PRELIMINARY WELLHEAD PROTECTION AREA DELINEATION: RECOMMENDED METHODS FOR KARST AQUIFERS IN NORTHWEST AND SOUTHWEST GEORGIA

by

WILLIAM H. McLEMORE, BOBBY JONES, and DAVID B. WENNER

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ENVIRONMENTAL PROTECTION DIVISION
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INTRODUCTION

Regulatory Background

State Wellhead Protection (WHP) programs, established by the Safe Drinking Water Act (SDWA) in 1986, protect wellhead areas from pollutants that may adversely affect the health of individuals. Wellhead Protection Areas (WHPAs) are zones defined by the SDWA as "surface and subsurface areas surrounding a water well or well field, supplying a public water system, through which pollutants are likely to move toward and reach such wells or well field" (EPA, 1993). In Georgia, the WHP Program, administered by the Geologic Survey Branch of the Georgia Environmental Protection Division (EPD), only applies to municipal wells (e.g., wells supplying drinking water to counties, cities, and towns). Public wells serving subdivisions, trailer parks, campgrounds, restaurants, and other uses besides municipal are not covered by Georgia's WHP rules.

As part of its EPA-approved WHP Program, EPD committed to preparing WHP Plans for the approximately 1200+ Georgia municipal water supply wells in ten years (i.e., from July 1, 1993 to June 30, 2003). Further, EPD would do this utilizing two geologists funded out of an EPA Ground-Water 106 grant that was only adequate to pay for salaries and travel. This meant that each geologist would have to prepare plans for approximately 60 wells each year in order to maintain the regulatory schedule. To achieve this schedule, the geologists simply would not have time to perform scientifically rigorous hydrogeologic studies such as tracer tests and/or aquifer tests. EPD recognizes that such techniques would produce WHP Plans that are superior to plans using the methods described in this document. Nevertheless, with the above in mind, it is EPD's intent to first screen and prepare WHP Plans for the 1200+ municipal wells and then at a later date perform more rigorous analysis on a subset of the wells that are deemed most likely to be susceptible to pollution.

Overview

Utilizing EPA's DRASTIC methodology (Aller, et al., 1987), EPD (Trent, 1992) developed a ground-water pollution susceptibility map for the State of Georgia. This map, which subdivides the State into areas of high, medium, and low susceptibility, shows the karstic carbonate terrains of both northwest and southwest Georgia as having high susceptibility. In areas of high ground-water pollution susceptibility, EPD is especially concerned about ground-water pollution or contamination of drinking water wells; therefore, EPD permits are more restrictive (e.g., some types of facilities are prohibited or enhanced spill and leak detection are required at facilities). In these areas, WHPAs should be large (i.e., more conservative).

The methods employed to delineate a WHPA for municipal wells and well fields vary widely, depending upon the type of aquifer, geologic setting, and financial resources available. Because of the uniqueness of each well's environment, methods that work in one situation may be totally inappropriate for another situation. An incorrect application of a particular/specific method may cause more harm than good, especially if a false sense of security is created. Nowhere is this more evident than in applying methods recommended for delineating a WHPA for matrix-flow media to conduit-flow dominated karst aquifers.[1]

For wells completed in karstic terrains, a WHPA comprises two separate zones; namely:

(1) The Control Zone: Within this zone, the owner shall control all activities so that there are minimal sources of potential pollution near the well bore. The Control Zone (CZ) shall be a circle, extending outward from the well bore 25 feet for pervious surface materials or 15 feet for impervious surface materials, such as concrete.

(2) The Management Zone: Within this zone, specific potential pollution sources are prohibited or specific activities must be performed according to WHP Rules. In those areas identified by EPD as being karstic, there shall be an Inner Management Zone (IMZ) of 500 feet and an Outer Management Zone (OMZ) generally determined by hydrogeologic mapping.[2] IMZ protective criteria are more stringent than those for the OMZ.

The primary focus of this report, therefore, is to recommend a methodology to EPD for the delineation of OMZs for WHPAs in karstic terrains in Georgia, particularly for those wells (and well fields and springs) where there is a paucity of data.

When EPD initiated it's WHP Program in 1993, it recognized that karstic terrains presented a unique set of conditions. The State feared that a release or spill of a pollutant near a sinkhole/swallowhole in the OMZ could rapidly enter the ground-water regime with minimal attenuation through overlying residual soils. Upon reaching the water table, the pollutant could flow down gradient through the irregularly-shaped conduits and rapidly reach the well with little to no attenuation. Moreover, because most natural geologic systems are anisotropic to some degree, a conduit having a preferential direction could provide an ill-defined pathway by which a pollutant could travel a considerable distance to a well (e.g., a pumping well's area of influence would be irregularly shaped).[3] Consequently as previously mentioned, Georgia's WHP Program specified that the OMZ of a WHPA for a pumping well in a karstic terrain be established primarily by using hydrogeologic field mapping methods and secondarily/optionally by using tracing techniques using dyes, benign solutes, or natural radioactive or stable isotope tracers and/or subsurface exploration or aquifer testing.

Before proceeding further, it is important to remember that not all carbonate aquifers are karstic. In fact, in Georgia, most of the use of the Upper Floridan aquifer (Georgia's most important aquifer) is from areas where the Upper Floridan is confined and isolated from the surface by lithologies having low hydraulic conductivity. Further, in the more topographically rugged portions of northwest Georgia, such as where carbonates of the Conasauga Group crop out on hill slopes south of Vans Valley in Floyd County, fractures are "tight" and solutional enlargement is nil (Golder Associates, 1996). Here there is minimal void space into which surficial soils can be "eroded" and true karstic conditions do not exist.

EPD's WHP Plans concentrated on (a) unconfined Piedmont aquifers, (b) unconfined sandy Upper Coastal Plain aquifers, and (c) confined Coastal Plain aquifers. Development of WHP Plans for karstic aquifers was placed in abeyance until methodologies (i.e., this study) could be developed to delineate the OMZ for WHPA's in karstic aquifers.

This report, the initial draft of which was prepared under contract to the Geologic Survey Branch of the Georgia Environmental Protection Division (EPD) by Bobby Jones and David Wenner of the Department of Geology of the University of Georgia, recommends methods to define a preliminary WHPA for two different types of karst aquifers in Georgia. The first includes the largely unconfined aquifers of the Valley and Ridge Province of northwest Georgia (for a general description, see Cressler, 1964, for Walker County). The second is the semi-confined Upper Floridan aquifer system that occurs primarily in the Dougherty Plain of the Coastal Plain Physiographic Province of southwest Georgia (for a general description, see Torak and McDowell, 1996, Watson, 1981, Mitchell, 1981, and Hicks, et al., 1983). The term "preliminary" in this report describes a methodology that a municipality or EPD could employ readily to delineate a WHPA in a karstic terrain. The methodology, obviously, could be further refined as more data become available.[4]

In the Valley and Ridge Physiographic Province, the most important aquifer is the Knox Group

[1] In this report, the term "matrix-flow" designates flow through interstitial pores; and "conduit-flow" designates flow through irregular conduit cavities. There is also a third type of ground-water flow in karstic terrains, albeit of less significance; namely fissure flow where the pathways are fractures or bedding planes. Such flow, however, appears to be relatively unimportant for WHP purposes because (a) below the water table most fissures are solutionally-enlarged to form conduits and (b) if the fissures are not solutionally-enlarged, then they tend to be 'tight" and probably yield insufficient water to supply most municipal needs.

[2] Depending upon the availability of data and/or analysis, hydrogeologic mapping may not be needed for all municipal supply wells in karstic terrains. Some of the more recently permitted municipal water supply wells are designed on the basis of extensive engineering and/or hydrogeological analysis. Where such data are available, they should be used in lieu of hydrogeologic mapping.

[3] Besides causing an irregularly shaped area of influence of pumpage, anisotropy also may cause ground-water flow paths not to be perpendicular to potentiometric contours (Lynn Torak, USGS, 1998, personal communication; also see Freeze and Cherry, 1979 (pgs 174-178)). Thus, the common practice of contouring water levels to define a cone of depression, ground-water pathway, or contributing area to a well, while doable in anisotropic media, should be used with caution.

[4] Based on our review of data in EPD's files, the availability of "hard" data, such as pumping tests or measurements of hydraulic conductivity, in karstic areas of Georgia is rare. Where such data do exist, they tend to be site specific (e.g., assessments of hazardous waste sites, ground-water monitoring plans at solid waste sites, etc.). This means that for most WHP Plans, EPD will have to delimit WHPAs using hydrogeologic mapping methods exclusively.

(including the Newala Limestone).[5] The hydrology of the Knox Group predominantly involves conduit-flow through an extensive network of fracture-controlled, solution openings throughout the Paleozoic-aged dolostone and limestone (Cressler, 1964). In contrast, the primary aquifer in the Dougherty Plain is the Upper Floridan aquifer, composed primarily of the Tertiary-aged Ocala Limestone. The Upper Floridan has dual porosity flow pathways. Most flow occurs within fracture-controlled solution openings (i.e., conduit flow). Some flow, however, occurs as diffuse matrix-flow through the porous limestone (Beck and Arden, 1984). Both the Knox and the Upper Floridan underlie a mantle of clayey residuum.

This report has six major parts: (1) a general discussion of karst geomorphology, (2) Georgia karst hydrogeology, (3) a discussion of Alabama WHPA methodologies and experiments using tracer tests in Georgia, (4) a general discussion of WHPA delineation methods in karstic terrains, (5) recommendations of methods to be used in northwest Georgia, with an example of a WHPA for Chickamauga, Georgia, and (6) recommendations of methods to be used in southwest Georgia, with an example of a WHPA for Colquitt, Georgia. The approaches for WHPA delineation described here for use in the carbonate aquifers of northwest and southwest Georgia were modified from methods described in the EPA's 1994 handbook, *"Ground Water and Wellhead Protection".* The methods presented are only the first steps to be used for delineating WHPA's in karstic terrains.

The audience of this report is a geologist or engineer who has a reasonable understanding of ground-water hydrology and hydrogeologic mapping. For example, the need to perform lineament trace analysis is pointed out; this report, however, does not explain how to perform such an analysis. We (the authors) assume that the person delineating the WHPA already knows how to do this.

As a final point of caution, each well site is different and it is the responsibility of the investigator to modify our (the authors) recommended procedures to fit the local hydrogeology. In particular, it is important to decide if the well is completed in an aquifer dominated by solution conduits. For wells completed in carbonate rocks characterized by true matrix or fracture/bedding plane flow, then other WHPA delineation methods can be used.

Karst Geomorphology

Karst is a term that defines an irregular topography that commonly forms over limestone or dolostone. The irregularities of the land surface in karst areas result from the sub-surficial removal of rock mass by dissolution of calcite and dolomite (Freeze and Cherry, 1979) into which surficial materials are deposited by downward percolating water. Karst areas normally have cave systems developed as a result of dissolution along fractures, bedding planes, or other openings.

Karstic topography is characterized by any <u>one</u> of the following types of distinctive surface and subsurface features (Quinlan, et al., 1992)[6]:

1. sinkholes/swallowholes (with or without a discrete opening at their bottom);

2. dry valleys in humid climates;

3. abundant high yielding springs;

4. caves/caverns;

5. sinking streams;

6. solutionally-enlarged joints, faults, and/or bedding planes;

7. grikes (soil-filled, solutionally-enlarged joints or grooves); and

8. karren (solutionally-enlarged water-carved grooves on rock, commonly subparallel).

These landforms or features result in a unique hydrogeologic environment characterized by conduit-flow through a carbonate aquifer, where ground water commonly flows through joints, faults, and bedding planes that have been solutionally-enlarged. Figure 1 illustrates the relation between the karstic surface features and karst hydrogeology.

Many of these features, however, are not readily observable on air photos or on topographic maps, especially when they occur beneath a thick mantle of residuum or alluvium. This can be the case in many areas in both northwest and southwest Georgia, where the Knox Group and Ocala Limestone commonly underlie a cover of thick residuum, locally more than 100 feet thick.

Georgia Karst Hydrogeology

Within the hydrogeologic community in Georgia, there are two schools of thought regarding analysis of ground-water flow in fractured and conduit-flow media. The first school of thought argues that Darcy's Law is not valid in such media; and that pollutant pathways and travel times are not predictable using currently available methods. Advocates of this idea argue that a comprehensive understanding of the entire fracture (solution cavity) system is necessary to predict pollutant behavior in the subsurface. For practical purposes, this is not possible because one can never locate or identify anything more than a small subset of the fractures (solution openings). The second school of thought, which we support, argues that while the above is true in the micro scale, it generally is not true in the macro scale; and pollutant behavior in the subsurface is reasonably predictable.[7]

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[5] The Knox Group may be locally semi-confined. The residuum-rock interface is often variable, characterized by pinnacles and crevices.

[6] The karstic Dougherty Plain of southwest Georgia is further enhanced by a paucity of surface streams.

[7] It is recognized that Darcy's Law may not be valid where large conduits exist, such as Chickamauga, where major springs near the wells discharge some 25-40 million gallons of water per day. In this regard, there must be some relatively large conduits feeding these springs. Such large springs are relatively rare in Georgia, thus it would be reasonable to assume that Darcy's Law is applicable for much of the carbonate areas in the state. Further, by "reasonably predictable", we do not mean that one can predict the pathway of individual molecules or ions of pollutants;

The concept of applying Darcy's Law and conservation of mass to solutionally-enlarged fractures (or bedding planes) is primarily one of scale. At the scale of inches or feet, the solution cavities or conduits may not intersect. As pointed out by Freeze and Cherry (1979), if the fracture (solution cavity) density is extremely low, it would be necessary to analyze flow in individual fractures (solution cavities). However, at a scale of hundreds or thousands of feet, the fractures (solution cavities) may sufficiently intersect so that a "continuum" forms. Again as pointed out by Freeze and Cherry (1979), Darcian analysis of flow in fractured (solution cavity) rocks can be carried out using a continuum approach. This approach is valid since the fracture spacing (solution cavities) is sufficiently dense that the media act in a hydraulically similar fashion as matrix-flow media. Thus, the central question is whether or not a continuum of solutionally-enlarged fractures (or bedding planes) occurs in the Knox Group of northwest Georgia and in the Ocala Limestone of southwest Georgia, such that the solution features cause the media to act in a manner similar to matrix-flow media.

In northwest Georgia, the dolostones of the Knox Group are Cambro-Ordovician in age and have been subjected to multiple major tectonic events. Field inspection and mapping of Knox quarries and outcrops by McLemore in 1967 (see McLemore and Hurst, 1970) suggests that extensive fracturing is ubiquitous to the Valley and Ridge of Georgia; and the idea of a hydraulic continuum is reasonable and appropriate at the scale of a WHP Plan for wells completed in the Knox Group.

The Ocala Limestone, however, is of much younger geologic age (Upper Eocene) and has never been subjected to significant tectonism. Numeric ground-water modeling of the Upper Floridan aquifer in the Dougherty Plain by the U.S. Geological Survey (Torak and McDowell, 1996) assumes that Darcy's Law and conservation of mass are reasonable and appropriate at a regional scale. According to Torak (1996, USGS, personal communication), because the model can simulate actual pumpage effects validates the idea that ground-water flow in the Upper Floridan aquifer can be analyzed using a Darcian approach.

A "karstic" aquifer contains a continuum[8] among three end-member ground-water flow regimes (Gaspar, 1987). These include matrix-dominated, fissure-dominated (i.e., fractures and/or bedding planes), and conduit-dominated flow (see Figure 2). In the karstic terrain of northwest Georgia, ground water flows primarily through conduits; here matrix-flow is of lesser importance. In contrast, the carbonate aquifers of southwest Georgia, because of their more porous nature, are influenced to a greater extent by matrix-flow. It is still the conduit system, however, that primarily determines the direction and flow character of the Upper Floridan aquifer. The role that matrix-flow provides in this system is storage, supplying water to the conduits under low-flow conditions or acting as a reserve in high flow conditions. In both northwest and southwest Georgia, the overlying residuum provides storage for the conduit-flow.

Hydraulic gradients in karstic terrains are important to consider as in any other flow regime. In isotropic porous media, such as some sand or clay sediments, ground-water flow paths are generally perpendicular to potentiometric contours mapped from water-level measurements. However, from a theoretical point of view, karstic systems do not necessarily behave this way at the very local level (e.g., near the well). The difficulty involved in mapping locally deviated "water tables" in karst is well known (Walker, 1956). Figure 3 illustrates this point. Due to the multilayered network of conduits, which may be contained in an aquifer, a well may or may not intersect a particular conduit that may or may not contain water at a particular time. In addition, ground water may occupy different conduit systems with flow occurring in different directions as the "water table" rises following precipitation events. Further, conduit structure and fabric are dependent upon a number of factors such as the orientation of pre-existent fractures and bedding plane contacts at the time(s) of development or the preferred pathways produced by limestone dissolution. Nevertheless, if a continuum of solution cavities does exist, as appears to be the case in both northwest and southwest Georgia, then a reasonable approximation of ground-water flow directions is perpendicular to the potentiometric contours, particularly at the scale of a WHPA.

In karst, the larger the spacing between potentiometric contour lines, the more likely that conduit-flow occurs since little hydraulic gradient is needed to move large quantities of water. Conversely, steep head gradients should occur where flow is not through significant conduits. For example, at a proposed limestone quarry site in the Conasauga Group in Floyd County, Golder Associates (1996), using a dense network of monitoring wells, mapped a steep vertical decline in the water level of 327 feet over a horizontal distance of 2450 feet. Utilizing extensive rock cores, Golder Associates correlated the steep potentiometric gradient to the "tight" and non-solutioned character of the fractures within the rock mass.

The above, however, probably is somewhat moot for wellhead protection in Georgia as there rarely are sufficient wells to create a potentiometric map for a specific WHPA. Nevertheless, as will be discussed in later sections, WHPAs for southwest Georgia Upper Floridan wells can use information obtained from regional potentiometric maps. These regional potentiometric maps represent actual ground-water levels (Lynn Torak, USGS, 1997, personal communication).

One of the challenges in developing WHPA models in areas underlain by carbonate rocks is ascertaining whether a particular site should be characterized by conduit or matrix-flow. As previously mentioned, we assume (and recommend to EPD) that the Paleozoic-aged carbonate rocks of northwest Georgia be considered characterized by conduit-flow through solutionally-enlarged fractures/bedding planes and that the Upper Floridan aquifer of the Doughtery Plain be considered characterized by both conduit-flow through solutionally-enlarged fractures/bedding

rather the center of mass of the pollutant plume is predictable in time and space.

[8] The term "continuum" used by Gaspar (1987) has a different meaning than the same term used by Freeze and Cherry (1979). Gaspar uses the term to describe the inter-relation between the three types of ground-water flow regimes; whereas Freeze and Cherry use the term to mean that fractures (and solution cavities) have a dense spacing and are so highly interconnected that Darcy's Law is valid.

planes and matrix-flow with conduit-flow being more significant than the matrix-flow.[9]

Three ways to distinguish between a spring (or well) supplied by conduit-flow and a spring (or well) supplied by matrix-flow is by monitoring changes in turbidity, temperature, and specific conductivity before, during and after several large storms (Quinlan, et al., 1992). For example, Quinlin and others (1992) note that after large storms, a Kentucky spring fed by conduits showed increased turbidity with the coefficient of variation of specific conductance measurements varying from 10 to 25 percent. In contrast, a spring fed by matrix-flow appeared clear or only slightly turbid with the coefficient of variation in specific conductance measurements varying by less than 5 percent. If Quinlan and others' (1992) conclusions are correct, then it is reasonable to assume that conduit-flow predominates in the carbonate rocks of northwest Georgia, whereas both conduit as well as matrix-flow occur in southwest Georgia, even if conduit-flow predominates.[10]

Because ground-water flow in the carbonate aquifers of both northwest and southwest Georgia is conduit-flow dominated, these aquifers are heterogeneous and anisotropic. General inspection of a variety of geologic maps suggests that rock fabric and hydraulic conductivity anisotropy should be more significant in northwest Georgia than in southwest Georgia. The difference in anisotropy between northwest and southwest Georgia is a result of the different geologic histories of the two areas. Northwest Georgia has been subjected to several major episodes of tectonism and NW-SE compressive forces complexly folded and faulted the Paleozoic rocks. Major faults and major fold axes as well as the general topography have a pronounced NE-SW trend. In northwest Georgia, we interpret $K_x >> K_y$ with a well's area of influence to be ellipsoidal, where x is generally in the NE-SW direction and y is generally in the NW-SE direction. On the other hand, inspection of maps of aquifer properties of the Upper Floridan aquifer from the Dougherty Plain (Hicks, et al., 1983; Torak and McDowell, 1996; and Torak, et al., 1991) did not reveal any obvious directional trends. Here, we interpret $K_x \geq K_y$ with a well's area of influence being close to circular, where x and y are any direction but are perpendicular to each other. There does appear to be an exception to this; in proximity to the Flint River, sinkholes are more common and K tends to be larger (interpreted from Hicks, et al., 1983). This suggests that porosity and $K_{\text{proximal to the Flint River}}$ > porosity and $K_{\text{distal to the Flint River}}$.

Recharge to a carbonate aquifer may be from point or line sources (Quinlan, et al., 1992). Point recharge occurs from some sinkholes or sinking streams and line recharge occurs from

[9] These recommendations should not be accepted "carte blanche". As is discussed later on page 11, the person delineating the WHPA should make a general assessment regarding which flow mechanism is most appropriate.

[10] Complaints to the Geologic Survey about muddy spring water are more common for northwest Georgia springs than for southwest Georgia springs (McLemore, personal observation). This should not be construed to mean that southwest Georgia streams are exclusively fed by matrix flow and do not have a conduit component.

losing streams. Recharge further can occur through some closed depressions. Assessments of ground-water pollution incidents by the Georgia Geologic Survey suggest that recharge through closed depressions may be a common mechanism of recharge in carbonate terrains in both northwest and southwest Georgia.

The type of recharge is important when establishing a WHPA. Soil characteristics, such as clay content or drainage properties, which are commonly found in county soil survey reports, can be used to estimate infiltration rates to an unconfined (or semi-confined) aquifer. Areas where soil infiltration rates are low may produce more runoff than areas where more rapid infiltration can occur. Obviously, the more a WHPA is characterized by rapid infiltration, the more vulnerable the ground water is to rapid transport of surface pollutants to the water table. Inspection of long-term hydrographs, maintained by the U.S. Geological Survey (see Cressler, et al., 1995, for recent data) indicates no long term trends in the unconfined aquifers of both northwest and southwest Georgia. This suggests that the water table fluctuates in response to seasonal precipitation changes (e.g., the aquifers are replenished every year and experience no long-term water level declines). Therefore, for the purposes of WHP, it should be assumed that any release of pollutants to the surface will result in some of those pollutants eventually reaching the water table in less than one year.

Natural discharge falls within two general categories: points/areas and aquifer-stream interactions. The primary discharge points in karst systems are springs. Springs result from the "water table" intersecting the ground surface along a fracture, conduit, localized impermeable zone, fault or other feature impeding downward ground-water flow. Springs may be large (e.g., some of the largest springs in Georgia occur in the karstic terrains of northwest and southwest Georgia) and thus are commonly visible. Some large springs, however, may be unrecognizable if located at the bottom of creeks, streams or rivers[11]. The larger springs commonly have discharge rates orders of magnitude larger than the pumping rates of municipal wells. Wetlands may be a source of area discharge, especially where an intermittent or perennial stream originates in and drains the wetland. More significant than either springs or wetlands is aquifer-stream flow. Most streams in both northwest and southwest Georgia are partly "fed" by ground-water that either "seeps" or just "flows" into the stream. During drier times of the year, the base flow contribution is the primary source of water in perennial streams (see Torak and McDowell, 1996, for a detailed discussion of this concept relevant to the Upper Floridan aquifer of southwest Georgia).[12]

Artificial recharge may occur along the annular space of ungrouted wells, drainage wells (e.g., the construction of drainage wells was promoted in southwest Georgia as an effective means of controlling yellow fever carrying

[11] Numerous springs are known to occur in the Flint River, where they provide unique habitat for striped bass. The existence of these springs was not known until the 1960s.

[12] During times of very high stream flow, such as occurred during a July 1994 large storm, rivers and streams may actually recharge the aquifer for short periods of time.

mosquitoes in the early 1900s), and altered sinkholes (e.g., altering sinkholes to receive storm water runoff has been occasionally used in southwest Georgia). Artificial discharge features include wells and drainage ditches.

Both the Knox and Upper Floridan aquifer systems respond to changes in recharge (primarily precipitation) and discharge (base flow contribution to streams and pumping). The response, however, appears to be more rapid for the Knox than for the Upper Floridan. For example, in the city of Chickamauga in northwest Georgia, a summer shower over a mile away from the local discharge point at Crawfish Springs resulted in a marked increase in turbidity and discharge in less than 12 hours (John Culpepper, 1995, personal communication). Such a "flashy" (i.e., Culpepper's words) turbidity response to large rain events also has been noted by the Geologic Survey in springs that discharged from the Upper Floridan aquifer into the Flint River, especially when linked to a nearby sinkhole collapse. Away from the Flint River, however, this phenomenon has not been noted. For example, no correlation between precipitation and turbidity, water levels, or sinkhole collapse has been recognized at any of the City of Colquitt's wells (Ronny Holt, 1995, personal communication).

Alabama Wellhead Protection Area Delineation Methodologies in Karstic Terrains

As part of this evaluation of methods of delineating wellhead protection areas in karstic terrains, an assessment of Alabama methodologies was performed. Alabama was selected because the Alabama Department of Environmental Management (ADEM) has an EPA-approved wellhead protection program and the state has a similar geology.

Although they use somewhat different terms, ADEM's WHPA II protection area generally corresponds to EPD's OMZ. For such areas, ADEM requires that the area be based on "hydrogeologic flow boundaries" established by measurements (ADEM, 1991). An example of such a boundary delineation was provided to EPD by ADEM. This delineation was for the Leeds Water Authority and was performed by the Alabama Geological Survey (Baker and Raymond, 1994 and Guthrie, et al., 1995).

The Leeds Water Authority obtains water from fractured unconfined Paleozoic limestone aquifers and provides water to the town of Owens Cross Roads, which is a few miles east of Birmingham. This area, which is complexly folded and faulted, is karstic and is characterized by sinkholes, springs, and caves. The aquifer supplies water to two shallow wells (< 125 feet deep), which are only a few feet apart.

As part of its delineation study, the Alabama Geological Survey performed dye tracing studies and made water level measurements in a number of nearby domestic wells. Dye was injected into test wells that had been drilled especially for the delineation project. Maps (see Plate 7 of Baker and Raymond, 1994) show (a) water level contours generally coinciding with topographic contours and (b) dye trace pathways perpendicular to the mapped water level contours. Ultimately, the Alabama Geological Survey established the WHPA II outer boundary (i.e., the OMZ for Georgia) as the local drainage basin in which the two wells occur.

As will be discussed in later sections, Georgia's OMZ in northwest Georgia, where wells are completed in Paleozoic carbonate aquifers, also will be the local drainage basin. In other words, ADEM and EPD will achieve similar results, albeit by different methodologies.

Tracer Test Experiments

When EPD initially embarked on delineating WHPAs, tracer testing was deemed as a viable technology for defining the OMZ. To this end, the two junior authors, under contract to EPD, experimented with Krypton tracers at both Chickamauga and Colquitt (Jones, et al., 1998). Krypton, an inert gas, was considered preferable to dyes as Krypton is odorless, tasteless, colorless, and has no known toxicity. As it turned out, none of the candidate sites for Krypton injection proved to be appropriate for either political or technical reasons. Examples include the unwillingness of a local water plant operator to cooperate, the prolific water yielding characteristics of the local carbonate aquifers which would dilute the tracers to unmeasurable concentrations, and the lack of injection sites that were clearly hydraulically connected to the aquifer. Jones and others (1998) conclude:

> In summary, the use of Kr as a ground water tracer has the potential to address some specific wellhead protection questions. However, the costs and technical complications involved in adding the tracer, and collecting and analyzing samples seems to very much restrict its usage in most wellhead protection programs. This seems especially true in the karstic areas of Georgia.

Upon learning this, EPD abandoned the idea of using tracers as a WHPA delineation method and concentrated exclusively on development of hydrogeologic mapping techniques, which are the focus of this report.

GENERAL DISCUSSION OF METHODS FOR WHPA DELINEATION

Overview

The more traditional geometric approaches to delineating a WHPA, as outlined in Table 1, are recommended in areas where matrix-flow exists. However, in the two main areas of Georgia where carbonate lithologies occur, in northwest and southwest Georgia, a gradation exists between conduit-dominated and matrix-dominated hydrogeologic conditions. That is, there may be some areas within karstic terrains, where use of geometric methods is reasonable (refer back to footnote 9). This is because karst features do not occur everywhere in northwest and southwest Georgia in regions underlain by carbonate rocks. Thus, the first step in the proper delineation of a WHPA for a well in these two regions is to assess which hydrogeologic condition exists in an area. In other words, the investigator must make a decision as to whether to employ geometric methods or to employ one of the other methods outlined in Table 1 to delineate the WHPA. This section of the report reviews some more recognizable features that allow an investigator to decide which approach is more feasible.

In karstic terrains, a WHPA defined by the arbitrary radius, calculated fixed radius and simplified variable shape methods does not properly consider the complexity of the flow system. No consideration is given to location or type of topography, recharge, vertical flow, or anisotropy. The above three methods, therefore, need to be used with caution since they probably are only useful in cases where conduit-flow is limited or non-existent. They, however, may be a useful starting point if heterogeneities and anisotropies are considered in modifying their shape to fit the local geomorphology. For municipal wells, where none of the karstic topographic/landform features listed on page 5 above occur within two miles of the well, traditional geometric methods probably could be used to delineate a WHPA.

Delineation of WHPA's using simple analytical methods generally requires the gathering of subsurface information on aquifer properties (e.g., derived from pump test data, aquifer thickness, measurements of hydraulic conductivity, etc.). As previously mentioned, such types of data are rare in Georgia, except at regulated facilities. Moreover, these methods commonly require assumption of two-dimensional uniform porous media and ignore the effects of hydrologic boundaries, aquifer heterogeneity and non-uniform recharge. Without considerable measurements of aquifer properties, simple analytical methods would be difficult to use in delineating WHPA's in karstic terrains in Georgia.

Computer-based semi-analytical and numerical flow and transport models are complex, expensive and time consuming WHPA delineation methods (EPA, 1994). Some computer models are flexible enough to include heterogeneity, anisotropy and transient behavior in flow systems. If properly discretized, numerical models can simulate fracture/conduit flow at WHPA scale. This approach has been rarely used because it requires a thorough understanding of the aquifer parameters and considerable modeling expertise. MODFLOW, however, is now available in a Windows[13] environment using menus; in such a "user-friendly" software, development of WHPA utilizing numeric models should become more common.

According to Quinlan and others (1995), only hydrogeologic mapping has the ability to include the high anisotropic and heterogeneous flow conditions characteristic in karst aquifers without the time investment associated with numerical flow/transport modeling. Consequently, many environmental protection agencies, communities, and consultants prefer hydrogeologic mapping to delineate WHPA's. Such maps typically encompass a systematic and integrated appraisal of: soil and geomorphology, geology, hydrology, and hydrochemistry. For a detailed description of this methodology, the reader is referred to the *EPA Handbook* (1994). While some well-specific information can be obtained from published reports, unfortunately in both northwest and southwest Georgia, few of these data exist in sufficient detail to delineate a WHPA. Therefore, it should be assumed that delineation of each Georgia WHPA will require a site specific field mapping investigation utilizing primarily surface methods in northwest Georgia and both surface and subsurface methods in

[13] Windows is a trade name of the Microsoft Corporation. Use of this trade name does not imply any endorsement by EPD.

southwest Georgia. Refinement of a preliminary WHPA based on this approach could be followed by tracer tests to establish connections between possible sources of pollution and a municipal well (Quinlan, et al., 1995).

Vulnerability mapping, which is a variation of hydrogeologic mapping methodology, is specifically recommended for the full delineation of OMZs in karstic terrains in northwest Georgia and the partial delineation of OMZs in karstic terrains in southwest Georgia. Vulnerability mapping involves delineating areas of high susceptibility to ground-water pollution based on surface and subsurface properties that either promote or inhibit movement of pollutants from the surface to the water table (EPA, 1994).[14]

Vulnerability mapping is a reasonable approach for assessing the susceptibility of a well to ground-water pollution from surface sources in any hydrogeologic setting. Further, there is no assumption of a uniform porous medium, nor a requirement for detailed measurements of aquifer parameters. The surface method uses a variety of data from office-available maps and air-photos to observable surface features and incorporates: mapping lineaments and fracture traces nearby and especially in areas upgradient to the well; mapping watershed boundaries coupled with particle-tracking analysis; mapping other major structural features such as strikes and dips of outcrops and fold axes; and mapping geologic contacts that could potentially serve as possible hydrologic boundaries. The subsurface method involves using published isopach, potentiometric, hydraulic conductivity (and transmissivity) data and other similar data to estimate general aquifer properties.

We further recommend that a "Zone of High Vulnerability" (ZHV) be mapped in the OMZ in the general vicinity of the well; where possible, doing this should make the WHPA delineation more site-specific.[15] The ZHV lies within and is a subpart of the OMZ; its use is recommended to provide an increased level of protection to the well, especially in those areas proximate to the well where pollutants could rapidly reach the well. In general the ZHV should include:

1. continuous or discontinuous concentrations of sinkholes, swallowholes, closed depressions, and sinking streams in the vicinity of the well;

2. continuous or discontinuous concentrations of more permeable/porous soils near the well;

[14] The terms "vulnerability" and "susceptibility" are commonly used in a variety of EPA/EPD regulatory programs. For WHP, vulnerability refers to a type of geologic mapping; it should not be confused with vulnerability assessments, where wells are screened for pollutants and/or contaminants for which they should be tested (e.g., EPD has performed a vulnerability assessment of asbestos in wells and those wells in the vicinity of asbestos-bearing rocks are routinely tested for asbestos). Also for WHP, assessing the susceptibility of a well to pollution is different than the development of the state-wide ground-water pollution susceptibility map (Trent, 1992) that was developed using EPA's DRASTIC methodology.

[15] Mapping a ZHV may not always be possible. We were not able to do so for the City of Colquitt wells described in this study.

3. continuous or discontinuous concentrations of private wells in the vicinity of the well; and

4. continuous or discontinuous concentrations of lineaments-fracture traces near the well.

The methodology for delineating a ZHV is described later.

Principles of Vulnerability Mapping

The first step is to create a basemap; we recommend using a standard 1:24,000 topographic map.[16] On the basemap, the well is accurately located with the IMZ delineated by a 1/2-inch circle (i.e., 500 feet). Transparent overlays are recommended to delineate significant hydrogeologic features such as wetlands, sinkholes, other types of wells, and more permeable soils.

The second step is to gather relevant hydrogeologic information; we recommend that the following types of information be gathered or developed:

1. location and mapping of natural areas or features indicative of enhanced recharge, including mappable surface features such as sinkholes, losing streams, areas where the residuum is thin or absent, and lineaments;

2. location and mapping of natural areas or features indicative of discharge, such as springs or perennial streams;

3. standing bodies of water (these may be either recharge or discharge features at different times of the year);

4. location and mapping of artificial discharge features, such as wells or drainage ditches;

5. location and mapping of no-flow boundaries and, if possible specified flow and/or head-dependent flow boundaries; and

6. in northwest Georgia, particularly, simplified particle tracking analysis.

The published and unpublished technical literature should be examined. These would generally include county soil surveys (modern soil surveys are available for many but not all Georgia counties), which have information on soil porosity, permeability, soil thickness, depth to ground water, locations of sinkholes and springs, bedrock outcrops, and so forth. Such information can be used to identify features indicative of enhanced recharge/discharge. U.S. Fish and Wildlife Service 1:24,000 wetlands maps, available at the Geologic Survey, are an excellent source of wetland locations (i.e., commonly shallow aquifer discharge locations). All of northwest Georgia was mapped by the USGS during the 1960s and early 1970s; the reports are available from the Georgia Geologic Survey. Reports on the hydrogeology of southwest Georgia, including several potentiometric maps, are also available from the Georgia Survey. Considerable unpublished information is available from EPD's Land Protection Branch (solid-waste landfills and underground storage tanks), Water Resources Branch (well construction, pump tests, and incidents of well pollution), and the Hazardous Waste Management Branch. The files of these agencies should be examined and relevant information plotted on one or more transparent overlays. Lithologic logs and some drillers logs may be available from the Georgia Geologic Survey or from the USGS.

Several types of mappable features are essential to consider in a karstic flow system, including the locations of sinking streams, surface-water bodies, sinkholes and springs. These are typically located from topographic maps and soil surveys and by actually "walking the land". In addition, lineaments may be indicative of vertical or high-angle fractures that can serve as pathways from the surface to the water table as well as deeper portions of the aquifer. Studies have shown that wells located on lineaments or fracture traces have higher yields than those wells located in unfractured areas (Brook and Sun, 1982). This is interpreted to reflect increased porosity associated with fractures and dissolution features. Lineaments are defined as natural linear features, ranging from hundreds of meters to kilometers in length (identifiable on aerial photographs, satellite images, Side Looking Radar (SLAR), and topographic maps) that are believed to be surface expressions of bedrock fracture zones (Brook and Sun, 1982).

Fracture trace analysis[17] is very useful for defining possible fractures and fracture intersections that, in turn, reflect locations where surface pollution may quickly reach the aquifer. Fracture trace analysis is described in more detail by Siddiqui and Parizeck (1971) for "classic" type karst terrain such as exists in northwest Georgia and by Brook and Sun (1982) for the karstic regions in the Dougherty Plain in southwest Georgia.

Mapping of no-flow boundaries is critical. For most northwest and possibly some southwest Georgia karstic terrains, these will be drainage divides for the upgradient tributary basin (i.e., watershed basin), not the main stem stream basin in which the well occurs. For example, as is illustrated in Figure 4A, the drainage basin for Perennial Stream A is delimited (dashes). The main stem stream, which within the general study area is the ultimate zone of discharge[18], represents the downgradient limits of the drainage basin.

Defining the upgradient watersheds in southwest Georgia can be difficult, because in some portions of the Dougherty

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[16] The State of Georgia is completely covered by 1:24,000 topographic maps.

[17] Fracture trace analysis and lineament analysis are the same. Most geologists use the terms "fractures" and "lineaments" interchangeably. The distinction between the two is that subtle changes in topography, soil type, soil moisture along fractures are expressed as map or photo lineaments.

[18] The assumption that a main stem stream acts as a linear zone of ultimate discharge has two limitations. Firstly underflow in an unconfined aquifer system has been documented in the Piedmont near Barnesville (Steele, et al, 1995) and near Lawrenceville (Michael Peck, 1996, personal communication); these two situations involved drawdown detected in monitoring wells opposite a perennial stream from a pumping well. Determining whether unconfined aquifer flow actually occurs beneath streams would require comprehensive pump testing and is beyond the scope of WHPA assessments. Secondly, this approach is only meaningful if the adjacent and main stem streams are in the same aquifer.

Plain there is little or no surface drainage. Here, we recommend transferring published potentiometric contour lines to the master topographic map; and then using the Uniform Flow Equation methodology described in Appendix A, calculate the downgradient and upgradient null points (i.e., where the drawdown curve coincides with original potentiometric surface) and the lateral no-flow boundaries.

Simplified particle tracking analysis involves "drawing-in" the paths of an imaginary suite of molecules of water (or pollutants) as they would flow from upgradient no flow boundaries to downgradient discharge points and areas. This is illustrated in Figure 4B; and the methodology is described in Appendix B. Simplified particle tracking depends on the following assumptions:

1. the water table (or potentiometric surface) is a subdued reflection of the topographic surface;

2. the solution conduits form a continuum (i.e., at the scale of a WHPA, ground-water flow is more or less perpendicular in a downgradient direction to the potentiometric surface contours); and

3. Darcy's Law reasonably describes ground-water flow in the WHPA.

If these three assumptions are valid in the WHPA, then the particle tracks should be congruent with ground-water flow lines and should be perpendicular to topographic contours.[19] This means that particle tracks can be simply constructed by drawing lines from a suite of origination points evenly spaced along all upgradient no-flow boundaries, which are also topographic divides. The particle tracks will move downgradient (actually downhill), perpendicular to topographic contours until the ultimate zone of discharge or a natural or artificial discharge point is reached. Generally the particle traces will delimit the shortest linear distance from the origination point to the nearest discharge feature (i.e., perennial stream or main stem stream).

The third step is to synthesize the above information. Assuming the topographic gradient is less than two percent, the OMZ is the upgradient drainage basin of the tributary of the perennial stream in which the municipal well is located.

The ZHV is an area in the general vicinity of the well where one or more of the following conditions apply:

1. simplified particle tracking suggests that ground-water flow is directly to the vicinity of the well;

2. landform features (i.e., sinkholes), porous/permeable/thin soils, private wells, lineaments (i.e., fracture traces) indicative of enhanced recharge are concentrated; and

3. features suggestive of discharge (i.e., springs, wetlands, etc.) tend to be lacking.

Delineation of the ZHV, by its very nature, is subjective; no two geologists will delineate the ZHV exactly the same way. However, by utilizing the above criteria, ZHVs delineated by different geologists should be more or less the same size and shape. Nevertheless, because there is an element of subjectivity, we recommend that all OMZ and ZHV delineations be checked by an experienced supervisor, preferably a registered geologist (PG) or registered engineer (PE).

General Recommended Procedures

Overview

The following is a summary of some general methods for delineating a WHPA for a karstic terrain in northwest and southwest Georgia. A detailed description of each method follows.

A. Obtain the most current information on the well(s) under investigation. Plot such well(s) and the 500-foot IMZ on a "master topographic map".[20]

B. Locate and collect data on any nearby wells in the area that may potentially affect the municipal pumping well in question. Locate and collect other relevant hydrologic data including wetlands from 1:24,000 National Wetlands Inventory maps (available from the Geologic Survey), porous soils having higher than average hydraulic conductivities (soils where infiltration and recharge might be more likely) from county soil maps, from 1:24,000 topographic maps, hydrologic/geomorphic features such as sinkholes, closed depressions, sinking streams, and springs that might be indicative of enhanced recharge or discharge, state and federal geologic reports and maps, and data from other EPD Branches. Plot such locational data on the "master topographic map".

C. Perform preliminary OMZ delineation. As appropriate using topographic boundaries, delineate and plot watershed boundaries for the tributary basin in which the well(s) is (are) located. Plot this boundary on the "master topographic map". Then using an overlay, perform particle tracking analysis for a suite of locations first from along the watershed boundary and second along and from any topographic ridges within the watershed. While delineation of watershed boundaries is relatively straightforward in northwest Georgia, it may be very difficult to do in the Dougherty Plain area of southwest Georgia where the surface drainage system is very poorly developed or non-

[19] In the Dougherty Plain of southwest Georgia, the potentiometric surface of the Upper Floridan aquifer has only been mapped at a regional level. The inter-relationship between this surface and local topography is not well defined. Here particle tracking analysis probably would be of little value in most areas.

[20] In general, we recommend plotting observable data/information such as wells, springs, sinkholes, and so forth on the "master topographic map" and interpreted information such as fracture-traces or lineaments on overlays.

existent. Therefore in the Dougherty Plain area of southwest Georgia, application of the Uniform Flow Equation, as described in Appendix A, coupled with the 5-year travel time analysis (EPA, 1994) represents an alternative method of initially delineating the OMZ.

D. Perform an initial field investigation and locate all visible springs, sinkholes, and sinking streams in the general vicinity of the well(s) using topographic and aerial photographs and plot them on a "master topographic map". Using published geologic maps as a guide, confirm and plot relevant geologic contacts or structural geologic features (i.e., strike and dips, fold axes, etc.) proximate to the well being studied on the "master topographic map".

E. Conduct fracture trace/lineament analysis. Plot these data on a second overlay. Develop preliminary ZHV and OMZ.

F. Perform a second on-site evaluation to locate any additional springs, sinkholes, sinking streams, drainage ditches, pits, ponds, lagoons, vertical shafts and so forth in the vicinity of the well(s); and also to:

1. talk to the "water supervisor" of the community to evaluate well responses (quality, levels) under various conditions (i.e., storms, drought, flooding, etc.); and

2. interview local residents about flood events sinking streams, sink collapse features and other geomorphic features.

Plot such information on the "master topographic map".

G. On the basis of all of the above, determine the final ZHV and OMZ and plot them on the "master topographic map". The ZHV should be a subpart of the OMZ.

H. Synthesize all maps and overlays and develop a map showing the WHPA that includes the well location, 500-foot IMZ circle, OMZ boundary, and ZHV boundary on the "final map".

We estimate that all of the above work can be done in about 44-72 hours, exclusive of any travel time and report writing, which would add about an additional 20 hours. Therefore it should be expected that a geologist performing this work could complete a wellhead protection plan about every 1½ to 2 weeks. This, however, would not include any pollution source inventory of the OMZ. Normally, the pollution source inventory would be done at the time of second field evaluation.[21]

Well Information

[21] We recognize that at the time of the second field evaluation, the ZHV and OMZ have only been preliminarily defined; nevertheless, by identifying potential pollution sources outside the OMZ, a third field evaluation can be avoided.

There are four types of well information; namely: well logs (geologic and "as built"), aquifer (pump) tests, published reports, and unpublished consultant's reports. Of these, "as built" diagrams delineating how the well was actually constructed and aquifer test results are most useful. "As built" diagrams generally depict cased intervals, grouted intervals, screened intervals, pump setting, pump size, and so forth. Often, "as built" diagrams are prepared by a professional engineer.[22] If "as built" diagrams are not available, then well construction data sheets are often available from EPD (typically the Drinking Water Program, but possibly the Water Resources Management Program[23]), the water system, the well driller, the Georgia Geologic Survey or the USGS. Aquifer tests, if available, can provide useful information on the size and configuration of the well's area of influence. If an aquifer test has been performed, then the area of influence, if established, would be the ZHV.[24] Geologic (including various types of downhole electric logs) or lithologic logs can provide useful information about fractured intervals, solution cavities/voids/zones of lost circulation, and so forth; these may be available from the aforementioned sources. Published reports typically contain tables and data sheets on wells; such tables and data sheets are typically based on extensive data files (for example: the USGS maintains a Ground Water Site Inventory (GWSI) data base in which information on several thousand wells is stored in retrievable digital format). Finally, consultant's reports, if available, may contain siting rationale, preliminary pollution source inventories, information on geologic hazards (such as sinkhole inducement) as well as all of the above types of information.

Because of the importance we place on gathering relevant well information, it is recommended that EPD not accept any WHPA delineation where there has not been an inspection of the above information sources and the person preparing the WHP plan maintain a "sign off" sheet confirming that these information sources have been searched. A recommended "sign off" sheet is provided in Table 2.

Once the above information has been obtained, the well location and the IMZ should be plotted on the "master topographic map" and the background information placed in the WHPA file. For a person familiar with EPD's and USGS's files, this task would require about 4-8 hours for data gathering and about 4-8 hours for analysis.

Information on Other Wells

An inventory of other, proximal higher yielding non domestic wells should be performed. Generally this task should

[22] Regretfully, we are aware of "as built" construction diagrams prepared by Georgia well drillers that are fabricated merely to conform with EPD rules or the Water Well Standards Act. Caution should be used in relying exclusively on information from well drillers.

[23] The Drinking Water Program regulates the quality of water in a well and well construction criteria. The Water Resources Program regulates ground-water withdrawals, if such withdrawals exceed 100,000 gallons per day. A number of municipal water supply wells are regulated by both programs.

[24] We specifically recommend that the area of influence, where drawdown from the pumping well is zero, be defined as the ZHV.

be performed simultaneously with the above task and would require an additional 4-8 hours. Nearby wells that hydraulically share common fractures, solution cavities, and overburden storage can exert influence on the well being studied. Furthermore, information on such wells may be transferrable to the well being studied if this other well is in a similar geologic and topographic setting. In southwest Georgia, it is important to locate and collect information on irrigation wells. Such wells may pump several million gallons per day and could locally alter the flow regime. The sources of information, cited above, should be examined for information on other wells. The Water Resources Management Program of the Water Resources Branch, which permits industrial and irrigation wells withdrawing more than 100,000 gallons per day, maintains locational data bases on these wells. Irrigation well data can be obtained from the Geologic Survey Branch. Information on other wells should also be plotted on the "master topographic map".

Other Relevant Hydrologic Data

Other relevant hydrologic data include:

A. Wetlands from 1:24,000 National Wetland Inventory maps.

B. Information on thin or porous soils from Natural Resource Conservation Service (formerly the Soil Conservation Service) county soil maps.

C. Geomorphic data from 1:24,000 topographic maps.

D. Geologic data from state and federal reports and maps.

E. Information from other EPD Branches, particularly the Land Protection Branch and the Hazardous Waste Management Branch.

Any relevant data from these sources should be plotted on the "master topographic map". We estimate that these data can be obtained in about one day and can be analyzed in about one day. Similar to well information, we recommend that EPD not accept any WHPA delineation where the above sources have not been inspected and the person preparing the WHP plan confirm on a "sign off" sheet that these information sources have been searched.

Initial OMZ Delineation Utilizing Watershed Delineation/Uniform Flow Equation/Particle Tracking Analysis Methods

This task is directed primarily at initially defining the OMZ. As previously mentioned, watershed boundaries in karstic areas do not necessarily correspond to ground-water flow boundaries. Nevertheless, it is reasonable, at least as a first approximation, to include the entire watershed boundary upgradient of the production well in most settings. Establishing the upgradient watershed boundary is critical to defining the outer boundary of the OMZ. In most areas of northwest and some areas of southwest Georgia, this is relatively straightforward. However, in those portions of southwest Georgia, particularly the Dougherty Plain, where surface drainage is absent or poorly defined and the aquifer is semi-confined,

application of the Uniform Flow Equation, coupled with the 5-year travel time analysis, is recommended to initially delineate the OMZ. A description of the application of the Uniform Flow Equation modified from in EPA's handbook (1994) is in Appendix A.[25]

Delineating a watershed boundary involves connecting all of the topographic highs and topographic divides for the drainage basin upgradient (i.e., upslope) from the well. As previously mentioned, in the Dougherty Plain area where surface drainage is poorly developed, initial delineation of the OMZ utilizing the Uniform Flow Equation, coupled with the 5-year travel time analysis is recommended. We believe this recommendation is reasonable and appropriate even though the equation's governing assumptions, discussed below, do not strictly apply to the Upper Floridan aquifer of southwest Georgia. These assumptions and their relevance to the Upper Floridan aquifer of southwest Georgia are:

1. The aquifer is flat or slightly dipping. This assumption is valid for southwest Georgia.

2. The aquifer is homogenous. This assumption is reasonably valid for southwest Georgia as aquifer thickness and lithologic facies changes do not appear to vary significantly within the general area of any single OMZ. Further, hydraulic characteristics such as storage coefficient and transmissivity may vary over relatively short distances (for example, see Table 3 of Warner, 1997); these variations are generally of the same order of magnitude and are not deemed significant enough to invalidate the assumption that the aquifer is homogeneous

3. The aquifer is isotropic. This assumption is probably valid away from the Flint River. There is indirect evidence that in close proximity to the Flint River, hydraulic conductivities may be higher proximal to the river (refer back to page 8).

4. The aquifer is confined. The residuum overlying the Upper Floridan contains considerable clay and has relatively low vertical hydraulic conductivity (see Torak and McDowell, 1996) and is generally described as being semi-confined. For this reason, the assumption of confinement, while not strictly valid, is still reasonably appropriate.

EPA (1994) also points out that the Uniform Flow Equation can be used for unconfined aquifers, using the saturated thickness of the aquifer, "provided that drawdown is small (less than 10 percent)" in relationship to the saturated thickness. Inspection of potentiometric maps of the Upper Floridan aquifer by ourselves

[25] Strictly speaking, the Uniform Flow Equation only applies to an isotropic confined aquifer. In southwest Georgia, as previously mentioned, the Upper Floridan can reasonably be assumed to be isotropic; confining conditions, however, are not truly met; thus our use of the equation should only be considered as an "approximation".

indicates that there are no identifiable cones of depression; thus drawdowns tend to be diffuse. Further, inspection of long-term hydrographs (see Cressler, 1995) of monitoring wells in the vicinity of large irrigation wells reveals no significant drawdowns. Therefore, it is reasonable to assume that drawdowns in the Upper Floridan aquifer of the Dougherty Plain area are not common and when considering the above three conditions, use of Uniform Flow Equation in this area is reasonable and appropriate.

Once the OMZ is initially defined, particle tracking analysis should be performed. The purpose of particle tracking analysis is to demonstrate that releases in the watershed potentially would reach the well. If particle tracking analysis suggests that a release would not reach the well, the boundaries of the watershed should be revised. A general methodology for performing particle tracking analysis is provided in Appendix B. Particle tracking should be performed for the following locations:

1. the watershed boundary;

2. the boundary of the IMZ;

3. closed topographic highs within the watershed; and

4. a series of imaginary circles having radii of 2000 feet per million gallons of pumpage (e.g., this means that a well pumping one million gallons a day or less would have a single imaginary circle having a radius of 2000 feet whereas a five million gallon per day well would imaginary circles at 2000, 4000, 6000, 8000, and 10,000 feet).

Assuming that the following are at lower potential energy, particle tracks should converge on closed topographic depressions/sinkholes within the watershed, perennial streams within the watershed, the main stem stream, or the pumping well. Particle tracks that do not converge on or pass near the pumping well may originate at a location that does not contribute ground water to the well and thus should not be considered part of the WHPA. The example provided in Appendix B illustrates particle tracks that do not converge on the well and thus represent areas outside of WHPA. Delineation of the watershed boundary and particle tracking analysis should take about 2-4 hours per well. Application of the Uniform Flow Equation should take about eight hours for the first well in a well field and about two hours each for other wells.

Initial Field Investigation

At this point, the initial field investigation is appropriate. The location of the well and any other proximal higher yielding wells should be confirmed and accurately located, preferably using a global positioning system (GPS). Using topographic maps, geologic maps, and aerial photographs, the locations of recharge features, discharge features, geologic contacts, and geologic structures proximal to the well should be located and plotted. The general boundary of the watershed also should be confirmed. During this same field visit, initial "face to face" contact with the water supervisor and the pollution source inventory of the Control Zone and the IMZ should be performed. Exclusive of travel time, this task should not take more than 4-8 hours per well.

Fracture and Lineament Trace Analysis and Development of Preliminary ZHV and OMZ

Fracture and lineament trace analysis can be done by inspecting topographic maps and aerial photographs of the watershed for surface expressions of fractures/faults/solution conduits and geologic/bedding plane contacts. This analysis is useful in establishing the ZHV. From 1:24,000 topographic maps, these features may be expressed as straight stream segments (i.e., trellis and pseudo-trellis drainage patterns), linear and curvilinear ridges and valleys, parallel ridges and valleys, aligned wetlands, sinkholes, and springs, and so forth. From aerial photographs[26], the aforementioned topographic features should be confirmed; in some instances, some topographic features may be identified on aerial photographs that are not detectable on topographic maps. On color infrared aerial photographs, fractures/faults/solution cavities and geologic/bedding plane contacts may be expressed as linear changes in color tone (probably reflecting changes in soil moisture content), linear rock outcrop patterns, and aligned wet areas. Care should be exercised to exclude linear "manmade" features such as roads and trails, power lines, fence lines, channelized streams, and property lines.

All such tracelines within the watershed should be plotted on a second overlay. Tracelines, and more importantly traceline intersections proximal to the well, should be included in the ZHV. If tracelines and traceline intersections are more or less evenly distributed in the watershed, we recommend that the ZHV include the 5-10 percent of the tracelines that are closest to the well; if the tracelines and traceline intersections are not evenly distributed, we recommend that the ZHV include any concentration of tracelines, which intersect the 500-foot radius IMZ.

Once aerial photographs and topographic maps are on hand, this task should take about 2-4 hours. Ordering maps and topographic maps, however, may take several hours; and actual delivery may take several weeks.

At this point, the preliminary ZHV and OMZ should be reasonably developed so that field evaluations (actually ZHV and OMZ confirmation) and pollution source inventory activities can begin.

Final Field Investigation

At this time, the final field investigation, which we estimate will take about eight hours exclusive of travel time, is in order. The first step is to query the water supervisor asking questions about changes in turbidity, changes in flow, sinkhole occurrence/sinkhole inducement, past and present problems, impact of precipitation on water quantity and quality[27], pumping rate changes, changes in

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[26] We recommend using color-infrared photographs, which are available from the USGS in Sioux Falls, South Dakota.

[27] It is important to ascertain how the well responds to heavy rains and periods of drought. If, for example, heavy rains cause turbidity, especially within 12-24 hours, it is probably safe to conclude that there is a close and direct connection to the surface. In contrast, if long periods of drought do not affect well yield or water level, then the source of the water to the well is probably from geographically extensive area, from a large storage reservoir (probably residuum), or both.

pump depth, and similar features. After interviewing the water supervisor, the next step is to perform a foot-traverse of the preliminary ZHV confirming (measuring and locating) geologic contacts, rock outcroppings, strike and dips, domestic wells, and previously unrecognized sinkholes, swallowholes, wet areas, and closed depressions. Foot traverses also provide the opportunity to interview local residents asking them questions similar to those asked of the water supervisor. The final step is a vehicle-traverse of the entire watershed (i.e., the OMZ) searching for any indication of a geologic feature, such as a regional brittle fault, which could provide a pathway for pollutants to move into the watershed from adjoining areas.

Although not part of the actual delineation of the ZHV or the OMZ, this field visit would be the appropriate time to perform the pollution source inventory. The time required for the pollution source inventory is dependent on the number of potential sources.

Compilation of Maps, Overlays, and Other Information

The last task in delineation of a WHP area in a karstic terrain is the synthesis of all information gathered and preparation of the actual WHPA map. This probably can be done in about eight hours including map preparation. The map should show the 500 foot IMZ boundary, the ZHV boundary, and the OMZ boundary (which will probably be the watershed boundary in northwest Georgia and a generally rectangular area, established from the Uniform Flow Equation with an upgradient 5-year travel time extension in southwest Georgia). Because delineation of the ZHV boundary is subjective and delineation of the OMZ boundary may be subjective, we recommend that all ZHV and OMZ boundary delineations be reviewed by a supervisor and that at least one-fourth of the delineations be field checked.

DELINEATION OF WHPA'S IN THE KARSTIC REGIONS OF THE VALLEY AND RIDGE OF NORTHWEST GEORGIA AND THE DOUGHERTY PLAIN OF SOUTHWEST GEORGIA

Northwest Georgia

The Valley and Ridge Province of northwest Georgia consists of a series of folds and thrust faults involving sedimentary rocks of Paleozoic age. The highest yielding aquifers are in limestone and dolostone formations, namely limestones of the Conasauga Group, Knox Group (dolostone and limestone), and Chickamauga Limestone, with the Knox Group being the most productive of the three. Flow in the karstic areas is mainly through fractures and solution features that produce discharge rates as high as 40 Mgd from springs. The residuum, which overlies the Knox Group, is mainly chert and clay remains from dissolution of the Knox bedrock and can vary considerably in thickness.

What follows is a detailed discussion of the methods employed at a specific site, consisting of two municipal wells (Wells 1A and 1B) for the City of Chickamauga, Georgia.[28] Both wells are completed in the Knox Group (and Newala Limestone). Approximately 1500 feet southeast of the two City wells are the Walker County Authority wells (TPW1, TPW2, and TPW3); these wells are not the focus of this study. The locations of all five wells are shown on Figure 5.

The City's two wells are immediately adjacent to a very large, high-flowing (25-40 Mgd) springs, known as Crawfish Springs. The general vicinity of the wells contain numerous sinkholes and closed depressions. As pointed out earlier, ground-water flow occurs primarily through very large subsurface, solutionally-enlarged conduits controlled by both bedding and fractures in carbonates of the Knox Group. When the City was founded, Crawfish Springs were the principle sources of water; however, because of ill-defined problems generally referred to as "surface water influences", wells replaced the spring water sources. The most recent well, 1B, was installed in 1994.

Well data, including drillers logs and pumping yields, for the two City wells were obtained from EPD's Drinking Water Program and were updated with current information gathered during the site visit. The locations of the two City wells and the three other nearby wells were established using GPS methods during the site visit.

To cover the entire watershed, four 1:24,000 topographic maps were assembled to create a "master topographic map". Geologic contacts, obtained from the published literature (Cressler, 1964), were plotted on the "master topographic map". Next watershed boundaries for the primary tributary, Coke Oven Creek, were plotted on the "master topographic map". The watershed extends northwestward to Missionary Ridge and southeastward to Chickamauga Creek, which serves as the main stem stream and the ultimate zone of discharge (see Figure 6).

As previously mentioned, particle tracking analysis was not performed at the time of the original study; rather this technique was recognized later and then applied retroactively to the Chickamauga study. Figure 6 illustrates the watershed boundary delineation as well as particle tracking analysis. A search of EPD's Water Resources, Land Protection, and Hazardous Waste Management branches revealed no data that would alter the configuration of the ZHV or the OMZ.

Aerial photographs, which were examined stereoscopically, and topographic maps were analyzed to locate possible lineament patterns and aligned patterns of sinkholes.[29] These are shown on Figure 5. One of the more pronounced NW-SE lineaments coincides with Crawfish Springs.

During the site visit, the area immediately updip and upgradient from

[28] For this study, WHPA delineation was done twice. First, the two University of Georgia authors (Jones and Wenner) delineated the WHPA and provided the delineation, with accompanying methodology, to EPD; second, McLemore expanded on the earlier work by gathering wetland, soils, and other geologic information as well as having Geologic Survey associates search the files of Water Resources, Land Protection, and Hazardous Waste Management Branches.

[29] These features were drawn on clear acetate overlays attached to the photographs. Because of differences in scale between the photographs and the 1:24,000 topographic maps, only those lineaments identified on both photographs and topographic maps were actually plotted on the master topographic map.

both the wells and Crawfish Springs was traversed on foot to identify and locate karstic features that might be interconnected to the underground water supply. These features, in turn, were plotted on the "master topographic map". GPS methods were used to locate those features that were not identifiable on the topographic map. Later the road network covering the entire drainage basin was traversed by car. Because of the thick residuum and lack of surface exposure, Cressler's (1964) geologic contacts and strikes and dips could not be verified in the immediate vicinity of the City's wells[30]; the projections, however, were assumed to be correct and were plotted on the "master topographic map".

The Water Supervisor for the City and the Walker County Water Treatment Plant Manager were both queried about changes in water quality, response to pumping, and the influences of heavy precipitation and drought on well water levels. Their observations proved to be very useful in developing an understanding of the ground-water flow system in the vicinity of the wells. Relevant information obtained from these two interviews includes:

> A. Spring discharge was not noticeably affected by installation and pumpage of any of the City's and Walker County Water Authority's nearby wells.

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[30] The general validity of Cressler's geologic mapping was confirmed by McLemore and Hurst (1970). Furthermore, the Paleozoic portion of the 1:500,000 State of Georgia Geologic Map (1976) is based on Cressler's mapping. Cressler's mapping is assumed to be reasonably accurate.

B. During development of well 1B, the south spring at Crawfish Springs showed a temporary increase in turbidity. This suggests that well 1B is hydraulically connected to the south spring.

C. Pumping tests on well 1B showed a water level drawdown in well 1A. This suggests that the two wells are hydraulically connected.

D. Pumping tests at the wells at the Water Treatment Plant showed no effect on well 1B. This suggests that two City wells and the Treatment Plant wells are not efficiently hydraulically connected.

E. Twelve to twenty four hours after an isolated rain, well 1B had a slight increase in turbidity. This suggests that well 1B is being recharged rather quickly and locally.

F. Crawfish Springs experience more turbidity after rain events now than in past years. This suggests that the spring is presently being more efficiently recharged than in the past. [Note: increased construction activity in the general area also might cause an increase in turbidity; however, there was no obvious new construction seen during the field visits to the area.]

Upon plotting all of the field and office-generated data onto the "master topographic map", it was apparent that the majority of sinkholes and sinking streams occurred at or near the contact between the Newala Limestone and the Knox Group (see Figure 5). This would seem to indicate that the geologic contact also represents a pathway where flowing ground water has preferentially dissolved the carbonate rocks, thereby increasing porosity (and probably increasing hydraulic conductivity). To geometrically visualize this concept, a cross-section (Figure 7) was constructed in an attempt to assess whether the two City wells, and the three water treatment plant wells, are hydraulically interconnected or influenced by this apparent zone of higher hydraulic conductivity at the Newala-Knox contact. Well logs for well 1B indicate that the larger solution conduits are located at a depth of 216-238 feet. Back projection of Cressler's (1964) general dip for the Chickamauga area of 5°SE from the 216-238 foot interval in well 1B generally coincides with Cressler's Newala-Knox contact (see Figures 5 and 7). On the other hand, back projection of higher porosity intervals from the three water treatment plant wells could not be correlated to the Newala-Knox contact. We interpret the above to mean that the two City Wells are influenced by a zone of higher porosity (and presumably a zone of higher hydraulic conductivity) associated with the Newala-Knox contact, whereas the water treatment plant wells, some 1500 feet southeast of wells 1A and 1B, are not influenced by the Newala-Knox contact. This interpretation is supported by results from the pumping test on one of the water treatment plant wells, which did not influence either well 1A or 1B.

Due to the very high rate of discharge (25-40 Mgd), we interpret local ground-water movement to be toward Crawfish Springs. Crawfish Springs consist of two distinct springs that converge at the outlet. Well 1B appears to be hydraulically connected to the southern spring; it is not known if well 1B is connected to the northern spring. Therefore, the source of ground-water flow supplying the southernmost spring probably also supplies the City's two municipal wells.

Since the majority of sinkholes and sinking streams occur at or near the Newala-Knox contact, this area is considered to be very vulnerable to rapid transport of pollutants in the ground-water regime to the City's two wells (Figure 5). Therefore, those portions of the contact in the vicinity of the two wells were included in ZHV. To the north and northwest of the two wells, the ZHV boundary was delineated to include the majority of the numerous sinkholes and sinking streams northwest of the geologic contact (Figure 5). To the south and east of the City's wells and Crawfish Springs, the ZHV was extended to include a sinkhole about 1000 feet north of the quarry (Figure 5).

Figure 8 illustrates the configuration of the final IMZ, the OMZ, and the ZHV for the Chickamauga area.

Southwest Georgia

The karstic terrain of the Dougherty Plain of southwest Georgia is similar to the karst in regions of north Florida. Topography is very gentle and surface drainage is poorly developed. The Eocene and Oligocene-age Ocala Limestone of this region, which comprises the Upper Floridan aquifer, has high primary porosity, with the rock often appearing "sponge-like", as well as having an extensively developed conduit system. The Ocala Limestone of the Dougherty Plain area has several significant differences from the carbonate rocks of northwest Georgia: namely; it is essentially flat-lying rather than steeply dipping, thus geologic contacts are limited; it has much higher primary porosity; it is relatively isotropic; and it is semi-confined.

Overlying the Ocala is a residuum, composed primarily of clay or sandy clay, with relatively low hydraulic conductivity. This residuum serves to semi-confine the aquifer. Recharge to the Upper Floridan aquifer is primarily through sinkholes, swallowholes, closed depressions, and through the residuum where it is thin, missing, or more permeable (Torak and McDowell, 1996). Direct infiltration of precipitation, through the clayey residuum, is of lesser importance than the above. Natural discharge from the Upper Floridan is to surface streams and springs.[31] In the Dougherty Plain, the aquifer's dual porosity allows rapid flow through the conduits and "slower" flow through the intergranular pores. The primary and secondary porosity of the aquifer also provide considerable storage; wells constructed in the Upper Floridan typically are high-yielding (i.e., 1000+ gallons per minute).

For southwest Georgia, three municipal wells for the City of Colquitt were selected to demonstrate the methodology for WHPA delineation. The City is in the Dougherty Plain on the east bank of Spring Creek near the geographic center of Miller County. Surface soils in the area are well drained stream-transported sands to poorly drained clayey residuum. Few surface streams dissect the area. The residuum, estimated from well logs, in the Colquitt area varies in thickness form 50-75 feet. Here, the Ocala Limestone varies in thickness from about 125 feet (Kwader and Wagner, 1982) to about 250 feet (Torak, et al., 1991).

The City of Colquitt has three municipal water-supply wells within a few hundred feet of each other. Information on these wells was obtained from the Drinking Water Program of the Water Resources Management Branch. Well #3 is the main well and wells #1 and #2 are maintained for emergency backup. All three wells (see Figure 9) are cased-off through the residuum (and some of the uppermost part of the aquifer) and are completed open-hole in the Upper Floridan aquifer, as follows (records from Layne-Atlantic Company): well #1 drilled 180 feet and cased 50 feet; well #2 drilled 235 feet and cased 75 feet; and well #3 drilled 210 feet and cased 150 feet. According to the driller's log, well #3 encountered a mixture of mostly clay with some sand from 3 to 50 feet before reaching the top of the Ocala Limestone at a depth of about 90 feet. Near the contact, the Ocala is a "powder" limestone mixed with sand. We attribute the sand to be fill in void openings. At a depth of about 150 feet, the driller lost circulation, suggesting a large solution opening (i.e., a void). Drilling was terminated at 210 feet where the driller encountered a brown limestone, which we interpret to be the underlying confining Lisbon Formation. These depths and thicknesses are consistent with Watson's (1981) structural contour map and isopach map for the Ocala Limestone. All three wells, along with the 500-foot IMZ, were plotted on the "master

[31] Springs commonly occur on the banks of the Flint River and larger streams (i.e., Spring Creek, Ichawaynochaway, etc.), appearing as true springs, such as Radium Springs, ill-defined seeps, or "blue holes", where discharge is underwater below the river/stream surface.

topographic map", which is a single 1:24,000 topographic quadrangle.

Large irrigation wells are common in Miller County; such wells, if close to the municipal wells, have the potential to impact ground-water flow in the WHPA. An inspection of EPD's GIS data base (derived from EPD permit files) of irrigation wells indicated that no irrigation wells were within two miles of the three municipal wells.[32] Therefore, large irrigation wells are not considered to impact the WHPA. A review of Water Resources Management Program files indicated that there are no large Upper Floridan industrial water supply wells in Colquitt. Furthermore, a search of EPD's Land Protection and Hazardous Waste branches revealed no data that would alter the configuration of the OMZ.

There are few surface geologic data in the Colquitt area. The most useful data have to be extracted from published hydrogeology reports and county soils maps. Based on Watson's (1981) potentiometric contour map, ground-water flow in the general Colquitt area is northeast-southwest toward Spring Creek, which flows almost due south into Lake Seminole (Figure 10). Using photographic methods, Watson's 1981 potentiometric contours were enlarged to 1:24,000 and plotted on the "master topographic map". Furthermore, soil series classified by the Soil Conservation Service as being more "permeable" also were plotted on the "master topographic map".

Small streams in the Colquitt area are ill defined and intermittent, generally flowing directly into Spring Creek or into the riverine swamp adjacent to Spring Creek, which represents the zone of ultimate discharge (see Figure 10). Because of the poorly developed surface drainage in the Colquitt area, we elected not to attempt to delineate the OMZ by mapping the watershed boundary. Rather we utilized the Uniform Flow Equation method, coupled with the 5-year travel time analysis (see Appendix A). The Uniform Flow Equation permits the calculation of the distance of the capture zone upgradient, downgradient, and sidegradient distances to the pumping well (see Figure 11).[33] The upgradient, downgradient, and sidegradient distances respectively are: $Y_{up} = Q/Ti$; $Y_{down} = -Q/2\pi Ti$; $X_{lateral} = \pm Q/2Ti$ where Q is the pumping rate, T is the transmissivity, and i is the hydraulic gradient. To develop a conservative estimate of the OMZ for well #3, a lower estimate of transmissivity for the Ocala was used (20,000 ft^2/day, Lynn Torak, USGS, 1997, personal communication). The permitted pumping rate is 300,000 gallons per day (40,000 ft^3/day). The hydraulic gradient is .001 (calculated from Watson, 1981). Calculation of the above three equations

[32] During the time period that this manuscript was in review, EPD obtained digital aerial imagery for all of Georgia. Thus aerial photographs of all of Georgia can be produced as needed in a matter of a few hours. Such imagery should be used to locate irrigation systems.

[33] It is important to note that application of the Uniform Flow Equation is only appropriate for isotropic and confined aquifers. Based on our work and our review of the cited references, we believe that the aquifer in the vicinity of Colquitt is reasonably isotropic and semi-confined. Therefore we feel justified in applying the Uniform Flow Equation in the Colquitt area as well as the remainder of the Upper Floridan aquifer of the Dougherty Plain area.

results in Y_{up} = 2000 feet, Y_{down} = -318 feet, and $X_{lateral}$ = ±1000 feet.

In order to take into account the upgradient area influenced over a period of time, the 5-year travel time was calculated using the equation d = tKi/n where d is the distance upgradient, t is time in days, K is the hydraulic conductivity, i is the gradient, and n is the effective porosity. Using a K = 160 ft/day (K = T/b, where T = 20,000 ft²/day and b = 125 feet), and n = .2 (Hayes, et al., 1983), d was calculated to be 1460 feet. Adding Y_{UP} of 2000 feet to d of 1460 feet extends the OMZ 3460 feet in the upgradient direction (see Figure 11).[34]

Since flow, while a continuum, is directed mostly along fracture and bedding plane conduits, the OMZ must represent an area that takes into consideration:

1. draining ability of overlying soils;

2. mappable lineaments from aerial photographs;

3. possibility for conduits to be parallel to potentiometric contours,

4. 5-year time of travel from the aforementioned equations;

5. application of these calculations to wells #1, #2 and #3; and

6. overlapping of all three OMZs to protect all three wells with a single WHPA including a single OMZ and ZHV.

The estimated OMZ relies heavily on calculations based on a set of analytical equations. Since the aquifer is highly transmissive and heterogeneous, numerical calculations may not properly estimate the size of the capture zone or the 5-year travel time.

Upon plotting the OMZs for all three City wells on a 1:24,000 topographic map, we noted a number of closed depressions in the general vicinity of the combined OMZ, but slightly outside and northwest of the combined OMZ (see Figure 12). Because closed depressions are considered to be potential primary areas of aquifer recharge and because these closed depressions are immediately upgradient from the combined OMZ, we elected to enlarge the OMZ to include these closed depressions. The net result of this exercise is that the OMZ for the three City of Colquitt wells is a hybrid OMZ that considers analytical measurements and actual hydrogeologic features (see Figure 12).

The final part of delineating a WHPA for the three City wells would be establishment of the ZHV. As previously mentioned, the ZHV represents continuous and discontinuous concentrations of sinkholes, swallowholes, closed depressions, permeable soils, private wells, and lineament/fracture traces. In the Colquitt area, however, no such concentrations occur, and thus a ZHV could not be established.

CONCLUSIONS

Methodologies are presented to delineate WHPAs in karstic terrains of northwest and southwest Georgia. The methodology for northwest Georgia involves delineating the OMZ by mapping the watershed boundary plus performing particle tracking analysis. In southwest Georgia, the OMZ is delineated by using the Uniform Flow Equation to calculate the downgradient and sidegradient boundaries and the Uniform Flow Equation added to the 5-year travel distance to calculate the upgradient boundary. A subdivision of the OMZ, the ZHV, which is delineated by vulnerability mapping is recommended, wherever possible, for both northwest and southwest Georgia.

[34] Increasing K or decreasing n would increase 5-year travel distance significantly.

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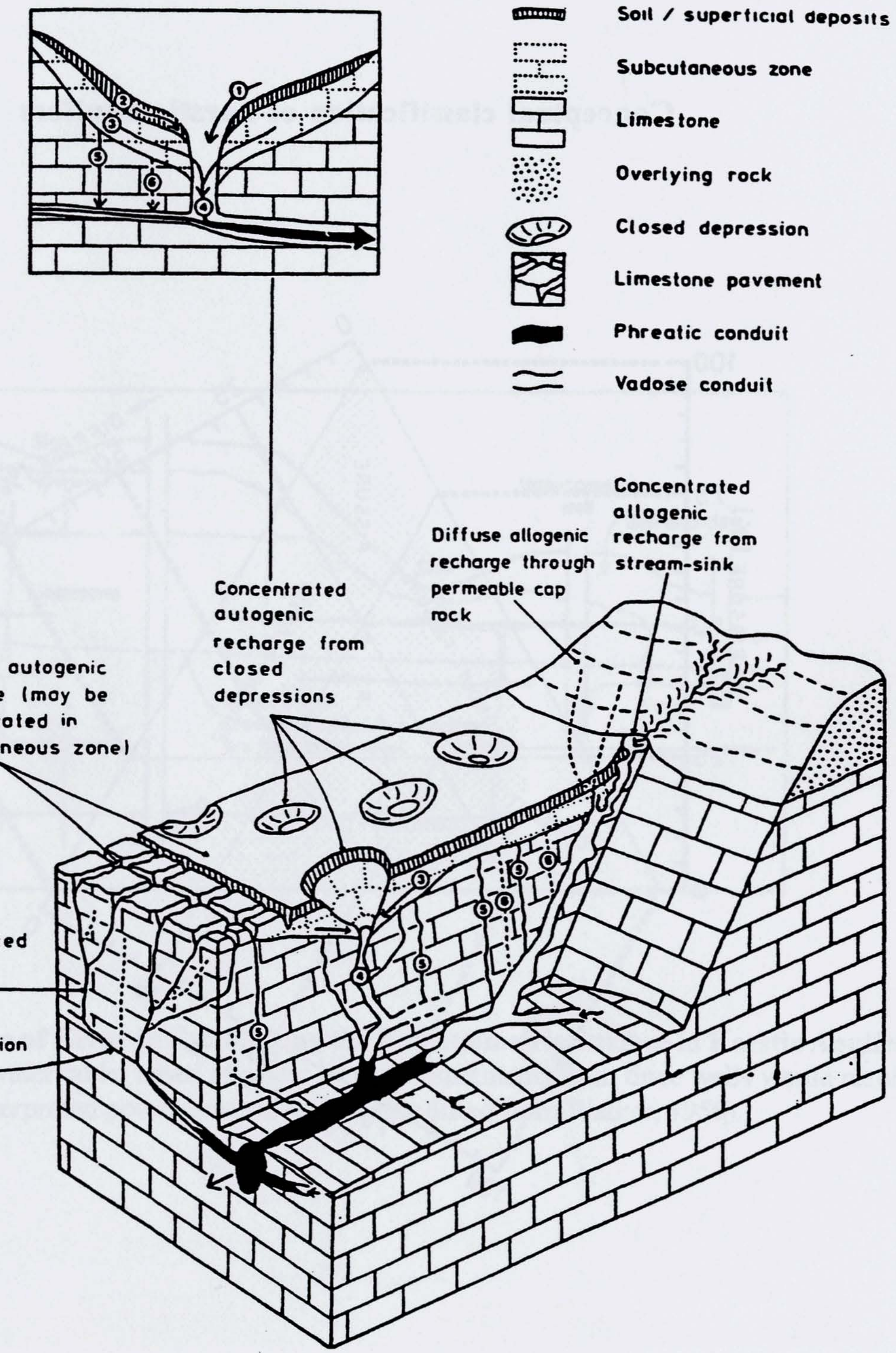


Figure 1. Conceptual Model of Conduit-dominated Flow in a Karst Aquifer. Number transfer mechanisms are (1) overland flow, (2) through-flow, (3) subcutaneous flow, (4) shaft flow, (5) vadose flow, and (6) vadose seepage (from Gunn, 1986).

Conceptual classification of karstic aquifers

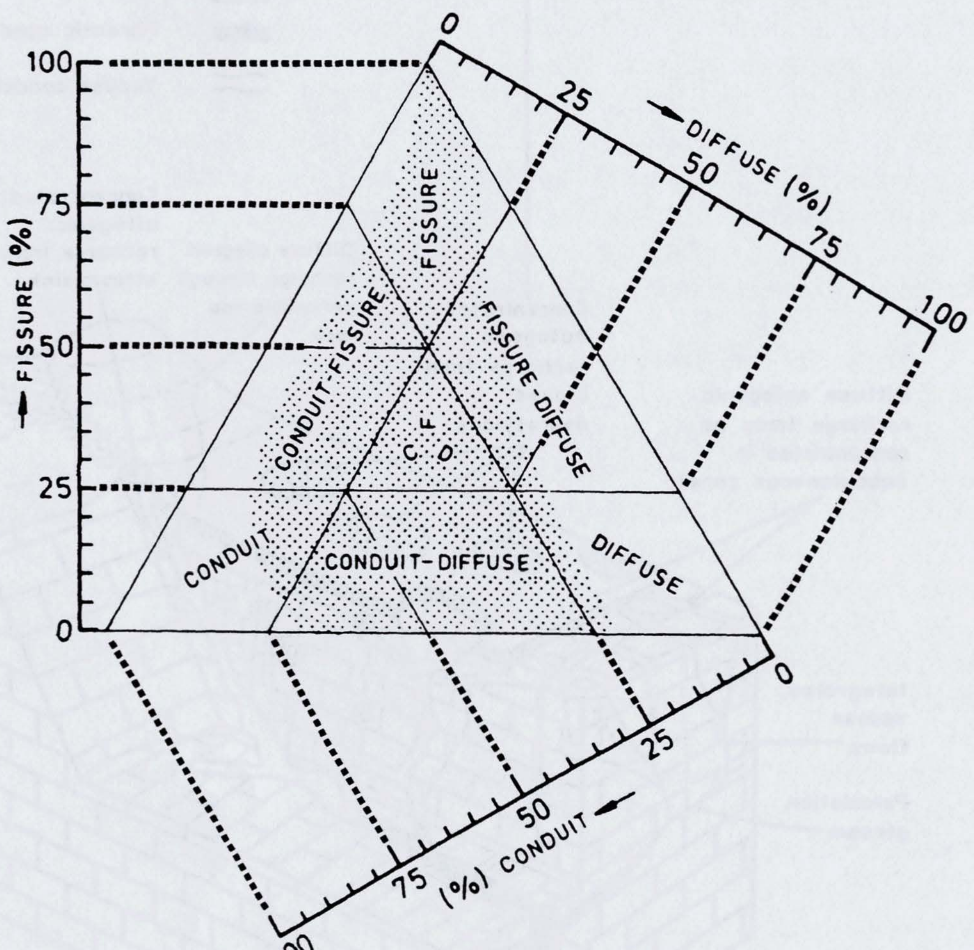


Figure 2. A Conceptual Classification of Karstic Aquifers. On the left-hand side of the triangle flow is turbulent, on the right-hand side the flow is Darcian, and in the dotted area, the flow is mixed (from Gaspar, 1987).

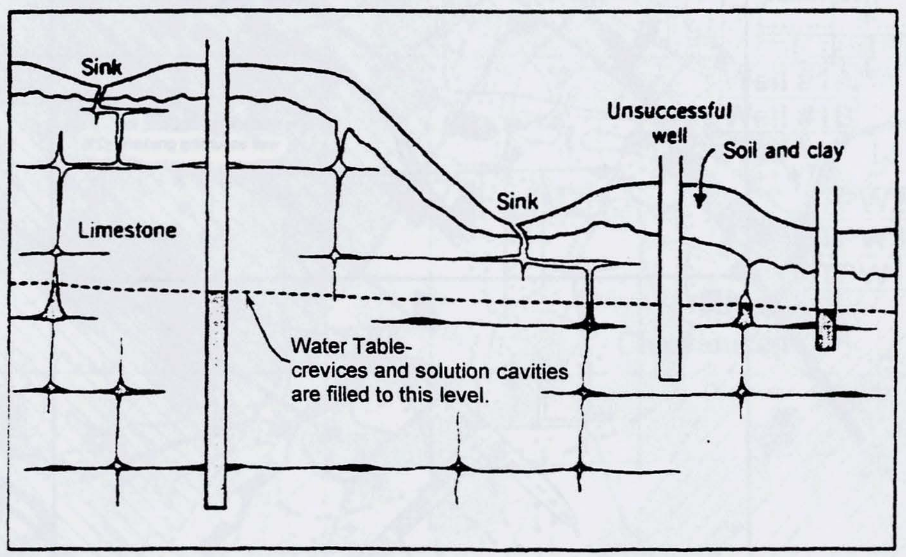


Figure 3. Source of Error in Establishing the Potentiometric Surface in Karstic Aquifers. Mapping of the water table, based on water level measurements from three wells would result in an incorrectly interpreted potentiometric surface (modified from Walker, 1956).

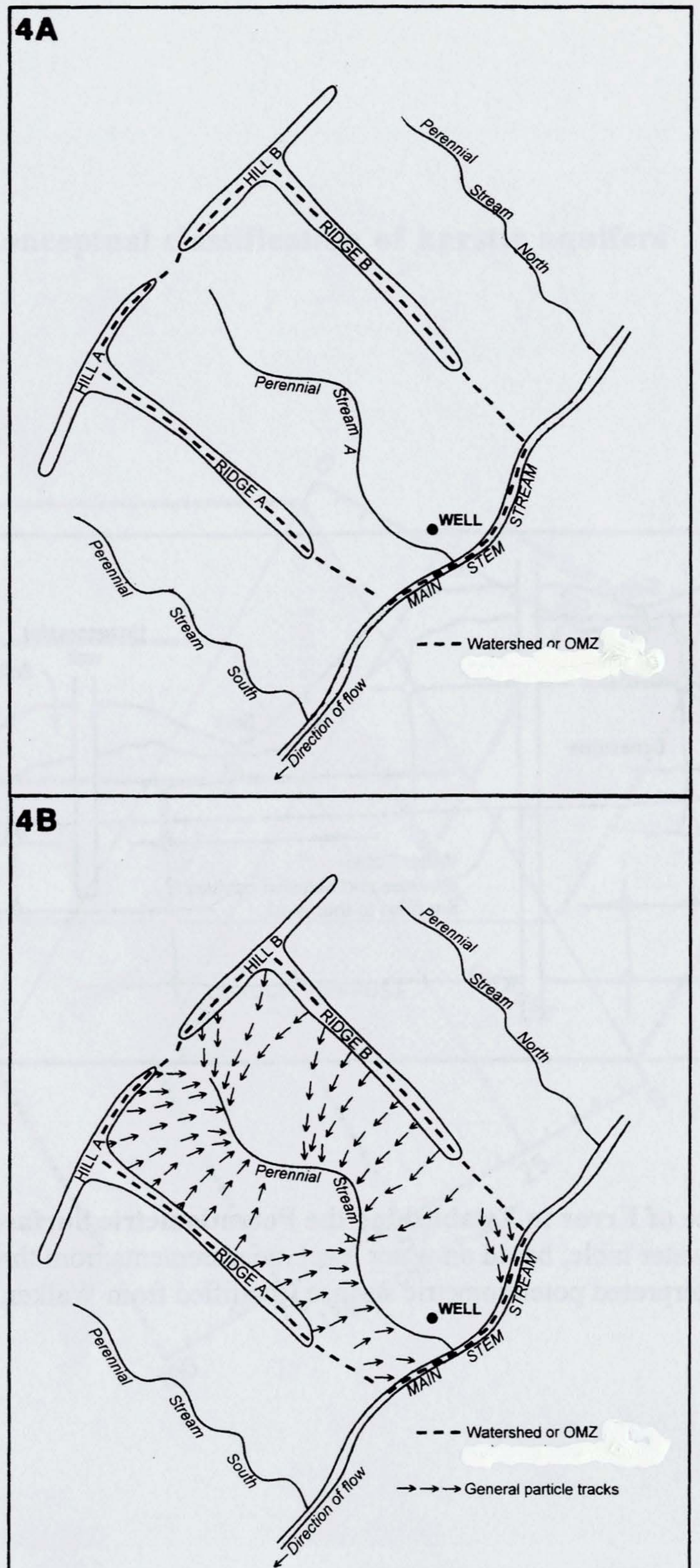


Figure 4. (4A) General Concept for Delineating a Watershed Boundary as an Outer Management Zone (OMZ); (4B) General Particle Tracking Analysis. Particle tracking analysis is more completely described in Appendix B.

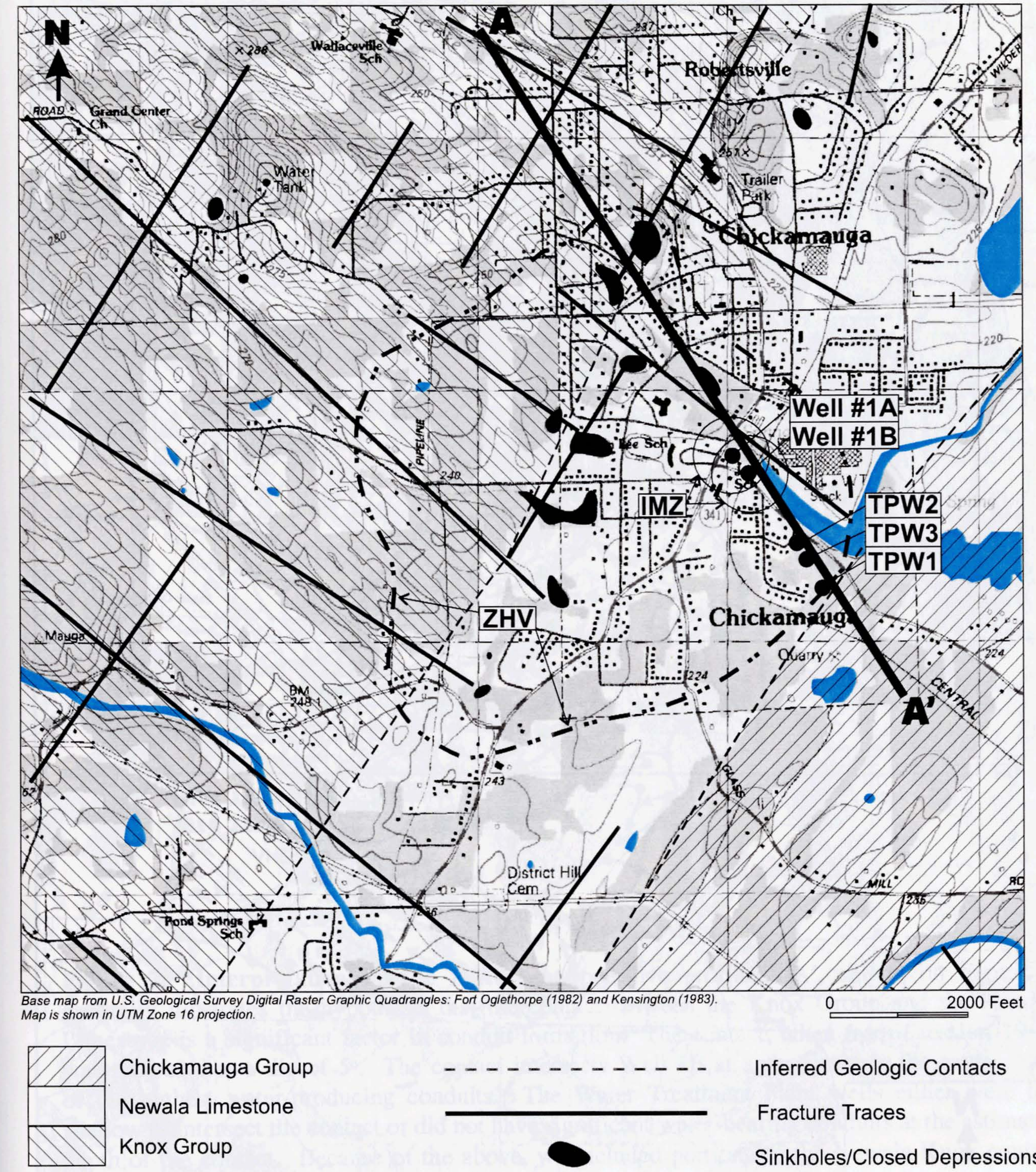


Figure 5. General Hydrogeology of the Chickamauga Area, Georgia. Wetlands are shown in blue. A-A' shows the approximate location of an interpretative profile illustrated in Figure 7.

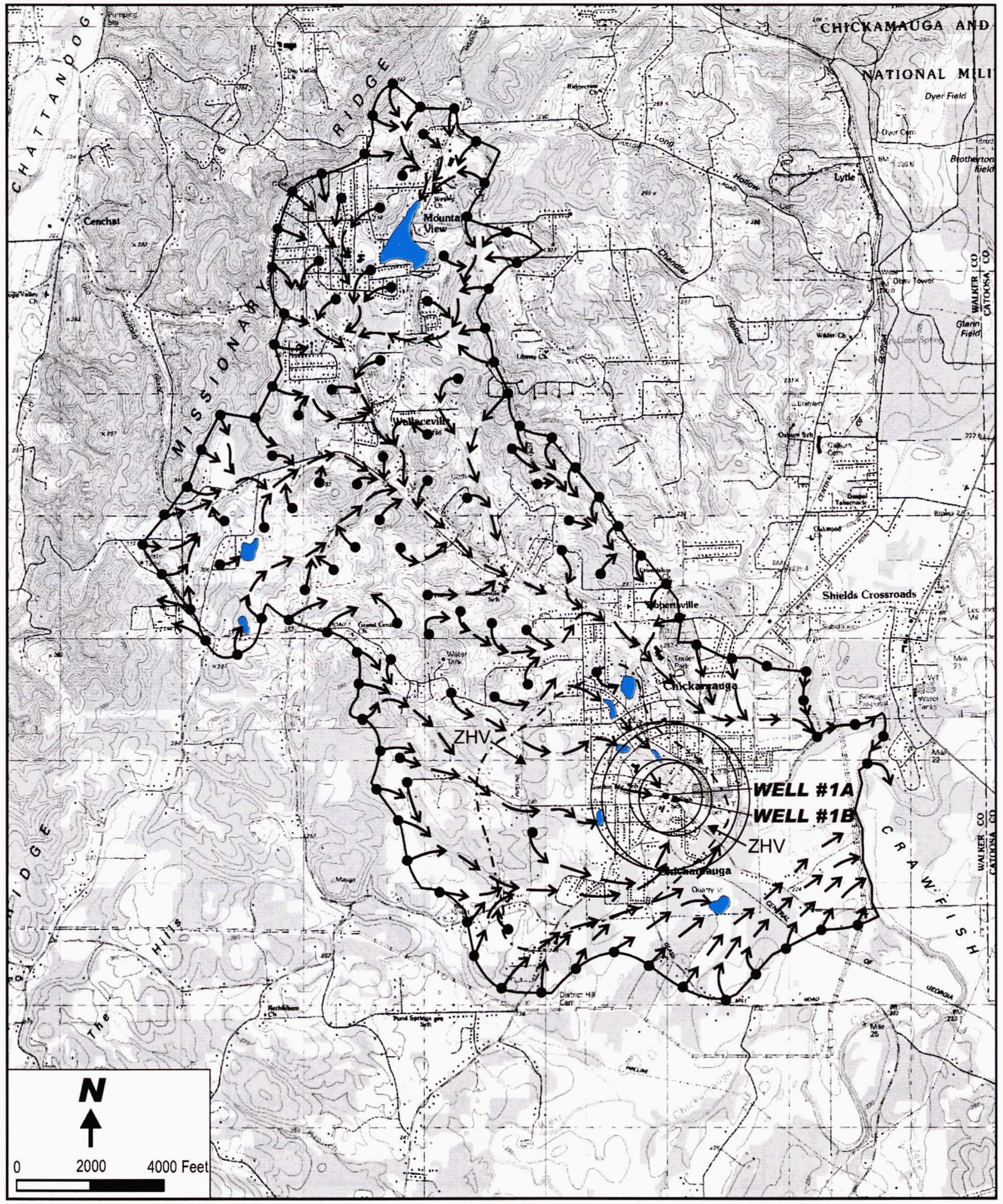


Figure 6. Watershed Boundary and Particle Tracking Analysis for Wells 1A and 1B. Blue areas indicate closed depressions. Circles surrounding wells 1A and 1B are 2000' and 4000' (see Page 22 for the use of such imaginary circles for particle tracking analysis.).

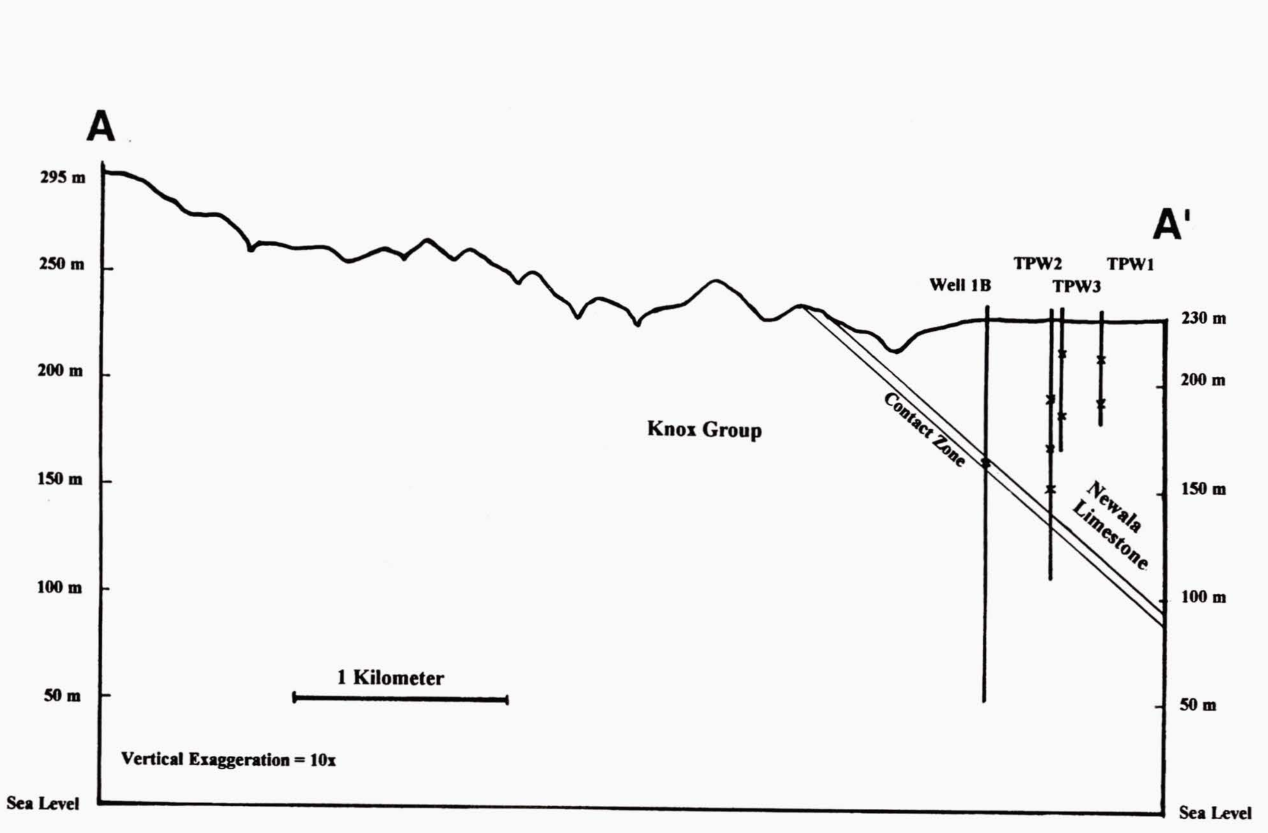


Figure 7. Interpretative Profile A-A'. Interpretative profile A-A', shown on Figure 5, generally illustrates the hypothesis that the contact between the Knox Group and the Newala Limestone is a significant factor in conduit formation. The contact, taken from Cressler, 1964, was projected at a dip of 5°. The contact intersects Well 1B at approximately the same depth of the highest water-producing conduits. The Water Treatment Plant wells either were too shallow to intersect the contact or did not have significant water-bearing conduits at the estimated depth of the contact. Because of the above, we included portions of the Newala-Knox contact in the ZHV.

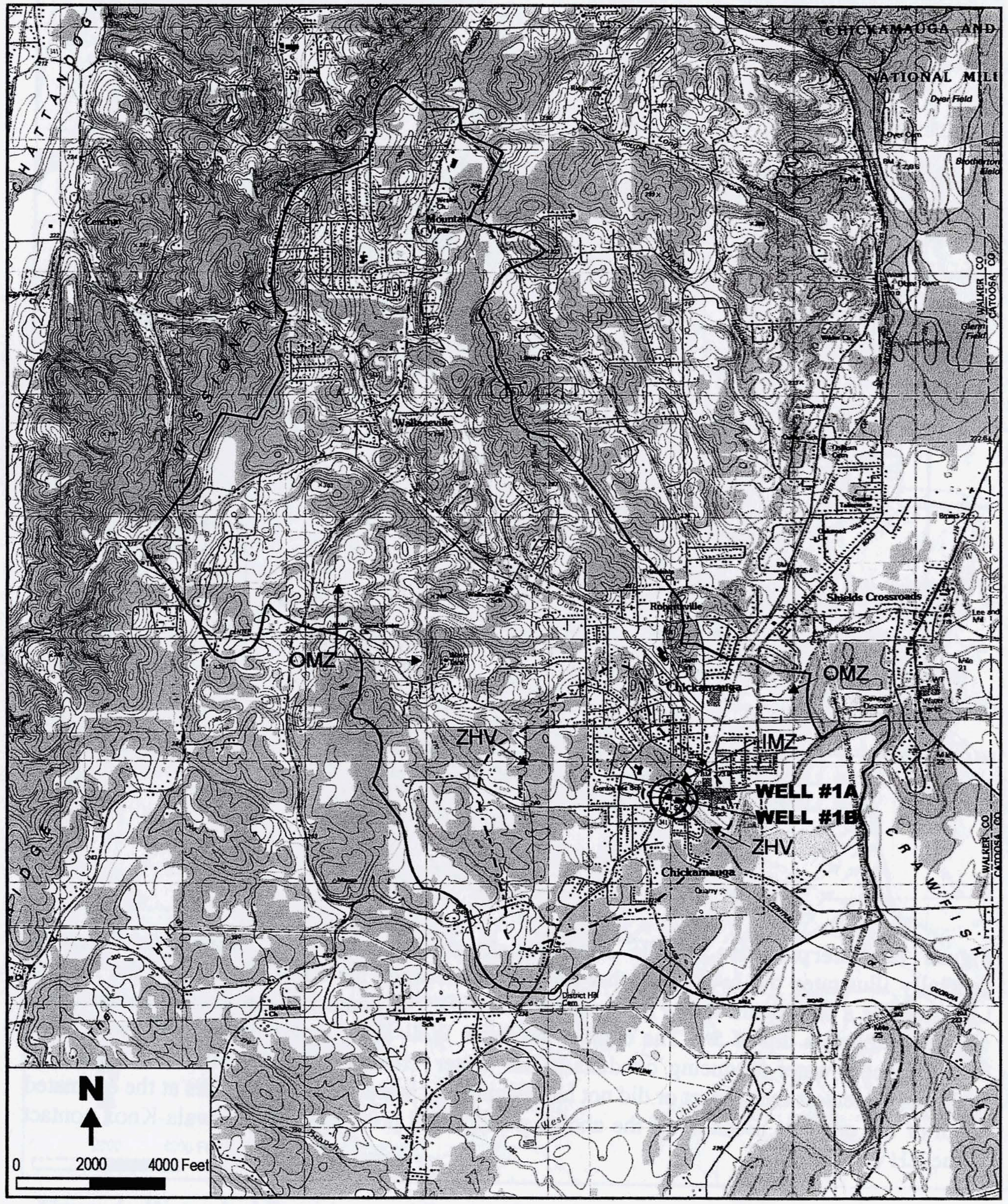


Figure 8. Wellhead Protection Area for Wells 1A and 1B.

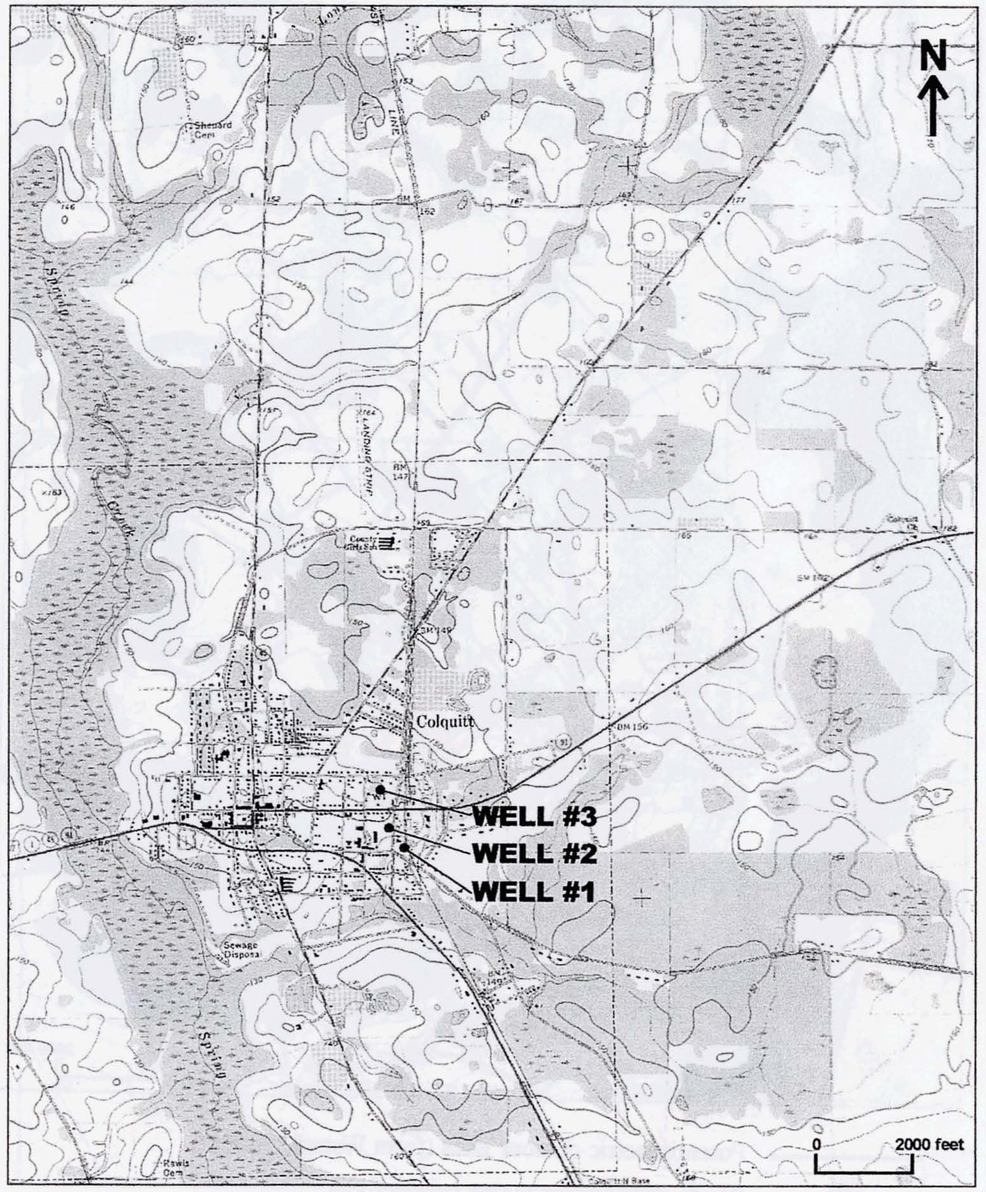
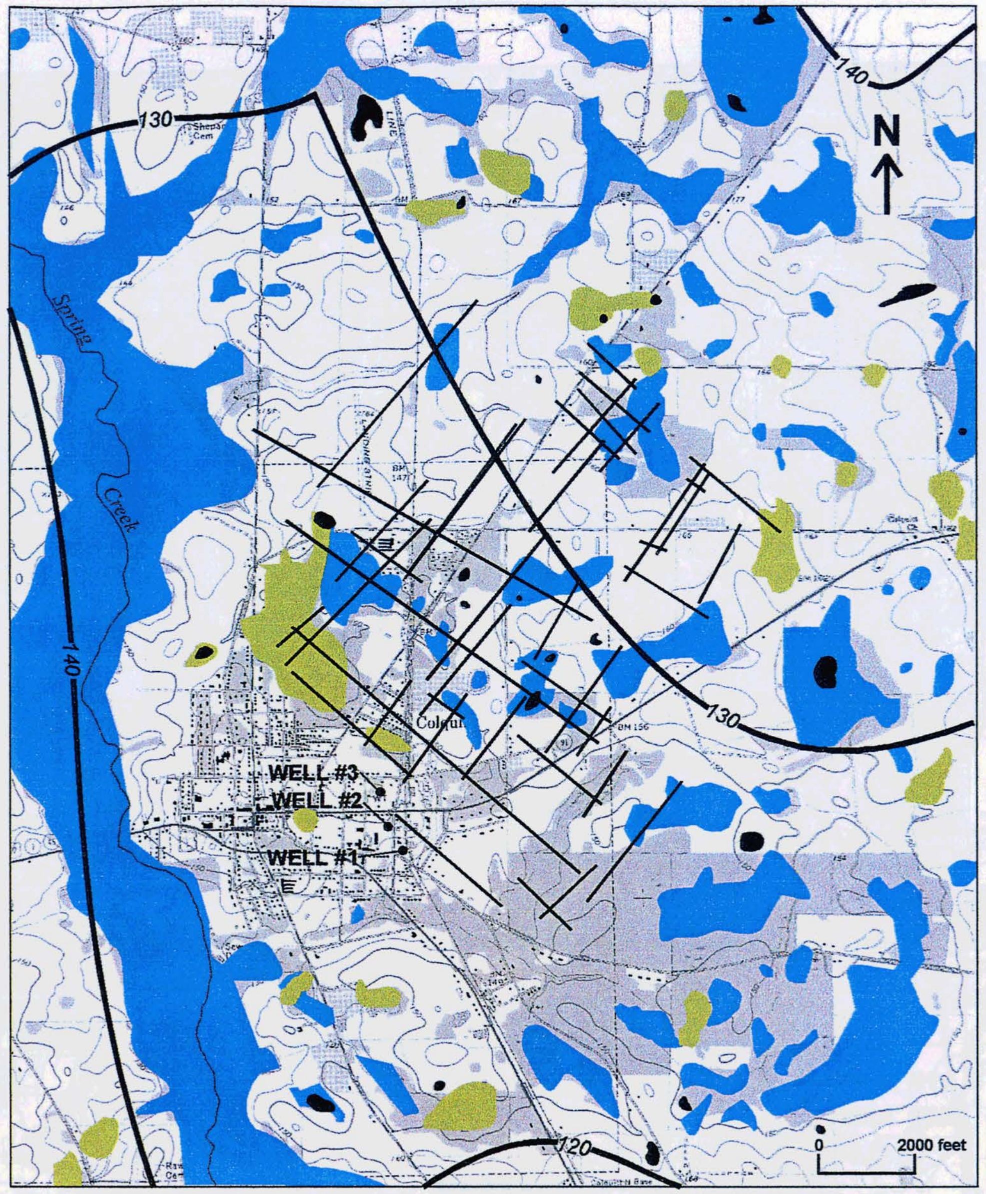


Figure 9. Locations of Three Municipal Water -Supply Wells near Colquitt, Georgia.



Potentiometric contour lines (from Watson, 1981)

Sandy soils having higher conductivity

Soils characteristic of closed depressions (i.e., possible sinkholes)

Topographic closed depressions (i.e., also possible sinkholes)

Lineaments (i.e., fracture traces)

Figure 10. Potentiometric Surface of the Upper Floridan Aquifer and Lineaments, Indications of Enhanced Recharge, and Indications of Possible Sinkholes near Colquitt, Georgia. Several hydrogeologic characteristics of the general Colquitt, Georgia area are presented in this figure. The potentiometric contours indicate general flow toward and discharge to Spring Creek. Lineament information is from this study. Information on sandy soils that may contribute to enhanced recharge and soils associated with closed depressions is from the Soil Conservation Service Maps of Miller County. Topographic closed depressions are shown in black. Closed depressions are believed to be suggestions of sinkholes or other areas where recharge to the aquifer is enhanced. Wetlands not associated with either closed depressions or soils characteristic of closed depressions are shown in blue.

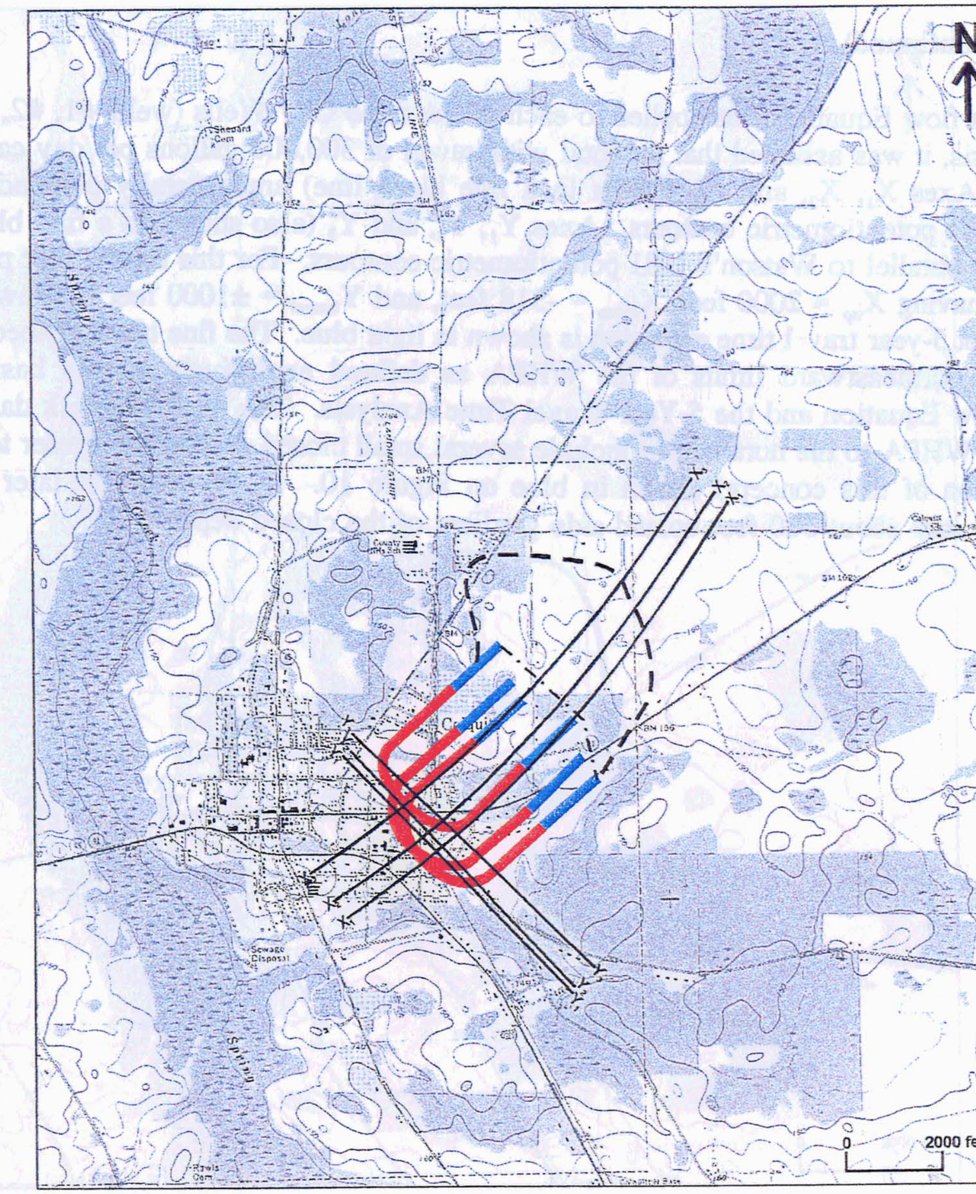


Figure 11. Application of the Uniform Flow Equation and the 5-Year Travel Time Analysis to the Three City of Colquitt Wells. See next page for explanation.

Figure 11 (continued).

The Uniform flow Equation was applied to each of the three City Wells (wells #1, #2, and #3). In the analysis, it was assumed that the total withdrawal of 300,000 gallons per day came from each well. Axes X_1, X_2, and X_3 (shown in a fine black line) are generally perpendicular to Watson's 1981 potentiometric contours. Axes Y_1, Y_2, and Y_3 (also shown in a fine black line) are generally parallel to Watson's 1981 potentiometric contours. For this figure, that portion of the WHPA having X_{up} = 2000 feet, X_{down} = -318 feet, and $Y_{lateral}$ = ±1000 feet is shown in red. The 1460 foot 5-year travel time extension is shown in light blue. The fine black dashed/dot line delimits the northeastward limits of the WHPA as defined exclusively on the basis of the Uniform Flow Equation and the 5-Year Travel Time Analysis. The medium black dashed line expands the WHPA to the northeast to include several small closed depressions (refer to text for an explanation of this concept) shown in blue on Figure 10. In drawing this later line, we attempted to stay about 500 feet up and side gradient of the closed depressions.

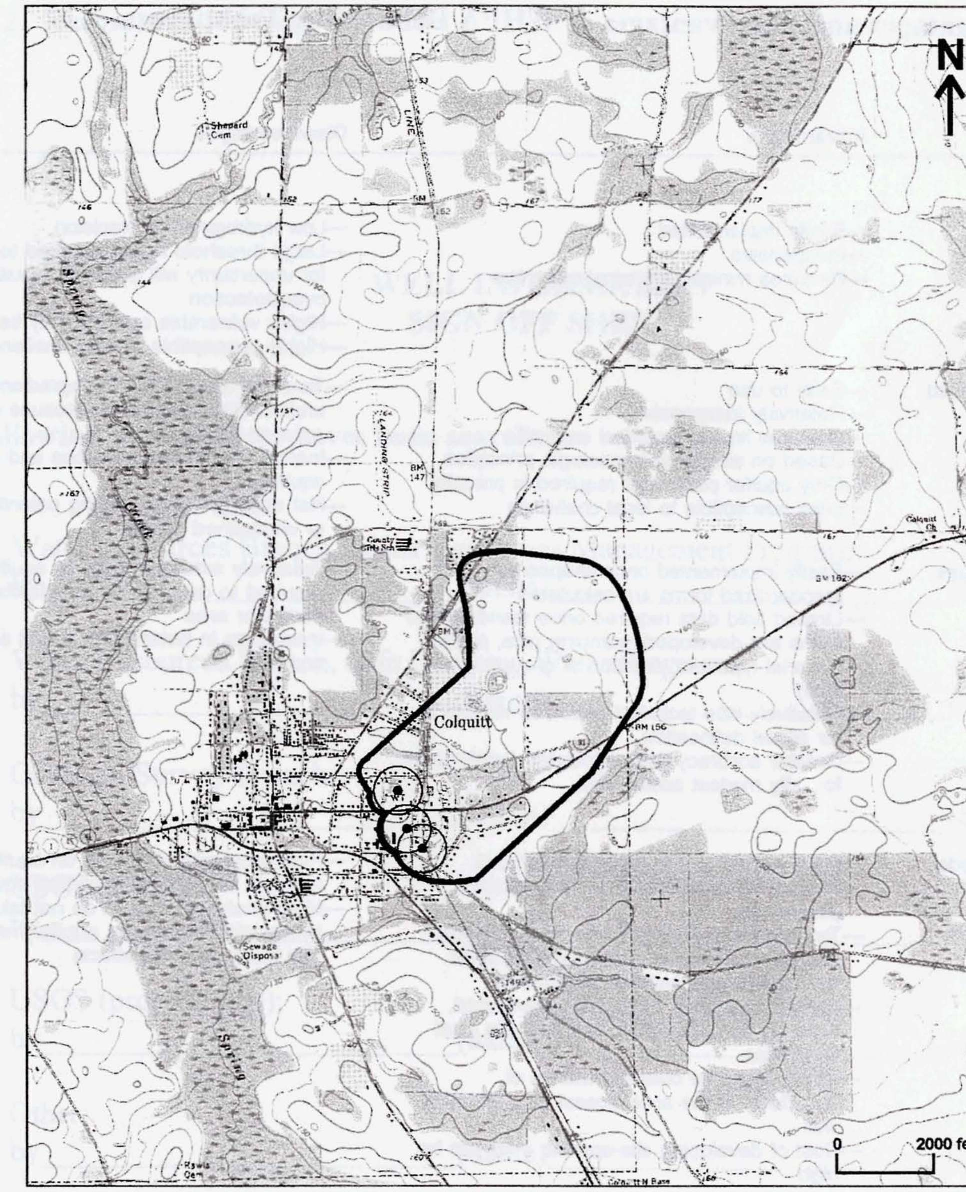


Figure 12. Wellhead Protection Areas for the Three City of Colquitt Wells. Note that 500 foot IMZ extends 182 feet further down gradient than Y_{down}.

Table 1. Advantages and Disadvantages of WHPA Delineation Techniques.

Methods/Criteria	Advantages	Disadvantages
Geometric Methods		
Arbitrary Fixed Radius (distance)	—Easily implemented —Inexpensive —Requires minimal technical expertise	—Low hydrogeologic precision —Large threshold radius required to compensate for uncertainty will generally result in overprotection —Highly vulnerable aquifers may be underprotected —Highly susceptible to legal challenge
Cylinder Method (calculated fixed radius)	—Easy to use —Relatively inexpensive —Requires limited technical expertise —Based on simple hydrogeologic principles —Only aquifer parameter required is porosity —Less susceptible to legal challenge	—Tends to overprotect downgradient and underprotect upgradient because does not account for ZOC —Inaccurate in heterogeneous and anisotropic aquifers —Not appropriate for sloping potentiometric surface or unconfined aquifer
Simplified Variable Shapes (TOT, flow boundaries)	—Easily implemented once shapes of standardized forms are calculated —Limited field data required once standardized forms are developed (pumping rate, aquifer material type and direction of ground water flow) —Relatively little technical expertise required for actual delineation —Greater accuracy than calculated fixed radius for only modest added cost	—Relatively extensive data on aquifer parameters required to develop the standardized forms for a particular area —Inaccurate in heterogenous and anisotropic aquifers
Other Methods		
Simple Analytical Methods (TOT, drawdown, flow boundaries)	—More accurate than simplified variable shapes because based on site-specific parameters —Technical expertise required, but equations are generally easily understood by most hydrogeologists and civil engineers —Various equations have been developed, allowing selection of solution that fits local conditions —Allows accurate characterization of drawdown in the area closest to a pumping well —Cost of developing site-specific data can be high	—Relatively extensive data on aquifer parameters required for input to analytical equations —Most analytical models do not take into account hydrologic boundaries, aquifer heterogeneities, and local recharge effects
Hydrogeologic Mapping (flow boundaries)	—Well suited for unconfined aquifers in unconsolidated formations and to highly anisotropic aquifers such as fracture bedrock and conduit-flow karst —Necessary to define aquifer boundary conditions	—Less suitable for deep, confined aquifers —Requires special expertise in geomorphic and geologic mapping and judgement in hydrogeologic interpretations —Moderate to high manpower and data collection costs
Computer Semi-Analytical and Numerical Flow/Transport Models (TOT, drawdown, flow boundaries)	—Most accurate of all methods and can be used for most complex hydrogeologic settings, except where karst conduit flow dominates —Allows assessment of natural and human-related affects on the ground water system for evaluating management options	—High degree of hydrogeologic and modeling expertise required —Less suitable than analytical methods for assessing drawdowns close to pumping wells —Extensive aquifer-specific data required —Most expensive methods in terms of manpower and data collection/analysis costs

Table 2. Recommended Sign Off Sheet

WELL INFORMATION
SIGN OFF SHEET

The following data sources haves been searched:

(1) Water Resources Branch, Water Resources Management Program:
by________________(name)________________________(date).

(2) Water Resources Branch, Safe Drinking Water Program:
by________________(name)________________________(date).

(3) Geologic Survey Branch:
by________________(name)________________________(date).

(4) USGS (GWSI):
by________________(name)________________________(date).

(5) USGS (project files):
by________________(name)________________________(date).

(6) Other:
by________________(name)________________________(date).

All of the above data sources have been searched for information on the municipal well needing a WHPA delineation and other nearby municipal, industrial, and agricultural wells that may provide relevant information.

Approved:____________________(supervisor's name)______________(date).

APPENDIX A

USING THE UNIFORM FLOW EQUATION AND THE 5-YEAR TRAVEL TIME TO CALCULATE THE OMZ IN KARSTIC AREAS OF SOUTHWEST GEORGIA CHARACTERIZED BY POORLY DEVELOPED DRAINAGE

In portions of the Dougherty Plain of southwest Georgia, surface drainage is poorly developed. Runoff flows to sinkholes, swallowholes, and closed depressions, from which infiltration, through the residuum into the Upper Floridan aquifer, occurs. In such areas, watersheds are not well defined; therefore, delineation of an OMZ by defining the watershed boundary is inappropriate. In such areas, a two step methodology to define the OMZ is recommended; as follows:

A. Use the Uniform Flow Equation to delineate the well's zone of influence or the boundary of the area contributing ground water to the well.

B. Expand the boundary in the upgradient direction to take into account the amount of ground water that will flow into the zone of influence over the next five years.

According to EPA (1994), the Uniform Flow Equation has been widely used for the delineation of wellhead protection areas where a sloping water table results in an asymmetrical cone of depression. The general equation is:

$$-y/x = \tan[(2\prod Kbi/Q)y]$$

The net result will be an elongated area with the x axis generally perpendicular to the potentiometric contours and parallel to the flow lines and the y axis parallel to the potentiometric contours and perpendicular to the flow lines. As previously discussed on pages 20-22, the Uniform Flow Equation was developed for confined aquifers but can be used for unconfined aquifers provided that drawdown is small (less than 10 percent in relation to saturated thickness (EPA, 1994)).

Before initiating the first step, the x and y axes need to be defined. On a 1:24,000 topographic map, upon which the potentiometric contours have been superimposed, two lines are drawn. The x axis line passes through the well, perpendicularly intersecting the potentiometric contours (i.e., it is a streamline). The y axis line passes through the well, perpendicularly intersecting the x axis line (i.e., it is an equipotential line). Because potentiometric contours are rarely straight, both the x and y axis lines probably will be slightly curvilinear.

The first step is to calculate x, in both the upgradient and downgradient directions, and y, which is lateral flow, using the following equations (from EPA, 1994; see Table 4-4, Ground-Water Divide Calculations, on pg. 77 and Section 4.5.1 on pgs. 79-80):

X_{up} = Q/Kbi or = Q/Ti;

X_{down} = -Q/2πKbi or = -Q/2πTi; and

$Y_{lateral}$ = ±Q/2Kbi or = ±Q/2Ti,

where Q is the permitted pumping rate, K is the hydraulic conductivity, b is the saturated thickness of the aquifer, and i is the hydraulic gradient. T or transmissivity may be substituted for Kb (i.e., T = Kb). X_{down} defines the downgradient flow boundary (null point); X_{up} defines the upgradient divide; and $Y_{lateral}$ defines the maximum width of the sidegradient zone of contribution. Application of the Uniform Flow Equation is illustrated in Figure A-1.

As can be seen in Figure A-1, $\pm Y_{lateral}$ reaches a maximum distance at the upgradient boundary of the zone of influence (i.e., at X_{up}). To construct the ground water divide (see part (b) of Figure A-1) is difficult because only two points on this curve (i.e., the null point on the X axes (X_{down}) and the X_{up}, $Y_{lateral}$ point) are defined and more than two points are required geometrically to define a curved line. Therefore for the recommended methodology to be used by EPD, we assume that $\pm Y_{lateral}$ reaches a maximum distance at the well's water level (e.g., a line drawn from $+Y_{lateral}$ to $-Y_{lateral}$ that passes through the well). This difference produces a slightly larger OMZ. This concept is illustrated in the dashed line shown on part (b) of Figure A-1.

The second step involves extending the OMZ upgradient beyond the zone of influence to include ground-water flow into the zone of influence over the next five years. This is done by adding the 5-year travel time distance to X_{Up}. The equation for the 5-year travel time is d = tKi/n, where t is 1825 days, K is the hydraulic conductivity, i is the gradient, and n is the effective porosity. For the Upper Floridan aquifer of the Dougherty

Plain area of southwestern Georgia, n typically is about 0.2 (from Hayes, et al, 1983). With the above in mind, $OMZ_{upgradient}$ = Q/Kbi + tKi/n.

Some southwest Georgia municipalities use multiple wells, rotating pumpage between them. Where this is the case and the wells are within ½ mile of each other, we recommend that Q be the total permitted pumpage and that the OMZ be constructed to include each well's individual OMZ, assuming each well produces the total Q. In other words, the OMZ will represent the well field rather than an individual well. This will result in a larger and a more conservative OMZ.

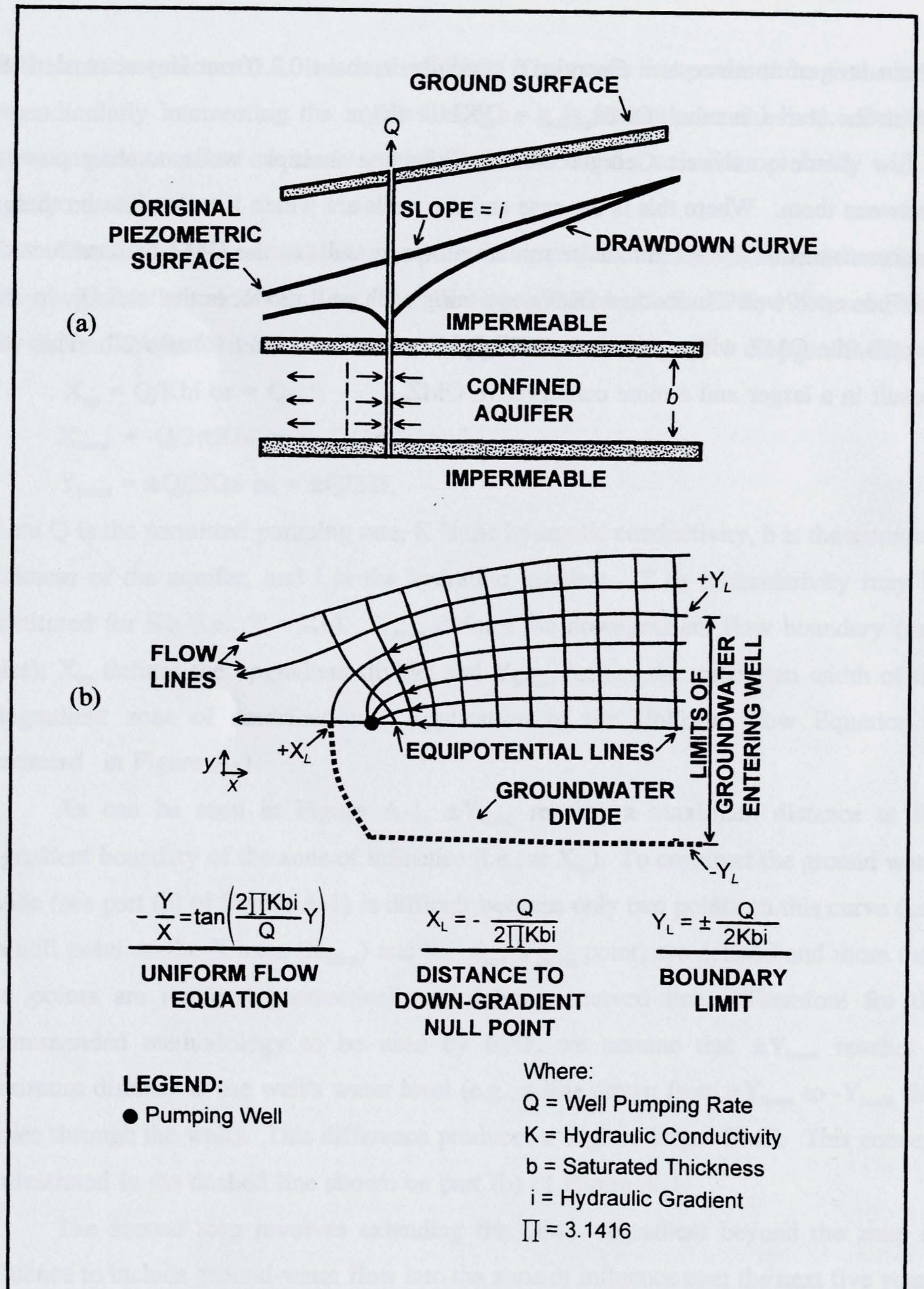


Figure A-1. Flow to a Well Penetrating a Confined Aquifer Having a Sloping Potentiometric Surface: (a) Vertical Section; (b) Plan View (from EPA, 1994). The Uniform Flow Equation takes into account the changes in cone of depression around a pumping well in an area characterized by a gently sloping potentiometric surface.

APPENDIX B

METHODOLOGY FOR PERFORMING PARTICLE TRACKING ANALYSIS

Particle tracking analysis, described herewith, is a map-based, semi-analytical technique to be used to "double-check" the watershed boundary delineations (i.e., delineation of the OMZ) and to better define the ZHV. The methodology should not be confused with numerical particle tracking, such as can be produced using MODPATH. The methodology attempts to follow the path of an imaginary molecule or ion that firstly is released at the land surface, secondly vertically infiltrates into the ground to the water table, thirdly goes into solution, and fourthly begins to travel, along with ground water, down the potentiometric surface. Sorption, dilution, dispersion, and travel time are ignored; also ignored are the chemical characteristics of the particle (i.e., DNAPL, radioactive material, salt, etc.). The methodology, however, does assume that ground-water flow is under unconfined conditions, the continuum approach described on page 6 is applicable, and that stream-aquifer interconnections are efficient.

Referring to Figure B-1, the methodology is as follows:

A. The first step is to delineate the watershed boundary on a 1:24,000 topographic map. Along this boundary, a series of imaginary release points are more or less evenly distributed at a distance of about 1000 feet (i.e., ± ½ inch on the map).

B. Within the watershed, a second series of imaginary release points are more or less evenly distributed at the above interval along secondary ridges and isolated hills.

C. From each of the imaginary release points, a short arrow, about ¼ inch in length, is drawn perpendicular to the topographic contours. Immediately downslope from the first arrow, a second arrow is drawn perpendicular to the topographic contours. This is repeated until the arrows, which now form a pathline, reach an intermittent or perennial stream.

D. Upon reaching an intermittent or perennial stream, the arrows change direction and the pathline now parallels the stream continuing downstream (also downslope and down the potentiometric surface) to a sinkhole, swallowhole, the well, or the main stem stream.

E. Assuming that the pumpage from the well illustrated in Figure B-1 is 1000 gpm, draw a 2000′ circle and then repeat steps 3 and 4 above. In other words, there will be a series of release points along the circle.

Particle tracks that move into a different watershed indicate that the watershed boundary is incorrectly drawn. If this is the case, the boundary should be re-examined to determine the reason for this.

Wherever a pathline of particle tracks appears to "dead-end" into a sinkhole, swallowhole, and so forth, the "dead-end" probably represents an area of concentrated recharge to the aquifer. Such an area would be especially vulnerable for pollutants (perhaps moving in the stream) to enter the aquifer. Any such area should be included in the ZHV except where other particle track pathlines occur downslope from the sinkhole, swallowhole, and so forth (this concept is illustrated in Figure B-1).

Particle tracking analysis, as described above, is not meant to be used as part of pollution studies; it's utility is better defining a WHPA in karstic terrain in northwest and southwest Georgia. We envisage that the analysis will require only a few hours to perform for a typical Georgia WHPA delineation.

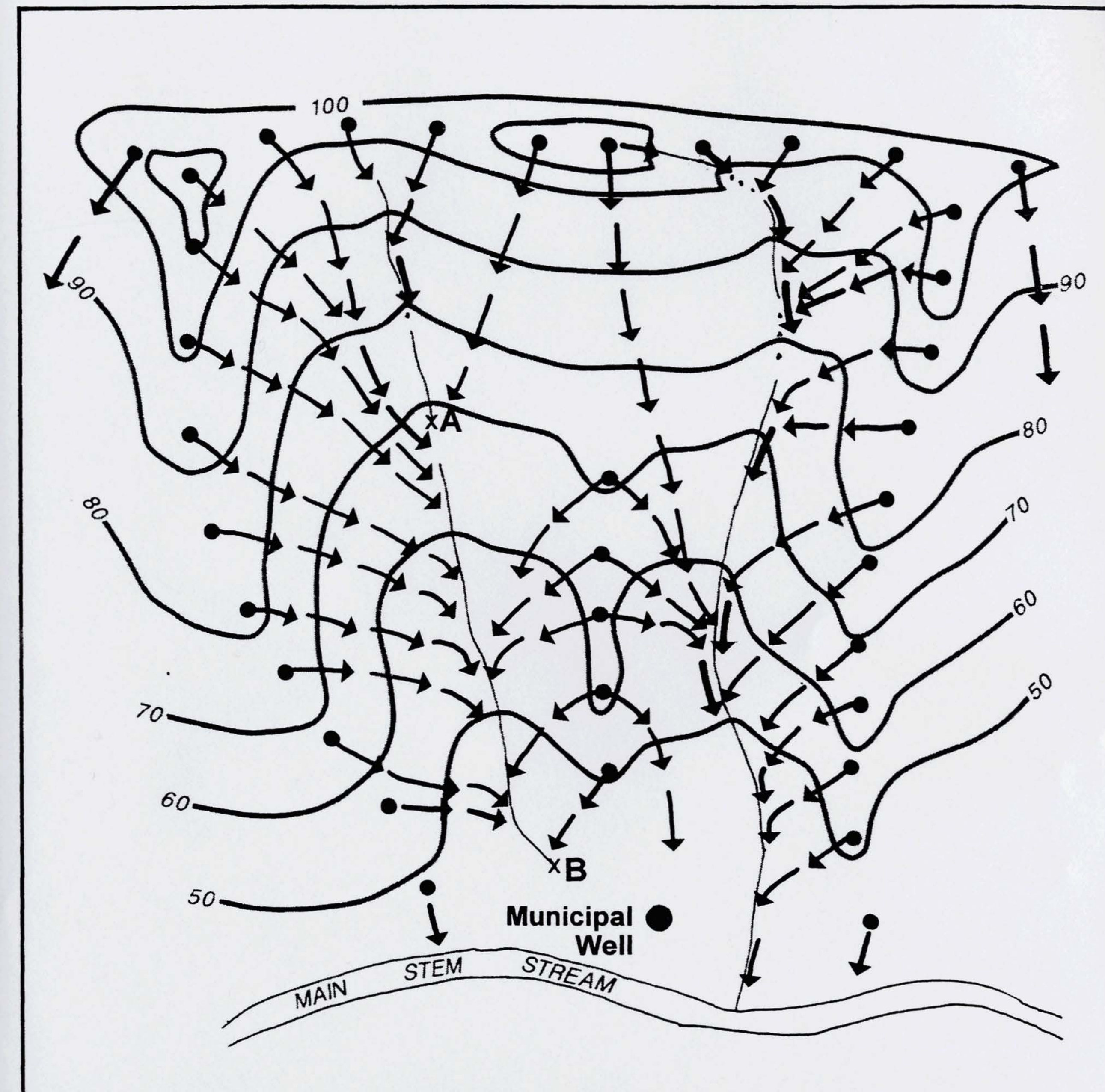


Figure B-1. Particle Tracking Analysis. The figure illustrates the concept of particle tracking analysis to create pathlines for imaginary release points to a municipal well. The scale of the illustration is 1:24,000; the contour interval is 10 feet; topographic contour lines are thicker than the lines delineating streams; "x" indicates where a stream recharges the aquifer via a sinkhole. In this illustration, sinkhole B would be within the ZHV whereas sinkhole A would not be within the ZHV.

Cost: $2479
Quantity: 250