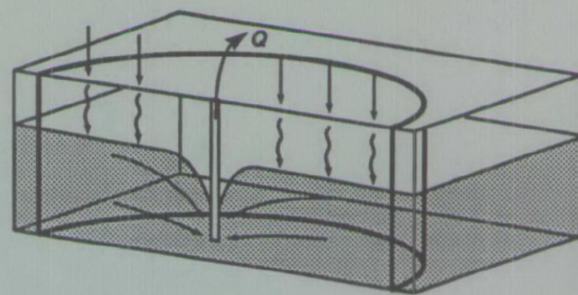
United States
Environmental Protection
Agency

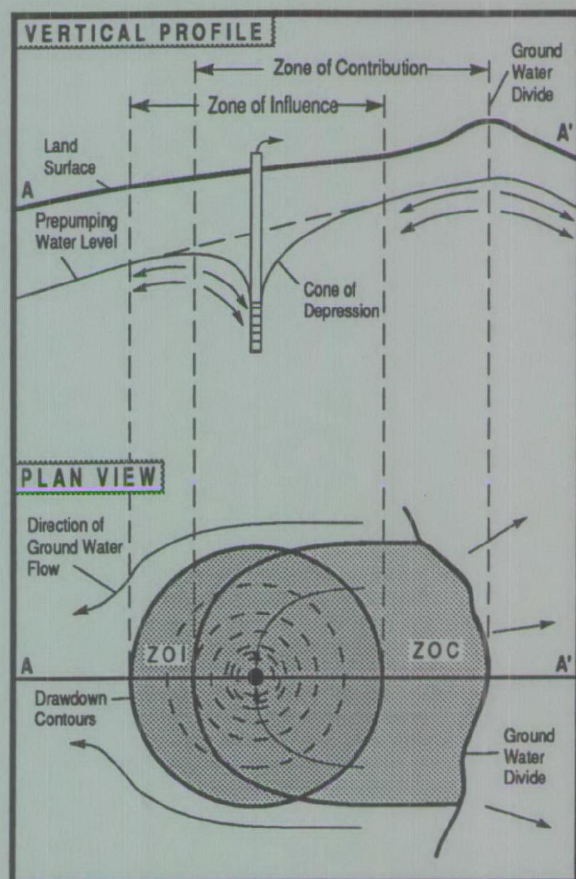
Office of Water
(WH-550)

EPA 813-B-92-003B
September 1992

EPA

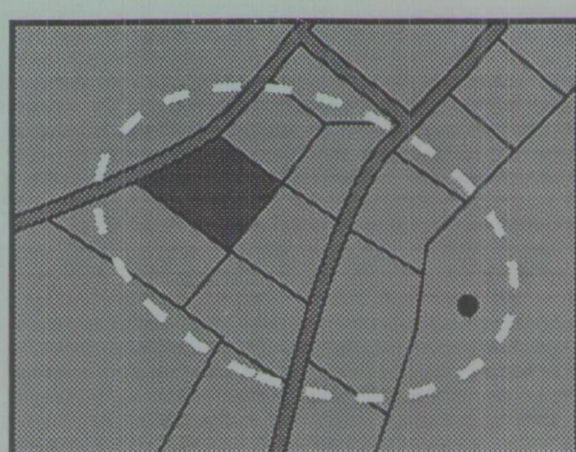


WELLHEAD PROTECTION IMPLEMENTATION TRAINING



Module 2: Delineation

Briefing and Detailed Instructor's Notes



Slide # D-01

Photo of fenced-in wellhead

Typical Wellhead

Source: Horsley & Witten, Inc., 1991

Key Points to Cover:

- This module discusses delineation of wellhead protection areas (WHPAs)
- Although the fence around the wellhead shown in this slide provides some protection from vandalism, it fails to protect well water quality from contaminant sources even a few feet away
- Many wells are located in commercial or industrial areas, and potential contaminant sources, such as the gas station shown across from the wellhead, may be very close to the well
- Management measures can be used to alleviate contamination pressures on existing wells and to avoid siting of new wells in areas that have, or will have, contaminant sources within contributing areas

Notes

Typical Wellhead **Slide # D-01**

This module discusses the definition of and theory behind the wellhead protection area. This requires presentation of technical material; the instructor may wish to review ground water concepts from a reference book or from materials listed in Module 9, the Annotated Bibliography. The instructor should evaluate the technical sophistication of his/her audience and present concepts at an appropriate level. This may mean omitting some slides for an audience with little scientific background or providing a quick review of the terminology slides for an audience with technical expertise. The module begins with the wellhead.

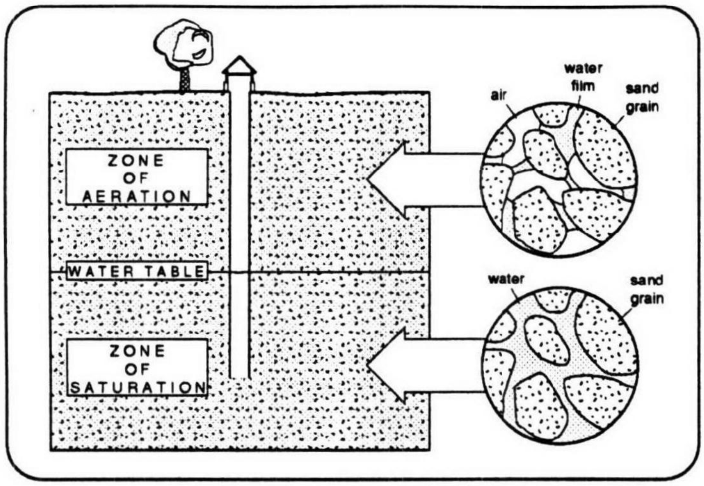
This slide is used to introduce wellheads as the point of water supply and the focus of wellhead protection (WHP).

The wellhead is the location where a well enters the ground. Usually, a pump is mounted on top of the wellhead, as shown here. The wellhead and pump are typically located in a well house which provides protection from weather and tampering. The fence around the wellhead in this slide is probably intended to provide protection against vandals. Indeed, it probably protects would-be vandals from electrical shock more effectively than it protects ground water from contamination.

A wellhead protection area (WHPA) is intended to protect the quality of ground water before it is withdrawn from the ground. It is intended to protect against and to alleviate contamination threats for existing supply wells, but it can also be used to protect future wells. The WHPA's major focus is preventative rather than remedial.

There is a wide range of effectiveness of wellhead protection. The area of protection can range from a delineation of a half mile radius, to watersheds or contributing areas measured in square miles. Wellhead protection can also range widely with respect to type and level of management--from padlocks, fences, and outright land ownership to land use zoning, hazardous materials restrictions, and public education. (These management techniques are discussed in Module 4.) Different protection areas and techniques must be designed to fit the variety of hydrogeologic settings and contaminant threats of public water supply wells across the country.

The instructor may wish to point out the gas station shown close to the wellhead in this slide as a potential threat to well water quality.



Saturated-Unsaturated Zone

Source: Horsley & Witten, Inc., 1991

Key Points to Cover:

- In order to understand WHPA delineation, a brief introduction to ground water science is needed

- Ground water is the water that saturates rock or soil in the subsurface environment. That part of the ground containing ground water is called the saturated zone. That part of the ground containing water and air is called zone of aeration or the unsaturated zone. If the saturated zone is sufficiently permeable to be capable of yielding usable quantities of water to wells, it may be termed an aquifer, or water-bearing rock. Aquifers may be composed of either consolidated or unconsolidated material. (Consolidated material means rock, such as granite or sandstone. Unconsolidated means material such as sand or gravel)

- The water table is the top surface of the water-saturated zone. Its elevation usually varies seasonally, with the highest elevations occurring in late winter or spring. The water table elevation is measured in observation wells

- Recharge is water that percolates down from the land surface, through the unsaturated zone to the water table. Ground water moves in response to gravity, to discharge at a lower elevation, often to a surface water body

Notes

Saturated-Unsaturated Zone **Slide # D-02**

This slide is used to define a few standard ground water terms and develop a working understanding of fundamental ground water concepts in order to discuss WHPA delineation.

Water in the ground occurs in the pore spaces or voids in the rock. In the example in this slide, the rock is sandstone, and the pore spaces are the interstices between the sand grains. In a compact and consolidated rock such as granite, the only pore spaces are cracks. This explains why sand can hold (and yield) much more water than granite.

Water in the zone where all of the pore spaces are completely filled with water (water-saturated) is called ground water. The zone that is partially filled with air and partially filled with water is called the zone of aeration, or the unsaturated zone. A water-saturated rock is termed an aquifer if it can yield usable quantities of water.

The water table is the top surface of the saturated zone and, therefore, the top surface of ground water. The water-table elevation is measured in observation wells. The water level in a well will be at the same elevation as the water table, unless the ground water is under pressure, as in a confined aquifer.

Precipitation recharges the ground water system by percolating, under the influence of gravity, down from the land surface through the aerated zone to the water table. Rain and snow melt cause pulses of recharge to reach the saturated zone, raising the water table. In many temperate areas of the United States, the water table naturally rises in late fall, winter, and early spring, and declines in late spring, summer, and early fall. There is less seasonal fluctuation in water tables in arid and tropical regions of the country (e.g., Arizona, Hawaii, Florida).

Hydrologic Cross Section

Hydrologic cross section showing aquifer, confining layers, stream and well

Source: USGS, 1987

Key Points to Cover:

- This slide is used to introduce basic ground water terms that are needed to understand delineation theory and methods
- Recharge is derived primarily from precipitation.
- The underground pathways from recharge areas to wells may be complicated by the permeable (conductive) and impermeable (poorly conductive) layers of rock through which the water must travel. Consequently, the WHPA may include recharge areas at a considerable distance from the wellhead. Artesian wells which tap aquifers confined beneath impermeable layers commonly exhibit this characteristic
- Time of travel for ground water varies with the type of aquifer (soil, bedrock, etc.) and with the distance the water travels. Rates may vary from a few feet per year, in low permeability deposits such as silt or clay, to a few feet per day, in permeable sand, gravel, and fractured rock
- Pumping of wells induces localized changes in ground water flow, creating a cone of depression in the water table immediately surrounding the well, or in the pressure surface surrounding an artesian well

Notes

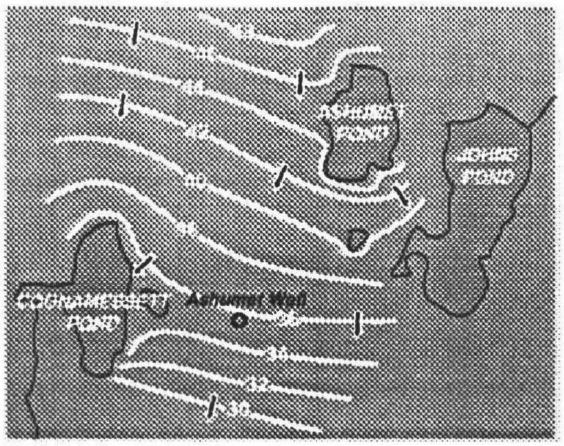
Hydrologic Cross Section **Slide # D-03**

Ultimately, all recharge of ground water is derived from precipitation. Knowledge of the pathways of water from recharge to withdrawal through wells is needed to design protection of the water's quality. This slide shows a cross-section through an aquifer, illustrating water pathways.

Underground pathways from areas of recharge to wells may be complicated by the geologic plumbing system, i.e. permeable (conductive) and impermeable (poorly conductive) layers of rock, through which the water must travel. The bulk of water passing through the ground takes the path of least resistance (most conductive path) while only small amounts leak through the poorly conductive, confining layers. Consequently, recharge areas may be at a considerable distance from wellheads if poorly conductive confining layers are present. Wells completed in aquifers confined beneath poorly permeable layers, such as the Edwards Aquifer in San Antonio, Texas (see slides D-09 and D-10), exhibit this displacement of recharge (and the WHPA) to locations where the permeable aquifer rock is exposed to inflow from precipitation.

Time of travel for ground water varies with the pathway length and depth and the conductivity of the intervening geologic materials along the pathway. Rates of ground water movement may vary from feet per day in shallow gravel alluvium to fractions of a foot per year in deeply buried poorly permeable silt and clay. Generally speaking, the deeper the pathway, the slower the rate of ground water movement.

Pumping of a well lowers the water level in the well and, in turn, in the aquifer surrounding the well, thereby creating a pressure gradient toward the well. This gradient is the driving force for water to flow from the aquifer into the well. The decrease in pressure around a well is manifested as a depression in the water table. This depression takes the shape of a cone with its point down exactly at the location of the well, and has therefore been labeled the "cone of depression" by hydrologists.



Water Table Map, Sand and Gravel Aquifer

Source: USGS, 1984

Key Points to Cover:

- The direction of ground water flow is determined from water level measurements in observation wells. From measurements of the water table elevation in wells, a contour map of the water table can be prepared, as shown for a water table aquifer in the Ashumet Pond area, Massachusetts
- Ground water flows perpendicular to water table contours, from higher elevations to lower elevations, e.g. from 48 to 30 feet elevation for the area shown on the slide
- Direction of ground water flow may be altered by pumping wells, which temporarily or permanently draw down the water level and cause cones of depression in the water table around the wells. Pumping causes localized reversals of the normal ground water flow

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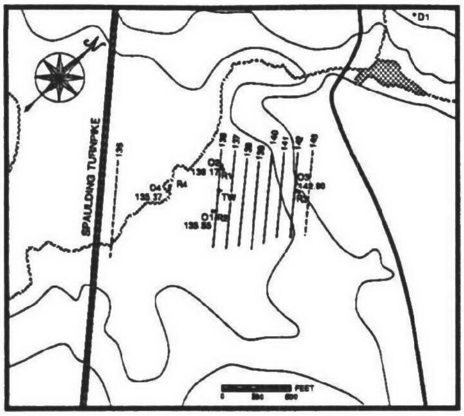
Water Table Map, Sand and Gravel Aquifer **Slide # D-04**

The instructor should evaluate his or her audience to determine the need to explain water table contours and mapping before proceeding to discuss using contours to determine ground water flow direction.

A fundamental tool for describing 3-dimensions on a 2-dimensional surface (map) is the contour line. Contours can be used to represent a third dimension such as the elevation of the land surface (topographic maps), the water table, a pressure surface, or some other property like the aerial distribution of concentrations of a contaminant in ground water. Contour lines can be thought of as the intersections of the land or water surface with a series of equally spaced horizontal planes. More simply, they are lines connecting points of equal elevation on the surface being mapped. The contours used in this illustration show the elevation of the water table every 2 feet (30 feet, 32 feet, 34 feet, etc.).

Contour maps of the water table are constructed by interpolation and extrapolation from water level measurements made in observation wells and plotted on maps. The ponds in this water table map are areas where the water table is above the land surface and pond elevations are virtually the same as ground water elevations. The instructor might point out that the ponds act as an express lane for the southerly flow of water, offering less resistance than the aquifer. The map in this slide was prepared from measurements at 50 observation wells and the ponds.

Ground water flows from areas of high potential energy to areas of lower potential energy in response to the force of gravity. The most direct (straight line) flow response is perpendicular to the contour lines. Therefore, a series of arrows pointing downgradient (from high levels to lower levels) can be drawn to describe the flow field (i.e., directions of ground water flow) at this site. This type of construction assumes that the aquifer's ability to conduct water is homogeneous over the mapped area.



Water Table Map, Bedrock Aquifer, Dover, New Hampshire

Source: Griswold and Vernon, in press

Key Points to Cover:

- Measurement of the water table and direction of ground water flow may be costly and time-consuming in certain geologic environments, such as bedrock, where it is difficult and expensive to install enough monitoring wells to construct a water table contour map

- Generally, water table contours parallel land contours, but this is not always the case, as shown in this slide

- The water table map shown here was developed as part of investigations for installation of a new public water supply well in a bedrock aquifer in Dover, New Hampshire

Notes

Water Table Map, Bedrock Aquifer, Dover, New Hampshire

Slide # D-05

This slide is an example of a water table map superimposed on a topographic map. The contours on the surface of the water table show as a series of straight lines with a 1-foot contour interval. The topography (shape of the land surface) is shown by curved contour lines with a 20-foot contour interval.

This is a water table map of a fractured bedrock aquifer at Dover, New Hampshire, that was prepared as part of the investigations for the development of a new public supply. The water table contours were constructed from water level measurements in the 9 wells shown on the map. The most expensive part of preparing a water table map is usually well construction.

The most difficult part of preparing a water table map is obtaining water level measurements from all of the wells at approximately the same time. The instructor may wish to emphasize that because ground water gradients may be small, and because water table levels vary seasonally and in response to recharge events and pumping, it is essential that the measurements used to construct the map are from the same point in time. Mixing water levels measured at different times when preparing a water table map may result in grossly erroneous interpretations of gradients and flow directions.

Cross-section of water table and discharge to cedar swamp, showing flow lines and clusters of monitoring wells

Hydrologic Cross Section--Cedar Swamp

Source: Horsley & Witten, Inc., 1991

Key Points to Cover:

- Ground water movement is three-dimensional; it moves vertically as well as laterally. For example, there is an upward component to flow in areas of discharge, such as in the cedar swamp shown here. Flow also may have an upward component at points of discharge to streams, rivers, and coastal shores

- There may be a downward component to ground water flow in recharge areas

- Vertical components of flow are measured with wells open at different depths below the water table

Notes

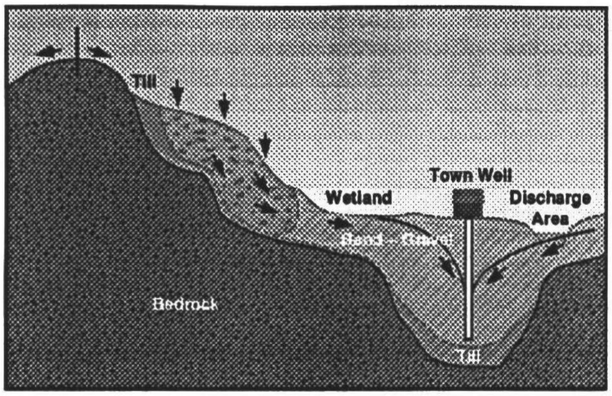
Hydrologic Cross Section--Cedar Swamp **Slide # D-06**

The instructor may wish to explain to the audience that a cross section is a diagram of a vertical slice through the ground.

Ground water movement is three-dimensional. Water is conducted through the ground much like heat is conducted through a solid object. It does not flow over the surface of the water table as some textbook diagrams might lead you to believe. Ground water movement has vertical components as well as lateral components. This is a reason why ground water flow may seem difficult to visualize and mathematically complicated to describe.

In the cross section shown in this slide, there is an upward component to flow near areas of ground water discharge, such as the cedar swamp. Conversely, there is a downward component to flow in recharge areas, where water is being added to the saturated zone from above.

Just as horizontal gradients (the water table map) are determined from measurements of water levels in observation wells at different lateral locations, vertical gradients are determined from measurements in observation wells set at different depths (vertical locations) in the aquifer. The instructor may point out different depths of openings at the ends of observation wells shown in the slide. Flow directions in the vertical plane of the cross section are drawn perpendicular to the equipotential lines (contour lines of equal water level potential) which were constructed from the observation well measurements.



Buried Valley Aquifer

Key Points to Cover:

- Buried valley, or valley fill, aquifers are common in many parts of the country. They may be glacial or alluvial in origin
- A ground water discharge area commonly occurs in the original river valley, if a topographic depression remains under present conditions, as is shown in this slide
- The sand and gravel that fills the original valley is usually highly permeable, allowing much of the precipitation which falls to recharge the aquifer
- Runoff from less permeable areas, such as bedrock outcrops, may also contribute recharge to the aquifer, after it flows over the land surface to a permeable deposit where infiltration is possible

Notes

Valley Fill Aquifer **Slide # D-07**

Valley fill aquifers, sometimes misleadingly called buried valley aquifers, are common in many parts of the United States and the world. They are composed of unconsolidated layers of highly permeable sand and gravel, and varying amounts of poorly permeable silt and clay that partially fill valley areas. These aquifers are the result of deposition from running water (streams) and are described as alluvial or glacial in origin. Because of their locations and origins, they are commonly long, thin, and narrow in shape. They are almost always crossed by streams, usually by streams that run over them lengthwise.

Valley fill aquifers occupy low areas. Their surfaces are usually permeable sands and gravels which readily accept recharge from precipitation. They also receive recharge from streams and other runoff that drain into the valleys from adjacent upland areas.

Wells in valley fill aquifers can induce infiltration of stream water (i.e., "pull" water from a stream into the ground water system by creating a pressure gradient), thereby artificially increasing recharge and increasing well capacity. For example, one of the most productive wellfields in the northeastern United States produces about 5 million gallons per day for the city of Schenectady, New York, from a small aquifer (less than 1/2 square mile in area) next to the Mohawk River. The instructor may wish to cite valley fill aquifers known to the audience as examples.

Streams that cross valley fill aquifers may be described as "gaining" or "losing". Most of the streams crossing these aquifers in humid areas, where precipitation is abundant, are gaining streams. In these aquifer/stream systems, normal water flow is from the ground into the stream, hence the stream gains flow (base flow) in a downstream direction. In arid and semiarid areas, particularly where streams drain out of mountains onto valley fill alluvial deposits, streams naturally lose water to the underlying permeable aquifers.

Cross-section of aquifer layers

Floridean Aquifer

Source: USGS, 1984

Key Points to Cover:

- The water bearing properties of carbonate rocks such as limestone may be greatly enhanced by solution channels and cavities. Ground water travel rates may be very rapid in these channels. For example, ground water may travel 1000 or more feet per day in cavernous limestone, while in sand and gravel aquifers, it may travel 1-10 feet per day, and in silt/clay formations, it may move less than 1 foot per day

- In this slide, the sand and gravel formation shown below the limestone also functions as an aquifer, although ground water flow is interrupted by the interspersed lenses of less permeable silt and clay

- Limestone aquifers having solution channels and large cavities are common in the southeast states; the geologic condition is termed "karst"

Notes ______________________________

Floridean Aquifer **Slide # D-08**

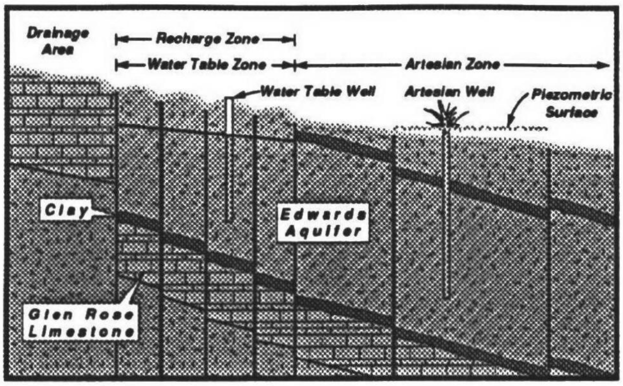
The water bearing properties of carbonate rocks (limestone, and dolostone) may be greatly enhanced through solution enlargement of pore spaces. Because these rocks are somewhat soluble in water, circulating ground water can dissolve and remove some of the rock from the linings of pore spaces, thereby enlarging the pores and making them more conductive of water. Where carbonate rock has been subjected to solution, it may become a very productive aquifer. Where carbonate rock has not been subjected to solution, it may be no more productive an aquifer than fractured granite, for example.

The carbonate Floridean Aquifer shown in cross-section in this slide is actually in Georgia. Aquifers and ground water do not recognize state lines or other political boundaries. The carbonate aquifer is indicated by the brickwork-like pattern. Another aquifer composed of sand and gravel (shown in yellow) lies below the carbonate rock.

Carbonate aquifers affected by solution are common in the southeastern states. Solution of the rock leads to the formation of caverns and underground channels that follow the paths of the original fracturing in the rock. In many areas of carbonate rock, dissolution of rock and enlargement of caves becomes so advanced that the roofs of the caves collapse forming sink holes and other irregular features in the land surface. Such terrain is called "karst" by geologists, after the name of the province in Yugoslavia considered the type locality for these erosional land forms.

Although the enlargement of underground spaces increases the storage of ground water and the permeability of the rock, and therefore the yields of wells, the patterns of ground water flow are largely dependent on the original fracture patterns in the rock. Further, because the fracture patterns are difficult to map or predict, it is very difficult to determine the recharge areas that contribute to wells in karst terrain. In some karst areas, tracers have been added to ground water and tracked to determine which areas contribute to wells.

Because of the very large openings through which the ground water moves, large foreign (potentially contaminating) objects can be transmitted over long distances, and much of the filtration effect common to most ground water sources is absent. Imagine the displeasure of the water superintendent who discovered grapefruit rinds in his well.



Hydrologic Cross-Section--Edwards Aquifer

Source: Texas Water Commission, 1988

Key Points to Cover:

- The Texas Edwards Aquifer provides an interesting example of a confined aquifer that results in an artesian, or free flowing, well
- The recharge zone, to the left in this slide, allows water to infiltrate to the water table. Ground water flowing to the right becomes confined under a layer of clay

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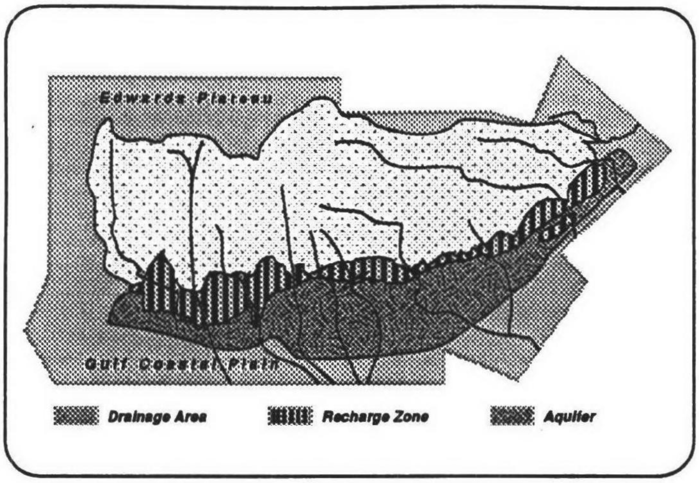
Hydrologic Cross-Section--Edwards Aquifer **Slide # D-09**

The Edwards Aquifer near San Antonio, Texas, is an artesian (i.e. under pressure) aquifer confined beneath a layer of clay. In the slide, a cross section through the aquifer is shown. The aquifer is exposed at the surface on the left (north) and overlain by a wedge of clay on the right (south). Water recharges the aquifer where it is exposed at the surface and flows gradually to the south where it is pumped out of wells, discharges through naturally flowing wells and springs, or slowly leaks upward through the clay. An aquifer is classified as artesian when the water level in wells rises above the top of the aquifer. (Non-artesian aquifers are termed "water table aquifers".)The instructor may point out the zones where the Edwards Aquifer is artesian and water table, and point to where the water level rises above the top of the aquifer.

The level to which water would rise in wells above the top of the artesian portion of the aquifer defines a surface called the potentiometric surface (or piezometric surface). It is analogous to the water table in an unconfined aquifer. If the potentiometric surface is higher than the land surface, the well will be free flowing. At places where the water table or the potentiometric surface rises above the land surface and a confining layer is absent or breached, natural flowing springs may form.

The instructor may wish to mention the catfish farmer with a flowing well in the Edwards Aquifer. His farming operation used so much water that it threatened the yields of other wells, and the yields of natural springs. The instructor may also wish to mention the Texas Blind Salamander, an endangered species that lives in natural springs issuing from the Edwards Aquifer. If the spring dries up because of withdrawal from the aquifer, the salamander's unique habitat will be eliminated. Ground water protection is not just an issue of ground water quality. Ground water quantity must also be considered.

Slide # D-10



Plan View--
Edwards Aquifer

Source: Texas Water Commission, 1988

Key Points to Cover:

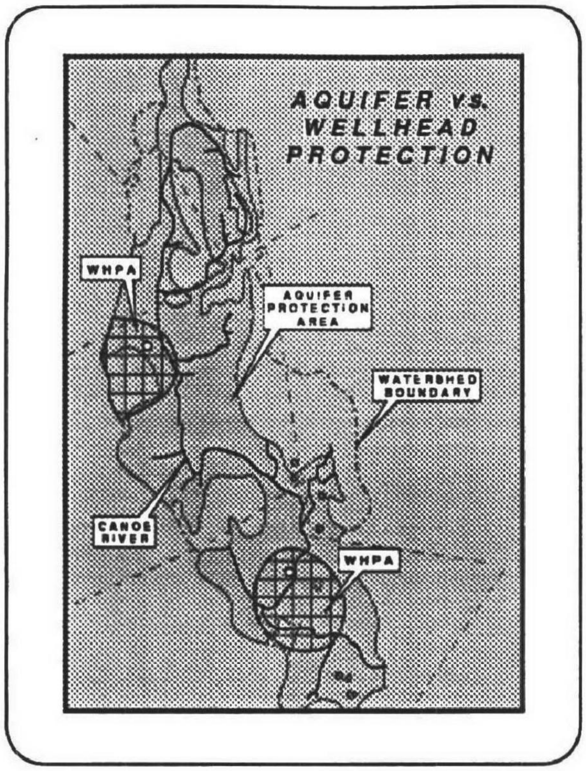
- Due to geologic conditions, recharge to the Edwards Aquifer is limited to the striped band shown in this slide, where the confining clay is absent and the aquifer formation outcrops at the land surface
- Precipitation on the drainage area flows as overland runoff and in streams to the permeable recharge area, and then into the confined aquifer

Notes

Plan View--Edwards Aquifer **Slide # D-10**

Because of the geologic structure, recharge to the Edwards Aquifer is limited to the striped band shown on this slide. This recharge area is the outcropping of the Edwards Aquifer where it is under water table conditions and where precipitation can infiltrate the top of the Edwards Sandstone and percolate down to the water table. Recharge to the Edwards Aquifer is also derived from the overland runoff and streams that drain onto the recharge band from the uplands to the north. Streams to the south of the recharge area flow over the poorly permeable confining layer and do not recharge the aquifer.

For this and other artesian aquifers, the recharge area is displaced from the wellhead, perhaps many miles. Consequently, the recharge area may be under a different jurisdiction than the water withdrawal point.



Aquifer vs. Wellhead Protection

Key Points to Cover:

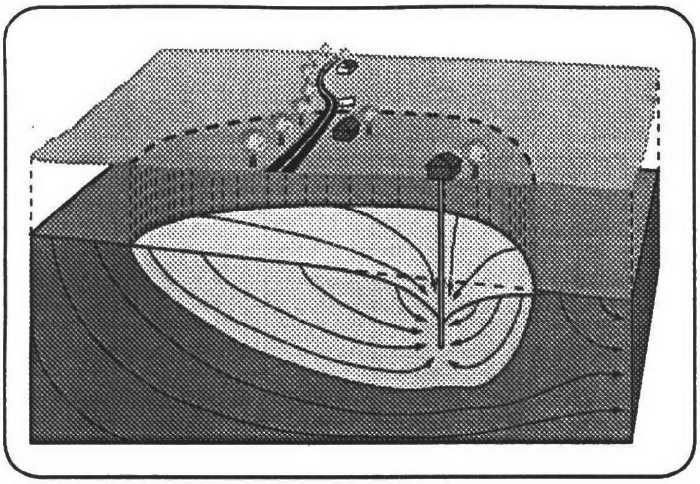
- The wellhead protection area which supplies the well may be much smaller than the area of the whole aquifer, as shown in this slide
- In order to insure long-term protection of the drinking water supply, management measures may be advised for a larger portion of the aquifer than the WHPA, depending on the accuracy of the delineation method used to determine the wellhead protection area

Notes

Aquifer vs. Wellhead Protection **Slide # D-11**

A wellhead protection area may be much smaller than an aquifer protection area. In this slide, the WHPA is delineated as that part of the aquifer which contributes water to the well. The water quality at the production well is more directly influenced by factors, such as land use, within the WHPA than by factors in the aquifer as a whole.

In this example the aquifer protection area is delineated from geologic mapping and the WHPA is delineated from a combination of geologic mapping and hydraulic analysis of the pumping well and the aquifer.



Aquifer vs. WHPA-- Cross-Section

Key Points to Cover:

- A WHPA is a portion of an aquifer, defined by both natural flow and pumping conditions
- Management of only the WHPA does not consider future expansion of water supply needs. The WHPA is delineated in order to determine what area should be protected, but WHPAs for potential wells should also be subject to management measures
- The extent of an aquifer upgradient of a well that contributes to the well may be determined with a flow net analysis. This analysis is a straight-forward geometric exercise: because ground water flows perpendicular to water table contours, boundaries may be drawn that divide water which flows into the well, or surface water resource, from that which flows past it

Notes

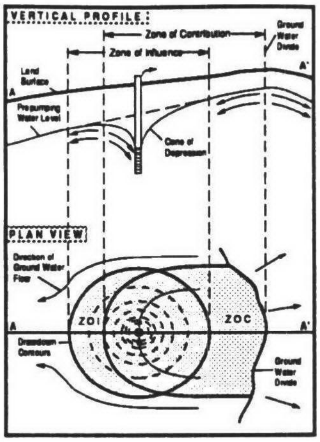
Aquifer vs. WHPA--Cross-Section **Slide # D-12**

This slide shows a cross section of a WHPA that was delineated by hydraulic analysis based on hydrologic properties of the aquifer (from aquifer pumping tests) and application of the Theis non-equilibrium flow equation for ground water flow near a pumping well. The WHPA may also be delineated by application of computer simulation models, using more aquifer-specific data than is required by the analytical approach. This WHPA defines the zone of the aquifer from which the well captures water. It is specific to the conditions of the aquifer and the well, and depends on the pumping rate of the well.

This WHPA, shown on the land surface in the slide as the dark green area, is a subset of the aquifer. Management tools can be focused on the WHPA to protect the quality of water produced by the well.

The zone of contribution to the well (in yellow) is predicted by superimposing the effects of pumping (cone of depression) on the water table of the natural flow system, and then making a flow net analysis of the resultant shape of the water table under pumping conditions. The instructor may remind the audience that flow directions can be plotted from water level contours (equipotential lines) by constructing arrows pointing downgradient and perpendicular to the contours.

Note that in the example in the slide, ground water from the left (upgradient) side of the cross section flows under the well and does not contribute to the well yield. This is a dramatic example of the complexity of analyzing and predicting the three-dimensional flow of ground water.



Zones of Influence and Contribution

Source: EPA, 1989

Key Points to Cover:

- A pumping well draws down the water table in its immediate vicinity, the zone of influence (ZOI), creating a cone of depression
- The drawdown effect extends a given distance radially from the well, with the radius a function of well construction, pumping rate and duration, and aquifer properties
- Close to the well, the drawdown is sufficient to reverse the direction of ground water flow, causing water that would be downgradient under static (no pumping) conditions to contribute to the well
- Further from the well, the influence of pumping, drawdown, is insufficient to reverse the direction of flow, but is still greater than zero
- The area over that part of the aquifer which contributes water to the well, the zone of contribution or ZOC, may extend in an upgradient direction as far as the natural ground water divide and is often considered to be the WHPA's principal zone of contribution

Notes

Zones of Influence and Contribution **Slide # D-13**

This slide is used to discuss relatively technical material. The instructor may wish to omit this slide for a general audience.

The diagram in this slide shows how the impacts of a pumping well are superimposed upon the natural water table to determine the portion of the aquifer that contributes to the well. The process is called superposition and is merely the summing of water levels to obtain a new water level. This diagram is in two parts, a plan (map) view and a cross section linked by projection from the horizontal to vertical planes.

Pumping of a well lowers the water level around the well, forming a cone of depression. In a homogeneous aquifer (i.e. uniform properties of transmissivity), this lowering of the water table is an inverted cone with its point at the well and its base on the original water table. The shape of the cone becomes increasingly steep near the point, while the base of the cone is circular. At some distance from the well, the pumping ceases to influence the water table. This is the maximum extent of the cone of depression and defines the zone of influence (ZOI) of the well. Beyond this radius, the well has no effect on the original water level in the aquifer. The instructor may trace the circle representing the edge of the cone of depression on the map, and point out the difference between the pre-pumping water level and the cone of depression in the cross section.

The steepness of the cone and the radius of the ZOI are unique to each site because they are dependent on specific properties and conditions in each aquifer and each well. They are not transferable from site to site. Major factors controlling the shape and size of the cone of depression include aquifer hydraulic conductivity, aquifer thickness, storage coefficient, pumping rate and pumping duration.

The effect of combining the cone of depression with the pre-pumping water table is to change the direction of ground water flow in the vicinity of the well. In the cross-section view close to the well, but downgradient of the well (left side), the drawdown is sufficient to reverse the direction of ground water flow, causing water that would have flowed away from the well under non-pumping conditions to contribute to the well. The instructor may trace the arrows pointing to the well screen in the cross section, and show where the projected area of contribution would be (left of the well) in the map view. Further downgradient (left) of the well in the cross section view, the drawdown is insufficient to reverse the direction of ground water flow. Even though pumping the well causes drawdown (influences the water table) in the area, it does not cause the area to contribute to the well. The instructor may point out that one of the most prevalent errors is the assumption that the cone of depression is equivalent to the zone of contribution to a well.

The divide on the downgradient side of the well is located at the highest point on the new water table as can be seen in the cross section view. The instructor may point out the divide on both the cross section and the map. This divide forms the downgradient boundary of the zone of contribution (ZOC) to the well. It is the null point, or stagnation point, where the regional gradient reverses and flows toward the well. It is important to note that because the water table is very flat around the null point, ground water in this zone tends to stagnate, flowing neither toward nor away from the well.

Upgradient of the zone of influence, the water table slopes toward the well both before and during pumping, and although this zone of the aquifer is beyond the zone of influence, it contributes water to the well. This upgradient zone of contribution may extend to the regional natural ground water divide.

The land surface directly overlying the zone of contribution (ZOC) is in the path of recharge to the ground water that eventually supplies the well and is, therefore, the prime target for management to protect the well's water quality.

NON-TEXT PAGE

Methods of Delineation

Key Points to Cover:

- There are several methods for delineation of wellhead protection areas, ranging from the simple to the complex, with corresponding increases in cost and effort

- Using the simple methods, the wellhead protection area is a circle

- Using the more complex methods, or a combination of methods, the WHPA is a more complicated shape

- Delineation methods may or may not include field investigations. Inclusion of such work, as well as site specific data, makes the WHPA more accurate

- Many states have already determined which wellhead delineation methods are to be used for all WHPAs in the state. Communities in such states, therefore, will not need to select a method unless there is reason to believe that that state-required method is not appropriate (e.g., very different hydrogeology from rest of state)

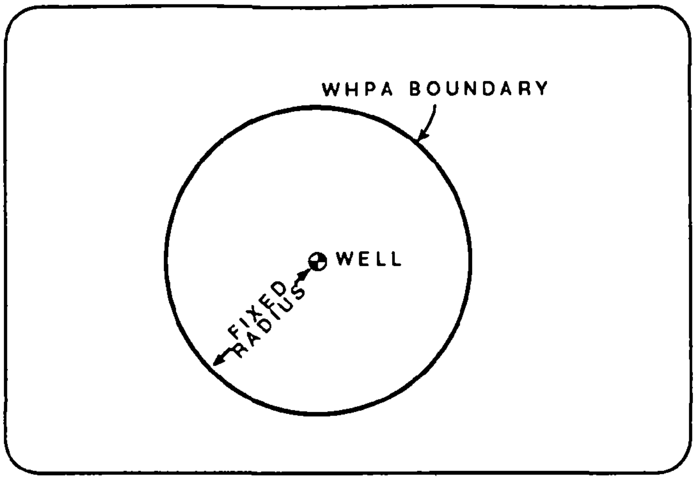
Notes

Methods of Delineation **Slide # D-14**

There are several methods of delineating wellhead protection areas, ranging from simple to complex, with corresponding cost and effort for their completion. The next six slides illustrate and comment on the characteristics of these methods.

Selection of a delineation method requires an understanding of the characteristics of each of the methods, including cost of delineation, degree of accuracy of delineation, and risk of contamination to the water supply. Generally, the more complex the delineation method, the more precise and the more expensive it will be to complete. Commonly, the complexity of WHPA shapes increase with the inclusion of more site-specific data and more analytical effort.

Many states, tribes, and territories have determined the delineation procedure to be used for wells under their jurisdiction. For presentations in these regions, the instructor may prefer to limit discussion to the method specified by the existing WHP program. Therefore, one or more of the following six slides may be omitted.



WHPA Delineation Methods: Arbitrary (Discretionary) Fixed Radius

Key Points to Cover:

- A circle drawn around the well forms the WHPA
- Radius may be a combination of setbacks needed for different contaminants, but should represent the minimum distance needed to attenuate the most conservative contaminant
- Quick, inexpensive and simple to apply, this method is often used for interim protection or as a first step in a protection plan
- Local hydrology dictates accuracy since actual contaminant travel rates and assimilation will vary with the aquifer material, the depth of the unsaturated zone, and other factors
- The radius is arbitrary only in the sense that site-specific calculations are not performed. The selected radius must be justified by the state, tribe, or community

Notes

WHPA Delineation Methods: **Slide # D-15**
Arbitrary (Discretionary) Fixed Radius

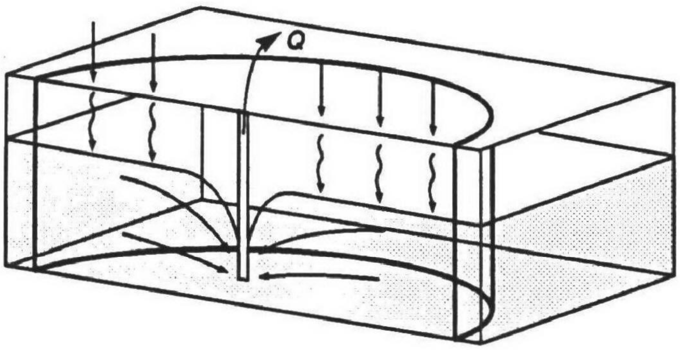
The simplest WHPA is a circle centered on the well. The radius of the circle may be fixed. For example, one state adopted a three-year interim radius of one-half mile for all public supply wells withdrawing 100,000 gallons or more per day until more precise delineations are prepared.

The instructor should note that the radius is arbitrary only in the sense that site-specific calculations are not performed. The radius selected must be based on science. The rationale for selecting a radius may be determined during the WHP process, or it may be borrowed from an existing EPA-approved WHP program. Note that states with approved programs may require the use of a specific radius or delineation method.

Most commonly the arbitrary (discretionary) fixed radius is based on minimum setback distances for contaminant attenuation. For example, most health regulations require a 200 or 300-foot sanitary protection radius to protect a well from pathogen (microbial) contamination. Private well regulations commonly require a 100-foot setback between wells and septic systems. These setbacks have their basis in research on the persistence of pathogens in different types of soils, geologic materials, and hydrologic environments.

The arbitrary fixed radius is quick, inexpensive, and simple to apply. However, it must be adapted to the characteristics of the locality where it is applied. For example, setbacks that are effective in sand aquifers on the Atlantic Coastal Plain in New Jersey would be inadequate in karst terrain aquifers in Kentucky.

Slide # D-16



WHPA Delineation Methods: Calculated Fixed Radius

Source: Horsley & Witten, Inc., 1991

Key Points to Cover:

- Under the calculated fixed radius method, the WHPA is a circle centered on the well
- The radius may be calculated using a time-of-travel approach or a hydrologic budget approach. In the latter approach, the WHPA is sized to balance the amount of water removed by pumping with that supplied by recharge
- Local conditions including well construction, aquifer characteristics, and pumping rates may be incorporated into radius calculations
- The accuracy of the calculated fixed radius is limited in that it does not account for all of the factors that influence contaminant transport, including the slope of the water table and the effects of significant hydrologic boundaries

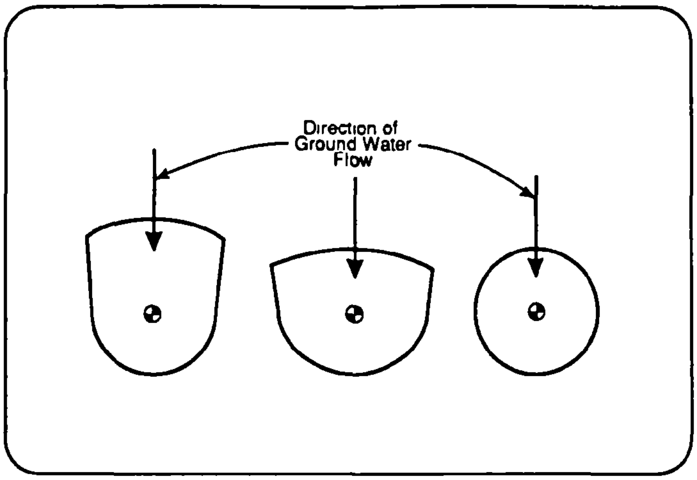
Notes

WHPA Delineation Methods: Calculated Fixed Radius **Slide # D-16**

The radius of the WHPA circle may be calculated by a mass balance approach. Here, the radius is selected to circumscribe an area large enough to provide average recharge from precipitation equivalent to the anticipated pumping rate of the well or wellfield.

The radius of the WHPA circle may also be calculated using a time-of-travel approach. Here, the volume of ground water which flows to the well within a specified time period is determined, based on ground water flow rates for the aquifer. For example, the WHPA might be sized to include "five-year's worth" of ground water.

These methods can incorporate site-specific conditions, such as pumping rate and aquifer transmissivity, but many assumptions, which lead to imprecision, are also required. For example, these methods assume a flat water table with no slope and no regional ground water flow.



WHPA Delineation Methods: Simplified Variable Shapes

Key Points to Cover:

- Using the simplified variable shape method, the WHPA is non-circular, but is elongated in the direction of ground water flow
- The method utilizes geometric shapes designed to approximate the hydrologic characteristics associated with pumping wells in a particular area
- Typically, a simplified variable shape is developed for one well and then transferred to other wells in the region. This may lead to errors if the hydrologic conditions are not equivalent
- Initial calculations as to size of the shape may follow the arbitrary (discretionary) or calculated radius methods

Notes

WHPA Delineation Methods: **Slide # D-17**
Simplified Variable Shapes

The simplified variable shapes method for delineating WHPAs attempts to make a standard modification of the fixed radius circle methods to account for uniform regional flowconditions. Geometric shapes other than a circle are designed to approximate the effects of regional hydrologic conditions. The method is sometimes referred to as the "cookie cutter" approach because all of the WHPAs commonly turn out to have the same fundamental shape.

WHPAs in a uniform flow field (sloping water table) become elongate "U" shapes with the arms of the U pointing upgradient and perhaps extending to the natural ground water divide. They are typically designed to accurately represent conditions at one site and are then transferred to other wells in the same region. As in the case of the calculated fixed radius method, these WHPAs may vary in size depending on pumping rates. The instructor may mention that in thick aquifers, water from far up the natural gradient may pass below a well, as was the case in slide D-12. In such a case, the WHPA will be elliptical rather than U shaped.

While the simplified variable shape WHPA more accurately defines the area which contributes water to a well than the circle WHPA, the method assumes somewhat similar conditions at all wells in the region of application. This assumption is a source of error for this method.

Diagram and equations for model

WHPA Delineation Methods: Uniform Flow Analytical Model

Source: Todd, 1980

Key Points to Cover:

- The Uniform Flow equation may be used to analytically model a WHPA
- The equation requires data on well pumping rate, hydraulic conductivity, saturated thickness of the aquifer, and the natural hydraulic gradient. The analytical model can only be as accurate as the input parameters
- The model calculates the boundary within which ground water contributes to the well, shown as the white partial ellipse. The white lines at the top of the diagram represent ground water flow paths which do not contribute water to the well, i.e. they are outside the zone of contribution

Notes ____________________

WHPA Delineation Methods: **Slide # D-18**
Uniform Flow Analytical Model

This slide is used to discuss relatively technical material. The instructor may wish to omit this slide for a general audience.

The uniform flow equation (Darcy's law) can be used to predict the location of ground water flow divides to define the boundary of the zone of contribution (ZOC). This analytical method requires the following data:

Well pumping rate
Hydraulic conductivity of the aquifer
Saturated thickness of the aquifer
Regional hydraulic gradient.

This method requires more site-specific hydraulic data than the previous methods. It can be the source of the derivation of the type shape for the simplified variable shape method. Hydraulic conductivity for the site is usually derived from an aquifer test performed by pumping the well and analyzing the drawdown measured in observation wells.

The flow lines in the slide (with arrowheads) show which areas of the aquifer contribute water to the well and which areas do not. The null point, or stagnation point, is the location of the gradient reversal (divide) downgradient of the well as was shown previously in slide D-13. The instructor may wish to turn back to slide D-13 to reinforce this concept. The boundary limit is the dividing line between flow lines that bypass the well and flow lines that go to the well. Again, the instructor may wish to turn back to slide D-13, and perhaps slide D-12, to reinforce these concepts.

WHPA Delineation Methods: Volumetric Flow

Diagram and equation for model

Source: EPA, 1987

Key Points to Cover:

- The Volumetric Flow equation may also be used to model a WHPA
- The equation requires data on pumping rate, length of well screen or open interval, aquifer porosity, and a selected time of travel such as 5 or 10 years. As with the Uniform Flow equation, the delineated WHPA can be only as accurate as the input parameters. Because it computes distances under the assumption of average velocity, a large margin of error may occur with this method since the aquifer may actually conduct water at different rates in different directions and at different depths

Notes

WHPA Delineation Methods: **Slide # D-19**
Volumetric Flow

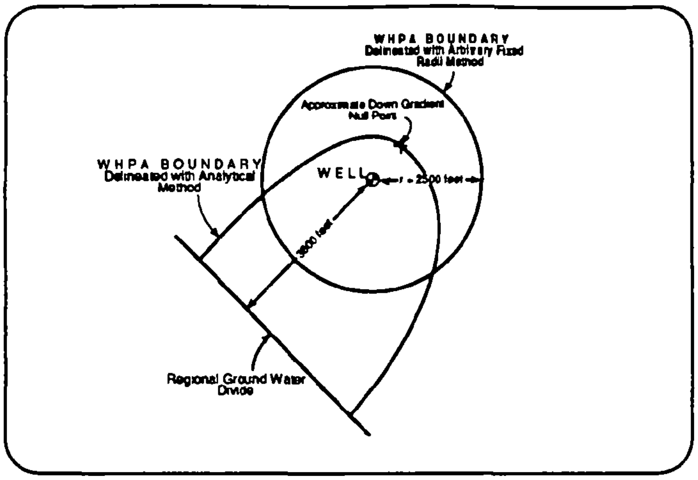
This slide is used to discuss relatively technical material. The instructor may wish to omit this slide for a general audience.

One approach to estimating that part of an aquifer which contributes to a well is to compute of the volume of a cylinder surrounding the well which contains a volume of water equivalent to the total water pumped.

The computation uses the equation for the volume of a cylinder, and requires the following input data:

Pumping rate
Duration of pumping
Aquifer thickness
Aquifer storage coefficient , or specific yield.

This method assumes average pore velocity and does not provide for longitudinal dispersion of contaminants caused by variations of hydraulic conductivity owing to stratification of an aquifer. It is applied to an assumed flat water table with no regional flow. The resultant radius is dependent on the selection of pumping duration. Although the calculation is simple and inexpensive, the result is relatively inaccurate and vulnerable to subjective manipulation (for example, selection of pumping duration).



WHPA Delineation Methods: Combination

Key Points to Cover:

- Using a combination of delineation methods and site specific data produces WHPAs of variable shapes
- The WHPA may be divided into zones, based on the different methods used, e.g. an immediate protection zone determined by arbitrary fixed radius and a more extensive zone determined with mapping and modeling
- Hydrologic mapping and field investigations may be used to make generic modeling more site specific. Techniques include dye trace studies, geophysics, and isotope aging
- Different techniques may generate different WHPAs, leading to more questions than answers
- It is important for management measures to be applied equally and universally within the WHPA, without specification of location or facilities, so that control measures can be sustained if the WHPA boundaries are changed or refined

Notes

WHPA Delineation Methods: Combination **Slide # D-20**

The preceding delineation methods produce somewhat different WHPAs. These can be combined to produce a tiered WHPA with each tier having different levels of protection or regulation. Additional field investigations may also delineate different WHPAs.

The instructor may wish to include examples with which the audience may be partially familiar. Some examples follow:

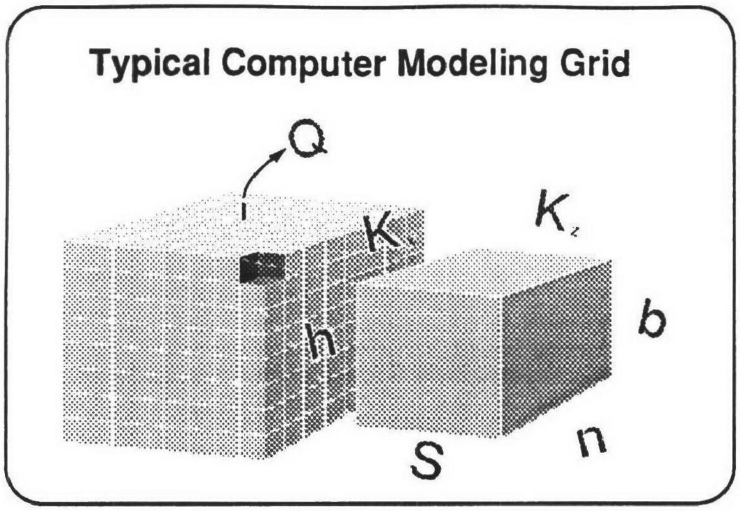
The arbitrary (discretionary) fixed radius has commonly been used for sanitary protection for many years and it continues to be used to provide a high level of protection in the immediate vicinity of the well. It is particularly effective for preventing contamination of shallow water table aquifers from pathogens, and is commonly used in conjunction with an aquifer boundary protection zone, or an analytically determined WHPA.

In carbonate aquifers, dye trace studies are used to delineate highly vulnerable WHPAs within less sensitive aquifer protection zones derived from geologic mapping. Several delineation methods based on hydrologic mapping, geophysical surveys, and isotopic dating can be combined with minimum protection fixed radius methods.

An overlay approach in which WHPAs are determined by several methods may be used to rank successive zones by degree of threat. For example, an analytically delineated U-shaped zone of contribution may be subdivided by time-of-travel to the pumping well, where the area within a 5-year travel zone is considered a greater threat than an area within a 10-year travel zone.

The proliferation of many different WHPAs may generate doubt about the ability to accurately define a safe protection zone or may undermine the credibility of the efforts Where several WHPAs are determined for a single well or wellfield, an evaluation of the relative accuracy of the different WHPAs should be conducted in order to dispel the fear that the selection process is a WHPA lottery. Generally, the more site-specific information used to generate the WHPA, the more accurate it is likely to be.

Once a WHPA is designated, it is important to apply management measures within the area without specification of location (addresses) or facilities (company names).



Numerical Modeling

Source: Horsley & Witten, Inc., 1991

Key Points to Cover:

- Numerical modeling involves using a computer program to simulate the effects of a pumping well or wells on water levels in an aquifer system
- This method provides one of the most detailed ways to delineate a WHPA, and potentially the most expensive
- Numerical models use a modeling grid consisting of individual cells or nodes to represent an aquifer system. For each cell, data inputs include; water level (h), permeability or hydraulic conductivity (K), storage coefficient (S), porosity (n), and pumping rates (Q). The output is then used to delineate the WHPA. It is often combined with information on hydrogeologic boundaries to further refine the WHPA
- Be careful that enough hydrogeologic data are available to develop an accurate model. To insure accuracy, the model should be calibrated against known field conditions such as a measured water table map or a pump test. No model should be tested unless it is calibrated
- This technique provides the ability to model complex interactions between a pump ing well or leaky streams or lake beds. Models can also simulate the effects of lithologic changes such as layering of geologic formations or geologic boundaries

Notes

Numerical Modeling **Slide # D-21**

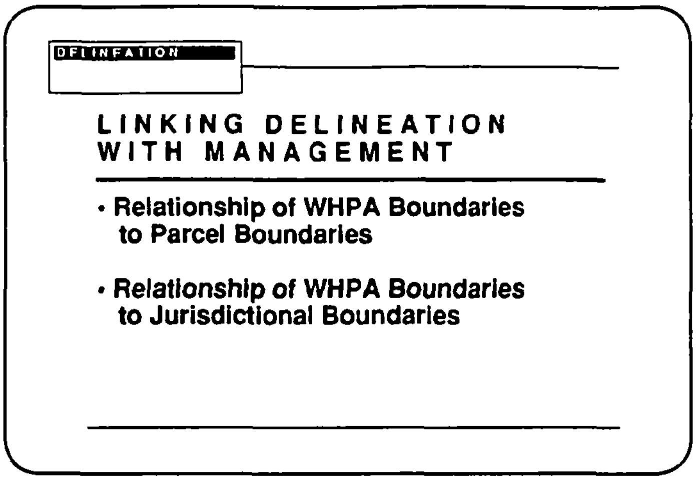
Numerical, or computer modeling is the last of the techniques described here to delineate WHPAs. Compared to the other techniques, modeling requires the greatest hydrogeologic data and technical knowledge, and, therefore is typically the most expensive. If done correctly however, the computer model can provide the most accurate and defensible approach for WHPA delineation.

Numerical modeling involves the use of a computer program to simulate the ground water levels within an aquifer in response to pumping wells. The aquifer is divided into individual cells or nodes as shown in the slide. This can be done in two dimensions or in three dimensions as shown here. Individual inputs values are assigned to each cell. They typically include the water table elevation or hydraulic head (h), the permeability or hydraulic conductivity (K), the storage coefficient (S), the saturated thickness (b), and in some applications, the aquifer porosity (n). The pumping rate of the well (Q) is included for the cell in which the well is located. The computer calculates solutions to the ground water flow equation for each cell of the model taking into consideration the water level in each adjoining cell. This is done in an iterative process until virtually no changes result from one iteration to the next. At this point the model has "converged" on a solution, and is prepared to stop computing.

The output for most numerical models is a listing of water table elevations or head values for each cell in the model. This can then be used to contour water table contours showing direction of ground water flow which then can be used to delineate the WHPA. With more complicated models, the final delineation can incorporate the effects of changes in geology in the aquifer, nearby, impermeable, geologic boundaries, or the effects of pumping on surface water such as streams or lakes which can provide induced infiltration.

It is important to stress that models are only as good as the information used to develop them. If sufficient data are not available for an aquifer, a sophisticated numerical model may provide results that may be less accurate than more simple analytical models. Also, for the results of a model to be believable, the model must first be calibrated against known water levels measured in the aquifer. If this can be done accurately, it is easier to believe the final predictive simulation. A numerical model that has not been tested against known field conditions should not be trusted.

A description of over 60 models available for delineating WHPAs entitled "Model Assessment for Delineating Wellhead Protection Areas" is available from the US EPA Office of Ground Water and Drinking Water.



Linking Delineation with Management

Key Points to Cover:

- Wellhead protection areas are based on hydrogeological conditions, and therefore do not correspond to jurisdictional or ownership boundaries
- Commonly, a WHPA may cross municipal boundaries, necessitating coordinated management by all jurisdictions involved
- In order to ensure effective management, parcels that lie partially in the WHPA should be considered in the WHPA
- The delineated WHPA must be transferred to the community's planning maps which may be on a different scale. Such a transfer should be as conservative as possible; for example, include entire lots in the WHPA where the delineation cuts partially across a lot
- Use of a geographical information system (GIS), where available, allows the delineated WHPA to be graphically compared to other mapped districts and boundaries

Notes

Linking Delineation with Management **Slide # D-22**

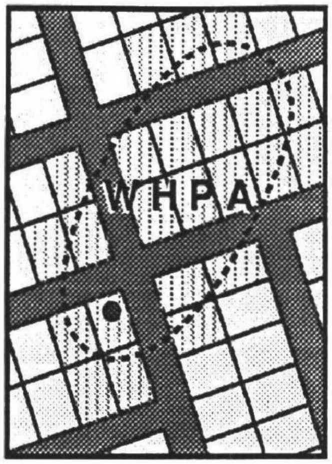
Ground water flow is not constrained by jurisdictional or ownership boundaries; therefore, WHPAs which are based on hydrologic conditions also do not conform to town lines, tribal boundaries, state lines, or property bounds.

As a consequence of these conditions, coordinated management by multiple jurisdictions may be required where WHPAs cross boundaries.

When determining where WHPA management is to be applied on moderate to densely developed or subdivided land, tax assessors parcel maps are commonly used. Generally, in order to insure effective management and control, parcels which lie partially in the WHPA should be considered wholly in the WHPA. This approach, when uniformly applied, has effectively avoided debate and erosion of standards, and has withstood challenge.

The transfer of the delineated WHPA to planning maps in an extremely important step of the protection process. This transfer is discussed further in Module 3.

Slide # D-23



WHPA vs. Parcel Boundaries

Source: Horsley & Witten, Inc., 1991

Key Points to Cover:

- As shown, the ownership lines commonly used as boundaries do not necessarily correspond with wellhead protection area boundaries

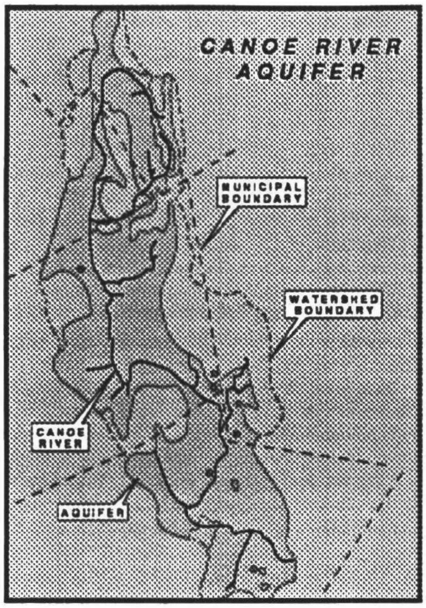
- Where the WHPA delineation bisects a lot, the entire lot should be placed into the final WHPA map in order to maximize ground water protection. Such a practice is common to many ordinances and bylaws where, for example, the more restrictive zoning applies across an entire lot which actually lies in two zoning districts

Notes

WHPA vs. Parcel Boundaries **Slide # D-23**

This slide shows a WHPA and land parcels from a tax assessor's map. When the parcel sizes are small as with individual home lots, a standard, non-controversial, approach has been to subject the entire parcel to the management of the WHPA, if any part of the parcel is in the WHPA. In this slide, the shaded parcels are managed as if they are entirely within the WHPA. The instructor may note that in reality the parcel sizes are much smaller than the WHPA shown in the slide.

Also, remember that all delineation efforts involve some margin of error, an important point as communities develop their wellhead management programs.



Aquifer vs. Municipal Boundaries

Key Points to Cover:

- Frequently, an aquifer is shared by more than one community, and the aquifer boundaries do not coincide with municipal/tribal boundaries
- For wellhead protection to be effective, all communities sharing the resource should coordinate management measures

Notes ___

Aquifer vs. Municipal Boundaries **Slide # D-24**

Aquifers and WHPAs may be shared by more than one community, and the need for management may not be distributed among the communities (jurisdictions) in proportion to the benefit gained from the water resource.

For wellhead protection to be effective, all communities sharing the recharge area to the resource must coordinate management measures. The diligent and effective management measures of one community can be negated by a lack of cooperative and equivalent management in another community. No management plan is complete without resolution of interjurisdictional aspects.

Shared ground water resources tend to foster a good neighbor attitude between communities for the common good of both.

Jurisdictional issues may be particularly important for tribes, e.g., if WHPAs extend off tribal lands (see Module 7).

Diagram of static water table map

Static Water Table Map-- Eastern Shore, Virginia

Source: Horsley & Witten, Inc., 1991

Key Points to Cover:

- The Eastern Shore of Virginia is a long, narrow peninsula bounded by the Atlantic Ocean and Chesapeake Bay. The majority of ground water is withdrawn from deeper confined aquifers, and withdrawals for private agriculture and industry exceed public water supply withdrawals
- This slide shows static, or non-pumping, water table conditions; the next two show existing pumping conditions and permitted pumping conditions
- Water table contours are shown in blue
- The arrows show the direction of ground water flow
- Conducted in low-income areas in Virginia
- This series of slides show the effects of pumping rates on wellhead areas

Notes

Static Water Table Map-- **Slide # D-25**
Eastern Shore, Virginia

This is the first of a series of three slides showing non-pumping hydrologic conditions and predicted pumping conditions for the Eastern Shore of Virginia. This case study can be used to illustrate the fact that the amount of water withdrawal from the ground can affect the quality of the water. Ground water protection efforts often must consider issues of withdrawal rates. The area is a long narrow peninsula bounded by the Atlantic Ocean on the east and the Chesapeake Bay on the west. Withdrawals for agriculture and industry exceed withdrawals for the public water supply, and most of the water is withdrawn from deeper confined aquifers. The confined aquifers are recharged by leakage through the overlying confining layers, and although the aquifers are confined, the whole system acts like a water-table aquifer bounded by sea water. Water flows through the system by recharging from the land surface, flowing through the alternating permeable aquifers and poorly permeable confining layers, and discharging near the shore lines on either side of the peninsula.

This slide is a map showing the static, or non-pumping, water table. The blue water table contour lines range from sea level to slightly more than 26 feet above sea level. The instructor may wish to review the orientation of the slide (north is to the left), trace the outline of the shore, and point out the high water table contours near the axis of the peninsula and the low contours at the shore.

Arrows showing the direction of ground water flow from the axis of the peninsula to the shore lines are also shown. The instructor may wish to review that the flow lines are constructed perpendicular to the water level contours.

Finally, the instructor may wish to point out that the Eastern Shore of Virginia has the lowest per capita median income in the state, a fact that dispels many myths about resource protection in low-income areas.

Slide # D-26

Water table map under existing pumping conditions

Water Table under Existing Pumping--Eastern Shore, Virginia

Source. Horsley & Witten, Inc., 1991

Key Points to Cover:

- The static water table map changes dramatically under pumping for several large agricultural wells, as shown on this slide
- The blue lines represent water table contours, the red lines are the WHPA boundaries

Notes ______________________________

Water Table under Existing Pumping-- Eastern Shore, Virginia **Slide # D-26**

Existing withdrawals create dramatic changes in the configuration of the water table, and consequently the ground water flow system. Several wells pumped for agricultural purposes on the peninsula capture flow from large portions of the aquifer and divert flow from the shorelines.

Again the water table contours are shown in blue. Large depressions in the water table (cones of depression) centered on the wells have developed in response to the withdrawals. The instructor may wish to review the concepts of cone of depression, zone of influence (ZOI), zone of contribution (ZOC), and wellhead protection areas (WHPA) described in earlier slides (D-11 through D-13).

The red lines in this slide are zones of contribution used as WHPAs. They are constructed based on water table contours that reflect pumping conditions.

Slide # D-27

Water table map under permitted pumping conditions

Water Table under Permitted Pumping Conditions-- Eastern Shore, Virginia

Source. Horsley & Witten, Inc., 1991

Key Points to Cover:

- Permitted pumping rates for the large wells are greater than those rates currently in use. Under permitted conditions, the water table map again changes
- The blue lines represent the water table contours, the red lines outline WHPAs
- As is shown by this slide, under permitted conditions, the WHPAs include portions of the ocean and bay. Consequently, salt water intrusion into the wells may be anticipated if the wells are pumped at the permitted rates
- As is suggested here, WHPA analyses should include future potential conditions as well as existing conditions

Notes

Water Table under Permitted Pumping Conditions-- Eastern Shore, Virginia **Slide # D-27**

This third slide of the Eastern Shore of Virginia shows the possible future conditions where the wells are pumped at their permitted rates. The greater pumping rates cause development of larger cones of depression, larger zones of contribution (outlined here in red as WHPAs), and dramatic revisions to the flow directions in the ground water flow system.

Nearly the whole peninsula is within one WHPA or another. The instructor may wish to ask the audience to reflect and comment on the significance of this observation, including some broad conclusions about past, present, and future waste disposal in the area.

Much of the water table is drawn down below sea level as shown by the water table contours, and several WHPAs extend into the Atlantic Ocean and/or the Chesapeake Bay. These extensions predict that salt water intrusion into these wells and other wells on the peninsula is likely to occur if the wells are pumped at the permitted rates. Wellhead protection delineation can help communities identify discrepancies between the permitted pumping rate and the pumping rate that helps maintain ground water quality.

Photo of zoning map with existing and future pumping rate WHPAs

WHPA Overlay

Source: Nelson et al., 1988

Key Points to Cover:

- The WHPA to the two municipal water supply wells, shown as triangles, is shown in green for existing pumping conditions of 0.5 million gallons per day

- Under maximum future pumping conditions of 1 million gpd, according to well construction and aquifer characteristics, the WHPA is larger, shown as the outside solid and dashed lines

- An abandoned landfill, shown as the black square, falls within the maximum pumping conditions of the WHPA. By controlling the rate of pumping, potential contamination from this landfill can be avoided

- This scenario again emphasizes the importance of delineating both existing and future wellhead protection areas as part of the WHP program

Notes

WHPA Overlay **Slide # D-28**

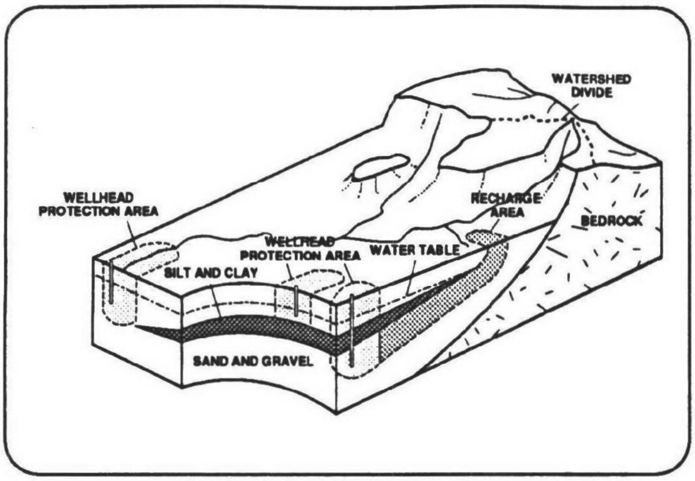
This slide compares WHPAs for existing and future pumping rates. Two wells shown near the center of the slide as black triangles are pumped at 0.5 million gallons per day (mgd) to produce the WHPA shaded green on the map.

Under maximum future pumping conditions of 1 mgd, the WHPA is much larger. Actually the slide shows two larger WHPAs delineated by two different methods, shown as a solid black line and a dashed black line. The two larger WHPAs are remarkably, and somewhat reassuringly, similar.

An abandoned landfill, shown as a black square, is outside the green 0.5 mgd WHPA, but is within the 1 mgd WHPA. That threat to ground water quality may be controlled by limiting water withdrawal to a level which would not draw recharge from the landfill site.

This scenario emphasizes the value of delineating both existing and potential future wellhead protection areas as part of the WHP process.

Slide # D-29



WHPAs in Arid and Semi-Arid Regions

Source: Horsley & Witten, Inc., 1991

Key Points to Cover:

- In arid and semi-arid regions of the United States, recharge areas may lie at a distance from the wells, at higher elevations where the temperature is cooler and not all precipitation evaporates. As shown in this slide, there is no recharge in the valley, where nearly all precipitation is evaporated, and the silt and clay lenses restrict infiltration to the labelled recharge area

- This slide shows WHPAs delineated using a simple model in red. To be accurate, the WHPAs should include the distant recharge areas as well. Management measures should be applied to both red and blue areas, although different techniques may be applicable to the two areas

Notes

WHPAs in Arid and Semi-Arid Regions **Slide # D-29**

The hydrology of arid and semi-arid regions may add complications to the sources of ground water and therefore to WHP.

At the far left of the block diagram in the slide is a WHPA for a simple water table situation.

The middle WHPA is for a well in a water table aquifer bounded beneath by a confining layer. It is not much different from the first WHPA.

The WHPA at the right side of the block diagram receives water from two different aquifers (red and light blue). The upper aquifer is a water table aquifer, and its WHPA is the red zone. The lower aquifer is confined and its WHPA is displaced up the side of the valley to an area from which recharge can enter the aquifer and travel beneath the confining layer to the well. Management measures should be applied to both the red and light blue areas, although different techniques may be applicable to control different threats.

In a similar, but somewhat more hydrologically complicated arid situation, the bulk of water recharging the aquifer that supplies a water table well in an arid valley may come from higher elevations on the sides of the valley. Lower temperatures, more precipitation, and lower evaporation rates allow recharge at higher elevations, but not in the valley. Under these circumstances, recharge to the well is displaced up the side of the valley. However, because there may not be a confining layer at the well, sources of contamination adjacent to the well may still constitute a water quality threat. For example, a large spill of aviation fuel on the land near such a well could still contaminate ground water even though water does not naturally recharge the aquifer from land near the well. WHPA delineation must take into account local hydrologic conditions. No single WHPA delineation approach is universally most appropriate.

Although aquifers may be deep and confined in arid and semi-arid regions, they are nevertheless vulnerable to contaminants reaching them via poorly constructed or abandoned wells.

Slide # D-30

Photo of topographic map showing WHPAs and surface watershed

Julian, California, WHPA

Source Horsley & Witten, Inc., 1991

Key Points to Cover:

- Calculated fixed radius WHPAs under 100 and 400 gallons per minute pumping rates are shown for a proposed well in Julian, San Diego County, California (outlined as black circles)
- The green triangle is the site, with the well location shown as a black dot
- The surface watershed to the well is shown in blue
- This slide points out the difference between ground and surface water contributing areas to a well, and the importance of considering both when delineating the WHPA and when planning management strategies

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Julian, California, WHPA **Slide # D-30**

In the Julian, California, example in this slide, calculated fixed radius WHPAs for withdrawal rates of 100 and 400 gallons per minute (gpm) are shown as black circles.

The well location is a black dot within the green area of the site.

The surface drainage to the site is shown in blue. This is the watershed for all surface water with the potential of getting into the well. Surface drainage from outside this watershed drains in a different direction.

As shown in this example, the surface watershed and the WHPA may not coincide. The surface drainage area may extend beyond the WHPA, or the WHPA may extend beyond the surface drainage area. Both the surface watershed and the WHPA can contain sources of contamination which may threaten the well's water quality, and are, therefore, important to consider in the planning of management strategies.

Photo of topographic map showing WHPA using drawdown modeling

Descanso, California, WHPAs

Source: Horsley & Witten, Inc., 1991

Key Points to Cover:

- WHPAs for two wells in Descanso, San Diego County, California, were analyzed using a distance-drawdown model. As shown, the WHPAs vary with the number of years selected for the pumping duration

- Due to the dry climate, the two rivers shown, the Descanso and the Sweetwater, are intermittent. When they are flowing, they contribute considerable water to the WHPAs. When they are dry, ground water inputs are more important

- In dry conditions, when ground water inputs are important, septic system effluent supplies 11% of the water budget to the wells. Septic system management is thus critical for wellhead protection

- In dry climates, normal to above average precipitation rates as well as drought conditions should be considered in WHPA delinations

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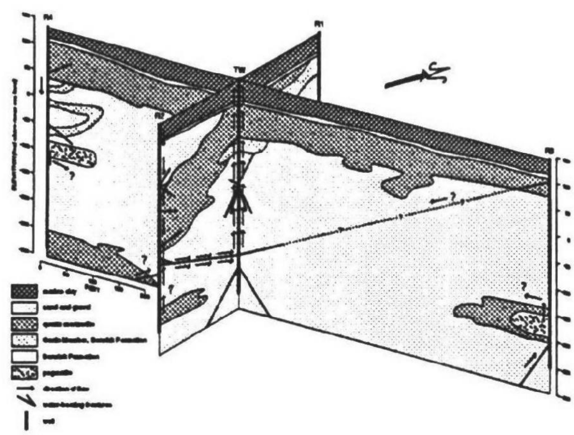
Descanso, California, WHPAs **Slide # D-31**

WHPAs for two wells in Descanso, San Diego County, California, were delineated using a drawdown model for 1 year and for 5 years of pumping. The WHPAs are much larger for 5 years than for 1 year.

Because of the dry climate, the Descanso and the Sweetwater Rivers, which flow over the aquifers and past the wells, are intermittent streams and their flow can vary dramatically from month to month and from year to year in response to variations of precipitation. The rivers can be major sources of recharge to the aquifer and the wells during high flow periods. When the streams are dry, the wells derive their water from storage in the aquifer and some recharge from precipitation. Because these changes in conditions can cause large temporary changes in the zones of contribution to the wells, a conservative worst case set of conditions is usually assumed when developing the WHPA

In dry conditions, when the rivers are dry and well water is derived largely from ground water storage and recharge, septic system effluent supplies 11 percent of the water produced by these wells Ground water quality management for these wells must account for dilution or attenuation of contaminants in the effluents

Slide # D-32



Fence Diagram, Bedrock Aquifer in Dover, New Hampshire

Source: Vernon and Griswold, in press

Key Points to Cover:

- Aquifers in fractured bedrock may require special consideration
- This fence diagram shows the geologic conditions underlying a proposed new water supply well (labelled TW) in Dover, New Hampshire
- The arrows show the direction of ground water flow in fractures in the rock

Notes

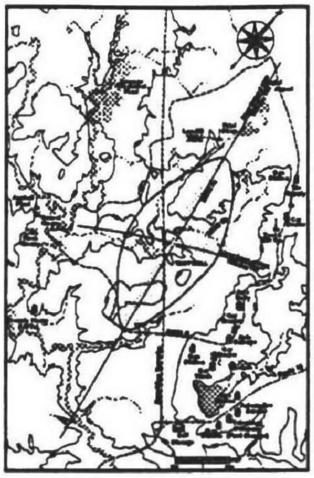
Fence Diagram, Bedrock Aquifer in Dover, New Hampshire **Slide # D-32**

The next two slides show hydrogeologic conditions and a WHPA for a well in a fractured bedrock aquifer in Dover, New Hampshire. This first slide shows a fence diagram (two intersecting cross sections)

The new water supply well is labeled TW and located at the intersection of the two sections of the diagram. Arrows show the directions of ground water flow in fractures in the bedrock.

The instructor should ask the audience to remember the orientation of the fence diagram by pointing out the north arrow. This will help to orient this vertical section with the map in the following slide.

Slide # D-33



Dover, New Hampshire, Bedrock Aquifer WHPA

Source: Vernon and Griswold, in press

Key Points to Cover:

- For a well in fractured bedrock, the main WHPA was delineated as a cross-shaped area immediately overlying the major fractures. This WHPA includes the areas between the fracture zones which may recharge the fractures
- An additional WHPA, consisting of the surface watershed with appropriate boundaries, was also delineated
- Time of travel dye trace studies as well as hydrologic mapping and borehole geophysics were used in these delineations
- This slide also shows nearby contamination sources. One ultimate goal of wellhead protection area delineation and contamination identification (next module) is to produce a map such as this, comparing the WHPA to pollution sources

Notes

Dover, New Hampshire, Bedrock Aquifer WHPA **Slide # D-33**

The primary WHPA was delineated as a cross shaped area immediately overlying the major fracture traces in bedrock. Recharge to the fractures, which are the source of water to the well, comes from the unconsolidated overburden which overlies the fractures where they intersect with the top of bedrock. The primary WHPA for this well was modified to include the areas between the arms of the cross. A secondary WHPA consisting of the surface drainage to the well area was also delineated, based on topography.

Time of travel dye trace studies as well as hydrologic mapping and borehole geophysical logs were used to verify and modify these WHPA delineations.

The slide also shows nearby potential sources of contamination. One ultimate goal of wellhead protection area delineation and contamination identification is to produce a map such as this which helps to identify risks to well water quality from pollution sources

This is a high cost, highly technical approach to wellhead delineation. For additional information, refer to EPA's technical assistance document on delineation of wellhead protection areas in fractured bedrock.

Slide # D-34

Diagram of proposed subdivision showing WHPAs to private wells

Delineation for Private Wells

Source Horsley & Witten, Inc., 1991

Key Points to Cover:

- Wellhead protection area delineation techniques may also be applied to private wells
- For example, this slide shows a proposed residential subdivision with WHPAs delineated for each private well. This information can be used to appropriately position septic systems to avoid contamination of drinking water supplies, a common problem on and between small lots
- Note the difficulty in siting a drainage well in Lot 9

Notes

Delineation for Private Wells **Slide # D-34**

Wellhead protection area delineation techniques may also be applied to private wells. In the example shown here a calculated elliptical ZOC was developed for each well.

This example is of a proposed residential subdivision utilizing private wells and on-lot septic systems on Cape Cod in Massachusetts. The aquifer is a shallow water table glacial outwash plain within a regional ground water flow system grading gently to sea level. Aquifer properties for the area were known to be uniform, well pumping rates were estimated on occupancy estimates for the size of the homes, and the water table configuration was known.

The primary intent of this mapping effort was selection of appropriate positioning of wells and septic system leaching facilities to minimize the probability of subsurface cross connection of withdrawals for water supply and effluent from septic systems on small lots.