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Delineation of Source-water Protection Areas in Karst Aquifers of the Ridge and Valley and Appalachian Plateaus Physiographic Provinces: Rules of Thumb for Estimating the Capture Zones of Springs and Wells

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Introduction

The goal of this document is to help delineate the approximate capture zones for springs and public water-supply wells in karst aquifers of the Ridge and Valley and Appalachian Plateaus Physiographic Provinces (Figure 1). These Rules of Thumb (RTs) are relatively low-cost approaches that can be used by ground-water technical personnel, and which are likely to be more accurate than fixed-radius methods. The initial intent of the US Environmental Protection Agency (EPA) was to develop RTs applicable to all karst areas in the US, but regional differences among karst settings limit the RTs described here to the Appalachians.

This document is written for ground-water technical professionals in agencies that implement either the state Wellhead Protection Program (WHPP) or the Source Water Assessment and Protection Program (SWAPP), or those who are interested in supporting the goals of these programs. With the aid of ground-water technical professionals, this document can also be used by those with no technical background.

Historical background

Section 1453 of the Safe Drinking Water Act (SDWA) 1996, as amended by Congress in 1996, established the Source Water Assessment and Protection Program, which required all states to submit individual Source Water Assessment Plans (SWAPs) to EPA for approval and subsequent implementation by the state. SDWA 1996 made it clear that these programs were established "for the protection and benefit of public water systems", and further required all states to make complete assessments of their public drinking-water supplies by May 2003. Under these SWAPs, each state and participating Indian Tribe will: delineate the boundaries of areas in the state (or on Tribal lands) that supply water to each public water supply (PWS), identify significant potential sources of contamination, and determine the susceptibility of each system to those sources of contamination. State analysis of these assessments will indicate the susceptibility of each PWS in a source-water protection area (SWPA) to the inventoried sources of contamination in that area.

Figure 1. Ridge and Valley and Appalachian Plateaus Physiographic Provinces.

The EPA published its national Source Water Assessment and Protection Program guidance document on August 6, 1997 (EPA, 1997). The document outlines in detail the minimum program elements required for EPA approval for meeting the stated goals of the program – that is, the protection and benefit of each PWS. The EPA's review and approval of these programs revealed a number of consistencies in states' approaches. In most cases, the states conducted contaminant-source inventories and susceptibility analyses for each PWS within individual SWPAs, rather than for PWS clusters within area-wide SWPAs. Most state SWAPs rely heavily on EPA-approved WHPPs for protection of ground-water sources of drinking water and have essentially met the SDWA 1996 requirements under their existing state WHPPs.

For various reasons, mainly for convenience in the absence of effective guidelines, many states have used arbitrary or calculated fixed radii to delineate wellhead protection areas (WHPAs) and SWPAs. Most fixed-radius approaches, while meeting minimal requirements for public-health protection, are problematic even in hydrogeologic settings with the lowest probable risk of contamination. The fixed-radius approach has significant deficiencies that are particularly troubling in karst settings. The approach is flawed by the assumption that water flows equally from all directions, and can significantly underestimate wellhead and spring capture zones. This is a particular problem in karst, because of its high vulnerability to contamination, high ground-water velocities and limited opportunity for in-situ remediation. In karst settings, the calculated fixed-radius approach, based on a porous-media assumption, is not a significant improvement over the arbitrary fixed-radius approach. The porous-medium assumption does not apply to karst.

To strike a balance between enhancing public-health protection and minimizing cost, EPA has developed several RTs for voluntary use by states that would like more protection at relatively low cost. These RTs, described below, provide simple ways to delineate WHPAs and SWPAs for springs and wells in karst aquifers of the Appalachians (both the Ridge and Valley and Appalachian Plateaus Provinces). The original intent was to develop RTs applicable to other karst settings as well. However, regional differences between the Appalachians and other karst settings, including the patterns of conduits, fractures, and flow directions in relation to geologic structure, are too great to allow this. The EPA hopes that these RTs will encourage ground-water technical experts in other karst settings to look for commonalities in flow characteristics that might be used to develop RTs helpful in their settings.

Purpose

This document provides RTs for approximating the capture zones of springs and PWS wells in the karst aquifers of the Appalachians. These RTs are relatively low-cost approaches that are likely to be far more accurate than fixed-radius methods. States in the Appalachians may consider using these RTs in their source-water assessments, to obtain a better balance between degree of public-health protection and cost. The EPA urges Appalachian states not only to consider using these RTs in place of fixed-radius methods, but also to consider moving beyond these RTs to more-accurate delineations through more site-specific delineation approaches.

These RTs require more effort than fixed-radius methods, but are fairly inexpensive, and in nearly every case, provide more-accurate estimates of capture zones for wells and springs (and, therefore, significantly more protection to PWSs). However, the RTs are not foolproof.

Many sophisticated methods, such as computer modeling, hydrogeologic mapping, and tracer testing, are available to analyze complex ground-water systems. However, many data are needed to make the methods work, particularly in highly heterogeneous systems. Computer modeling rarely works in karst regions unless the models account for turbulent-flow conduits. Even dye tracing, which is usually considered the most convincing tool for delineating ground-water basins in karst, is not physically or economically feasible in some cases, and rarely gives more than an outline of the major conduit flow. Geophysical surveys may help to delineate the local geologic framework and major conduits, but the surveys cannot determine detailed flow patterns and divides in karst. However, all these methods provide significant information and analysis, and EPA encourages their use to supplement the RTs in this document. All these methods must be performed by experienced professionals.

Simple guidelines such as these RTs greatly over-simplify the complex ground-water flow systems in Appalachian karst, " … karst groundwater protection is much more complicated than the protection of porous aquifers, because the karst systems heterogeneity requires generally much time and combination of different research methodologies." (Biondic, 2002). Nevertheless, the RTs apply fairly well to Appalachian karst aquifers. Examination of 149 dye traces in karst of West Virginia described by Jones (1997) shows that more than 75% could have been predicted by applying the techniques described here. Nearly all other traces were in massive carbonate rocks with complex and poorly mapped structure. Some of the predictable traces covered distances as much as 15 miles. The techniques also work well in areas in well-bedded carbonate rocks in low-relief plateaus such as those of the Mammoth Cave area in Kentucky (see dye traces by Quinlan and Ray, 1981, *in* White and White, 1989). These two field studies are the only American examples widely available in published form.

These RTs are least applicable in those areas of the Appalachian Plateaus where there is a thick cap of insoluble rock and limestone is exposed as only a narrow band at the bottoms of deep valleys. They also may fail to apply in massive, intensely faulted carbonates, for example, parts of the thick Cambrian-Ordovician carbonates in the Valley of Virginia.

Vulnerability of karst aquifers

Karst aquifers are among the most highly vulnerable to contamination, particularly where the overlying soil is thin (Appendix 1). This vulnerability results from: (1) the presence of point-source recharge features such as sinkholes, (2) solutionally widened flow paths, and (3) rapid velocities of ground water and contaminants. These characteristics reduce the time and matrix surface areas for in-situ, water-quality improvement by water-soil-rock interactions and chemical or microbial breakdown of contaminants. Point-source recharge features and wide flow paths limit natural filtration, although a thick regolith can provide some in-situ, natural remediation of water quality.

Problems in predicting karst ground-water patterns

It is difficult to identify ground-water flow paths and divides in karst aquifers. This difficulty arises from the extreme heterogeneity and anisotropy that typify karst aquifers, and from changes in ground-water patterns with different stages of flow. For example, ground-water flow paths, divides, and basin boundaries can shift in response to rising ground-water levels during and after major precipitation events. Also, conduits in the unsaturated zone can behave rather independently, causing ground-water basins to interfinger and overlap at any given time.

Nature of karst ground-water flow in the Appalachians

Water flows overland from ridge tops, then enters the ground in upland regions, primarily through recharge features (for example, sinkholes, sinking streams, fissures), and exits at springs in low areas, mainly stream valleys (Figure 2). Diffuse infiltration can also take place through the soil or through a caprock of permeable material such as sandstone. Where insoluble rock overlies soluble rock in an upland area, recharge features tend to develop along the contacts. On steep slopes that do not readily develop sinkholes, diffuse infiltration can occur through the soil or into bedrock fissures. In the Appalachian karst, small valleys are often dry, as they lie above the local potentiometric surface. The only perennial surface streams are major entrenched rivers that serve as outlets for ground water, as well as for streams that are perched on insoluble, low-conductivity rocks.

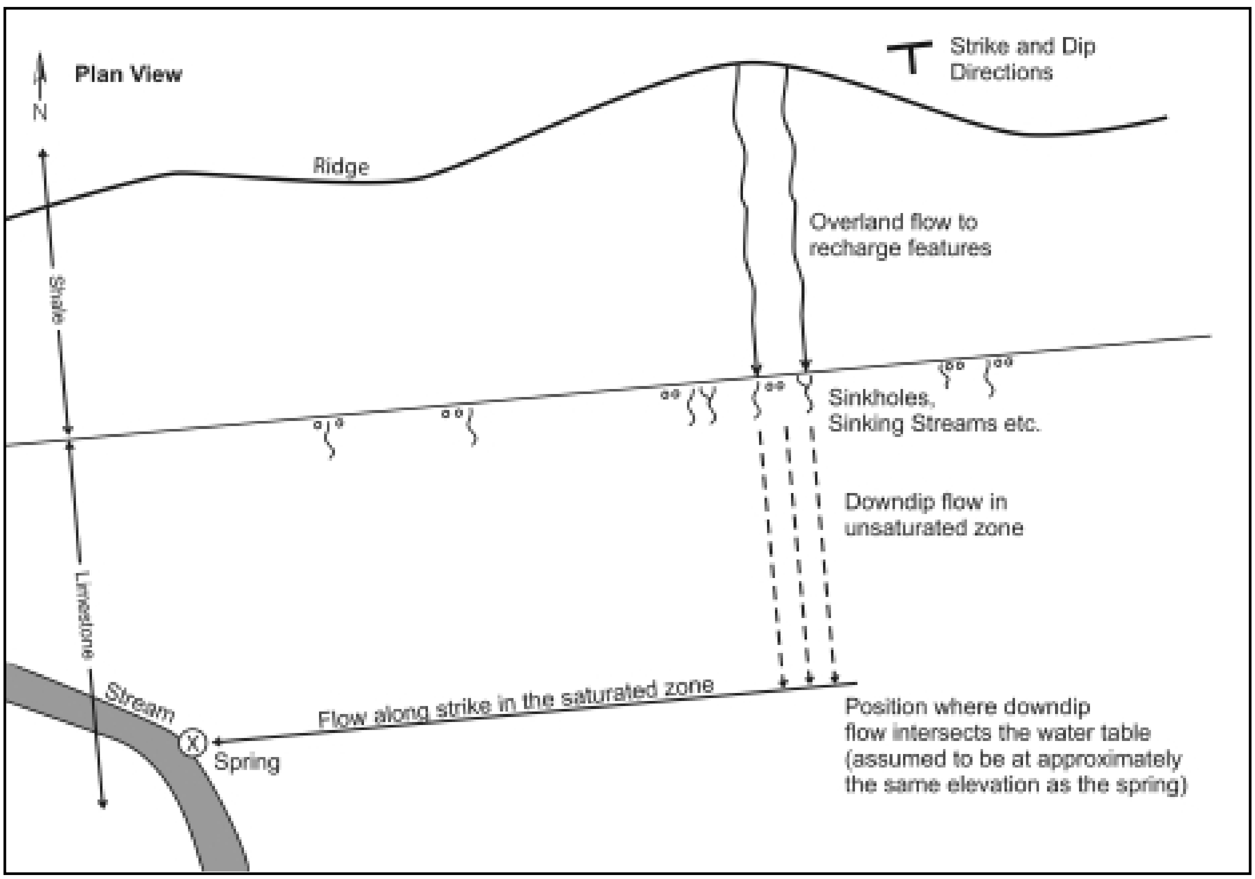


Figure 2. Generalized karst ground-water flow in the Appalachians.

From recharge points, the pattern of individual ground-water flow paths tends to have a strong downdip component in the unsaturated (vadose) zone and a strong tendency to follow the strike in the saturated (phreatic) zone (Figure 3). In karst areas, solution conduits develop along the routes of greatest vadose and phreatic water movement. These conduits carry high-velocity turbulent flow, and they include caves that are large enough to explore. In the Appalachians, some of these conduits reach tens of meters in diameter. The statements about preferred flow routes in this section are supported by the mapping of accessible conduits.

The reason for the downdip tendency of vadose water is that gravitational water follows the steepest available paths through the unsaturated (vadose) zone. Vertical or steeply dipping fractures are not always able to transmit all the water that enters from karst recharge features. This forces water to overflow along the next-steepest openings, which are generally extensive bedding-plane partings. In this way, much of the water follows the dip of the strata, jogging downward across the beds wherever a sufficiently wide fracture is encountered that offers a steeper path. Major flows of karst ground water, thus, follow stair-step patterns to the water table with a strong lateral offset in the direction of the stratal dip. This tendency is most common in well-bedded rocks, especially where there are insoluble interbeds. It also applies to well-fractured rocks, but to a smaller degree.

In steeply dipping rocks, vadose water drains along steep paths to the water table. In gently dipping rocks, vadose water can remain perched along bedding-plane partings for distances up to several kilometers before reaching the water table; thus, there can be a great horizontal dislocation between where the water infiltrates and where it ultimately reaches the water table.

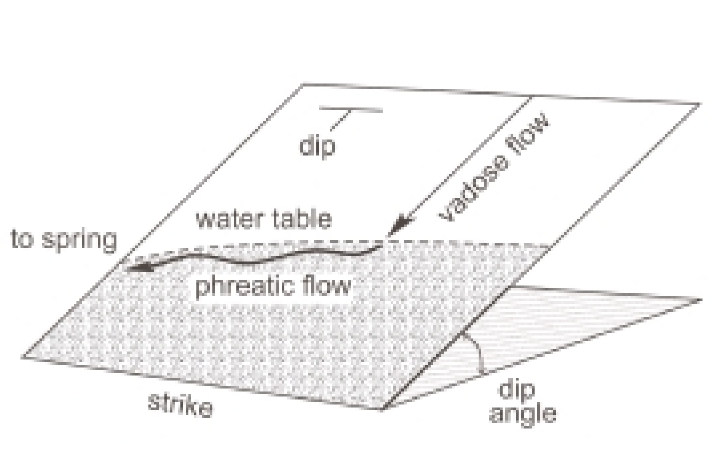


Figure 3. Idealized view of water flow through dipping, dominantly bedded rocks. Vadose water tends to flow down the dip of the beds, following bedding-plane partings or perched on thin insoluble strata. Where it reaches the water table, the flow tends to follow approximately the strike of the beds to the most efficient outlet. Most phreatic flow follows shallow paths because fractures and partings become narrower with depth. (The strike-oriented pattern is favored because it is the intersection between the water table and the favorable dipping bed that delivers the incoming vadose water. In places the vadose water may jog downward along discordant fractures from one bed to another, but then resumes its downdip trend.)

Where the vadose flow reaches the water table, the dip of the strata loses its influence, because gravity is more or less offset by the increasing hydrostatic pressure with depth. Instead, the water follows the most “efficient” path to the nearest available surface outlet – that is, the path that provides the least resistance for a given amount of flow. Because the incoming vadose water is already following favorable partings and fractures, those same openings continue to serve as the optimum paths for flow at, and just below, the water table, in the saturated (phreatic) zone. The preferred phreatic paths are, therefore, along the strike of the dominant structures, at their intersection with the low-gradient water table that is typical of high-permeability karst aquifers. In places, the major flow routes usually loop down below the water table, but the overall low-gradient, strike-oriented trend dominates, especially in steeply dipping rocks. Appendix 2 clarifies the patterns of flow within a spring capture zone and provides a simplified description of the basic premise behind the RTs.

Fractures and partings become narrower with depth, owing to the pressure of overlying rock, and as a result, the most favorable flow routes are at shallow depth, at or just below the water table. This trend is disrupted to some extent in strongly faulted and folded rocks, but even in these areas the majority of ground-water flow is close to the water table.

For the purpose of delineating capture zones, it is important to consider two relationships:

1) The position of a strike-oriented conduit is determined by the location of the most abundant sources of incoming vadose flow. Most of these are located updip from the strike-oriented conduit.

2) The location of the strike-oriented conduit, in turn, determines the general location of the spring outlet. Thus, the general pattern of underground drainage to the spring can be anticipated.

The prevalence of these patterns was noted in statistical summaries by Palmer (1986, 1999a) on the basis of geologic mapping of karst conduits, with supporting evidence from dye traces. These two articles (short entries in symposium volumes) were intended only to draw attention to a promising approach, rather than to recommend immediate application. However, the reliability of this approach in predicting approximate spring capture zones came to the attention of EPA for use in this document.

Turbulent-flow conduits are surrounded by large areas of bedrock that contain only diffuse laminar flow along narrow fractures, partings, and intergranular pores. This diffuse seepage drains into the conduits in much the same way that it flows into surface streams. Thus, if the pattern of conduits were known, the pattern of the surrounding diffuse flow could be predicted. Linear zones of low head, as detected by piezometric data from wells, generally indicate the approximate location of phreatic conduits. Vadose conduits cannot be detected in this way.

Both vadose and phreatic conduits can cross under topographic divides. This is least likely where soluble rock is overlain by a thick cover of insoluble rock, such that the soluble rock is exposed only near the bottoms of stream valleys. In these areas, underground karst drainage usually follows paths roughly parallel to the stream valleys, because that is where fractures are most likely to have widened by stress release. The capture zone for a spring extends beyond the outcrop area of the soluble rock, if surface runoff is contributed from neighboring insoluble rocks.

Water in karst aquifers is highly susceptible to contamination for the reasons stated above. However, most of the water-quality problems are limited to conduits, which represent only a tiny volume of the entire aquifer, despite the fact that they carry the majority of the aquifer's discharge. The surrounding zones of laminar flow are less susceptible to contamination, since their recharge is rather diffuse. In addition, their ground-water flow is tributary to the conduits, except for brief intervals during rising floods, when conduit flow is temporarily reversed into the surrounding network of pores and fissures, as a form of bank storage. The presence of a regolith does not affect the utility of the RTs.

Rule-of-Thumb topics

The RTs described in this document are outlined in Table 1.

Rules of Thumb for estimating the capture zones for springs in Appalachian karst aquifers:	**Rules of Thumb for estimating the capture zones for wells in Appalachian karst aquifers:**
RT 1.1: For dominantly bedded aquifers	**RT 2.1:** For steeply dipping aquifers, either dominantly fractured or dominantly bedded
RT 1.2: For dominantly fractured aquifers	**RT 2.2:** For gently dipping, dominantly bedded aquifers
	RT 2.3: For gently dipping, dominantly fractured aquifers

Table 1. Rules of Thumb for delineating approximate capture zones for springs and wells in Appalachian karst aquifers.

Figure 4 is a flowchart summarizing the general RT process.

Estimating a spring's capture zone requires information on geologic structure, topography, and the hydrologic budget for the spring's actual ground-water basin. With the RT methods, calculated capture zones for neighboring springs may overlap slightly, because the techniques are designed to overestimate the areas slightly. Estimating a well's capture zone requires knowing the spring capture zone in which the well is located, the directions of maximum and minimum hydraulic conductivity, and the size of the cone of depression. The geologic setting of a well is similar to that of the spring capture zone in which the well is located.

In the section titled "Field tests", RT 1.1 was used to estimate the capture zones for two large karst springs. The results were very close to published estimates of the capture zones based on dye tracing.

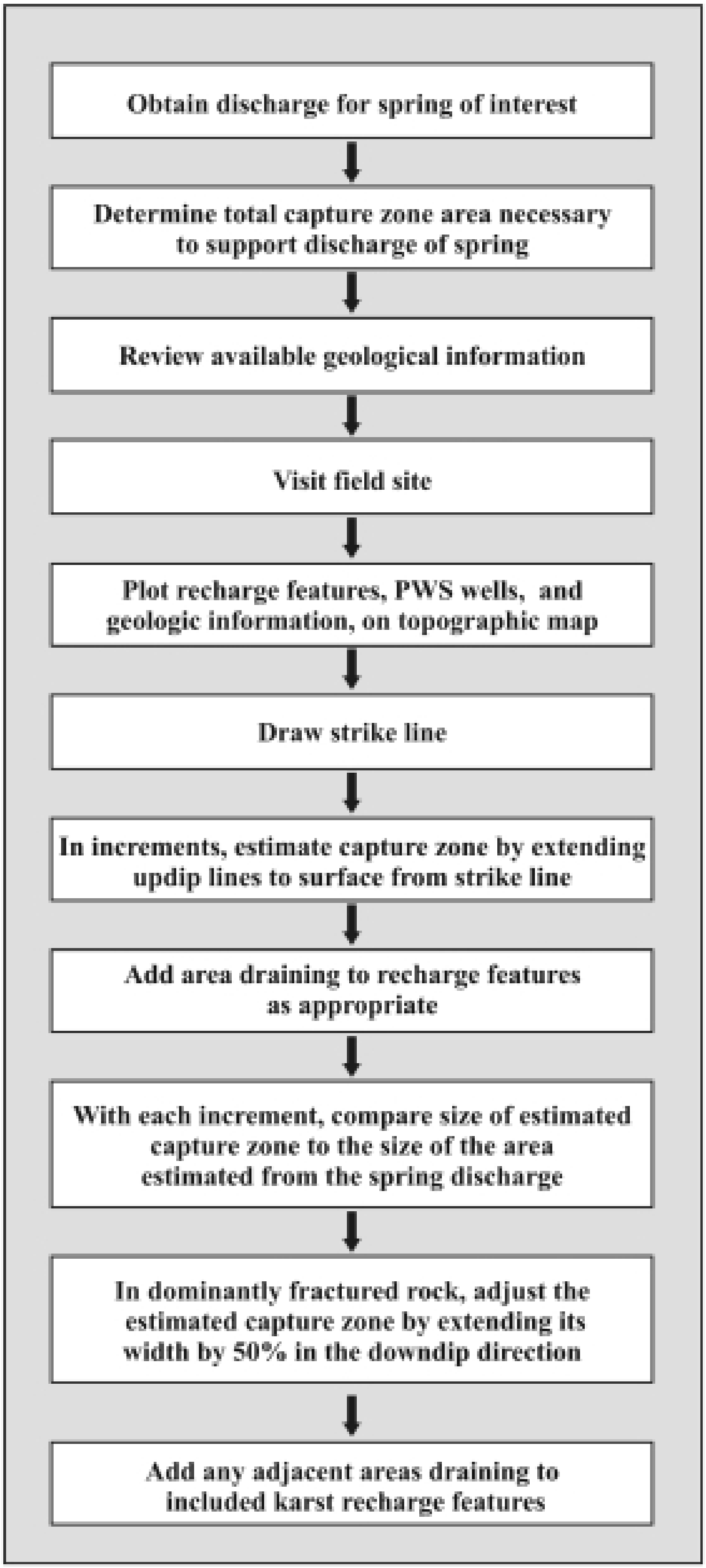


Figure 4. Flowchart for general Rules-of-Thumb process for estimating the capture zones for karst springs and wells in the Ridge and Valley and Appalachian Plateaus Provinces.

Part I: Rules of Thumb for estimating capture zones of karst springs in the Ridge and Valley and Appalachian Plateaus Provinces

Introduction

The RTs for approximating the capture zone of a spring are described below. The EPA used the following criteria in developing these RTs: (1) they should apply to the majority of springs in Appalachian karst settings, (2) they should be conceptually simple, (3) they should be relatively low cost, (4) it must be feasible for them to be performed by ground-water specialists at state SWAPP-implementing agencies, or by local hydrogeology graduate students supervised by someone versed in karst hydrology, and (5) estimates of parameters needed to use the RTs are available from state geological surveys or US Geological Survey (USGS) offices; nearby university geology departments may also be sources of relevant information. Engineers and geoscientists knowledgeable about karst hydrology can also apply these techniques. Some states may require that such work be performed by licensed professionals. The EPA estimates that the delineation of a spring capture zone with the RTs below can be completed within several days by professionals or within a week or two by graduate hydrogeology students. (The majority of the time required to estimate a well's capture zone is spent delineating the spring capture zone in which the well is located.)

Traditional methods

There are three traditional methods for delineating the capture zone of a karst spring. Method 1, described below, is no more time consuming than the RTs, but it is difficult to apply in extensive karst areas. The last two described below can be costly and time consuming. The RTs described later are suggested if the resources are not available to apply these traditional methods. However, the RTs can also provide initial estimates of capture zones that facilitate applying the traditional methods. The traditional methods can be used alone or in combination. They are summarized here, because they provide insight into the nature of ground-water flow in karst.

1. Many spring capture zones can be approximated from the distribution of recharge features (sinkholes, sinking streams, fissures, etc.). Karst springs are fed primarily by such features, many of which are visible on topographic maps. The capture zone for a karst spring can often be roughly outlined by identifying clusters of sinkholes and sinking streams in the upland surrounding the spring, and including any surface drainage into them. This qualitative approach is best used only as a preliminary step in applying one or more of these traditional methods.

   To constrain the size of the spring's capture zone, the spring's discharge is measured during a period of high base flow. Assuming that recharge is uniform over its capture zone, the size of the capture zone of a spring is proportional to the spring's discharge. This relationship can be estimated from USGS stream-flow records, which include stream basin area and discharge for every monitored drainage basin (available in hardcopy, and also online at http://water.usgs.gov/nwis/sw). High base-flow discharge per unit area of the major river basin in the area is calculated from stream-flow records and basin-size information. The value of high base-flow discharge per unit area is then used in combination with spring-discharge rate, to determine the size of the spring's capture zone.

Example: If the high base flow for the major river in an area is 0.5 $feet^3/second/mile^2$, and the discharge of the spring, measured during high base flow, is 3.0 $feet^3/second$, then the size of the basin that feeds the spring will be approximately 6 $miles^2$.

The discharge per unit area of a karst spring is usually slightly larger than that for neighboring surface streams, because evapotranspiration is smaller in basins in which most of the flow is underground. This technique does not indicate the location of capture-zone boundaries. This procedure for estimating the size of the spring's capture zone is part of the RTs described later. However, the RTs provide a more valid delineation of spring capture zones where large areas of karst drain to several different springs, and where the divides between capture zones cannot be defined by the extent of karst recharge features.

2. Ground-water drainage divides can be roughly delineated from water levels in wells. However, the ground-water divides detected with wells rarely indicate the full capture zones of karst springs, because vadose water can easily cross over water-table divides. Divides can also shift with changes in ground-water stage. It is necessary to make all measurements during periods of similar base flow. All wells must penetrate the karst aquifer in question, but they must not extend through it into lower aquifers.

3. Dye tracing is the most reliable way to delineate spring capture zones, if there are abundant recharge features into which the dye can be introduced. This procedure must be performed only by those with extensive dye-tracing experience. State regulations on the use of tracers must be observed. The technique uses small concentrations of non-toxic dye (for example, fluorescein), which ideally emerge at springs in non-visible concentrations of typically a few parts per billion. Positive traces are identified by dye breakthrough curves from continuous or intermittent monitoring. Tracer studies can be costly, time-consuming, and sometimes confusing (for example, where subsurface drainage divides overlap at different levels, or shift laterally as water levels change), and they do not always provide positive results (that is, the dye may not be detected after injection). Poor technique or background noise from other sources of fluorescence can lead to false positives. In addition, dye tracing does not reveal the exact pattern of conduits between injection and detection sites.

Where time or resources are not sufficient to apply the traditional methods, the following Rules of Thumb can provide estimates of spring capture zones with relatively little cost or effort.

Resources needed to perform the Rules of Thumb for springs

A small amount of basic hydrogeologic information is needed to perform the RTs. Some data may have to be obtained independently, if not readily available from other sources. Although dye tracing and potentiometric mapping would help to refine delineations based on the RTs, it is usually because these data are not available that the RTs are employed. Required information is:

1. Discharge records for streams in the area, to obtain an approximate rate of recharge to the aquifer.

2. The spring's discharge rate, measured at high base flow, at least several days after a significant precipitation event. The most appropriate flows generally occur in February in the southern part of the Appalachians and in March in the northern part. Although spring discharge data may be available from other sources, the reader can refer to Appendix 3, which describes a simple method for measuring spring discharge.

3. Determination of whether the carbonate rock is dominantly fractured or dominantly bedded, and whether steeply dipping (>5 degrees) or gently dipping (<5 degrees). "Dominantly fractured" in this context means that there are prominent joints and/or faults, discordant to the bedding. "Dominantly bedded" means that beds and bedding-plane partings are more conspicuous than discordant fractures. In most cases, the distinction will be clear. Where it is not, a compromise between the RTs can be applied. That is, the capture zone would consist of the superimposed capture zones for both settings.

4. A geologic map of the area, preferably at 1:250,000 scale or larger (that is, more detailed), from which the strikes and dips in the spring's capture zone can be determined, and which provides information on the elevation of formation contacts. Geologic/hydrogeologic descriptions of the area are helpful. These include, but are not limited to, published or unpublished: reports, isopach maps, structural maps, and well-log descriptions.

5. Topographic maps, preferably at the 1:24,000 or 1:100,000 scale; aerial photographs and county soil-survey maps at these or similar scales are also helpful. Walking the streams and estimated capture zone can reveal significant features not recorded on maps and photos.

Rule of Thumb 1.1: Dominantly bedded karst aquifers

This RT assumes that the hydraulic head in the strike-oriented main conduit is not substantially higher than the head at the spring to which it drains. The elevation of a spring is, therefore, a reasonable approximation of the elevation of the water level in the conduit draining to the spring. In the Appalachians, these conditions appear to be the norm in carbonate rocks that are dominated by bedding-plane partings. Palmer (1999a) estimates that in predominantly bedded carbonate rocks about 75% of the main conduits will fall within 10 degrees of the strike line, and that about 90% of the vadose conduits that feed them will be oriented within 10 degrees of the dip direction. At least 80% of the vadose conduits should have no more than a 10-degree downward discordance across the strata.

The Rule of Thumb consists of the following steps:

Step A: Obtain the high base-flow discharge for the spring of interest. This may be available from the USGS, state geological survey, or nearby universities. However, if this information is lacking, spring discharge can be estimated by the simple method described in Appendix 3.

Step B: Determine the total surface area of land necessary to supply the discharge to the spring. Consult USGS stream-flow records to estimate the discharge per unit area for surface streams (see Traditional Method 1, above). Assume that this value is roughly the same as that for springs (it will usually be somewhat smaller for streams than for springs). Use equation 1, below, to estimate the size of the capture zone needed to supply the spring discharge:

Equation (1):

$$\frac{\text{spring discharge (length}^3\text{/time)}}{\text{ground-water recharge rate (length/time)}} = \text{size of spring capture zone (length}^2\text{)}$$

Make sure the units in the equation are compatible, so they cancel to produce the desired units on the right-hand side. If the ground-water recharge rate is not available, use the discharge per unit area from the published records for nearby streams:

$$\frac{\text{spring discharge (feet}^3\text{/second)}}{\text{discharge per unit area (feet}^3\text{/second/mile}^2\text{)}} = \text{size of spring capture zone (miles}^2\text{)}$$

This equation should be applied over as long a period of data as possible, to reduce the effect of discharge fluctuations. However, even for shorter periods, it provides a valid first approximation.

Step C: Review available geologic information to determine the strike and dip of the carbonate rocks in the upland above the spring. Examine topographic maps and aerial photos for likely recharge features (sinkholes, etc.).

Step D: Visit the field site to look for recharge features not shown on maps and aerial photos. If feasible, walk upstream and downstream a few thousand feet along the stream into which the spring of interest drains, in a search for additional springs. Some may function as overflows for the main spring, but they will usually be dry during periods of low flow.

Step E: Plot the field information (Figure 5) on a large-scale topographic map, for example, a scale of 1:24,000 or 1:100,000. Where multiple springs are in close proximity (within about 1000 feet), consider them to be one large spring with a combined discharge, located at the outlet that is at the lowest elevation. On the map, mark the carbonate rock's strike and dip directions, and its dip angle (Figure 3). Plot any PWS wells on the map (it may be necessary to estimate capture zones for several springs in order to find the one in which a given well is located.)

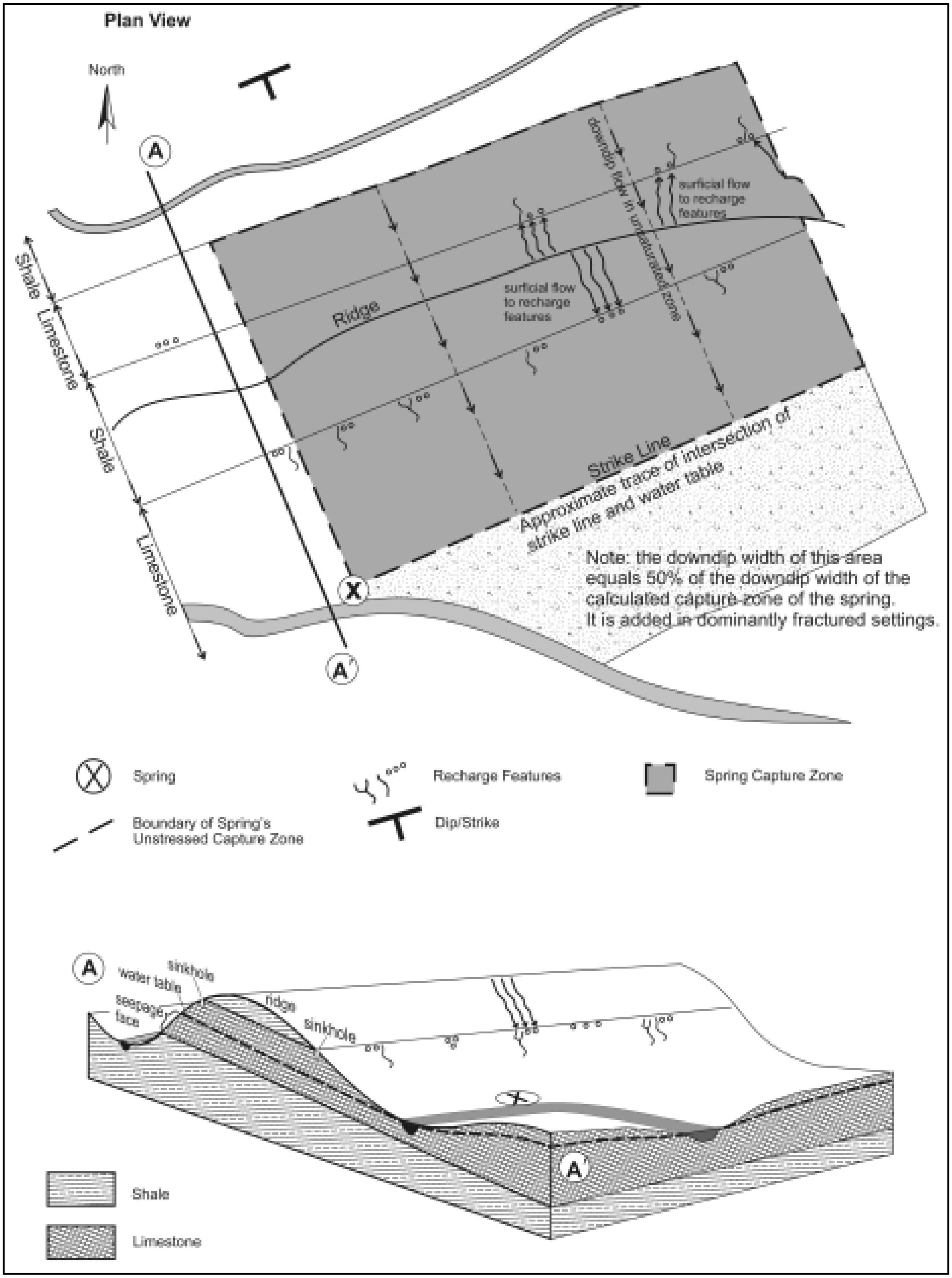


Figure 5. Spring capture zone in plan and three-dimensional views.

Step F: From the spring, draw a line parallel to the average strike of the beds, into the karst area that feeds the spring. This line is a rough approximation of the main solution conduit that feeds the spring. (This line extends into the region of recharge features identified on the map.) The length of this line depends on how large a capture zone is needed to supply the spring's discharge (Figure 5).

Step G: From the spring, extend a line up the dip of the beds until it intersects the surface. This requires knowing the dip angle (from the geologic map or similar information) and elevations of the land surface (from the topographic map).

Example: If the spring elevation is 600 feet, assume that the main solution conduit feeding it is at the same elevation (represented by the strike line). If the dip is 10 degrees to the east and the local land surface lies at 900 feet, a line projected upward along the dip from the strike line will intersect the surface at a point equal to $[(900\text{-}600)/\tan(10^{\circ})] = 1700$ feet west of the strike line.

Proceeding along the strike line, away from the spring, draw additional updip lines at intervals until they, too, intersect the land surface. Connect the points where the updip lines intersect the surface. With each additional step, calculate the total accumulated area enclosed by the lines, and compare it to the estimated capture zone of the spring determined in Step B. Stop when the two areas are equal. As each new area is added, include any additional land area that lies outside the zone defined above, but which contributes surface runoff to it. Do not draw a boundary through a cluster of recharge features; rather, include the entire cluster. Do not extend the estimated capture zone into obviously non-karst regions in which surface drainage is away from the spring. The capture zone can extend beneath an insoluble, low-conductivity caprock (Figures 6 and 7), provided that the soluble aquifer containing the spring in question extends beneath it, and that the contact between the two lies above the spring level. The capture zone should not cross entrenched rivers with perennial flow, although it can extend across small streams perched on insoluble, low-conductivity caprock (Figure 7).

The resulting shape is roughly a quadrilateral (only approximately, because, 1- the irregularity of the land surface prevents the updip boundary from being a straight line, and 2- additional land area, as noted above, may contribute surface runoff). Figure 5 shows the updip projection from the strike line, reaching the surface without passing beneath the topographic divide. Alternative settings are described at the end of these Steps.

Step H: If the enclosed area is too small to account for the spring discharge, expand the estimated capture zone into adjacent areas that contain karst recharge features. Expand the boundaries incrementally, in equal steps, into all of these karst areas, regardless of direction, until the size of the capture zone is sufficient to account for the spring discharge. Do not allow the capture zone to cross perennial streams, unless they are perched on insoluble low-conductivity strata above karst aquifers. This procedure is especially appropriate where the dip is steep, because the capture zone delineated by

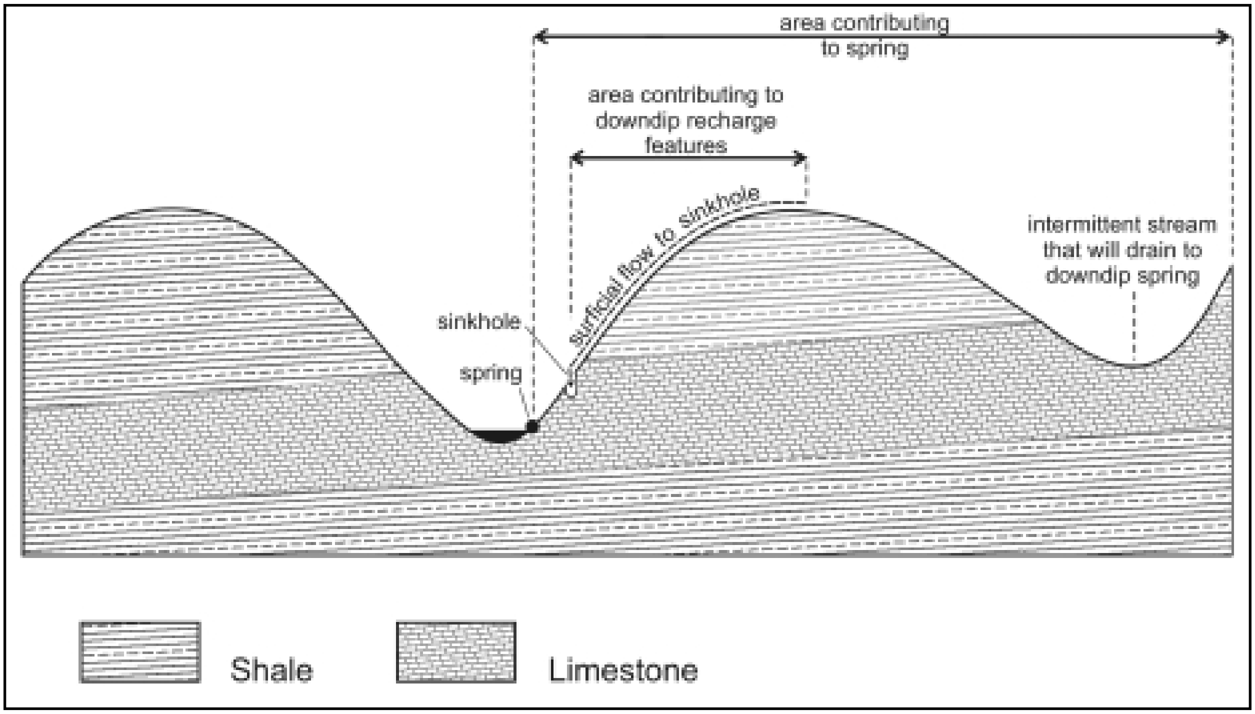


Figure 6. Cross section view of a spring capture zone where the updip projection of the karst aquifer extends beyond the ridge, and the updip valley is floored by carbonate rock.

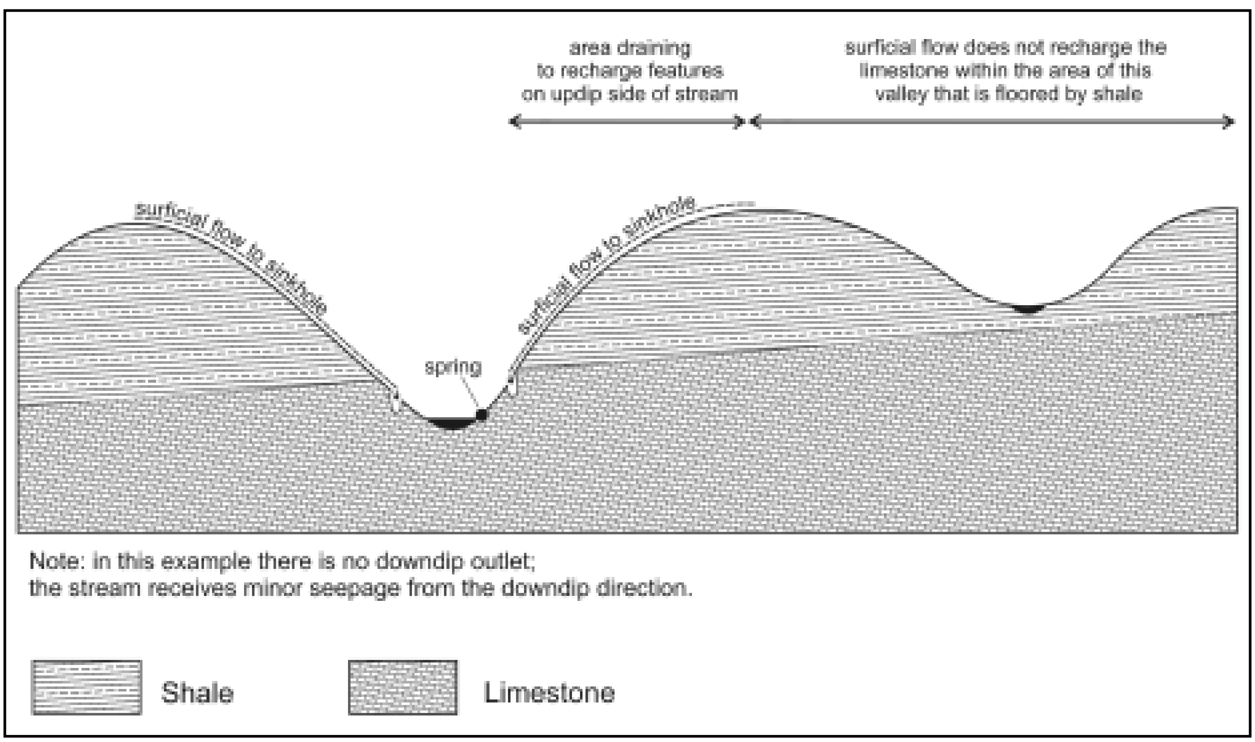


Figure 7. Cross section view of spring capture zone where the updip projection of the karst aquifer extends beyond the ridge, and the updip valley is separated from the underlying carbonate rock by an intervening thick shale.

Step G will be a very narrow strip that is unlikely to be large enough to deliver the necessary recharge to the spring.

If the updip projection in Step G extends beneath a topographic divide, drainage within the capture zone is slightly more complex, as shown in Figures 6 and 7. If any adjacent areas contribute surface runoff to this delineated capture zone, the capture zone should be expanded to include these areas. An example of such an area is an updip valley floored by carbonate rock (Figure 6). Such a valley is unlikely to contain a major surface stream. Any area of surface runoff that does not contribute water to the area in Step G should be excluded from the spring capture zone. An example of such an area is an updip valley separated from the underlying carbonate rock by an intervening thick shale (Figure 7).

Some springs may be located in such a position that the strike line could be drawn in either direction. For example, if the spring is located at the northernmost bend in a river, and the strike is east-west, the strike line could obviously be drawn in either direction - east or west - and still extend into the upland karst area. It is unlikely that the capture zone extends in both directions, although field examples are known in which this is the case. In some cases, the appropriate direction may be clear from the distribution of karst recharge features. In the absence of a clear distribution, the safest approach would be to extend a strike line in both directions, following the instructions above, until the necessary capture-zone area is obtained in *each* direction. This would give a total capture zone twice the necessary size to account for the spring discharge.

The capture zone for a large spring may include areas drained by smaller, perched springs. If the spring of interest is itself a perched spring, the procedure for delineating its capture zone will be the same as described in Steps A-H above.

Rule of Thumb 1.2: Dominantly fractured karst aquifers

In dominantly fractured rocks, the flow pattern is roughly similar to that described above, but the dip-and-strike control is less apparent. Water more readily follows fractures across the bedding. As a result, the downdip portion of flow will be less extensive, and the main conduit feeding the spring is less likely to be along the strike. The general relationships still hold, but the estimated capture zone is less likely to be valid and should be modified. (Palmer [1999a] estimates that although the average trend of phreatic conduits centers around the strike of the beds, only 50% of them will fall within 50 degrees of the strike. Eighty percent of vadose conduits have trends that fall within 50 degrees of the dip direction, and 55% of them have less than 10 degrees downward discordance across the beds.)

Thus, in these settings it is best to start with RT 1.1 and then modify the capture zone by adding a strip in the downdip direction about half the width of the original quadrilateral (Figure 5). (There is no solid quantitative basis for this value; it is simply a safety factor that takes into account known examples of updip flow in fracture-dominated aquifers.) In addition, any adjacent areas containing karst recharge features should be added. In expanding the boundaries in these two ways, no perennial surface streams should be crossed. The resulting area is likely to be larger than necessary to account for the spring discharge, but this simply reflects the greater uncertainty of the method.

Field tests

The approaches above were tested at two sites by the senior author, who was unfamiliar with either site. The first site was Graham (Plum) Springs, one of the largest in the Mammoth Cave area of Kentucky. Although this area is not in the Appalachians, it contains prominent bedding, and the local strike and dip are well mapped, making it a likely candidate for RT 1.1. The capture zone estimated with this RT is shown superimposed on the capture zone determined by extensive dye traces and potentiometric data from well logs (Figure 8; see Quinlan and Ray, 1981, *in* White and White, 1989).

The second site was Davis Spring, in Greenbrier County, West Virginia, the largest spring in the state. In Figure 9, the estimated capture zone defined by RT 1.1 is shown superimposed on the capture zone estimated by Jones (1997) on the basis of dye tracing. The strike line extending from Davis Spring follows the axis of a syncline, and so the updip projection was made in both directions away from the strike line.

It is clear that these RT delineations provide a far better match than would a fixed-radius delineation. Materials for performing the necessary steps were limited to those available from the USGS library in Reston, Virginia. That is, maps and literature were available, but aerial photos were not used and no field work was performed. Each of these delineations was performed in 2 to 3 days. However, the author was saved about 1 day of effort for each, because the sizes of the spring capture zones were already known without resorting to measurements and calculations of spring discharges. The author found that the second delineation was performed more rapidly than the first, because the technique quickly became routine.

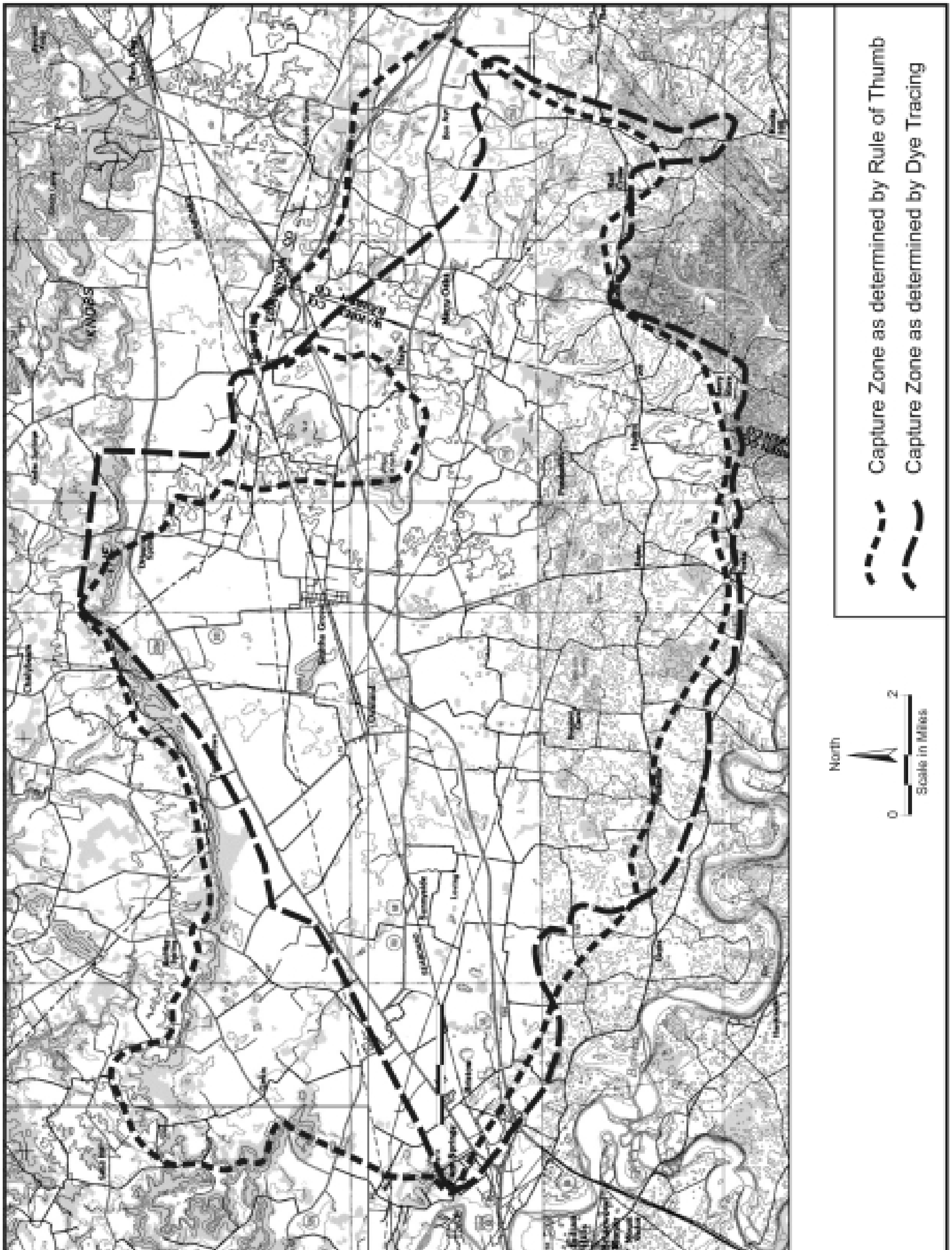


Figure 8. Graham (Plum) Springs, Mammoth Cave area of Kentucky. The capture zone estimated with RT 1.1 is shown superimposed on the capture zone determined by extensive dye traces and potentiometric data from well logs (see Quinlan and Ray, 1981, *in* White and White, 1989).

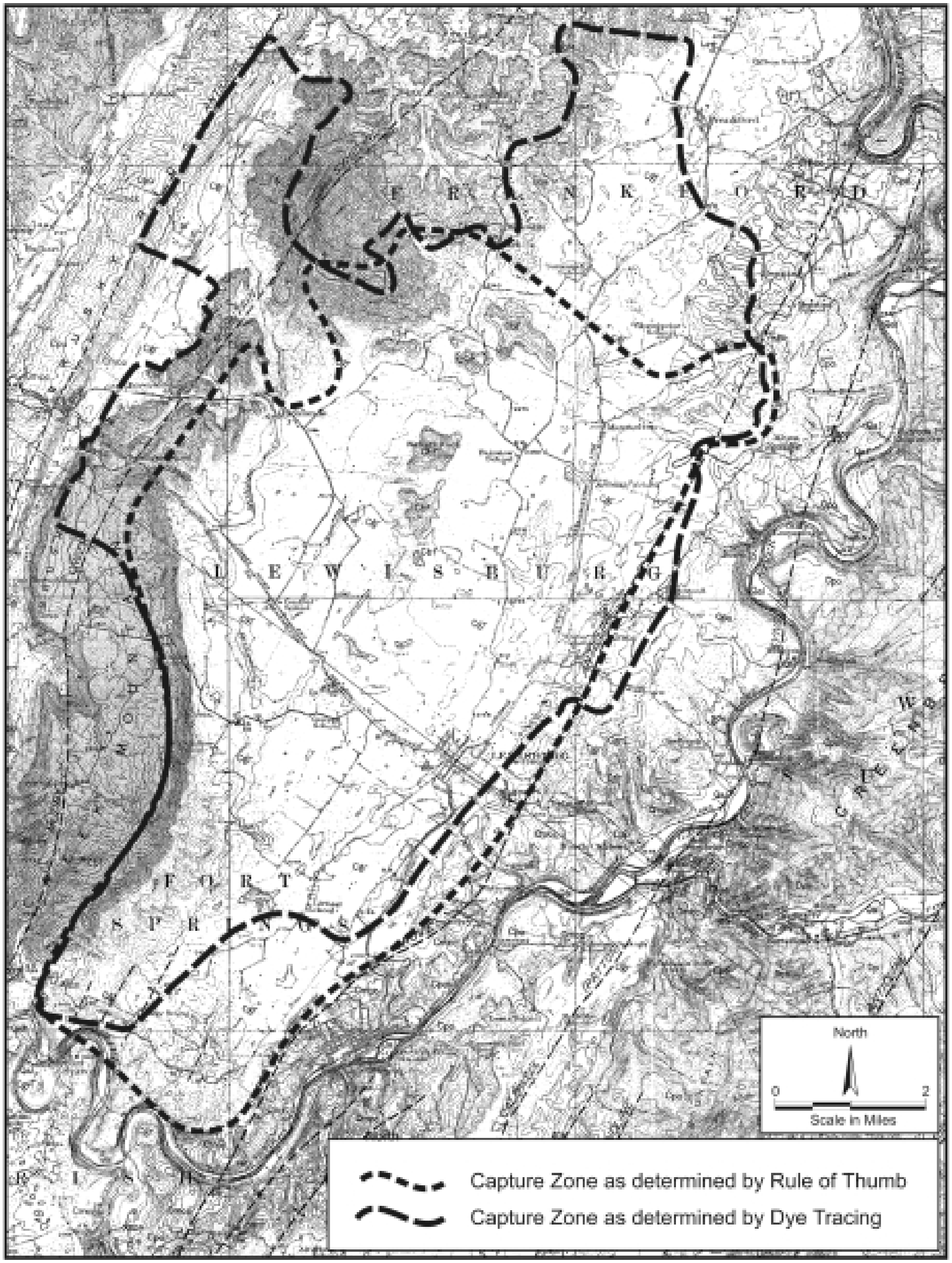


Figure 9. Davis Spring, Greenbrier County, West Virginia. The capture zone estimated with RT 1.1 is shown superimposed on the capture zone estimated by Jones (1997) on the basis of dye tracing. (The strike line extending from Davis Spring follows the axis of a syncline, and so the updip projection is made in both directions away from the strike line.)

Part II: Rules of Thumb for estimating the capture zones for wells in karst aquifers of the Ridge and Valley and Appalachian Plateaus Provinces

Introduction

There are three well RTs presented in Part II. These are listed in Table 1 (page 7).

Most wells in Appalachian karst obtain their water from narrow fissures (fractures and partings), many of which are enlarged only slightly by dissolution. Conduits are sparse, and relatively few wells obtain their water from them. Conduit-fed wells can be identified by negligible drawdown or by turbid water during high flow (for example, after heavy rains). Wells draw an insignificant amount of water from matrix blocks in the dense Appalachian limestones. Therefore, the RTs below take into consideration only conduits and narrow fissures.

Ground-water travel time is a useful criterion in WHPA or SWPA delineation in porous media. However, in karst aquifers travel time can be so short that it generally is not a meaningful criterion for estimating capture zones for wells.

The areas delineated by these RTs may be quite extensive. The estimated capture zone for a well in a karst aquifer may be closer in size to that of a surface-water basin than to the capture zone of a well fed by laminar flow in a porous medium (unless that well is conjunctively delineated to include the surface-water catchment area). Capture zones in karst aquifers may be overestimated. This overestimation is justified by, and results from: (1) high-velocity flow through fissures and solution conduits over large distances, (2) uncertainty in identifying exact ground-water flow paths, and (3) shifting of ground-water divides in response to storm events.

To obtain a first approximation for a well capture zone (that is, its WHPA/SWPA boundary) in Appalachian karst, the approach to estimating a spring's capture zone (see Part I) will be combined with standard approaches to delineating well capture zones. Although the resultant capture zone likely will be very large, there will be critical areas within it that would be the focus of protection-management activities. These critical areas are uphill from, and surrounding, recharge features such as sinkholes and sinking streams. (In the downhill direction, EPA informally suggests a critical-area setback at least equal to the state setback [often called the "health setback" or WHPA "inner zone"] for protecting a PWS well against direct spills. Generally, this setback ranges from 100 to 400 feet, depending on the state. If a state is without such a setback, EPA informally suggests a minimum of 100 feet). Recharge features can frequently be identified on large-scale (for example, 1:24,000) topographic maps and aerial photographs, but it is more reliable to identify them in the field.

Structural characteristics used in the Rules of Thumb

There are two critical structural characteristics that must be evaluated in order to use the RTs for wells. These characteristics are (1) steepness of the dip and (2) dominant type of permeability, that is, bedding-plane partings vs. fractures discordant to bedding. In plateaus, the dip is usually less than about 5 degrees. At the other extreme, where rocks are folded (as in the

Ridge and Valley Province), most dips are steeper. Table 2 is a 2 x 2 matrix showing the hydrologic conditions produced by these end members. (K_{max} and K_{min} are maximum and minimum hydraulic conductivity, respectively.)

Dip Angle	**Flow is Dominated by Bedding-Plane Partings (Dominantly Bedded)**	**Flow is Dominated by Fractures Discordant to Bedding Planes (Dominantly Fractured)**
Gently dipping (< 5 degrees)	Horizontal anisotropy is small, ($K_{max} \approx K_{min}$), although there is much strike-oriented flow for the same reason as in the box below. (Vertical anisotropy can be great, causing perching of vadose water and strong downdip flow.)	Horizontal anisotropy is great, usually about 10X ($K_{max} \approx 10\ K_{min}$), with K_{max} oriented roughly parallel to the dip. Perching of vadose water is not common.
Steeply dipping (> 5 degrees)	Apparent horizontal anisotropy can be great, because dipping bedding-plane partings restrict horizontal water movement. Effective K_{max} is in the direction of the strike, usually about 10 K_{min}. Vadose water follows steep routes to the water table along bedding.	Horizontal anisotropy typically with $K_{max} \approx 10\ K_{min}$, with K_{max} in the direction of strike. This can be disrupted by complex folds and faults, but is fairly consistent. Most vadose water takes steep paths to the water table along fractures, with little perching.

Table 2. Structural characteristics critical to use of the Rules of Thumb

The user must determine whether the rock is dominantly bedded or dominantly fractured. Although there is a continuum between the two, most Appalachian karst aquifers fall near one of the two end members. Geologists or hydrogeologists at the USGS or state geological survey are likely to be able to make this distinction. Otherwise, outcrops of the karst rock should be examined to determine if many beds are visible or if joints are more prominent. Even where there are many small fractures, unless they cut through large sections of strata (for example, tens of feet), bedding-plane partings probably dominate over fractures. This is especially true where there are numerous interbeds of relatively insoluble material, such as shale.

The user must also determine whether beds are gently dipping (<5 degrees) or steeply dipping (>5 degrees). This can either be measured in the field or determined from a geologic map or geological report.

Resources needed to apply the Rules of Thumb

Once the spring's capture zone is delineated (RTs 1.1 and 1.2, above), the only additional information required to determine the well's capture zone is the well's discharge (preferably average-annual, or average long-term, discharge).

Assumptions

The authors have made several assumptions regarding ground-water flow to wells in the Appalachian karst. Failure of these assumptions will lead to errors in delineating capture zones. For that reason, the RTs are designed to overestimate somewhat, capture-zone areas. The assumptions are:

1. The boundaries of a spring's capture zone are not distorted significantly by the pumping of a well. A high-discharge well located near the headward boundary (that is, the boundary farthest along strike from the spring) of a spring's capture zone is likely to distort that boundary. However, the scale of the distortion is much smaller than that of the error in estimating the position of the boundary and can usually be ignored. If desired, it is possible to adjust for this distortion by modifying the boundary as discussed in "Example with an alternative well position", below. A well located near the strike-line boundary of a spring's capture zone is not likely to distort that boundary.

2. Aquifer tests in wells that do not intersect a conduit have response curves rather similar to those for porous media. Although it might seem possible to use standard laminar-flow well equations to estimate cones of depression, the great heterogeneity of karst aquifers and the uncertainty of the hydraulic parameters make this approach unreliable.

3. In wells that tap conduits, pumping causes no reversal of gradient, and so the capture zone for the well will be essentially the same as it would be for a spring located at that same point.

4. Where anisotropy is likely (see Table 2), the cone of depression for the well will be elongate. The reader can use the following guidelines:

   If a well is sited in a gently dipping, dominantly bedded Appalachian karst aquifer, then the aquifer is likely to behave in an isotropic manner, and the cone of depression will not be significantly elongate.

If a well is sited in a steeply dipping aquifer, regardless of whether it is dominantly bedded or dominantly fractured, then K_{max} is approximately along the strike direction, and

$$\frac{K_{max}}{K_{min}} = \left[\frac{d_{max}}{d_{min}}\right]^2 ; \; K_{max} \approx 10\, K_{min};$$

$$d_{max} / d_{min} \approx \sqrt{10}$$

$$d_{max} \approx 3\; d_{min} ,$$

where d_{max} and d_{min} are the lengths of the major and minor axes, respectively, of the cone of depression. Thus, when $K_{max} \approx 10\, K_{min}$, the ratio of the major and minor axes of the cone is approximately 3:1 and the cone is an ellipse.

Although there is a gradation between them, the transition between the K_{max} and K_{min} ratios of about 1:1 and about 1:10 is rather sharp in the Appalachian karst.

Rule of Thumb 2.1: Steeply dipping aquifers (either dominantly fractured or dominantly bedded)

Step A: Determine the size of the well's capture zone:
Equation 2 is used to estimate the size of the contribution area needed to supply a well over the long term:

Equation (2):

$$\frac{\text{average annual well discharge rate (length}^3\text{/time)}}{\text{ground-water recharge rate (length/time)}} = \text{size of well capture area (length}^2\text{)}$$

This equation is valid only over long periods of measurement, because of fluctuations in recharge rate and in well discharge rate. However, even for shorter periods, the equation tends to give a reasonable first approximation of the size of the capture zone. The estimated recharge rate can likely be provided by the USGS and/or state geological survey.

Step B: Define the capture-zone ellipse:
Once the size of the capture zone is estimated, the K_{max} and K_{min} ratios (see Table 2) are used to define the capture-zone ellipse (see assumption 4 above); in doing so, it is assumed that the well is not pumping from a conduit.

Step C: Determine separately, and then superimpose, the capture zones for both of the following scenarios:

Scenario 1: The well draws from a fissured part of the aquifer, rather than from a conduit. The direction of K_{max} approximately coincides with the strike direction. The capture-zone ellipse, determined in the previous Step, is drawn on a map. The ellipse is oriented such that its major axis is parallel to the direction of K_{max}. The well is located essentially in the center of the ellipse. (Figure 10 depicts the capture zone of a well, located far enough from the headward boundary of the spring's capture zone that there is no interference, in a steeply dipping aquifer.) $K_{max} \approx 10\ K_{min}$, regardless of whether the aquifer is dominantly fractured or dominantly bedded. In dominantly fractured settings, the major fracture set that accounts for K_{max} is roughly parallel to the strike of the beds (Deike, 1969). The direction of K_{min} is determined by the minor fracture set perpendicular to K_{max}.

Although the authors wish to avoid the use of a fixed radius, they suggested for added protection, that the minimum capture-zone radius be no less than EPA's informal suggestion of 0.5 mile for fractured-bedrock aquifers.

Scenario 2: The well dominantly withdraws from a conduit. Solution conduits are long and narrow, and some tributaries are likely to extend to the updip boundary of the spring's capture zone. However, for practical purposes, the location of individual conduits is considered to be unknown.

To estimate the approximate capture zone that feeds the conduit, follow these steps:

(1) Estimate the extent of the spring capture zone in which the well is located (use RT 1.1 or 1.2).
(2) Estimate the size and shape of the cone of depression, as shown above.
(3) From the edge of this cone closest to the spring, draw a line in the updip direction as far as the edge of the capture zone defined for the spring (Figure 10).
(4) From the downdip edge of the cone, draw a second line parallel to the strike, in the direction away from the spring, to the far end of the spring's capture zone. The probabilities that flow will deviate from the dip and strike directions, as described in Part I, can be taken into account in drawing these lines. However, this deviation likely will not cause significant errors in the capture-zone boundary and an adjustment is probably unnecessary, particularly if EPA's informally suggested 0.5-mile radius circle is used. If the 0.5-mile radius circle extends further downdip than the calculated cone, instead draw the line from the downdip edge of the circle. In addition, add any adjacent areas draining to contained recharge features.

Thus, the well's potential capture zone includes that portion of the spring's capture zone that lies both updip and upgradient along the strike from the well. There is little chance of recharge to the well from beyond the cone of depression in either the downdip direction or in the direction of the spring. (Considering that the capture-zone boundary is an estimate, the authors suggest, in order to be protective, that if the cone of depression or the 0.5-mile radius circle extends beyond the strike line, the capture zone includes all of the cone or circle, respectively, that does not extend beyond a perennial

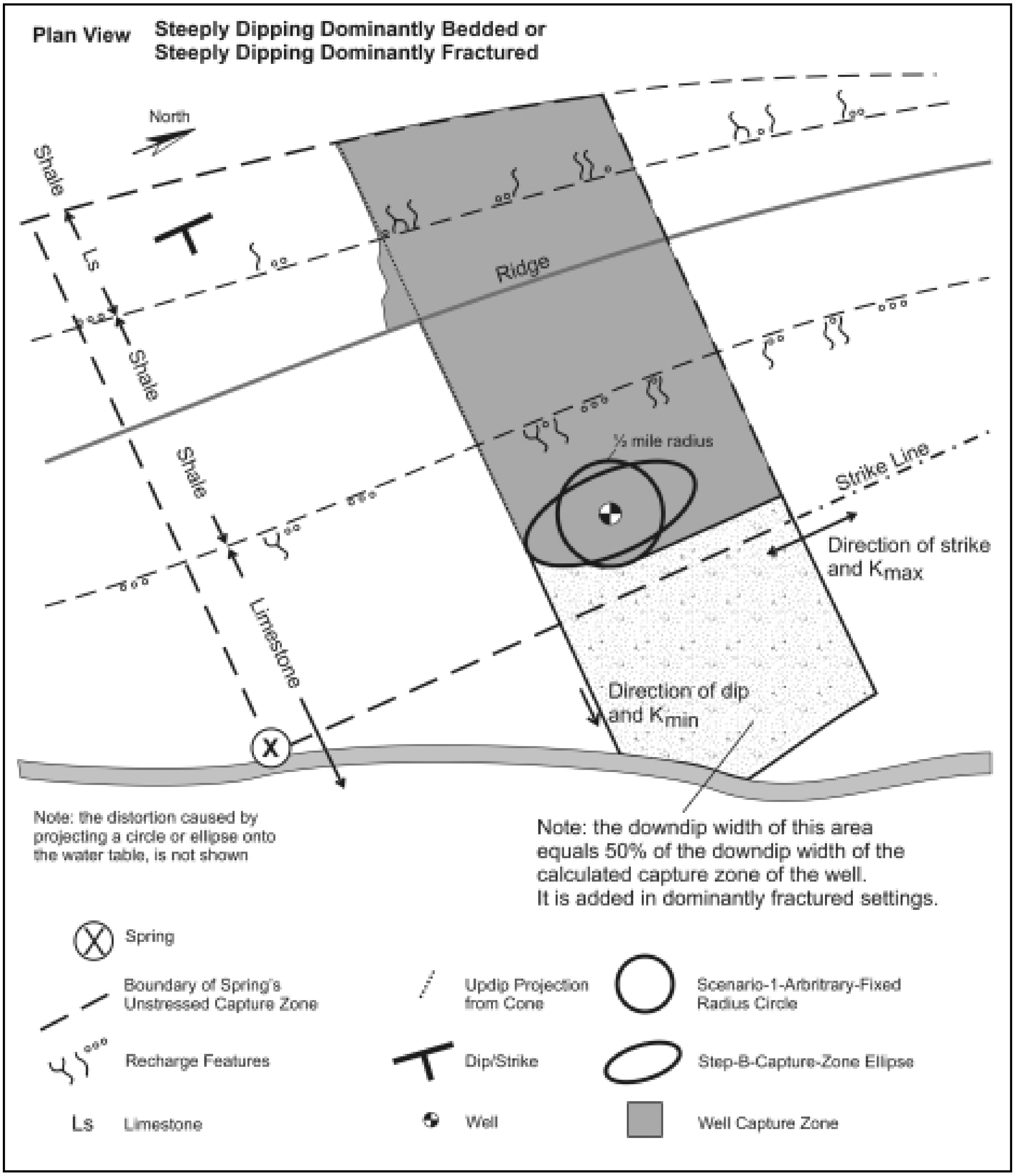


Figure 10. Capture zone of a well, located far enough from the headward boundary of the spring's capture zone that there is no interference, in a steeply dipping aquifer, regardless of whether the aquifer is dominantly fractured or dominantly bedded.

stream. If both cross the strike line, the authors suggest including all of the cone rather than all of the circle [see Figures 12 and 13, below].) Any land areas draining to the contained recharge features are added to the well's capture zone.

Consider now that the well in Figure 10 is instead located <u>near</u> the headward end of the spring's capture zone (Figure 11). As in Figure 10, the well is sited in a steeply dipping karst aquifer.

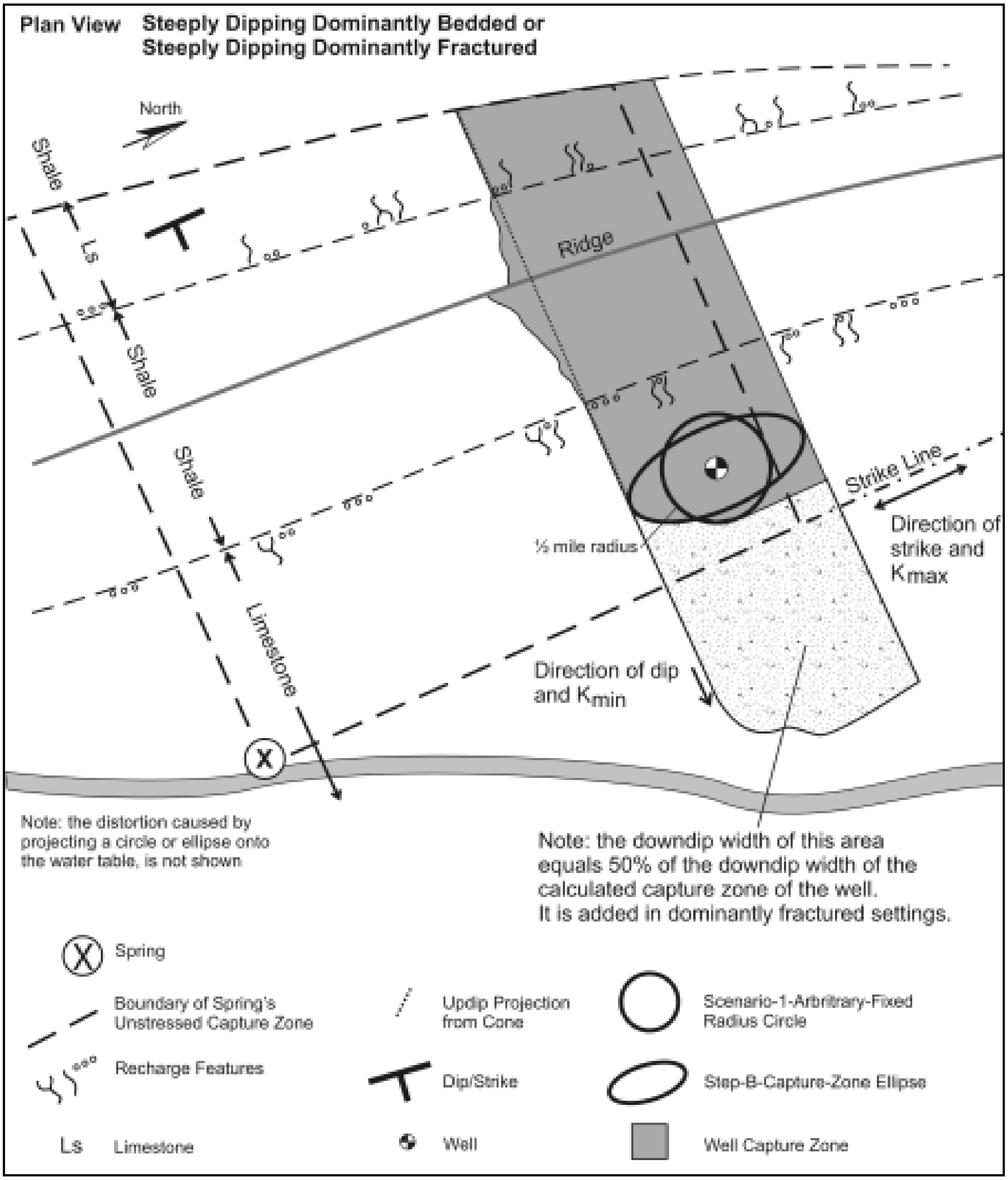


Figure 11. Capture zone of a well, located near the headward boundary of the spring's capture zone, in a steeply dipping aquifer, regardless of whether the aquifer is dominantly fractured or dominantly bedded.

The well can draw water from outside the spring's capture zone if the cone of depression extends beyond it, although the additional area is rarely significant, especially in view of the uncertain nature of the spring's capture-zone boundary. In this case, the capture zone for the well is estimated simply by drawing lines updip from the two ends of the cone nearest and farthest from the spring (Figure 11). These lines terminate at the updip boundary of the spring's estimated capture zone. Any land areas draining to the contained recharge features are added to the well's capture zone. Note that, in this example, because the well was located near the boundary of the spring's capture zone, the width of the well's capture zone is relatively narrow.

Step D: In dominantly fractured settings, modify the capture zone by adding a strip in the downdip direction about half the dip-direction width of the original well capture zone. In addition, any adjacent areas draining to contained recharge features should be added. In expanding the boundaries in these two ways, no perennial surface streams should be crossed. The resulting area is likely to be larger than necessary to account for the well's discharge, but this simply reflects the greater uncertainty in dominantly fractured settings.

Rule of Thumb 2.2: Gently dipping, dominantly bedded aquifers

The same approach as that described above is used in this setting. However, here, because [$K_{max} \approx K_{min}$], the ellipse above collapses into a circle. Its area is determined as described above. The well is located at the center of the circle (Figure 12). In this example, the well is sited near the headward end of the spring's estimated capture zone. Figure 13 shows a similar situation, except that the well is not located near the headward end of the spring's capture zone.

Rule of Thumb 2.3: Gently dipping, dominantly fractured aquifers

In this setting, the same approach is used as that described in RT 2.1, above. However, here $K_{max} \approx 10\ K_{min}$, and K_{max} is in the dip direction. Figure 14 shows a well distant from the headward end of the spring's estimated capture zone. (In this example, the spring's capture-zone boundary abuts a cluster of recharge features. The spring's capture-zone boundary has already been adjusted to include the surface area draining to these features; thus, the well's capture zone includes this area, too.)

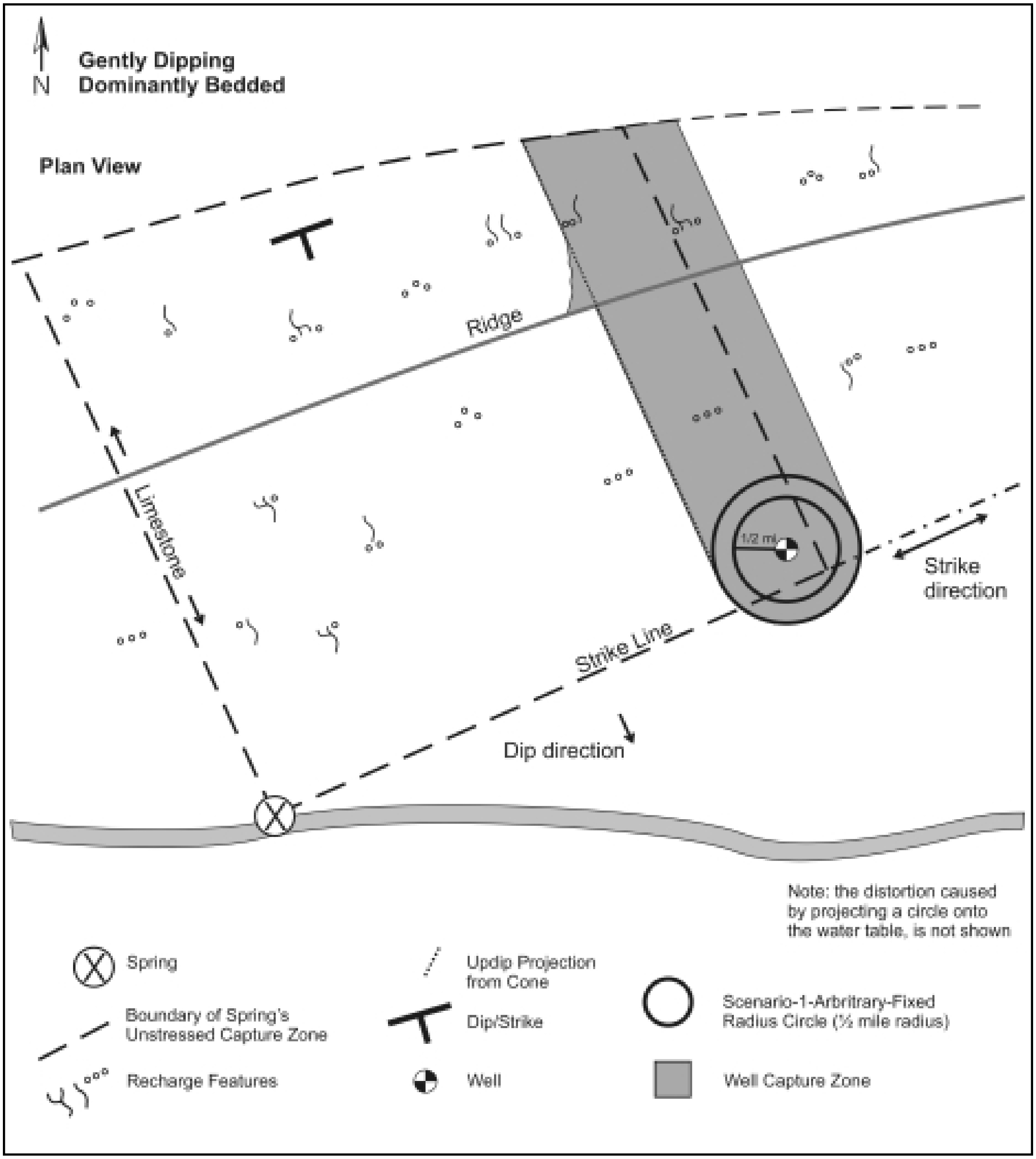


Figure 12. Capture zone of a well, located near the headward boundary of the spring's capture zone, in a gently dipping, dominantly bedded aquifer.

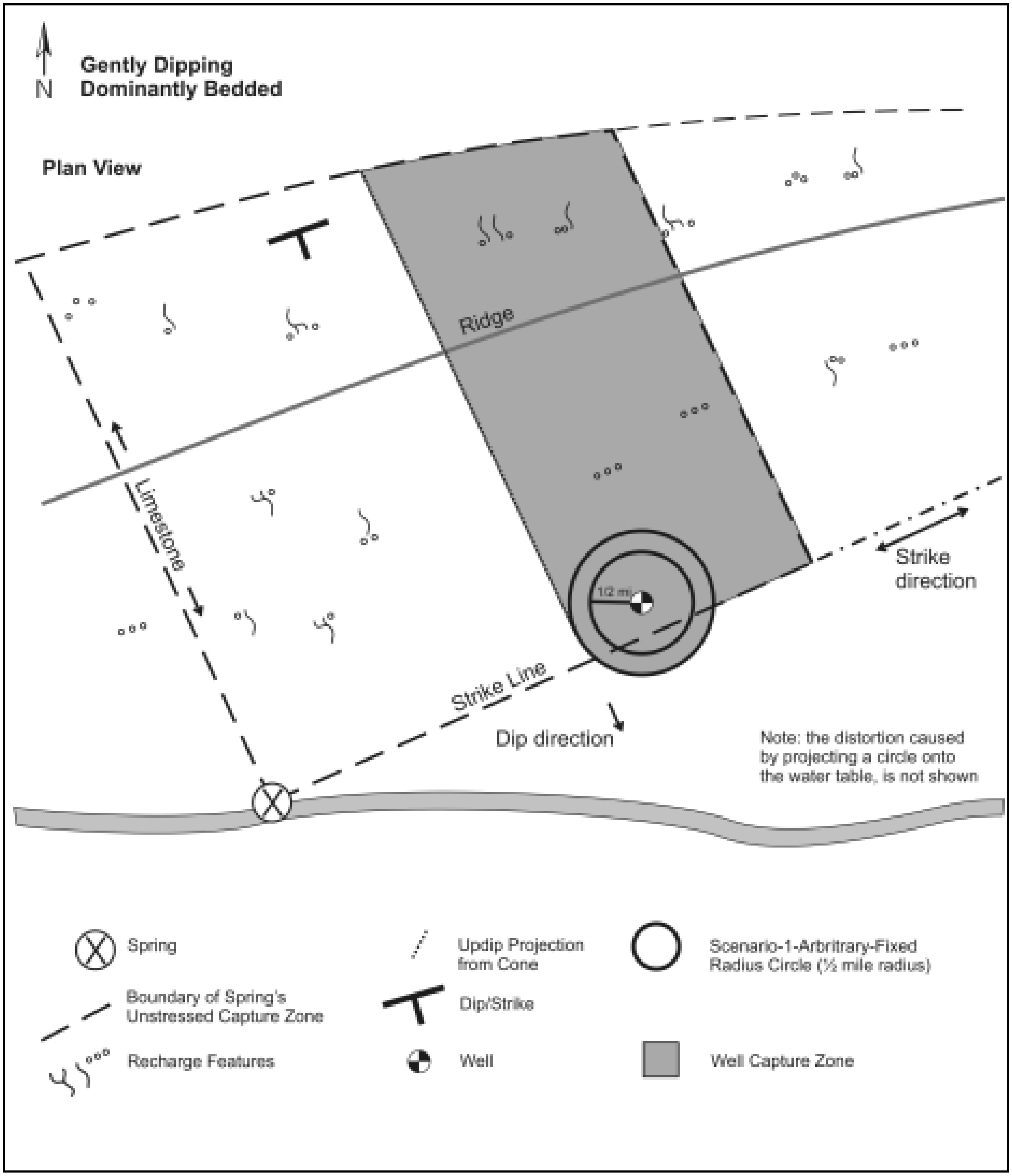


Figure 13. Capture zone of a well, located far enough from the headward boundary of the spring's capture zone that there is no interference, in a gently dipping, dominantly bedded aquifer.

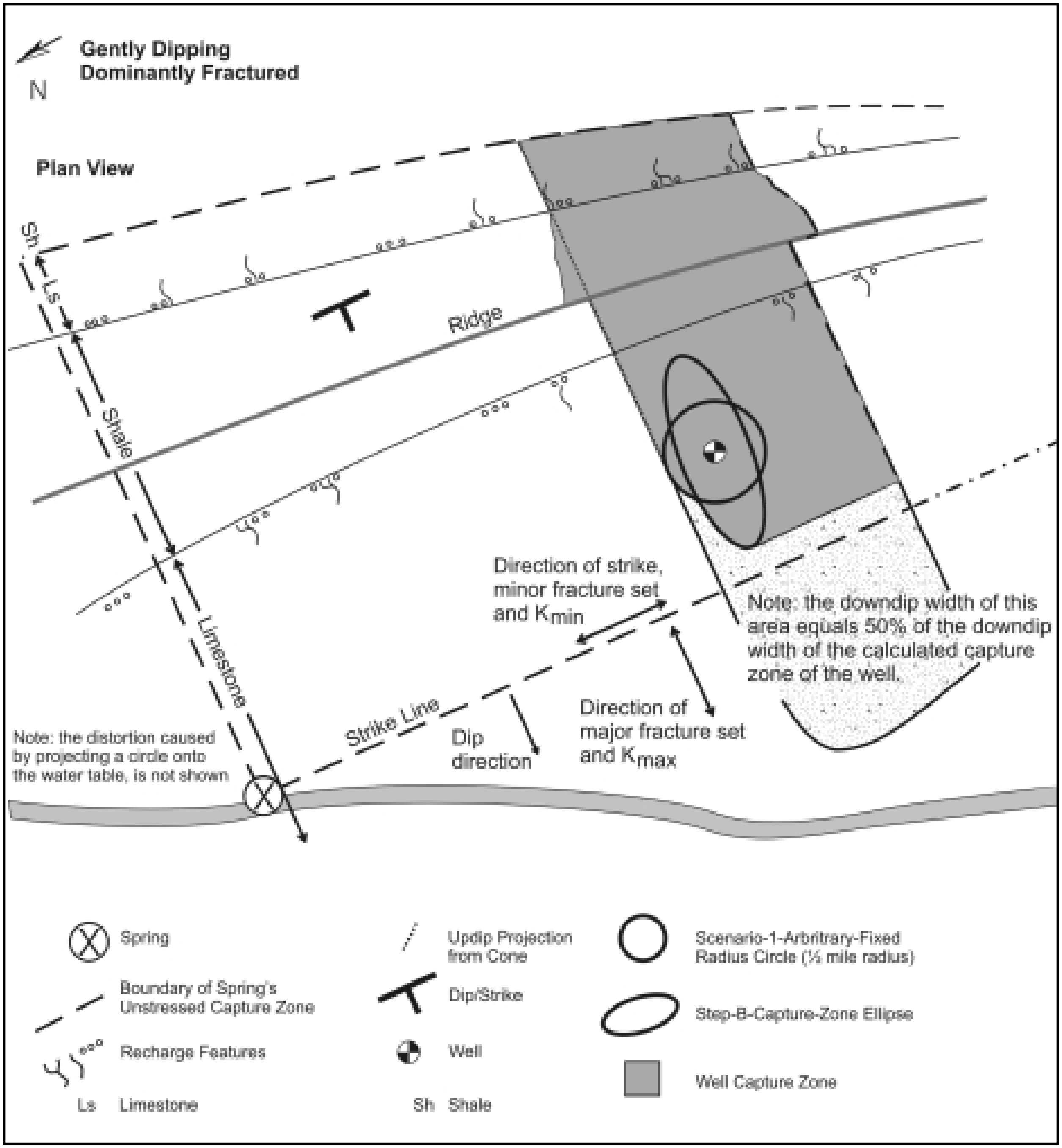


Figure 14. Capture zone of a well, located far enough from the headward boundary of the spring's capture zone that there is no interference, in a gently dipping, dominantly fractured aquifer.

List of References

Biondic, Bozidar, January 8, 2002, electronic communication, Institute of Geology, Croatian Geological Survey.

Brahana, J. V., John Thrailkill, Tom Freeman, and W. C. Ward, 1988, Chapter 38 Carbonate Rocks, The Geology of North America, Vol. O-2, Hydrogeology, Geological Society of America, pages 333-352, in Hydrogeology, William Back. Joseph S. Rosenshein and Paul R. Seaber, eds., 1988, Geological Society of America.

Deike, R. G., 1969, Relations of Jointing to Orientation of Solution Cavities in Limestones of Central Pennsylvania, American Journal of Science, v. 267, pages 1230-1248.

Dingman, S. Lawrence, 1993, Physical Hydrology, Prentice-Hall, Inc., Englewood Cliffs, NJ.

Jones, William, K., 1997, Karst Hydrology Atlas of West Virginia, Karst Waters Institute, Special Publication 4, pages 90-91.

McDowell, Robert, C., George J. Grabowski Jr. and Samuel L. Moore, 1981, Geologic Map of Kentucky, US Geological Survey in cooperation with the 10th Kentucky Geological Survey and the 11th Kentucky Geological Survey, map, 1:250,000-scale, sheet 1 of 4.

Palmer, A. N., 1999a, A statistical evaluation of the structural influence on solution-conduit patterns, Karst Waters Institute, Charles Town, WV, Special Publication 5, pages 187-195.

Palmer, A. N., 1999b, Anisotropy in carbonate aquifers, Karst Waters Institute, Charles Town, WV, Special Publication 5, pages 223-227.

Palmer, A. N., 1986, Prediction of contaminant paths in karst aquifers: Proceedings of First Conference on Environmental Problems in Karst Terranes and Their Solutions, Dublin, Ohio, National Water Well Association, pages 32-53.

Price, Paul H. and E. T. Heck, 1937, Greenbrier County showing general and economic geology, West Virginia Geological Survey, map, 1:62,500-scale, east sheet (Map II).

Rantz, S. E., and others, 1982, Measurement and computation of streamflow; Volume 1. Measurement of stage and discharge; Volume 2. Computation of discharge; US Geological Survey Water Supply Paper 2175.

Quinlan, James F., and Ralph O. Ewers, 1989, Subsurface Drainage in the Mammoth Cave Area, *in* Karst Hydrology Concepts from the Mammoth Cave Area, William B. White and Elizabeth L. White, eds., 1989, Van Nostrand Reinhold, NY NY, pages 76, 78, 85.

Quinlan, James F., and R. A. Ray, 1981, Groundwater basins in the Mammoth Cave Region, Kentucky, Friends of the Karst Occasional Publication Number 1, map (Plate 1 *in* Karst Hydrology Concepts from the Mammoth Cave Area, William B. White and Elizabeth L. White, eds., 1989, Van Nostrand Reinhold, NY NY) .

US Environmental Protection Agency, 1997, State Source Water Assessment and Protection Programs Guidance, Final Guidance, EPA 816-R-97-009, 152 pages.

US Geological Survey, 1986, Water Fact Sheet Hydrologic Hazards in Karst Terrain, Open-File Report 85-677, 2 pages.

US Geological Survey, with Tennessee Valley Authority, 1986, Campbellsville Kentucky 1:100,000-scale metric topographic base, map.

US Geological Survey, with Tennessee Valley Authority, 1985, Bowling Green Kentucky - Tennessee, 1:100,000-scale metric topographic base, map.

White, William B. and Elizabeth L. White, eds.,1989, Karst Hydrology Concepts from the Mammoth Cave Area, Van Nostrand Reinhold, NY NY, 346 pages.

Appendix 1

WATER FACT SHEET

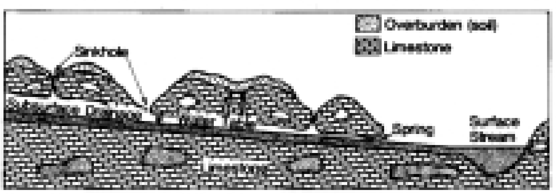
U.S. GEOLOGICAL SURVEY, DEPARTMENT OF THE INTERIOR

HYDROLOGIC HAZARDS IN KARST TERRAIN

NOTE: Figures on this Fact Sheet are two-dimensional and appear to show rocks and surficial material floating on cave streams. This was done to emphasize the concept of an open flow system. In reality, the third dimension would show the material above and below the cave streams to be connected in places.

WHAT IS KARST?

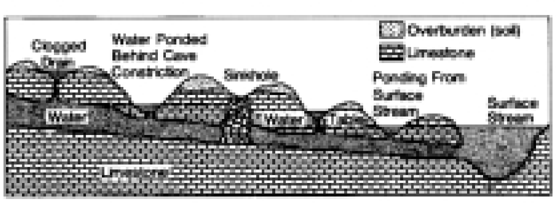
Karst or karst terrain refers to a type of topography formed in limestone, dolomite, or gypsum by dissolution of these rocks by rain and underground water, and is characterized by closed depressions or sinkholes, and underground drainage. During



the formation of karst terrain, water percolating underground enlarges subsurface flow paths by dissolving the rock. As some subsurface flow paths are enlarged over time, water movement in the aquifer changes character from one where ground-water flow was initially through small, scattered openings in the rock to one where most flow is concentrated in a few well-developed conduits. As the flow paths continue to enlarge, caves may be formed and the ground-water table may drop below the level of surface streams; surface streams may then begin to lose water to the subsurface. As more of the surface water is diverted undergound, surface streams and stream valleys become a less conspicuous feature of the land surface, and are replaced by closed basins. Funnels or circular depressions called sinkholes often develop at some places in the low points of these closed basins.

SINKHOLE FLOODING

Ponding in sinkholes of surface runoff from storms is a part of the natural hydrologic system in karst regions. Ponding occurs during periods of intense rainfall when the rate of storm

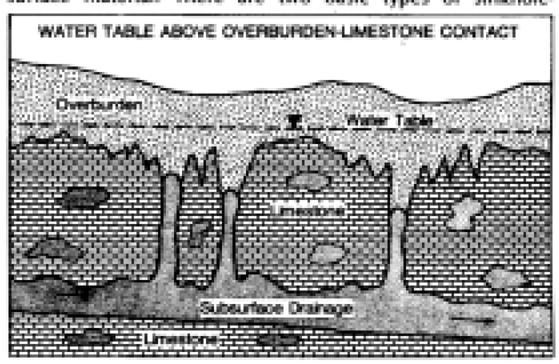


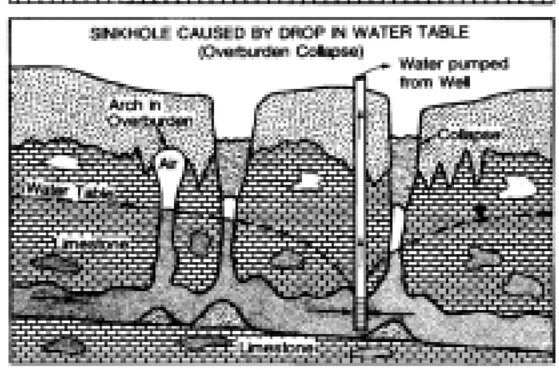
water runoff exceeds the drainage capacity of sinkholes. Water in underground conduits can back up into sinkholes when the rate of storm water inflow exceeds the drainage capacity of either the cave stream or the receiving surface stream.

Urban structures are often built near sinkholes where flooding problems may be aggravated by (1) increased rates of runoff from impervious roofed or paved areas, (2) decreased storage due to sinkhole grading and filling, and (3) clogging of sinkhole drains by debris and silt.

HOW DO SINKHOLES DEVELOP?

Sinkholes develop as a result of the collapse of surface or near-surface material. There are two basic types of sinkhole-

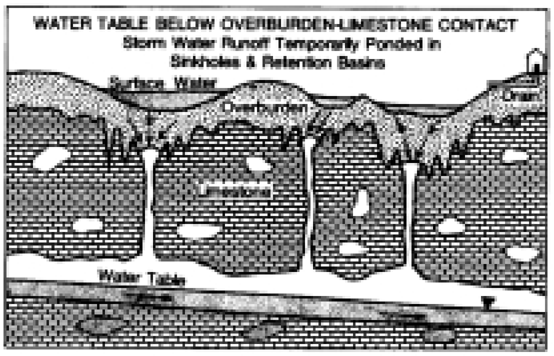


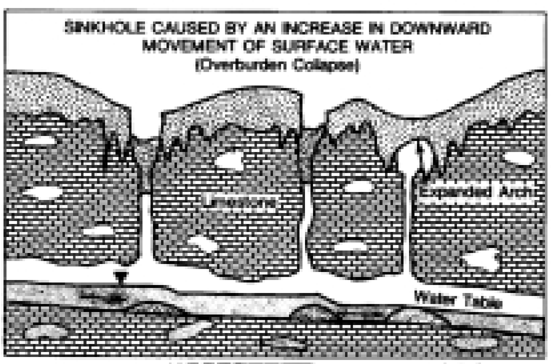


forming collapses: (1) limestone collapses and (2) overburden collapses into underlying limestone cavities. Limestone collapses generally occur due to the enlargement of cave passages in limestone. The enlargement causes the roofs above the passages to weaken and eventually collapse to create sinkholes. Overburden collapses are more common than limestone collapses and generally result in overburden slumping into openings or cavities in the underlying limestone.

In areas where the water table is usually above the overburden-limestone contact, collapses often occur when the water table drops below the overburden-limestone contact, either during droughts or during high-volume pumping. Phys- ically the collapses in this case are caused by loss of buoyant support for the overburden arches over openings in the limestone. Collapses are also caused by sloughing of saturated overburden down the opening, enlarging the arch, and eventually causing collapse at the land surface. When the water table fluctuates above and below the overburden-limestone contact, collapse may result from repeated wetting (swelling) and drying (shrinking) of material supporting overburden arches.

Overburden collapses also may occur in situations where the water table is usually below the overburden-limestone contact. Construction and land use changes that concentrate surface runoff in drains and impoundments may locally increase the downward movement of water resulting in slumping of saturated overburden into openings in the limestone. Loading of the surface by structures or ponded water, or vibrating the surface by blasting may also occasionally cause the collapse of overburden arches.





Although sinkhole-forming collapses occur naturally, many are induced by pumping or by constructing facilities that alter surface drainage. Collapses cause millions of dollars in damages each year to reservoirs, roads, buildings, and homes. In most States, losses are not usually covered by homeowners insurance policies.

GROUND-WATER CONTAMINATION

Shallow aquifers in karst terrains are extremely vulnerable to contamination. The aquifers receive water either by percolation through the soil or by concentrated flow directly into the aquifer from sinkholes and disappearing streams. In many karst areas, subsurface streams are simply surface streams that, after disappearing underground, flow through subsurface conduits to reappear at springs where they become surface streams again. Because these underground streams flow at velocities commonly between 0.1 and 5 miles per day, contaminants may move in a shorter period of time than contaminants in aquifers that are unaffected by karst development.

Contaminants associated with agricultural activities, such as fertilizers, nitrate and bacteria from livestock waste, or organic compounds from pesticides, are potential problems in karst terrains. Contaminants associated with urban storm water runoff, such as lead, chromium, oil and grease, and bacteria from pet-animal wastes, may be a threat to people using water supplies in karst terrains and to cave aquatic life. Dye-tracing techniques have shown that septic tank effluent can travel through the thin soils that are characteristic of most karst terrains into the aquifer and to springs in only a few hours. Water samples collected at some springs following heavy rains contain bacteria that probably are derived from human wastes, indicating that recharge water flushes effluents from septic tank drain fields into the shallow limestone aquifer.

Contamination problems are aggravated in karst terrains by the common practice of disposing of soil and liquid wastes in sinkholes where they may be washed directly into the aquifer. The development and widespread use of hazardous materials has increased the threat from this practice.

Leaks, spills, or deliberate dumping of toxic or explosive chemicals are a particularly serious hazard for karst terrains. Chemicals that leak from buried tanks may be carried into conduits or caves below by percolating water following heavy rains. Most conduits or caves become completely water-filled at some downstream point forming natural traps for floating chemicals that accumulate against the ceiling. Not only are these materials a threat to water supplies and cave aquatic life, but, upon vaporizing, they may become highly concentrated in the cave atmosphere and rise through fractures in the overlying lime-stone to enter inhabited structures on the surface. Occasionally homes in urban areas must be evacuated because fumes in base-ments reach explosive levels.

The degree of contamination of shallow aquifers in karst terrain depends primarily upon whether these aquifers receive distributed or concentrated recharge, and upon the proximity and types of sources of contamination. Springs and water wells in karst terrain, if supplied entirely by distributed recharge through thick overburden or from sources distant from contaminated areas, may be free of contaminants and therefore excellent sources of potable water. However, many springs and water wells in karst terrain receive concentrated recharge from a nearby area where sources of contamination are present.

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Appendix 2: Clarification of karst flow patterns

This appendix is designed to clarify the patterns of flow within the spring capture zones described in Part I. The description here is simplified to show the basic premise behind the Rules of Thumb.

A cross section (Figure 15) is shown through a typical capture zone, viewed in the direction of the strike (that is, strike is into/out of the page). The main solution conduit (A) that drains to the spring is shown, and is assumed to lie at the same elevation as the spring.

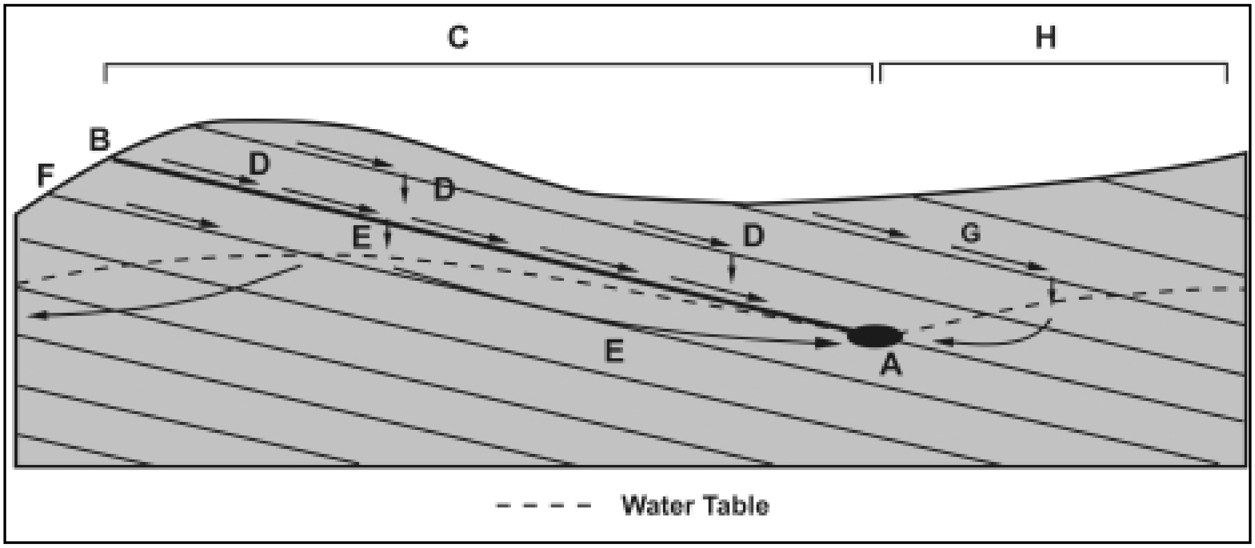

Figure 15. Cross section through a typical capture zone, showing the basic premise behind the Rules of Thumb. (View is in the direction of the strike, that is, strike is into/out of the page.)

The capture zone for the spring includes the region updip from the strike-oriented conduit. A line is drawn up the dip from the strike line (that is, the conduit) until it intersects the surface (point B). Within zone C (extending between A and B), vadose water (in the unsaturated zone) drains essentially down the dip, cutting across the beds in places where it follows steep paths along fractures. The pattern of flow is shown by the descending arrows. Major flows (such as D) form solution conduits tributary to the strike-oriented conduit. Minor seepage (E) through fissured parts of the aquifer may reach the water table and follow the hydraulic gradient into conduits (mainly the strike-oriented one).

Any areas of surface runoff that drain into zone C are included in the spring's capture zone (not shown).

Zone F lies beyond the estimated capture zone in the updip direction. Infiltration into this zone is limited. Vadose seepage drains more or less down the dip, reaches the water table, and flows down the hydraulic gradient into the stream valley to the left.

By jogging downward along fractures, much of the vadose water that infiltrates within zone C reaches the water table and drains toward the right into the strike-oriented conduit (especially in dominantly fractured aquifers). However, some vadose water may pass above the strike-oriented conduit as downdip flow (G). This water reaches the water table to the right of the conduit but then flows against the dip to the conduit. The delineation of the spring's capture zone remains valid.

However, in dominantly fractured rocks, some water is able to infiltrate to the right of zone C and still reach the conduit by flowing against the dip (zone H). Field experience suggests that the width of zone H is typically less than half the width of zone C. A width equal to 50% of the width of zone C is suggested to give an ample safety margin. This additional strip will increase the area of the estimated capture zone beyond what is needed to supply the spring's discharge, but it is appropriate to do so, in view of the uncertainty of flow paths in highly fractured karst aquifers.

Piezometric measurements in wells can help to delineate the water-table divides. However, this information does not take into consideration the lateral-flow component of vadose flow. Vadose flow commonly crosses water-table divides, especially in dominantly bedded aquifers.

Appendix 3: Simple method for measuring spring discharge

Introduction

The goal of this appendix is to provide a simple method for estimating spring discharge rate, a critical parameter value needed in the Rules of Thumb described in the preceding sections. Numerous hydrology texts discuss standard methods for obtaining this value. The US Geological Survey (USGS), among others, has published considerable information on the subject, much of it available at the USGS website www.usgs.gov.

The method below is a simplified (though less accurate) method for obtaining spring discharge, incorporating information from Rantz, et al (1982) and Dingman (1993). The accuracy of the method should be sufficient for the purposes of the Source Water Assessment and Protection Program.

Most karst springs in the Appalachians form discrete streams of their own, which flow on the surface for a short distance to a surface stream. Measuring the discharge in the surface channel of such springs is not difficult. However, a small number of Appalachian springs discharge directly into the beds of surface streams; measuring their discharge is difficult and beyond the scope of this method. For the vast majority of Appalachian springs, the method below is useful. Water issuing from karst springs typically forms shallow streams that are fairly easy to measure without danger. Do not attempt to enter streams containing rapidly flowing water or water more than knee deep.

Resources needed

Users will need: hip boots or chest waders, floats (for example, wood chips), stopwatch, meter stick or yardstick, tape, string and a half dozen stakes.

Method for estimating spring discharge

Spring discharge should be measured during the period of high base flow in nearby surface streams. In the southern Appalachians, high base flow typically occurs in February, several days after a significant precipitation event. In the northern Appalachians it typically occurs in March, several days after a significant precipitation event.

Spring discharge is determined in the following steps: (1) measure the velocity of the water in the channel issuing from the spring, (2) measure the area of a cross section through which the spring discharge flows, and (3) obtain the discharge by multiplying the velocity by the cross-sectional area.

Velocity of flow in the channel

Velocity varies with depth within a stream and with distance from shore. A commonly used approximation is that the average velocity of a vertical column of water in a stream is equal to 0.85 times the velocity at the surface (Dingman, 1993). The generalizations in this assumption are acceptable for the purposes of Source Water Protection. Velocity should be measured over a length of channel approximately 10 times the channel width (Dingman, 1993).

Step 1: Draw a string across the channel, perpendicular to the channel axis, and stake the string at both ends. The string traverse should be along a straight reach of the channel. Measure the width of the channel at the traverse. Similarly, draw a second string across the channel at a distance upstream of the first approximately equal to 5 times the channel width. Repeat with a third string approximately 5 channel widths downstream of the first string. (If the channel is not long enough, these distances can be shortened, with a slight decrease in accuracy.) Measure the length of the stream channel between the upstream and the downstream traverses. The upstream traverse marks the starting location for the velocity measurement, and the downstream traverse marks the end. The middle traverse is where the cross-sectional area is calculated.

Step 2: Along the upstream traverse, gently toss the floats, all at once, onto the stream surface (Figure 16a). It will likely take a little practice to distribute the floats across the channel, so the user should have a large supply of floats available.

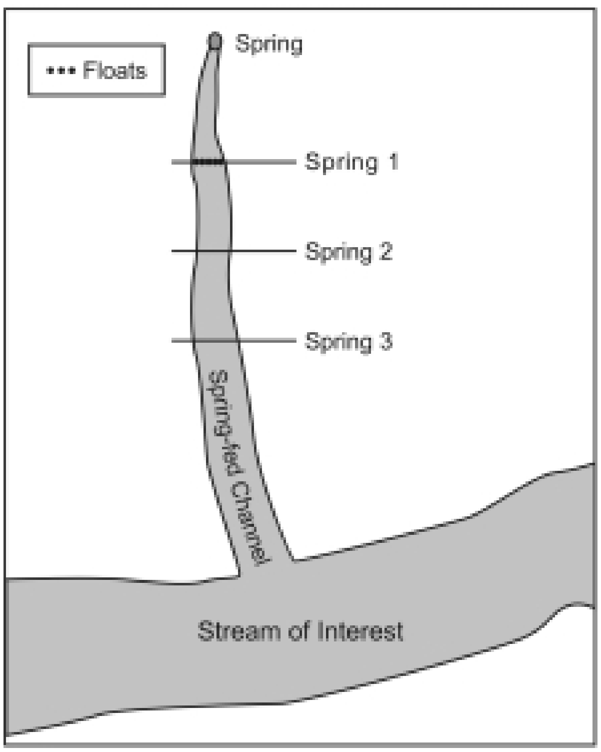

Figure 16: a) Position of floats at the beginning of a stream-velocity measurement.

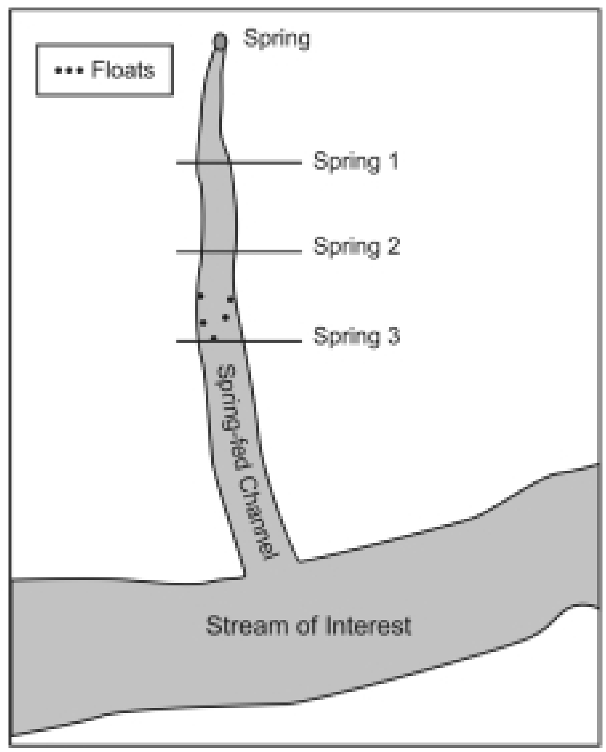

Figure 16: b) Position of floats at the end of a stream-velocity measurement.

Step 3: Measure the time required for the floats to travel to the downstream traverse (Figure 16b). The first arrival time is used, because it yields the largest (that is, the most protective) estimate of the spring capture zone.

Step 4: Repeat this travel-time measurement several times. Average the results. Calculate the resulting velocity by dividing the distance between the upstream and downstream traverses by the average first-arrival travel time.

Step 5: Determine the average velocity of the most rapid vertical column of water by multiplying the surface velocity obtained in Step 4 by 0.85. It might appear that Steps 4 and 5 defeat the purpose of using the maximum reading in Step 3. However, this method assures not only that the spring capture zone is not underestimated, but also that it is not grossly overestimated. In a smooth, uniform channel with rapid flow, the resulting discharge estimate will be fairly accurate.

Cross-sectional area of the stream

The stream cross-sectional area is the width multiplied by the average depth.

Step 1: At the middle traverse, divide the stream channel into uniform intervals. For example, in a 10-foot-wide channel, mark the string at one-foot intervals (Figure 17).

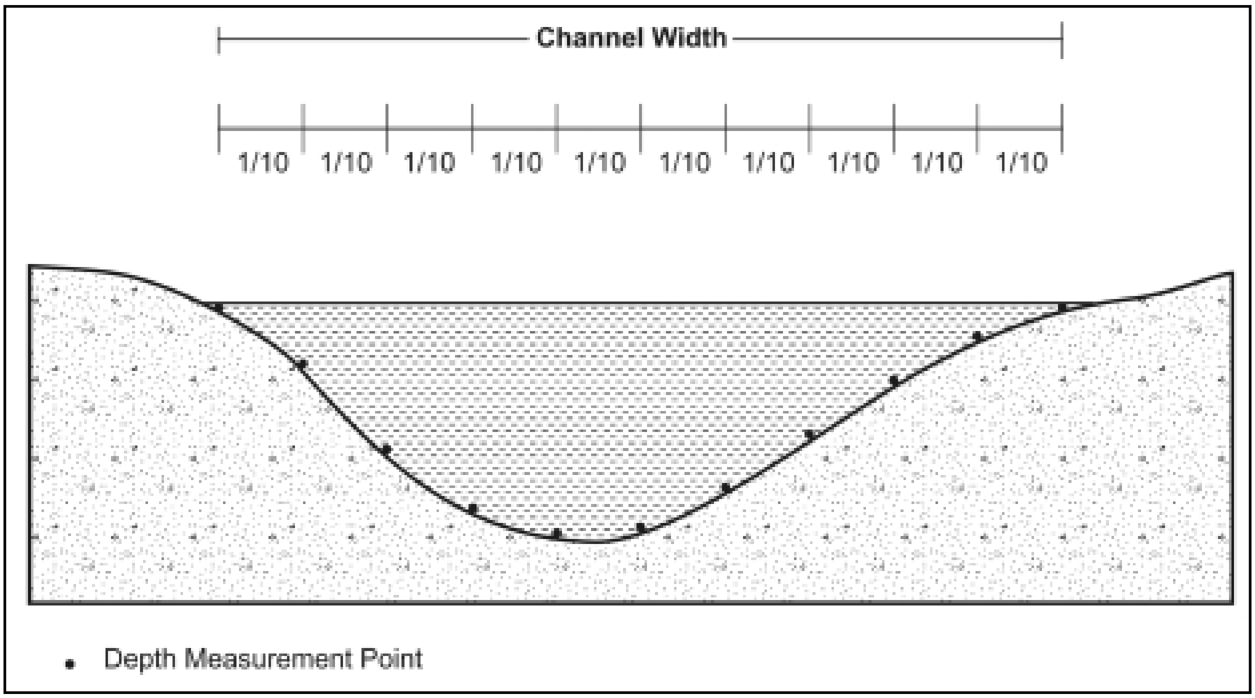

Figure 17: Cross section of a stream, with locations of depth-measurement points.

Step 2: At each mark, measure the stream depth with a thin meter stick or yardstick. Minimize the standing wave by facing the thin edge of the measuring stick into the current. Include one zero depth (to represent one edge of the stream - but not both).

Step 3: Average the depths and multiply the result by the width of the stream. This gives the cross-sectional area of the stream. Be sure to use homogeneous units. For example, if channel width and length are measured in feet, convert the average stream depth to feet.

Calculate the spring discharge with equation 3

Equation 3:

$$\text{Spring Discharge} = (\text{Stream Velocity}) \times (\text{Stream Cross-sectional Area})$$

Calculate the size of the spring capture zone

Calculate the size of the spring capture zone with equation 1, in Part I, using an estimate of ground-water recharge (which can usually be obtained from the USGS or the state geological survey), and the discharge rate estimated with equation 3.

Hypothetical example:

In this example, an estimate of 0.8 feet/year of ground-water recharge is supplied by the USGS District Office.

Velocity of flow in the channel:

Step1: Strings are placed across the channel marking three traverses, as described above. Channel width at the middle traverse is measured to be 6.0 feet. The stream-channel distance between the upstream and downstream traverses is measured to be 60 feet.

Step 2: Floats are released onto the surface of the channel along the upstream traverse.

Step 3: The time elapsed between releasing the floats at the upstream traverse and the first float arrival at the downstream traverse is measured to be 53 seconds.

Step 4: Repeating Step 3 gives times of 51 seconds and 55 seconds. The average time is, thus, 53 seconds.

Step 5: Divide the length (60 feet) by the time (53 seconds) to obtain the velocity (1.13 feet/second). Multiplying the velocity by 0.85 yields 0.96 feet/second.

Cross-sectional area of the stream:

Step 1: The middle string is marked every 0.6 feet and channel depth is measured at every mark, in this example, 0.0 feet, 1.2 feet, 1.9 feet, 2.2 feet, 2.4 feet, 2.1 feet, 1.8 feet, 1.3 feet, 0.8 feet and 0.6 feet. Note that the zero depth at only one streambank is included in the measurements.

Step 2: The average stream depth at this traverse is, therefore, $(0.0 + 1.2 + 1.9 + 2.2 + 2.4 + 2.1 + 1.8 + 1.3 + 0.8 + 0.6) \div 10 = 1.43$ feet.

Step 3: The cross-sectional area of the stream at the traverse is: 1.43 feet x 6.0 feet = 8.6 feet^2 (rounded off to nearest tenth).

Spring discharge:

As shown in equation 3, the discharge is the adjusted velocity calculated above (0.96 feet/second) times the cross-sectional area (8.6 feet^2) = 8.3 feet^3/second. Since one year (365.25 days) = 31,557,600 seconds, the measured spring discharge is equivalent to about 262,000,000 feet^3/year (rounded off to reflect uncertainty).

Size of spring capture zone:

The size of the spring capture zone is calculated with equation 1, in Part I, using the recharge estimate of 0.8 feet/year and 27,878,400 feet^2/mile^2:

$$\frac{262{,}000{,}000\ \text{feet}^3/\text{year}}{0.8\ \text{feet/year}} = \frac{327{,}500{,}000\ \text{feet}^2}{27{,}878{,}400\ \text{feet}^2/\text{mile}^2} = 11.8\ \text{mile}^2$$