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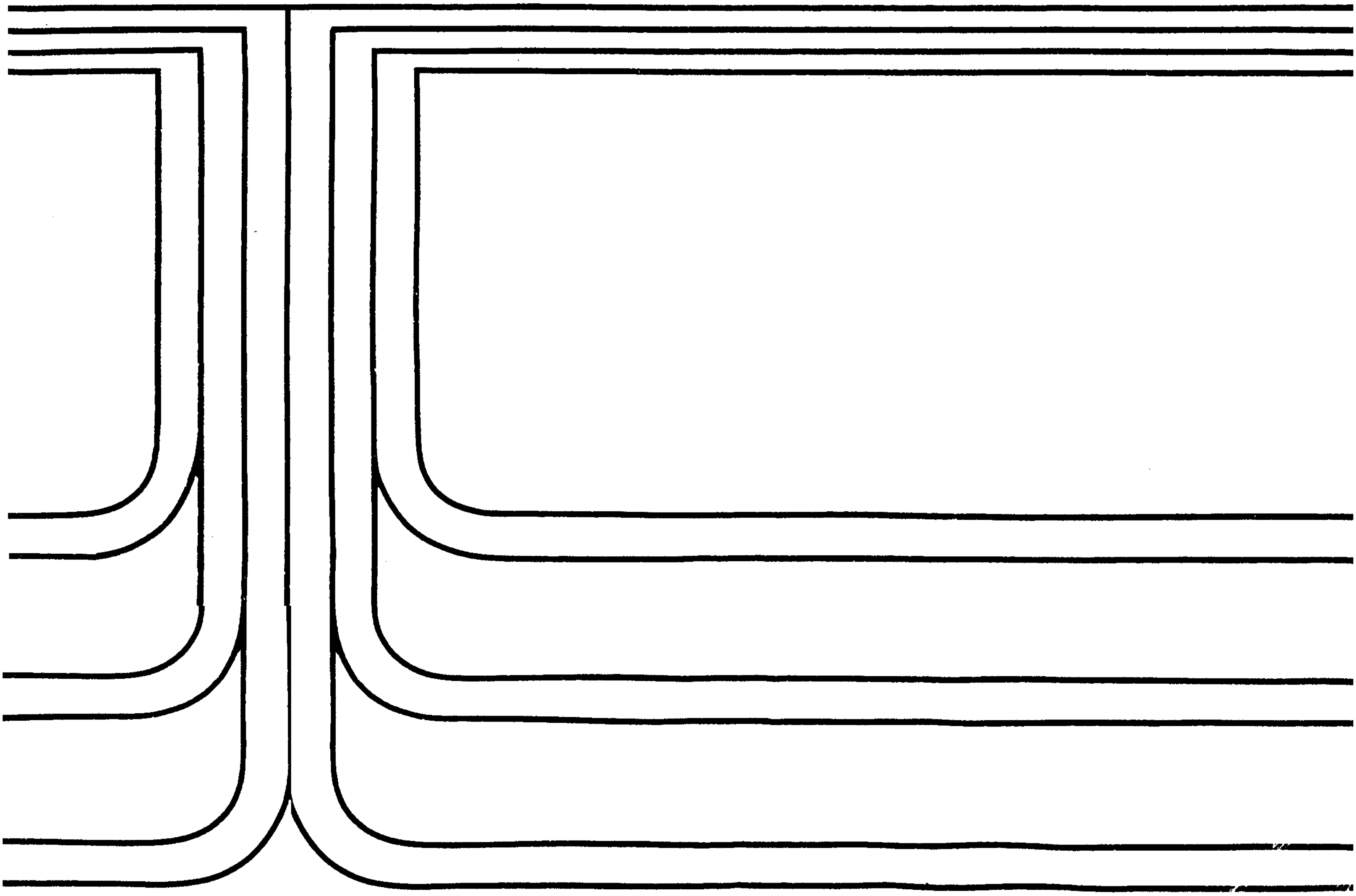
Applicability of Wellhead Protection Area Delineation To Domestic Wells

A Case Study



APPLICABILITY OF WELLHEAD PROTECTION AREA DELINEATION TO DOMESTIC WELLS: A CASE STUDY

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Contents

List of Tables and Figures

APPLICABILITY OF WELLHEAD PROTECTION AREA DELINEATION TO DOMESTIC WELLS: A CASE STUDY

Introduction

The 1986 Amendments to the Safe Drinking Water Act (Act) established the Wellhead Protection (WHP) Program to protect ground water that supplies drinking water to public water-supply (PWS) wells and wellfields. Wellhead protection for a community supplied by numerous private wells requires a different approach than that for wellhead protection of PWS wells. The higher density of private wells within a community may cause wellhead protection areas to overlap where hydrogeology is not sufficiently known and long ground-water travel times are needed to meet protection goals.

Protection of Private Wells

Before developing a private-wellhead protection plan, a community should consider its protection goals and determine if a wellhead protection program will help meet them. Several communities have already expressed interest in developing a program. Tillery, NC is one such community. The Wellhead Protection Area (WHPA) delineation approach developed for that community and lessons learned from that activity are described below.

Case Study: Tillery Area, North Carolina

Background

The greater Tillery, North Carolina, study area is an approximately 130 square mile area in north-central Halifax County (Figure 1, insert). The area is rural; the population is approximately 3,000.

Over 95 percent of the community's water supplies are obtained from about 1,700 small-capacity domestic wells, one PWS school well and seven wells supplying stock and irrigation water. Community residents, having become increasingly concerned about possible contamination of drinking-water wells, decided to develop and implement a community-based, private-wellhead protection program. The Environmental Protection Agency (EPA), interested in assessing the advisability of such a protection program, offered technical assistance in the delineation portion of the program. All management decisions would be made by the community.

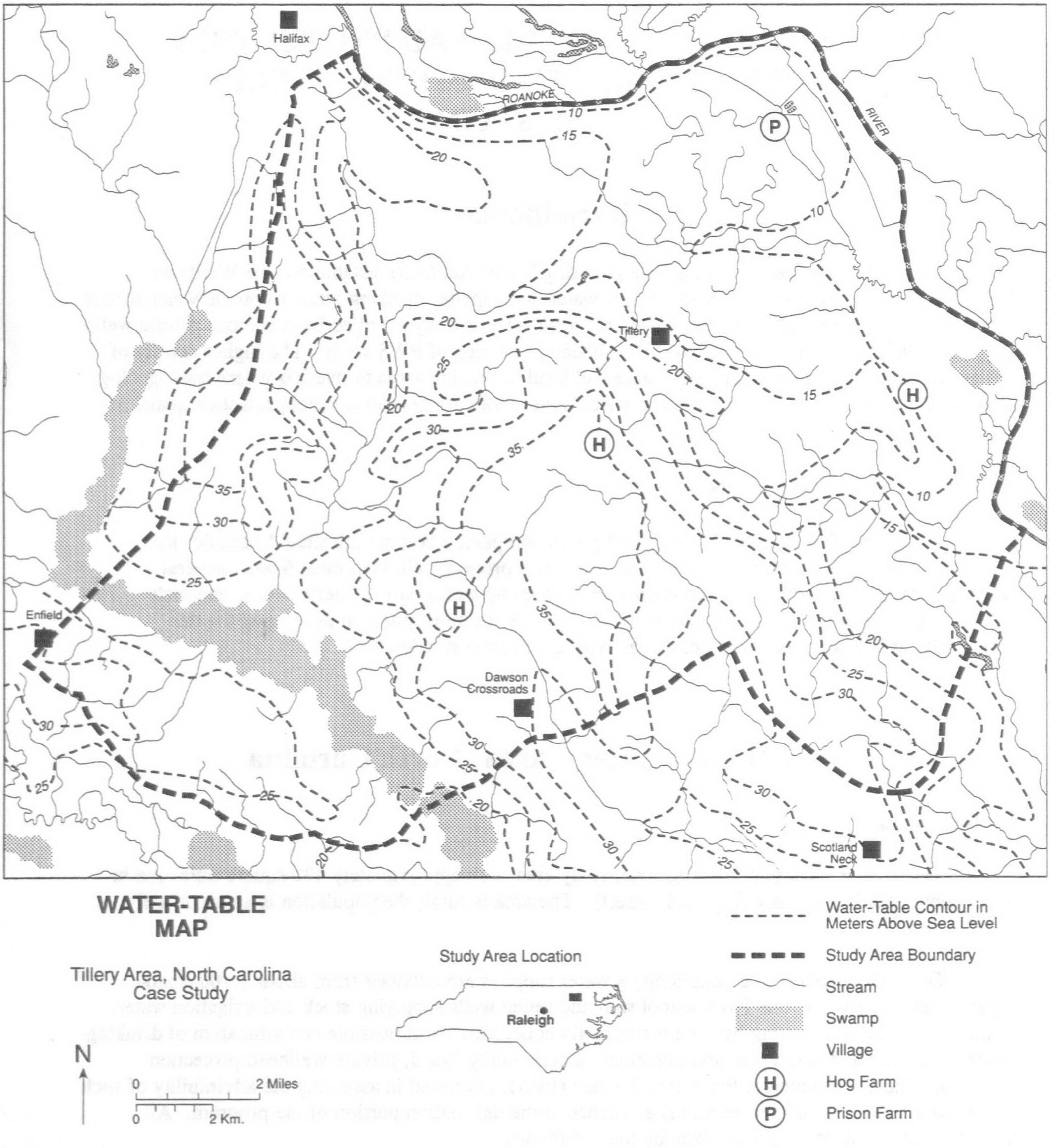

Figure 1. **Map Showing Water-table Elevation, Tillery Area, North Carolina**

Hydrogeology

Only one useful well log is available for the study area. However, based on information for the surrounding area, the following generalized sequence of hydrogeologic units (Winner and Coble, 1989, and Giese et al., 1991) is described (Table 1).

Wellhead Protection Program Development

All known domestic wells are of very-low yield and withdraw from the surficial aquifer. Older formations provide small to moderate supplies to the PWS well and to agricultural wells in the study area.

Developing the delineation component of a community-based, private-wellhead protection program requires a somewhat different approach than that for a State-level program focusing on protection of PWS wells. The differences between these types of programs are related to the feasibility of accurately describing the hydrogeology at each well site, and to the level of ability of the implementors (typically community residents) to transfer calculated WHPA boundaries to each well.

Community needs and availability of funds for technical expertise are critical issues to consider during development of the WHPA-delineation approach. The Tillery-area community is an economically disadvantaged one lacking funds for technical assistance or collection of additional data. Tillery residents also lack the technical training to measure water levels or accurately locate wells on topographic maps.

The community's WHP goal is to protect wells until public water supplies can be purchased from outside the County in approximately 15-20 years. The focus of the protection is to help residents manage their property to control potential sources of contamination to their drinking-water wells.

Because community members will be implementing the program, the issue arose regarding the number of hydrogeologically discrete subareas into which the study area should be divided. (More subareas allow greater accuracy in WHPA calculation, but make transfer of calculated boundaries to individual wells more prone to error by the implementor.)

Delineation Approach

Method Selection

After consideration of data availability, costs and desired level of accuracy, EPA chose to use the WHPA 2.2 GPTRAC computer model to calculate WHPA boundaries. The code is a steady-state, two-dimensional, user-friendly, semi-analytical flow model developed for EPA that calculates, contours and displays ground-water time-of-travel isochrons around a pumping well (Blanford and Huyakorn, 1993).

Table 1. Hydrogeologic Units in the Study Area.

Unit	Description	Comments
Surficial aquifer ("water-table" aquifer)	beds of sand, silty sand, and clay, possibly with isolated sand and gravels[1];	yields small supplies; source for all known domestic wells in the study area
Yorktown confining unit (may include some post-Yorktown clays)[2]	clay and sandy clay with some local beds of fine sand or shell[3]	
Yorktown Aquifer	"composed largely of fine sand, silty and clayey sand, and clay and is characterized by shells and shell beds throughout"[4]	may yield small to moderate supplies; no known wells are supplied by this unit in the study area
Upper Cape Fear confining unit	"nearly continuous clay, silty clay and sandy clay beds"[5]	
Upper Cape Fear Aquifer	layers of sand, some silty or clayey, alternating with clay layers	may yield moderate to large supplies; supplies two known wells in the study area
Lower Cape Fear confining unit	"clay and sandy clay beds"[6]	
Lower Cape Fear Aquifer	layers of sand, some silty or clayey, alternating with clay layers	may yield moderate to large supplies; supplies six known wells in the study area
Crystalline bedrock	varies among metavolcanics schists, gneisses, granites	no known wells developed in these rock types in the study area

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[1] after Winner and Coble, 1989.

[2] Giese et al., 1991.

[3] Winner and Coble, 1989.

[4] Ibid.

[5] Ibid.

[6] Ibid.

Parameter Values

The WHPA 2.2 model requires values for several parameters: recharge to the aquifer, transmissivity of the aquifer (and confining layer, if any), porosity, hydraulic gradient, aquifer (and confining layer, if any) thickness, and well-discharge rate. If these variables are not sufficiently constant across an area, division into subareas is required.

Parameter values for this study were obtained from the literature; no additional data were collected. Because water-level data from wells were lacking, surface-water features on topographic maps (U. S. Geological Survey, 1985, 1974a, 1974b, 1962, 1961 and 1960) were used to develop a water-table map (Figure 1) from which hydraulic gradients could be obtained. Porosity of all aquifers was estimated to be 0.2 (20 percent). U. S. Geological Survey reports (Giese et al., 1991; Winner and Coble, 1989) supporting the Coastal Plain Aquifer-System Analysis provided the information from which all other aquifer-parameter values were obtained or estimated for use in the WHPA 2.2 model.

The absence of reliable, site-specific geologic information for the study area, made moot the issue of subdividing the area based on hydrogeologic variability. However, the surficial aquifer was divided into six subareas based on hydraulic gradient (Figure 2).

Criterion and Thresholds

EPA selected the ground-water time of travel (TOT) criterion and the 2-, 5-, 10- and 20-year thresholds. The community would choose the level-of-protection threshold that best met community needs.

Water Discharge Rate

EPA assumed that all wells pump continuously year round at a constant rate, rather than periodically. The rate assumed for each well was that rate that would provide the total yearly well discharge estimated for the well. This approach was necessitated by the steady-state nature of the WHPA 2.2 model, the lack of availability of pumping schedules and the large number of wells in the study area. Where more than one well withdrawing from the same formation serves the same facility, the total demand at the facility was considered to be met by one well only. Total daily discharges were determined as described below.

Domestic Wells

The community was unable to provide an estimate of daily well yield. The number of residents per home ranges from one to eight, more homes having four residents than any other number (Grant, 1995). EPA considered four to be a high estimate; however, because a high estimate yields conservative (that is, protective) WHPAs, four residents per well was assumed for WHPA calculations. National water-use statistics show that average, domestic, per capita use in the southeastern U.S. is 100 gallons per day (gpd) (Solley et al., 1993). EPA chose 400 gpd/well as an estimate of local household demand.

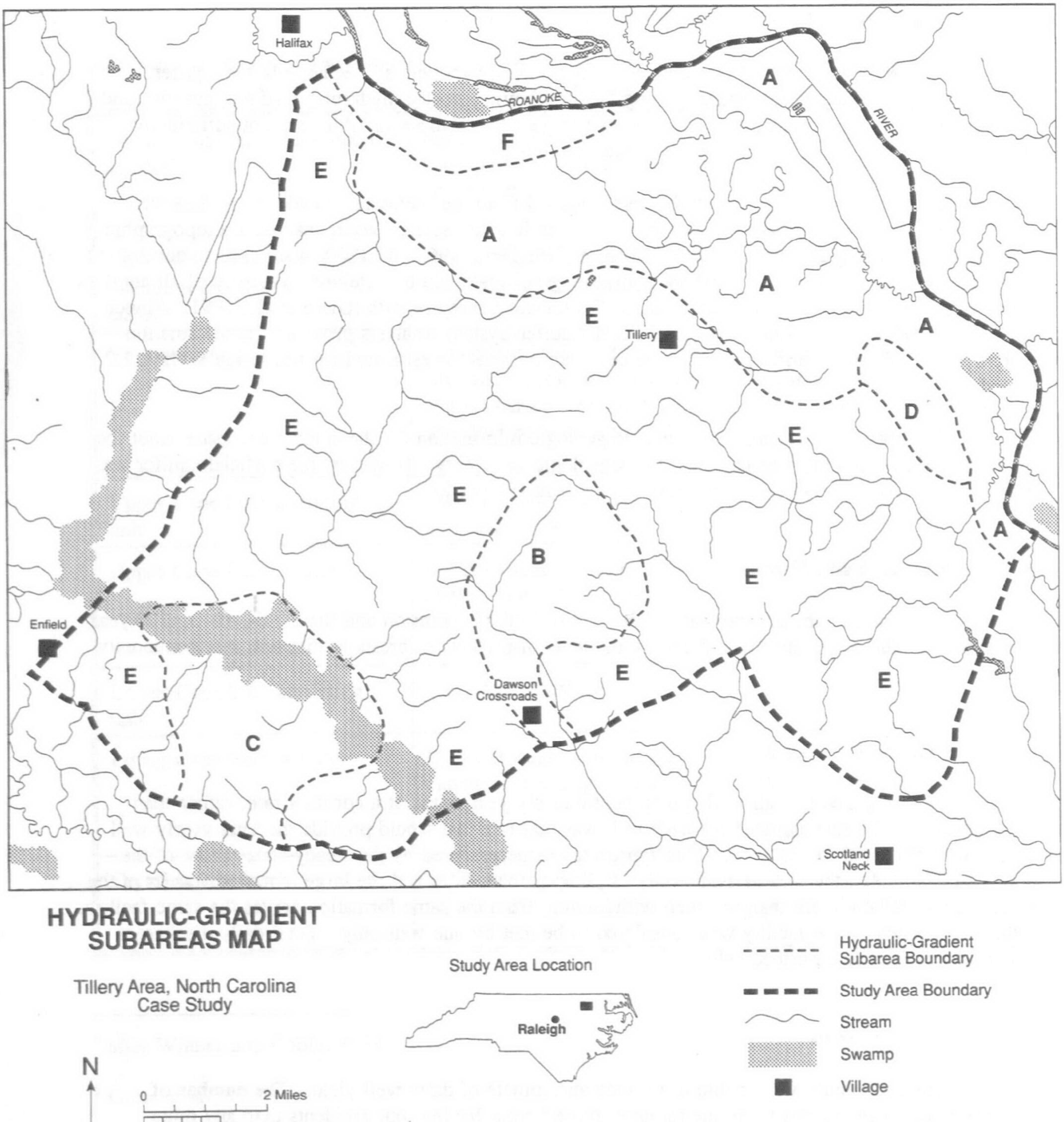

Figure 2. **Map Showing Subarea Boundaries, Tillery Area, North Carolina**

Non-domestic Wells

Two agricultural wells are located at the prison farm and are screened in the Lower Cape Fear Aquifer. EPA estimated from the purposes of the wells that the equivalent continuous discharge for the facility was 5.1 gallons per minute (gpm). The PWS well is a school well that withdraws from the Lower Cape Fear Aquifer. A school official's estimate of water use was 3,600 gpd (2.5 gpm).

Two additional wells screened in the Lower Cape Fear Aquifer supply two hog farms for agricultural and human-consumption purposes. Demand at each hog farm was estimated to be 86.8 gpm.

A third hog farm is supplied by three wells withdrawing from the Upper Cape Fear Aquifer. These wells are believed to serve agricultural and human consumption needs. The total average facility demand was estimated to be 14.6 gpm.

Model Runs

Confined Aquifers

The WHPA 2.2 model provides the user with confined-, semi-confined-, and unconfined-aquifer options. In the study area, all aquifers below the water-table aquifer are confined to some extent. To test the tightness of the confining layers, two 20-year scenarios were each run for the Upper Cape Fear Aquifer and for the Lower Cape Fear Aquifer; ground-water flow in each aquifer was modeled individually. In each scenario, the well representing the greatest facility discharge in the formation was modeled. That is, for each scenario, the discharge of the Lower Cape Fear well was 86.8 gpm; the discharge for the Upper Cape Fear well was 14.6 gpm.

In the first scenario, the vertical hydraulic conductivity estimated from Giese et al., 1991, and confining-unit thickness estimated from Winner and Coble, 1989, were input. In the second scenario, for purposes of comparison, the aquifer was modeled as totally confined.

For each formation, both scenarios produced virtually identical WHPAs. That is, for a well discharge equal to, or less than, that input to the model, 1) hydraulic interference with a well in a different aquifer will not occur, and 2) the tightness of the overlying unit allows the aquifer to be treated as completely confined.

That these aquifers may be treated as highly confined has importance in the WHP Program, because confining layers offer some degree of protection for a well. The Tillery community might choose to use a smaller-than-calculated WHPA for the seven private wells discharging from the Lower Cape Fear and the Upper Cape Fear aquifers.

Surficial Aquifer

The largest value of the water-table gradient was selected in each subarea, because this condition results in the longest (most protective) contaminant-flow distances. In each subarea, a model scenario was run to test for well interference among wells located 500 feet apart (the most closely spaced conditions in the aquifer in the study area). This scenario showed that no well interference occurred unless wells were aligned directly downgradient from each other. In that case, there was no interference parallel to the prepumping direction of ground-water flow and only slight interference perpendicular to that direction. For this reason, well interference was considered negligible and model scenarios for each subarea were run for 2, 5, 10 and 20 years (Figure 3) for one well only.

Results

Because the axis of a WHPA is oriented parallel to ground-water flow (assuming aquifer isotropy and homogeneity), errors in depicting the position or curvature of water-table contours result in misorientation of the WHPA. Such errors are particularly significant in the case of narrow WHPAs, resulting from wells with small discharge relative to the regional ground-water flow, like those WHPAs calculated for wells in the surficial aquifer in the study area. In these cases, a minor error may cause the calculated WHPA to lie outside the true area of ground-water contribution. Compounding these errors are the errors associated with failure of the aquifer to meet the assumptions of isotropy and homogeneity.

Surficial Aquifer

The unlikelihood that the calculated narrow WHPA boundaries could be precisely oriented, led EPA to provide the community with circular WHPAs for wells in the surficial aquifer. These WHPAs were constructed with radii equal in length to the long axes of the calculated WHPAs, as measured from the well to the upgradient boundary (see Table 2).

Table 2. Long-Axis Lengths of Calculated Wellhead Protection Areas for Wells in the Surficial Aquifer.

Subarea	2-year WHPA (in feet)	5-year WHPA (in feet)	10-year WHPA (in feet)	20-year WHPA (in feet)
A	200	450	950	1,800
B	200	500	1,000	1,950
C	350	800	1,700	3,300
D	450	1,000	2,000	3,950
E	550	1,400	2,750	5,600
F	1,050	2,600	5,250	10,500

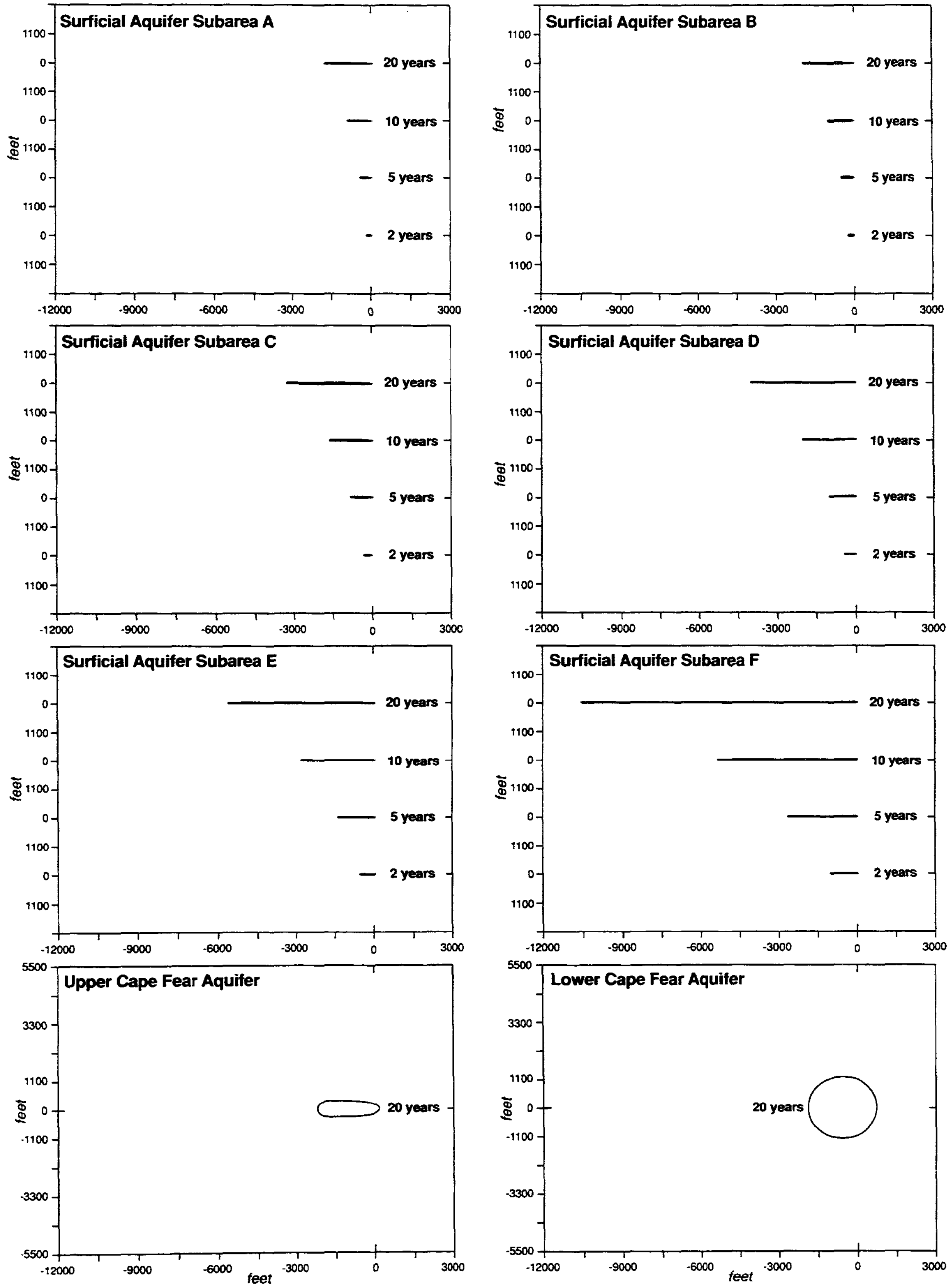

Figure 3. Calculated Wellhead Protection Areas

EPA considered the error associated with overly large WHPAs to be far less of a problem than the likely error that misoriented WHPAs would lie outside the true area of ground-water contribution to the well. That is, EPA considered the error of over protection to be less of a problem than the failure to protect.

EPA suggested to the community that where WHPAs overlapped, for the sake of simplicity, the protection area should be drawn along the common boundary. That is, well interference should be considered negligible. Where a WHPA included part of more than one subarea, the community would decide whether or not to modify the WHPA in some way to reflect the effect of the adjacent subarea(s) on WHPA size.

Twenty-year circular boundaries were not provided to the community, because 20-year WHPAs would provide protection similar to the 10-year boundaries; that is, 10- and 20- year boundaries would encompass virtually the entire study area. Each set of 2-, 5-, and 10-year boundaries was coded by letter to the appropriate subarea and was provided on transparent film at the 1:24,000 scale.

Confined Aquifers

The potentiometric surfaces (Giese et al., 1991) of the confined aquifers are smoother than the water table in the surficial aquifer, because the potentiometric surfaces are not surface-water controlled. As a result, WHPAs are somewhat easier to orient. EPA provided the Tillery community with calculated 20-year WHPAs for the maximum confined-aquifer discharges noted above and considered those boundaries to be quite protective. As stated above, the community may wish to designate smaller WHPAs.

North Carolina's Wellhead Protection Program suggests a setback of approximately 300 feet for a PWS well pumping 2.5 gpm. Although non-community transient wells are not included in the State Program, EPA suggested that the community consider using the 300 foot setback for the Dawson Crossroad school well. (The community might also want to consider using the 1000-foot setback necessary to enter the North Carolina Monitoring Waiver Program.)

Conclusions

The Safe Drinking Water Act, through the WHP Program provides a mechanism for differential protection of ground water that supplies PWS wells and wellfields. These wells and wellfields are, in most cases, sufficiently separated that their WHPAs are distinct and differentially protectable. However, application of the WHP Program to areas supplied by numerous individual wells is problematic, because the goal of isolating clearly defined areas for priority protection may not be achievable.

The Tillery community hopes to define WHPAs with large enough TOTs to allow natural remediation of contaminants until an alternative water supply becomes available in 15-20 years. Residents hope to preferentially protect and manage contaminant sources within WHPAs and, where possible, site such sources external to the WHPAs. Because WHPAs are so large (virtually the entire study area is incorporated into 10- and 20- year circular WHPAs and much of subareas C, D, E and F is incorporated into 5-year circular WHPAs), larger TOTs cause individual wells to become part of one large wellfield. That is, by moving sources of contamination away from one well, they are frequently moved closer to another in a common protection area. When multiple wells constitute one large wellfield, the entire aquifer within the wellfield's WHPA must be managed. Thus, for large areas with many wells, WHP becomes synonymous with aquifer protection.

The community has three management options. The first two options require that the community be able to approximately locate their wells on topographic maps and determine the very general direction of ground-water flow. Two types of uncertainty are present in these first two options, the uncertainty associated with well location and the hydrogeologic uncertainty that causes imprecision in WHPA calculation and in the magnitude and direction of the water-table gradient.

The first option is that residents identify the general direction of ground-water flow where they live and, wherever possible, site contaminant sources downgradient from their wells. Sources can be located fairly close (about 25 feet) to a well; as can be seen from Figure 3, the WHPA boundary in the downgradient direction is near the well. Although these sources will be upgradient from other wells, TOT to neighboring wells can be maximized in this fashion. The ground-water TOT between a well and its downgradient neighbor can be estimated by comparing the distance between the wells to the lengths of WHPA radii.

The second option is that quarter-circle WHPAs be used. These WHPAs would provide a "buffer" on the sides of the narrow, calculated WHPAs. If the community uses quarter-circle WHPAs with radii equal to those of circular WHPAs, much of the study area would still be incorporated into the 10-year WHPAs, but 5-year WHPAs would be differentially protectable in most of the study area (that is, in subareas A, C, D and much of E, and in B except near Dawson Crossroads where well density is high). However, with this option, some areas of actual ground-water contribution to wells likely would fail to be protected. Most of these failures would occur in areas where the direction of the hydraulic gradient radically changes, and also near the top of hills where zones of contribution are, because the hydraulic gradient is 0, circular.

The third option is that the community selects the 2-year TOT (differentially protectable WHPAs in all subareas except F) and vigorously manages those WHPAs. Because 2 years is so short a period, management of WHPAs should be coupled with contaminant-reduction measures across the entire study area. Although this approach includes WHP techniques (e. g., defining TOT and direction of travel in order to delineate the WHPA), the approach has a large component of aquifer protection. (Regardless of the option chosen, a high-priority activity should be to reduce the likelihood of drinking-water contamination resulting from the poor well construction prevalent in the area. Although replacement of wells is not economically realistic, less costly improvements should be considered, such as placing concrete pads, and/or berming the soil, around wells.)

The larger the TOT selected, the more individual well owners will need to rely on each other in order to manage contaminant sources that have the potential to affect their own and each others' wells. Cooperative source management by neighbors may also be needed where smaller WHPAs intersect property boundaries. In this, as in any other aquifer-protection activity, cooperation among neighbors is a key to protection.

Recommendations

A WHP Program will not provide distinct management areas for numerous low-capacity wells where the hydrogeology is not sufficiently known and long travel times are needed to meet protection goals. Before embarking on a costly WHP effort, a community should consider its management goal, hydrogeologic setting and population distribution.

The location of private wells close together causes their WHPAs to overlap, necessitating protection of large community areas as opposed to discrete areas where differential management can be applied. Drinking-water protection may not be achievable by relocation of contaminant sources, but rather by contaminant reduction or vigorous contaminant-source management.

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