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Wellhead Protection in Confined, Semi-Confined, Fractured, and Karst Aquifer Settings

Protection areas around wells producing from confined, fractured, and karst aquifers are, because of their complex hydrogeology, more difficult to define than protection areas for wells in porous media settings. This factsheet provides background information explaining the need to define protection areas for wells that draw public drinking water from several complex hydrogeologic settings: confined, semi-confined, fractured, and karst aquifers. These settings include aquifers in which the ground water is not open to the atmosphere, or the aquifer does not consist of unconsolidated porous media. Several figures illustrate these settings in a general way.

A wellhead protection area (WHPA) is the surface and subsurface area surrounding a public water supply well or wellfield that contributes recharge to, and through which contaminants are likely to reach, that well. Because contaminants from sources within a WHPA are likely to reach the well, EPA has developed the Wellhead Protection Program to prevent ground water contamination in those areas.

Figure 1 shows a geological cross section through an unconfined (that is, water-table) aquifer. These are aquifers in which ground water at the top of the saturated zone is at atmospheric pressure (open to the atmosphere). In Figure 1, the aquifer is a porous medium comprised of sand and gravel. Well pumpage has caused the cone of depression that is shown

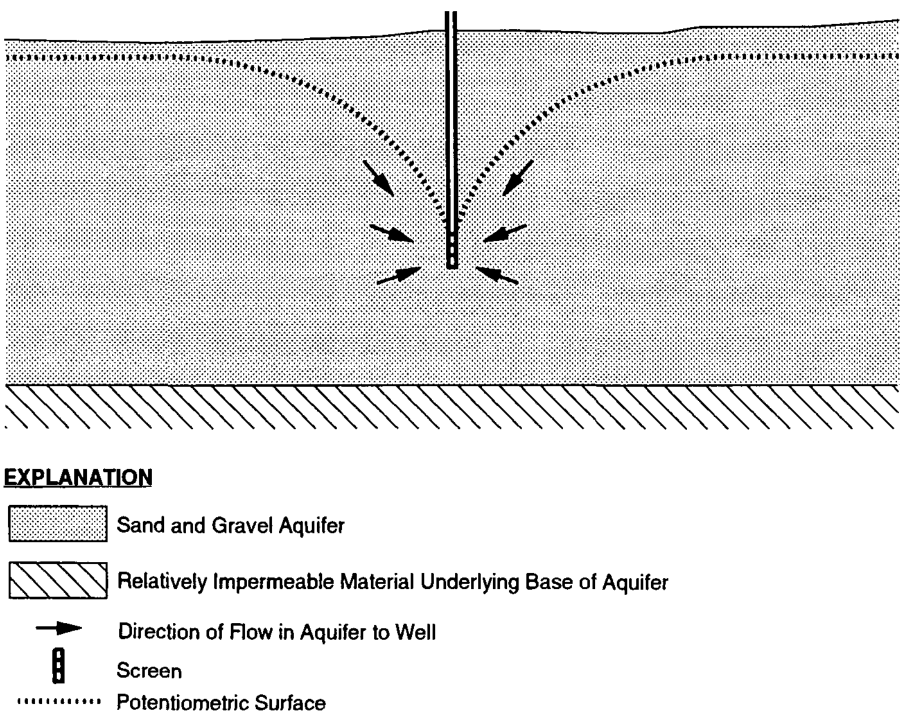


Figure 1. Well Pumping From an Unconfined Aquifer

in the potentiometric surface (also referred to as "water table" in a water table aquifer) around the well. Because ground water in such aquifers is open to the atmosphere, wells in these aquifers are particularly susceptible to contamination from sources in close proximity.

Confined Aquifers

In confined-aquifer settings, it is important to protect, not only the WHPA surrounding the well, but **also** that portion of the aquifer recharge area that supplies recharge, and potentially contaminants, to the well. Because this recharge area can be at a great distance from the well, it is important to understand the nature of the ground water flow paths in order to determine which part of the aquifer recharge area is to be protected.

In a confined aquifer, ground water is not open to the atmosphere and is generally above atmospheric pressure. A confining layer (aquitard) of lower-permeability material restricts the upward and downward movement of the ground water into or out of the confined aquifer. In many cases, a confined aquifer is found between two aquitards in a geologic sequence.

Water levels in cased wells that tap confined aquifers are usually above the top of the aquifer. Water may even flow to the land surface. In the context of wellhead protection, a confined aquifer is still considered confined even if water levels have dropped below the base of the confining bed as a result of, for example, well pumpage. The imaginary surface defined by the level to which ground water would rise in wells that are open to the atmosphere is referred to as the potentiometric surface. In the figures that follow, the cone of depression in the potentiometric surface around the well is caused by well pumpage.

The degree to which an aquifer is confined varies. Water flow in a truly confined aquifer (Figure 2) -- one in which the overlying aquitard is very highly impermeable -- lacks a downward component. Therefore, the aquifer receives no recharge of water (or contaminants) from directly above. Recharge is limited to areas beyond the extent of the overlying aquitard, where the

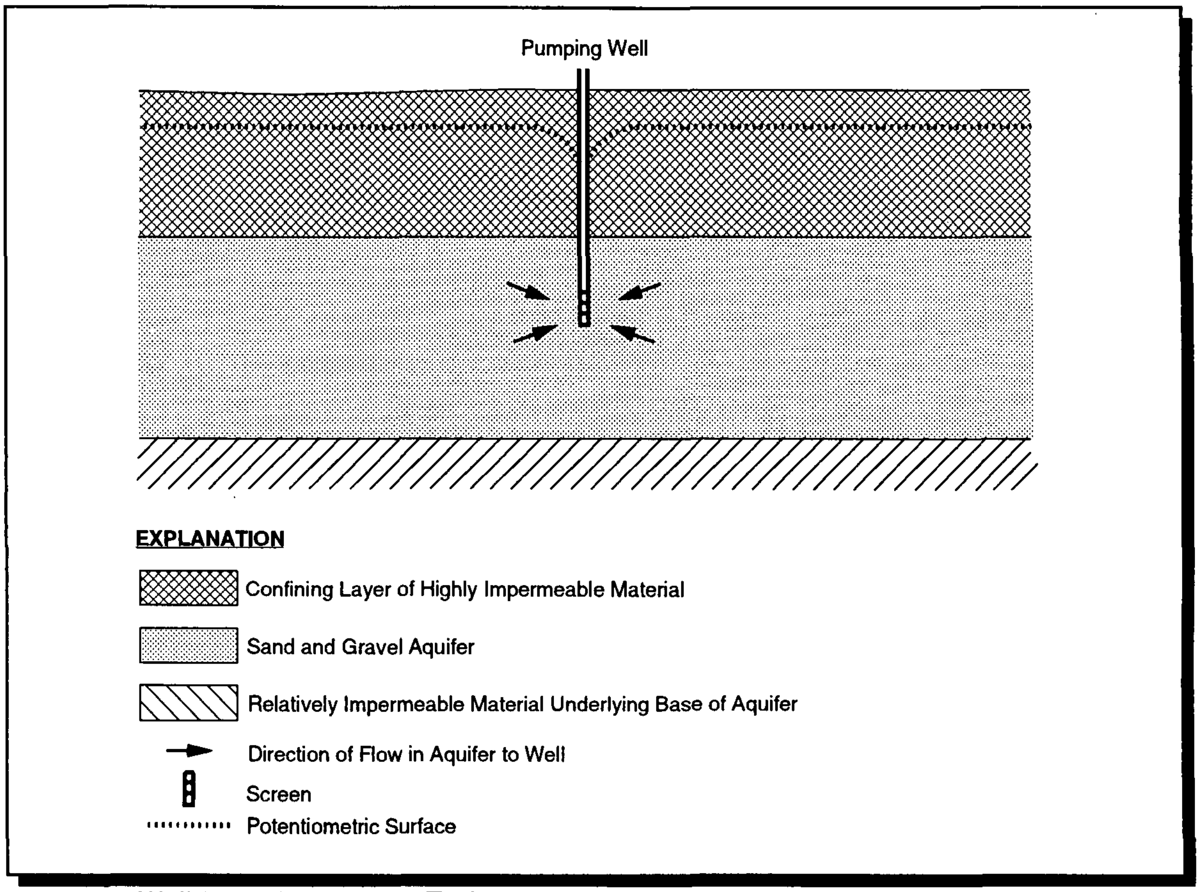


Figure 2. Well Pumping From a Truly Confined Aquifer

aquifer is not confined. These recharge areas are frequently at great distances from the wells that tap into the aquifer. Therefore, except for a small protection area immediately surrounding the well casing to ensure no contaminant movement along any imperfections in the casing, grouting or backfill around the well, **a WHPA surrounding the well itself may serve no protective function in the case of a truly confined aquifer.**

Most aquitards, however, contain "breaches." Some of these breaches are natural, caused by local variations in the materials that make up the aquitard, by local thinning or "pinching out" of the aquitard, or by conduits such as sinkholes, faults, or fractures. Other breaches, such as open boreholes and cracked well seals, may be caused by humans. Figure 3 depicts a confined aquifer in which a sandy zone of much higher permeability and a borehole breach the overlying aquitard.

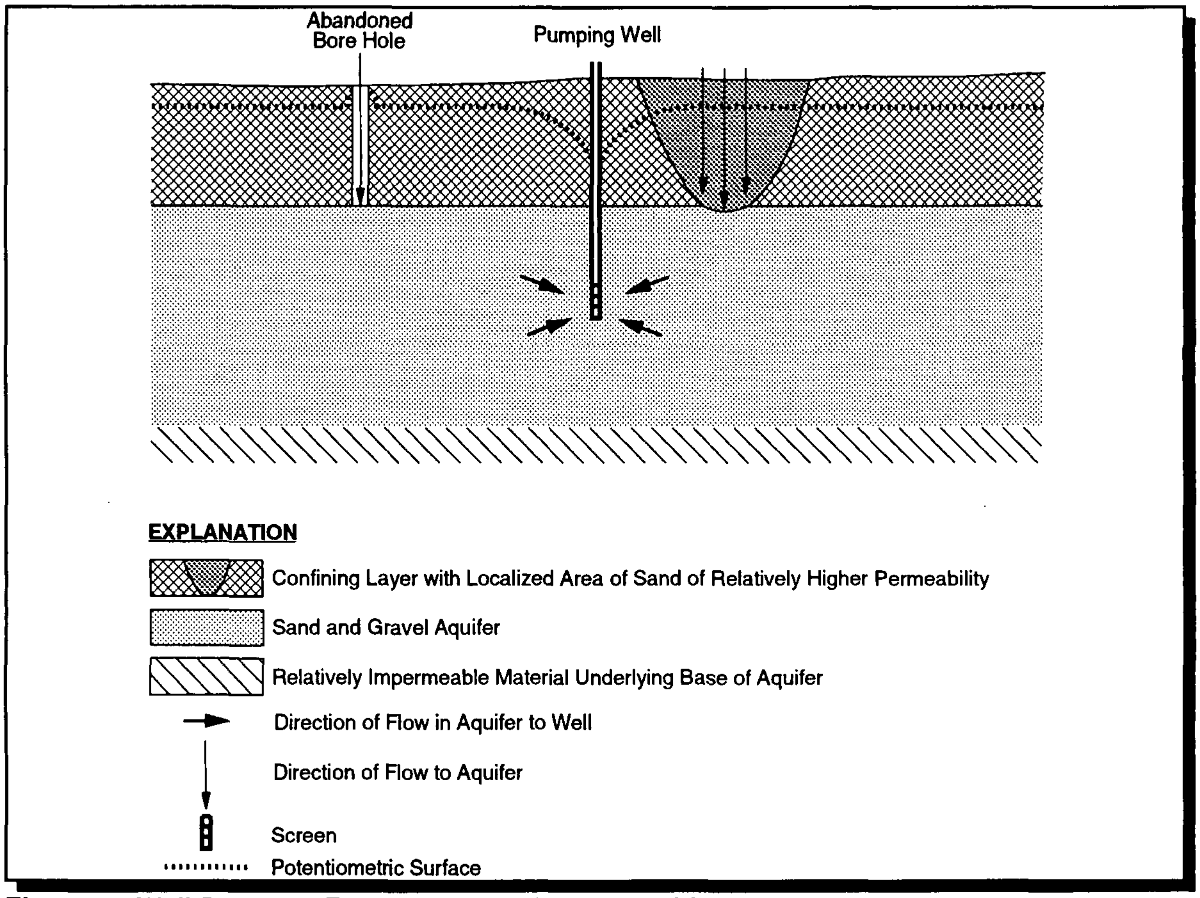


Figure 3. Well Pumping From a Confined Aquifer with Breaches

When potentiometric levels in a confined aquifer are low enough (perhaps as a result of well pumpage) to permit ground water to flow downward through the overlying aquitard, breaches serve as conduits for the movement of water and contaminants into the aquifer. These breaches may provide a relatively short path between a contaminant source and a well screen.

In leaky, or semi-confined aquifers, a layer of moderately low permeability (such as the sandy clay shown in Figure 4) overlies the aquifer. Even if a leaky aquitard is continuous (unbreached), the aquifer will slowly receive recharge water from above if pumping or other factors cause ground water flow to have a downward component. **From the perspective of wellhead protection, a leaky-confined setting is similar to the breached-confined setting: In both cases, contaminants may enter the aquifer not only in remote recharge areas but also near the well.**

Fractured and Karst Aquifers

Many aquifers are composed of rocks that transmit water primarily (or exclusively) through cracks, fractures, cavities, and caverns. These aquifers consist of coarsely or finely fractured rock and rock with karst and mature karst features. These aquifers may be confined, partly confined, or unconfined.

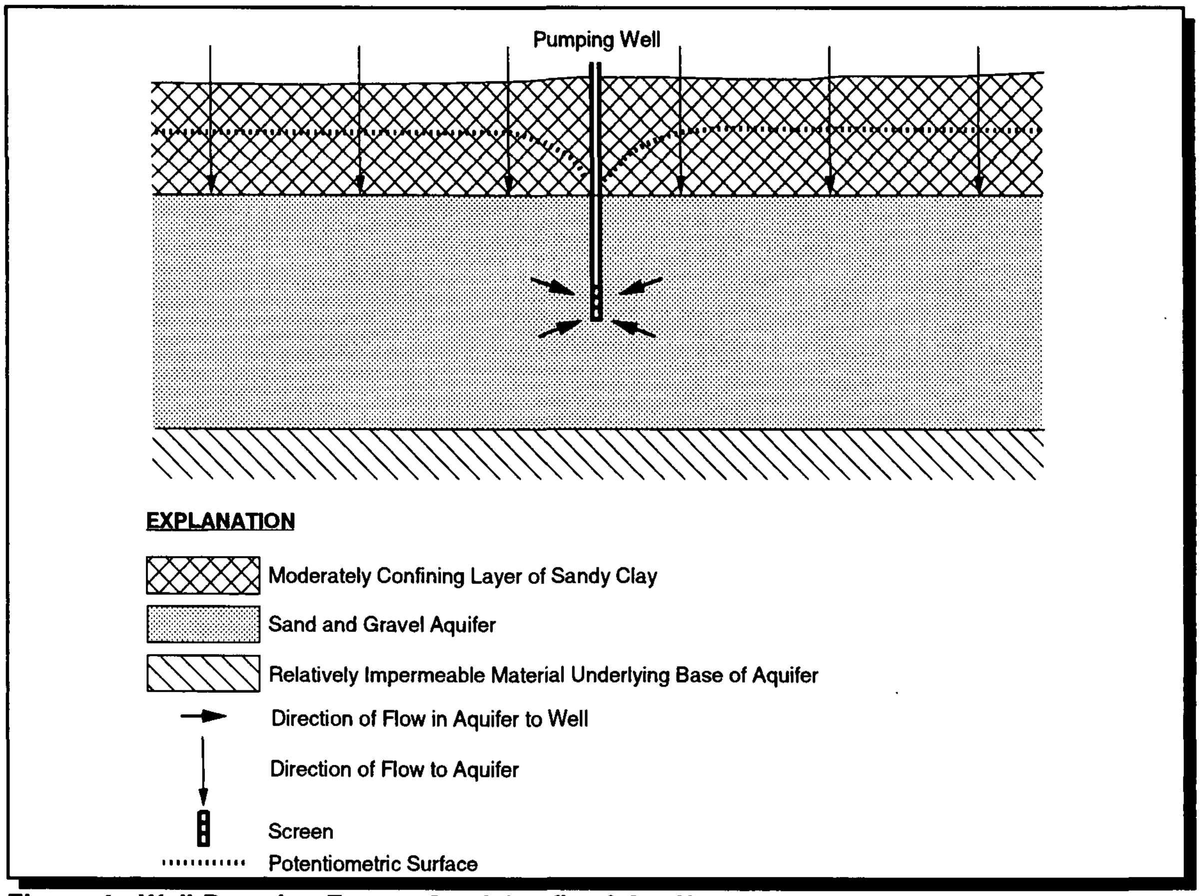


Figure 4. Well Pumping From a Semi-Confined Aquifer

Water movement in a rock with pervasive, fine, intersecting fractures (Figure 5) may be very similar to water movement in a porous medium such as sand. For this kind of fractured-rock setting, WHPA delineation techniques used for unconsolidated porous settings may be appropriate, although some methods have been found to be more applicable to finely fractured settings than other methods (USEPA, 1991a). The larger and more widely spaced the fractures, the less is the similarity to unconsolidated porous media, and the less appropriate is the use of delineation methods designed for wells in porous media.

Karst features develop in rocks where ground water has widened fractures and porous zones into solution cavities by dissolving soluble minerals. Generally, this widening is limited to carbonate rocks such as limestone and dolomite. Karst aquifers (Figure 6) typically contain solution cavities along fractures and along contacts between rock layers. Karst aquifers are generally within several hundred feet of the land surface.

Sometimes a karst aquifer with fairly uniform porosity and without cavernous flow may be similar enough, at the scale of WHPA delineation, to a porous medium that porous-media WHPA delineation techniques may be used. However, in mature karst (Figure 7), solution openings are large, well-developed, and often partially cavernous. Sinkholes, closed depressions, and pipes (vertical solution cavities often filled with weathered rock and soil) are common features of mature karst aquifers. In this setting, contaminant movement may be measured in feet per minute rather than feet per year, as is common for unconsolidated porous media. Because large volumes of water move very rapidly through the large solutional openings, use of delineation techniques developed for porous media is not appropriate.

Protection of ground water quality of wells and springs tapping karst aquifers is particularly difficult because: (1) ground water flow is complex, and different fractures or cavities may contain waters from totally different sources that mix where openings intersect; (2) wide fractures and large, well-developed solution cavities in mature karst provide little if any contaminant attenuation by the aquifer; and (3) sinkholes or open fractures and cavities may provide a direct connection

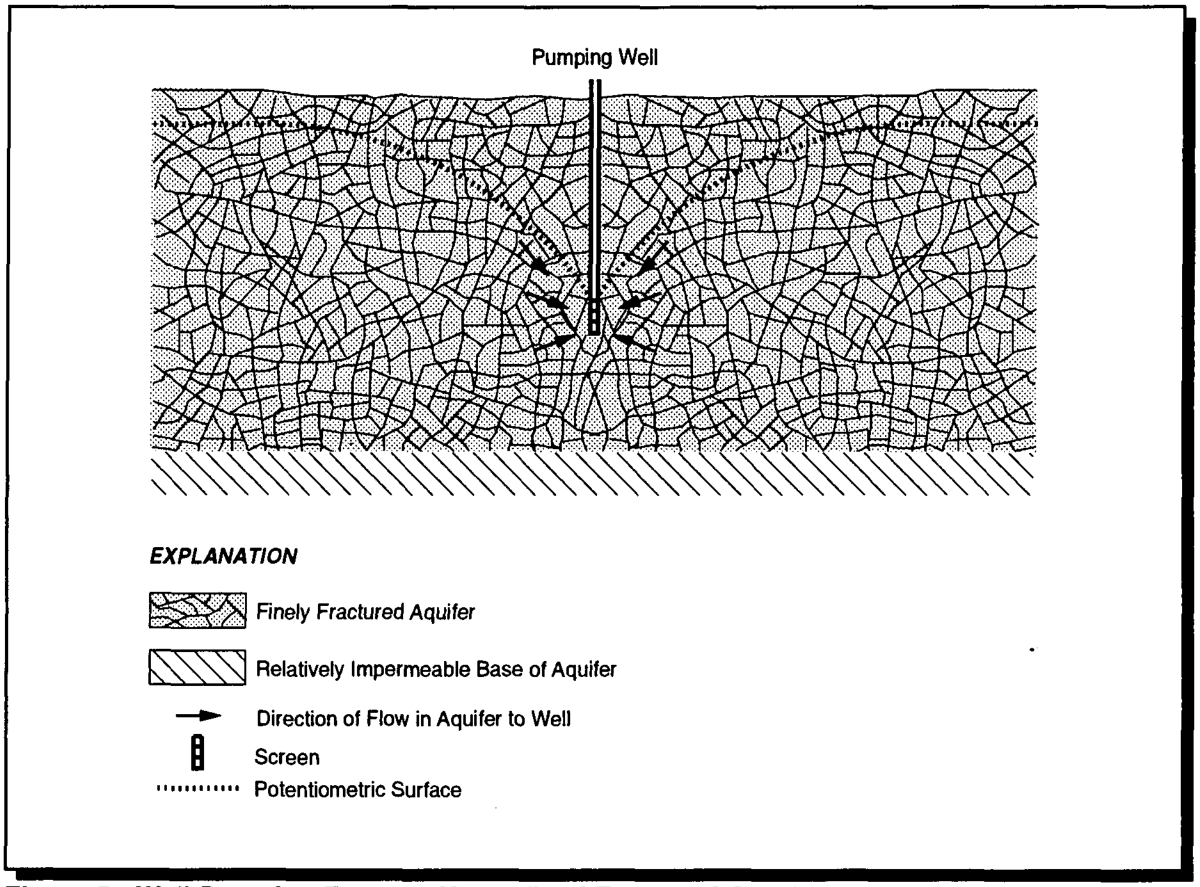


Figure 5. Well Pumping From an Unconfined Fractured Aquifer

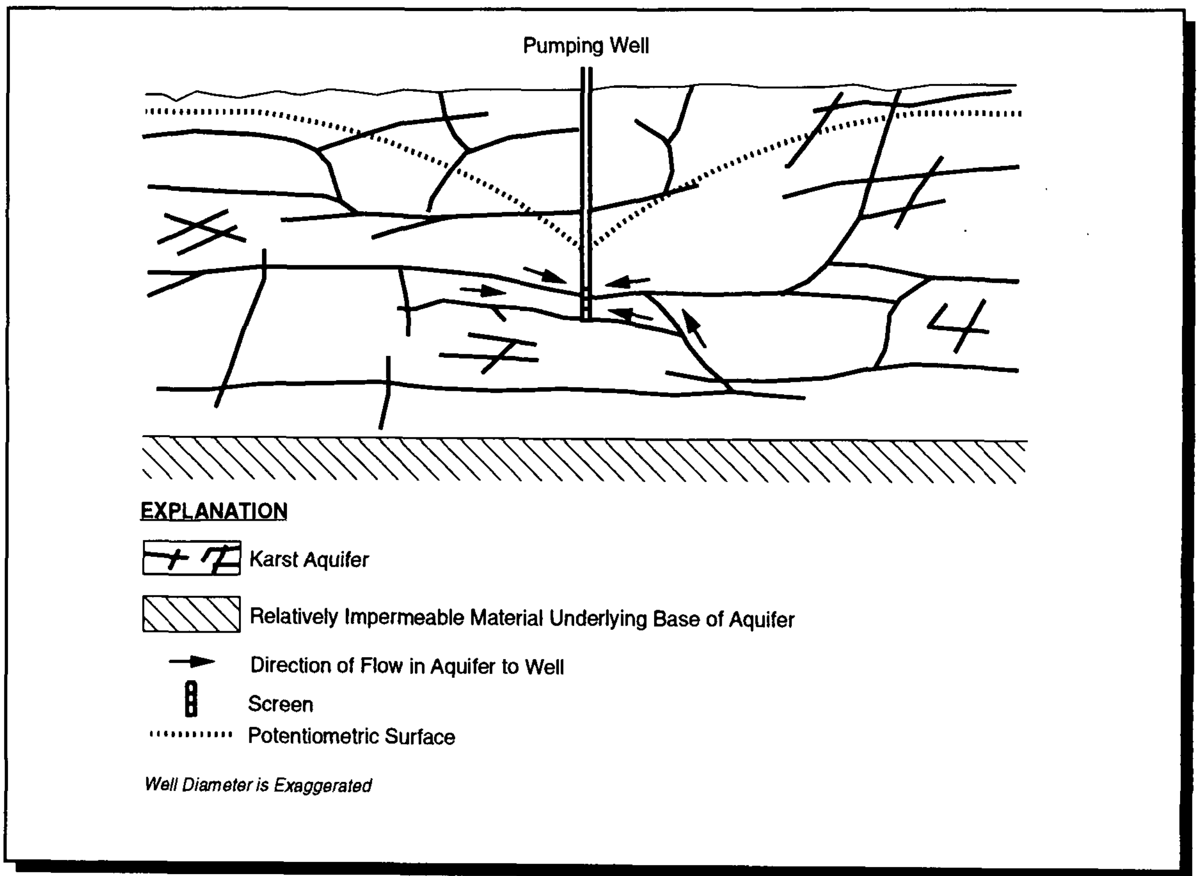


Figure 6. Well Pumping From an Unconfined Karst Aquifer

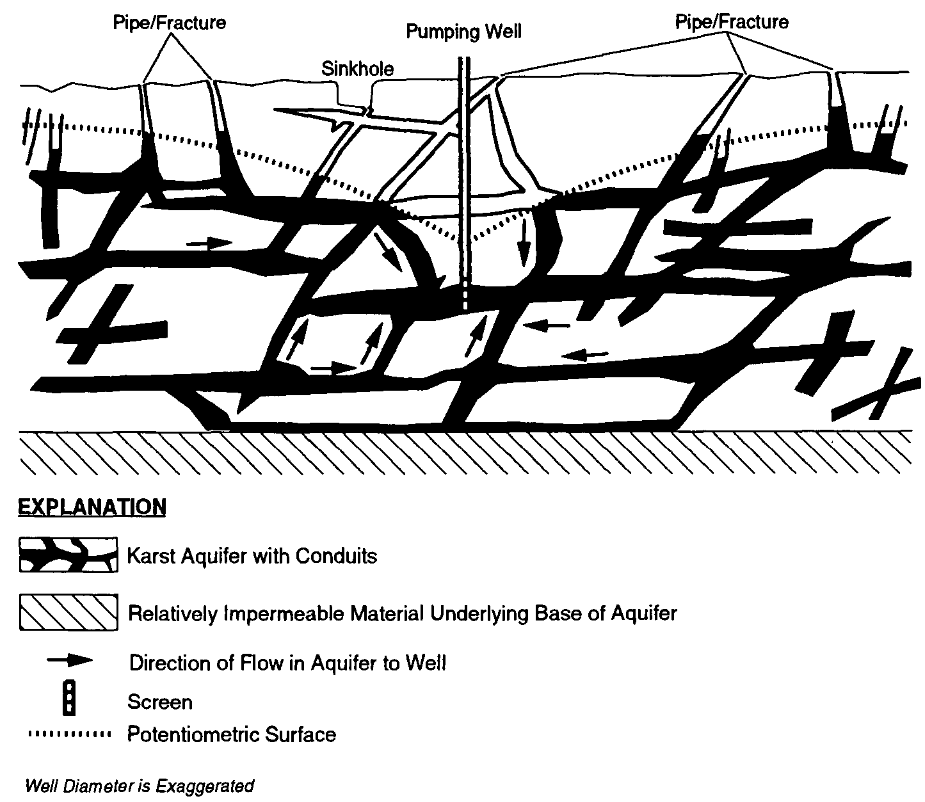


Figure 7. Well Pumping From an Unconfined Mature Karst Aquifer

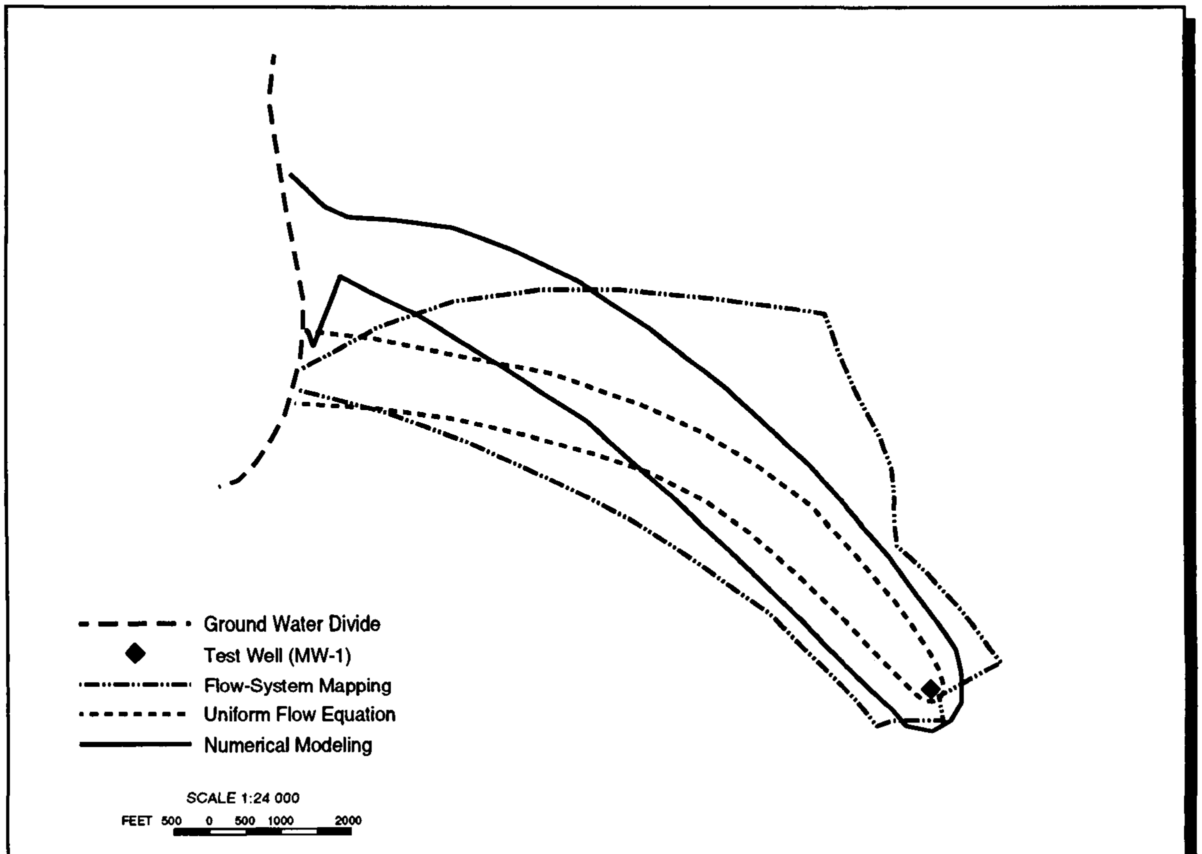
from the land surface to the aquifer. **Although WHPA delineation is difficult in these settings, wellhead protection is particularly important because contaminants can move rapidly and extensively throughout karst aquifers.**

WHPA Delineation Methods for Confined, Fractured, and Karst Aquifers

Because of potentially high flow velocities and complex flow routes in karst and coarsely fractured settings, and remote locations of recharge areas in confined settings, methods such as arbitrary and calculated fixed radii, may be of limited or no value when applied to fractured, karst, or confined aquifers. Additionally, application of some porous media methods to finely fractured settings has been found to more poorly approximate a well's recharge area than application of other porous media methods.

Hydrogeologic mapping, particularly when combined with dye tracing and lineament analysis can be used to delineate WHPAs in karst settings. USEPA, 1988, provides helpful information for using dye tracing to determine flow paths in karst settings. The publication describes both qualitative and quantitative dye tracing. Qualitative dye tracing involves "tagging" a sample of water with a tracer and then monitoring several ground water locations for the reappearance of the dye-laden water. The reappearance of the dye may be observed visually or through passive detectors and then identified via chemical or instrumental analyses. After qualitative dye tracing is used to identify ground water sites that are in hydraulic connection with the injection site, quantitative dye tracing may be performed to give estimates of peak concentration, dispersion, and persistence. Quantitative dye tracing is considerably more labor intensive than qualitative dye tracing and is performed less frequently.

USEPA, 1991a, describes several methods for delineating WHPAs in fractured aquifers that behave as porous media and discusses method effectiveness. The methods presented are: Vulnerability Mapping, Flow-System Mapping, Flow-System Mapping With Time-of-Travel Calculations and With the Uniform Flow Equation, Residence Time Approach and Numerical Flow/Transport Models. Figure 8 shows a comparison of WHPAs delineated with three different methods. The document also assesses which of the methods presented are applicable to fractured aquifers that do not behave as porous media.



(From USEPA, 1991a, p. 62)

Figure 8. Comparison of wellhead protection areas delineated with three different delineation methods. The hydrogeologic setting is a fractured aquifer that behaves as a porous medium.

USEPA, 1991b, describes Cone of Depression methods and Time of Travel methods that can be used for delineating WHPAs in confined aquifers whose regional potentiometric surface has a negligible slope. The document also presents a Zone of Contribution With Identification of Flow Boundaries method and several Zone of Transport With Time of Travel Contours methods that are applicable where the regional potentiometric surface has a non-negligible slope. Figure 9 depicts the difference in capture zones calculated with the WHPA Model for two hydrogeologic settings, identical except for the slope of the regional potentiometric surface. The publication also describes approaches for determining the presence and degree of confinement provided by an overlying aquiclude.

The reader is referred to these publications for further information on delineating WHPAs in karst, fractured, and confined settings.

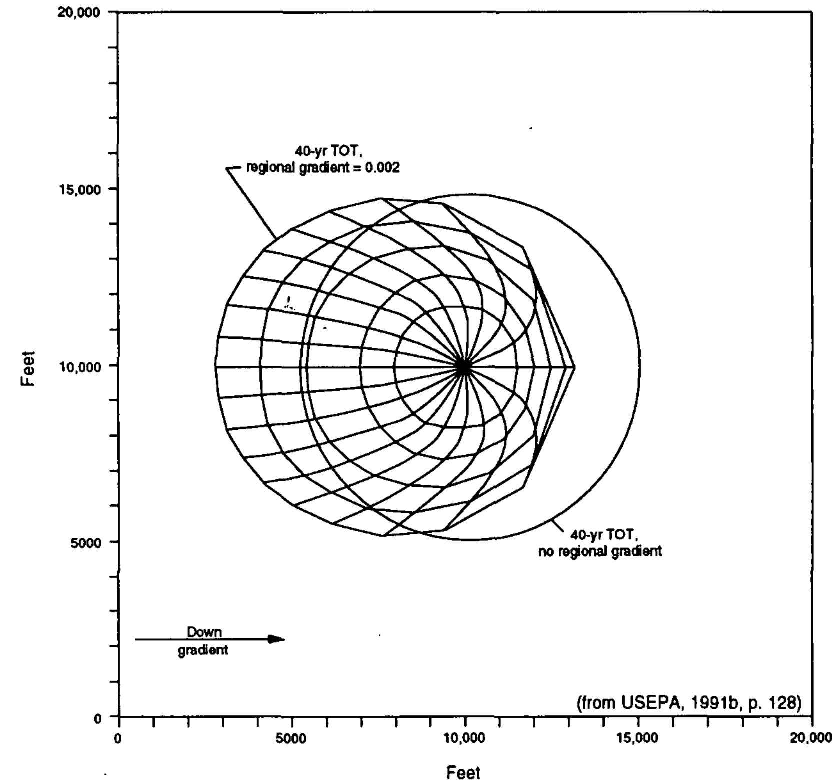


Figure 9. Wellhead protection areas of 5-, 10-, 20-, 30-, and 40-year time of travel (TOT) assuming a potentiometric surface with a regional slope of 0.002, and a wellhead protection area of 40-year time of travel assuming a flat regional potentiometric surface. The method used was the semianalytic WHPA computer program.

References

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U.S. Environmental Protection Agency. June 1991b. *Wellhead Protection Strategies for Confined-Aquifer Settings*, U.S. EPA 570/9-91-008. 168 pp.