# Simple models of the relationship between well and spring flows in basalt aquifers

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## ABSTRACT

The Northland Regional Council requested assistance from GNS Science with regard to the question of finding technically appropriate but simple ways to estimate the effects of groundwater takes on spring flows in the basalt aquifers that exist within that Region. This report was prepared in response.

Basalt aquifers are fractured rock systems in which groundwater flows primarily through the fracture network. However, to some degree the unfractured blocks of the matrix also contribute. Such dual porosity systems are by nature complex and the information to accurately model them seldom exists. However, the simplification of modeling them as equivalent porous media is frequently used and some data to support this approach at the larger scale of capture zones has been developed.

Similarly, delineating the source area of springs in basalt aquifers is also complex. However, unlike a pumping well, it can reasonably be assumed that the source area of a spring will be upgradient of the location of the spring.

Simple mathematical models of capture zones for wells are available that can be used to define both the capture zone for the well and the source area of the spring. Two such analytical models are presented in this report: (1) the steady state model of Grubb (1993); and (2) the transient model of McElwee (1990). These can be used in a regulatory approach to assist in considering the implications of consenting a well in the vicinity of a spring within the circumstances of a basalt aquifer. Such a regulatory approach is proposed and an example of its application given.

Use of these models requires limited site-specific information, some of which can be estimated from knowledge of the circumstances of the well and spring. Since these models involve simplifying assumptions (e.g., that the aquifer is homogeneous and isotropic and the well is fully penetrating and producing only horizontal flow), this approach cannot be considered precise. However, it may be sufficient to provide a good first cut for relatively small wells and springs in many cases. It cannot replace more detailed site-specific analysis where larger wells and springs are involved and proposed uses constitute major projects.

# 1.0 BACKGROUND DISCUSSION

The Northland Regional Council (NRC) is concerned about finding technically appropriate but simple ways to estimate the effects of groundwater takes on spring flows in basalt aquifers that exist within that Region. Therefore, NRC requested assistance from GNS Science in this regard.

## 1.1 Basalt Aquifers

Basalt is fine-grained igneous rock of volcanic origin containing about 50 percent silica that has congealed from a molten state. Basalt is the most common extrusive rock, comprising more than 90 percent of all volcanic rock (Columbia Encyclopaedia, 2004 and Tarbuck and Lutgens, 1993). Basalt may come in various structural configurations depending on the circumstances of formation. Basalt formations may be vertically or horizontally oriented with primary hexagonal or pentagonal "columnar jointing patterns" that form as the molten material cools. Secondary fractures commonly form perpendicular to primary ones. Vertical orientations may occur in the form of repeated vertical intrusions called "sheeted dykes" while horizontal orientations like that in the Columbia River Basin of Washington and Idaho, USA, may occur as "flood" basalts (Lipson, 2002; Morgenstern and Syverson, 1988; and Rothery, 1997). There are substantial deposits of basalt rocks in the vicinity of Whangarei and other Northland locations (Smith, et al., 1993).

Basalt aquifers are composed of fractured rock. The flow of water through fractured rock systems depends on both the nature of the fractures and the remaining unfractured blocks of the matrix (i.e., a dual porosity system). Flow through fractures is primarily a function of the nature and size of apertures as well as the nature of the fracture network (i.e., number, location, orientation, and connectivity of fractures) and can be accurately modeled only if that information exists. Any method used to model fractured rock systems will involve gross simplifications. Fractured rock systems have been modeled using discrete fracture, dual porosity, and equivalent porous media (EPM) approaches. However, "because no system has sufficient data to model the ground-water flow using discrete-fracture models" and data for even dual porosity modeling are frequently lacking, the EPM method is most commonly used (Anderson and Woessner, 1992; Cobb, et al., 2006; Hsieh, 2003; and Lipfert, 2002). Despite the gross simplification involved, the EPM method has been successfully used to represent fractured rock groundwater systems in many cases. The degree of success may be a function of both the nature of the fractures and the unfractured blocks as well as the scale involved. In general, use of the EPM method appears to be most appropriate when the density of the fracture network is high, the hydraulic conductivity of the unfractured blocks is high, and the scale is large (Anderson and Woessner, 1992; McKay, et al., 1997; Lipfert, 2002; and Scanlon, et al, 2003). Of particular relevance is the conclusion from one study that "for the scale of the well capture zone, fractured bedrock behaves as a porous equivalent medium and may be modeled as such" (Lipfert, 2002).

## 1.2 Springs

Springs represent an intersection of the groundwater with surface topography. There are various types of springs which have been classified based on their specific geologic setting. Davis and De Weist (1966) provided nine illustrations of different types of spring geology;

one of which was in basalt. These are shown in Figure 1 (Figure 2.33 from Davis and De Weist, 1966). Todd (1980) later combined some of these to reduce the number of classifications to four. These are shown in Figure 2 (Figure 2.15 from Todd, 19880). The basalt example in Figure 1 (i.e., Figure 2.33i in Davis and De Weist, 1966) would be a type of contact spring in Figure 2 (Figure 2.15b in Todd, 1980). In general, it can be seen that “the most common cause” of springs is “a vertical or horizontal variation of permeability” (Kreye, et al., 1996).

There are methods available for delineating the source areas of a spring. These generally require collection of sufficient field data to define “the distribution of hydraulic head and configuration of the flow system” as that is what determines the source area of springs (Kreye, et al. 1996). This is unlikely to be a simple task in many cases because the underlying geology may be complex and there may not be relevant data. However, since the driving force in spring flow is gravity and not a pump, it is reasonable to assume that the source area will be topographically upgradient of the spring location.

## 1.3 Capture Curves

The objective of ensuring that a new water supply well not interfere with the flow of a nearby spring can be achieved if it can be shown that the capture zone of the well (bounded by the capture curve) will not intersect the source area of the spring. Obviously, this requires estimates of both the capture zone of the well and the source area of the spring.

Fetter (1994) presents a concise definition of what a capture zone is:

> (A) capture zone consists of the up-gradient and down-gradient areas that will drain into a pumping well. If the water table is perfectly flat, the capture zone will be circular and will correspond to the cone of depression. However, in most cases the water table is sloping, so the capture zone… will be an elongated area that extends slightly down-gradient of the pumping well and… in an up-gradient direction. Capture zones are controlled by the time it takes for water to flow from an up-gradient area to the pumping well (and with)… sufficient time will eventually extend up-gradient to the closest ground-water divide.

Simple equations were presented by Grubb (1993) to calculate capture zone boundaries for pumping wells in both confined and unconfined aquifers for steady-state flow conditions. Groundwater flowing outside the boundary will pass by the well while groundwater within it will ultimately be drawn to the well. Because it is for steady-state conditions, the resulting capture zone has an open-ended “U” shape as shown in Figure 3 and 4 (albeit with somewhat different symbology). The maximum downgradient end of the capture zone is called the stagnation point. Groundwater at distances shorter than that point is drawn back into the pumping well while groundwater at distances beyond it continues to flow away from the well. The equation defining the capture curve using consistent units is:

$$x = \frac{-y}{\tan\left[\frac{2\pi Kbi}{Q}\right]}$$

Where: K is aquifer hydraulic conductivity;
b is aquifer saturated thickness;
i is hydraulic gradient prior to pumping; and
Q is the constant pumping rate of the well.

The equation for the position of the downgradient stagnation point (variously $X_L$ or $x_0$) is:

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

and the equation for the maximum half width of the capture zone as x approaches infinity (variously $Y_L$ or $y_{max}$) is:

$$+ or - Y_L = \frac{Q}{2Kbi}$$

Lahm (2005) provides an Excel spreadsheet program that was developed by himself and E. Scott Bair of Ohio State University that implements these equations. This can be run in current versions of MS Excel (including Windows 2000 and XP) and, since it is interactive, allows rapid quantification and visualization of steady-state capture curves. A copy of the Excel file for this spreadsheet program is provided as Appendix A. Figure 5 shows the spreadsheet. Input variables describing the aquifer and well are shown in red. These are K, b, I, and Q. They must be entered in consistent units. Q may be input in units of liters/second (L/sec) because the spreadsheet is capable of using this to calculate Q in consistent units of $m^3$/day. The program calculates $X_L$ and $Y_L$, a series of representative values of x for appropriate y locations based on $Y_L$, and shows the shape of the capture curve.

For relatively short periods of time (i.e., transient conditions), the upgradient end of the capture zone would be truncated giving the capture zone the overall appearance of an ovular shape located asymmetrically around the well; the upgradient end being further from the pumping well and much larger than the downgradient end bounded by the stagnation point (see Figure 6). The capture zone curve boundary shown in Figure 5 was calculated using the computer software program CapCurve developed at the Kansas Geological Survey (McElwee, 1990). Input variables for this curve were:

b = 10 m
Effective porosity ($n_{eff}$) = 0.10
Darcy velocity = 0.5 m/sec
Q = 1,728 $m^3$/day
Time (t) = 30 days
Number of points to plot = 100

These are meant to describe a well and aquifer system similar to that for which the steady-state capture curve is shown in Figure 5. By comparison of Figure 6 with Figure 5, it can be seen where the transient capture curve after 30 days fits within the ultimate steady-state boundaries of the capture curve. CapCurve is an old batch FORTRAN program with an executable code that can be run in MS-DOS. Since it is not interactive, it is awkward to use compared to today's programs. A copy of the executable code is provided as Appendix B.

Both of these models, Grubb (1993) and McElwee (1990) involved simplifying assumptions. For the Grubb (1993) model, these include that the aquifer is homogeneous, isotropic, horizontally infinite, has no leakage or recharge, and is at steady state and that the well is fully penetrating with all flow being horizontal (i.e., the Dupuit assumption that vertical gradients are negligible). For the McElwee (1990) model, flow is transient rather than at steady state.

## 2.0 POSSIBLE REGULATORY APPROACH

The above information could be applied to consideration of a consent for a new relatively small well in the vicinity of a spring within a basalt aquifer in the following manner:

1. Obtain information on the exact locations of the spring and well and plot these on a topographic map. For example, using a handheld global positioning system (GPS) unit the New Zealand Map Grid (NZMG) coordinates could be obtained. Due to the limited available precision with such equipment, the separation distance between the spring and well should be relatively large (i.e., greater than 100 m). For smaller distances, the separation distance should be measured with a tape.

2. Review the topography involved in the vicinity of both the spring and well and their orientation with respect to likely up and downgradient directions. Because the groundwater potentiometric surface is normally a subdued reflection of surface topography, in the absence of actual water level measurements from reference points of known elevation, surface topography provides a reasonable first estimate of the potentiometric surface and, therefore, the direction of ground water flow. Where actual groundwater level data from wells and the spring itself exists (the spring provides a known groundwater elevation data point), this should be used in conjunction with topographic information.

3. Use the Excel spreadsheet program of Appendix A to estimate the steady-state capture zone for both the well and the spring. In this case, the "capture zone" for the spring will be assumed to be its source area. In the case of the spring, the "nose" of the resulting capture zone between the location of the spring and the calculated stagnation point can be assumed to be cut off by a line through the spring perpendicular to the assumed direction of flow. Using the Excel spreadsheet program requires an estimate of K, b, i, and Q. To the extent possible, site specific data should be used for these variables. This should be possible in the cases of b and Q. That information should be provided by the well owner applying for the consent in the case of the well. If b is not completely known, the length of the screened or open interval of the well can be used instead. This is equivalent to assuming completely horizontal flow and will not be too greatly in error for relatively productive aquifers. b in the case of the spring is

more complex, but it is necessary to use the best information available to estimate it. Spring Q should reflect actual measurements. K can be estimated from a pump test of the well, which should provide a reasonable estimate of transmissivity (T) and knowledge of b (K times b equals T). In the absence of site specific information for K, information from similar nearby areas or the literature may be used. For example, Freeze and Cheery (1979) indicates that the hydraulic conductivity of permeable basalts ranges from about 0.08 to 800 m/day and that the midpoint of this range is approximately 8 m/day. In the absence of site specific knowledge for i, it is recommended that surface topography be considered. As noted above, for a shallow aquifer i and surface topography should be related. There is also information from a study in New Jersey (USA) indicating that over distances on the order of one mile (1.61 km) hydraulic gradients were found to be approximately 50 percent of the topographic gradient (Spayd and Johnson, 2003).

4. In considering the estimated capture zones for the well and spring, there are two cases:

    a. The estimated capture zones do not intersect. In this case, in the absence of information to the contrary it may be assumed that the well will not interfere with spring flow and that, therefore, it is reasonable to approve the consent.

    b. The estimated capture zones do intersect. In this case, the nature of this intersection can be explored further by using the CapCurve computer program of Appendix B to construct a closed transient capture zone for both the well using a pumping period appropriate to the circumstances for the well. Using CapCurve requires an estimate of b, $n_{eff}$, Darcy velocity (i.e., K times i), Q, and pumping time. Estimates for all of these except $n_{eff}$ have already been made in order to utilize the Excel spreadsheet program of Appendix A. The effective porosity of basalt aquifers is variable depending primarily on the nature of the fractures but also various other factors. Walton (1991) gives the range for total porosity in basalt as 0.05 to 0.50 and a range of 0.01 to 0.05 for "dense" igneous rocks. However, because the primary porosity of basalt and other igneous rocks is normally low, a value of 0.02 has been recommended in New Jersey (Spayd and Johnson, 2003) and can be used as a default in the absence of better information. A pumping time appropriate for the circumstances of use for the proposed well should be used. For example, a pumping time of 5 days at a time might be appropriate if the well will be operated intermittently during weekdays and not on the weekend. If this eliminates the intersection of the capture zones of the well and spring, proceed as in part 4.a. above. If not, additional site specific information is necessary to make a better informed decision.

## 3.0 EXAMPLE CALCULATION

Assume that it has been proposed to install a new well which will have a 10 m screened interval and pump at a rate of 20 L/sec approximately 300 m downgradient of a spring but about 100 m cross-gradient from it. The spring also flows at a similar rate. It is known that the hydraulic conductivity is about 100 m/day and that the hydraulic gradient is about 0.005 m/m. Is the consent application for this well be acceptable?

The variables noted above for this example are essentially the same as those used in producing Figures 5 and 6. It can be seen from Figure 5 that for the geometry involved the estimated capture zone of the well will intersect the "capture zone" that has been estimated to be the same as the source area for the spring. Therefore, a decision to grant a consent for this well would not be acceptable without additional site specific data to determine the extent of interference with the spring (i.e., an appropriate pump test of sufficient duration). However, if the well would only be used for transient periods not exceeding 30 days at a time, the capture zone for it estimated used CapCurve would extend less than 250 m upgradient and not intersect the assumed source area of the spring. Therefore, in that case, the consent would be acceptable without additional data.

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# FIGURES

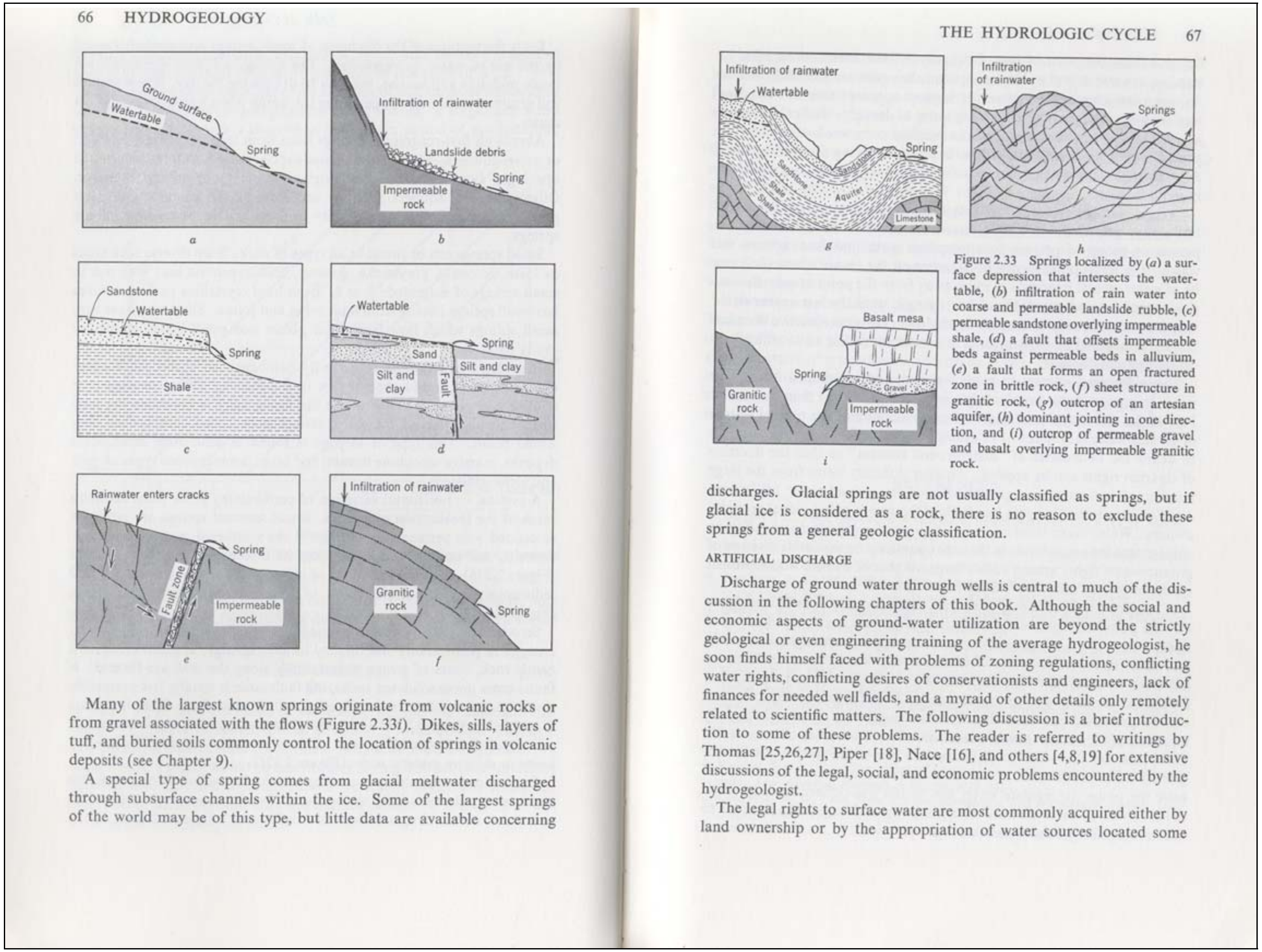


**Figure 1** Types of Springs (Figure 2.33 from Davis and De Weist, 1966).

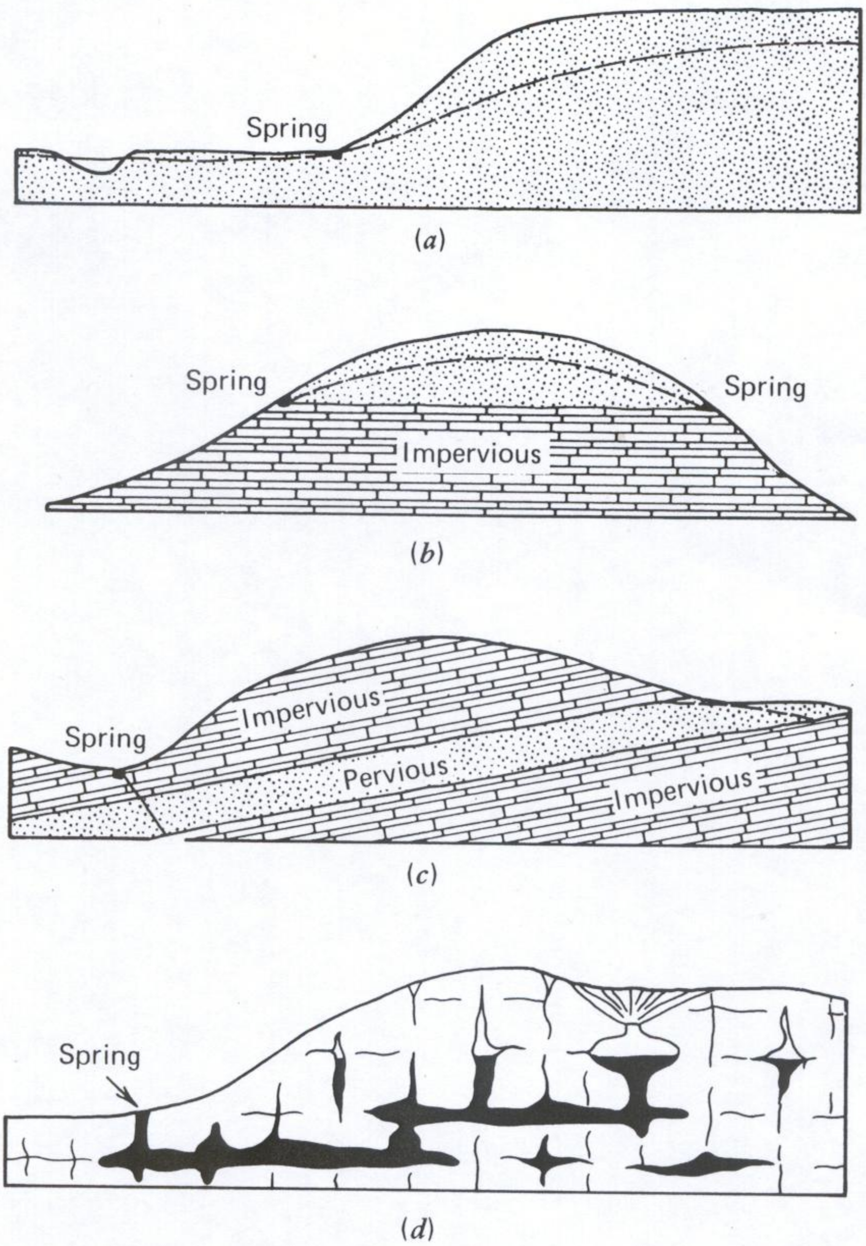


**Fig. 2.15** Diagrams illustrating types of gravity springs. (*a*) Depression spring. (*b*) Contact springs. (*c*) Fracture artesian spring. (*d*) Solution tubular spring (after Bryan[6]; copyright © 1919 by the University of Chicago Press).

**Figure 2** Types of Springs (Figure 2.15 from Todd, 1980).

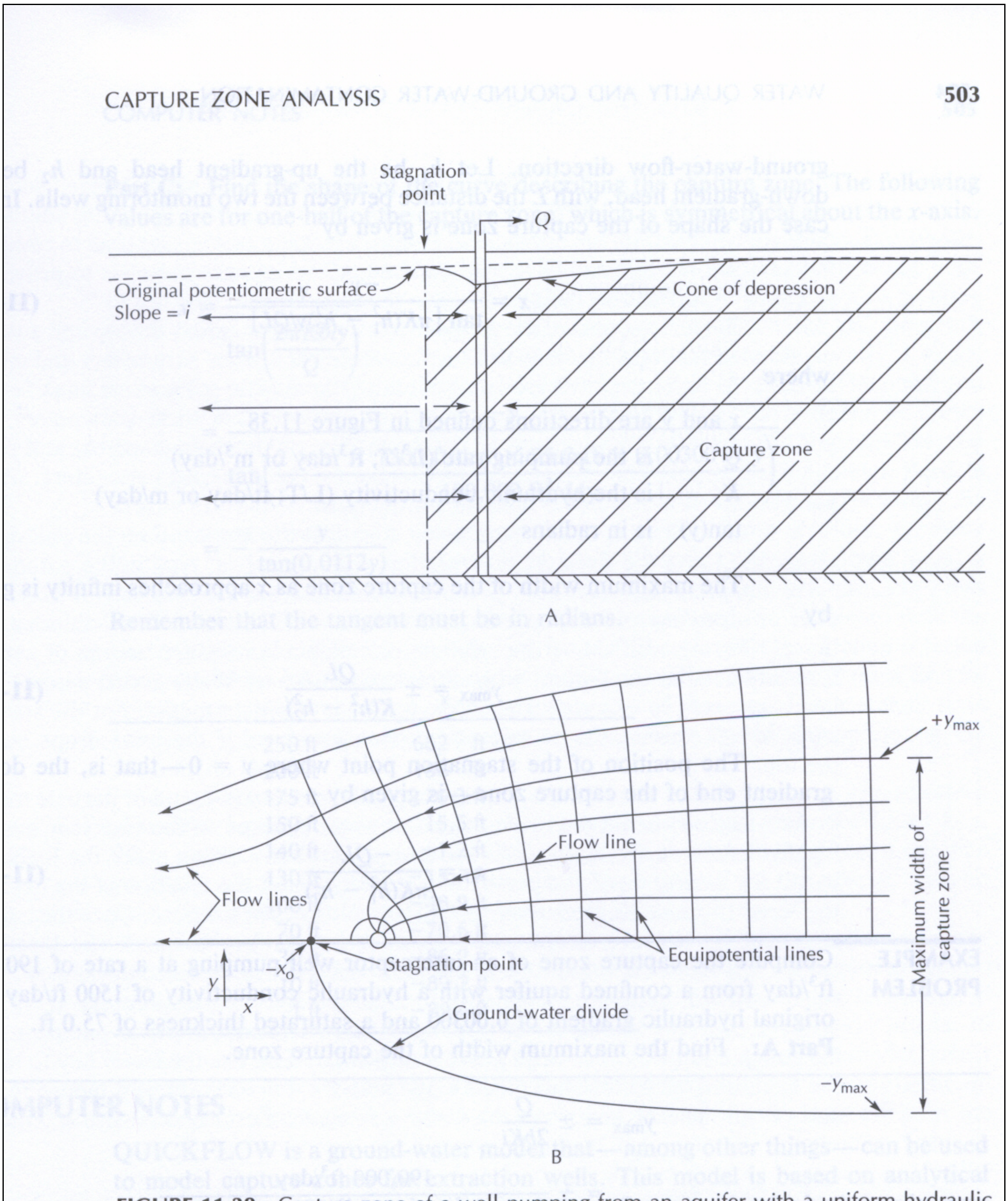


**FIGURE 11.38** Capture zone of a well pumping from an aquifer with a uniform hydraulic gradient. **A.** Cross-sectional view. **B.** Top view of equipotential field.

**Figure 3** Steady State Capture Zone (Figure 11.38 from Fetter, 1994).

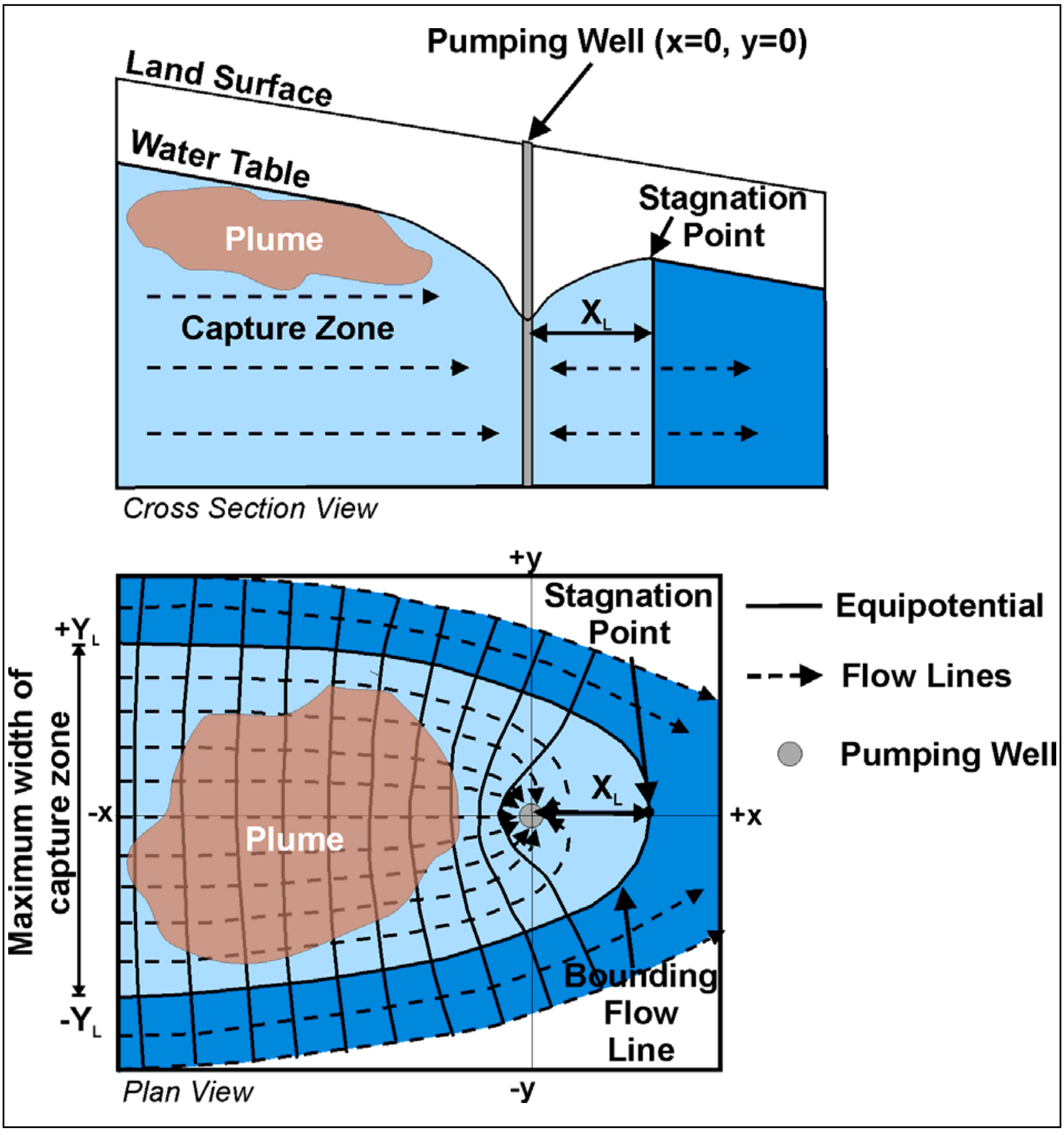


**Figure 4** Steady State Capture Zone (Figure from Lahm, 2005).

## Computed Capture Zone Curve

**Aquifer Parameters**

| | | |
|---|---|---|
| K = | 100 | m/day |
| b = | 10 | m |
| T = | 1,000 | $m^2$/day |
| i = | 0.005 | m/m |

**Well Location & Pumping Rate**

| | | |
|---|---|---|
| Q = | 20 | L/sec |
| Q = | 1,728 | $m^3$/d |
| X = | 0 | |
| Y = | 0 | |

**Capture-Curve Geometry**

| | | |
|---|---|---|
| $X_L$ = | -55.0 | m |
| $Y_L$ = | 173 | m |

**Computed Curve** *(quad. 1 & 2)*
PRIMARY CURVE *(y > 0)*

| Calc. x (ft) | Input y (ft) |
|---|---|
| -55 | 0.1 |
| -51 | 26 |
| -38 | 52 |
| 0 | 86 |
| 34 | 104 |
| 88 | 121 |
| 190 | 138 |
| 288 | 147 |
| 479 | 156 |
| 1036 | 164 |
| 2692 | 169 |
| 37963 | 173 |

**Computed Curve** *(quad. 3 & 4)*
MIRROR IMAGE *(y < 0)*

| *Calc. x (ft)* | *Input y (ft)* |
|---|---|
| -55 | -0.1 |
| -51 | -26 |
| -38 | -52 |
| 0 | -86 |
| 34 | -104 |
| 88 | -121 |
| 190 | -138 |
| 288 | -147 |
| 479 | -156 |
| 1036 | -164 |
| 2692 | -169 |
| 37963 | -173 |

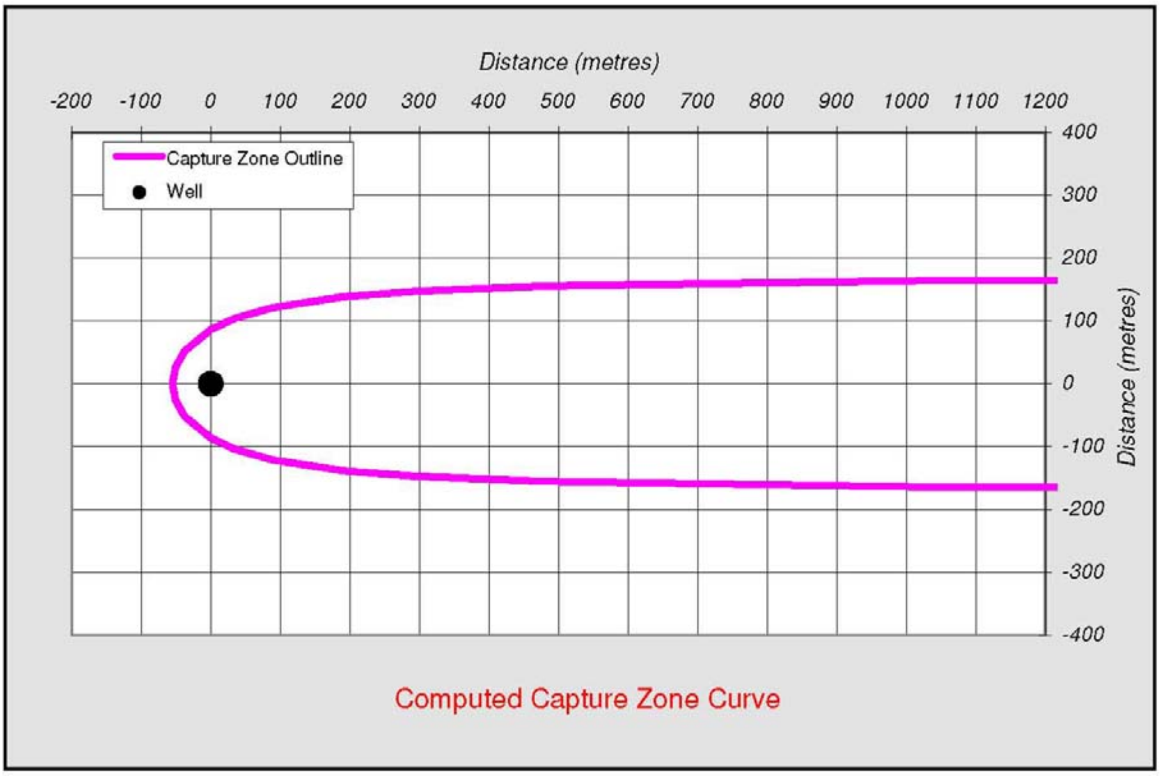


**Figure 5** Example Excel Spreadsheet Steady State Capture Zone Input/Output.

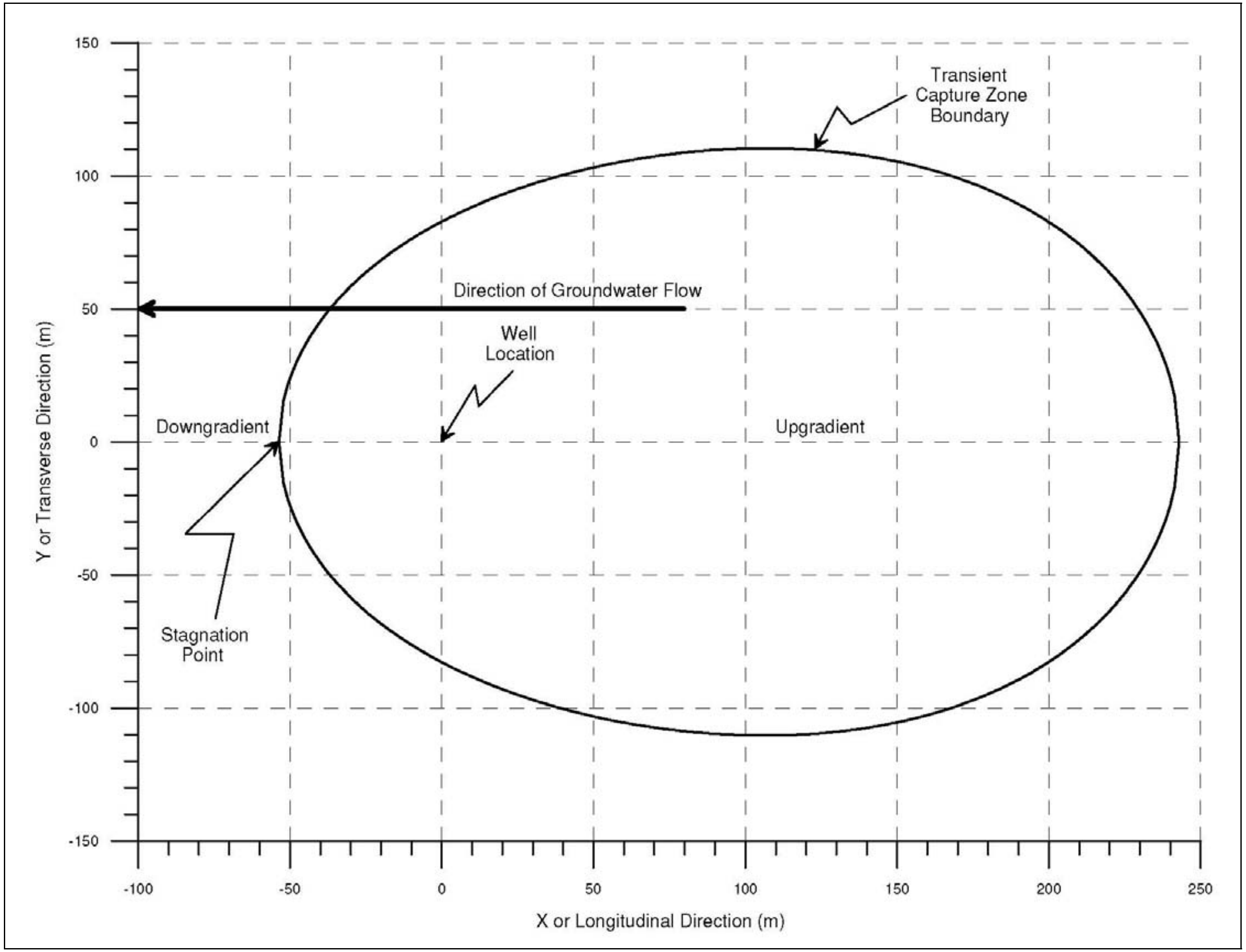


**Figure 6** Example CapCurve Transient Capture Zone Output.

# APPENDICES

## APPENDIX A EXCEL STEADY STATE CAPTURE CURVE SPREADSHEET PROGRAM FILE

This file is located on the CD in back cover of report.

## APPENDIX B CAPCURVE MS-DOS TRANSIENT CAPTURE CURVE PROGRAM EXECUTABLE FILE

This file is located on the CD in back cover of report.

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