COMPUTER METHODS FOR EVALUATING WELLHEAD PROTECTION AREAS

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Introduction

Throughout Mississippi there are approximately 440 shallow (less than 350 feet deep) public water-supply wells that may be vulnerable to surface contamination, depending on the geohydrologic conditions in the vicinity of the wells. Vulnerability to contaminants originating at or near land surface is generally greatest for shallow wells completed in unconfined aquifers. Deeper wells completed in confined aquifers generally are less vulnerable to surface contamination, but these wells also can be susceptible to contamination, depending on a variety of factors. These factors include the relative difference in head between the aquifer in which the well is completed and adjacent aquifers, the geohydrologic properties of the confining unit, and natural or human-induced breaks in confinement such as faults, abandoned wells and boreholes, and corroded well casings.

The 440 shallow, public water-supply wells are located in a variety of geologic settings ranging from interbedded lenticular, irregular sand and clay beds of Miocene age in the southern part of the State to fractured or jointed limestones of Paleozoic age in the northeastern part. One way of preventing contaminated groundwater from entering wells and springs is by establishing areas of protection around them. Since the establishment of such areas of protection necessarily restricts some uses of the land so designated, it is vital that the technical basis of the designation be scientifically valid, objective, and unambiguous.

History of the Concept of Wellhead Protection Areas

The concept of defining the area from which a public water-supply well receives its water and identifying this area for special protection from surface contamination seems to have been first implemented in the more densely populated European nations. At least 11 European countries have developed ground-water protection programs comparable to the Wellhead Protection Area (WHPA) program of the United States Environmental Protection Agency (USEPA) (1987). West Germany and the Netherlands have the most extensive experience in wellhead protection. The wellhead protection strategies of these two nations involve the use of analytical methods to define zones of increasing protection. For example, in the Netherlands, a first zone of protection immediately around the well is purchased by the water authority. A second zone is defined by the 60-day time-of-travel (TOT) boundary. The protection of this zone is designed to prevent microbial contamination of the well. Additionally, a third "water protection" zone, roughly comparable to the WHPA boundaries is defined. The third "water protection" area is subdivided into areas defined by the 10-year and 25-year TOT boundaries, which are approximately 800 and 1,200 meters from the well in the Netherlands. The outermost zone, referred to as the "far recharge area," lies between the 25-year TOT boundary and the outer boundary of the area of recharge contribution to the well.

Only a few States in the United States had been active in wellhead protection prior to 1986. The 1986 amendments to the Safe Drinking Water Act (SDWA), however, authorized two new provisions for ground-water protection. These are the WHPA and the Sole Source Aquifer (SSA) demonstration program (USEPA 1987). Both are designed to support the development of State and local efforts to protect groundwater resources. The intent of the WHPA program is to establish State regulations that adequately protect the wellhead areas of all public water systems from contaminants that may adversely affect human health.

The SDWA incorporates the fundamental definition of a Wellhead Protection Area (WHPA) as: the surface and subsurface area surrounding a water well or wellfield, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or wellfield. The extent of a wellhead protection area, within a State, necessary to provide protection from contaminants which may have any adverse effect on the health of persons is to be determined by the State in the program submitted under subsection (a). Not later than 1 year after the enactment of the Safe Drinking Water Act Amendments of 1986, the Administrator shall issue technical guidance which States may use in making such determinations. Such guidance may reflect such factors as the radius of influence around a well or wellfield, the depth of drawdown of the water table by such well or wellfield at any given point, the time or rate of travel of various contaminants in various hydrologic conditions, distance from the well or well field, or other factors affecting the likelihood of contaminants reaching the well or wellfield, taking into account available engineering pump tests or comparable data, field reconnaissance, topographic information, and the geology of the formation in which the well or well field is located.

Several county governments in the State of Florida have extensive groundwater protection programs. Florida has also passed legislation establishing a statewide wellhead protection program for vulnerable aquifers. The State of Vermont is developing a statewide wellhead protection program that would require that maps of the cones of influence of public supply wells and primary and secondary recharge areas be used as the basis of the permitting activities of the state.

Massachusetts, Connecticut, and Nebraska, although not directly requiring designation of wellhead protection areas, incorporate the concept in other environmental regulations. Most other States are currently determining appropriate regulations to govern the protection of public ground-water supplies.

Methods Used

Three methods were used in the analysis of flow components near shallow public water-supply wells in Mississippi. These consisted of:

1) The calculated-fixed-radius criterion -- a calculated fixed-radius method based on a volumetric flow equation.

2) The area-of-contribution criterion -- an analytical method defining the entire theoretical area which supplies water to the well.

3) The time-of-travel criterion -- a semi-analytical method defining the area from which water would move to the well in a specified time interval. Each of these methods is described below.

The Calculated Fixed-Radius Criterion

Simplicity is the primary advantage of the calculated fixed-radius method. This method defines a circular area around the well and does not consider the regional flow system. However, unlike more arbitrary methods which specify a radius without reference to well and aquifer characteristics, the calculated fixed-radius method considers the pumping rate of the well and the porosity of the aquifer material. The calculated radius encloses a cylindrical volume of aquifer material containing the volume of water that will be pumped from the well during a specified time period. Because this method does not consider the effects of the regional flow system, the method tends to define too large an area downgradient of the well site and too small an area upgradient of the well site if a regional hydraulic gradient exists. The equation used in the calculated fixed-radius calculations is:

$$r = \sqrt{\frac{Qt}{\pi nSL}} \qquad (1)$$

where

r is radius from the well, in feet;
Q is pumpage of the well, in cubic feet per day;
t is time interval in days;
n is aquifer porosity (dimensionless);
SL is length of well screen or open interval, in feet; and
n is approximately 3.14159.

An assumption in the formulation of this equation is that all water supplied to the well comes only from that part of the aquifer opposite the well screen. This assumption generally will cause an overestimation of the required radius because, for isotropic aquifers, radial flow conditions generally will exist throughout the full thickness of the aquifer, rather than just through the screened interval, at radial distances greater than about twice the thickness of the aquifer. For anisotropic aquifers, radial flow conditions generally will exist at about twice the thickness of the aquifer multiplied by the square root of the ratio of horizontal hydraulic conductivity to vertical hydraulic conductivity (Jacob 1963). The computer program to perform the calculated fixed-radius calculation uses a straightforward application of the above formula.

The Area-of-Contribution Criterion

The area-of-contribution criterion uses a set of analytical equations to define the area from which a well derives water. The equations used for this method are the uniform flow equations as derived by Todd (1980). This analytical method incorporates, for each well, site-specific data that include the regional hydraulic gradient and the pumping rate of the well. Aquifer geometry is incorporated in the definition of the upgradient limit of the contributing area. The site-specific nature of this criterion should produce better estimates of the contributing area as compared to fixed-radius methods. The disadvantages of this method, as compared to a calculated fixed-radius method, are that the method requires more extensive hydrologic data and more computation time.

Consider the flow field surrounding a pumping well located in an area with a regional hydraulic gradient, i, as shown in figure 1. Assuming a cartesian coordinate system in units of feet centered on the well with regional flow in the negative X direction, the half-width of the flow field boundary, YL, transverse to the flow direction will, as X becomes large, asymptotically approach:

$$Y_L = \pm \frac{Q}{2Kbi} \tag{2}$$

where

K is hydraulic conductivity, in feet per day;
b is saturated thickness, in feet;
i is regional hydraulic gradient (dimensionless); and the remaining symbols are as previously defined.

The downgradient null point, X_L, where no flow occurs to the pumping well will be located where the gradient induced by the pumping well equals the regional hydraulic gradient, as represented by the equation:

$$X_L = \frac{-Q}{2\pi Kbi} \tag{3}$$

The locations of points, (X,Y), on the boundary between these two points, define the boundary of the contributing area and can be calculated from the expression:

$$\frac{Y}{X} = -\tan\left[\frac{2\pi Kbi}{Q} Y\right] \tag{4}$$

For this criterion, a computer program was written to solve the above equation at 100 equidistant increments of Y between 0 and + Y_L feet. The negative half-plane is axially symmetric with the positive half-plane.

The Time-of-Travel Criterion

This method is semi-analytical in that an analytical equation which computes travel time from a point to the well is solved iteratively for different points until a point on the desired time-of-travel boundary is found. This method incorporates the same site-specific data as the area-of-contribution method and shares the advantages of that method. A disadvantage of the time-of-travel method is that, because of the iterative nature of the method, it is considerably more computationally intensive than the fixed radius or area-of-contribution criterions. However, use of the method may be preferred when the area-of-contribution is very large. For a flow field surrounding a pumping well in an area with a regional hydraulic gradient, average travel time from a point upgradient of the well can be described as:

$$t = \left[\frac{n}{Ki}\right]\left[r + Z\ln\left(\frac{Z}{Z+r}\right)\right] \tag{5}$$

where

r is the distance of the point where time of travel will be calculated from the well, in feet;
Z is defined by $\frac{Q}{2\pi Kbi}$, in feet;

and the remaining symbols are as previously defined.

Coordinates of the upgradient point on any desired time-of-travel boundary may be obtained from the above equation by using an iterative algorithm. The upgradient point on the time-of-travel boundary is the most distant of any point on the boundary in the case where a regional gradient exists. Other points on the desired time-of-travel boundary must be determined using a particle-tracking methodology. In the particle-tracking method, the movement of an imaginary water particle is iteratively traced through small increments of time. The following equations apply:

$$X_{t+1} = X_t - VN - \frac{V_t X}{r_t} \tag{6}$$

and

$$Y_{t+1} = Y_t - \frac{V_t Y}{r_t} \tag{7}$$

where

VN is the particle velocity due to the regional gradient, $\frac{Ki}{n}$,in feet per day;

Vt is the particle velocity at time t, due to the influence of the pumping well, $\frac{Q}{2\,bnr_t}$, in feet per day;

rt is the distance to the point at time, t, in feet; defined by

$$\sqrt{X_t^2 + Y_t^2}$$

and the remaining symbols are as previously defined.

Coordinates of points on any desired time-of-travel boundary may be calculated by iteratively applying the above equations. For this criterion, a computer program was written that uses a binary search iteration strategy to find points on the 5-year time-of-travel curve along 45 rays spaced at 4-degree intervals in the positive Y half-plane. As in the area-of-contribution method, symmetry about the x-axis is invoked to specify the lower half of the curve.

Programming Details

The computer program used to calculate and display the boundaries of the areas determined using the three previously discussed criteria is written in standard Fortran 77 (Appendix A). The program uses CALCOMP® (The use of trade of product names in this report is for identification purposes only, and does not constitute endorsement by the U.S. Geological Survey) basic software style subroutine calls to provide graphic display of the calculated areas. Several libraries of graphic display routines implement call compatibility with the CALCOMP® software for other brands and types of graphic display hardware. The original development version of the program was linked with an implementation of call compatible graphics display subroutines known as DIGS, for Device Independent Graphics System, written by Arlen Harbaugh of the U.S. Geological Survey.

The program was developed on a PRIME® 9955 II computer system using Prime's F77 Fortran compiler. On this system, the program provides an interactive environment for determining wellhead-protection areas based on the described criterion. Calculation time on the Prime system for the time-of travel criteria (by far the most computationally intensive of the three methods) can take as much as about 20 seconds. The program was later ported to an IBM® PC/AT type microcomputer, using the Ryan-McFarland RM/FORTRAN® 2.4 Fortran 77 compiler. On this platform, the time-of travel calculations can take several minutes, even with a math co-processor .

Application Example

Physical and construction data about wells are stored in the U. S. Geological Survey's Ground-water Site Information (GWSI) system database. Table 1 is an example of the type of data found in GWSI. These data contain the hydrologic information needed to determine which public-supply water wells might require protection from contamination. If, for example, it was desired to define a wellhead protection area for the wellfield containing wells B059 and B060, the data listed in Table 1 and additional data on areal hydrologic conditions would be used in the analysis. Multiple wells that are close together can, for wellhead protection purposes, be treated as a single well with a discharge equal to the sum of the discharges of the individual wells. The additional hydrologic parameters not in the GWSI database needed to define a wellhead protection area are listed in Table 2. These data would be obtained from analysis of electric logs of the well or of nearby wells and from potentiometric maps of the aquifer of interest. These data are input to the computer program described previously, which produces an output summary of results (Fig. 2). Effective presentation of program results is best made in graphic form, however, as shown in Figure 3. This figure was constructed by superimposing computer-plotted curves of the boundaries of the time-of-travel and zone of contribution criteria on a U. S. Geological Survey 7-1/2 minute topographic map and by adding appropriate annotation and explanation. A significant improvement in speed and ease of use might be realized by integrating the calculations of the program described here with the graphic display capabilities of a Geographic Information System (GIS) to obtain directly a product similar to figure 3, without the need for manual overlay and preparation.

References

Jacob, C.E., 1963, Methods of determining permeability, transmissibility and drawdown: U. S. Geological Survey Water-Supply Paper 1536-I, 341 p.

U. S. Environmental Protection Agency, Office of Ground-Water Protection, 1987, Guidelines for delineation of wellhead protection areas, Washington, D.C.

Todd, D.K., 1980, Groundwater hydrology: John Wiley & Sons, 535 p.

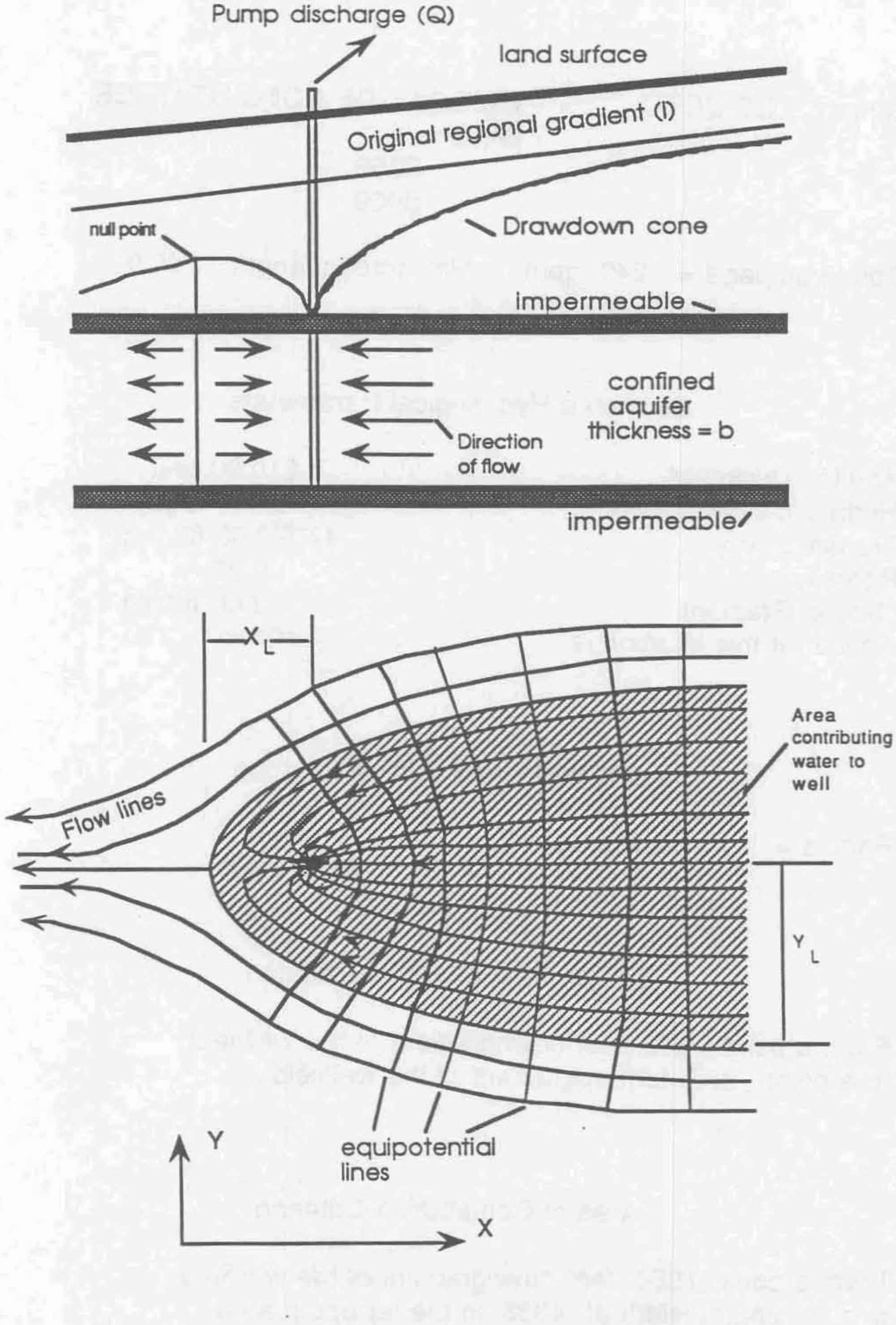

Figure 1.-- Generalized cross-section and flow net for area-of-contribution criterion.

County : DE SOTO   Wellfield : DE SOTO UTILITIES
Wells :
B059
B060

Total pumpage = 240. gpm   Max screen length : 20.0

Estimated Hydrological Parameters

Aquifer Thickness	:	210.00 feet
Hydraulic Conductivity	:	67.00 ft/day
Transmissivity	:	14070.00 ft2/day
Porosity	:	0.20
Natural Gradient	:	2.00 ft/mile
Aquifer at this location is	:	Confined

Calculated Fixed Radius Criterion

Radius = 2591. feet

5 Year Time of Travel Criterion

From a point 652. feet downgradient of the wellfield
to a point 967. feet upgradient of the wellfield.

Area of Contribution Criterion

From a point 1380. feet downgradient of the wellfield
to a maximum width of 4335. in the far updip area.

Figure 2.-- Example of wellhead protection program output.

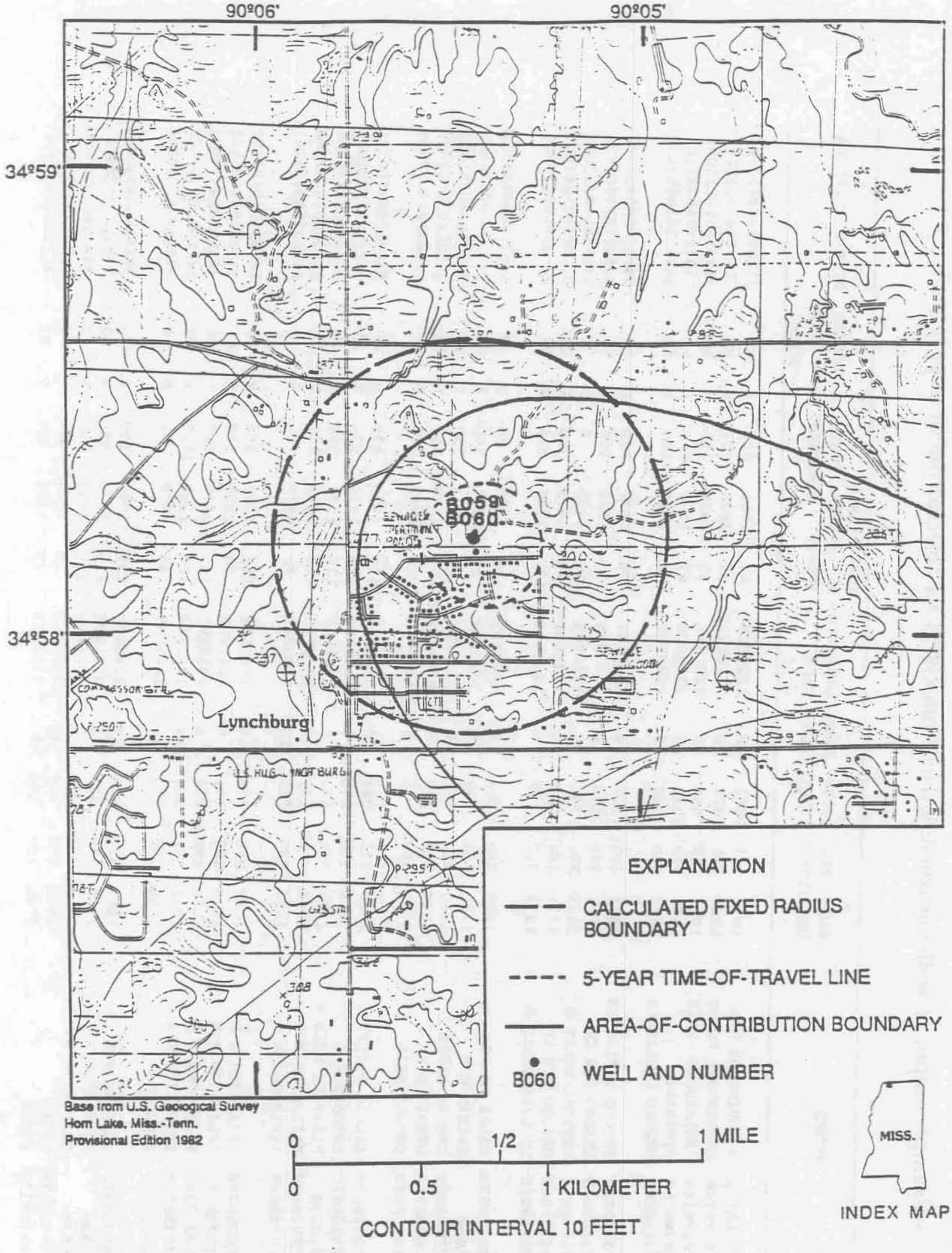

Figure 3.–Calculated fixed radius boundary, five-year time-of-travel line and area-of-contribution boundary for DeSoto County wells B059 and B060 near Lynchburg, Mississippi.

Table 1.--Example output of well-construction data from GWSI for selected public supply wells

CO NO.	WELL NO.	LOCATION	OWNER	DATE DRL	ALT (FEET)	DEPTH (FEET)	DIAM (IN)	GEOLOGIC UNIT CODE	WATER LEVEL DEPTH (FEET)	WATER LEVEL YEAR	PUMP (GAL/MIN)	USE	SCREEN LENGTH (FEET)	SITE IDENTIFIER
031	E027	SENES22T08NR17W	N COVINGTON W A	1974	445	292	12	122MOCN	87	1981	566	P	60	313852089412601
031	F004	NENWS24T08NR16W	SANDERSONS FARMS	1962	275	170	18	122CTHLU	25	1981	400	N	46	313902089335201
031	F005	NENWS24T08NR16W	SANDERSONS FARMS	1962	285	164	18	122CTHL	35	1981	711	N	40	313859089335001
031	K001	NWNES22T07NR15W	SEMINARY	1964	300	247	16	122MOCN	87	1963	351	P	67	313344089294102
033	B059	SENWS30T01SR08W	DESOTO UTILITIES	1972	300	105	6	124SPRT	46	1972	120	N	20	345811090053001
033	B060	SENWS30T01SR08W	DESOTO UTILITIES	1972	300	105	6	124SPRT	46	1972	120	N	20	345812090052701
033	D005	SWNWS28T01SR06W	DESOTO WTR CO	1952	360	290	8	124SPRT	110	1952	200	P	35	345821089504101
033	D022	NWNWS20T01SR06W	MINERAL WELLS W	1965	360	272	8	124SPRT	90	1965	0	P	35	345910089513001
033	D032	SWNWS28T01SR06W	DESOTO WTR CO	1971	360	220	6	124SPRT	124	1979	300	P	50	345820089504001
033	D033	NWNWS20T01SR06W	MINERAL WELLS W	1972	340	275	6	124SPRT	109	1980	286	P	74	345930089515801
033	D064	NWSES33T01SR05W	RALPH WOODS	1980	390	140	4	124SPRT	100	1980	30	P	17	345718089435401
033	F034	S26T02SR08W	NESBIT W A	1972	280	330	8	124SPRT	82	1974	150	P	38	345256090010601
033	F082	NENWS25T02SR08W	CASTLE CREEK	1974	320	256	10	124SPRT	90	1974	350	P	40	345320090001001
033	F092	NESES26T02SR08W	NESBIT W A	1976	285	335	6	124SPRT	105	1976	250	P	52	345254090002901
033	F096	SENWS06T02SR08W	DESOTO UTIL	1982	300	78	8	124SPRT	42	1983	150	P	20	345632090052601
033	G016	NWNWS23T02SR07W	SIGNAL UTILITY	1970	385	322	10	124SPRT	144	1970	572	P	64	345412089550901
033	G020	SENES34T02SR07W	BRIGHTS W A	1966	370	271	8	124SPRT	127	1979	270	P	30	345215089552801
033	G070	NES02T02SR07W	PLEASANT HILL W	1981	365	292	8	124SPRT	135	1981	300	P	40	345631089540201
033	H034	SWSWS01T02SR06W	FAIRHAVEN W A	1964	400	286	8	124SPRT	135	1979	150	P	31	345600089473001
033	H042	NENES21T02SR06W	LEWISBURG W A	1965	380	289	10	124SPRT	90	1979	200	P	35	345403089495001
033	H061	NESWS11T02SR06W	FAIRHAVEN W A	1973	380	315	10	124TLLT	111	1973	300	P	44	345531089482401
033	H068	NENES21T02SR06W	LEWISBURG W A	1970	380	251	8	124SPRT	90	1970	150	P	41	345402089195101
033	H073	SWSWS01T02SR06W	FAIRHAVEN W A	1971	400	254	6	124SPRT	135	1979	168	P	40	345559089473501
033	K013	SESES13T04SR08W	TRINITY WATER C	1966	360	334	14	124SPRT	126	1966	1000	P	60	344903089594501
033	L005	SWNES18T03SR07W	HERNANDO	1968	380	335	10	124SPRT	160	1968	750	P	54	344940089585001
033	L014	SWSWS30T03SR07W	BELMONT W A	1966	400	271	8	124SPRT	131	1974	190	P	36	344720089590501
033	L054	S18T03SR07W	HERNANDO	1975	360	325	10	124SPRT	125	1975	500	P	50	345910089585001
033	L058	S30T03SR07W	BELMONT W A	1977	380	338	6	124SPRT	138	1977	242	P	40	344754089583101
035	D028	NWNWS01T04NR13W	PETAL	1955	155	124	12	112TRCS	10	1964	600	P	34	312047089154301
035	D029	SWSWS01T04NR13W	PETAL	1962	154	134	10	112TRCS	20	1962	750	P	31	311958089153501

Table 2.--Additional aquifer and hydraulic characteristics needed to define area contributing water to wells B059 and B060

[ft, feet; ft/d, feet per day; ft^2/d, foot squared per day; ft/mi, foot per mile]

Aquifer Thickness	:	210 ft
Hydraulic Conductivity	:	67 ft/d
Transmissivity	:	14,070 ft^2/d
Porosity	:	0.20
Regional Gradient	:	2.00 ft/mi
Aquifer at this location is	:	Confined