined aquifers. Chapter 4 describes general wellhead protection strategies. Chapter 5 describes hydrodynamic approaches for delineating wellhead protection areas, and Chapter 6 describes the different approaches for developing wellhead protection areas for semiconfined and highly confined aquifer settings. Chapter 7 provides methods for determining wellhead protection areas for well fields. Chapter 8 describes two case studies, and Chapter 9 provides recommended approaches. A detailed description of the two case studies is included in the appendices, as well as a short discussion on the national distribution of confined aquifers and a glossary of important terms used in the document.

Definition of a Confined Aquifer

Before wellhead protection areas are delineated for wells, the aquifer setting has to be defined as to whether it is highly confined, semiconfined, or unconfined. Before addressing the question of degree of confinement, more basic issues need to be addressed. What is the importance of confinement to wellhead protection? Are general hydrogeologic definitions of confinement acceptable for wellhead protection? The following definition is recommended in the context of wellhead protection strategies and is referred to as the wellhead protection area definition:

"A confined aquifer is a section of an aquifer overlain by low-permeability strata that lower the probability of ground-water contamination from surface sources" (fig. 1).

The critical elements of this definition are (1) there is a low probability of contamination from the ground surface and (2) this low probability results from the presence of overlying low-permeability strata. By this definition, ground water in a confined aquifer need not exist under greater-than-atmospheric pressure, and/or rise above the top of the aquifer in wells. This definition differs from classical definitions because its primary focus is the potential for contamination from the surface. The wellhead protection area definition is an expansion of the definition used in the American Geologic Institute (AGI) Glossary of Geologic Terms: "An aquifer bounded above and below by impermeable bed or beds of distinctly lower permeability than the aquifer itself" (Bates and Jackson, 1987).

The wellhead protection area definition is preferred to classical definitions of confined aquifers because it addresses the hydrogeologic setting that causes confinement rather than the hydrologic phenomena resulting from confinement. It has implications about the age of the water within the confined aquifer. If the confining unit prevents contaminants from reaching the confined aquifer, the unit will also prevent easy movement of water to the aquifer. Geochemical indicators of absolute or relative age, and numerical or analytical calculations of vertical leakage, provide a very important approach for identifying confinement.

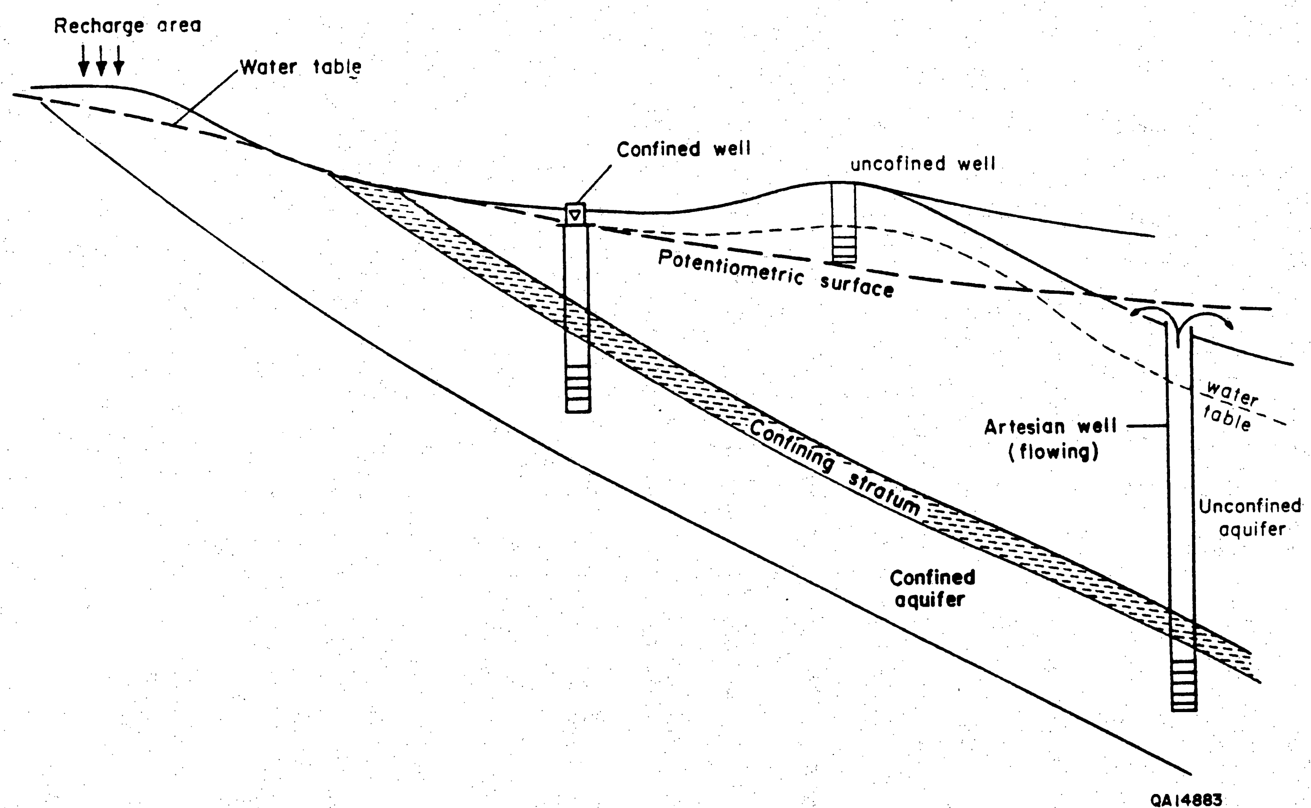


Figure 1. Schematic of a confined aquifer (unconfined in outcrop area).

The wellhead protection area definition addresses the presence of confining beds above the aquifer only, and not "above and below" as Stated in the American Geological Institute definition, because the dominant source (and therefore the higher probability) of contamination from a wellhead protection perspective are from disposal practices on or near land surface.

Distinction between a Semiconfined Aquifer and a Highly Confined Aquifer

A confined aquifer can be semiconfined or highly confined. A semiconfined (leaky) aquifer (fig. 2), as defined by the American Geological Institute glossary, is "A confined aquifer whose confining beds will conduct significant quantities of water into or out of an aquifer" (Bates and Jackson, 1987). The sensitivity to contamination of the semiconfined aquifer should be considered higher than that of a highly confined aquifer because the semiconfined aquifer can receive significant quantities of water through the confining strata.

A highly confined aquifer, in contrast, receives only minor leakage through confining strata. The sensitivity to contamination of a highly confined aquifer is low. However, artificial penetrations such as abandoned boreholes are potentially important pathways that may permit contaminants to pass through the confining strata and migrate into a producing well.

Importance of Understanding Degree of Confinement in Context of Wellhead Protection

Different wellhead protection strategies are recommended for unconfined (water table), semiconfined, and highly confined aquifers. These strategies are based on (1) the sensitivities of the aquifers to contamination, (2) the differences in well hydraulics, and (3) the differences in the distributions of vertical recharge.

(1) Unconfined, semiconfined, and highly confined aquifers have different sensitivities to contamination, the water-table aquifer being the most sensitive and the highly confined aquifer being the least sensitive. The unconfined aquifer is not overlain by confining strata to retard contaminant

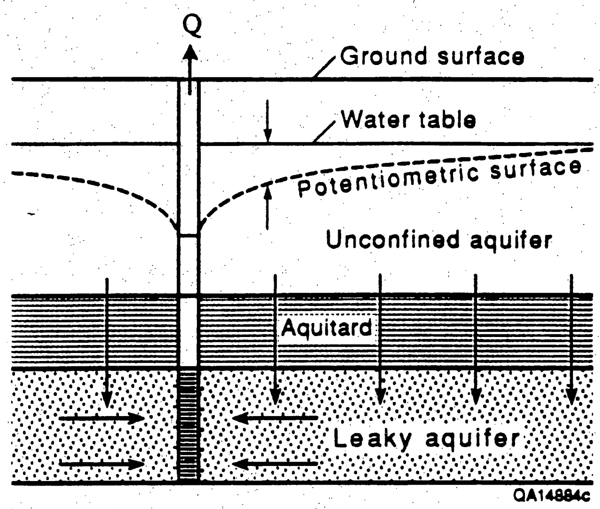


Figure 2. Schematic of a semiconfined (leaky) aquifer.

migration; the semiconfined aquifer has an overlying confining unit, but it is leaky; and the highly confined aquifer has an overlying confining layer that is essentially impervious to areally distributed leakage.

(2) For the unconfined aquifer, the size of the cone of depression (COD) from a pumping well is controlled by the recharge rate and the specific yield (storage) of the aquifer. For the semiconfined aquifer the amount of leakage from shallower unconfined aquifers affects the size of the cone of depression. For the highly confined aquifer the cone of depression can become very large because of the lack of leakage.

(3) The pathways of vertical fluid movement for unconfined, semiconfined, and highly confined aquifers also differ. In unconfined aquifers, vertical fluid movement to the water table is typically unimpeded and areally distributed through the unsaturated zone above the water table. A semiconfined aquifer allows leakage of significant quantities of water through the confining bed; consequently, flow paths through the semiconfining bed are presumed to be areally distributed and may include artificial penetrations as well as natural geologic pathways. This is in contrast to a highly confined aquifer, in which the probability of leakage through the confining unit is very low (but not necessarily zero). The overlying confining bed of a highly confined aquifer may contain a very small number of discrete pathways which can include natural penetrations, such as faults and fractures, or artificial penetrations, such as wells and abandoned bore holes.

The wellhead protection strategies for unconfined, semiconfined, and highly confined aquifers differ for hydrogeologic reasons. The U.S. Environmental Protection Agency (1987) recommends a variety of approaches for unconfined aquifers which include (1) time of travel (TOT), (2) zone of influence (ZOI), that is, extent of cone of depression, and (3) zone of contribution (ZOC) approaches. For semiconfined and confined aquifers, this document recommends either a time of travel or an integrated cone of depression/time of travel approach.

CHAPTER 2. CHARACTERISTICS OF A CONFINED AQUIFER

In this section, the typical geologic, hydrologic, and hydrochemical phenomena that are characteristic of confined aquifers are investigated, and some of the exceptions and complexities are discussed. Figure 1 is a schematic diagram of a confined aquifer.

Geologic Characteristics

Confining Beds

Confining beds are typically composed of low-permeability materials, composed typically of shale, silt, or clay. Most low-permeability strata overlying large coastal plain aquifers are composed of clay and silt. However, any low permeability bed can function as a confining stratum. Dense limestones and dolomites, chalks and marls, volcanic lava flows, evaporite deposits (for example, halite and gypsum beds), as well as unconsolidated sediments, may serve as confining units.

There is no established permeability range for confining strata (the term permeability is used interchangeably with hydraulic conductivity in this text). Permeability (hydraulic conductivity) for sand/sandstone aquifers can range from 10^{-4} to 10^{2} cm/sec (10^{-6} to 1 ft/sec). Low-permeability rocks typically have permeability values below 10^{-3} cm/sec (10^{-5} ft/sec). Permeability of a confining unit typically is three orders of magnitude lower than the permeability of the producing aquifer.

Confining beds can be extremely heterogeneous, that is, permeability varies significantly in the horizontal and vertical directions. Variability is in large part a function of the geologic setting and geologic history of the strata. Marine shales (shales originally deposited under marine conditions) will be relatively homogeneous, whereas continental shales may be composed of a wide range of sediment types and, therefore, have a wide range of permeabilities. This is particularly true for deltaic sediments, continental redbeds, and glacial deposits that may all function as confining strata.

Fractures and faults may cut confining beds and greatly increase their permeability. These structural features may be areally distributed, for example, in glacial drift in the North-Central United States, or may only occur in discrete zones, such as a single fault zone. The density and distribution of these features will have an important impact on degree of confinement and on the type of wellhead protection strategy employed.

Confined-Aquifer Lithology

A confined aquifer may be composed of a variety of different lithologies. In addition, in a confined aquifer, permeability may be heterogeneously distributed as it may be in any aquifer. For example, a sand aquifer is not composed solely of sand; frequently, shales may be interbedded with permeable sands or sandstones (fig. 3). This presence of low-permeability units within a permeable aquifer may create confinement even though there is no laterally extensive overlying aquitard (fig. 3). Furthermore, the contact between the top of an aquifer and the base of an overlying aquitard may be transitional. Defining the top of an aquifer and the base of an aquitard may be difficult.

The geology (mineralogy, degree of lithification, type of porosity, and so forth) of the confined aquifer may dictate some of the hydrologic and hydrochemical characteristics often associated with confined aquifers, such as low storativity and the type of water chemistry that is associated with long residence times or long flow paths.

Hydrologic Characteristics

Confined aquifers are hydrologically different from unconfined aquifers, as evidenced by the nature of various hydrologic phenomena, such as elevation of the potentiometric surface, cyclic water-level response to barometric or tidal phenomena, cone of depression, storage coefficients, and leakage values.

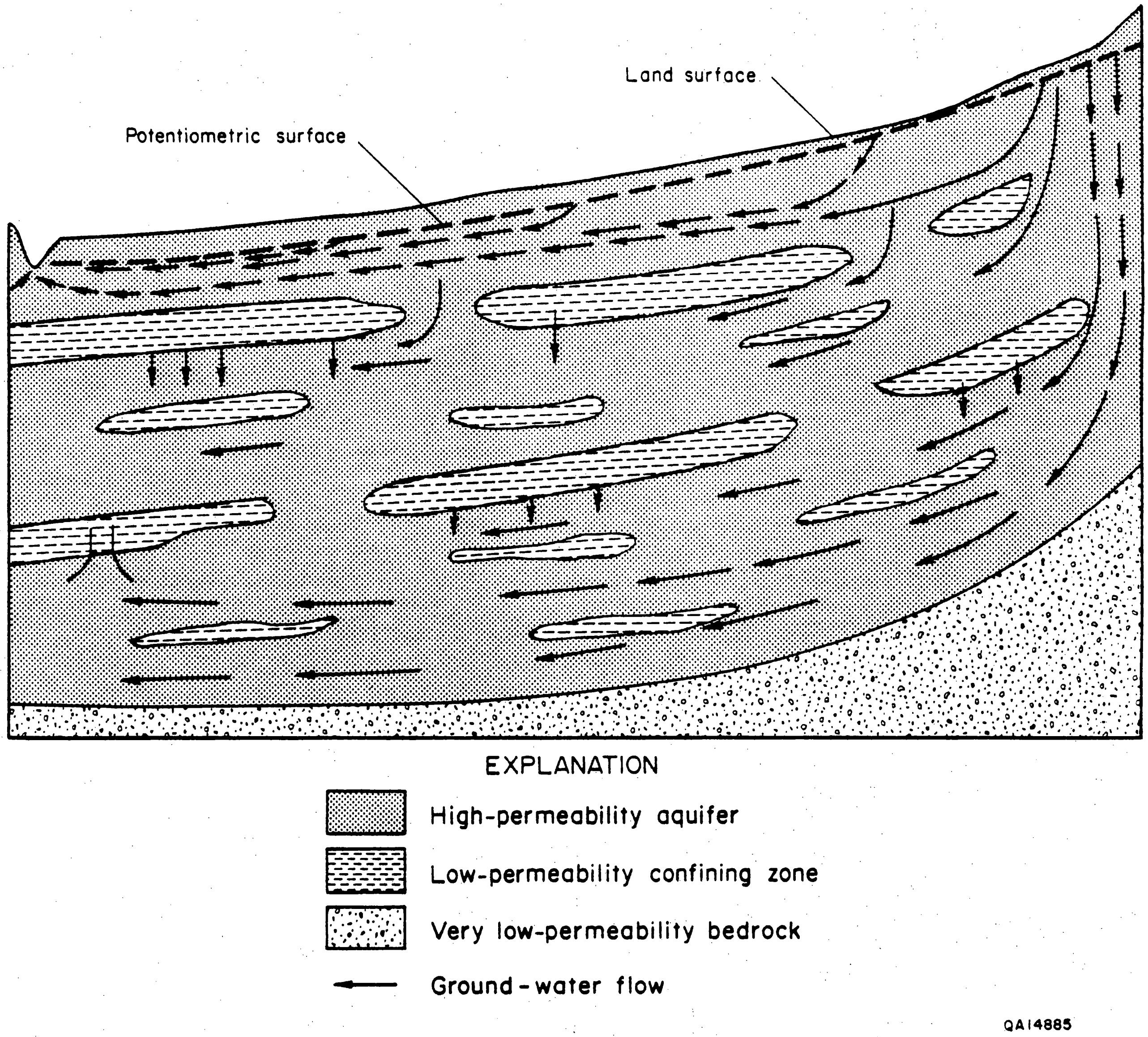


Figure 3. Aquifers may contain low-permeability strata that are interbedded between permeable strata and may cause confining conditions. Ground-water production from beneath a low-permeability strata would be from a confined aquifer even though a geologic map would show the permeable formation cropping out, a hydrogeologic setting which traditionally would be defined as unconfined.

Elevation of Potentiometric Surface

In an unconfined aquifer, there is direct contact between the atmosphere and the ground water along the entire upper surface (water table) of the saturated section; in comparison, the potentiometric surface of a confined aquifer (the surface defined by the elevation to which water rises in wells that are open to the atmosphere) is often above the top of the aquifer. The potentiometric (piezometric) surface of a confined aquifer may rise above the land surface resulting in flowing (artesian) wells (fig. 1). The reason for this is described next.

Ground water flows in an aquifer from zones of recharge to zones of discharge. The elevation of a water level in a well represents the potential energy of the ground-water system at that well. Water flows from higher potential energy to lower potential energy; the highest potential occurs in the recharge zone and the lowest potential occurs in the discharge zone. The system loses its potential energy by frictional loss (resistance) as it flows through the aquifer, as expressed by Darcy's law:

$$q = Ki \quad (1)$$

where q = the ground-water flow rate,

K = the hydraulic conductivity, and

i = the hydraulic gradient.

In the simplest situation, where aquifer permeability is uniform and flow rate is constant, the potential energy (head) loss is constant and the potentiometric surface has a constant gradient (fig. 1). A more complex scenario results when the permeability of the aquifer varies. In coastal plain aquifers, continental sands/sandstones are interbedded with marine or deltaic shales. Relatively permeable fluvial sandstones at the outcrop become interbedded with deltaic or marine shales downdip, resulting in overall average lower down-gradient permeability. According to equation (1), the hydraulic gradient is inversely proportional to hydraulic conductivity; that is, for a given flow rate, steeper head gradients are required for ground water to flow through a low-permeability zone compared to ground-water flow through high-permeability zones.

In early days of ground-water exploitation of confined aquifers such as the Dakota sandstone aquifer, South Dakota, or the Gulf Coast aquifer in Texas, many wells flowed at land surface because the aquifer was under artesian conditions. Artesian conditions often indicate a confined aquifer setting.

Water elevations below the top of an aquifer do not mean that the aquifer is unconfined. Water elevations below the top of a confined aquifer may occur naturally or artificially. A potentiometric surface below the top of a confined aquifer can occur if an aquifer is more easily discharged than recharged. This phenomenon is being recognized in some of the aquifers in the western United States.

Potentiometric surfaces below the top of confined aquifers may occur locally and regionally because of ground-water production. Cones of depression from individual pumping wells may result in a potentiometric surface being beneath the top of an aquifer. Similarly large-scale, regional, long-term, ground-water production for agricultural and municipal use, such as the San Joaquin Valley, California, or the greater Houston, Texas, region may result in the regional lowering of a potentiometric surface that, through time, drops below the top of an aquifer. In the context of the WHPA definition of confined aquifers, such aquifers are considered to be confined.

Direction of Vertical Ground-Water Flow

The relative elevations of the potentiometric surfaces of a confined aquifer and an overlying water-table aquifer define the direction of vertical ground-water flow, indicating whether potential contaminants can migrate from the water-table aquifer to deeper confined aquifers. The direction of vertical leakage between an unconfined and a lower aquifer is dependent upon whether the potentiometric surface for the deeper confined aquifer is above or below the upper aquifer's water table. If the potentiometric surface for the confined aquifer is above the water table, then there is a potential for upward flow from the deeper aquifer (fig. 4a). Upward flow implies that contaminants cannot move

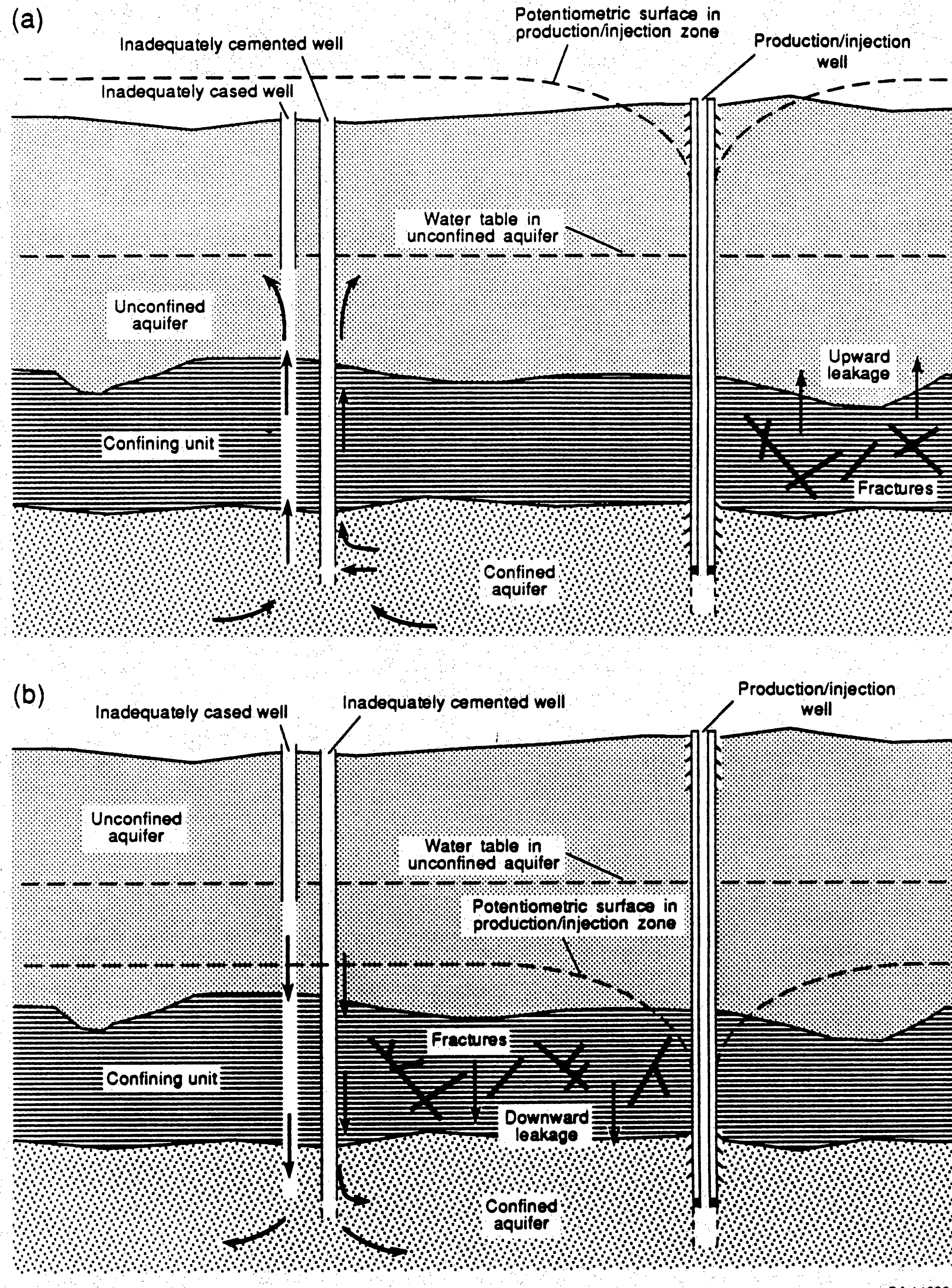


Figure 4. (a) Confined aquifer where the potentiometric surface is higher than the water table of the overlying unconfined aquifer. The potential for ground- water flow is upward. (b) Confined aquifer where the potentiometric surface is lower than the water table aquifer. The potential for ground-water flow is downward. Downward flow is needed for contaminants to migrate from a shallower unconfined aquifer to a deeper confined aquifer (from U.S. Environmental Protection Agency, 1987).

from the shallow to the deep. If the potentiometric surface for the confined aquifer is below the water table, there is potential for downward flow and, thus, a potential for contamination (fig. 4b).

Downward flow can occur around a well when a cone of depression from a pumping well is lower than the water table of an upper aquifer. Downward flow can also occur regionally as a result of a naturally lower potentiometric surface or because of long-term regional ground-water production.

Vertical leakage may contribute a significant percentage of the overall flow of water to an aquifer on a regional and well field basis. Even though the vertical permeability per unit area of an aquitard may be low in comparison to the permeability of an aquifer, there may be significant vertical leakage to the aquifer because of the extensive lateral area of the aquitard in comparison to the thickness of the aquifer.

Rates of leakage can be calculated by using an equation similar to that for calculating horizontal flow, that is, by using Darcy's law. Leakage can be defined as

$$q_v = K' (h_o - h)/b' \qquad (2)$$

where q_v = rate of vertical leakage per unit area

h_o = water level for the confined aquifer

h = water level at the water table

K' = vertical hydraulic conductivity

b' = thickness of aquitard.

The rate of vertical leakage per unit area is controlled by the vertical hydraulic conductivity of the aquitard and the hydraulic gradient across the aquitard. K' values are often given as gpd/ft^2 or cm/sec. No one has compiled a range of leakage values, but K' values greater than 10^{-2} gpd/ft^2 (5×10^{-7} cm/sec) generally will permit significant leakage across the aquitard. The rate of vertical leakage is an important consideration in differentiating highly confined from semiconfined aquifers.

Flow Velocity and Age

Ground water in confined aquifers commonly has a low hydraulic gradient, a low ground-water flow velocity, and contains relatively old water. Figure 5 compares the potentiometric surface of the Floridan aquifer with the degree of confinement. Where the low-permeability confining unit is present, the potentiometric surface of the Floridan is relatively flat compared with the gradient of the Floridan in northern Florida where the aquitard has been eroded. In confined aquifers of the coastal plain, hydraulic gradients are very low (<0.0001) and flow velocities may be in the range of 1 to 50 ft per year. Flow velocities in the Carrizo aquifer, a typical sandstone aquifer dipping toward the Gulf of Mexico in the Texas Coastal Plain, range from 5 to 30 ft per year with the higher rates in the outcrop area (Pearson and White, 1967).

Ground water in confined aquifers may be very old because of low velocities. Kreitler and Pass (1980) identified, with ^{14}C, waters that were 5,000 to 15,000 yr old in the updip section of the Wilcox aquifer, a large Tertiary-aged sandstone formation in East Texas. Pearson and White (1967) measured water ages of 25,000 yr 20 mi downdip in the Carrizo aquifer in South Texas. Ages of waters in the confined section of the Chalk aquifer, where it underlies the London Clay of the London Basin (England) exceed 25,000 yr (Smith and others, 1976). Ground waters from a confined aquifer in Hermosillo, Mexico were estimated to be 30,000 yr old (Payne and others, 1978).

Storativity

The storativity of an aquifer is defined as the unit volume of water that a unit volume of aquifer releases "from storage" under a unit decline in hydraulic head (Freeze and Cherry, 1979). For a confined aquifer with the potentiometric surface above the top of the aquifer, this release of water results from the compressibility of the aquifer material and a slight expansion of water. In response to a decline in head, compressible aquifers (unconsolidated sands with interbedded clays) release significantly more

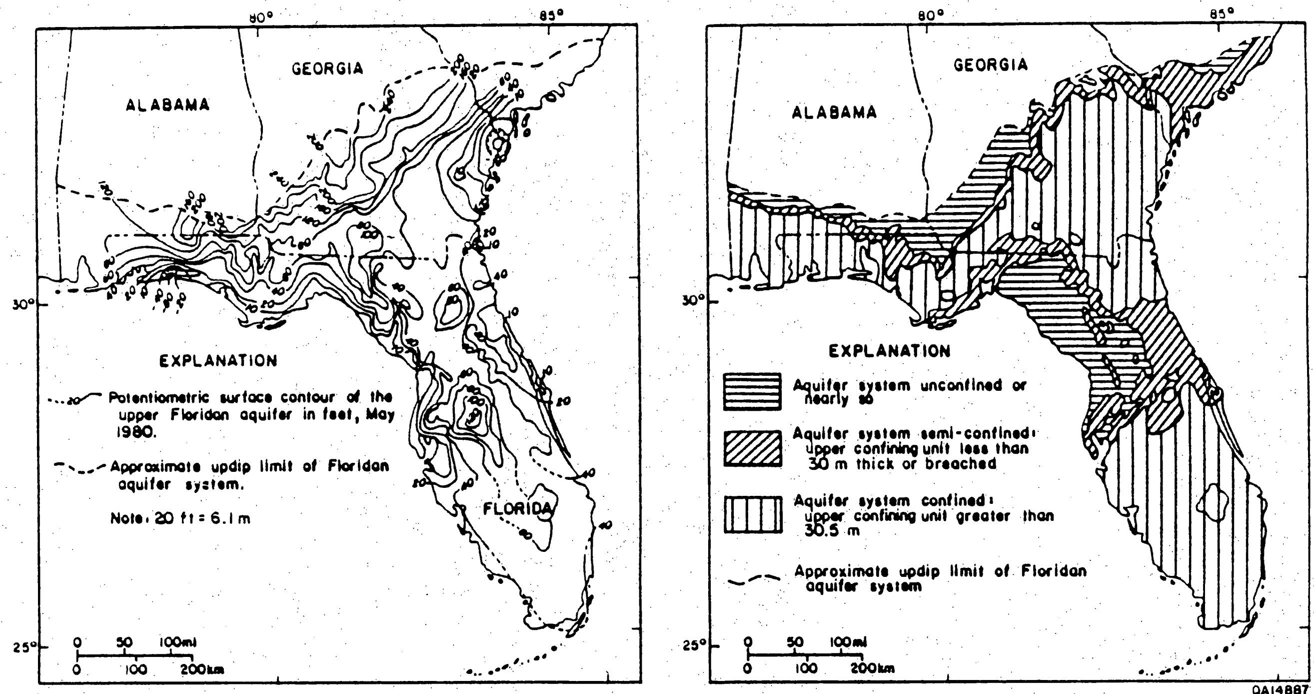


Figure 5. Comparison of potentiometric surface of Floridan aquifer to unconfined, semiconfined, and confined sections of the Floridan aquifer. The potentiometric surface becomes flatter where the Floridan becomes highly confined (modified from Johnson and Miller, 1988).

water than noncompressible aquifers (limestones and sandstones). In contrast to confined aquifers, water-level declines in unconfined aquifers cause drainage of water from the pore spaces, that is, the saturated section becomes thinner. The storage term for unconfined aquifers is referred to as specific yield.

The release of water from storage for either confined or unconfined aquifers results from a decrease in head values, for example, as a result of the pumping of a well. The water released by drainage of pores spaces in an unconfined aquifer is significantly greater than the water released by compressing the pore spaces in a confined aquifer. Specific yield for unconfined aquifers ranges from 0.30 to 0.01 (Freeze and Cherry, 1979). Confined aquifers commonly have low-storativity values compared to unconfined aquifers. Storativities for confined aquifers commonly range from 0.005 to 0.00005. However, the storativity values for very compressible aquifers, characterized by clay compaction, approach specific yield values for unconfined aquifers. Storativity often is used as a method to differentiate confined from unconfined aquifers.

Cyclic Water-Level Responses Resulting from Atmospheric Pressure Changes

Water levels in wells of confined aquifers typically exhibit small cyclic changes in elevation, which may occur with a frequency of once or twice a day. Water levels in wells of unconfined aquifers typically do not show such a daily cyclic change in elevation. Cyclic responses of the water levels in wells result from changes in overburden pressures (ocean tides), dilation of the aquifer (earth tides) or changes in atmospheric pressure at the well bore. Atmospheric pressure changes probably have the greatest impact on water levels because of the magnitude of the changes and their widespread occurrence. The water elevation in a well is the elevation to which the water will rise to equilibrate with atmospheric pressure. Changing weather systems (high pressure and low pressure cells) can cause atmospheric pressure changes (fig. 6). In addition, atmospheric pressures change continually throughout the day as a result of heating and cooling of the atmosphere (fig. 6). In a confined aquifer, the only point where the potentiometric surface is in direct contact with the atmosphere is in the well

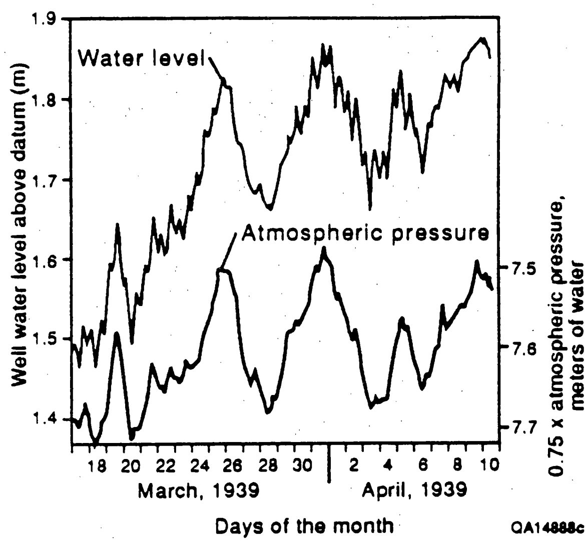


Figure 6. Weather-related barometric changes and their effect on the water levels in a well penetrating a confined aquifer (modified from Todd, 1980). Reprinted by permission of John Wiley and Sons, Inc., New York, New York.

bore. Increases in atmospheric pressure will force the water elevation in the well down. Decreases in atmospheric pressure will permit the water elevation in the well to rise. The rest of the aquifer will not respond to this change in atmospheric pressure because the overlying aquitard acts as a rigid cover. Only water levels in water wells open to the atmosphere respond to atmospheric pressure changes. In contrast, the water table in an unconfined aquifer is in contact with the atmosphere everywhere; therefore, atmospheric pressure changes are transmitted equally to the water table and not just to the well; therefore, water elevation in a well does not show daily water-level fluctuations with daily pressure changes (fig. 7). The presence of these small cyclic water-level changes can be used to differentiate confined from unconfined aquifer settings.

Cone of Depression

During the pumping of a water well, water levels drop and a cone of depression of the potentiometric surface develops around a well. The water produced from a well in a confined aquifer comes from three sources: (1) water flowing laterally from the aquifer into the well; (2) water flowing vertically from aquitards above or below a producing aquifer. This water either originates from within the aquitard (aquitard storage) or from leakage through an aquitard; and (3) from storage in the producing aquifer (fig. 8). In an aquifer with a negligible regional hydraulic gradient, the perimeter of the cone of depression defines the boundary, at a given time, of the areal extent of the lateral flow in the aquifer and of vertical flow from adjacent confining units.

A graph of water-level decline, resulting from ground-water pumpage from a highly confined aquifer, follows a characteristic curve known as the Theis curve and has a generally asymptotic shape (fig. 9). The only source of water from a highly confined aquifer is the water flowing laterally to the well. Because there is no vertical leakage, the cone of depression must continue to enlarge over time, and water levels will continue to decline even after long periods of time. For semiconfined aquifers, the drawdown of water levels and the lateral extent of the cone of depression stops when the amount of vertical leakage equals the well discharge. A series of leaky aquifer curves can be used to calculate the

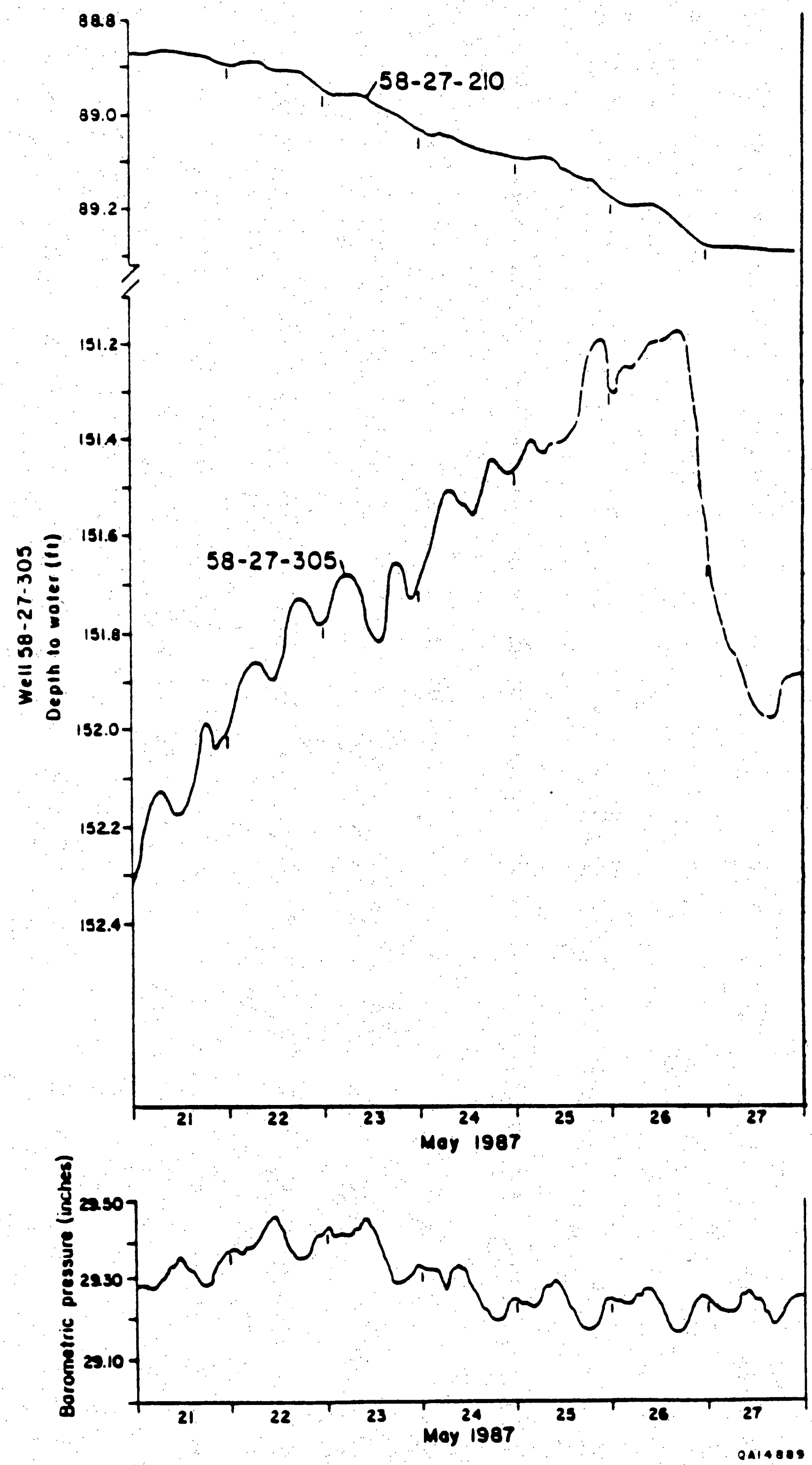


Figure 7. Example of daily water-level changes in two wells from the Edwards aquifer, Georgetown, Texas. The cyclic water-level curve for well 58-27-305 shows two maximum values per day that are related to barometric changes and exhibit confined aquifer response. The flat water-level response for well 58- 27-210 exhibits an unconfined aquifer response and shows longer term water- level declines from local pumpage (modified from Senger and others, 1990).

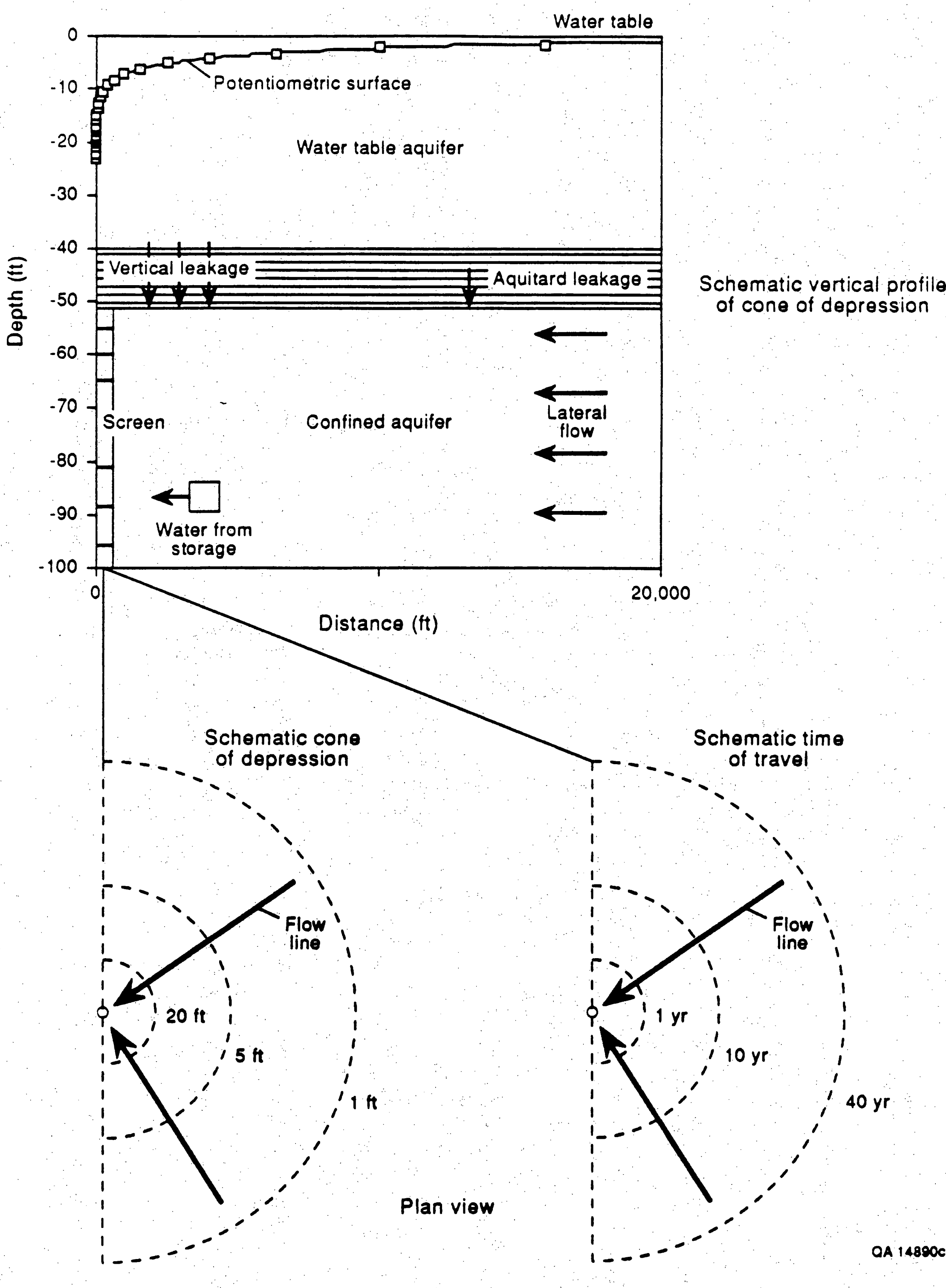


Figure 8. Sources of water from a pumping well in a confined aquifer and schematic drawings for a cone of depression and time of travel contours.

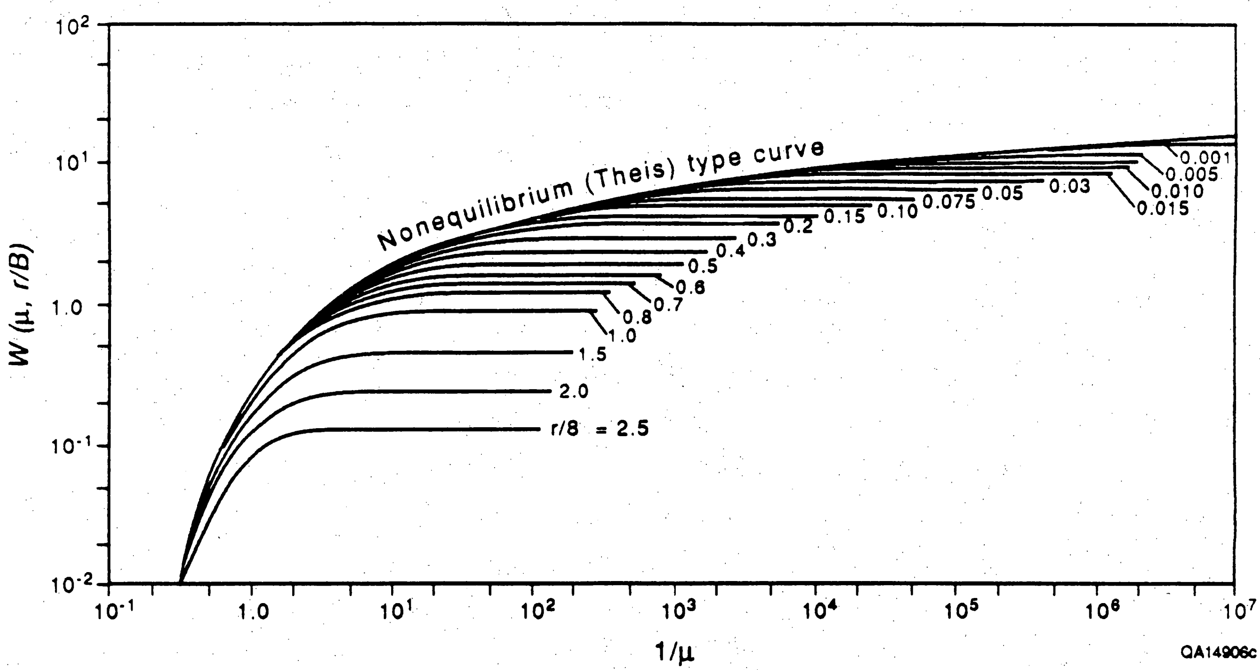


Figure 9. Theis curve and leaky aquifer curves (from Todd, 1980). Reprinted by permission of John Wiley and Sons, Inc., New York, New York.

amount of leakage (fig. 9); the greater the leakage, the greater the r/B value for the different curves. For very leaky systems, drawdown can be minimal, and water levels will stabilize rapidly. Figures 10, 11, and 12 show pump-test data for a highly confined aquifer, a moderately leaky semiconfined aquifer, and a very leaky semiconfined aquifer.

The flow of ground water toward a well is related to changes in head caused by pumping the well. Horizontal head gradients toward the well permit lateral flow to the well; in the case of confined aquifers, vertical head gradients across aquitards permit vertical leakage and water from aquitard storage; and head changes permit compression of the aquifer and the "squeezing" out of water from aquifer storage. There is no flow to the well from areas where there is no vertical or horizontal head gradient toward the well. This simple statement offers an important insight toward understanding the area that contributes water to a producing well. The aquifer external to the cone does not contribute to the water produced at the well assuming there is no, or a negligible, regional gradient. Once the cone has stabilized, theoretically, there is no contribution of water from storage. There is no longer any change in water levels with time and, therefore, no additional compressing and squeezing of water out of the aquifer. All of the contribution of water comes from vertical leakage.

Leakage through an aquitard has been observed. Neuman and Witherspoon (1972) conducted a 31-day aquifer test in the Oxnard aquifer, Oxnard, California. The confined Oxnard sand and gravel aquifer is overlain and underlain by aquitard/aquifer pairs (fig. 13). Monitoring wells were installed and monitored in the three aquifers and two aquitards. By the end of the 31-day aquifer test, water levels had dropped in the producing aquifer as well as the aquitards and in the overlying and underlying aquifers. Vertical permeability was estimated at 2.9×10^{-2} gpd/ft^2. This example graphically demonstrates that leakage from overlying or underlying aquifers *does* occur and that contamination through an aquitard *can* occur.

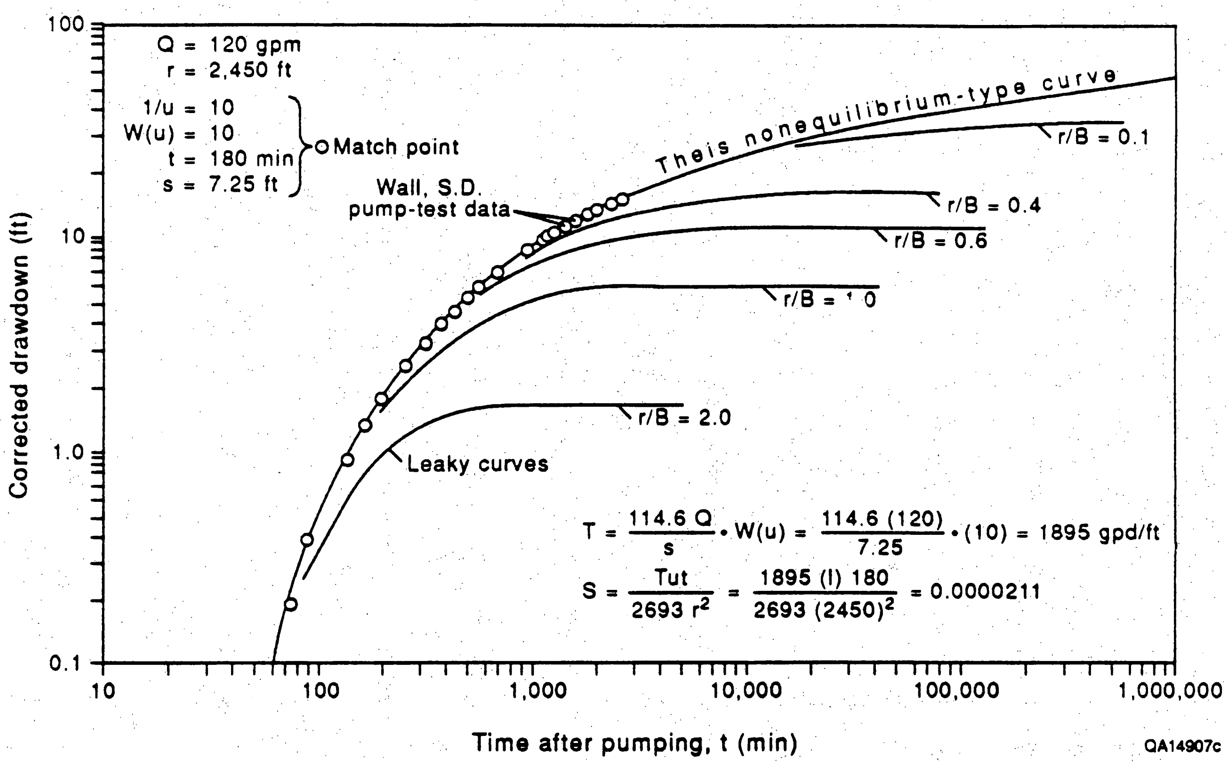
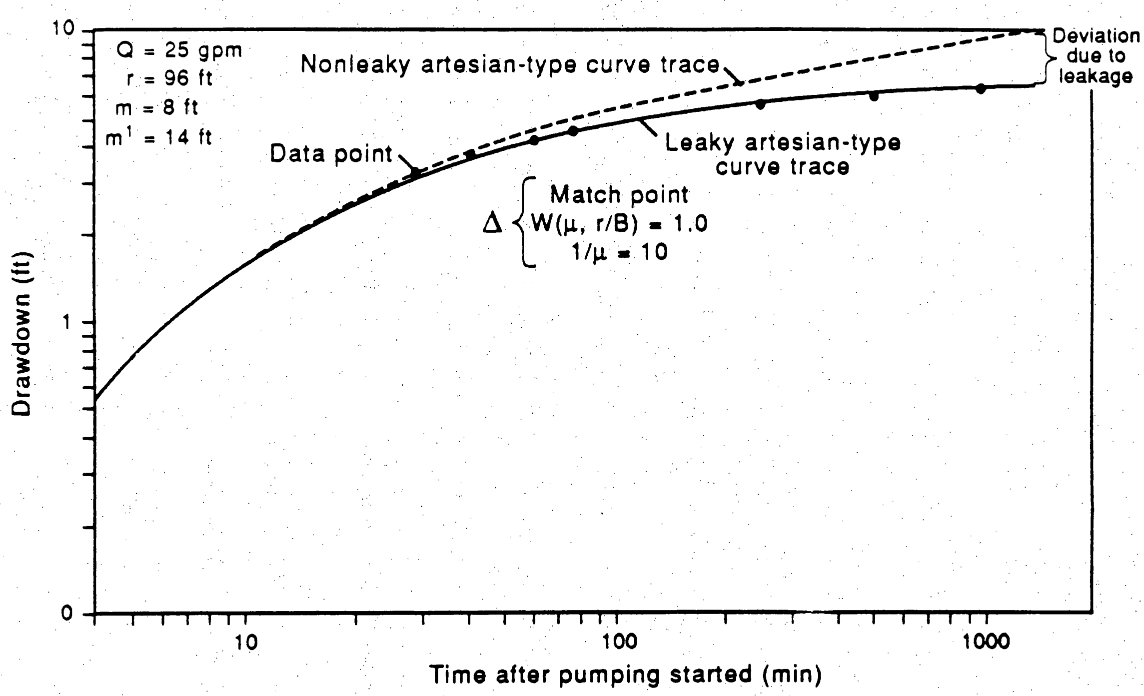


Figure 10. Example of pump test (drawdown versus time) for nonleaky aquifer, Dakota sandstone (from Greis, 1976).



$$T = \frac{114.6\ QW(\mu,\ r/B)}{s}$$

$$T = \frac{1.146 \times 10^2(2.5 \times 10)1.0}{1.9}$$

$$T = 1510 \text{ gpd/ft}$$

$$S = \frac{T\ \mu\ t}{2693 r^2}$$

$$S = \frac{1.51 \times 10^3(1 \times 10^{-1})3.3 \times 10}{2.693 \times 10^3(9.2 \times 10^3)}$$

$$S = 0.0002$$

$$r/B = 0.22$$

$$r/B = \frac{r}{\sqrt{T/(P'm')}}$$

$$P' = \frac{Tm'(r/B)^2}{r^2}$$

$$P' = 1.51i\left(\frac{10^3[1.4 \times 10]4.8 \times 10^{-2}}{9.2 \times 10^3}\right)$$

$$P' = 0.11 \text{ gpd/ft}^2$$

$$P = \frac{T}{m}$$

$$P = \frac{1510}{8}$$

$$P = 189 \text{ gpd/ft}^2$$

QA14908c

Figure 11. Example of pump test (drawdown versus time) for moderately leaky confined aquifer, Indiana, (from Walton, 1962).

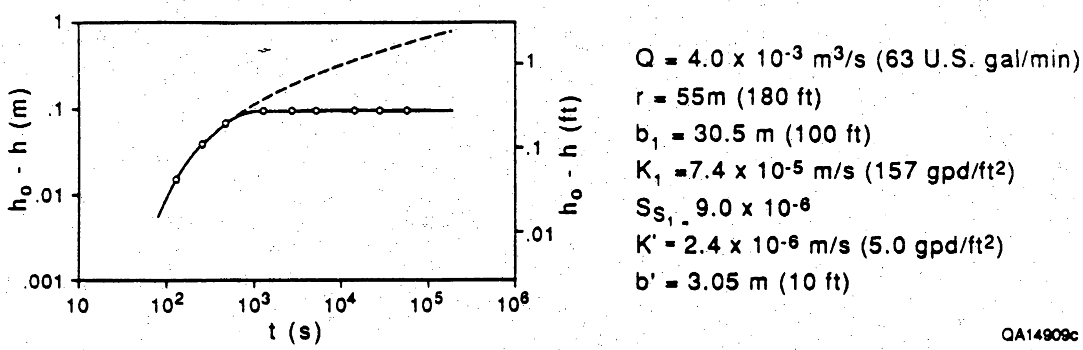


Figure 12. Example of pump test (drawdown versus time) for very leaky unidentified aquifer (from Freeze and Cherry, 1979). Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

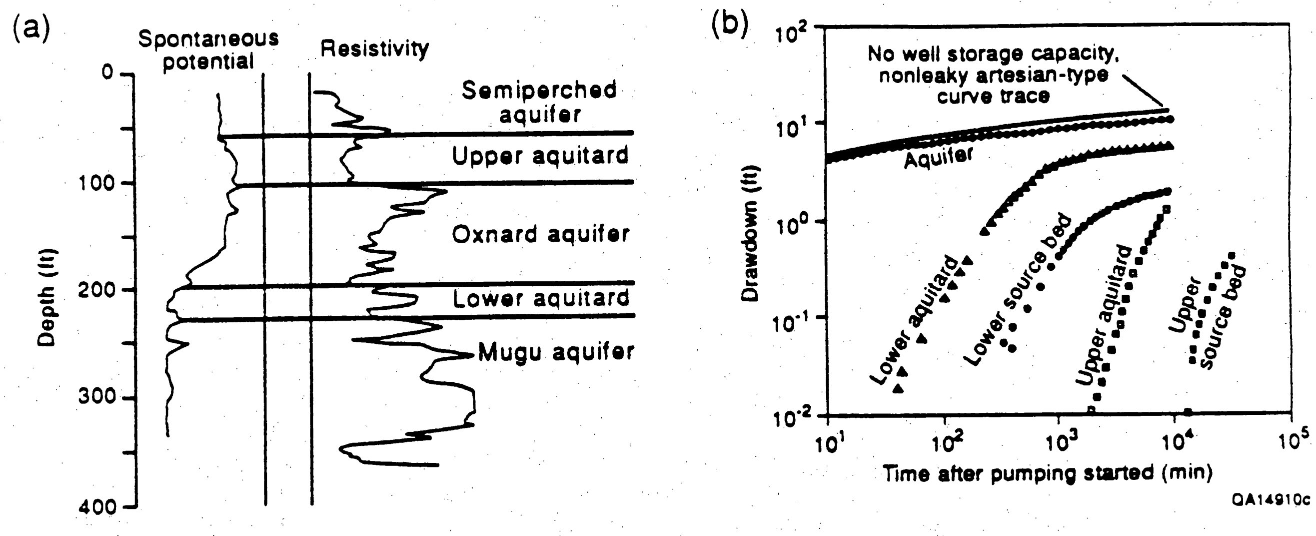


Figure 13. Geologic setting and pump test data from confined Oxnard aquifer, overlying and underlying aquitards, and overlying and underlying aquifers (from Neuman and Witherspoon, 1972). Example shows that there is leakage through an aquitard.

Hydrochemical Characteristics of Ground Water in Confined Aquifers

Hydrochemical characteristics of ground water typically reflect aquifer lithology and residence time of ground water. Because of the large geographic extent of many confined aquifers, ground water within such an aquifer may be relatively old and may have traveled over relatively long distances. Both age and distance of travel control the chemical and isotopic composition of the waters. The chemical composition of ground water typically changes as it flows from zones of recharge to zones of discharge. Recharge zones for confined aquifers are typically oxidizing, have low pH levels, and relatively high concentrations of nitrate, sulfate, and calcium. As ground water flows downdip, it becomes more reducing, typically shows an increase in pH, and its total dissolved solids (TDS) concentrations increase. Nitrate (NO_3) and sulfate (SO_4) concentrations decrease significantly, calcium (Ca) decreases, and sodium (Na) and bicarbonate (HCO_3) concentrations increase (Back, 1966; Kreitler and others, 1977; and Fogg and Kreitler, 1982). Figure 14, a cross section through the Atlantic Coastal Plain, New Jersey, shows the evolution from a low-total-dissolved-solids mixed-composition water in the recharge zone to a Na-HCO_3 to Na-Cl water downdip. If the general chemical evolutionary pathway is known the chemical composition of an individual sample can be used to determine whether the water came from the recharge zone or from the downdip confined section.

As the water flows down gradient from the recharge zone it also becomes progressively older. Tritium (^3H) concentrations will decrease to zero as the tritium (short-lived radioisotope of hydrogen in water with a half-life of 12.3 yr) disappears by radioactive decay. Presence or absence of tritium can be used to indicate whether a water was recharged more or less than approximately 40 yr ago (fig. 15). Anthropogenic chemicals in the ground water also provide an assessment of the age of the water. The occurrence of contaminants in a ground water, such as fluorocarbons, nitrates at high levels, and synthetic organic compounds, also indicates the addition of relatively young waters. Carbon-14 concentrations decrease as ground water flows downdip and becomes older. The age of ground water that is in the range of thousands of years can be estimated with ^{14}C analyses.

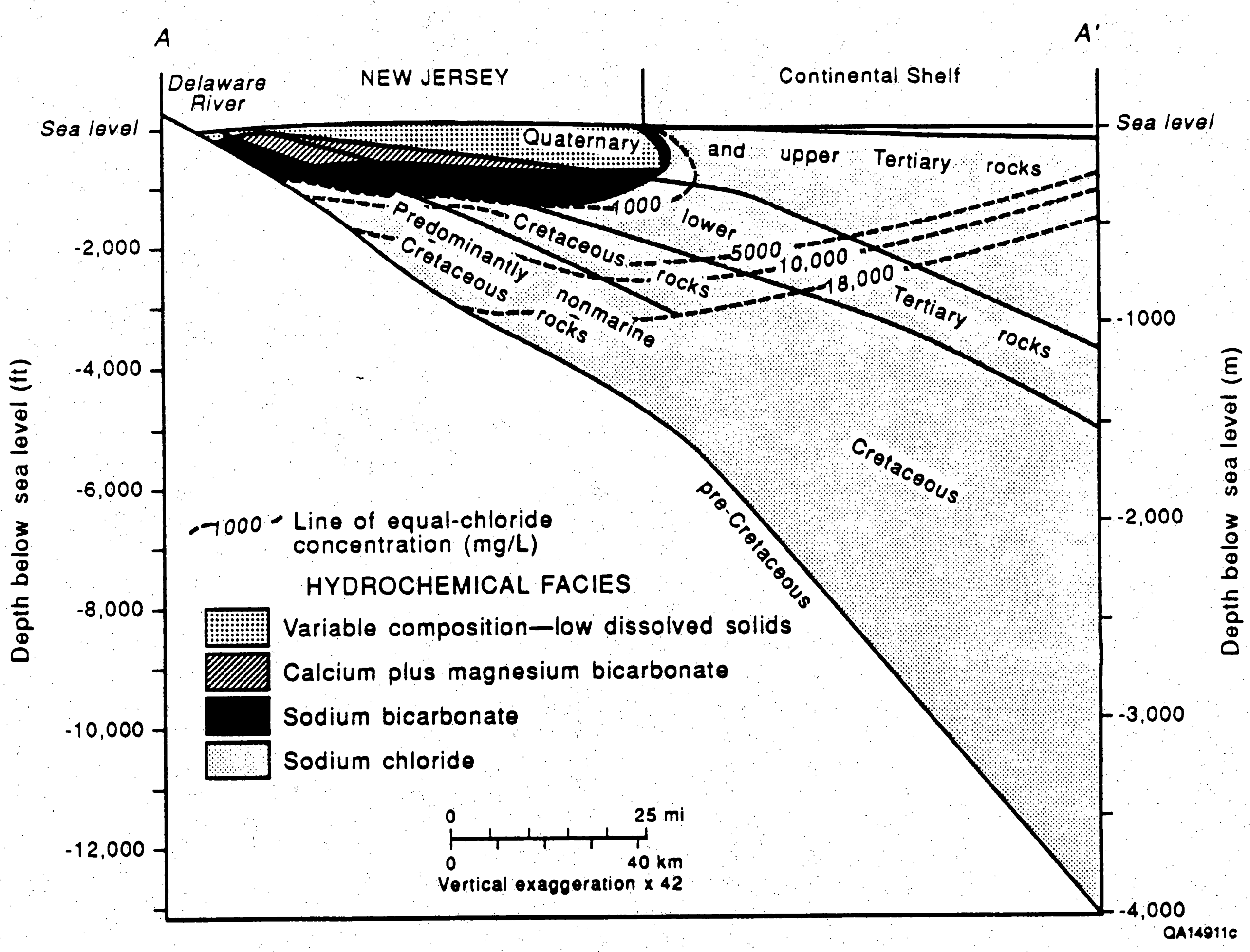


Figure 14. Evolution of hydrochemical facies from variable composition from Ca-HCO_3 to Na-HCO_3 to a Na-Cl for ground-water flow in the Atlantic Coastal Plain, New Jersey (from Meisler and others, 1988).

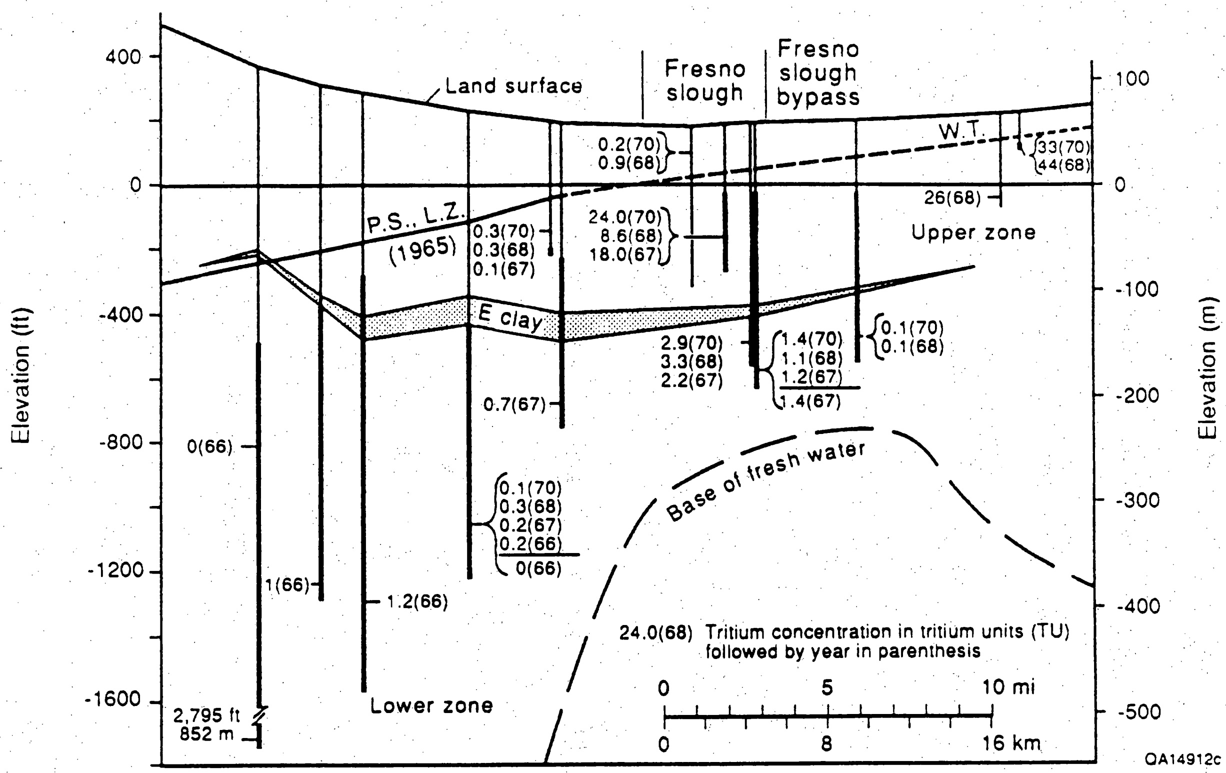


Figure 15. Example of tritium in ground water, Fresno County, California (Poland and Stewart, 1975).

Large-scale pumpage may alter the hydrochemistry of the ground water in a confined aquifer. Extensive and long-term pumpage may result in increased leakage through confining aquitards and subsequently alter the chemical composition of the ground water. A water sample collected from a natural system typically represents ground water that flowed from the outcrop to the point of collection. In contrast, a water sample collected from a well field that has been pumped at high volumes continually for 40 yr (as an example), may in fact result from leakage through overlying aquitards. This sample may have a different chemical composition and may be significantly different in age from the water sample collected from the natural system.

CHAPTER 3. APPROACHES FOR DETERMINING THE PRESENCE AND/OR THE DEGREE OF CONFINEMENT

Confined aquifers are less sensitive to ground-water contamination from overlying contaminants than are unconfined aquifers. It is not simple, however, to determine whether a well or well field under investigation is producing from an unconfined, semiconfined, or confined aquifer. As discussed in the previous section on the characteristics of confined aquifers, there are several characteristics that can be used to test for the presence and/or degree of confinement. The prime concerns in determining the presence and/or degree of confinement are to evaluate the sensitivity of the aquifer to potential contamination and to identify the potential pathway for contaminants migrating to a producing well. The methods listed below can be used to describe (1) the presence or absence of confinement, (2) the presence and degree of confinement (semiconfined versus highly confined), or (3) the degree of confinement after the presence of confinement has already been identified. Many of the methods, however, only identify the presence of confinement and not the degree of confinement because we often measure only the hydrologic, geologic, or hydrochemical phenomena that are caused by confinement and not the amount of leakage or the zones of leakage. We are limited in our techniques for delineating highly confined from semiconfined settings and particularly in quantitatively determining the degree of confinement.

The techniques described below can be used for assessing the presence and/or degree of confinement. There are three basic approaches for identifying the presence and/or degree of confinement: geologic, hydrologic, and hydrochemical. Each basic approach can be divided into different techniques. Geologic techniques identify the presence of confining strata, their spatial distribution, and their physical characteristics. Because some geologic techniques identify breaches in confining strata, the degree of confinement can be inferred. Hydrologic techniques identify whether the aquifer is confined and, for some techniques, the degree of confinement. Hydrochemical techniques indicate absolute or relative ages of waters, which can in turn be used to infer presence and/or degree of confinement.

The presence and/or degree of confinement should be considered in planning future areas for ground-water production as well as for safeguarding present water supplies. Highly confined aquifers will be inherently less susceptible to future contamination than will be unconfined or semiconfined aquifers. Mapping techniques are of particular benefit to planning and protecting future water supplies because of the inherent capability of maps to project and infer hydrogeologic properties into areas for which there are no data.

Geologic Approach

The geologic approach includes several techniques that identify the presence of a confining bed overlying an aquifer and define the physical characteristics of the bed. These techniques identify the thickness and areal extent of an aquitard and indicate potential permeability pathways which may permit contaminants to leak through a confining unit.

Classic Geologic Maps

Geologic maps have been used to determine confinement by depicting geologic formations. A formation is commonly composed of one predominant lithology, such as shale, limestone or sandstone, but often other rock types are included. Formations on geologic maps can be interpreted by hydrogeologists as being aquifers or aquitards, based on the formations' dominant lithologies and on the estimated ability to produce ground water. Aquifers are often considered to be unconfined because they crop out, or to be confined because they dip beneath a formation of lower permeability.

Outcrops, soil maps, aerial photographs, and borehole information (electric logs and driller's logs, for example) are the general types of data that are used for constructing geologic maps delineating confined aquifers. Many areas have been geologically mapped so published information may be available. Surface geologic mapping is routinely based on mapping of geologic formations in outcrops. Outcrop mapping should be supplemented with an aerial photograph interpretation to assist in the mapping of areal distribution of geologic formations. Fractures and faults in confining strata are important potential pathways for vertical flow and may be identified through aerial-photographic mapping that is verified in the field. Observation of fracture openings, and mineralization or oxidation along fractures, indicate that the fractures are a pathway for flow (Grisak and Cherry, 1975). All mapping approaches provide a two-dimensional, surface picture of the confining unit. They do not provide any subsurface information.

Environmental Geologic and Hydrogeologic Maps

Environmental geologic and hydrogeologic maps are a subset of classic geologic maps. Instead of depicting geologic formations, environmental geologic maps typically address a broad range of environmental issues. For example, in areas where floods are a primary concern flood-prone areas could be mapped. Hydrogeologic maps typically address only important aspects related to the underlying ground water. For confined aquifer settings, hydrologic criteria related to confined settings, such as lithology, faults and fractures, boreholes and wells, and so forth, should be depicted on hydrogeologic maps. These types of data are available from geologic maps, soil maps, topographic maps, aerial photographs, borehole information (electric logs, driller's logs), and water-level records, and are available from organizations, such as the U.S. Geologic Survey (USGS), State geological surveys, State water and environmental agencies, State public health departments, university geology and civil engineering departments, regional planning entities and councils of governments, and private consultants. The technique indicates the presence or absence of confinement to provide information on the degree of confinement. Geologic data need to be integrated with hydrologic and hydrochemical data.

Artificial penetration maps are a subset of hydrogeologic maps. A critical pathway for contaminants to migrate through normally impenetrable confining strata, may be through artificial penetrations such as abandoned or producing oil and gas wells, abandoned or producing water wells, seismic shot holes, injection wells, or any other excavations that might breach a confining stratum.

Examples of contamination via abandoned wells have been documented by Gass and others, 1977; Fairchild and others, 1981; Wait and McCollum, 1963. Figure 16 shows the density of abandoned oil and gas wells in one oil-producing county in West Texas. Anzzolin and Graham (1984) estimated that approximately 1.65 million abandoned wells exist in the United States. Penetrations may be cased (abandoned water wells, for example) or uncased (abandoned mineral or oil exploration holes that were never plugged). Uncased holes in lithified bedrock generally do not collapse and, therefore, remain open long after abandonment. Uncased boreholes in unconsolidated sediments may collapse from earth pressures and may be less of a problem. Cased boreholes generally remain open for a long time. Many uncased and abandoned boreholes may still contain drilling mud which may limit the amount of fluid flow within the borehole. The amount of leakage down artificial penetrations is difficult if not impossible to calculate. For this document it is assumed that leakage can occur through an artificial penetration such as an unplugged borehole. Therefore, any artificial penetration represents a point for potential vertical migration of contamination.

Mapping the location of artificial penetrations may be extremely difficult. Maps of artificial penetrations can be produced from a variety of data sources. Maps that depict all known artificial penetrations generally are not available because such maps would require the mapping of penetrations associated with different uses. Maps depicting water wells may be available from State water agencies. Locations of oil and gas wells and other wells used in the mineral industry may be available from other State agencies regulating water, oil and gas, and the mineral industry. This will vary from State to State. Abstract companies have ownership maps that may show the location of oil and gas exploration wells. Many abandoned boreholes, however, may predate State regulations requiring reports on the exact location and the plugging of artificial penetrations. Field mapping may require surveys with metal detecting equipment (for example, electromagnetic, resistivity, and magnetic techniques), aerial photographs, and interviews with present and past landowners. Door-to-door inventories may be the most effective way to locate artificial penetrations. Uncased, abandoned boreholes have no electrical signature and may be impossible to find. Hydrologic techniques that may identify boreholes include (1) monitoring ambient water levels to identify potentiometric highs

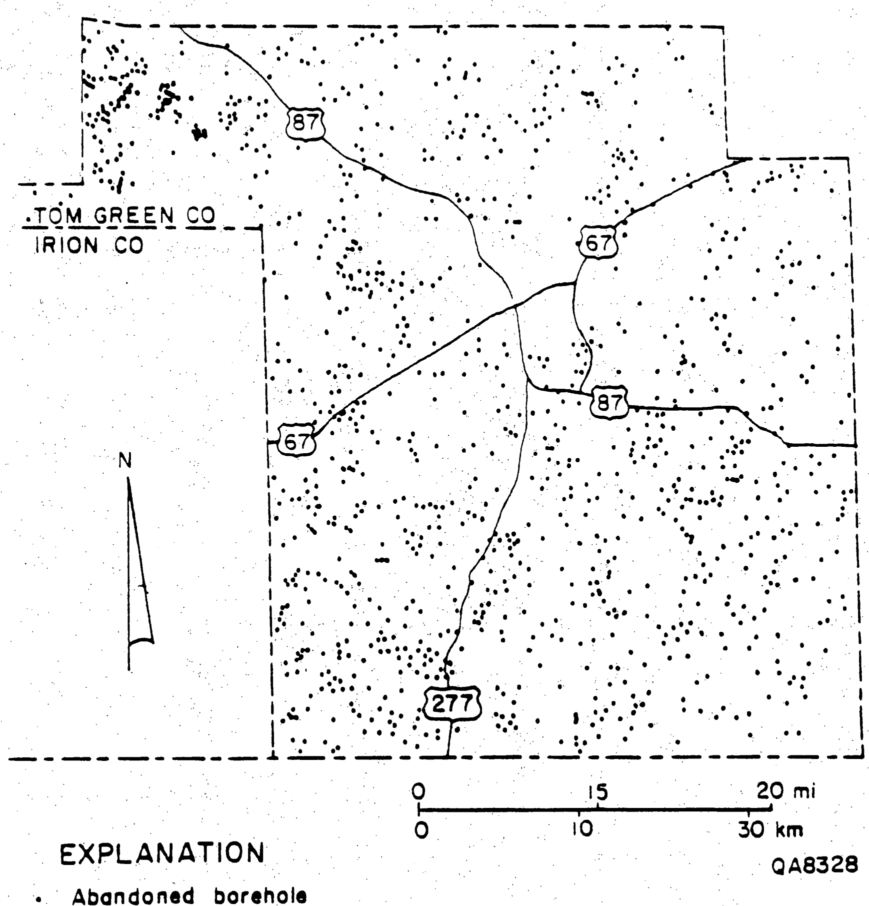


Figure 16. Map of Tom Green County, Texas, showing locations of abandoned oil and gas exploration boreholes (from Richter and others, 1990).

resulting from discrete points of leakage, (2) injecting water into an aquifer and looking for occurrence of flowing wells, and (3) pump-testing analysis to identify discrete points of leakage (Aller, 1984; Javandel and others, 1988). These hydrologic techniques have not been tested in the field.

Subsurface Geologic Maps

Construction of subsurface maps from geophysical logs or driller's logs in the vicinity of a water well or well field provides a "depth" perspective as to the distribution of low-permeability layers, which may provide confinement, but may not be evident from surface geologic information at the well or in the outcrop. When subsurface maps are integrated with surface geologic maps, they provide a three-dimensional picture of the distribution of confining beds. Well logs are routinely used for determining the best ground-water producing interval, but generally have not been used to define presence or absence of confining zones for the purpose of aquifer protection. Geophysical logs can be used to map low-permeability strata above and within aquifer units. A well log at a specific well or well field provides particularly relevant data. Where more abundant data are available, cross sections and map views of structures can be constructed, and thickness of an aquitard and presence of structural and lithological discontinuities can be determined. Integration of surface geologic maps with subsurface geologic and hydrologic information allows better assessment of confining conditions.

Hydrologic Approach

The hydrologic approach includes several techniques that generally define whether an aquifer is confined or not. These techniques include water elevation in a well, potentiometric surface maps, pump tests for storativity, pump tests for leakage response, continuous water-level responses, hydrologic measurements in confining strata, and numerical models. Most of the approaches measure or characterize a hydrologic response within the aquifer. Only two approaches, pump test for leakage and hydrologic measurements in confining strata, evaluate the hydrologic characteristics of the confining strata itself.

Water-Level Elevation in a Well

Determining the presence of confinement by the elevation of a water level in a well represents one of the simplest methods for determining confinement. If the water level is above the top of the aquifer, then the aquifer is confined (fig. 1). Appropriate water-level measurement data may exist or may have to be collected. Methods of measurement are steel tapes, electric lines, and air lines. Confined aquifers in which water levels are naturally below the top of the aquifer or in which water levels have declined below the top of an aquifer because of short-term or long-term pumping, are still considered confined because of the presence of an overlying low-permeability layer. However, this technique will not identify these aquifers as confined.

Potentiometric Surface

A potentiometric profile is the line or surface defined by the interpolation of water-level measurements in different wells (fig. 1). This technique is similar to that previously described for "Water-Level Elevation in a Well," except the potentiometric surface technique requires the use of several wells over the area of interest. This technique has the additional capability of determining how water levels in one well interrelate with other well water levels in the area. A single datum point often provides little insight into a hydrologic phenomenon. As more data are incorporated in a potentiometric surface, the presence of confinement can be examined in greater detail. This technique will not identify confined aquifers in which the potentiometric surface is below the top of the aquifer; nor will this technique determine the degree of confinement.

Pump Test for Storativity

Storativity values can be used to determine whether an aquifer is confined or unconfined, but should not be used to assess the degree of confinement. Storativity values for confined aquifers are generally 10^{-3} or less, whereas storativity values for unconfined aquifers are 10^{-2} or greater. The average storativity for the Ogallala aquifer, a major unconfined aquifer in the High Plains of Texas, is .08, whereas the average storativity for the Gulf Coast aquifer, the major confined aquifer along the Texas Gulf Coast, is .0009 (compiled from Myers, 1969). The low storativity values for confined aquifers result from compression of the aquifer matrix and the concomitant decrease in pore space. The higher storativity values from unconfined aquifers result from drainage of pore space. In highly compressible confined aquifers, such as coastal aquifers that contain interbedded clay strata characterized by high porosity and compressibility, storage coefficients may approach unconfined values and may not be characteristic of typically confined aquifers.

Storativity values can be calculated from water-level changes in observation wells during pumping tests using the Theis nonequilibrium equation or other equations that are modifications of the Theis equation. Monitoring wells for drawdown observations, however, may be difficult to find because municipalities often will not have closely spaced wells producing from the same water-bearing horizon.

Pump Test for Leakage

If drawdown data from an aquifer pump test exhibit leakage, leaky-aquifer solutions can be used to calculate vertical leakage through an aquitard. The likelihood of an aquifer to receive leakage can be reasonably well assessed when such information is integrated with a detailed geologic description of the confining strata. Presence of significant leakage can be determined from the general shape of the drawdown versus time curve. Figure 10 shows an aquifer test for a nonleaky aquifer, figure 11 shows moderate leakage, and figure 12 shows significant leakage. Leakage can be the result of higher permeability areas in the confining bed and/or natural or human-induced breaches of the confining strata.

Long-term pumping-test data may be needed to observe when the change in drawdown approaches zero, which is characteristic for leaky conditions. Data from observation wells are needed to quantify rates of leakage because the effects of well loss could impact drawdown in the pumping well. Estimated leakage values for all aquifers range from 10^2 to 10^{-5} gal/day/ft^2. These lower values (10^{-5} gal/day/ft) approach highly confined conditions with no leakage. Vertical leakage values for semiconfined aquifers are considered to range from 10^{-2} gal/day/ft^2 to 10^2 gal/day/ft^2.

Calculation of vertical leakage through confining strata probably represents the best hydrologic method for determining potential for contamination and for delineating highly confined from semiconfined aquifers. All calculations from pumping-test data, however, represent measurements of averaged hydrologic properties. Unless the permeability contrast between the pathway of leakage and the rest of the aquitard is significant, discrete points of leakage probably cannot be seen from aquifer response. Leakage from confining strata may represent a significant part of the ground water pumped from a well. Leakage does not necessarily originate from a shallow unconfined aquifer which may be a potential source for contamination, but may come from storage within the aquitard (Hantush, 1960; Neuman and Witherspoon, 1969a, 1969b, 1972). If the aquitard represents a complex interbedding of sands and shales, then the source of the water may come from the drainage of the interbedded sands. A more accurate picture of leakage through an aquitard can be made by installing monitoring wells in the aquitard itself to see how they respond to pumpage from the confined aquifer (Neuman and Witherspoon, 1972).

There are several papers on theoretical analysis of leaky aquifers (Hantush, 1959, 1960; Walton, 1962, 1979; and Herrera and Figueroa, 1969; Herrera, 1970; Neuman and Witherspoon, 1969a, b, 1972; Lai and Su, 1974). Calculation of leakage values for well fields, however, is not routine. There is limited information on which hydrogeologists can base their analyses.

Continuous Water-Level Responses

Continuous water-level elevation data can provide a simple and cost-effective method for determining whether an aquifer is unconfined or confined. Continuous water-level data for confined aquifers show daily fluctuations of water levels in wells because of daily atmospheric pressure changes. Water levels in wells of an unconfined aquifer will not show these natural, daily fluctuations (fig. 7). Major, longer term pressure changes, such as atmospheric pressure changes with weather changes, will also cause similar effects in wells of confined aquifers. Water-level response of confined aquifers to recharge events may be significantly different from those in unconfined aquifers. Recharge to confined aquifers through points of discrete leakage may indicate relatively rapid and large water-level changes, whereas water-level response in an unconfined aquifer is typically of a smaller magnitude.

Water-level fluctuations associated with barometric or earth-tide variations are relatively small and must be measured with equipment that is sensitive enough to measure centimeters of change and record at least every two hours. Drum recorders with floats or pressure transducers have the sensitivity and short time interval between measurements needed for these types of measurements. Measurement periods of at least one day are needed to observe daily fluctuations. Longer term measurements are needed to observe possible effects of recharge associated with precipitation.

Interpretation of continuous water-level recorder data is a sensitive technique for determining the presence of confinement, but cannot be used for assessing the degree of confinement. The use of continuous water-level recorder data for defining confinement may be most appropriate as an initial screening tool to determine whether an aquifer is confined.

Hydrologic Measurements in Confining Strata

The hydrologic characteristics of a stratum suspected of being confining can also be determined by monitoring hydrologic processes within the stratum itself. Other hydrologic approaches assess the presence and/or degree of confinement by measuring hydrologic processes in the confined aquifer beneath the confining stratum. Water-level changes in overlying strata during pumping in an aquifer indicate communication with the producing aquifer (Neuman and Witherspoon, 1972; Grisak and Cherry, 1975). Diurnal water-level fluctuations in overlying strata indicate confinement. Conversely, seasonal water-level changes that correlate to seasonal variations in precipitation suggest leakage (Williams and Farvolden, 1967).

Hydrologic measurements of leakage through an overlying strata are difficult to make because of the problem of identifying locations where the leakage is occurring. Permeability pathways through a suspected aquitard typically are vertical, making monitoring wells particularly difficult to place. The location and number of monitoring wells should be based on geologic mapping so that monitoring wells can be installed in leakage locations.

Monitoring wells in overlying strata can be used to test the confining nature of the strata, as well as to monitor for specific contaminants migrating through the strata. Monitoring of suspected aquitards is expensive compared with the other techniques described.

Numerical Modeling

Numerical modeling is a sophisticated technique that can be used to determine whether an aquifer is confined and the degree of confinement. The hydrologic characteristics of confining strata are estimated by altering hydrologic parameters (referred to as parameter estimation) of the confining strata and then simulating observed potentiometric surfaces. By estimating vertical leakage in the confining strata the degree of confinement can be estimated. A numerical model is an excellent method for synthesizing all available geologic and hydrologic information into a comprehensive picture. Creating a numerical model solely for defining confinement is probably more than is needed for determining whether an aquifer is confined and the degree of confinement. The previously discussed techniques are more cost effective for defining confinement.

A numerical model can be of great value in delineating a wellhead protection area. If a numerical model is to be developed for evaluating wellhead protection areas, then it may also be appropriate to use the model for determining the degree of confinement. Van der Heijde and Beljin (1988) give a compilation and review of numerical models appropriate for hydrogeologic characterization and development of wellhead protection areas.

Hydrochemical Approach

Hydrochemical techniques identify the age of ground water or the flow distance of water within an aquifer. With general water-chemistry data, we can determine if well water is characteristic of the recharge zone or of the down-gradient confined section of an aquifer. With radioactive isotopes we can estimate the age of the water and the approximate time when the water was recharged at land surface. The sensitivity of an aquifer to contamination can be estimated with the following water chemistry approaches.

General Water Chemistry

For large coastal plain aquifers with both outcrop and downdip sections, it may be difficult to determine if a well is located in the recharge zone or downdip in a confined section. This is especially true in the transitional area between outcrop and downdip sections. Ground-water chemistry may help determine whether a well is located in an unconfined recharge zone or in downdip confined sections. In coastal plain confined aquifers, waters in recharge zones are characterized by low pH, high eH, low TDS, high Ca/Na ratios, low HCO_3, low Cl, some NO_3, and some SO_4. As these waters flow downdip they chemically react with the rock matrix and the water chemistry changes, resulting in increases in pH, TDS, Na, HCO_3, and Cl, and decreases in SO_4, NO_3, and eH (fig. 14).

For settings known to be confined, significant leakage through aquitards may be identifiable. Chemical composition of a well water can be compared to the general composition of the ground water in the region to determine whether the water fits into the chemical composition of the regional-flow system. If not, local leakage may be occurring. Fogg and Kreitler (1982) observed "recharge" type of waters downdip in the Carrizo aquifer, East Texas, and concluded that uplifted salt domes had breached the confining layer permitting leakage to occur at that location.

Tritium and other Anthropogenic Chemicals

Large quantities of tritium, the radioactive isotope of hydrogen, and other anthropogenic chemicals such as Freon, have been added to the atmosphere in approximately the last 40 yr (1954 through 1990). These chemicals have been recharged through precipitation to the ground water at concentrations above natural levels on a global basis. The presence of these anthropogenic chemicals provides an estimate of the absolute age of ground water and, therefore, an estimate of the susceptibility of an aquifer to contamination by either vertical leakage or lateral flow. The lack of tritium in an aquifer may indicate the presence of confining strata. Conversely, the presence of modern concentrations of tritium (see detailed discussion on modern concentrations that follows) indicates either rapid horizontal flow or vertical leakage. With an understanding of the geologic setting, the relative importance of horizontal flow versus leakage can be determined. The use of tritium concentrations in ground water provides a powerful hydrochemical technique for determining the presence and/or degree of confinement of an aquifer.

The natural tritium in precipitation is estimated to be approximately five tritium units (TU's) (one tritium unit is equivalent to one ^3H atom in 10^{-18} H atoms). Large quantities of tritium, however, were added to the atmosphere with the first atmospheric nuclear weapons tests in the early 1950's. Atmospheric-tritium concentrations in the early 1960's were as high as 6,000 tritium units because of atmospheric testing, but have declined since then because of the U.S./U.S.S.R. moratorium on such testing (fig. 17) (Fritz and Fontes, 1980). Precipitation and, therefore, ground water that recharged after the early 1950's contained tritium concentrations significantly above natural background concentrations. Tritium concentrations in ground water that was recharged before the early 1950's have decreased by radioactive decay to concentrations below detection levels. Tritium has a half-life of 12.3 yr. Thus, ground waters with no measurable tritium today were recharged before the early 1950's, whereas ground water with tritium concentrations of two or more tritium units indicates the presence of a component of water that was introduced into the aquifer after 1954 and is, therefore, younger than approximately 40 yr.

The tritium techniques should be used to determine only whether a water is younger or older than 40 yr. More specific dates are complicated by the possibility of the mixing of older water (no tritium) with younger water (high tritium), variable tritium concentrations in atmospheric input, and continual, radioactive decay of tritium. The tritium in the atmosphere was at its maximum level in the 1960's, but concentrations have been decreasing ever since (fig. 17). Because of the decrease in nuclear testing, the atmospheric content and the amount of tritium in recharge water has also been decreasing. This makes it difficult to calculate specific times of recharge within the period from 1954 to the present. However, the ability to determine only if well water was recharged more than, or less than, 40 yr ago may be satisfactory for wellhead protection.

Fluorocarbons (Freon and other artificially created fluorinated organic compounds) have only been added to the atmosphere in the last 40 yr. These stable organic compounds have been recharged to the ground water in small but measurable quantities. Presence of fluorocarbons in ground water gives us an age-dating capability similar to that of tritium (Thompson and Hayes, 1979).

Only atmospherically derived anthropogenic chemicals are considered in this section. Other anthropogenic chemicals such as Trichloroethane (TCE) and other contaminants also enter aquifers and can be used to date the age of a water and identify the presence of vertical leakage, but are discussed in a later section because they are introduced to aquifers through local contaminant plumes rather than on a worldwide basis.

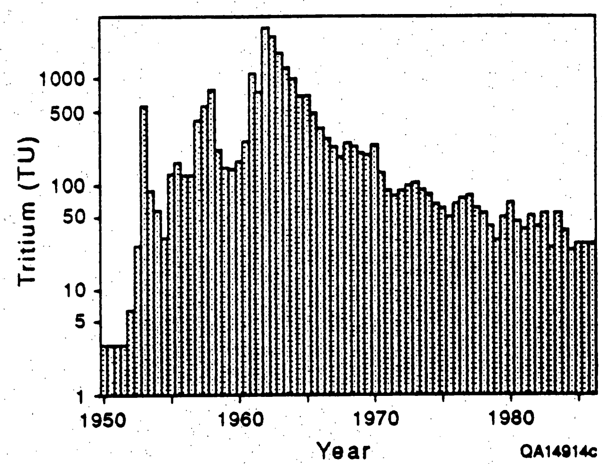


Figure 17. Tritium in precipitation data from 1950 to 1986, Ottawa, Canada (Robertson and Cherry, 1988).

The presence of tritium or fluorocarbons in a ground water indicates either recent lateral inflow or recent vertical leakage. The aquifer, therefore, has the potential to be contaminated from the surface. The hydrogeologic setting should be evaluated to determine the relative importance of lateral or vertical flow.

Tritium is measured by the liquid scintillation method on normal or concentrated water samples. Tritium analyses are not routinely performed on ground water; therefore, there is not an extensive data base of tritium concentrations. Because of the low concentrations (1 TU = 10^{-18} ^{3}H atoms), care needs to be taken in water sampling to prevent contamination. Laboratories analyzing tritium should have the ability to measure tritium concentrations as low as one tritium unit. Fluorocarbons, like tritium, are not analyzed on a routine basis. Fluorocarbon analyses are made with a gas chromatograph with an electron capture unit. Fluorocarbons are present in ground water at very low concentrations. Good sampling procedures are needed to prevent contamination.

The degree of confinement can be estimated from the age of the water if the presence of confinement has already been determined. If a well field contains modern ground water that has flowed through the confining strata then the aquifer is semiconfined. If the ground water is older than 40 yr, then the aquifer should be considered highly confined. The tritium technique has the greatest sensitivity of the geochemical approaches for defining confinement. It does not, however, identify pathways for leakage and therefore should be integrated with geologic and hydrologic investigations.

Carbon-14

The absolute age of ground water can be estimated from the activity of the carbon-14 (^{14}C) of dissolved bicarbonate. As with tritium, ^{14}C ground-water dates can be used to estimate the susceptibility of an aquifer to contamination by either vertical leakage or lateral flow. An old ^{14}C age could identify the presence of confinement, or, if confining strata had been previously identified, the degree of confinement. The use of ^{14}C for dating ground water is better suited for dating old waters than for dating modern waters. Because of its long half life, ^{14}C probably can be most effectively used as a dating tool for ground water for wellhead protection by determining if the ^{14}C age of the water is greater than 500 yr. Waters younger than approximately 500 yr are considered as "modern." Tritium, on the other hand, can be used to date ground water that is less than 40 yr old. Tritium is thus the preferred method for age determination to infer whether an aquifer is confined or not. Determining that ground water is thousands of years old using ^{14}C dating does provide a level of assurance not obtainable by any other technique and, therefore, has a role in wellhead protection strategies. Conversely, ^{14}C analyses should not be considered for aquifers where ground waters are expected to have short residence times.

Carbon-14, the radioactive isotope of carbon, is produced in the atmosphere by cosmogenic reactions. Atmospheric ^{14}C originates as dissolved CO_2 in rainwater and is recharged to an aquifer through normal precipitation/recharge processes. Two geochemical processes decrease the ^{14}C concentration in the aquifer. The ^{14}C concentration decreases because of radioactive decay. The half-life of ^{14}C is 5,730 yr. Carbon samples as old as 50,000 yr can be theoretically dated, but are complicated by geochemical reactions in the aquifer. The ^{14}C in dissolved CO_2 in rain is used in plant growth. Plant processes create high CO_2 and ^{14}C concentrations in the soil zone. This CO_2 with ^{14}C is then recharged to the ground water as carbonic acid. Carbonic acid may dissolve carbonate mineral material in the aquifer as the ground water flows through the aquifer. The mineral material being dissolved, however, contains "dead" carbon, that is, carbon with no ^{14}C. This addition of dead carbon dilutes the ^{14}C concentration of the bicarbonate in the ground water and requires corrections of calculated ages (Pearson and Hanshaw, 1970; Wigley, 1975).

Contamination

The presence of surface contaminants in a well field indicates a high sensitivity to future aquifer contamination, which may result either from lateral ground-water flow or vertical leakage. The location of the contaminant needs to be known to differentiate the two pathways (for example, lateral and vertical). Regardless of the pathway, however, the well's zone of contribution is sensitive to

contamination. It could be argued that the development of a wellhead protection area in an aquifer containing contaminants is after the fact; contaminants, however, may have reached the well's zone of contribution at concentrations below the Environmental Protection Agency's maximum concentration limit (MCL) or State primary standard. The presence of nonpoint source contaminants, such as nitrate fertilizer, may indicate pervasive leakage to an aquifer, although specific pathways may not be identifiable.

Hydrochemical measurements in confining strata

Previously discussed hydrochemical techniques have concentrated on making measurements within an aquifer to determine presence and/or degree of confinement. It is also appropriate to characterize the hydrochemistry of the overlying strata to determine the presence and/or the degree of confinement. The hydrochemical techniques of general water chemistry, tritium, and ^{14}C in confining strata can be used in a manner similar to that suggested for an underlying aquifer. An investigation of water chemistry in overlying strata could provide very valuable information on the presence and/or degree of aquifer confinement, but probably would provide more detail than is needed for defining confinement and developing a wellhead protection strategy.

Changes in Water Chemistry

Large volume ground-water production from a well or well field may significantly alter the hydrology and hydrochemistry of a confined aquifer. Head declines from pumpage may result in significant vertical leakage through the overlying confining strata. General water chemistry and tritium concentrations may change because of vertical leakage. Salt water contamination (Cohen and Kimmel, 1970), nitrate contamination (Eccles and others, 1976), and changes in general chemistry (Smith and others, 1976), are examples of changes in general water chemistry that have resulted from long-term ground-water pumpage. Evaluating water chemistry data through time for a well under consideration for wellhead protection may document leakage through confining strata.

Quantitatively Distinguishing Semiconfined from Highly Confined Aquifers

The previous discussion of geologic, hydrologic, and hydrochemical approaches provided several methods for distinguishing confined from unconfined aquifers and/or indicating some degree of confinement, but do not quantitatively differentiate semiconfined from highly confined conditions. In the next section on wellhead protection, different wellhead protection strategies are used for semiconfined and highly confined aquifers. An arbitrary but logical and justifiable division is presented to quantitatively separate highly confined from semiconfined aquifers.

The suggested method for differentiating semiconfined from highly confined aquifers, from the perspective of wellhead protection, is based on the ability to quantitatively assess whether an overlying aquitard can leak contaminants to the underlying aquifer in a reasonable period of time. The criterion to distinguish semiconfined from highly confined, therefore, is based on a vertical time of travel calculation. The calculation of vertical time of travel is a sensitive method for assessing the potential leakage through an aquitard.

Estimation of time of travel can be calculated in two ways. Calculations can be made with tritium data or with vertical leakage values and hydrogeologic data from a well or well field. Specifically, a 40-yr vertical time of travel is considered to be a reasonable "rule of thumb" for differentiating semiconfined from highly confined aquifers. A 40-yr time of travel means that the water at a well was recharged in approximately 1950, which coincides with the beginning of major industrial development, atmospheric atomic-bomb testing, and extensive agricultural fertilizer and pesticide use. Most contaminants in ground water in the United States today were probably introduced into the ground water no earlier than 40 yr ago.

The tritium technique determines whether the ground water in a confined aquifer contains tritium or not. If there is no appreciable tritium, then the time of travel of ground water is greater than 40 yr from its recharge, and the aquifer would be considered highly confined. If ground water in a confined aquifer contains more than a couple of tritium units, then the combined vertical and horizontal time of travel is less than 40 yr, and the aquifer would be considered a semiconfined aquifer and more sensitive to surface contamination. The tritium technique requires a basic hydrogeologic understanding of the aquifer to insure that the presence or absence of tritium reflects vertical leakage and not horizontal flow. For example, ground water in a highly confined, transmissive limestone aquifer might contain tritium because of lateral flow from a distant point of recharge and not from vertical leakage.

The second approach for differentiating semiconfined from highly confined aquifers is by calculating vertical time of travel from vertical thickness permeability values, porosity of the confining strata and vertical hydraulic gradient across the confining strata. The equation for calculating vertical time of travel across the confining layer is

$$T_V = \Theta \, L \, X / K' \, \Delta h \qquad (3)$$

where T_V = vertical time of travel (years) across the confining layer

Θ = porosity of confining strata

L = thickness of confining strata

X = travel distance across confining strata

Δh = hydraulic gradient across confining strata

K' = vertical permeability of the confining strata.

A hydrogeologic investigation and a pumping test of a well or well field provide the needed data.

The above equation can be rearranged to solve for the vertical permeability (K') that would be needed to separate a semiconfined from a highly confined aquifer:

$$K' = \Theta \, L \, X / T_V \, \Delta h. \qquad (4)$$

Assigning hypothetical values of:

T_V = 40 years

Θ = .20

$L = 10$ ft

$X = 10$ ft (contaminant is assumed to be at base of unconfined aquifer, that is, top of aquitard)

$\Delta h = 20$ ft

then

$K' = .025$ ft/yr

or

$K' = .005$ gpd/ft^2.

If the confining strata for this example has a K′ larger than .005 gpd/ft^2 then water can leak through the aquitard in less than 40 yr, and the aquifer should be considered semiconfined. For leakage values smaller than .005 gpd/ft^2 the time of travel across the aquitard would be greater than 40 yr, and the aquifer would be considered highly confined.

Vecchioli and others (1989) used a 5-yr vertical time of travel to differentiate highly confined from semiconfined aquifers in northern Florida and recommended the 5-yr time of travel as being practical. A 40-yr vertical time of travel is suggested in this document because it can be calculated not only by using pump-test data, but also by using tritium data. Having alternate approaches is important because not enough hydrologic data may be available to calculate accurate times of travel. Conversely, tritium analyses may be inappropriate, as in the case of a confined limestone aquifer, where horizontal flow may be fast enough that ground water contains tritium from lateral recharge and not vertical leakage.

In a case in which a pump test indicates leakage, but the tritium analyses show no tritium, the tritium data should be given priority and the aquifer should be considered highly confined. The leaky-pump test may be documenting leakage from within the overlying confining strata and not leakage through an overlying strata from a surface or shallow source. The lack of tritium indicates that the confining strata has effectively prevented recently recharged ground water from reaching the producing well.

Recommendations for Evaluating Confinement

The previous section catalogued three basic approaches for defining confined aquifers: geologic, hydrologic, and hydrochemical. Within each basic approach, several specific techniques were discussed. Some techniques are more appropriate because they better define the degree of confinement or because they are less expensive.

An Integrated Approach

The most important recommendation for determining the presence and/or degree of confinement is that the determination be based on an integration of geologic, hydrologic, and hydrochemical approaches. The geologic approach is necessary to determine whether there is a confining strata and whether there are pathways through the confining strata. The hydrologic and hydrochemical approaches document whether there is actually leakage through the confining bed. Collecting both hydrologic and hydrochemical data provides a method to compare one approach to another.

Geologic Approaches

Geologic maps or cross sections based on surface and subsurface geologic data are needed to identify the presence of confining layers. Artificial penetrations should be mapped, because they represent the most likely pathways for contaminants to leak through confining strata. Sources of contamination should be identified. Hydrogeologic maps specifically constructed for wellhead protection areas and based on geologic and artificial-penetration data are recommended.

Hydrologic Approaches

The most important hydrologic approach for evaluating degree of confinement is the calculation, from pump-test data, of the rate of vertical leakage through the aquitard. This technique is a direct determination of the leakiness of the overlying strata. The pump-test data for calculating vertical leakage will also be of value for calculating wellhead protection areas. Water-level data, potentiometric surface data, continuous water-level recorder data are easier and less expensive to obtain than leakage information but provide less information on the degree of confinement. Their greatest value will be for initial screening to determine the presence of confinement. Storativity data are less critical than leakage data and may be expensive to obtain. Monitoring wells in aquitards and numerical models may provide valuable information on the degree of confinement, but will be expensive.

Hydrochemical Approaches

The most important hydrochemical technique is the estimating of time of travel with tritium data, because the technique provides an absolute age for the water and gives a direct measure of the sensitivity of the aquifer to contamination from combined horizontal flow and vertical leakage. General water chemistry, presence of contaminants, and ^{14}C data are not as valuable as tritium data.

CHAPTER 4. DEVELOPING A WELLHEAD PROTECTION AREA

Definition of Wellhead Protection Area

A wellhead protection area refers to "the surface and subsurface area surrounding a water well or well field, supplying a public water system, through which contaminants are likely to move toward and reach such water well or well field" (U.S. Environmental Protection Agency, 1987, p. 1–2).

Confined aquifers are less sensitive to contamination from surface sources than unconfined aquifers because of the presence of overlying confining layers. As discussed previously such confining strata may be semiconfining, that is, they have the potential for extensive leakage on an areal basis, or they may be highly confining but be penetrated by discrete features such as faults or artificial penetrations.

Even though the potential for contamination of confined aquifers is less than for unconfined aquifers, contamination of confined aquifers occurs. And so, it is appropriate to consider wellhead protection areas for confined aquifers.

Protection Goals

The goals of a wellhead protection area for a confined aquifer are similar to those for any aquifer and include one or more of the following:

Providing Time to React to Incidents of Unexpected Contamination

This goal is met by delineating a remedial action zone, that is, an area delineated with a time of travel long enough to allow identification and cleanup of contaminants before they reach a well.

Lowering Concentrations of a Contaminant to Target Levels before Contaminants Reach a Well

This goal is reached by delineating a protection area large enough to attenuate potential containments to target levels. Attenuation may occur within the confining strata or the underlying aquifer. Confining strata may or may not attenuate contaminants. The clay minerals of many confining strata have the potential to adsorb contaminants. However, contaminant migration through an aquitard probably will be focused along openings such as fractures, where there will be less dispersion and dilution of a contaminant than through the aquitard material itself. Attenuation within the confined aquifer, from the wellhead protection area boundary to the well, may represent a significant proportion of the total attenuation from the contaminant source to the well.

Protecting All or Part of the Zone of Contribution from Contamination

The purpose of delineating a wellhead management zone is the prevention of contamination of all or part of a well's or well field's zone of contribution. A wellhead management zone that includes the entire zone of contribution of a well field in a confined aquifer may be very large. This factor combined with the generally lower susceptibility of contamination in such settings may lead to implementation difficulties. An alternate approach is to define a wellhead protection area based on some setback zone such as 10-, 20-, or 40-yr time of travel contours.

Hydrodynamic Criteria for Delineation of Wellhead Protection Areas for Confined Aquifers

The U.S. Environmental Protection Agency (1987) recommended five criteria as the technical basis for delineating wellhead protection areas. These criteria are hydrodynamic ones because they define the wellhead protection area by flow characteristics of the aquifer. For confined aquifers, these criteria should be integrated with a permeability pathway approach which is discussed in a later section of this document. The hydrodynamic criteria are:

1. Distance
2. Drawdown
3. Time of travel
4. Flow boundaries
5. Assimilative capacity

Distance

Using the distance criterion, a wellhead protection area is delineated by a fixed radius or dimension measured from the well to the wellhead protection area boundary. The distance criterion represents the simplest, least expensive, and most arbitrary criterion used for delineating a wellhead protection area for any aquifer. It is only recommended as a first, initial step until a more complete analysis can be made.

Drawdown

Drawdown is the decline in water-level elevation resulting from the pumping of a well. The areal extent over which drawdown occurs is referred to as the zone of influence or the areal extent of the cone of depression of the pumping well (fig. 8). For an aquifer with a negligible regional hydraulic gradient, the extent of the cone of depression is coincident with the area of downward leakage. This area of lowered head values provides the proper head gradient to permit potential leakage of surface contaminants down to a producing interval of a confined aquifer. The hydraulic potential for leakage decreases rapidly away from the well as head gradient across the aquitard decreases. For the confined setting, this potential for downward leakage does not automatically translate into the occurrence of vertical leakage. A permeable pathway must be present in the aquitard for leakage to occur.

The extent of the cone of depression may be larger than the area of downward leakage if the original potentiometric surface of the confined aquifer was higher than the water table of the overlying aquifer. Considering the typical limitation of data availability and the fact that the extent of a cone of depression is typically determined by a calculation rather than by measurement, an effort to delineate an area of downward flow as separate from the extent of the cone of depression may not be reasonably accomplished. The areal extent and depth of a cone of depression continues to increase with time until steady-State conditions are reached. Therefore, drawdown thresholds should be related to specified periods of time.

Time of Travel

Time of travel is a criterion using the time for ground water (or a ground-water contaminant moving at the same rate) to flow from a point of interest to a well. Isochrons (contours of equal time) of any required value can be depicted on a map (fig. 8). The lateral area contained within an isochron is referred to as a zone of transport (ZOT). As previously described, a vertical time of travel can be calculated for vertical leakage across a confining layer. Time of travel allows wellhead protection area delineation using calculations that consider both vertical- and horizontal-time of travel flow components.

Time of travel calculations for this manual are assumed to be based on advective ground-water flow. Advective flow of contamination represents Darcian flow, which is typically a conservative approximation for contaminant transport.

Flow Boundaries

The flow-boundary criterion for delineating a wellhead protection area uses the concept of locating ground-water divides or other physical hydrologic features that control ground-water flow and define the geographic area that contributes ground water to a producing well. This area is defined

as the zone of contribution. These physical boundaries can be geologic, such as faults across which no flow occurs, or hydrologic, such as ground-water divides. Ground-water divides can be natural, such as those that reflect topography, or be human induced, such as those created by a pumping well. In an aquifer with an original horizontal potentiometric surface, the zone of influence perimeter (the lateral extent of the cone of depression) coincides with a well's ground-water divide; only water within the zone of influence flows to the well, that is, the zone of influence equals the zone of contribution. Likely settings for an original potentiometric surface to approach being horizontal are deep, confined aquifers. Where the original potentiometric-surface gradient is not negligible, the zone of influence and zone of contribution do not coincide. In such a setting, the well's ground-water divide on the downgradient side occurs inside the zone of influence; on the upgradient side, the well's ground-water divide occurs outside and extends upgradient until it intersects a hydrogeologic boundary. The steepness of the original potentiometric-surface gradient needed to initiate flow external to the zone of influence is dependent on such aquifer parameters as hydraulic conductivity. The difference between the zone of influence and the zone of contribution in an aquifer with an original nonnegligible potentiometric-surface gradient may be quite small for small times of travel. However, as times of travel become large, significant differences may occur. If there is a significant natural hydraulic gradient across a site, then this component should be taken into consideration in delineating wellhead protection areas, particularly if larger times of travel are being used.

Assimilative Capacity

The assimilative capacity criterion uses the concept that the saturated and/or unsaturated section of an aquifer can attenuate contaminants to acceptable levels before the contaminant reaches a well screen. This attenuation process results from dilution, dispersion, adsorption, and chemical precipitation or biological degradation. These processes have all been documented to occur and play important roles in the remediation of contaminated ground water. However, consideration of these processes involves sophisticated treatment of contaminant transport phenomena, which requires detailed information on the hydrology, geology, and geochemistry of the area of investigation and is typically unavailable. The inclusion of these processes into wellhead protection strategies is, therefore, generally not realistic.

Recommended Hydrodynamic Criterion for Confined Aquifers

The recommended criterion for defining a wellhead protection area is time of travel. Distance does not accurately characterize the recharge zone. Use of the flow-boundary criterion is not generally recommended because ground-water divides in a confined setting may be difficult to identify. Assimilative capacity requires complex treatment of contaminant-transport phenomena which is beyond the scope of a practical application. A comparison of a wellhead protection area delineated using the time of travel criterion, with a wellhead protection area delineated by the cone of depression leads to the recommendation that time of travel is preferred to the cone of depression, because the lateral extent of a cone of depression increases as the leakage through the aquitard decreases, leading to unrealistically large wellhead protection areas (fig. 18).

Both the cone of depression and the time of travel contours become larger for a more confined aquifer, because less water is contributed from vertical leakage, and, therefore more water must come from lateral flow. Consequently, though perhaps counterintuitively, the wellhead protection area for a highly confined aquifer would be larger than for the semiconfined aquifer, even though the highly confined aquifer will be less sensitive to contamination than the semiconfined aquifer.

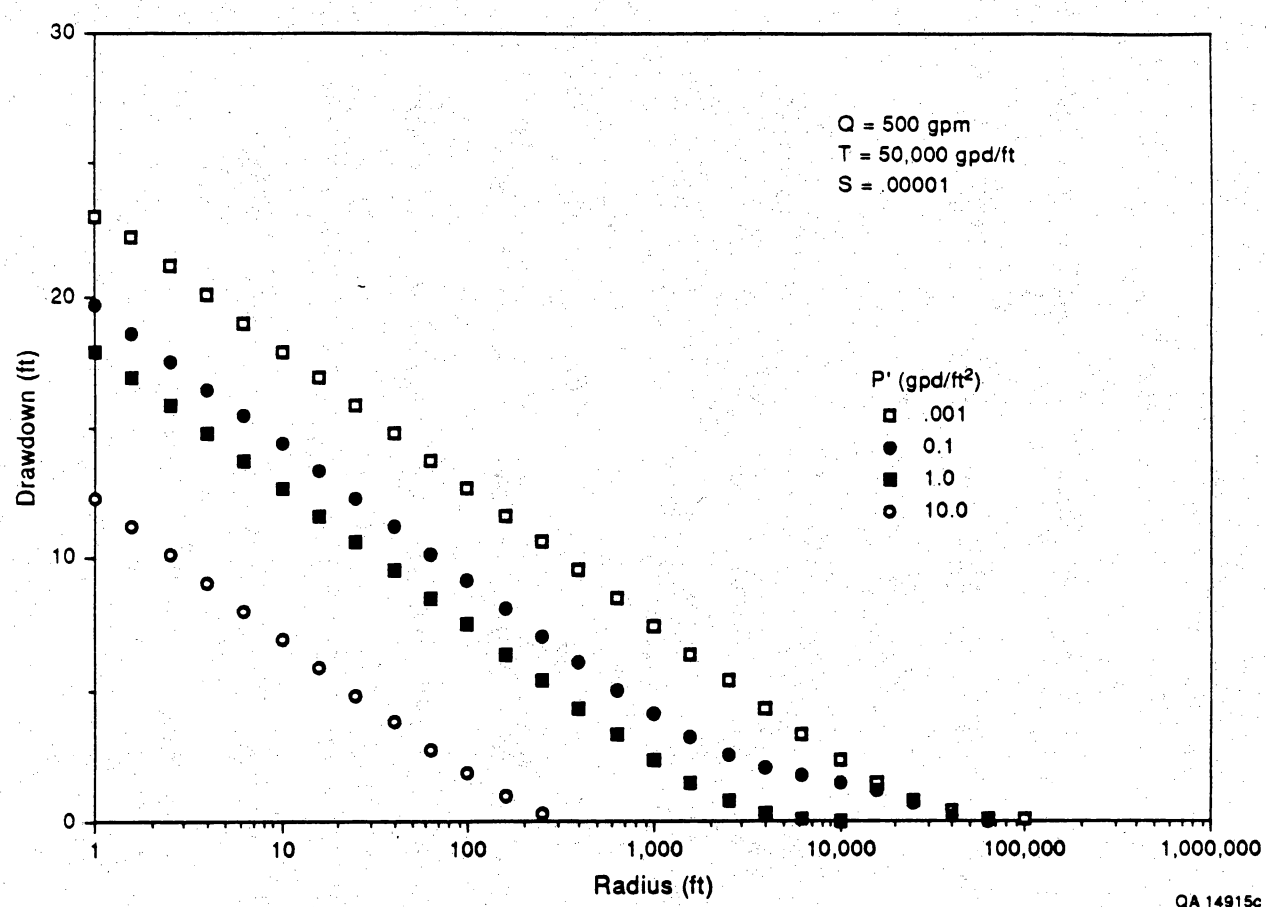


Figure 18. Simulation of drawdown versus log distance for hypothetical aquifer for different values of leakage using computer code PTIC (Walton, 1987). Note curves are linear. At the well maximum depth of drawdown can be determined. As drawdown approaches zero, the maximum lateral extent of the cone of depression can be estimated.

CHAPTER 5. METHODS FOR CALCULATING WELLHEAD PROTECTION AREAS

Methods for Calculating Wellhead Protection Areas for Confined Aquifers with Negligible-Gradient Regional Potentiometric Surfaces

Two approaches are considered for calculating wellhead protection areas for confined aquifer settings where the regional potentiometric surface gradient is negligible, (1) cone of depression and (2) time of travel.

Cone of Depression Approach

The lateral extent (as defined by a very small [<1-ft] drawdown contour) of a cone of depression defines the zone of influence surrounding a pumping well after a specific period of time. Three methods can be used to estimate the lateral extent of a cone of depression.

Drawdown in Monitoring Wells at Different Distances from a Producing Well Method

A drawdown versus distance curve can be plotted from drawdown values simultaneously observed in monitoring wells at different distances away from a producing well (fig. 8). A plot of drawdown versus the log of the distance, will give a straight line (fig. 18). The point where this line intersects the line of 0 to 1 ft drawdown defines the size of the cone of depression (Driscoll, 1986).

Drawdown versus Time in the Producing Well or in a Monitoring Well Method

The lateral extent of a cone of depression can also be estimated from data for time versus drawdown observed in a single well. The slope of the semilog plot of drawdown versus time can be used to estimate drawdown versus distance. The slope of a semilog plot of drawdown versus distance (fig. 19) (Driscoll, 1986) is twice the slope of the time versus drawdown curve.

Drawdown versus Distance Simulation Using Analytical Solutions and Simple Computer Models Method

The lateral extent of a cone of depression can be determined with analytical solutions and hydrologic parameter values derived from pump-test data or previously collected regional data if pump-test data are not available. Two techniques are available: the equilibrium technique, used when the cone of depression has reached equilibrium; or the nonequilibrium technique, used when the cone is still expanding. The radial distance of zero drawdown for a pumping well that has reached equilibrium (the cone of depression has expanded as far as it can) can be estimated with the Thiem equation (Thiem, 1906)

$$s = \frac{Q}{2\pi Kb} \log_e \frac{r_e}{r} \qquad (5)$$

where s = drawdown from original potentiometric surface

Q = discharge

K = hydraulic conductivity

b = aquifer thickness

r = radial distance at point of drawdown observation

r_e = radial distance of zero drawdown of cone of depression.

Davis and DeWiest (1966) and Lohman (1972) provide a detailed discussion of this equation. The second technique is to use the nonequilibrium Theis equation (Theis, 1935), from which the lateral extent of the cone of depression at different times can be calculated

$$s = \frac{114.6Q\,W(u)}{T} \qquad (6)$$

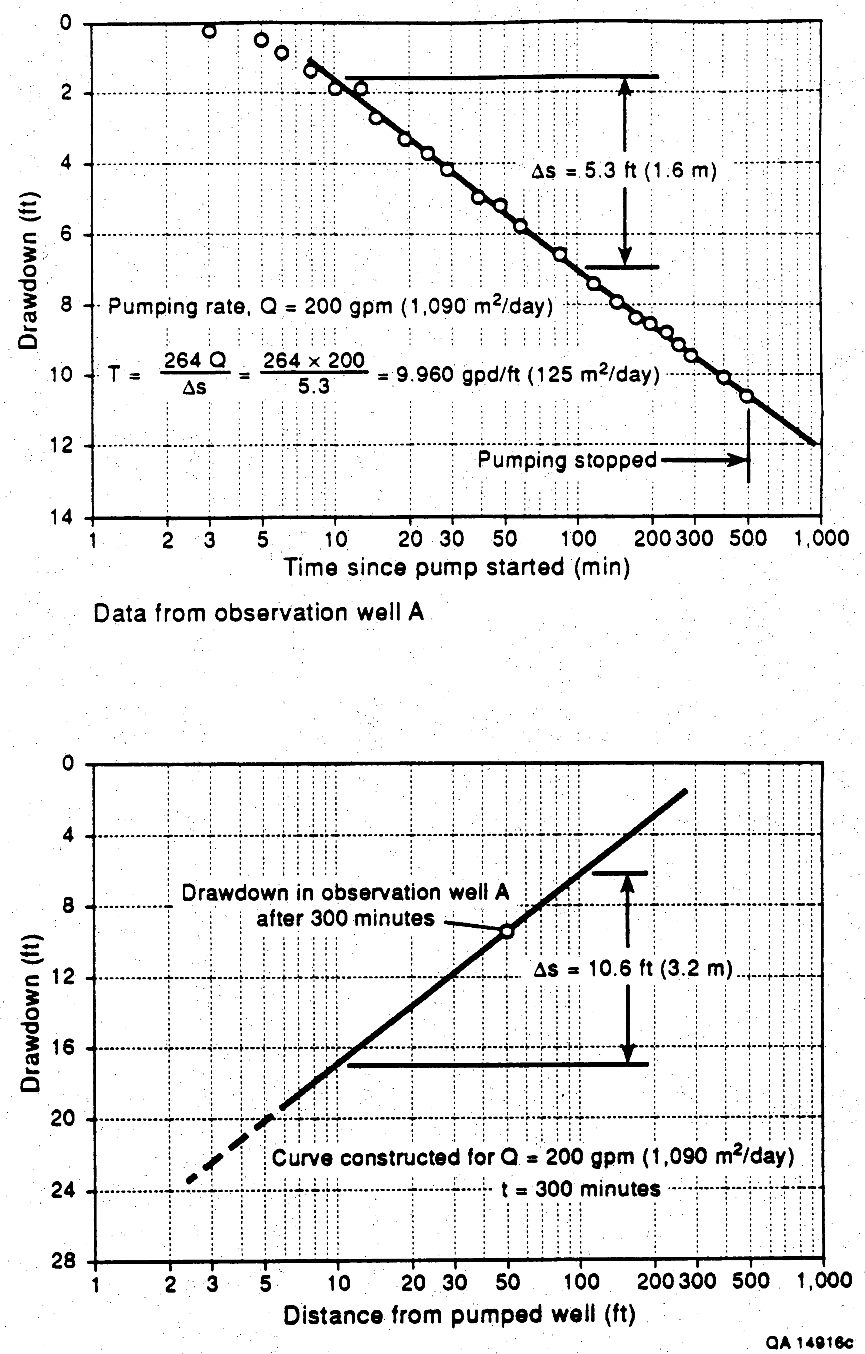


Figure 19. The lateral extent of a cone of depression of a pumping well can be determined with time versus distance data. The slope of drawdown versus log distance is twice the slope of drawdown versus log time. Example from Driscoll (1986). Used with permission from *Groundwater and Wells*, Edition 2, 1986, Johnson Filtration Systems Inc.

W(u) is the well function of "u" where

$$u = \frac{1.87r^2S}{Tt} \qquad (7)$$

s = drawdown

Q = discharge

T = transmissivity

r = radial distance to point of drawdown observation

S = storativity

t = time.

These equations are written for solution with English units (s[ft], Q[gpm], T[gpd/ft], r[ft], t[days]). Driscoll (1986) provides a detailed discussion of methods of solution for this general equation. An appropriate pumping period must be chosen that simulates the normal pumping period for the well under consideration for wellhead protection.

User-friendly computer programs can also be used to estimate the cone of depression for equilibrium or nonequilibrium conditions. Computer codes such as those described in Walton (1987) are semianalytical codes with relatively simple boundary conditions and simple designations of hydraulic conductivity, storativity, and leakage. More complex models can also be used to calculate drawdown versus distance where boundary conditions, vertical and horizontal hydraulic conductivity, storativity values, and so forth, can be varied on an element by element basis. Simulation of well-field hydraulics with interfering cones of depression from multiple-well production are best accomplished with numerical codes rather than analytical solutions or some of the simpler numerical models (see Van der Heijde and Beljin, 1988). The complexity of the code, however, should be matched with the availability of data. Sophisticated codes are often not appropriate when there are only limited data available.

Time of Travel Approach

Time of travel calculation is based on Darcy's law. Either the distance of flow for a given period of time or the time of travel for a given distance can be calculated from data on hydraulic gradient, transmissivity, porosity, and pump discharge. Time of travel calculations can be made either by incorporating the hydraulic gradient from the cone of depression and transmissivities, both obtained from pump-test data, into time of travel calculations or by using a simpler cylinder method, which does not require hydraulic gradient or transmissivity data, or by using WHPA model (Blanford and Huyakorn, 1990), a semianalytical time of travel model.

A 40-yr period is a convenient period to use for a time of travel calculation because 40 yr is an approximate break point between recently recharged (post-1950) waters containing tritium, and older (pre-1950) waters with no "bomb" tritium. Water with no measurable tritium should be older than 40 yr. If there is no tritium in ground water, then it will take at least 40 yr for currently recharging water to flow to a well either horizontally or vertically.

Cone of Depression/Time of Travel Method

The cone of depression/time of travel method calculates time of travel on the basis of the hydraulic gradient of the cone of depression. Calculations can be made through (a) simple analytical solutions such as the following equation, or (b) reverse-path calculation computer codes such as used by Shafer (1987) or Blanford and Huyakorn (1990).

(a) Analytical time of travel can be calculated from the following equation:

$$TOT = (\Delta l) * \Theta / K * i \qquad (8)$$

where TOT = time of travel threshold

Δl = distance of travel for a given time period

K = hydraulic conductivity

Θ = porosity

i = $\Delta h/\Delta l$ is the hydraulic gradient of the cone of depression between two points of measurement. Δh is the difference in hydraulic head between two points of measurement on a flow line (Δl).

To calculate time of travel contours, this equation can be arranged in the following form:

$$\Delta l = (TOT^{*}K^{*}\, i)/\,\Theta. \qquad (9)$$

The hydraulic gradient decreases rapidly away from the well (fig. 8) and, therefore, is not constant and is a function of Δl. The time of travel can be calculated by the following procedure. The time of travel for various incremental distances is estimated from the hydraulic gradient (i) for each increment (e. g. 0 to 10 ft, 11 to 100 ft, and 101 to 1,000 ft), pump test data and equation (8) (fig. 18). The total time of travel is the sum of each time of travel for each increment. The total time of travel is then plotted versus distance (fig. 20). Because the log of time of travel versus the log of distance is approximately linear, the distances for different times of travel can be estimated. Extrapolation beyond the farthest data point should be used with care. (This calculation can easily be made with a spreadsheet program on a microcomputer.) The distance of travel for a given time of travel can then be contoured to delineate a wellhead protection area.

(b) Time of travel contours can also be calculated from computer models that map the potentiometric surface and calculate ground-water flow paths in a reverse direction. Flow paths of a ground-water flow system can be calculated with either forward or reverse particle tracking numerical ground-water flow models. Forward tracking predicts where ground water or a contaminant in the ground water will flow in the future. Most ground water flow models that calculate flow paths are forward tracking. Forward tracking is particularly valuable for predicting where contamination from a

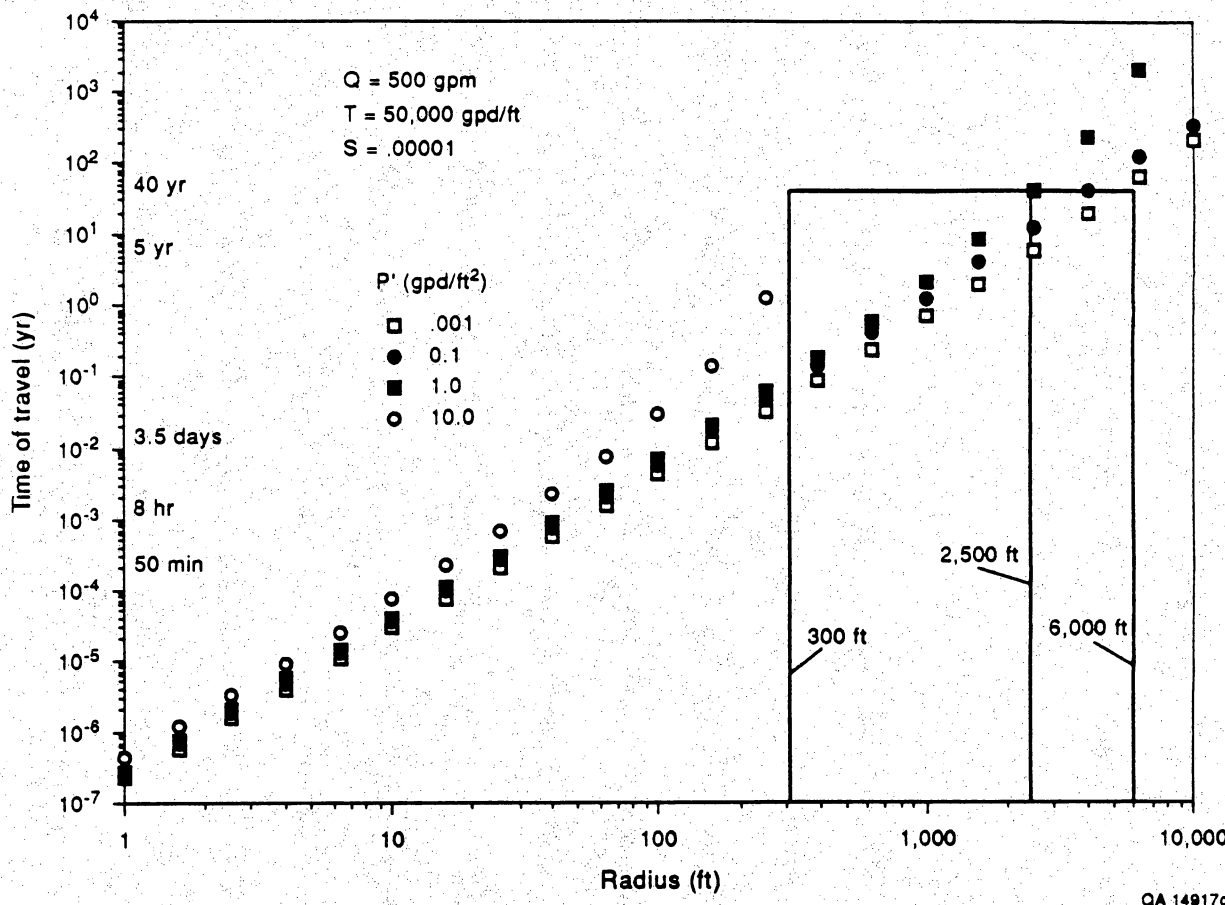


Figure 20. Simulation of time of travel (in years) for hypothetical aquifer for different values of leakage using computer code PTIC (Walton, 1987).

pollution site may flow and in what time period. In contrast, reverse-path calculations estimate where ground water and contaminants have flowed in the past. This approach is valuable for defining wellhead protection areas because it defines the "recharge area" for a well and the time of travel for water or a contaminant to get from a point to a well.

Calculation of reverse flow paths and travel times with numerical models is a two-step process. First, the water level at the well and the potentiometric surface for the surrounding area is calculated and, if desired, the problem of vertical leakage associated with semiconfined aquifers can be addressed. Many ground-water computer models can simulate ground-water flow. Second, reverse flow paths are calculated with codes such as WHPA (GPTRC-numerical option) (Blanford and Huyakorn, 1990) or GWPATH, the reverse-path numerical model of Shafer (1987) (fig. 21).

The use of reverse flow path and time of travel calculations has advantages and disadvantages. The advantages are that the method is the most sophisticated and provides the most realistic simulation. The disadvantage is that the method is the most complex.

An alternate approach to using a reverse-path calculation is to use a solute transport (forward tracking) code, but use the producing well or field as an injection well and calculate the distance to the edge of the hypothetical plume as it migrates away from the well for specific times. The plume boundary for a given period of time (time of travel) can be used to delineate a wellhead protection area. This approach being used by the Texas Water Commission to delineate wellhead protection areas for well fields may have advantages, since solute transport modeling specifically considers contamination migration.

Cylinder Method

The cylinder (volumetric) method is used by the Florida Department of Environmental Regulation, the U.S. Environmental Protection Agency (1987), and Vecchioli and others (1989). The

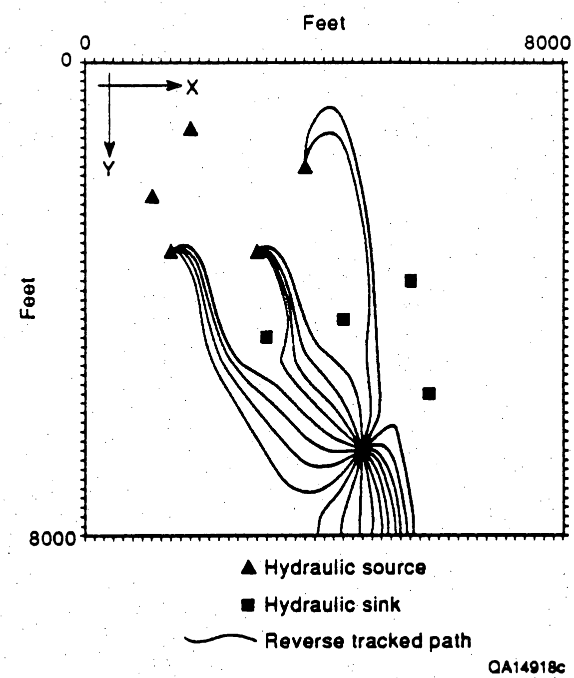


Figure 21. Example of reverse-path calculation (from Shafer, 1987).

method uses a volumetric-flow equation which calculates the radius (r) of a cylinder from which all water would be pumped out after a defined period of time (time of travel) (fig. 22). The equation is as follows:

$$r = (Qt/\pi\Theta H)^{1/2} \tag{10}$$

where Q = discharge

Θ = porosity

H = length of screened interval

t = travel time to well

The equation is a modification of Darcy's law for radial flow to a well, even though it uses neither hydraulic conductivity nor hydraulic gradient (Vecchioli and others 1989). The volumetric-flow equation assumes all flow is horizontal. In the context of confined aquifers, the aquifer is assumed to be highly confined and, therefore, there is no vertical leakage into the aquifer. This assumption results in a larger radius for a given time of travel than would be calculated for a leaky confined aquifer.

Semianalytical Method (WHPA Model)

The WHPA model is an integrated semianalytical model for delineation of wellhead protection areas (Blanford and Huyakorn, 1990) that was developed for the U.S. Environmental Protection Agency Office of Ground-Water Protection to calculate wellhead protection areas by calculating time of travel contours for negligible or sloping regional hydraulic gradients (fig. 23). The WHPA (1.0) originally did not consider vertical leakage and therefore could have caused time of travel contours and overall wellhead protection areas to be larger than needed; time of travel contours would be similar to those calculated by the cylinder method, because both neglect leakage. Recent modifications to the computer program (WHPA 2.0) allow vertical leakage and will permit time of travel calculations to leaky aquifer settings. (WHPA 2.0 was not available for testing during preparation of this manual.)

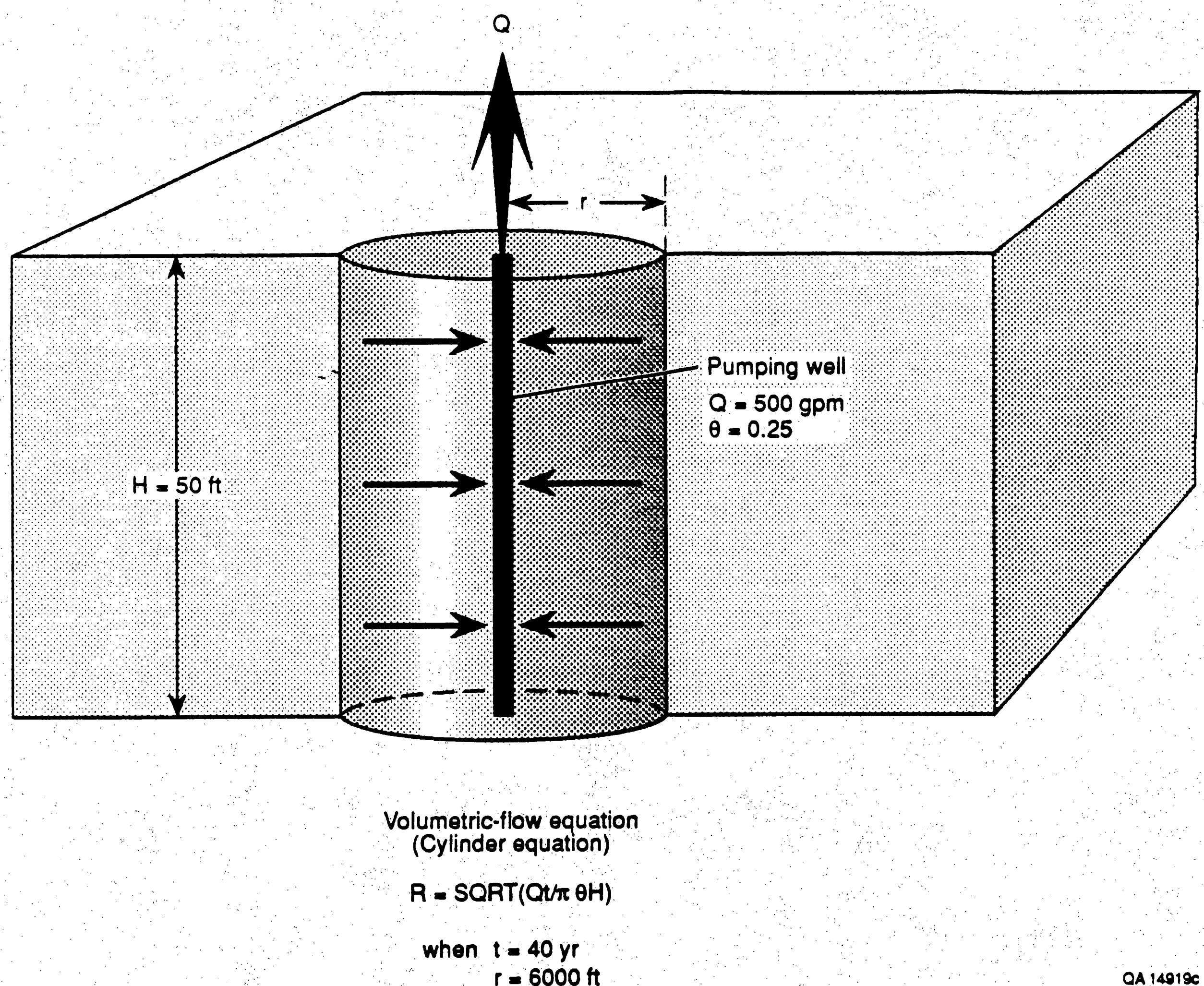


Figure 22. Cylinder or volumetric-flow equation approach for calculating time of travel for 40 yr. This approach gives a conservative time of travel because vertical leakage is not considered.

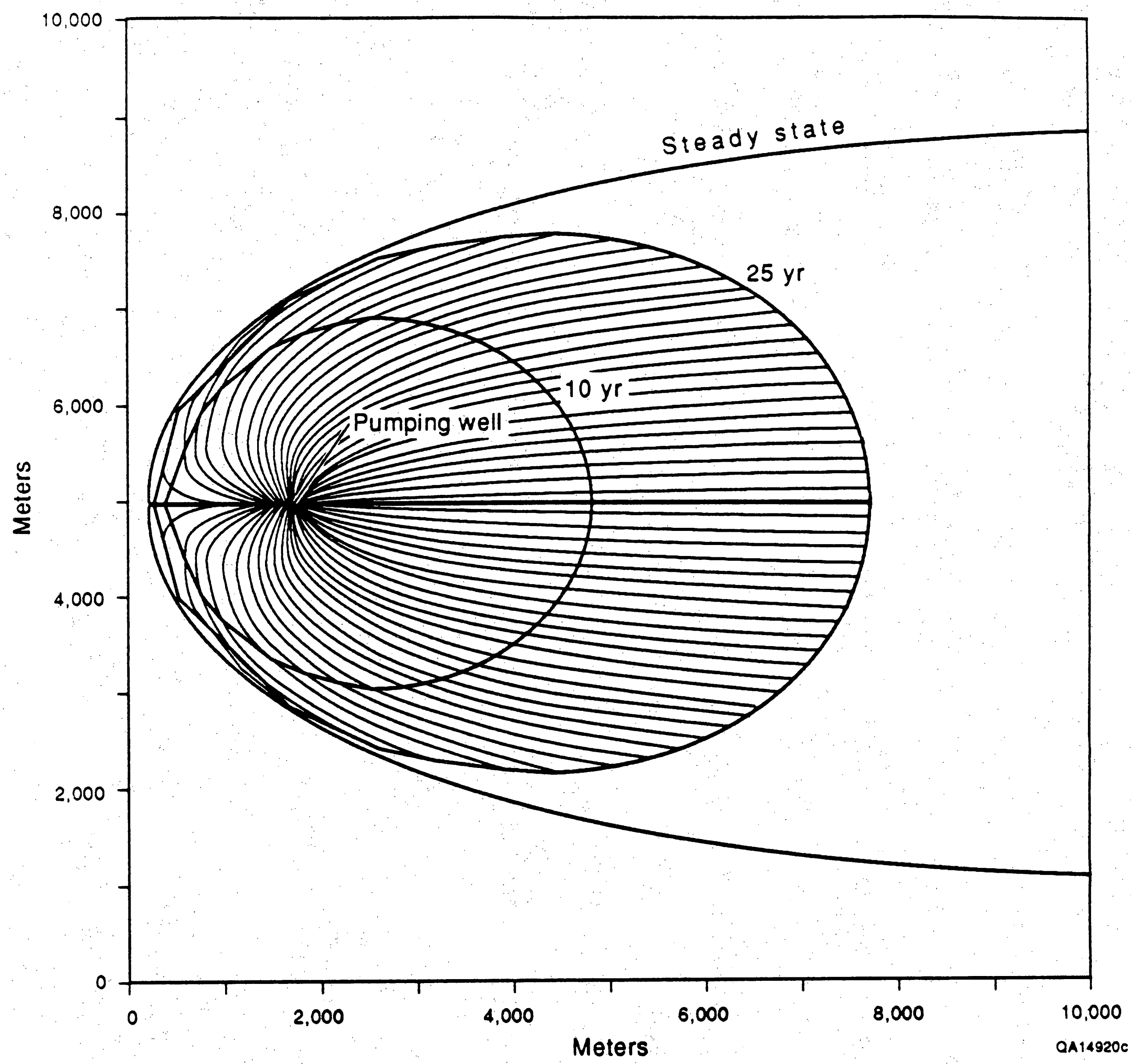


Figure 23. Example of reverse-path calculation using wellhead protection area (WHPA) computer program (from Blanford and Huyokorn, 1990).

Comparison of Approaches and Methods

Calculating a wellhead protection area from the cone of depression/time of travel method is recommended in preference to a method associated with the cone of depression approach or the cylinder method. The cone of depression/time of travel method is the most versatile of the three because it provides an accurate assessment of the wellhead protection area for both semiconfined and highly confined aquifers. By calculating the cone of depression the potential for vertical leakage is accounted for, and, by using a time of travel calculation the lateral extent of the wellhead protection area is limited to a reasonable size. The methods associated with the cone of depression approach will approximate the wellhead protection area calculated from the cone of depression/time of travel method for a semiconfined aquifer but can become very large for a highly confined aquifer. The cylinder method is a time of travel calculation which does not account for possible leakage and therefore considers all aquifers as highly confined. This may result in wellhead protection areas that are larger than needed.

The difference in size of the wellhead protection areas for semiconfined and highly confined aquifers can be demonstrated by using the three different methods to calculate a wellhead protection area for a hypothetical aquifer with: T = 50,000 gpd/ft, Q = 500 gpm, S = .0001, and leakage conditions that vary from highly leaky (P′ = 10 gpd/ft^2) to highly confined (no leakage). By using the cone of depression/time of travel method with a 40 yr threshold, the radius of the wellhead protection area ranges from 300 ft for the very leaky aquifer to 6,000 ft for the highly confined aquifer with most of the radius values from 2,500 to 6,000 ft for the more confining conditions (fig. 20).

The cone of depression methods create a wellhead protection area which may be significantly larger than one developed with the cone of depression/time of travel method. The radius of the cone of depression for a very leaky aquifer (P′ = 10 gpd/ft^2) is approximately 250 ft, whereas the radius of a cone of depression for a confined aquifer (no leakage) is greater than 20,000 ft (fig. 18). Calculated times of travel for the highly confined scenario from the outer edges of the cone of depression to the pumping well are greater than 10,000 yr, which is not realistic for implementing a wellhead protection area.

The calculated distance for 40-yr time of travel using the cylinder method is 6,000 ft for highly confined conditions, which is similar to the time of travel distance for the highly confined aquifer setting for the cone of depression/time of travel approach. The cylinder method, however, does not accurately calculate time of travel for the semiconfined condition, because the cylinder equation does not incorporate any leakage. WHPA (1.0) also calculates the 40-yr time of travel as 6,000 ft.

Calculation of Wellhead Protection Area for Wells in Confined Aquifers with a Regional Sloping Potentiometric Surface

In the previous section, the approaches for calculating wellhead protection areas assume that ground-water flow toward a well is dominated by well pumpage from an aquifer with a negligible initial potentiometric-surface gradient. Potentiometric surfaces in confined aquifers are typically characterized by very low gradients. Nevertheless, it is possible that steeper initial gradients can occur within confined aquifers and affect the shape of the cone of depression of a pumping well (fig. 24). The size and shape of the wellhead protection area is controlled by the regional hydraulic gradient, the aquifer transmissivity, and well discharge. For aquifers with regional potentiometric gradients between .0005 and .001 or greater wellhead protection area delineation methods that incorporate a sloping regional potentiometric surface should be considered (Todd, 1980; Bear and Jacob, 1965; Southern Water Authority, 1985).

There are two general approaches which incorporate an initial sloping potentiometric surface in estimating a wellhead protection area: (1) zone of contribution with the identification of flow boundaries and (2) zone of transport with time of travel contours which can be solved through solution of simple analytical equations or through computer application.

Zone of Contribution with Identification of Flow Boundaries Method

In this method, the zone of contribution is defined by flow boundaries within an aquifer. For a well pumping from an aquifer having a regional sloping potentiometric surface (fig. 24), the edge of the cone of depression on the down-gradient side will be relatively close to the well. On the up-gradient side, the transverse extent (in the Y-direction) of the zone of contribution increases asymptotically to a maximum, but the lateral extent (in the X-direction) extends infinitely, or until a hydrogeologic boundary is reached, in the up-gradient direction. The down-gradient null point and the maximum width of the zone of contribution can be solved analytically (Todd, 1980).

$$-\frac{Y}{X} = \tan\left(\frac{2\pi Kbi}{Q} Y\right) \qquad (11)$$

where X and Y are coordinates

Q = the pumpage rate at the well

K = hydraulic conductivity

b = the saturated thickness of the aquifer

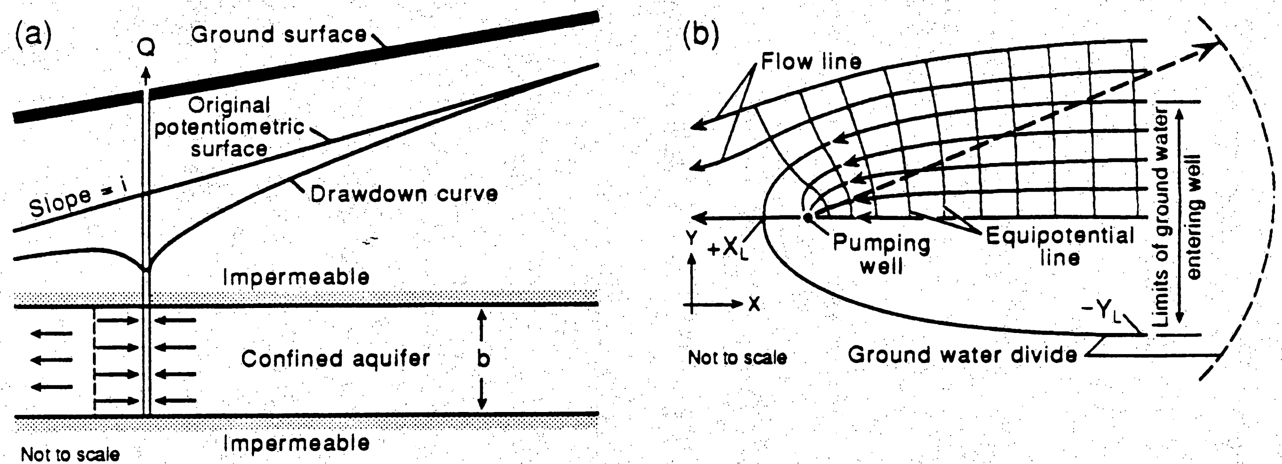
i = the hydraulic gradient of the initial, sloping potentiometric surface.

The down-gradient flow boundary (null point) is given by

$$X_L = -\frac{Q}{2\pi Kbi}. \qquad (12)$$

The transverse boundary limit is given by

$$Y_L = \pm\frac{Q}{2\pi Kbi}. \qquad (13)$$



Uniform-flow equation: $-\frac{Y}{X} = \tan\left(\frac{2\pi Kbi}{Q}Y\right)$

Distance to down-gradient null point: $X_L = -\frac{Q}{2\pi Kbi}$

Boundary limit: $Y_L = \pm\frac{Q}{2Kbi}$

Where: Q = Well-pumping rate
K = Hydraulic conductivity
b = Saturated thickness
i = Hydraulic gradient
π = 3.1416

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Figure 24. Ground-water flow field for cone of depression of a pumping well with a regional ground-water flow gradient. Uniform flow equation (Todd, 1980) can be used to calculate down gradient null point and lateral extent of zone of contribution.

The shape of the flow boundary can be calculated using equation (11), which can be solved by selecting Y values between zero and Y_L that are calculated from equation (13). However, no up-gradient flow boundary can be determined from these equations. The up-gradient boundary is generally selected to be the first hydrogeological boundary intersected by the zone of contribution or defined by a desired time of travel. The WHPA code, (Blanford and Huyakorn, 1990) described next, can also be used for calculating the shape of the flow boundary. Vertical leakage is not considered in equation (11), and so the welhead protection area using this method will be larger than it needs to be if there is significant vertical leakage.

Zone of Transport with Time of Travel Contours Approach

A zone of transport with time of travel contours can be calculated using three methods (1) the simple analytical solution method, (2) the semianalytical method, and (3) the time of travel reverse-path calculation method. All three methods calculate times of travel from which contours of equal time can be constructed.

Simple Analytical Solution Method

The time of travel for water to move along a line parallel to the hydraulic gradient, from a point to a pumping well, can be calculated from the following equation (modified from Bear and Jacob, 1965):

$$T_X = \frac{\Theta}{Ki}\left[X_L - \frac{Q}{2\pi Kbi}\ln\left(1 + \frac{2\pi Kbi}{Q}X_L\right)\right] \qquad (14)$$

where T_X = travel time from point X to a pumping well

Θ = porosity

X_L = distance from pumping well over which ground water travels in T_X (time); X_L is either positive or negative depending on whether point x is up gradient (+) or down gradient (–) of the pumping well

Q = discharge

K = hydraulic conductivity

b = aquifer thickness

i = hydraulic gradient

This equation is similar to that used by the Southern Water Authority (1985), which is included in the Environmental Protection Agency's general guidelines for delineating wellhead protection areas (U.S. Environmental Protection Agency, 1987).

The equation permits the calculation of the travel time from a given point to a pumping well. Calculation of travel distances for specific travel times have to be solved by trial and error but can be easily accomplished through the use of a spreadsheet program with a microcomputer. Travel distances and travel times can only be calculated along a line through the pumping well parallel to the regional hydraulic gradient. Complete delineation of the wellhead protection area around a well in an aquifer with a regional sloping potentiometric surface requires computer solution. The simple analytical solution method for determining a wellhead protection area does not account for any vertical leakage through an overlying aquitard if the aquifer is semiconfined. Therefore, as with the cylinder approach for confined aquifers with low regional potentiometric surfaces having negligible gradients, the calculated extent of the wellhead protection area should be considered larger than needed.

The best use of this equation may be for determining the importance of the regional potentiometric gradient on the shape of the wellhead protection area and whether the delineation of wellhead protection areas should be made with techniques that allow for a regional potentiometric surface with a non-negligible gradient. The ratio of the distance of ground-water travel in the down-gradient direction to that in the up-gradient direction for the same time of travel indicates how noncircular the wellhead protection area will be. As the shape of the wellhead protection area approaches a circle, the influence of the regional hydraulic gradient on times of travel becomes insignificant.

Semianalytical Method (WHPA Model)

WHPA is an integrated semianalytical model for delineation of wellhead protection areas (fig. 23) (Blanford and Huyakorn, 1990). WHPA is appropriate for calculating time of travel contours for confined aquifers with regionally sloping potentiometric surfaces. It is recommended in preference to the simple analytical solution described above because among other reasons the complete time of travel contours can be calculated, and not just at points along a line intersecting the well and parallel to the regional-flow gradient.

Reverse-Path Calculations Method

The time of travel from reverse-path calculations can be made with a regional potentiometric gradient or with a negligible hydraulic gradient. A more detailed description of the method is included on page 67.

Comparison of Methods

The zone of contribution method defines ground-water flow boundaries, but does not provide an up-gradient limit for a wellhead protection area. It provides a relatively simple method for defining a wellhead protection area and up-gradient boundaries can be determined by other methods.

A wellhead protection area can be calculated from the simple analytical solution method for travel times. The equation however limits travel time calculations to a down-gradient point and an up-gradient point along a line through the well and parallel to the regional flow gradient. The complete wellhead protection area cannot be delineated.

The WHPA computer program, a semianalytical solution for travel times, can be used for calculating wellhead protection areas. It provides a better approximation of the wellhead protection area than either the zone of contribution or simple analytical approach because it provides a complete areal delineation of the wellhead protection area.

Only the WHPA (2.0) computer code accounts for potential vertical leakage in semiconfined aquifers. Significant vertical leakage will cause wellhead protection areas to be smaller; therefore, any method that does not account for vertical leakage will result in a larger, that is, more conservative, wellhead protection area. (The WHPA code [2.0] that incorporates leakage was not available in time to be tested for this document.)

Reverse-path calculations provide the most sophisticated delineation of a wellhead protection area. The method requires two steps, (1) calculation of the regional potentiometric surface with a numerical flow model (this step accounts for vertical leakage) and (2) calculation of the reverse paths with a second code. Reverse-path particle tracking provides a more accurate delineation of the wellhead protection area than any other method, but may be more complicated than necessary for the delineation of many wellhead protection areas in confined aquifers.

CHAPTER 6. WELLHEAD PROTECTION AREAS FOR SEMICONFINED AND HIGHLY CONFINED AQUIFERS

Different permeability pathways are anticipated for semiconfined and highly confined aquifer settings and determining the locations of these pathways is important for both types of aquifers. The locations of these pathways should be given a higher level of wellhead protection, because they are the most probable zones where contamination may enter the aquifer.

Permeability Pathway Criteria for Semiconfined Aquifers

In the case of the semiconfined aquifer, there is, by definition, significant leakage through the aquitard. The potential for leakage is considered to be areally distributed across the wellhead protection area (fig. 25). The geologic and artificial penetration mapping techniques described in a previous section on defining confinement (Chapter 4) are recommended for describing the nature of leakage and mapping of possible leakage zones. If specific zones of leakage cannot be identified, then the entire wellhead protection area should be considered sensitive to the leakage of contaminants. Because the presumption of widespread leakage leads to a high level of protection throughout the wellhead protection area, identification of specific points or zones of leakage may be less critical than identification of potential contaminant sources.

Permeability Pathway Criteria for Highly Confined Aquifers

In contrast, the highly confined aquifer has essentially no or negligible, leakage through the aquitard. Nevertheless, minor leakage that cannot be identified from pumping tests may be important if it occurs through discrete high-permeability pathways (such as faults or wellbores) (fig. 26). Mapping geologic and artificial penetrations is recommended for describing the nature of leakage and for identifying possible leakage. For the highly confined setting, the potential for contamination of

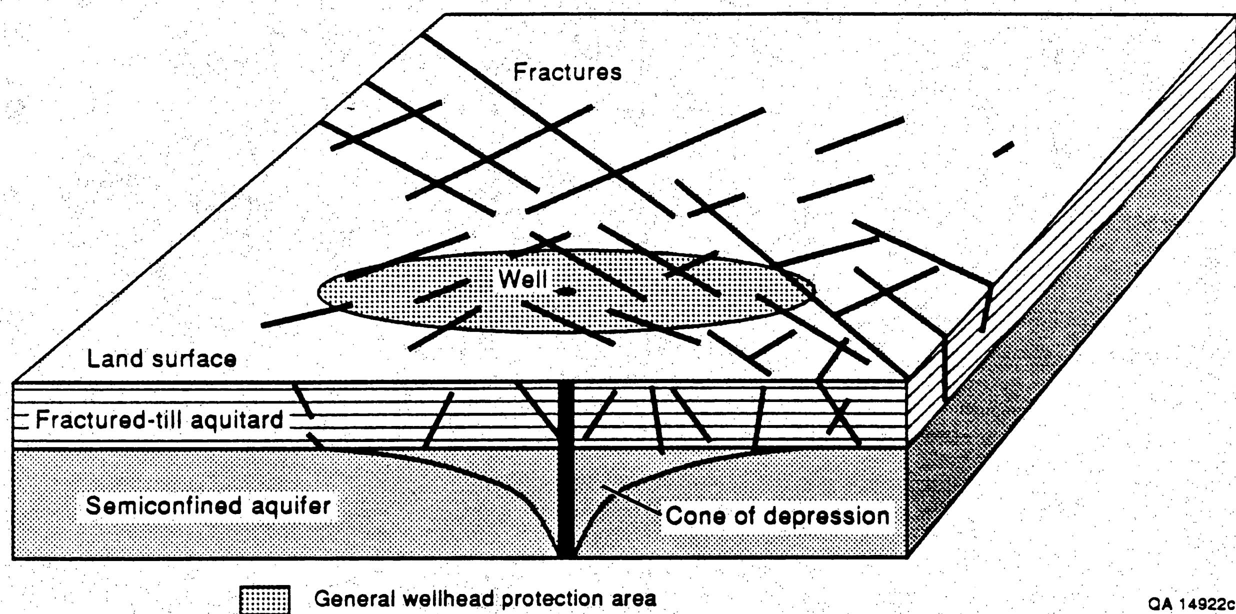

Figure 25. Schematic of areally distributed permeability pathways for semiconfined aquifer. Example is of a fractured till aquitard, which causes semiconfinement and an areally extensive potential for surface contamination. A wellhead protection area should include all the area within the circle.

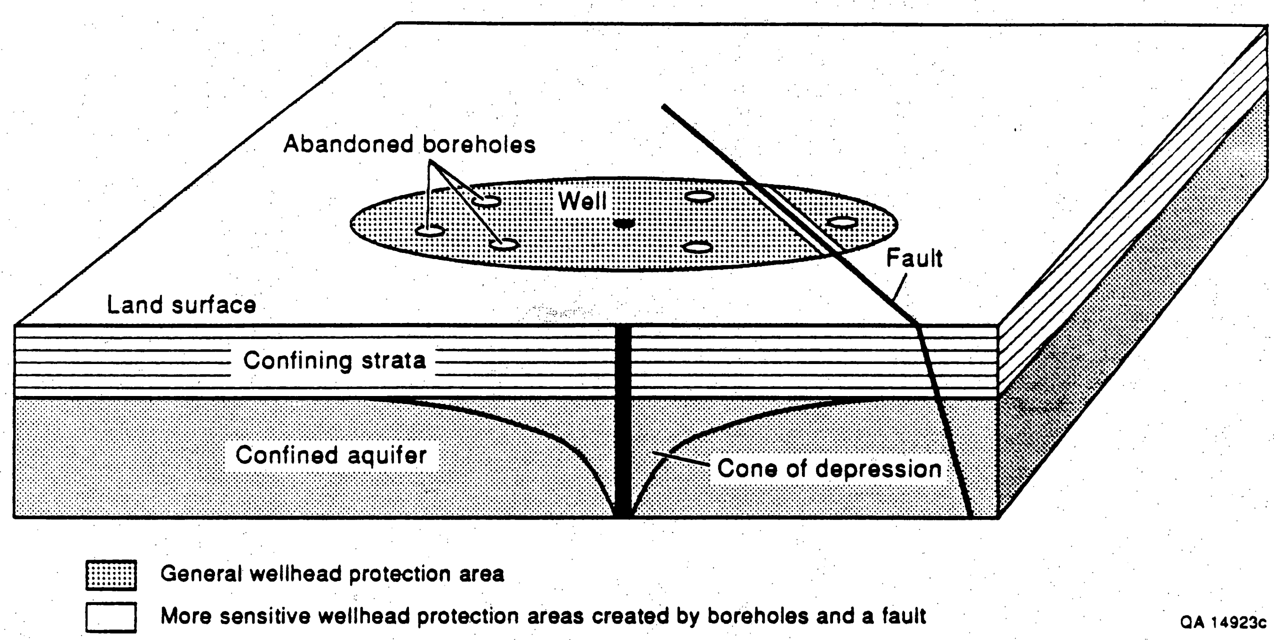

Figure 26. Example of wellhead protection area for highly confined aquifer where penetration of confinement has only occurred with abandoned boreholes and a fault.

well water is considered to be lower than for leaky aquifers. Potential pathways such as faults, fractures, and boreholes may have to be treated as highly restricted zones. Abandoned and unplugged boreholes may have to be sealed.

CHAPTER 7. CALCULATION OF WELLHEAD PROTECTION AREAS FOR WELL FIELDS

The previously described methods for calculating a wellhead protection area are based on the assumption of a single well. More complex configurations of wells occur and should be considered for wellhead protection. Three scenarios are considered. (1) Well fields where pumping wells have interfering cones of depression, (2) well fields where individual wells are screened at different intervals and cones of depression do not interfere, and (3) well fields where individual wells are screened in different aquifers, the shallower aquifer is semiconfined and the deeper aquifer is confined.

(1) Well fields in which pumping wells have interfering cones of depression. Ground water pumpage from multiple wells may result in a composite cone of depression that is deeper and wider than individual cones of depression and noncircular. Calculation of a wellhead protection area for a well in an aquifer with a negligible regional gradient should still be based on a cone of depression/time of travel approach. However, this calculation will probably require the use of numerical models that calculate the cone of depression and then time of travel contours to accurately assess the more complex area of time of travel. The wellhead protection area semianalytical solution and the reverse-path codes are appropriate. The WHPA code and other reverse-path codes are also the most appropriate methods for calculating wellhead protection areas for sloping regional potentiometric surfaces because they more accurately portray the interaction between well field hydraulics and the sloping regional potentiometric surface.

(2) Well fields in which individual wells are screened at different depth intervals and cones of depression do not interfere. The wellhead protection area should be based on the composite areas calculated for each well, using one of the previously described approaches (fig. 27). The problem is not so complex that a numerical model has to be used, since the cones of depression do not interfere; they only overlap.

(3) Well fields in which individual wells are screened in different aquifers, the shallower aquifer is semiconfined and the deeper aquifer is highly confined. The total wellhead protection area

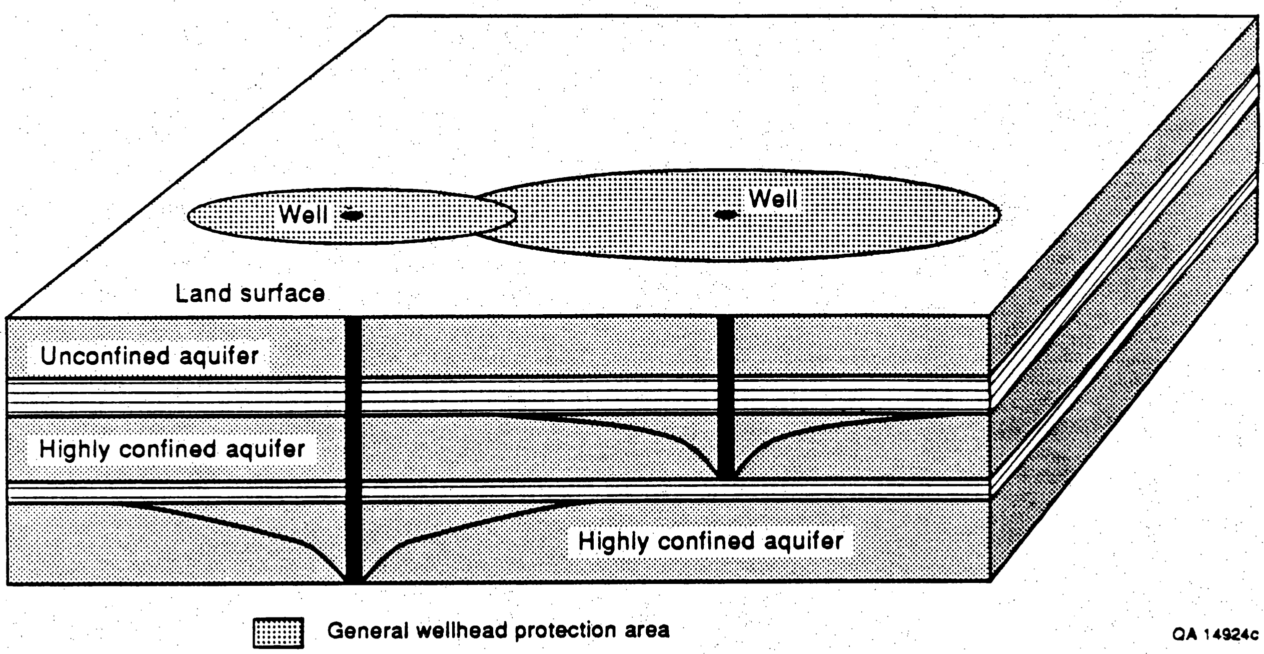

Figure 27. Example of overlapping wellhead protection areas for two wells in different confined aquifers. Total wellhead protection area is the composite area for the two wells. Cones of depression are overlapping but not interfering. Wellhead protection areas based on cone of depression.

should be the combination of the individual protection zones with each separate zone being protected according to its sensitivity to potential contamination (fig. 28).

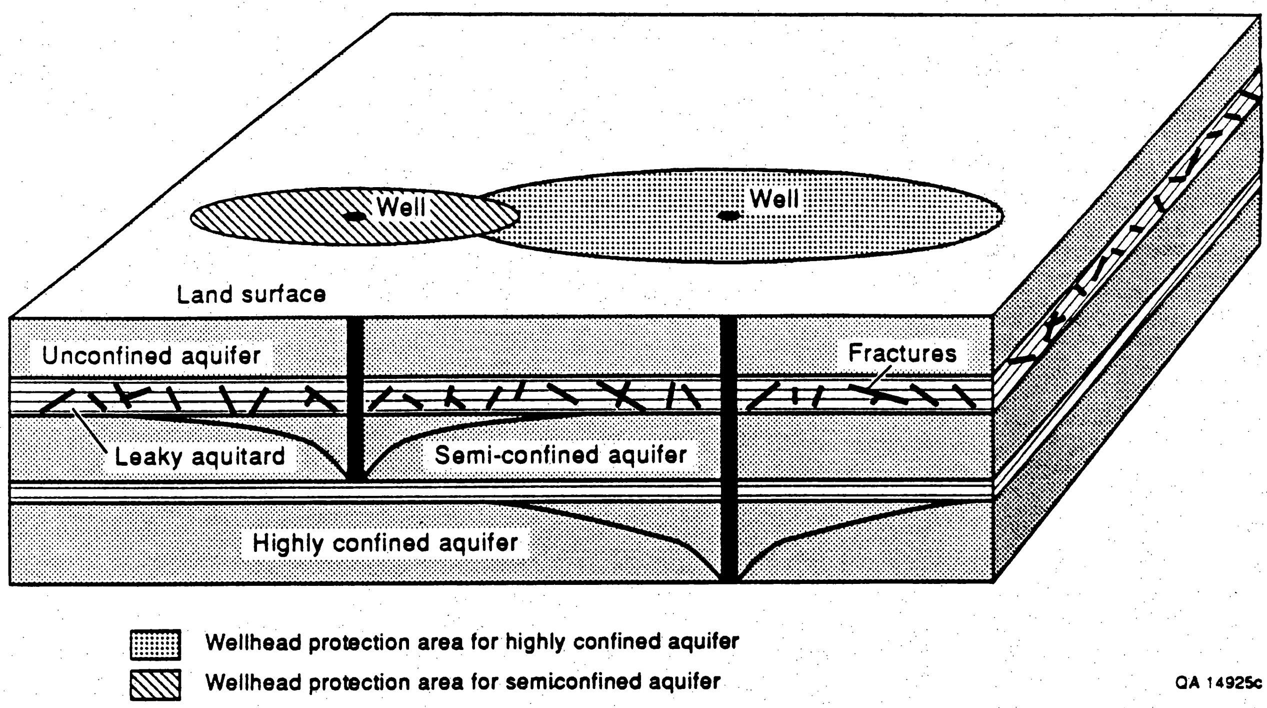

Figure 28. Overlapping wellhead protection areas based on cones of depression for a highly confined and a semiconfined aquifer. The protection area for more sensitive semiconfined aquifers is given the higher priority than the protection area of the highly confined aquifer where they overlap.

CHAPTER 8: EXAMPLES OF WELLHEAD PROTECTION STRATEGIES IN CONFINED AQUIFERS

The following examples describe the development of wellhead protection strategies for two confined aquifer settings. Wellhead protection areas were developed for two sites, one in Bastrop County and one in Wharton County, Texas (fig. 29), and are examples from the updip and the downdip sections, respectively, of a regional confined coastal aquifer. The examples are (1) to discuss assessing confinement and (2) to discuss determining a wellhead protection area. Evaluating the different criteria permits the decision on the degree and type of confinement. On the basis of this decision, a wellhead protection area delineation strategy is presented for each of the two examples. The development of wellhead protection areas for Bastrop and Wharton Counties is presented in detail in Appendix 1 to show the complexity of the process.

Bastrop, Texas

Example from the Updip Section of a Confined Aquifer

The first wellhead protection example is a well field in Bastrop County, Central Texas, located in the outcrop of the Wilcox aquifer. The well field is located about 5 mi north of the City of Bastrop and south of the Camp Swift Military Reservation (fig. 30). The well field consists of two active wells, 516 and 515, as well as eight inactive and abandoned wells. The well field is bounded to the south and west by a Federal Prison Facility, to the north by the University of Texas Cancer Research Institute, and to the east by a trailer park and small industrial park. Within one mile to the west of the well field, the Lower Colorado River Authority operates a medium-sized open-pit lignite mine. The Camp Swift well field is operated by the Aqua Water Supply Corporation, a local water cooperative, which supplies water to the town of Bastrop and rural areas in Bastrop, Lee, and Milam Counties for a population of about 20,000. The well field is located within the outcrop area of the lower Eocene Wilcox Group, which is comprised of three formations, (1) the Hooper Formation, (2) the Simsboro Formation, and (3) the Calvert Bluff Formation. The Simsboro Formation consists of relatively sand-

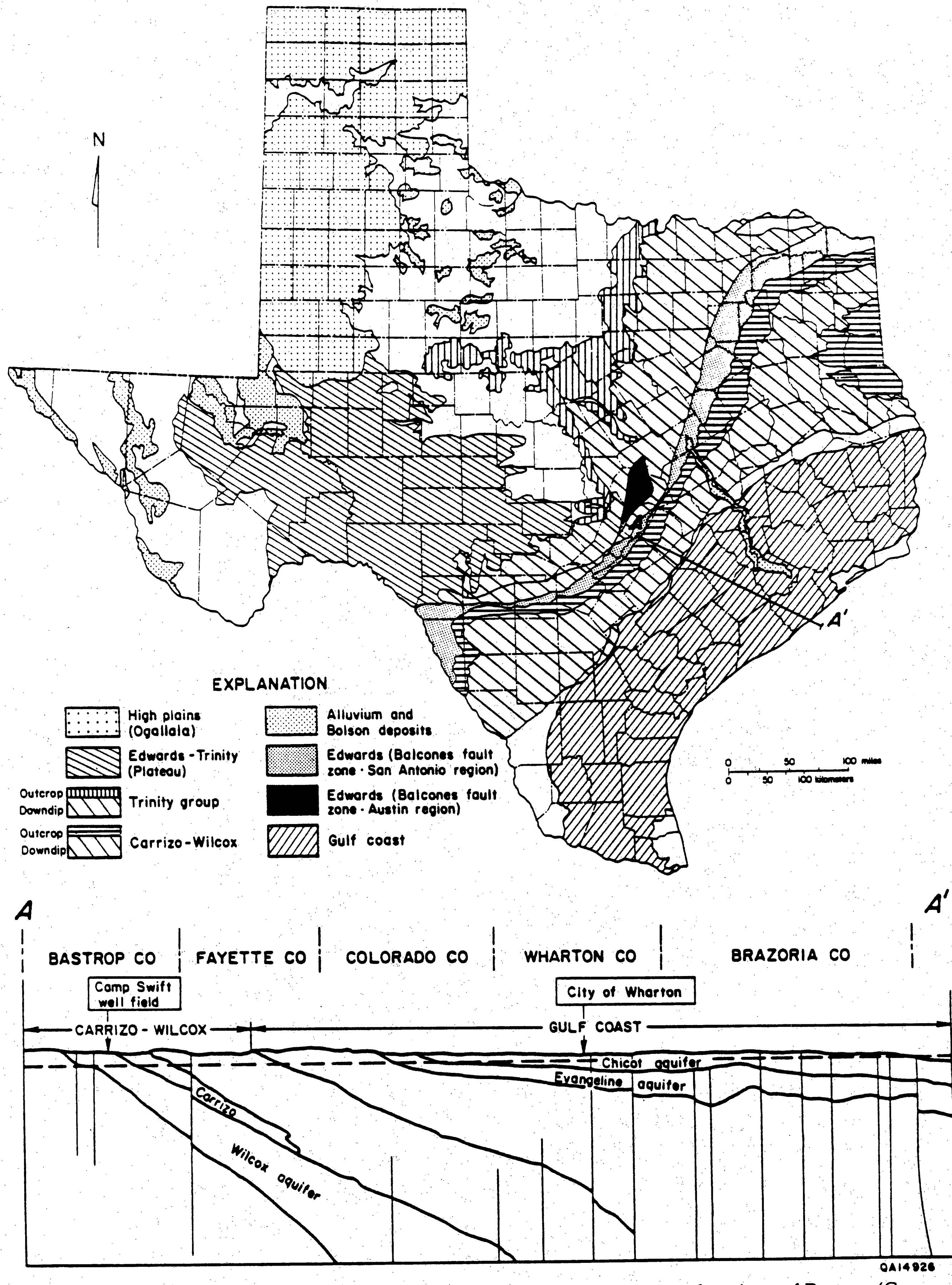

Figure 29. Geologic map and cross section of the Gulf Coast area, showing locations of Bastrop (Camp Swift well field) and City of Wharton.

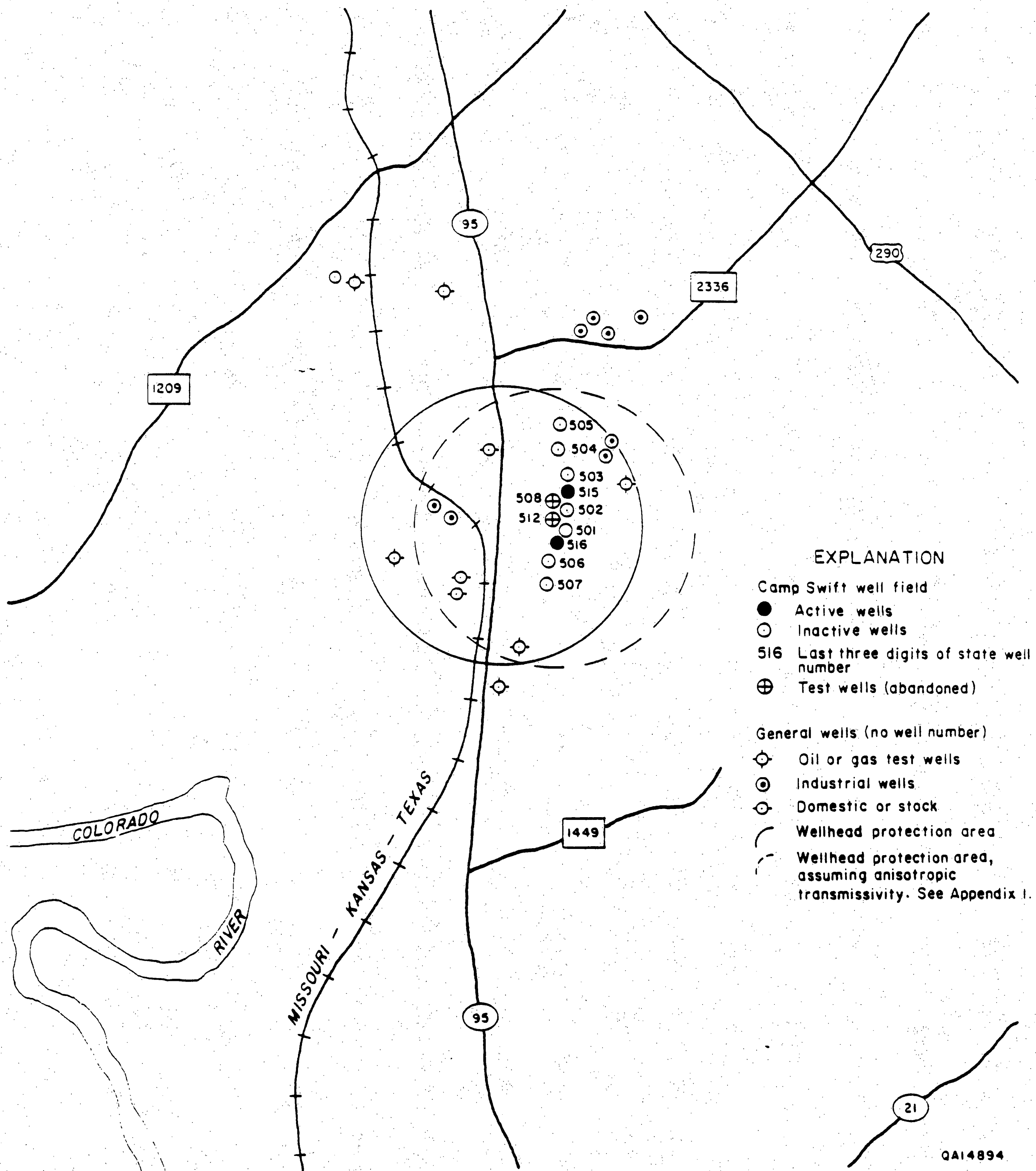

Figure 30. General highway map of Bastrop County showing the location of the Camp Swift well field and wellhead protection area for wells 515 and 516. The wellhead protection area defined by the dashed line is based on the anisotropic conditions observed during modeling. Appendix 1 provides a detailed description.

rich fluvial deposits and is the main waterbearing unit in the area. The recharge area for the Simsboro is along a 1- to 3-mi-wide outcrop belt which is about 2 mi west of the well field.

The wellhead protection area delineation strategy for this particular setting followed the steps outlined above and is discussed in detail in Appendix 1. The first step, determining the presence and/or degree of confinement was based on evaluation of geologic, hydrologic, and hydrochemical criteria. The Camp Swift well field was considered highly confined and has a low probability of contamination. The main indications were the presence of overlying shale strata, the absence of any tritium, relatively old ^{14}C ground-water ages, and the highly confined response from the aquifer tests.

The second step, delineating the combined wellhead protection areas for the two producing wells, 515 and 516 of the Camp Swift well field, follows the different approaches given above and is described in detail in Appendix 1. The recommended wellhead protection area is an approximate circle with a radius 6,000 ft, and is based on a 40-yr threshold and the time of travel approach for the two producing wells as shown in figure 30. Within the 40-yr capture zone, local higher protection zones are recommended in the vicinity of the main pathways for potential contamination. These pathways are considered to be localized, such as abandoned boreholes and existing wells.

Wharton, Texas

Example from the Downdip Section of a Confined Aquifer

The second wellhead protection example is a well field in the City of Wharton, Wharton County, Texas, located in the Gulf Coastal Plain of southeastern Texas (fig. 29). The well field is located in the downdip section of the Gulf Coast aquifer, a regionally extensive coastal plain aquifer. The City of Wharton is about 60 mi west of Houston and about 50 mi north of the coast of the Gulf of Mexico. The city water wells, serving approximately 70,000 people, are located on empty lots throughout the city (fig. 31). In particular, a wellhead protection area is designed for City of Wharton well 3, (also referred to as 406).

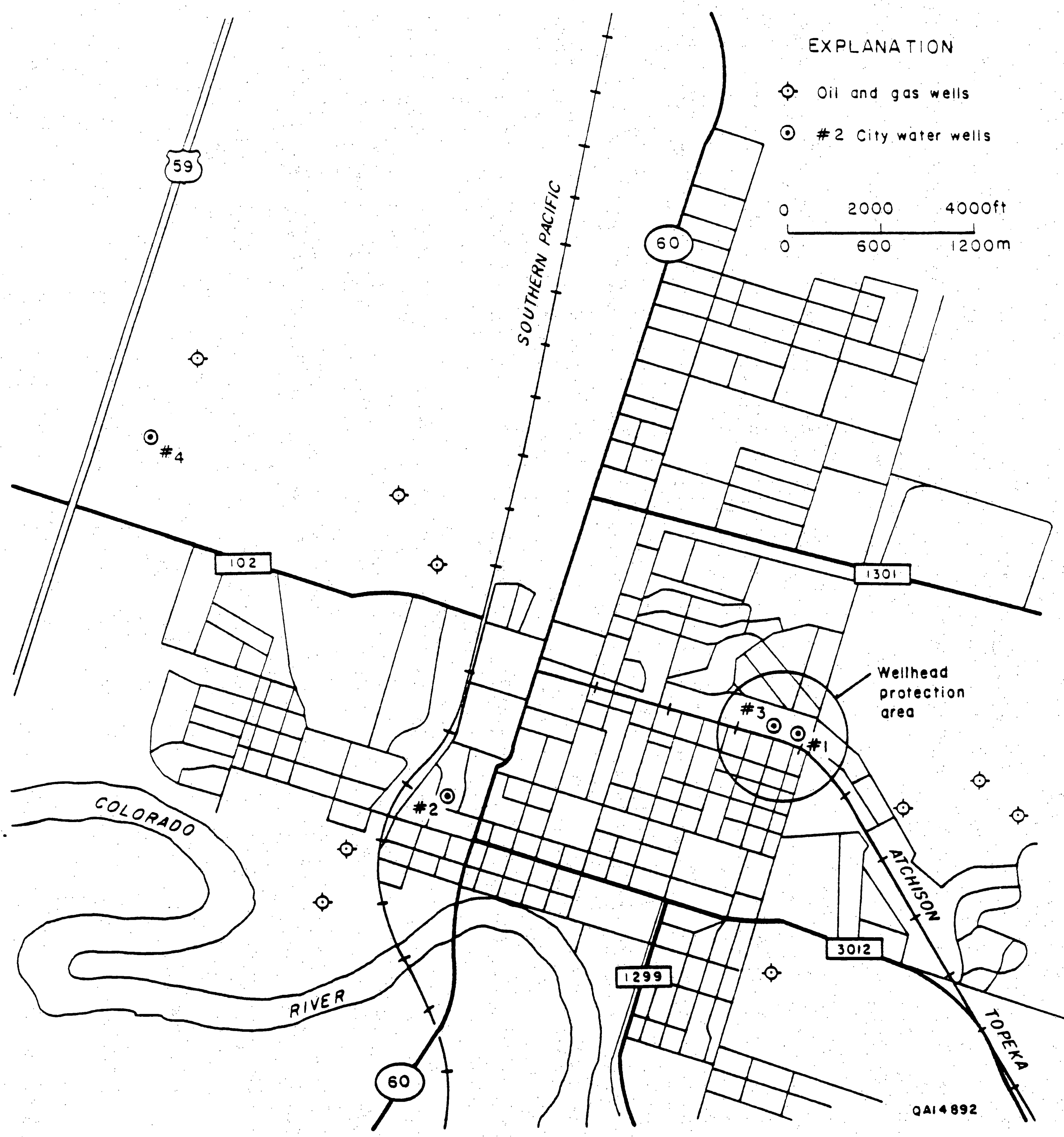

Figure 31. Map of Wharton, Texas, and vicinity, showing wellhead protection area for city of Wharton well no. 3 (well 406).

In Wharton County, the main hydrogeologic units consist of Pleistocene and Pliocene sequences of gravel, sand, silts, and clay. All Gulf Coast formations thicken toward the coast and crop out in belts that are nearly parallel to the shoreline. The wells produce from the Chicot aquifer from a depth of about 600 to 900 ft below sea level. The Chicot aquifer is overlain by a thick sequence of mostly clays (Beaumont Clay) which is considered the confining unit for the underlying Chicot aquifer. The Willis Sand is the major waterbearing unit of the Chicot aquifer, which crops out about 30 mi northwest of the City of Wharton. The outcrop area is the main recharge area.

The development of a wellhead protection area delineation strategy followed two steps, (1) determining the degree of confinement, and (2) delineating the wellhead protection area. Based on geologic, hydrologic, and geochemical criteria, discussed in detail in Appendix 1, ground water in well 406 is considered highly confined. Although pumping-test data indicate leaky behavior, leakage is interpreted to come from overlying and underlying sands, which were not screened. The old ^{14}C ground-water ages and absence of detectable tritium indicate very old ground water. The overall vertical hydraulic head distribution indicates a downward gradient; however, vertical permeability of the confining units is very low, preventing significant fluid movement. The recommended wellhead protection area for well 406 (fig. 31) is a circular area with a radius less than 1,000 ft and is based on the cone of depression/time of travel approach using a 40-yr threshold. Within this general area, the main pathways for contamination are abandoned boreholes and existing wells.

Comparison of Wellhead Protection Areas for the Two Examples

The delineated wellhead protection areas for Bastrop and Wharton, Texas show some differences owing to their different hydrogeologic settings.

In the Bastrop area the wells are within a highly confined aquifer with a measurable regional hydraulic gradient. This results in a slightly noncircular wellhead protection area with a radius of about 6,000 ft.

In the Wharton area the well is located in a highly confined aquifer setting with a negligible horizontal hydraulic gradient. Pump-test data indicate significant leakage, but the leakage is from adjacent overlying or underlying sands and not from shallow ground-water sources. The wellhead protection area is a circle with a radius of less than 1,000 ft.

The ground water in both locations is old. The highest priority areas for protection within the general wellhead protection area are those containing artificial penetrations.

CHAPTER 9: RECOMMENDED APPROACH FOR DEFINING WELLHEAD PROTECTION AREAS FOR CONFINED AQUIFERS

The recommended approach for defining wellhead protection areas for confined aquifers is as follows, and is diagrammed as a flow chart (fig. 32):

(1) The nature of confinement of the aquifer is considered to be either unconfined, or confined,

(a) If the aquifer is unconfined, recharge to the aquifer is considered pervasive. A wellhead protection area delineation strategy is developed based on the techniques in EPA's general guide: *Guidlines for Delineation of Wellhead Protection Areas* (U.S. Environmental Protection Agency, 1987).

(b) If the aquifer is confined, one should determine whether it is a semiconfined or highly confined system through methods that calculate a time of travel. A 40-yr vertical time of travel is suggested, but other time periods may be more appropriate for specific well settings. If the aquifer is semiconfined, the aquifer is overlain by a leaky aquitard in which leakage is assumed to be areally distributed throughout, in addition, there may be localized leakage through fault zones and boreholes. If the aquifer is highly confined, the aquifer is overlain by a nonleaky aquitard, and the only potential points of leakage are through discrete permeability pathways such as faults, fracture zones, and abandoned boreholes.

(2) The prepumping gradient of the regional potentiometric surface is determined. As a rule of thumb, if the regional gradient is 0.0005-0.001 or greater, it may affect the size and shape of the wellhead protection area. The impact of the regional gradient on the shape of the wellhead protection area can be estimated with equation (14). If the gradient is less than 0.0005, the size of the wellhead protection area will be controlled by the hydraulics of the pumping well.

For either scenario, a time of travel delineation criterion is recommended. For the scenario with a very low regional hydraulic gradient, assuming some degree of confinement, the time of travel calculation can be made with either the cone of depression/time of travel or the cylinder methods. If the necessary data are available, the cone of depression/time of travel method is recommended in

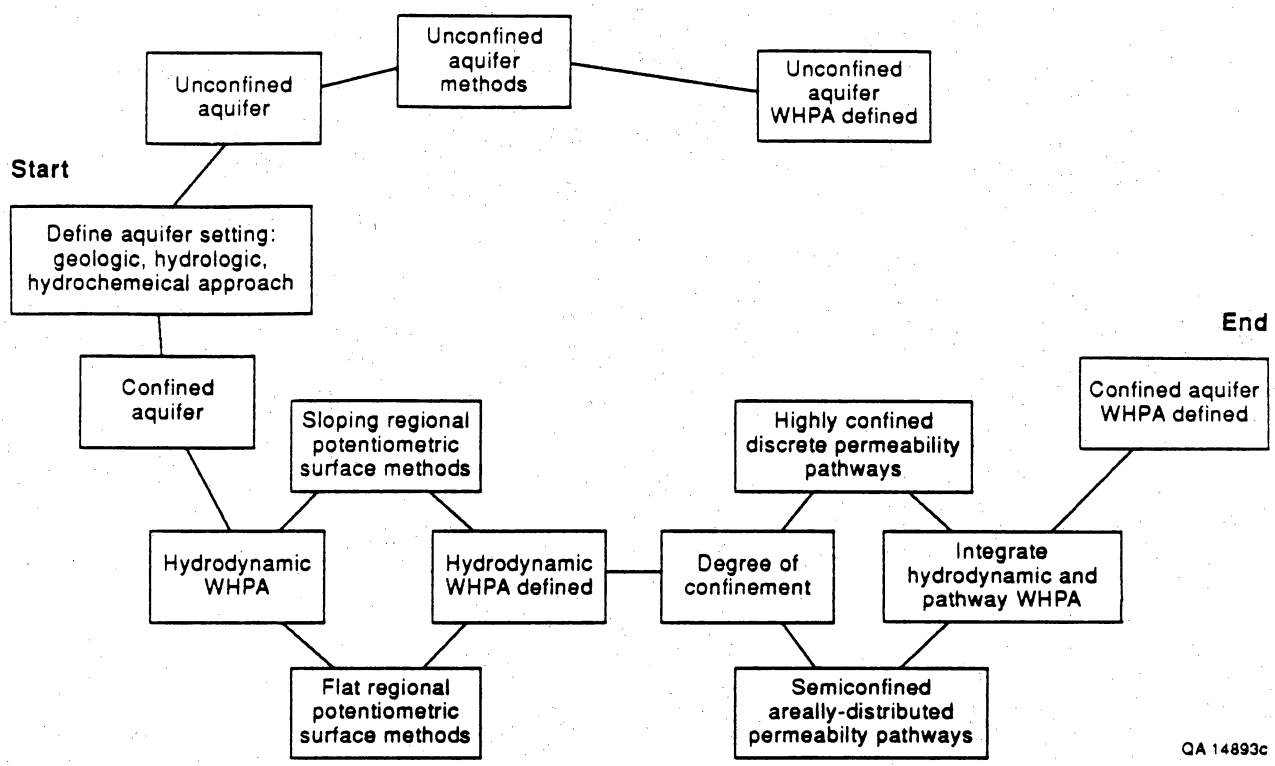

Figure 32. Flow chart for designing wellhead protection areas for confined aquifers.

preference to the cylinder method. For the scenario with a regional hydraulic gradient that could cause a noncircular wellhead protection area, one of the methods recommended for a sloping potentiometric surface should be used.

(3) After the general wellhead protection area is delineated, a permeability pathway map is made. This map defines the zones of potential, natural and artificial pathways through the aquitard, and is important to management of activities in the wellhead protection area. High-permeability pathways are distinguished to allow more protective measures to be taken in the more sensitive areas.

(a) For semiconfined aquifers, where significant leakage through the aquitard occurs, the entire regional area of the wellhead protection area should be considered as having a potential for vertical leakage.

(b) For the highly confined aquifer, the location of natural and artificial zones of leakage to the aquifer are of prime concern, because they represent the only pathways for contaminants to reach the producing aquifer.

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APPENDIX 1

COMPARISON OF WELLHEAD PROTECTION AREAS

TWO EXAMPLES

Bastrop, Texas

Example from the Updip Section of a Confined Aquifer

The first wellhead protection example for confined aquifers is the Camp Swift well field in Bastrop County, Central Texas (fig. 29). The well field (fig. 30) is located about 5 mi north of the City of Bastrop and south of the Camp Swift Military Reservation. The well field consists of two active wells and eight inactive and abandoned wells. Specifically, wellhead protection areas have been established for wells 516 and 515 (fig. 30); well 516 is the main water supply well and produces from an approximate depth of 500–700 ft, and well 515 is used as backup during high demand in the summer months and produces from a shallower depth of approximately 250–550 ft. The Camp Swift well field is operated by the Aqua Water Supply Corporation, a local water cooperative which supplies water to the town of Bastrop and to rural areas in Bastrop, Lee, and Milam Counties, Texas, for a population of approximately 20,000. The well field is bounded to the south and west by a Federal Prison Facility, to the north by the University of Texas Cancer Research Institute, and to the east by a trailer park and small industrial park. Within 1 mi to the west of the well field, the Lower Colorado River Authority operates a medium-sized open-pit lignite mine.

Hydrogeologic Setting

The area is characterized by a dry, subhumid climate with an annual precipitation of about 36.7 inches, which is less than the average annual potential evaporation (Follett, 1970). The topography is characterized by gently rolling to undulating hills with generally less than 150 ft of relief.

The area is in the updip part of the Gulf Coast Sedimentary Basin, a thick wedge of sedimentary rocks, ranging in age from Cretaceous to Quaternary. Ground water is produced from the Wilcox aquifer, which is composed of fluvial, deltaic, and marine deposits of Eocene age. The Wilcox strata crop out in broad parallel bands that trend to the northeast and dip gently to the southeast at approximately 2 to 3 degrees (fig. 33).

The well field is located within the outcrop area of the lower Eocene Wilcox Group, which is comprised of three formations, (1) the Hooper Formation, (2) the Simsboro Formation, and (3) the Calvert Bluff Formation. The Simsboro Formation consists of relatively sand-rich fluvial deposits and is the main waterbearing unit in the area. The recharge area for the Simsboro is along a 1- to 3-mi-wide outcrop belt that is about 2 mi west of the well field. Several faults have been identified in the vicinity of the Camp Swift area, but are relatively minor and probably have no influence on the regional ground-water flow regime.

Determining Confinement

The degree of confinement of the Camp Swift well field has been evaluated using geologic, hydrologic, and hydrochemical criteria described in earlier chapters. Only a limited number of methods were found appropriate, and they are discussed below.

Geologic Approach

1. Geologic Map and Cross Section

The Camp Swift well field is located on an outcrop of the Calvert Bluff Formation, the uppermost unit of the Wilcox Group (fig. 33). The Calvert Bluff Formation consists of fine- to coarse-grained sands and sandstones, interbedded with clays and mudstones and is generally less than 500-ft thick in the area. In general, this formation produces small amounts of water for domestic and livestock uses. The underlying Simsboro Formation, the main waterbearing unit of the Wilcox, consists of fine- to coarse-grained sands with smaller amounts of interbedded clay and mudstones and ranges in thickness from about 100 to 300 ft. Most of the wells in the area and all of the wells at the Camp Swift well field are completed in the Simsboro.

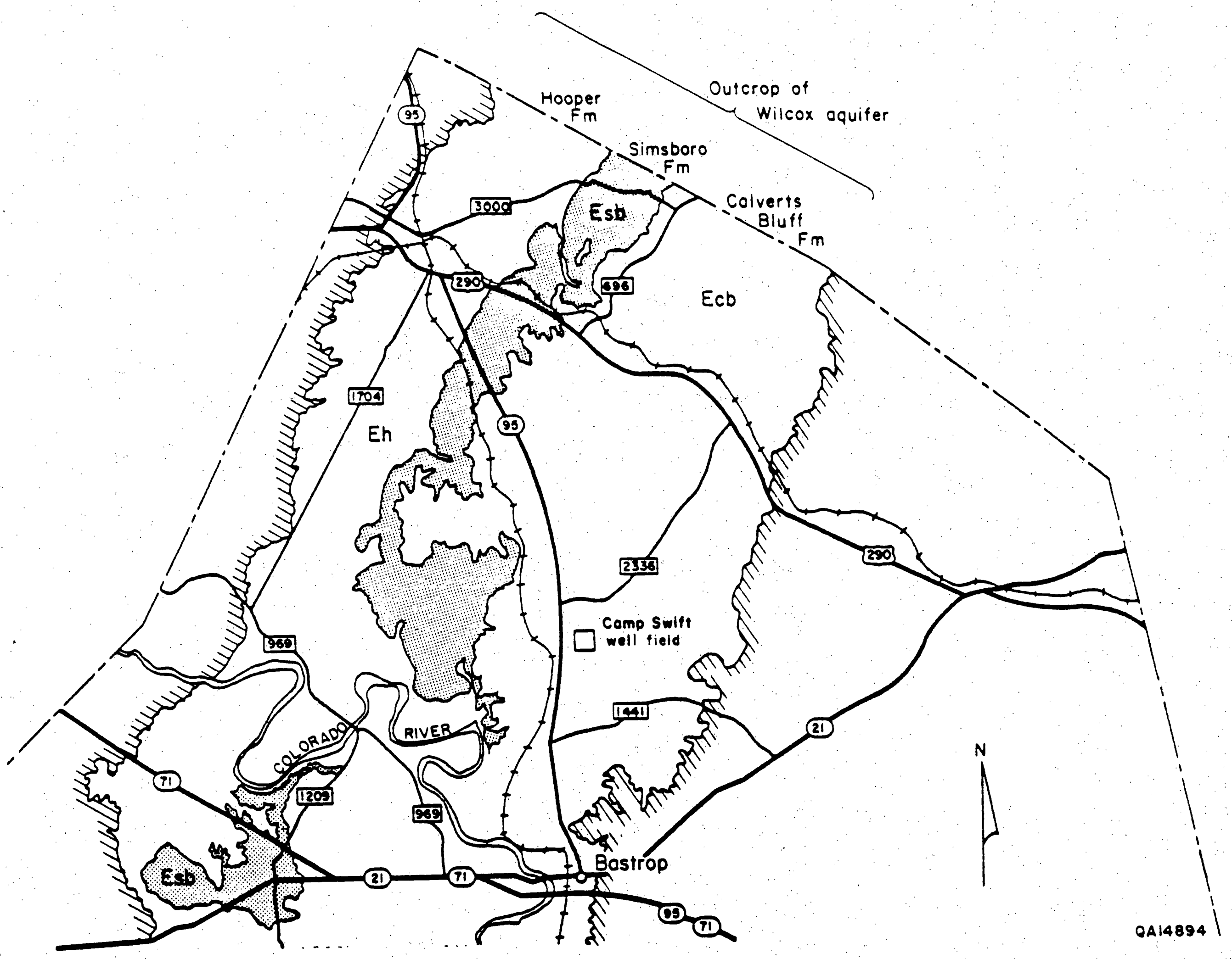

Figure 33. Geologic map of outcrop of Wilcox Group, Bastrop, Texas (Barnes, 1974).

The subsurface distribution of sand and shales is depicted along a cross section through the north-south oriented wells (fig. 34) based on driller's logs. The upper section is dominated by shales, whereas the deeper section is sand-rich and is the producing zone of the different wells. Although it is difficult to correlate the sand geometry across the section, the uppermost shale section, as much as 300-ft thick, appears to be continuous throughout the well field and indicates a relatively thick, confining aquitard on top of the producing aquifer. The presence of this thick, low-permeability layer shown on the geophysical and driller's logs is not evident from surface geologic maps.

Although the Camp Swift well field is located on a Wilcox outcrop, the Calvert Bluff Formation, which is considered regionally a minor aquifer, may act as a confining or semiconfining unit for the aquifer unit (Simsboro Formation) due to abundant clay and shale layers within the Calvert Bluff.

2. Other Mapping Methods

Henry and Basciano (1979) developed environmental geologic maps for the Wilcox Group of East Texas that identify areas of critical natural resources, such as aquifer recharge areas and areas of natural hazards such as flood-plain areas. The Camp Swift well field is located in a moderate-relief, sandy mud-oak forest, with shallow geology characterized by interbedded sand and mud and muddy sand. The general area of the well field is considered a recharge area; however, it is not as important a recharge area as the area to the west, corresponding to the outcrop of the Simsboro Formation.

The general soil map of Bastrop County (U.S. Soil Conservation Service, 1979) classifies the soil at the Camp Swift well field as Axtell fine sandy loam. This type of soil formed in clayey sediments interbedded in places with shale and sandstone. The soils have a loamy surface layer and low-permeability lower layer with high-water capacity. The soil characteristics suggest limited recharge potential.

Mapping artificial penetrations of the confining unit is crucial for the development of wellhead protection strategies. Abandoned boreholes are the most likely pathways for contaminants to migrate into a confined aquifer. Figure 30 denotes those known wells in the vicinity of the Camp Swift well field, including those which are abandoned and no longer used.

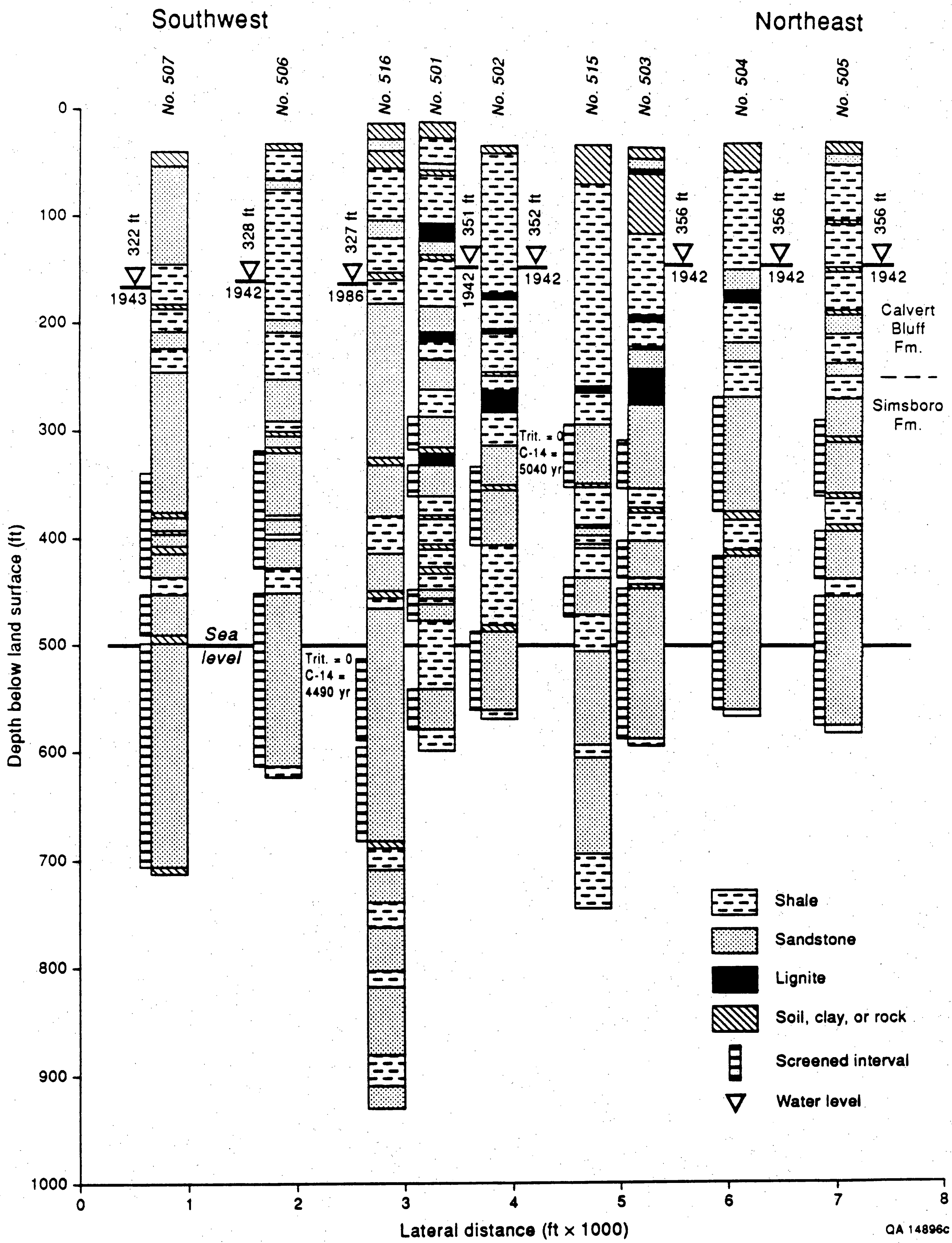

Figure 34. North-south cross section of driller's logs and geophysical logs at the Camp Swift well field.

Hydrologic Approach

1. Water-Level Data in Wells

Water-level elevations for the different wells in the well field are shown on figure 34. Water elevations are generally above the top of shale layers, indicating confined aquifer conditions. The regional potentiometric surface for Bastrop County, based on water-level measurements primarily of the Simsboro Formation, indicates a hydraulic gradient of 0.002 to the east-southeast in the general dip direction of the formations. This hydraulic gradient is typical for the outcrop region of regionally confined aquifers along the Gulf Coast.

The pattern of daily water-level variations from continuous water-level recorders can distinguish confined and unconfined aquifers. Continuous water-level records measured from well 505 show semidiurnal variations of approximately 1 inch and thus indicate confined conditions.

2. Pumping-Test Data

(a) Extent of the cone of depression

Water levels in observation wells, as far as 3,200 ft away from the producing well, drop during pumping. However, no water-level response was observed in well 502 during pumping of 516, which is located 1,800 ft away; the screened interval in 516 is somewhat deeper than those in the other wells (fig. 34), suggesting a lack of hydraulic communication between well 502 and well 516.

(b) Storativity

Calculated storativity values from the pumping test in the well field range between 0.0003 to 0.0005 with an average value of 0.0004 (Myers, 1969). These values are typical for confined aquifers in the Texas Gulf Coast.

(c) Leakage

In a confined or semiconfined aquifer, effects of leakage may be reflected in the drawdown curve during a pumping test. Drawdown in wells 503, 504, and 505 (fig. 35) from the pumping test in well 502 follow the typical Theis nonleaky curve (fig. 9), suggesting a highly confined condition.

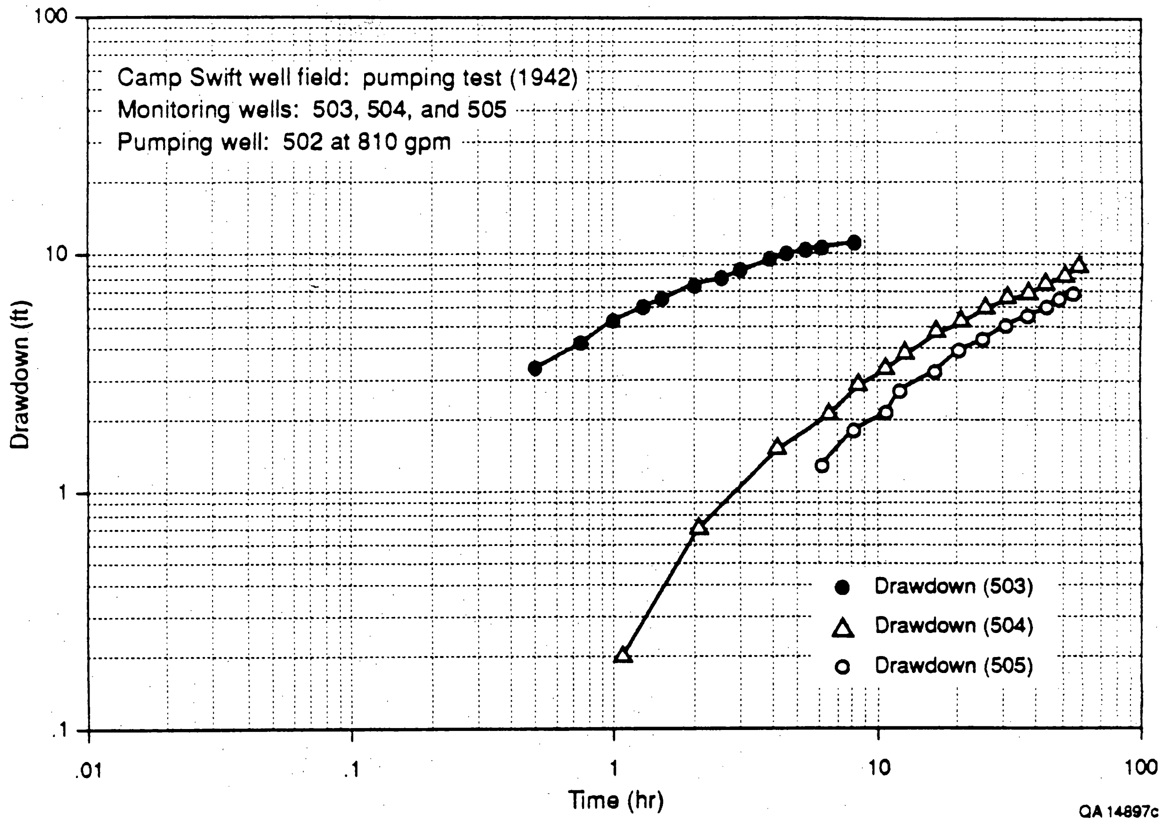

Figure 35. Log-log plot of drawdown versus time for monitoring wells 503, 504, and 505 during pumping test in well 502, Camp Swift well field.

In comparison, the pumping test in well 516 (fig. 36) indicates a relatively flat slope, more characteristic of leakage through an overlying aquitard. Note that the screened interval in well 516 is somewhat deeper than those of the other wells (fig. 34). Furthermore, relatively thick sands are shown above the screened intervals in well 516, which are separated from the screened sand interval by a relatively thin-shale layer. Consequently, leakage inferred from the pumping test in the deeper well 516 (fig. 36) apparently does not represent leakage from a shallow unconfined aquifer, but rather is leakage from a shallower sand layer of the confined aquifer that is not screened (fig. 34).

Hydrochemical Approach

1. General water chemistry

The chemical composition of ground water in a regionally extensive, confined sandstone aquifer typically shows a general change from a Ca-HCO_3 water in the shallow recharge sections to an Na-HCO_3 type for deeper ground water as a result of chemical reaction with aquifer rock. Thus, the general chemical composition of ground water can be used to infer the relative age of the ground water.

Figure 37 shows the distribution of hydrochemical facies in Bastrop County for the Wilcox Group aquifer. Those wells completed in the Simsboro Formation are marked separately. In the vicinity of the Camp Swift well field, the Ca-HCO_3-type water, a recharge-type water, extends relatively far downdip in the Simsboro. Toward the south, water in the Simsboro Formation is mostly a Na-HCO_3-type ground water, a water typical of older waters in a confined section. To the north, ground water shows a more complex facies distribution which is probably related to mixing of different waters and possibly different water-rock reactions. Although the water from the Camp Swift well field appears chemically to be recharge-type waters, the regional ground-water chemistry appears to be sufficiently complex to prevent a conclusion on the presence of confinement. A simple downdip evolution of ground water is not apparent.

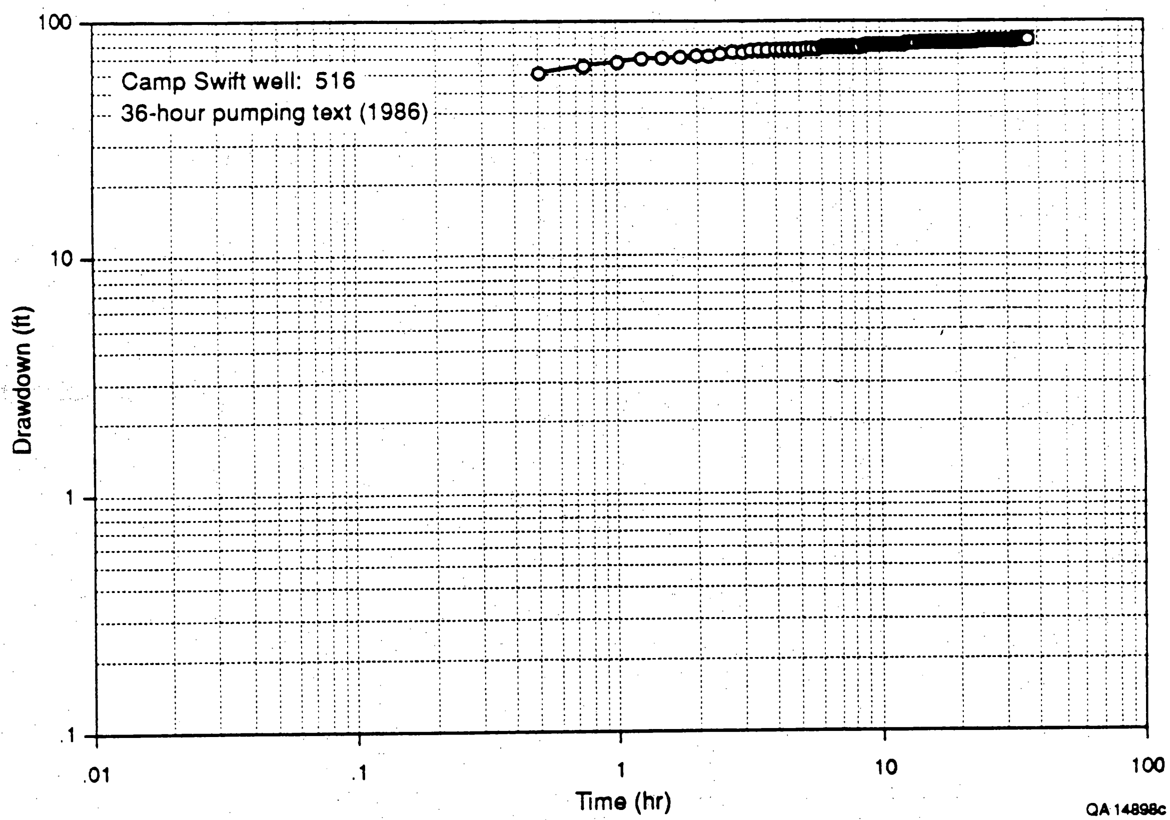

Figure 36. Log-log plot of drawdown versus time for pumping Camp Swift well 516 during 36-hr pumping test in 1986.

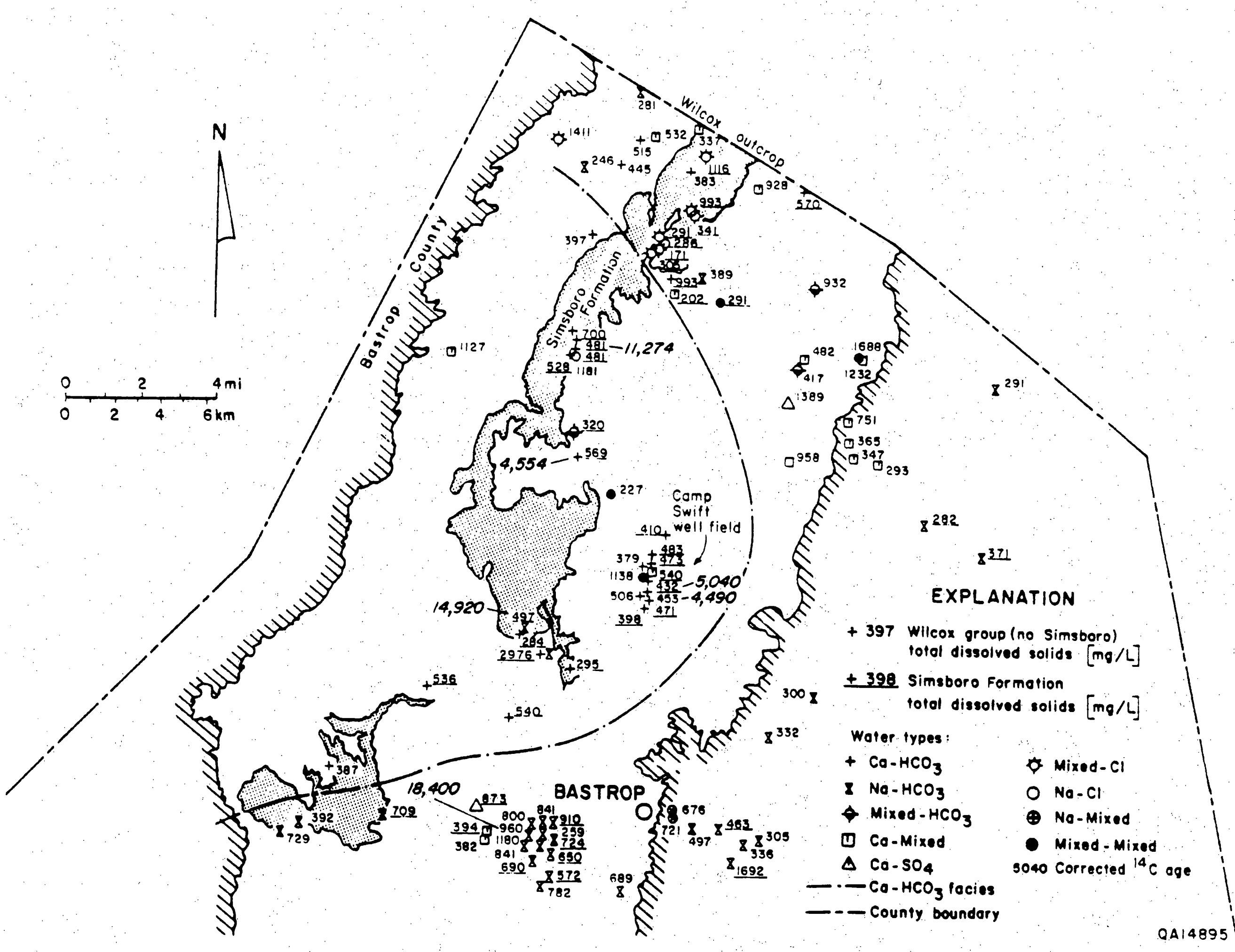

Figure 37. Distribution of hydrochemical facies and total dissolved solids and calculated carbon-14 ages for the Wilcox Group aquifer and Simsboro Formation.

Changes in the chemistry of water over time from a well may indicate vertical leakage through an overlying aquitard. At the Camp Swift well field, which has produced for almost 50 yr, no trends in variations of the chemical composition of ground water could be identified.

2. Carbon-14 age determination

Selected samples in the Bastrop area were analyzed for ^{14}C. Corrected ^{14}C ground-water ages, using the $\delta^{13}C$ approach (Pearson and White, 1967), range from about 4,490 yr to as much as 18,400 yr (figs. 34 and 37). The generally old age determined of the ground water in the area indicates a relatively long flow path from the recharge area to the well. Note that the Na-HCO_3-type ground water is much older than the Ca-HCO_3-type water.

3. Tritium

Tritium analyses performed on the same water samples (figs. 34 and 37) as those with ^{14}C analyses showed zero tritium concentration and indicate that the water is older than 40 yr. This is expected due to the old age determined from the ^{14}C analyses. The absence of tritium also indicates that no water has recharged relatively quickly by leakage along fractures or artificial penetrations and mixed with old ground water.

Conclusions on Confinement

The Camp Swift well field is considered highly confined. The main indications are the absence of any tritium, the old ^{14}C ages, and the highly confined response from aquifer pump testing. Although the general ground-water chemistry at the well field is characterized by Ca-HCO_3-type water, typical for recharge water, the tritium and ^{14}C data indicate that it is, nevertheless, ground water that was recharged a long time ago. Pumping-test data from wells 503, 504, and 505, representing the shallower zone, exhibit highly confined conditions. Pumping-test data from the deeper confined zone in well 516 indicate some leakage. The observed leakage in the deeper confined zone most likely originates from the shallower confined strata that were not screened rather than from shallow water-table aquifers.

Wellhead Protection Area Delineation

A wellhead protection area is delineated for the two main wells of the Camp Swift well field, well 516 in the main, deeper producing zone and well 515 in the shallower zone. Although pumping-test data from well 515 were not available, this particular well is located between wells 502 and 503 (fig. 34). Pumping tests were performed in well 502 using wells 503, 504, and 505 as monitoring wells (fig. 35). Screens in well 515 are assumed to be at similar intervals as 502; it is therefore reasonable to assume that hydraulic properties determined from a pump test in 502, and measured monitoring wells 503, 504, and 505, are representative for well 515.

Cone of Depression Approach

The lateral extent of the cone of depression for the shallower and deeper production zones has been estimated with two methods: (1) analytical methods that either calculate or measure drawdown versus distance and (2) numerical modeling to calculate the extent of the cone of depression. The analytical methods assume that the regional hydraulic gradient is zero. Only for the numerical modeling method is the regional gradient considered.

Analytical Solutions and Simple Computer Models Method. Well 516—The radius of the cone of depression is estimated from the 36-hr pumping test (fig. 36) at well 516, using a semilog plot of drawdown versus time. The corresponding semilog plot of drawdown versus distance can be constructed by multiplying the slope of the time-drawdown curve by (–2) and plotting the curve on a semilog plot of distance versus drawdown. The latter curve passes through a point representing measured drawdown at the pumping well (distance equals zero) or at a monitoring well (at known distance from pumping well); when the curve is extrapolated to 0 ft drawdown, the lateral extent of the cone of depression was determined to be approximately 3,500 ft.

Some uncertainty exists because the distance-drawdown curve is based on the measured drawdown at the pumping well and not at an observation well. Drawdown at the well may be affected by well loss and could be greater than actual water levels in the formation adjacent to the well. The distance-drawdown curve may therefore overestimate the extent of the cone of depression. Water-level measurements in observation wells would yield better information on the cone of depression, as they are not affected by well loss.

Analytical solutions for equilibrium (Thiem equation) and nonequilibrium conditions (Theis equation) can also be used to estimate the extent of the cone of depression. Calculating the extent of the cone of depression requires: estimates of transmissivity (a value of 34,500 gal/day/ft is obtained from the 36-hr pumping test in well 516 [fig. 36]), the pumpage rate (1,200 gpm), the well radius (0.5 ft), and a drawdown value at the well (84 ft). Assuming equilibrium conditions (Thiem equation), the radius of influence extends to 18,600 ft. For nonequilibrium, fully confined conditions (Theis equation) the radius of the 1-ft drawdown contour extends to 8,300 ft after 36-hr pumpage. Although some leakage could be inferred from the pumping-test data (fig. 36), the leakage rate was small and did not decrease the extent of the cone of depression when using either the Theis curve or the leaky type curves.

Well 515—The lateral extent of the cone of depression for the shallower aquifer (for example, well 515) was also calculated. Measured drawdown in monitoring wells 503, 504, and 505 (figs. 30 and 35) during the pumping test in well 502 were used to estimate the extent of the cone of depression. For each monitoring well, the measured drawdown at a given time after pumping started was plotted against the distance of the monitoring well from the pumping well. The intercept with the zero drawdown line gives the extent of the cone of depression. The drawdown measurements from the three monitoring wells after 8-hr pumpage indicate a similar lateral extent of the cone of depression of about 3,500 ft. After 55 hr of pumpage, the cone extends to about 10,000 ft.

Assuming equilibrium conditions, the zone of influence around well 515 ranges between 5,750 and 6,750 ft, based on a pumpage rate of 810 gpm, an average transmissivity of 27,770 gal/day/ft, and a well radius of 0.5 ft. By using the Theis equation, the radius of the 1-ft drawdown contour extends to about 8,790 ft after pumping for 60 hr.

Well 515—The cone of depression was simulated for the production zone of well 515. Transmissivities calculated from the pumping-test data can be used in a numerical model to check the analytical approach and to incorporate complexities, such as heterogeneous transmissivity and regional hydraulic gradients. For the Camp Swift well field, a numerical model was constructed that incorporates the aquifer as a single layer with initially uniform transmissivity. In addition, a uniform hydraulic gradient of 0.002 was assumed across the model in a west-east direction representing the regional hydraulic gradient in the Wilcox aquifer. The lateral dimensions of the model were 10,000 × 10,000 ft; the area was discretized by a 40 × 40 finite-difference grid. The model was implemented with the program MODFLOW, a USGS finite-difference ground-water flow model (McDonald and Harbaugh, 1980).

Using a uniform transmissivity value of 27,700 gal/day/ft based on the pumping test results at well 502 (pumping test in the shallow unit), the model could not reproduce the observed water-level declines in well 503, 504, and 505 (fig. 35). However, by reducing transmissivity by a factor of 4 in the west-east direction, perpendicular to the north-south orientation of the wells in the well field (fig. 30), simulated drawdown compared reasonably well with observed values (fig. 35). The simulated cone of depression is an ellipse with the long axis in the direction of the well configuration and the short axis perpendicular to a line through the wells. The short axis is approximately parallel to the dip direction of the hydrostratigraphic units. The drawdown ellipse along the axis extends approximately 5,000 ft (1-ft drawdown contour) along the short axis for a 60-hr pump test, whereas the ellipse along the long axis extends as far as 9,000 ft. Due to the reduced transmissivity in the general direction of the regional hydraulic gradient, the downdip extent of the cone of depression is only 500 ft shorter than the updip extent of the cone. The regional hydraulic gradient may not significantly alter the shape of the cone of depression for well 515. In this case geologic variability may be a more important control on the shape of the cone of depression than the regional potentiometric gradient.

Well 516—Water-level declines from the 36-hr pumping test in well 516 (deeper production zone) were also simulated using the MODFLOW model. A reasonable drawdown in the pumping well could be simulated assuming either isotropic or anisotropic conditions. For anisotropic conditions, transmissivity values of 34,500 gal/day/ft in the direction of the Camp Swift wells and 8,625 gal/day/ft perpendicular to the well alignment were used. The drawdown ellipse for the 36-hr pumping test in well 516 extends 4,500 ft along the short axis, and 8,000 ft along the long axis (along the line through the wells in the well field). MODFLOW only calculates the cone of depression and does not calculate flow paths.

Time of Travel Approach

Time of travel calculations were used to estimate the wellhead protection area for the shallower and deeper production zones. Calculations of times of travel for the two wells were done independently because the two main producing wells are not in hydraulic communication.

Cylinder Method. The cylinder method used by the U.S. Environmental Protection Agency (1987), described in an earlier section, uses a volumetric-flow equation that determines the radius of a cylinder from which all the water would be pumped out after a defined period of time. Using the 40-year time of travel, a radius of about 5,000 ft is calculated for well 516 (fig. 38), based on a pumpage rate of 1,200 gpm, a screened interval of 175 ft, and a porosity of 0.25. In comparison, the cylinder radius for well 515 is only 3,400 ft, based on a pumpage rate of 810 gpm, screened interval of 250 ft, and porosity of 0.25.

Cone of Depression/Time of Travel Method. An analytical estimate (cone of depression/time of travel method) of the position of the 40-yr time of travel contour can be obtained from the slope of the drawdown curve (fig. 36) for the 36-hr pumping test for well 516. The calculated radius is 4,000 ft, which is slightly greater than the inferred radius of the cone of depression using the semilog plot.

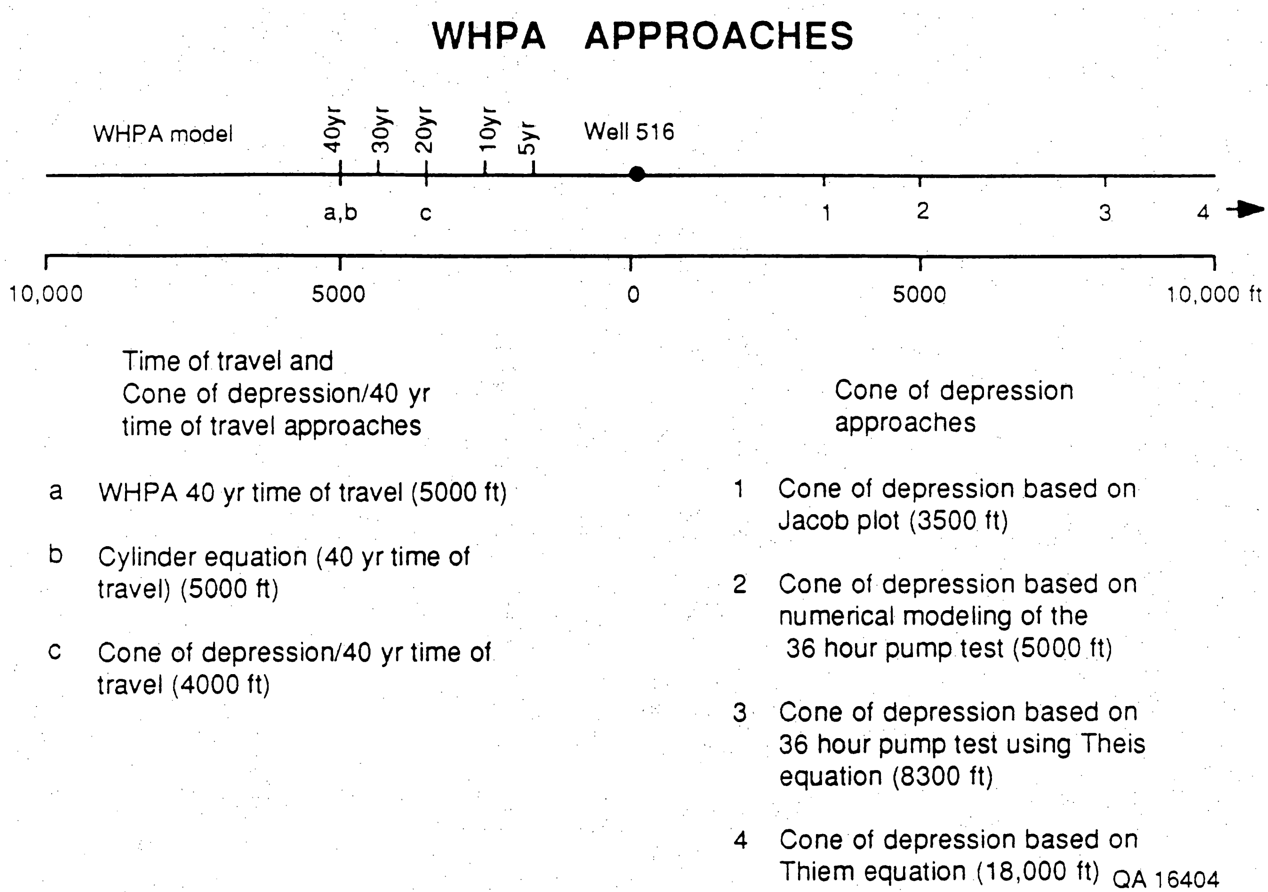

Figure 38. Radial distance for wellhead protection areas for well no. 516, Bastrop, Texas. Those distances on right side of figure used cone of depression approaches. Radial distance on left side of figure used time of travel and cone of depression/time of travel approaches.

Drawdown measurements from well 515 were not available, and the cone of depression/time of travel approach could not be applied to this well.

Semianalytical Method (WHPA Model). Calculation of 40-yr time of travel toward the pumping well was done using the wellhead protection area software package (Blanford and Huyakorn, 1990), which was developed for Environmental Protection Agency's wellhead protection program. WHPA is an integrated semianalytical model for the delineation of wellhead protection areas.

Figure 38 shows capture zones for the 5-, 10-, 20-, 30-, and 40-yr time of travel for well 516. The configuration is completely symmetric assuming isotropic transmissivity and no regional hydraulic gradient. Using an isotropic transmissivity of 34,500 gal/day/ft and a pumpage rate of 1,000 gpm, the 40-yr capture zone extends about 5,000 ft from the pumping well. Assuming a regional hydraulic gradient from left to right (west to east) of 0.002, the capture zones for the different time periods become asymmetric (fig. 39). The 40-yr capture zone extends 7,000 ft in the upgradient direction, whereas the downgradient extent is 3,300 ft. The lateral extent perpendicular to the regional gradient remains constant.

The WHPA program (Blanford and Huyakorn, 1990) does not incorporate the anisotropic transmissivities which were inferred from the numerical model simulations of water-level declines associated with the pumping test in well 502. However, when calculating capture zones that correspond to reduced transmissivity (lower by a factor of 4), the asymmetry of the capture zones is significantly reduced. With this lower transmissivity in the WHPA program, the resulting difference in distance between the upgradient and downgradient extent is less than 500 ft.

A similar flow pattern and capture zone was obtained for well 515 in the shallower production zone, based on a pumpage rate of 810 gpm, an isotropic transmissivity of 27,700 gal/day/ft, and a regional hydraulic gradient of 0.002. For this well, the upstream extent of the 40-yr capture zone is 4,700 ft, whereas the downstream boundary extends to 2,400 ft.

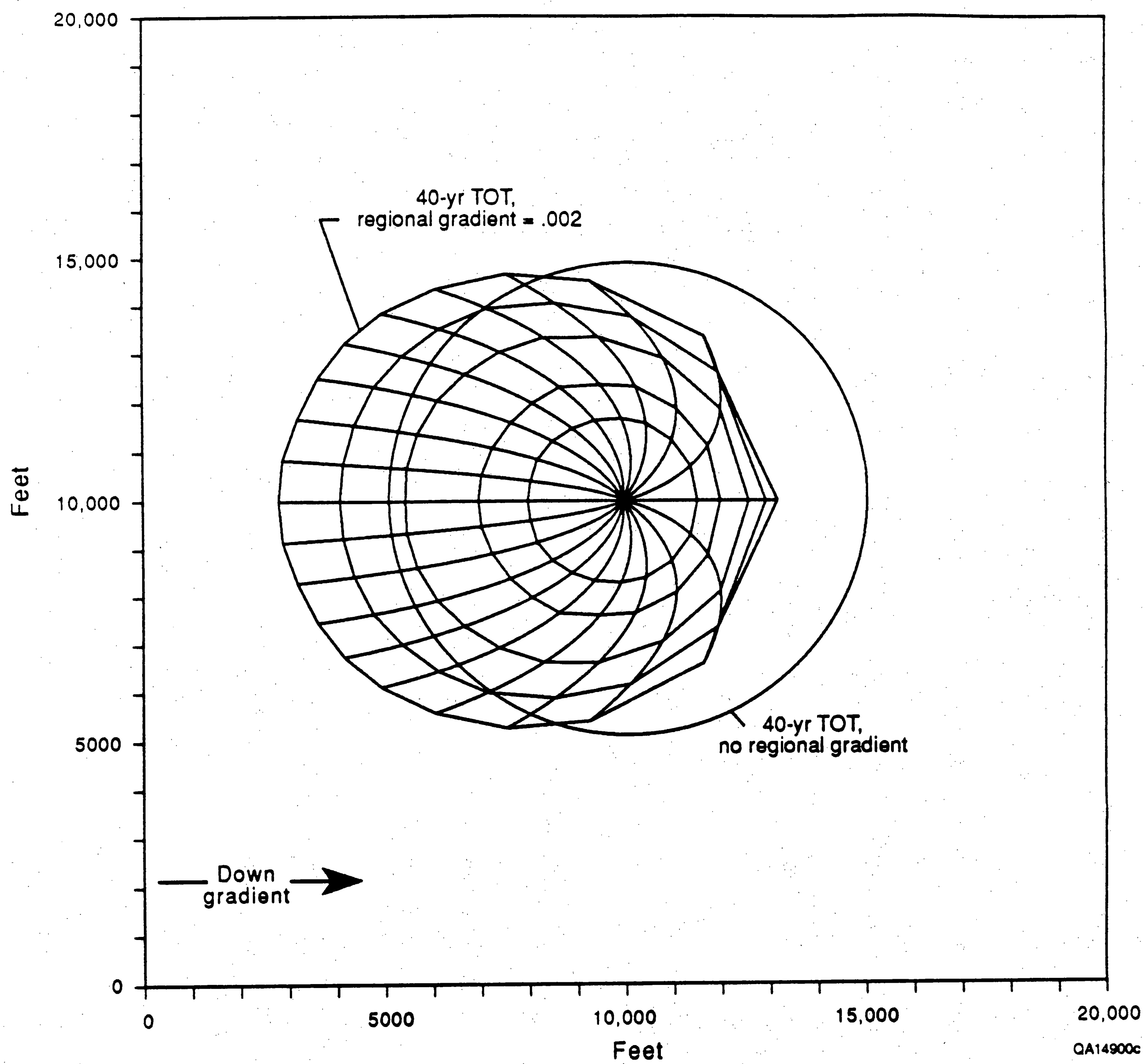

Figure 39. Capture zones for well 516 for the 5-, 10-, 20-, 30-, and 40-yr time of travel assuming a regional hydraulic gradient of 0.002. The 40-yr time of travel contour for the no-gradient scenario is included for comparison.

Recommended Wellhead Protection Area

Because of the higher pumpage rate, the 40-yr capture zone of well 516 includes nearly the entire capture zone of well 515, which is about 1,800 ft from well 516. Drawdown in the two wells is assumed not to interfere, based on the different hydrologic responses and the fact that screened intervals in well 516 are deeper than those in the other wells (fig. 34). It is therefore assumed that the capture zones for the two wells overlap, but do not interfere with each other.

Figure 38 shows the cone of depression calculation for well 516, using different methods. Analytical solutions of the Thiem equation for equilibrium conditions and the Theis equation for nonequilibrium conditions result in very large wellhead protection areas, which exceed the 40-yr time of travel contour, as computed by the WHPA program. The cone of depression/time of travel method using a 40-yr threshold, the cylinder method, and the WHPA program are recommended. Calculated radii of protection zones range from 4,000 to 5,000 ft, assuming isotropic conditions and no regional hydraulic gradient. Using the observed regional hydraulic gradient of 0.002, capture zones computed by the WHPA program become asymmetric, that is, the 40-yr capture zone extends 7,000 ft in the upgradient direction and 3,300 ft in the downgradient direction (fig. 39). The WHPA program does not incorporate effects of anisotropy. Anisotropy of transmissivity was inferred from the numerical model calibration of pumping-test results, with reduced transmissivity in the direction of the regional hydraulic gradient. Incorporating effects of anisotropy reduces the effect of the regional hydraulic gradient, resulting in a more circular wellhead protection area with a shorter upstream distance but increased downstream distance. Therefore circular wellhead protection areas were chosen (fig. 30).

As discussed earlier, the aquifer at the Camp Swift well field is considered to be highly confined, that is, it has a low probability of contamination. The main pathways for contamination are localized, such as improperly sealed, abandoned wells and boreholes. Figure 30 shows the recommended wellhead protection area, which includes an overlay of the 40-yr capture zone for the two producing wells and local protection zones in the vicinity of any existing well, representing higher-priority protection zones. In case the exact locations of abandoned wells are not known, the local, high-priority protection zone is enlarged to be certain that reported wells are included (noted by dashed circles).

Wharton, Texas

Example from the Downdip Section of a Confined Aquifer

The second example of delineation of a wellhead protection area in a confined aquifer is for a well in the well field of the City of Wharton, Wharton County, located in the Gulf Coastal Plain of southeastern Texas (fig. 29). The City of Wharton is about 60 mi west of Houston and about 50 mi north of the coast of the Gulf of Mexico. The city water wells are located on empty lots throughout the city (fig. 31). A wellhead protection area is designed for City of Wharton well 3 (also called 402), which is screened from 600 to 900 ft in the Willis Sand of the Chicot aquifer.

Hydrogeologic Setting

The area is humid, subtropical, and annual rainfall averages 41 inches per year, which is less than average annual potential evaporation (Loskot and others, 1982). The topography is relatively flat, characteristic of coastal plains of low relief. In Wharton County, the main hydrogeologic units consist of Pleistocene and Pliocene sequences of gravel, sand, silt, and clay. All formations crop out in belts that are nearly parallel to the shoreline and dip towards the Gulf of Mexico. The stratigraphic sequence can be divided into three hydrogeologic units (Loskot and others, 1982): (1) the Chicot aquifer, that includes the Willis Sand, Bentley Formation, Montgomery Formation, the Beaumont Clay of Pleistocene age, and Holocene Alluvium; (2) the underlying Evangeline aquifer, that includes the Pliocene Goliad Sand; and (3) the Burkeville confining layer that consists of the Upper Miocene Fleming Formation and underlies the Evangeline aquifer. The shallow Beaumont Clay consists of a thick sequence of mostly clays with only local sands and is considered a major confining unit for the Chicot and underlying Evangeline aquifers. Locally, the Beaumont Clay can produce some ground water from interbedded sand bodies. The Chicot aquifer reaches a depth of about 600 ft below sea level in the vicinity of Wharton. The Willis Sand is the major waterbearing unit of the Chicot aquifer. Its updip outcrop, the main area of recharge from Wharton County, is in Colorado County, which is approximately 30 mi northwest of the City of Wharton.

Determining Confinement

The degree of confinement of the well field has been evaluated using geologic, hydrologic, and hydrochemical criteria.

Geologic Approach

1. Geologic Map and Cross Section

The wells of the City of Wharton are located on alluvium of the Colorado River. Beneath the alluvium, the Beaumont Formation consists of thick clay with interbedded sand and acts as a confining unit for the underlying Willis Sand. The potential for confinement is not apparent from the outcrop map but from the subsurface data.

The subsurface distribution of sand and shale is depicted in figure 40, showing driller's logs and geophysical logs of the municipal wells of the City of Wharton. The entire geologic section contains interlayered sands and shales indicating the presence of confining layers, with thicker sands of the Willis Sand occurring at greater depth. Except for wells 1 and 3, which are about 70 ft apart, the sands of the different wells cannot be correlated to assess the lateral continuity of the clay layers (fig. 40).

2. Various Mapping Methods

Environmental geology maps by McGowen and others (1976) show clayey sands and silts as the dominant surficial deposits. The deposits are characterized by moderate permeability, drainage, and water-holding capacity in the Wharton area. The general soil map of Wharton County published by the U.S. Soil Conservation Service (1979) shows the predominant soil in the City of Wharton to be of the Miller-Norwood association. This soil type is characterized by moderately well-drained

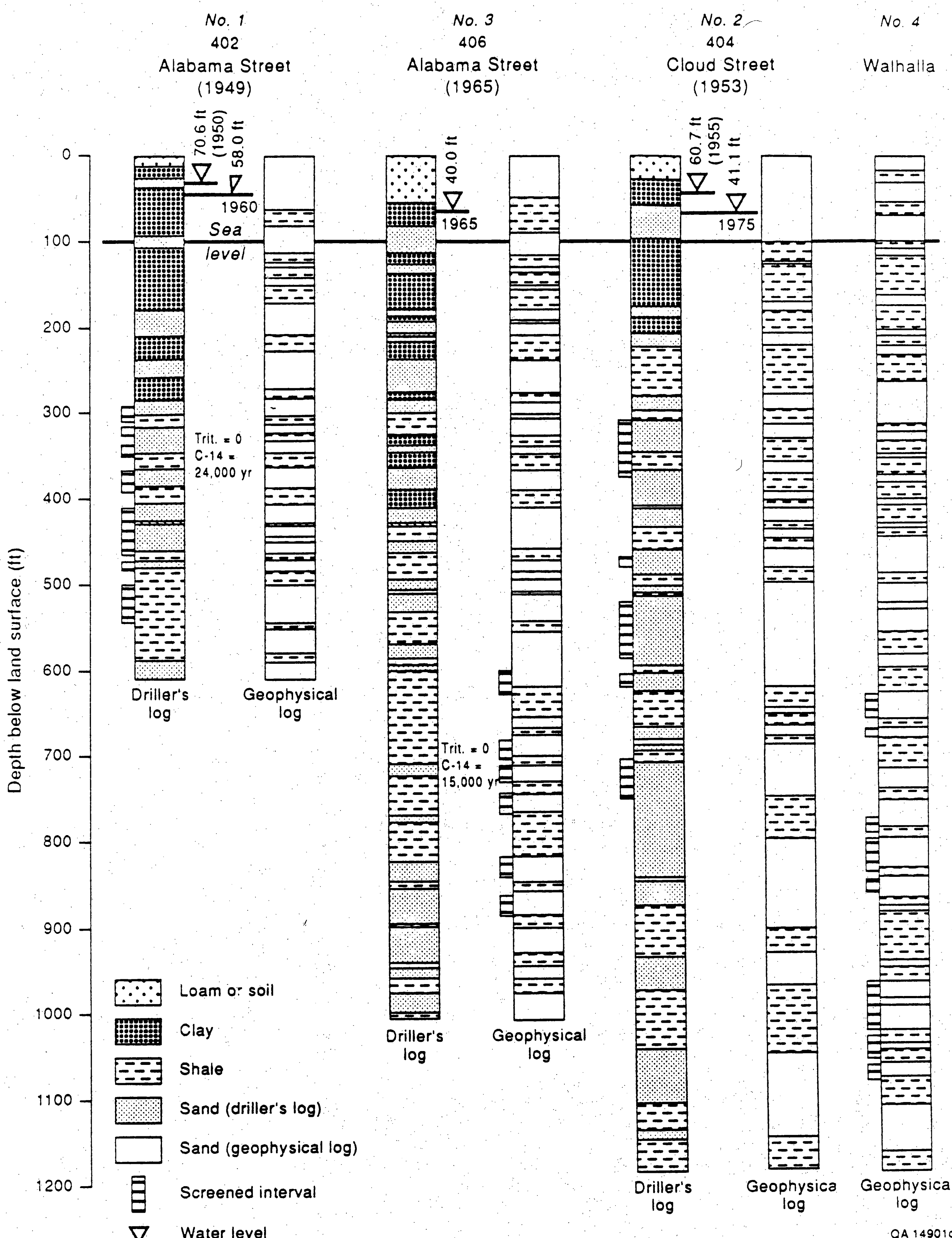

Figure 40. Subsurface distribution of sand and shales based on driller's logs and geophysical logs for City of Wharton wells.

calcareous soils on flood plains that are underlain by Recent loamy and clayey alluvium. The variability of surficial deposits does not give a clear indication of the potential for confinement.

Potential locations of artificial penetrations of the confining unit were obtained from maps available from the Texas Railroad Commission, which regulates the oil and gas industry in the State. The Commission's records indicate several oil wells at the outskirts of the City of Wharton, some of which are within a mile of the city water wells (fig. 31), but no drilling has been conducted in the city. If they are abandoned and inappropriately sealed, the oil wells may represent potential pathways for contamination. The well records, however, may not be complete, and additional information on the potential locations of artificial penetrations may be obtained from land-use maps and air photos that indicate industrial developments in the area.

Hydrologic Approach

1. Water-Level Elevations in Wells

Water levels for the different wells in Wharton are shown on figure 40. A potentiometric surface of the Chicot aquifer in Wharton County, however, was not constructed because of a wide range in measured water levels vertically, laterally, and over time within the aquifer. Ground water in the aquifer is used extensively in the county for agricultural and municipal uses which has resulted in water-level declines as much as 50 ft over the last 20 yr. A regional hydrologic cross section (Dutton and Richter, 1990) indicates a relatively small lateral gradient but a significant downward hydraulic gradient (fig. 41). The regional lateral hydraulic gradient is less than 0.0005. The vertical hydraulic gradient indicates a potential for shallow ground water to leak into the deeper aquifer units.

2. Pumping-Test Data

(a) Extent of cone of depression

A pumping test conducted at well 40 (fig. 42) did not produce drawdown in well 402, which is located about 70 ft away from the pumping well. Note, however, that the screened intervals are at

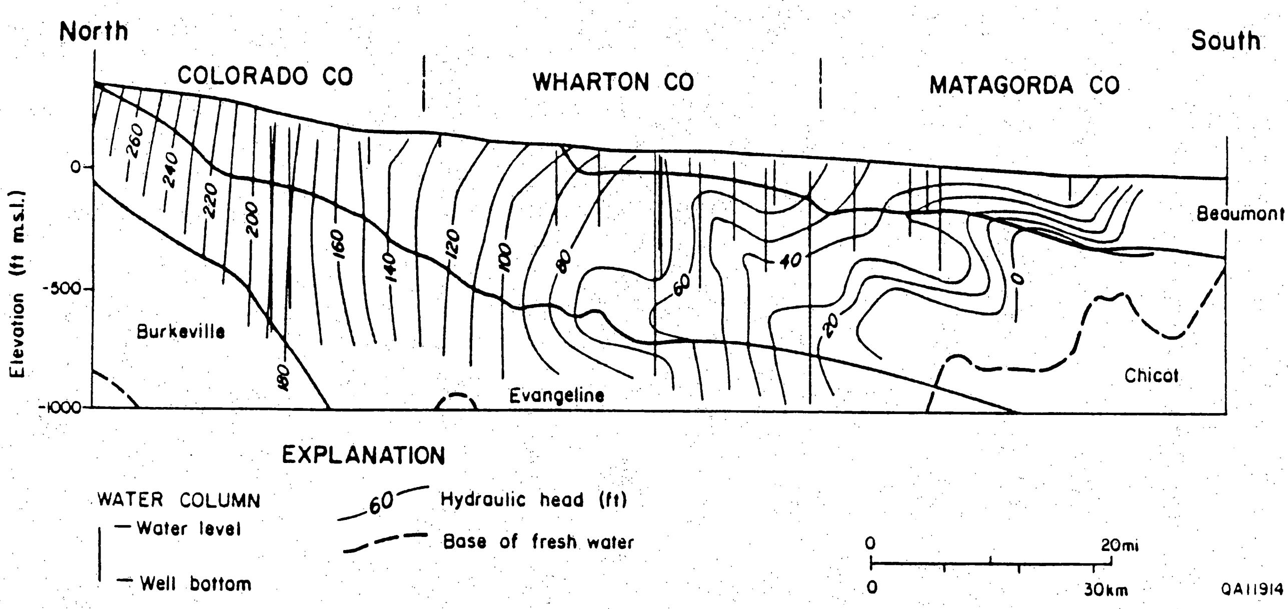

Figure 41. Regional hydrologic cross section through Wharton and adjacent counties showing vertical distribution of hydraulic heads (from Dutton and Richter, 1990).

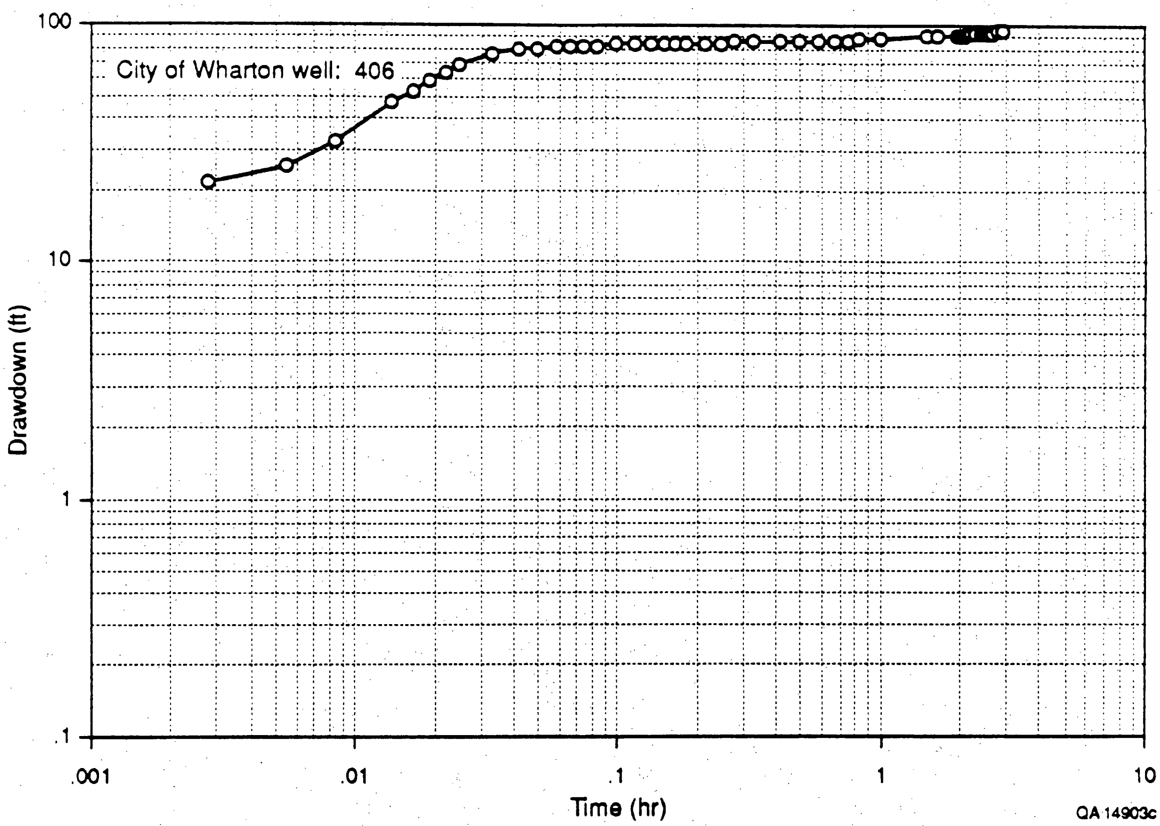

Figure 42. Log-log plot of drawdown versus time in the pumping well 406, indicating the drawdown stabilized after about 4 min.

different elevations in the two wells (fig. 40) and may be in poor hydraulic connection; thus, the cone of depression of well 406 may extend more than 70 ft.

(b) Transmissivity

Attempts to calculate transmissivity from a pumping test at well 406 on May 25, 1989, were limited due to measurement problems. Drawdown in the pumping well was determined from pressure changes in an air line. Leakage of the air line was noticed, and the drawdown curve may be somewhat affected by this leakage.

Using the straight-line segment of the second part of the drawdown curve (fig. 43) a transmissivity value of about 40,000 gal/day/ft is calculated. This value is relatively high for typical transmissivity for other wells in the Chicot aquifer. Matching the log-log plot of drawdown versus time (fig. 42) with leaky type curves gives an estimate of about 3,870 gal/day/ft.

A transmissivity of 14,000 gal/day/ft was estimated from model calibration with available data from the area. The 14,000 value is considered a better estimate of transmissivity.

(c) Storativity

Storativity was not obtained from the pumping test in well 406. Reported storativities for the Chicot aquifer in the vicinity of the city of Wharton are in the order of 10^{-2} (Dutton and Richter, 1990). Although the value is higher than the typical value of 10^{-4} for a confined aquifer, abundant clay layers within the aquifer (fig. 40) probably account for the higher storativity in the aquifer.

(d) Leakage

The log-log plot of drawdown versus time for a pump test on well 406 follows a very typical leaky type curve where the rate of drawdown became significantly reduced about 4 min after pumping started (fig. 42). However, without water-level measurements in a nearby monitoring well, leakage cannot be quantitatively estimated. Leakage from sand layers above and below the producing zone may occur (fig. 40), because not all of the sand intervals are screened, and some of the shale layers adjacent to the screened sand intervals are relatively thin.

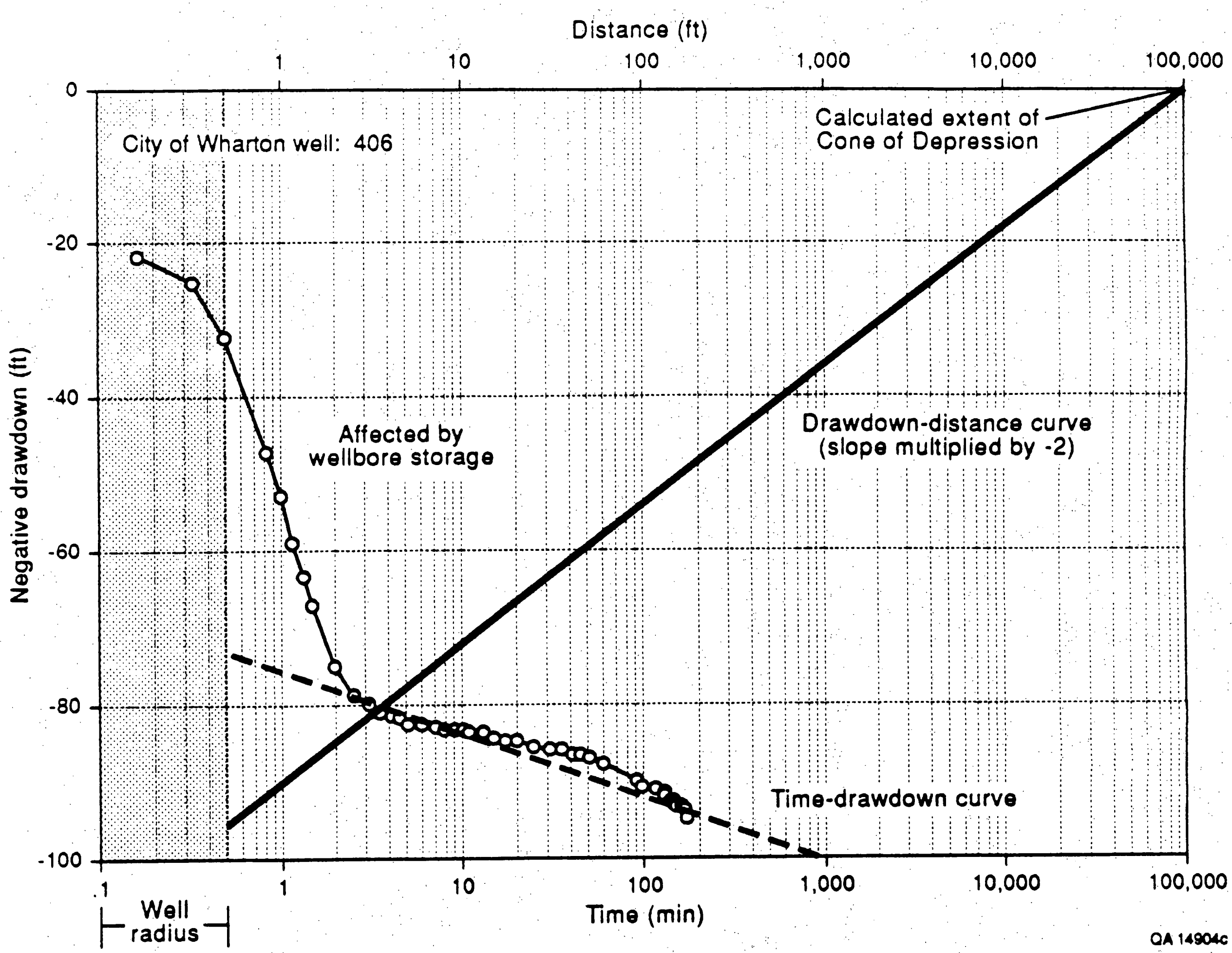

Figure 43. Semilog plot of negative drawdown versus time based on a 3-hr pumping test in well 406. Based on the slope of the straight line section, a distance-drawdown curve can be inferred, but is considered to be unrealistic.

Numerical Model. Due to the uncertainty in estimated transmissivities from the pumping test in well 406, a numerical model was used to test the sensitivity of drawdown to transmissivity. The results of the numerical model are discussed later in the wellhead protection area delineation section.

Hydrochemical Approach

1. General Water Chemistry

The distribution of hydrochemical facies along a vertical cross section in the direction of the regional dip of the hydrostratigraphic units is shown in figure 44. Most of the ground water in Wharton County in the Chicot and Evangeline aquifers is of a Ca-HCO_3 type.

The ground waters in the overlying Beaumont Formation are Na-HCO_3- and Na-Cl-type waters. This supports the hydraulic data indicating that the shallow Beaumont Formation is hydraulically separated from the deeper aquifer units. Although an overall downward hydraulic gradient is observed (fig. 41), shallow ground water has not reached the deeper aquifers because of the relatively low vertical permeability of the Beaumont Formation.

Records of water-chemistry data from the Wharton City wells do not show any changes through time, which indicates that the source of ground water has remained constant and has not been changed by extensive pumpage during the last several decades.

2. Carbon-14 Age Determination

Absolute ground-water ages based on ^{14}C analyses at two wells 406 and 402, were 15,000 and 24,000 yr (fig. 44), corresponding to the deeper Ca-HCO_3-type and shallower Na-HCO_3-type ground water, respectively. Both waters show very great ages. The Ca-HCO_3-type water in the deeper, but more transmissive, Chicot aquifer is younger than the Na-HCO_3-type water from the shallower, less transmissive Beaumont Formation. Ground water recharged to the Chicot from the west where the Beaumont is absent appears to have flowed beneath the overlying Beaumont Formation.

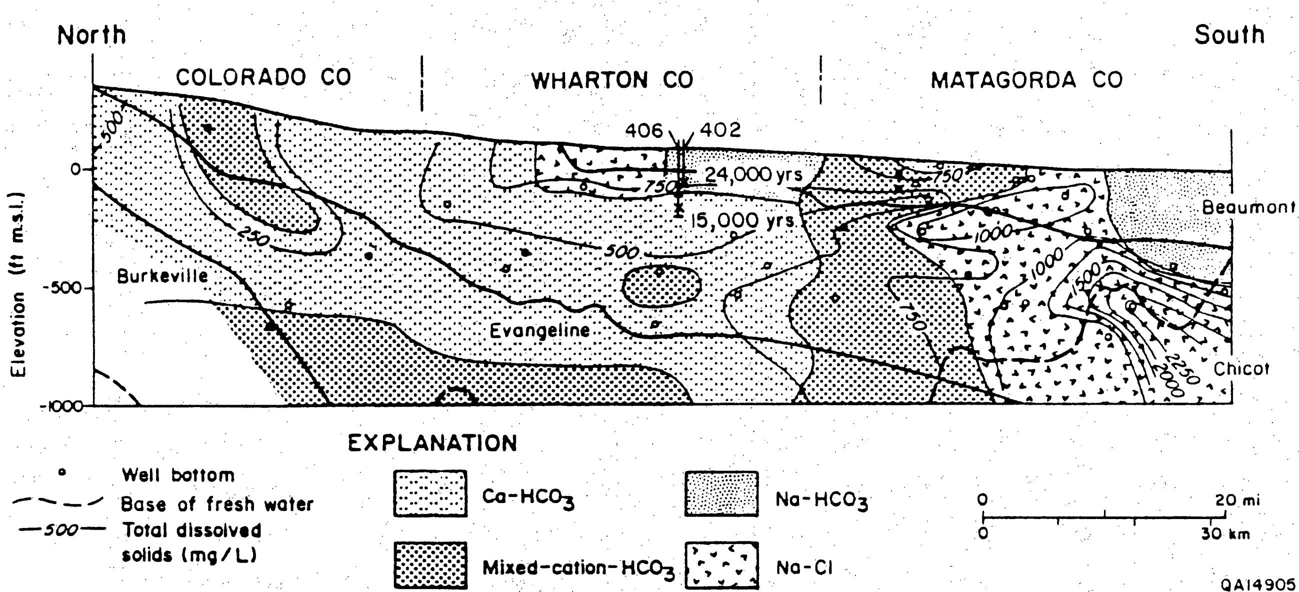

Figure 44. Distribution of hydrochemical facies along a vertical cross section in the downdip direction (from Dutton and Richter, 1990).

3. Tritium

Tritium analyses of water samples collected in wells 406 and 402 both indicated tritium concentrations below detection limit. This is consistent with the relatively great age based on ^{14}C analysis. The absence of any tritium also indicates that no rapid recharge occurs through localized features such as faults and fractures allowing mixing with younger ground water.

Conclusions on Confinement

The ^{14}C and tritium concentrations in well 406 indicate very old ground water. The producing zone of well 406, therefore, is considered highly confined. The hydraulic head distribution indicates an overall downward gradient; however, the difference in water chemistry and ground-water ages between the shallow and deep sections indicates a lack of significant downward ground-water movement. Although pumping-test data indicate a leaky behavior, leakage is interpreted to come from vertically adjacent sand units, which are not screened.

Wellhead Protection Area Delineation

A wellhead protection area was delineated for well 406 (Wharton city well 3; fig. 31), using the cone of depression and time of travel approaches.

Cone of Depression Approach

Analytical Solutions and Simple Computer Models Method. The semilog plot of negative drawdown versus time (fig. 43) shows two straight-line sections, (1) from 0.2 to 3 min and (2) from 3 to 200 min. The first section is affected by well-bore storage and does not represent aquifer conditions. The second section is affected by leakage. Using the relationship between the slope of the time-drawdown curve and the distance-drawdown curve, the extent of the cone of depression is estimated at about

100,000 ft (fig. 43). This value, however, is considered a gross overestimation due to the observed leakage into the aquifer. Leakage reduces the rate of drawdown, and thereby decreases the slope of the distance-drawdown curve. Calculating the lateral extent of a cone of depression with drawdown versus time data may not be appropriate if the aquifer is semiconfined and characterized by significant leakage.

Analytical solutions describing well discharge for equilibrium conditions (Thiem equation) and nonequilibrium conditions (Theis equation) are also used for estimating the radius of the cone of depression. Using a transmissivity of 14,000 gal/day/ft, based on the model calibration (discussed below), a pumping rate of 940 gpm, and a storativity of 0.01, the calculated radius of the 1-ft drawdown contour extends to 342 ft after 3 hr of pumpage.

For equilibrium conditions (Thiem equation), the extent of the cone of depression is calculated at 243 ft based on T = 14,000 gal/day/ft (fig. 45).

Because of the uncertainty in transmissivities estimated from the pumping test in well 406, a numerical model was used to test the sensitivity of transmissivity and storage on drawdown. Although, the hydrostratigraphy shows a highly heterogeneous aquifer (fig. 40), the simulations were performed using a one-layer representation of the aquifer. The regional hydraulic gradient in the vicinity of Wharton is very small (less than 0.001) and was assumed to be negligible. A semianalytical software package (Walton, 1987) was used to simulate drawdown in a single well under a variety of conditions. In this case Walton's program is well suited for wellhead protection delineation, as it computes not only drawdown in a pumping well but also calculates the distance-drawdown relationship.

In a series of simulations where transmissivity, storativity, and leakage were varied, the best fit with the observed data was obtained when using a transmissivity of 14,000 gal/day/ft, a storativity of 0.01, and an aquitard permeability that is only one order of magnitude lower than aquifer permeability. Both high storativity in and high leakage to the aquifer can be expected, considering the overall hydrostratigraphy (fig. 40). Based on these calibrated hydrologic properties, the calculated 1-ft drawdown contour extends to about 350 ft from the pumping well after 3 hr of pumpage.

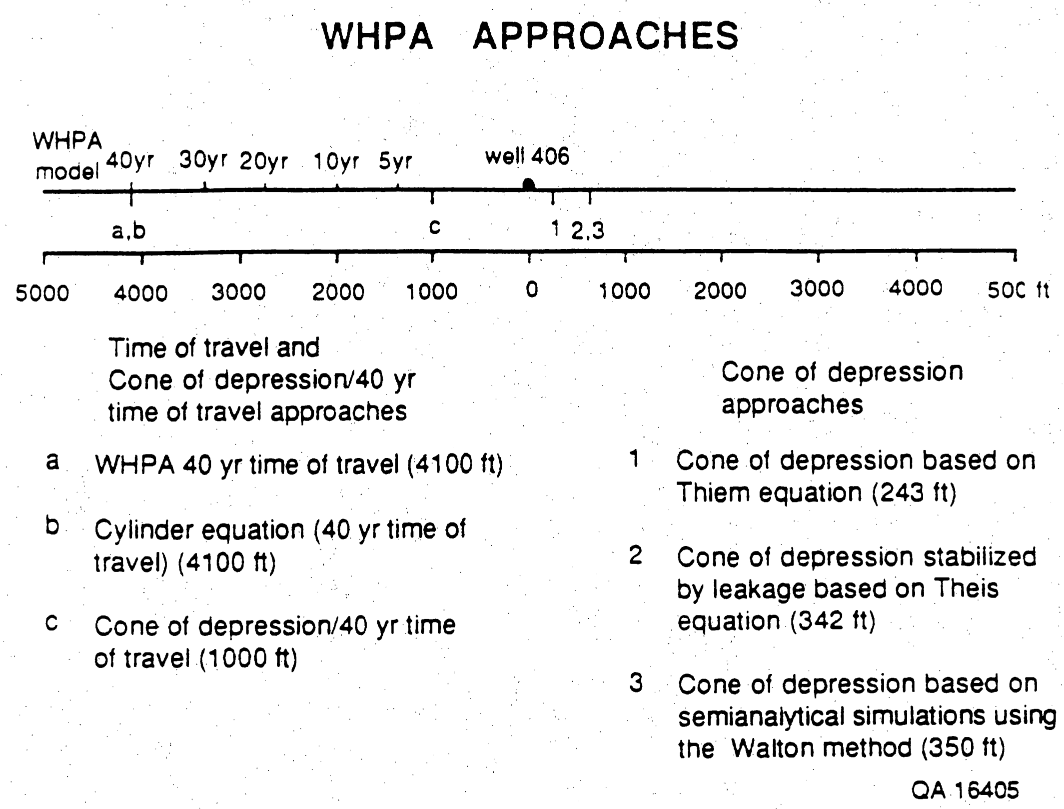

Figure 45. Radial distance for wellhead protection areas for well no. 406 for Wharton, Texas. The distances on right side of figure used cone of depression approach. Radial distance on left side of figure used time of travel approach and cone of depression/time of travel approaches.

Time of Travel Approach

Cylinder Method. Using the cylinder method, a radius of about 4,100 ft (fig. 45) was calculated for a 40-yr time period for well 406, based on a pumpage rate of 940 gpm, a screened interval of 200 ft, and a porosity of 0.25. This approach assumes no vertical leakage.

Cone of Depression/Time of Travel Method. Using the cone of depression/time of travel method with a 40-yr threshold, and a hydraulic gradient based on the lateral extent of the cone of depression of 350 ft and 90 ft drawdown at the pumping well, the wellhead protection radius is approximately 1,000 ft (fig. 45). In this case the 40-yr time of travel contour is larger than the lateral extent of the cone of depression.

Semianalytical Method (WHPA Model). The 40-yr time of travel for the pumping well was calculated using the WHPA computer program (Blanford and Huyakorn, 1990). As mentioned before, the version of the WHPA program that was used did not include the effects of leakage and thereby assumed a distance-drawdown curve typical for highly confined aquifers. Using a transmissivity value of 14,000 gal/day/ft, the 40-yr time of travel contour computed by the WHPA program extends to about 4,000 ft from the pumping well (fig. 45). With the regional hydraulic gradient assumed to be less than 0.0005 (fig. 41), all wellhead protection areas were circular in shape.

Recommended Wellhead Protection Area

A comparison of the results of the different methods is shown in figure 45. The time of travel calculations generally yield greater capture zones than the cone of depression calculations. The 350-ft radius for the cone of depression was based on a simulated 3-hr pump test. The actual size of the cone of depression could not be determined. A wellhead protection radius of 1,000 ft is considered a reasonable approximation for this leaky aquifer based on the cone of depression/time of travel method with a 40-yr threshold. The 4,000-ft radius from the 40-yr time of travel method using the volumetric-flow equation (cylinder method) or the WHPA computer program was calculated without consideration of the effects of leakage; thus, 4,000 ft overestimates the lateral extent of the cone of depression where the cone of depression is based on a 3-hr pump test. The WHPA program and the cylinder method give a conservative estimate of the wellhead protection area and are appropriate when information about aquifer properties, for example, transmissivity, leakage, and storativity, is not available. Local protection zones in the vicinity of existing wells should be established to provide higher priority protection zones.

APPENDIX 2

CONFINED AQUIFERS OF THE UNITED STATES, THE COMMONWEALTH OF PUERTO RICO, AND THE PACIFIC AND CARIBBEAN TERRITORIES

by

James Hamilton

Ground-Water Protection Division

Office of Ground Water and Drinking Water

U.S. Environmental Protection Agency

Washington, D.C.

Introduction

Major and significant minor confined aquifers (hereafter referred to only as "confined aquifers") occur throughout the United States, the Commonwealth of Puerto Rico, and the Pacific and Caribbean Territories (Back and others, 1988).

The map of confined aquifers of the United States (fig. 46) primarily is based on U.S. Geological Survey (USGS) information contained in Moody and Chase (1985). Other significant information comes from Heath (1984), Sun (1987, 1988), Weeks and Sun (1987), and Moody and others (1988). Figure 46 also incorporates information from Gerlach, 1970, Davies and others, 1984, and from telephone interviews with scientists at USGS district offices. Fenneman's 1946 map was used as a guide for confined-aquifer boundaries.

Only aquifers of drinking-, irrigation-, or stock-water quality are depicted on figure 46. Where researchers in adjoining States do not believe that strata serving as a significant aquifer in one State constitute a significant aquifer in the adjoining State, it was necessary to approximate the position of the boundary separating the presence and absence of a confined aquifer, to be near the States' common border. Dashed lines are used in figure 46 to represent such a boundary.

Acknowledgments

Numerous scientists from the U.S. Geological Survey (USGS) and the U.S. Environmental Protection Agency (EPA) provided information on the geographic distribution of confined aquifers. The time and efforts of these scientists are greatly appreciated.

The USGS scientists are: Gary Balding, Rick Benson, David Brown, William Carswell, David Click, Timmy Cummings, Dan Davis, Robert Faust, Herbert Freberger, Ector Gann, Joseph Gates, Roy Glass, Robert Graves, Steven Hindall, William Horak, Thomas Huntzinger, Jeffery Imes, Ivan James, Richard Karsten, James Kircher, John Kline, Alfred Knight, Richard Krause, James Kroheski, Larry

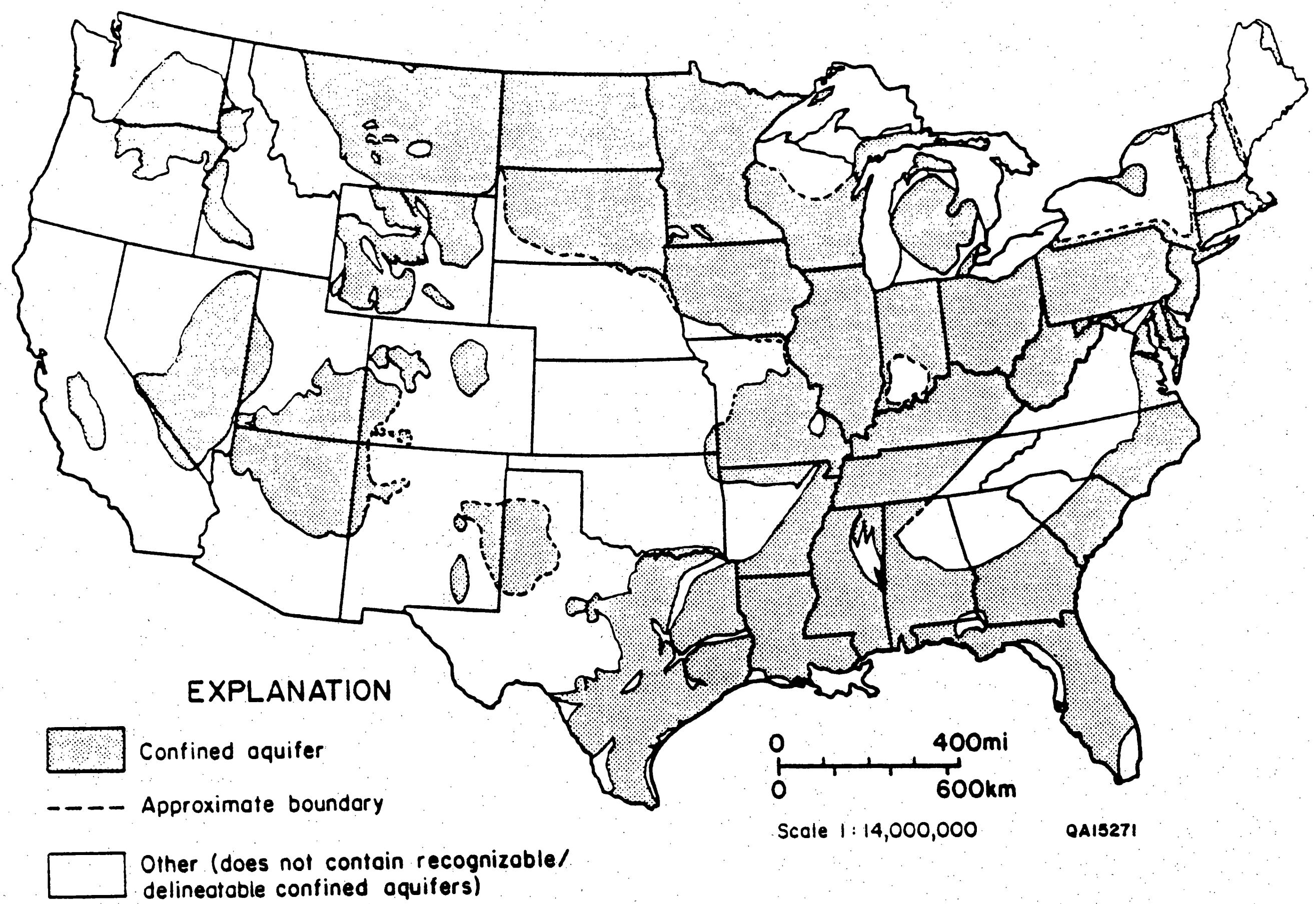

Figure 46. Major and significant minor confined aquifers of the United States.

Land, Gerald Lindholm, Robert MacNish, Joe Moreland, William Oakley, Glenn Patterson, Kathy Peter, Michael Planert, Stanley Robson, Michael Shulters, Dennis Stewart, Arturo Torres, Donald Vaupel, John Vecchioli, John Williams, and Thomas Winterstein.

The EPA scientist is John Malleck.

General Description of Confined Aquifers

For ease of discussion, aquifers of the continental United States are grouped into four general physiographic regions (fig. 47) (after Fenneman, 1946): (1) the Atlantic Coastal and Gulf of Mexico Coastal Plains from New York to Mexico; (2) the Appalachian Highlands from Maine to central Alabama, and the geologically similar Laurentian Uplands of Minnesota and Wisconsin; (3) the Midcontinent section, consisting of the Interior Plains and Interior Highlands, with mature basins and dissected plains; and (4) the western portion of the United States, consisting of the Rocky and Pacific Mountain Systems and the Intermontane Plateaus and Basins.

Physiographic Region 1

The Atlantic Plain and the Gulf of Mexico Plain contain confined aquifers. The unconfined areas within the general Physiographic Region include such aquifers as the Floridan, which is unconfined in the outcrop area but confined where buried deeply (Sinnott and Cushing, 1978; Burchett, 1986; and Moody and Chase, 1985).

Physiographic Region 2

All the New England States contained fractured, crystalline bedrock aquifers overlain by glacial deposits. In New Hampshire, Vermont, Massachusetts, and Connecticut, the bedrock aquifers are confined by overlying glacial till, and in some places by glacial-lake sediments. Rhode Island is not

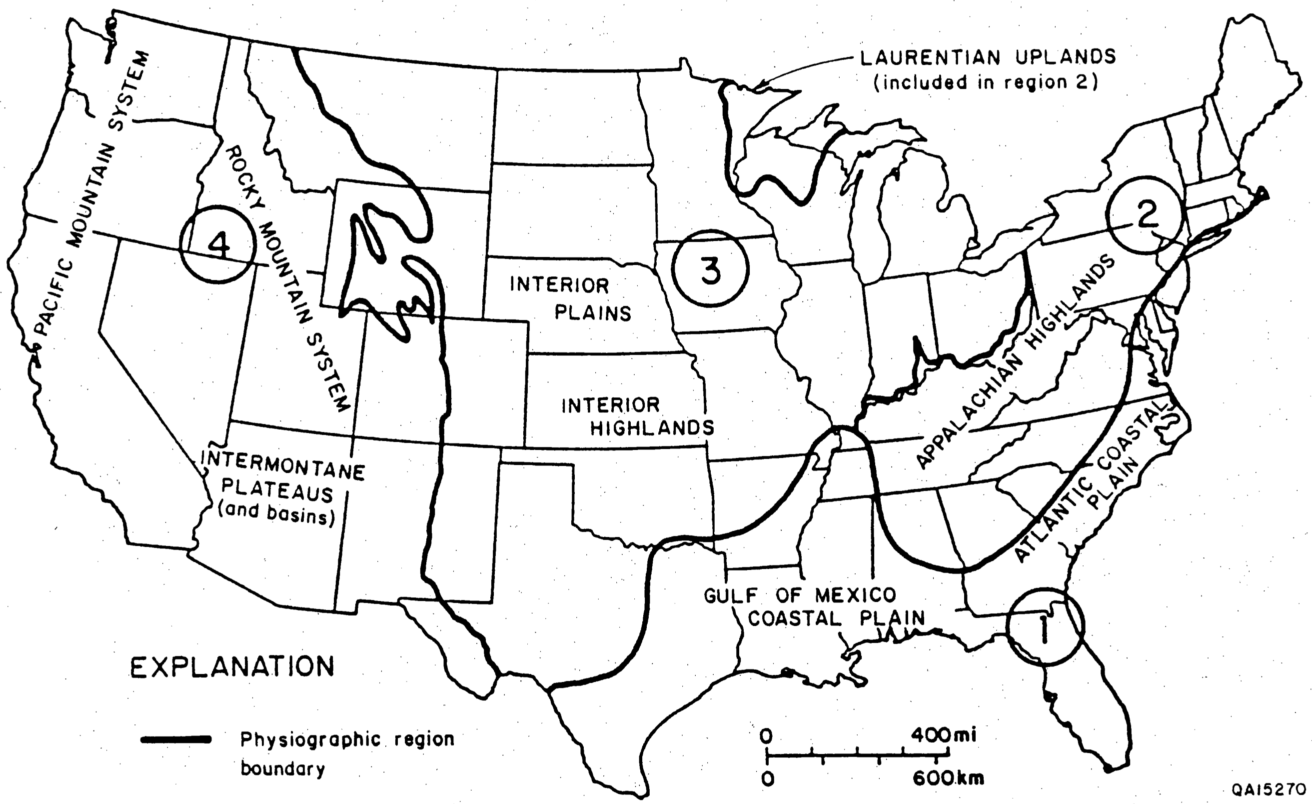

Figure 47. Physiographic regions of the United States.

depicted as containing confined aquifers (fig. 46) because the till that overlies bedrock is not considered to be confining in this State. Maine's aquifers of till, of glaciofluvial outwash, and of ice-contact deposits are generally unconfined and are found in most of the State. Carbonate aquifers in extreme northeastern Maine are confined (Sinnott and Cushing, 1978). Primarily unconfined crystalline aquifers that are pervasive throughout most of Maine may be locally confined in areas too small to depict in figure 46.

New York contains significant minor aquifers. These are: primarily unconfined carbonates; primarily unconfined stratified drift; and in small areas, confined sandstone aquifers and confined valley-fill deposits (Waller and Finch, 1982). South of New York, most of the northwestern half of the Appalachian Highlands essentially is an area of confined aquifers. The southeastern half consists of the Blue Ridge Mountains and Piedmont which contain crystalline aquifers that are primarily unconfined in Virginia, South Carolina, and Georgia. In eastern Tennessee, northern Alabama, and northern Georgia, the crystalline rocks are primarily unconfined (Zurawski, 1978). In North Carolina, similar crystalline rocks have been defined as confined, low-yield aquifers by the USGS. For purposes of this report, however, these aquifers are not considered significant because the sustained water yields come from the overlying, saturated regolith.

The Laurentian Upland is a recently glaciated surface on unconfined crystalline rocks (Weist, 1978). In Wisconsin the aquifers are unconfined, and in the northeastern part of Minnesota, the aquifers are a generally confined combination of crystalline, sandstone, and volcanic rocks. The southern extent of the Laurentian Upland in Wisconsin approximates the boundary between the northern unconfined aquifers and the more southern (Physiographic Region 3) Sandstone aquifer, that is confined in the east by the Maquoketa Shale and is locally confined elsewhere (Moody and Chase, 1985).

Physiographic Region 3

The Midcontinent portion of the United States consists of the Interior Plains and the Interior Highlands (Bloyd, 1974). A very large confined-aquifer area containing several extensive aquifers extends from Wisconsin to western Montana. One of the confined aquifers is the Fort Union Coal, which covers large parts of Montana, Wyoming, and the Dakotas. The coal is confined except for a narrow area around its perimeter where it either crops out or is shallow. In Wyoming, the Fort Union Coal is underlain by carbonate and sandstone aquifers that are also confined (Reeder, 1978).

The remainder of the Region, including the extensive High Plains aquifer area, is predominantly unconfined. Glacial-drift aquifers of northern Missouri are confined in buried valleys where overlain by relatively thick deposits of low-permeability outwash (Taylor, 1978; Moody and Chase, 1985). These minor aquifers are indiscernible at the scale of figure 46.

Physiographic Region 4

The Western United States is the Region of Intermontane Plateaus and Basins and the Rocky and Pacific Mountain Systems. This Region includes the extensive Columbia River Plateau, which encompasses southeastern Washington, eastern and central Oregon, the Snake River Plain of southern Idaho, and the northern portions of California and Nevada (Foxworthy, 1979; Whitehead, 1986). The confined aquifers within the area of the plateau are the Columbia River Basalt aquifers of Washington and Oregon and the western Snake River aquifer. The volcanic and sedimentary aquifers of the rest of the Columbia River Plateau are unconfined but may be locally confined in areas too small to be shown in figure 46.

The aquifers in most of the rest of the Region are unconfined except for the carbonate aquifers of the Great Basin's eastern half, located mostly in eastern Nevada and western Utah (Dettinger, 1989). Sediments of the Central Valley in California constitute one of the Region's most extensive aquifer systems; the southern half of the valley is confined (fig. 46) (Thomas and Phoenix, 1976; Moody and Chase, 1985).

Alaska, the Hawaiian Islands, and the Pacific and Caribbean Islands

Alaska has a varied and relatively complex geology. To date only one area has been determined to contain confined aquifers. This area is on the south coast near Cook Inlet, where basins and valleys surrounding a south-central embayment are filled with glacial till and fine-grained, glaciolacustrine materials that are interbedded with more permeable water-worked deposits of sand and gravel. The glacial outwash alluvium is confined by glacial, lacustrine, and estuarine deposits (Zenone and Anderson, 1978).

The Hawaiian Islands are composed of complex volcanics that are, for the most part, unconfined. Some basal ground-water (that is, water that floats on, or is in hydrodynamic equilibrium with, salt water) areas of the Island of Oahu have been described as being locally confined where cap rock is present.

In the Virgin Islands, ground water is primarily under water-table conditions except on the Island of St. Thomas. On that island, sand and gravel beds are locally confined by overlying alluvium. Information is not available to delineate these areas (Cosner and Bogart, 1972; Jordan and Cosner, 1973; and Jordan, 1975).

Most of the water in Guam is produced from limestone aquifers that are primarily unconfined (Ward and others, 1965).

Puerto Rico has a confined-aquifer area along the western and central portions of the north coast of the main island. In this area, the Cibao Formation and the Lares Limestone are unconfined at outcrops but are confined at depth (Torres, 1985; 1986).

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APPENDIX 3

Glossary

The purpose of this Glossary is to provide a list of terms used in this document and commonly used by hydrogeologists, as well as some specific terms used in ground-water contamination assessments and wellhead protection. The definitions provided in this glossary are not necessarily endorsed by the Environmental Protection Agency nor are they to be viewed as suggested language for regulatory purposes. Many of these definitions are from the U.S. Environmental Protection Agency (1987).

Advection. The process by which solutes are transported by the bulk motion of the flowing ground water.

Analytical model. A model that provides approximate or exact solutions to simplified mathematical forms of the differential equations for water movement and solute transport. Analytical models can generally be solved using calculators or computers.

Anisotropy. The condition of having different properties in different directions. The condition under which one or more of the hydraulic properties of an aquifer vary according to the direction of flow.

Anthropogenic. Involving the impact of man on nature; induced or altered by the presence and activities of man.

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

Aquifer test. A test to determine hydrologic properties of an aquifer, involving the withdrawal of measured quantities of water from, or addition of water to, a well and the measurement of resulting changes in head in the aquifer both during and after the period of discharge or addition. Same as pump test.

Area of influence. Area surrounding a pumping or recharging well within which the water table or potentiometric surface has been changed due to the well's pumping or recharge.

Attenuation. The process of diminishing contaminant concentrations in ground water, due to filtration, biodegradation, dilution, sorption, volatilization, and other processes.

Carbon-14 (^{14}C). A radioisotope of carbon with a half life of 5,730 years. Carbon-14 concentration can be used to estimate the age of a ground water (that is, the time since a ground water was recharged at land surface and flowed to the point of collection).

Cone of depression (COD). A depression in the ground-water table or potentiometric surface that has the shape of an inverted cone and develops around a well from which water is being withdrawn. Its trace (perimeter) on the land surface defines the zone of influence of a well. Also called pumping cone and cone of drawdown.

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

Contamination. The degradation of natural water quality as a result of man's activities.

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 vertical distance ground-water elevation is lowered, or the amount head is reduced, due to the removal of ground water. Also the decline in potentiometric surface caused by the withdrawal of water from a hydrogeologic unit. The distance between the static water level and the surface of the cone of depression. A lowering of the water table of an unconfined aquifer or the potentiometric surface of a confined aquifer caused by pumping of ground water from wells.

Fissure. A fracture or crack in a rock along which there is a distinct separation.

Flow line. The general path that a particle of water follows under laminar flow conditions. Line indicating the direction followed by ground water toward points of discharge. Flow lines generally are considered perpendicular to equipotential lines.

Flow model. A computer model that calculates a hydraulic head field for the study area using numerical methods to arrive at an approximate solution to the differential equation of ground-water flow.

Flow path. The path a water molecule or solute follows in the subsurface.

Fracture. A general term for any break in a rock, which includes cracks, joints, and faults.

Ground-water barrier. Rock or artificial material with a relatively low permeability that occurs (or is placed) below ground surface, where it impedes the movement of ground water and thus may cause a pronounced difference in the heads on opposite sides of the barrier.

Ground-water basin. General term used to define a ground-water flow system that has defined boundaries and may include more than one aquifer. The basin includes both the surface area and the permeable materials beneath it. A rather vague designation pertaining to a ground-water reservoir that is more or less separate from neighboring ground-water reservoirs. A ground-water basin could be separated from adjacent basins by geologic boundaries or by hydrologic boundaries.

Ground-water divide. Ridge in the water table, or potentiometric surface, from which ground water moves away at right angles in both directions. Line of highest hydraulic head in the water table or potentiometric surface.

Ground-water mound. Raised area in a water table or other potentiometric surface, created by ground-water recharge.

Head, total. Height of the column of water at a given point in a ground-water system above a datum plane such as mean sea level. The sum of the elevation head (distance of a point above datum), the pressure head (the height of a column of liquid that can be supported by static pressure at the point), and the velocity head (the height to which the liquid can be raised by its kinetic energy).

Heterogeneity. Characteristic of a medium in which material properties vary from point to point.

Highly confined aquifer. A confined aquifer that receives only minor leakage through overlying confining strata.

Homogeneity. Characteristic of a medium in which material properties are identical throughout.

Hydraulic conductivity (K). A coefficient of proportionality describing the rate at which water can move through a permeable medium.

Hydraulic gradient (i). Slope of a water table or potentiometric surface. More specifically, change in head per unit of distance in a given direction, generally the direction of the maximum rate of decrease in head. The rate of change in total head per unit of distance of flow in a given direction. The change in total head with a change in distance in a given direction. The direction is that which yields a maximum rate of decrease in head. The difference in hydraulic heads ($h_1 - h_2$), divided by the distance (L) along the flowpath.

Hydrogeologic unit. Any soil or rock unit or zone that because of its hydraulic properties has a distinct influence on the storage or movement of ground water.

Impermeable. Characteristic of geologic materials that limit their ability to transmit significant quantities of water under the head differences normally found in the subsurface environment.

Interference. The result of two or more pumping wells, the drawdown cones of which intercept. At a given location, the total well interference is the sum of the drawdowns due to each individual well. The condition occurring when the area of influence of a water well comes into contact with or overlaps that of a neighboring well, as when two wells are pumping from the same aquifer or are located near each other.

Isochrone. Plotted line graphically connecting all points having the same time of travel for water or contaminants to move through the saturated zone and reach a well.

Isotropy. The condition in which the properties of interest (generally hydraulic properties of the aquifer) are the same in all directions.

Leakage. The vertical flow of ground water; commonly used in the context of vertical ground-water flow through confining strata.

Maximum contaminant level (MCL). Maximum permissible level of a contaminant in water that is delivered to the users of a public water system. Maximum containment level is defined more explicitly in Safe Drinking Water Act (SDWA) regulations (40 CFR Section 141.2).

Observation well. A well drilled in a selected location for the purpose of observing parameters such as water levels or water chemistry changes.

Piezometric surface. See potentiometric surface.

Point source. Any discernible, confined, or discrete conveyance from which pollutants are or may be discharged, including, but not limited to, pipes, ditches, channels, tunnels, conduits, wells, containers, rolling stock, concentrated animal feeding operations, or vessels.

Porosity. The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment.

Potable water. Suitable for human consumption as drinking water.

Potentiometric surface. A surface that represents the level to which water will rise in tightly cased wells. If the head varies significantly with depth in the aquifer, then there may be more than one potentiometric surface. The water table is a particular potentiometric surface for an unconfined aquifer.

Radial flow. The flow of water in an aquifer toward a well.

Recharge area. Area in which water reaches the ground-water reservoir by surface infiltration. An area in which there is a downward component of hydraulic head in the aquifer.

Semiconfined aquifer. A confined aquifer whose confining bed may vertically conduct significant quantities of water.

Stagnation point. A place in a ground-water flow field at which the ground water is not moving.

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

Tritium (^3H). The radioactive isotope of hydrogen with a half-life of 12.3 years. The presence or absence of tritium in ground water provides a method for estimating when the water was recharged at land surface.

Unconfined aquifer. An aquifer over which there is no confining strata.

Well field. An area containing two or more wells supplying a public water supply system.

Wellhead. The physical structure, facility, or device at the land surface from or through which ground water flows or is pumped from subsurface, water-bearing formations.

Wellhead protection area (WHPA). 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.

Zone of contribution (ZOC). The area surrounding a pumping well that encompasses all areas and features that supply ground-water recharge to the well.

Zone of influence (ZOI). The area surrounding a pumping well within which the water table or potentiometric surfaces have been changed due to ground-water withdrawal.

Zone of transport (ZOT). The area surrounding a pumping well, bounded by an isochrone and/or isoconcentration contour, through which a contaminant may travel and reach the well.