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CZAEM User's Guide

Modeling Capture Zones of Ground-Water Wells Using Analytic Elements

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MODELING CAPTURE ZONES OF GROUND– WATER WELLS USING ANALYTIC ELEMENTS

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NOTICE

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The material introduced in the User's Guide should be fully understood prior to the application of the computer program CZAEM to field problems. Both the creation of the conceptual aquifer model and the interpretation of this program's output require an understanding of the Analytic Element Method and its implementation in CZAEM Interpretation of the output generated by the CZAEM program is the sole responsibility of the user.

FOREWORD

EPA is charged by Congress to protect the Nation's land, air, and water systems. Under a mandate of national environmental laws focused on air and water quality, solid waste management, and the control of toxic substances, pesticides, noise, and radiation, the Agency strives to formulate and implement actions which lead to a compatible balance between human activities and the ability of natural systems to support and nurture life.

The Robert S. Kerr Environmental Research Laboratory is the Agency's center for expertise for investigation of the soil and subsurface environment. Personnel at the Laboratory are responsible for management of research programs to: (a) determine the fate, transport, and transformation rates of pollutants in the soil, the unsaturated and the saturated zones of the subsurface environment; (b) define the processes to be used in characterizing the soil and subsurface environments as a receptor of pollutants; (c) develop techniques for predicting the effect of pollutants on ground water, soil, and indigenous organisms; and (d) define and demonstrate the applicability of using natural processes, indigenous to the soil and subsurface environment, for the protection of this resource.

The Capture Zone Analytic Element Model CZAEM is a practical, PC–based ground–water analysis tool that allows for the definition of the areas contributing recharge to pumping wells, including the influence of rivers, streams, and other surface water bodies. The solution is based on a new technique for ground–water modeling known as the analytic element method. Capture zone definition is fundamental in the design of remediation systems for source containment or pump-and–treat of contaminated ground water, and also in the delineation of protection areas around drinking water wells.

Clinton W. Hall

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ABSTRACT

The computer program CZAEM is designed for elementary capture zone analysis, and is based on the analytic element method. CZAEM is applicable to confined and/or unconfined flow in shallow aquifers; the Dupuit-Forchheimer assumption is adopted. CZAEM supports the following analytic elements: uniform flow, uniform infiltration over a circular area, wells, and line-sinks. The line-sinks can be used to simulate streams and the boundaries of lakes and rivers.

The program will generate and plot the envelopes of capture zones, the boundaries of capture zones corresponding to different times, dividing streamlines including stagnation points, streamlines, and piezometric contours.

A tutorial is provided to introduce the user to CZAEM and consists of two parts, each with three examples. Part A is concerned with introducing the user to the primary capabilities of the program along with elementary modeling techniques. Part B is aimed at advanced modeling techniques and commands. It is explained at the end of part B how to obtain hardcopy output from the program.

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ACKNOWLEDGMENTS

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Introduction

The Wellhead Analytic Element Model (WhAEM) package, a capture zone delineation tool for wellhead protection and pollution containment, is the result of a cooperative agreement between the USEPA, the Indiana University at Bloomington, and the University of Minnesota at Minneapolis. The package consists of two executable: the first contains the graphical pre-processor GAEP along with a manual describing its use; the second contains the computer program CZAEM Capture Zone Analytic Element Model. The latter program's intended use is for the modeling of problems where the flow is generated by few (say 50) features (small–scale problems), either together with GAEP, or by itself. The integrated WhAEM package is described in USEPA (1994).

The presented tutorial deals with the use of CZAEM as a stand-alone program, along with some applications to elementary problems.

Background

The objective of the project was to develop algorithms for determining, in relatively simple settings, the envelopes of capture zones of wells. The capture zone envelope of a well contains all water that will reach the well, given an infinite time period. Capture zones are divided into sub–capture zones (called subzones in the program), according to the source of the water in the zone (for example, a section of a river or a recharge well.) Also of interest are capture zones for a certain time period, called time zones in the programs. The capture zone for a given time period of length *t* is defined as that portion of a capture zone containing all water that reaches the well within a time period of *t*. As far as the authors know, the program CZAEM is the first program that fully computes and displays the boundaries of the capture zone envelope, subzones, and time zones, including dividing streamlines and stagnation points, for any well in the flowfield.

CZAEM is intended primarily for small-scale applications that can be handled with little effort and without the need for an advanced computer model. It will generate useful information for such problems, mostly in graphical form, and hopefully will increase the understanding of the shape and extent of capture zones. As CZAEM was not written with complex problems in mind, it is recommended that applications be limited to relatively simple problems. Complex problems should be dealt with by professionals with access to more powerful computer programs. This document contains a brief description of the method on which CZAEM is based, the analytic element method, a brief description of the program, and the tutorial.

The Analytic Element Method

The analytic element method is based on the superposition of analytic functions. Each of these functions satisfies the fundamental equations for ground-water flow exactly and has properties that make it suitable to model a certain feature of the aquifer. The method is described in detail by Strack (1989).

Although simple in principle, the analytic element method has grown into a complex framework of many specially developed functions, eliminating most of the limitations that used to be associated with analytical models. The analytic element method differs fundamentally from most of the classical numerical techniques. Important differences are:

1. The aquifer is unbounded in the horizontal plane.
2. The solution is analytical, and therefore no interpolation is required for computing heads or velocities. This allows the user to create contour plots and streamlines for any part of the aquifer, varying in size from several square feet to hundreds of square miles.

3. There is no numerical dispersion. Inaccuracies, for example in capture zone boundaries, are due solely to approximations made in the conceptual model and its implementation in the program.

The application of the method in CZAEM is elementary, and contains only a few analytic elements. These elements can be used to simulate river boundaries, streams, lakes, wells, uniform flow, and uniform infiltration over a circular area. The elements used to model river boundaries, streams, and lakes are called line–sinks. Line–sinks are mathematical functions designed such that they simulate a constant rate of extraction along a line between the end points of the line–sink.

The line-sinks may be used to model flow from a stream into an aquifer, with the groundwater table below the stream bottom. In this case the strength of the line–sink (defined as the extraction rate per unit length) can be estimated from the head in the stream and the resistivity of the stream bottom. The stream is then divided into sections, chosen such that the infiltration approximates the computed infiltration rate of the stream.

Another application of line–sinks is to model constant-head boundaries of rivers, lakes, or streams. In this application, the model is approximate in that the program computes the strength of each line–sink section to match the value of head entered. A fine subdivision in line–sink segments will render a better approximation of the real extraction rate along the stream than a coarse one.

The well function is used to model wells with either given head or given discharge. The solution generated by these well functions is accurate, even in the neighborhood of the well, as there is no numerical discretization.

The uniform flow function adds a uniform component to the far-field (this is the flow pattern far away from the area modeled.) Finally, the function for radial infiltration (called the rain function in the program) may be used to simulate uniform infiltration inside a circle.

THE COMPUTER PROGRAM CZAEM

The computer program CZAEM is an enhanced version of the computer program SLWL (Strack, 1989) with the capability added to generate capture zones of wells. The program is fully modular; the main modules are the following:

1. AQUIFER, for the input of aquifer data,
2. GIVEN, for the input of uniform flow and rain.
3. REFERENCE, for the input of the head at one point in the aquifer.
4. WELL, for the input and implementation of wells.
5. LINESINK, for the input and implementation of line–sinks.
6. GRID, for the generation of grids of values of piezometric heads, to be contoured.
7. PLOT, for the generation of piezometric contours.
8. TRACE, for the generation of streamlines.
9. CAPZONE, for the generation of capture zones.
10. CURSOR, for the retrieval of data using graphical input.
11. CHECK, for the retrieval of data using keyboard input.
12. IO, for the binary input and output of solutions

All of these modules, with the exception of CAPZONE, existed prior to the present project. The module CAPZONE is written in FORTRAN. The listing of this module is available separately from the USEPA. In order to facilitate implementation in other computer programs, it is indicated in the listing where and how functions providing necessary data to the module are to be called.

The user interface of CZAEM (modeled after SLWL) is a command-line interface. Such an interface differs from many of the current mouse-driven interfaces. It has the advantage of flexibility, but requires a longer learning period. Prospective users of CZAEM unfamiliar with the analytic element method or with the command-line interface of SLWL are urged to take the time to follow the examples in the tutorial. These examples are designed specifically to guide the user through the use of CZAEM progressively introducing several aspects of the program. A study of the first three examples is considered pre–requisite (preferably by hands-on application) before application of CZAEM The final two examples are used to introduce some of the more advanced features of the program.

In order to simplify the user interface, the command lines and menus are reduced to contain only the commands used in this tutorial. Other commands, useful for more advanced applications, are available but are left out of the menus. All commands, however, are listed in the help files provided with the program. Everywhere in CZAEM the user may obtain a brief help summary for a command by typing the command word in the current menu followed by a space and a question mark. A list of the commands that are available in a module will be displayed by entering the command word help.

INSTALLATION

An installation batch file called `czinst.bat` is supplied with the program CZAEM To install the program onto a hard drive, change to the disk drive containing the diskette and type

```
czinst a c
```

where `a` represents the disk drive containing the diskette and `c` represents the hard drive destinat ion. Further information regarding installation of the program and supported printer devices is contained in the file `read.me`. It is recommended to read this file prior to installation.

Example 1. Uniform Flow with a Well

A farmer wishes to engage in organic farming to complement his regular farming practices. In order to comply with regulations, he must irrigate his organic crops with ground water that does not contain the chemicals that are placed on his other fields. It is estimated that a minimum of 60 cubic meters of water per day is necessary to make the venture profitable. Therefore the following is required:

1. Field characterization to determine aquifer parameters.
2, A model to represent existing flow conditions.
3. An analysis of flow conditions due to the addition of the irrigation well.

Four monitoring wells were installed to determine the aquifer parameters (Figure 1.1). Soil tests indicate that the permeability and porosity are 6 m/day and 0.3, respectively. Surface elevations are relatively uniform at 250 m above sea level. Boring logs show the distance to a confining soil layer from the surface to be 100 m. These values, including ground–water elevations from the monitoring wells, allow for a model conceptualization of the aquifer (Figure 1.2). It is necessary to enter all values in consistent length and time measurements (i. e., if the discharge were given in units of gallons per minute, it would have to be converted to cubic meters per day prior to entering). The next step is to implement this representation in CZAEM

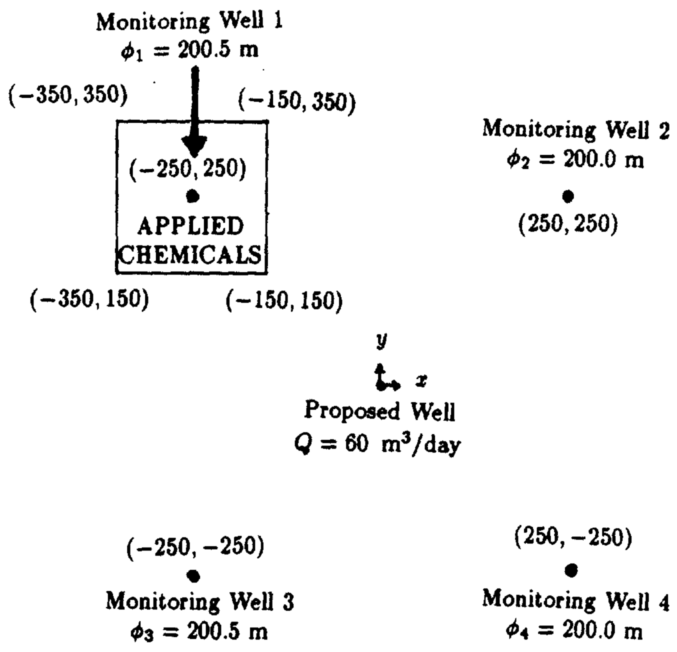

Figure 1.1 *Site map for Example 1.*

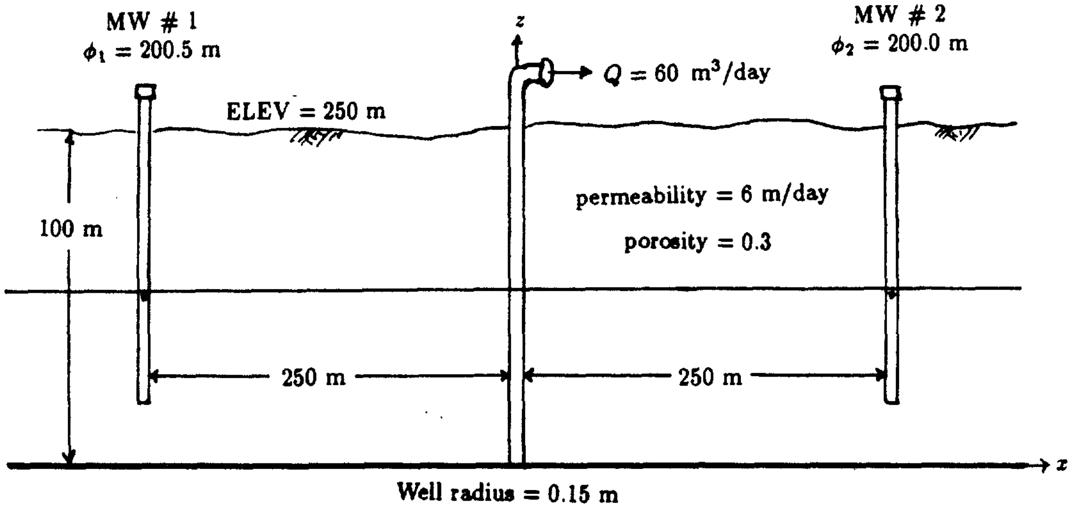

Figure 1.2 *Conceptual model of the aquifer.*

Entering the program CZAEM

Change to the CZAEM directory, which contains the executable file `czaem.exe`.

```
A:\ >D:
D:\ >CD CZAEM
```

Where D: represents the disk drive where CZAEM is installed. Enter CZAEM by typing

```
D:\ CZAEM>CZAEM
```

Before entering any data, a brief description of CZAEM'S structure is in order. On your screen is the MAIN menu of command words

```
\\\  Module=MAIN MENU           Level=0     Routine=INPUT            ///
ENTER COMMAND WORD FOLLOWED BY ? FOR BRIEF HELP FROM ANY MENU
<AQUIFER>      <WINDOW>[(X1,Y1,X2,Y2)/<ALL>/<PUSH>/<POP>]   <HELP>
<GIVEN>        <MAP>                                        <SWITCH>[FILE]
<REFERENCE>    <LAYOUT>                                     <SAVE>
<WELL>         <GRID>(NUMBER OF POINTS)                     <READ>
<LINESINK>     <PLOT>                                       <PAUSE>
<SOLVE>        <TRACE>                                      <RESET>
<CHECK>        <CURSOR>                                     <PSET>
                                                            <STOP>
```

Words in angular brackets, '< >', are commands; words in parentheses, '( )', are required arguments; words in square brackets, '[ ]', are optional arguments; and a slash, '/', indicates alternatives. Type only the command word and arguments, not the brackets. Some of the commands perform a function immediately, and some access other modules. If you enter another module, you may return to the previous module by typing

```
return
```

followed by an enter. Only the initial characters of the command words need to be entered, as many as required to be unique (four is the maximum you may have to enter, but you can enter more if you wish). In this tutorial, the command <RETURN> is commonly abbreviated

```
ret
```

Throughout this first problem, the full names of the bracketed terms shall be typed out; in subsequent examples in this tutorial, only the significant letters shall be used.

Entering aquifer data.

We enter the aquifer parameters in the module AQUIFER. Enter the module with the command <AQUIFER>. Note that all data must be input with consistent units. Enter

```
aquifer
```

CZAEM responds with

```
\\\ Module=AQUIFER              Level=1    Routine=INPUT              ///
<PERMEABILITY>(PERM)<THICKNESS>(THICK)<BASE>(ELEVATION)<POROSITY>(POROSITY)
<RESET><HELP><RETURN>
```

The permeability and porosity may be entered directly:

```
permeability 6
porosity 0.3
```

Note that the numbers and letters need only be separated by a space, This is also true for commands that require two values or more. In addition, values may be entered using exponential form (e.g., 0.6el and 300e-4).

The command <THICKNESS> requires as the argument the actual vertical extent of the aquifer (Figure 1.2). <BASE> is the elevation of the bottom of the aquifer above sea level (or any datum you chose). Enter

```
thickness 100
base 150
```

Note that BASE and POROSITY have default values of 0 and 0.3, respectively. Default values are used if the user does not enter parameter values. To return to the MAIN module, enter

```
return
```

CZAEM will respond by displaying the MAIN menu

```
\\\ Module=MAIN MENU            Level=0    Routine=INPUT              ///
ENTER COMMAND WORD FOLLOWED BY ? FOR BRIEF HELP FROM ANY MENU
<AQUIFER>      <WINDOW>[(X1,Y1,X2,Y2)/<ALL>/<PUSH>/<POP>]    <HELP>
<GIVEN>        <MAP>                                          <SWITCH>[FILE]
<REFERENCE>    <LAYOUT>                                       <SAVE>
<WELL>         <GRID>(NUMBER OF POINTS)                       <READ>
<LINESINK>     <PLOT>                                         <PAUSE>
<SOLVE>        <TRACE>                                        <RESET>
<CHECK>        <CURSOR>                                       <PSET>
                                                              <STOP>
```

Next enter the module GIVEN

```
given
```

CZAEM responds with

```
\\\ Module=GIVEN                Level=1    Routine=INPUT              ///
<UNIFLOW>(DISCHARGE)[ANGLE]<RAIN>(X,Y,RADIUS,RATE)<RESET><HELP><RETURN>
```

This module is where certain elements with given strengths (i.e., known discharges) are defined. The only element we can calculate at this point is uniform flow, or UNIFLOW. This value represents the amount of ground water flowing per unit length of aquifer. To compute the uniform flow components, use three of the four monitoring well water elevations and locations in conjunction with the Dupuit formulae for unconfined flow

$$Q_x = \frac{k[(\phi_1 - b)^2 - (\phi_2 - b)^2]}{2(x_2 - x_1)}$$

$$Q_y = \frac{k[(\phi_3 - b)^2 - (\phi_1 - b)^2]}{2(y_1 - y_3)}$$

$$|Q_\alpha| = \sqrt{Q_x^2 + Q_y^2}$$

$$\alpha = \tan^{-1}\left(\frac{Q_y}{Q_x}\right)$$

where

Q_x = **magnitude of flow in the x–direction**
Q_y = **magnitude of flow in the y–direction**
Q_α = **magnitude of flow in the direction of angle** α
k = **permeability**
ϕ_1 = **head at location** (x_1, y_1)
ϕ_2 = **head at location** (x_2, y_2)
ϕ_3 = **head at location** (x_3, y_3)
b = **base elevation**
α = **angle between direction of flow and the x axis (0 to 360°)**

(see Strack [1989]). UNIFLOW consists of a constant discharge per unit width of aquifer (magnitude) and a direction (angle). The magnitude is the resultant of Q_x and Q_y and the angle is measured from O to 360 degrees where O is the positive x–axis on the standard coordinate system (O is due East). Here we have the following:

$$Q_x = \frac{6[(200.5 - 150)^2 - (200 - 150)^2]}{2[250 - (-250)]} = 0.3015$$

$$Q_y = \frac{6[(200 - 150)^2 - (200 - 150)^2]}{2[250 - (-250)]} = 0$$

$$|Q_\alpha| = \sqrt{0.3015^2 + 0^2} = 0.3015$$

$$\alpha = \tan^{-1}\left(\frac{0}{.3015}\right) = 0$$

To enter, type:

```
UNIFLOW 0.3015 0
```

Note that the term angle in the command line is surrounded by [ ]; this indicates that it is an optional value and has a default. The default value is 0. Therefore, you could have just typed UNIFLOW 0.3015. Return to the MAIN module:

```
return
```

The amount of information entered thus far can adequately describe the shape of the phreatic surface. We must fix the elevation of that surface at some point by specifying a known head at a known location. We shall use monitoring well number 3 as our reference point as follows

```
reference
```

CZAEM responds with

```
(X, Y,REFERENCE HEAD)
```

You must enter the coordinates and ground–water elevation at the reference point. From Figure 1.1, enter

```
-250 -250 200.5
```

More thought must go into the choice of the reference point than appears in this first example. Its effect is to control the amount of water that comes from infinity (i.e., very far away). When fixing the reference point, the value of head at this location shall remain unchanged no matter what other elements are placed in proximity. This issue will become more clear in following examples. Note for now that a reference point is required to solve any ground-water flow problem with CZAEM

Solution and generation of contour plots.

The final step in completing the model of existing flow conditions is to solve for all unknowns. To do this, enter

```
solve
```

CZAEM responds with

```
ITERATION  1
SOLVING    1 EQUATIONS
10 .
```

Head and discharge may now be explicitly determined everywhere. We will make a contour plot of the head on the screen. Our region, or window, shall be four square kilometers centered around the proposed well. Enter the coordinates of the lower left– and upper right–hand corners as follows:

```
window -2000  -2000  2000 2000
```

We choose the number of points, distributed uniformly within this window, at which to compute heads. Higher numbers yield higher resolution from the contouring routine used for interpolation. This grid should not be confused with the mesh in a numerical technique such as finite elements or finite differences. It is best to specify the grid with values between 20 and 50 (maximum 150). Enter

```
grid 50
```

CZAEM responds with

```
10 . . . . . . . . . .
20 . . . . . . . . . .
30 . . . . . . . . . .
40 . . . . . . . . . .
50 . . . . . . . . . .
60 .
```

A beep indicates completion of calculations. To view the flow field, enter

```
plot
```

Note that a solution, window, and grid must be specified prior to any plot. Plot options and limits are displayed

```
<D>EFAULT [NUMBER OF LEVELS] <L>AYOUT
(MIN LEVEL [INCRENENT {>0}][MAX LEVEL]
(MAX LEVEL [DECREMENT {[<0}][MIN LEVEL]
MIN.  LEVEL=  1.9820S2+0  MAX.  LEVEL=   2.022123E+02
```

At this time, we are not interested in specific contours, so we use the default option and ask for twenty levels to be plotted between the extreme values. Enter

```
d 20
```

CZAEM responds with

```
START LEVEL   1.983000E+02  INCREMENT   2.000000E-01 PRESS ENTER
```

This shows the value of head at which contouring starts and the contour interval. When using default, the contours will be drawn from lower to higher head due to the positive increment. Press [enter] to view the flow field.

```
[enter]
```

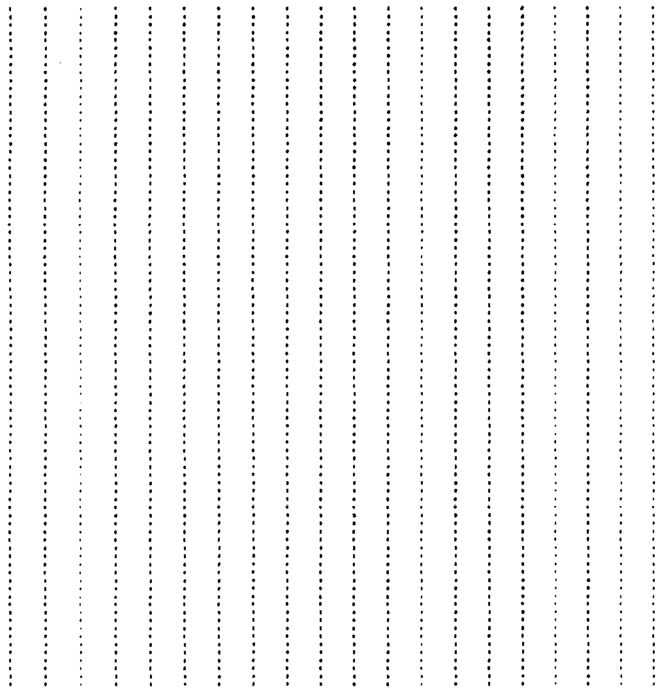

Figure 1.3 *Contour plot of the phreatic surface.*

The plot has straight contours as we move in the direction of flow. The results reflect uniform flow. Press [enter] to return to the MAIN command line after viewing the model of existing flow conditions.

Entering and analyzing the proposed well.

Enter the module WELL from MAIN

```
well
```

CZAEM responds with

```
\\\  Module=WELL              Level=1    Routine=INPUT            ///
<GIVEN><RESET><HELP><RETURN>
```

The problem specifies a given discharge. Figure 1.1 indicates that the well is placed at the center of the coordinate system and Figure 1.2 shows the well to have a radius of 0.15 m. We wish to enter a well with a known discharge.

```
given
```

CZAEM responds with

```
\\\  Module=WELL              Level=l    Routine=WELL GIVEN       ///
(X,Y,DISCHARGE) [RADIUS][[LABEL]]<COMMAND>
```

Following the instructions of the command line, enter

```
  0 0 60 0.15
 return
```

After entering a new element (the well), we must find a new solution, and again grid and plot to see the effects. We shall also zoom in on the area of interest. It is important to enter the new window size prior to gridding, otherwise the plot for the previous window will be placed over the new window giving erroneous results.

```
solve
window -500 -500 500 500
grid 50
plot
  d 20
  [enter]
```

Notice the drawdown around the well (Figure 1.4). Press [enter] to return to the MAIN command line, and enter the module TRACE

```
[enter]
trace
```

CZAEM responds with the command line

```
\\\  Module=TRACE;              Level=l    Routine=INPUT            ///
<WINDOW>[(xl,Y1,x2,Y2)/<ALL>/<PUSH>   /<POP>]<TOL>[TOLERANCE]<CURSOR>(<ON>/<OFF>)
<SWITCH><SET><PLOT><LAYOUT><CAPZONE><HELP><RETURN7
```

First plot the phreatic surface again

```
  plot
    d 20
    [enter]
```

To generate a streamline, move the cursor anywhere on the screen using the arrow keys and type

```
    trace
```

The direction in which the streamline progresses is the direction of flow. Repeat the above procedure by moving the cursor and typing trace again. Note that you can reduce the cursor step size by pressing the insert key. Generate several streamlines and see that the streamlines never cross,

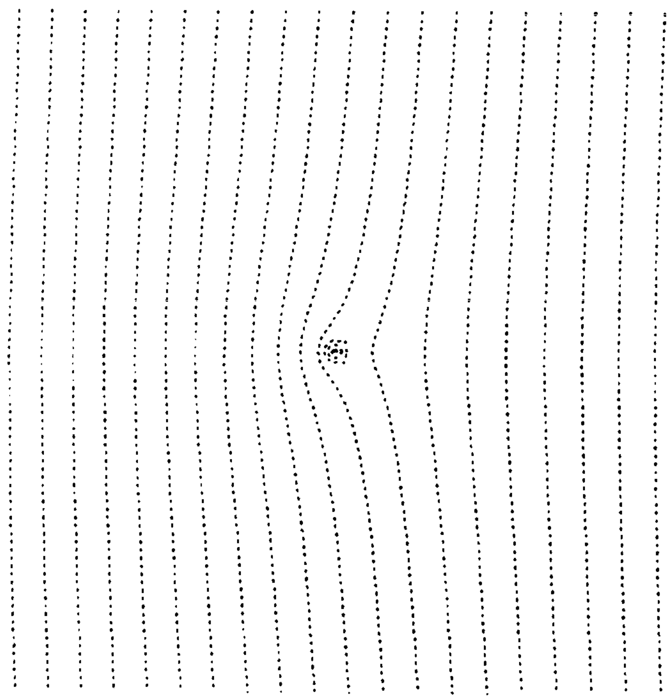

Figure 1.4 *Piezometric contours with the well present,*

Assuming that the mass of the chemicals applied to the crops is negligible with respect to the original flow, any streamlines passing under the crops represents the path of chemicals through the aquifer. It would be beneficial to identify the boundary of the crops in question. To draw a map of the field boundary, return to the MAIN module and enter the module MAP

```
 return
map
```

CZAEM responds with the command line

```
\\\  Module=MAP            Level=l   Routine=INPUT          ///
<CURVE><POINT><PLOT>(ON/OFF)<RESET><HELP><RETURN>
```

To view the map on the screen with each plot, set the <PLOT> option on

```
 plot on
```

We draw the crop boundary using the command <CURVE>. Start at one corner of the field and draw a line from corner to corner, completing the drawing by entering the first corner again. MAP will prompt for each set of coordinates.

```
 curve
    -350 150
    -350 350
    -150 350
    -150 150
    -350 150
return
```

Return to the module TRACE and move the cursor along the boundary to see if any chemically influenced water enters the well (Figure 1.5).

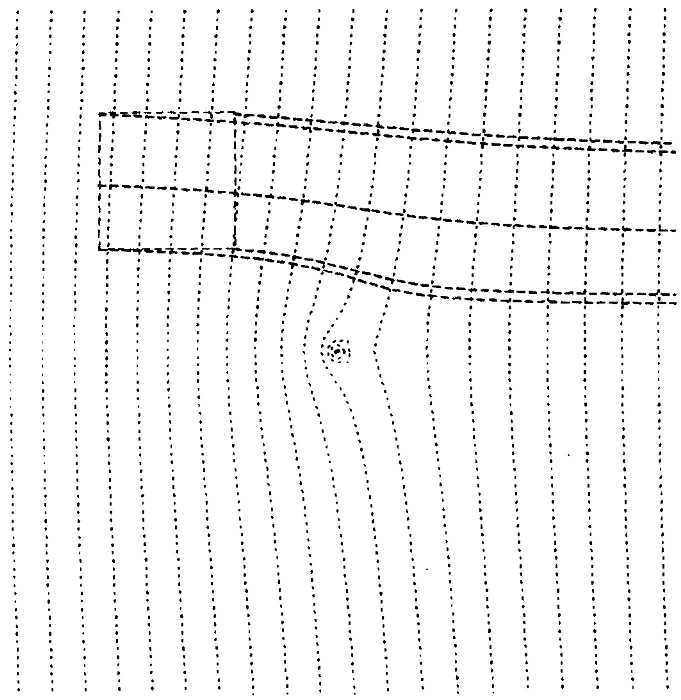

Figure 1.5 *The water beneath the field does not enter the well.*

Exiting the program CZAEM

To exit CZAEM return to the MAIN module and type

```
stop
```

This returns control to DOS.

EXAMPLE 2. WELL NEAR A RIVER

A high capacity well with a diameter of 0.6 m and a pumping rate of 1500 m^3/day is proposed to be placed near a river at a fixed location. We are asked to determine whether or not the well will capture river water. The hydrogeologic information is shown in Figures 2.1 and 2.2. The aquifer parameters are the following: permeability 5 m/day, thickness 50 m, base elevation 0 m, porosity 0.25, uniform flow 0.5 m^3/(m day) at 30°. In addition, piezometric head measurements are known at different points along the river.

In CZAEM enter the following data using consistent units from the MAIN command line

```
aqui
  perm 5
  thick 50
  base 0
  poro 0.25
 ret
given
  uni 0.5 30
 ret
```

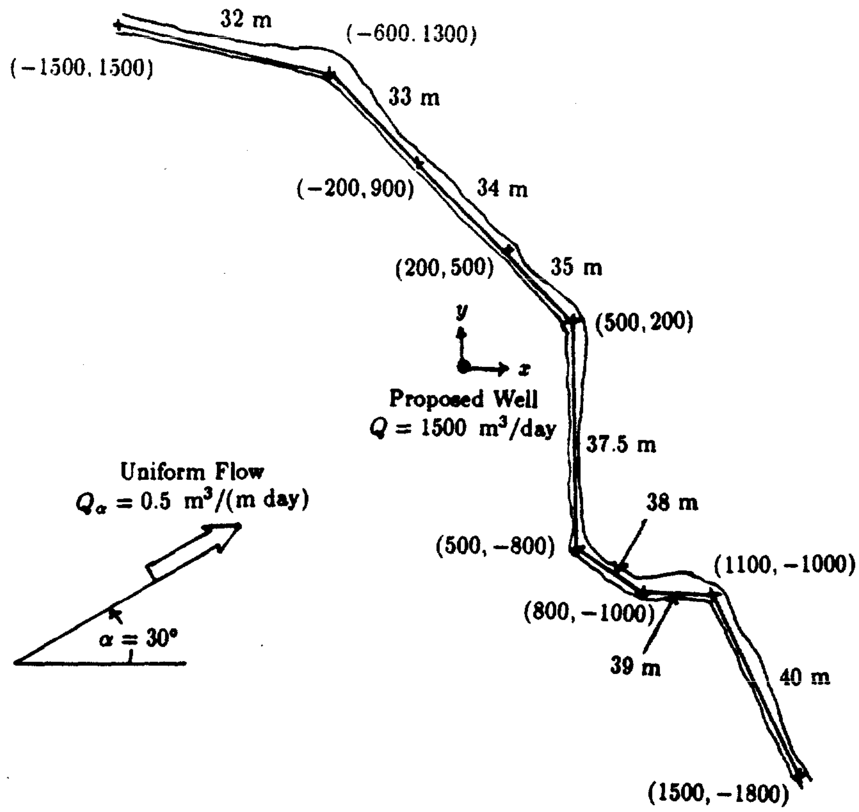

Figure 2.1 *Site map for Example 2.*

Entering line-sinks.

A river is simulated in CZAEM by a series of line-elements called line-sinks. We first need to break a river into straight line segments. Each line segment will be entered in the model as a line-sink. River discharge into or out of the aquifer is assumed to be constant along each segment The discharge is either known a priori or is calculated by specifying the head at the center of the line-sink resulting in given or head-specified line-sinks, respectively. A given line–sink extracts a fixed amount of water per unit length of line-sink without placing any restriction on the head distribution along the line-sink; a head–specified line-sink also extracts a fixed amount per unit length but creates a control point at its center which makes it possible to solve for the discharge such that the head at the control point equals that entered. Given line-sinks are entered in a similar fashion as wells. The input of head–specified line–sinks is outlined below. Enter the module LINESINK

```
linesink
```

CZAEM responds with

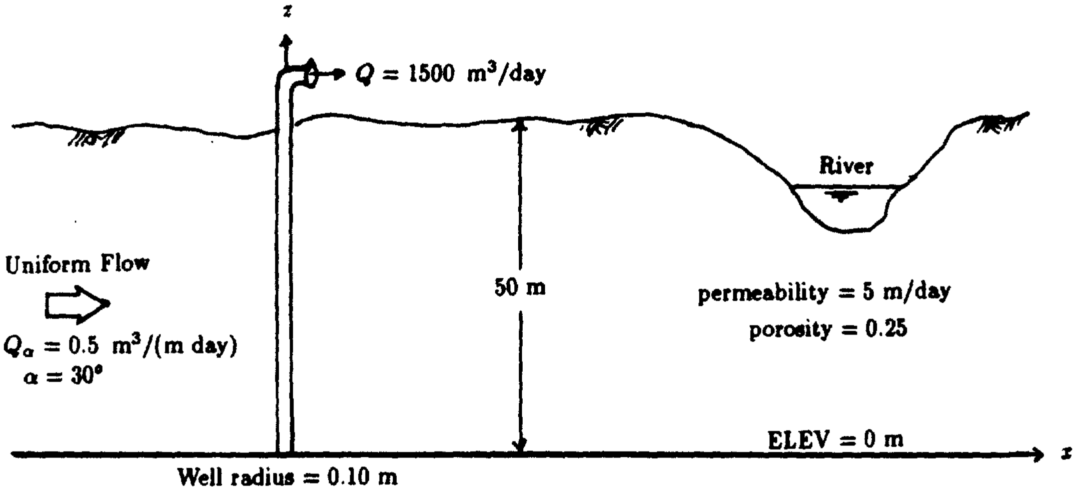

Figure 2.2 *Conceptual model of the aquifer.*

```
\\\   Module=LINE-SINK          Level=l    Routine=INPUT             ///
<given><HEAD><STRING>[<ON>/<OFF>]<TOLERANCE>[TOL]<HELP><RETURN>
```

Line-sinks with known strengths are entered through the command <GIVEN>, and those with known heads through the command <HEAD>. We have head–specified line-sinks; type

```
head
```

CZAEM responds with

```
\\\   Module=LINE-SINK   Level=l   Routine=LINE-SINK   HEAD     ///
(X1,Yl,X2,Y2,HEAD)[[LABEL]]<COMMAND>
```

CZAEM requests the coordinates of the starting point (X1,Y1), the coordinates of the endpoint (X2,Y2), and the head at the midpoint of each line-sink (HEAD), in that order. For clarity, start at any one end of a series of contiguous line–sinks and enter them in order of occurrence. We start from the north end of the river and enter the first line-sink

```
-1500 1500 -600 1300 32
```

After a line–sink is entered, CZAEM prompts for another line-sink.

```
\\\   Module=LINE-SINK   Level=l   Routine=LINE-SINK   HEAD     ///
(Xl,Yl, X2, Y2) , HEAD)[[LABEL]]<COMNAND>
```

Although the command line is not displayed, it is still active, and we may at any time enter <HEAD> to begin a head specified line–sink, <COMMAND> to see the command line, or <RETURN> to return to the MAIN module. Enter the remaining line–sinks and return to the MAIN module

```
-600  1300  -200   900  33
-200   900   200   500  34
```

```
    200   500   500   200  35
    500   200   500  -800  37.5
    500  -800   800  -1000 38
    800  -1000  1100 -1000 39
   1100  -1000  1500 -1800 40
ret
```

We have returned to the MAIN module. A visual check of our data entries is possible with the command <LAYOUT>. In this case we choose a window with a lower left corner at (-1500, -1500) and the upper right corner at (1500,1500).

```
window -1500 -1500 1500 1500
```

To view a layout of all the elements, type

```
layout
```

When finished viewing, press [enter] to return to MAIN.

The last piece of information required is the reference point. In this example the reference point is used as a calibrating parameter, rather than as a point of given location and head as in Example 1. Analytic element models such as CZAEM do not require a bounded model but deal with an infinite domain. The flow of water from far away (infinity) can be used to approximate physical sources and sinks that are present in the real aquifers but not represented in the model explicitly. This flow of water is regulated via the head specified at the reference point. The more the physical sources or sinks are included in the model the less the influence of the reference point. Since the reference point is often used to approximate complex features that are far away and left out of the model, its use as a calibration tool requires some experience with analytic element models. The reference point should be chosen far enough away from the area of interest that the head is not expected to change appreciably due to the introduction of any new element (e.g., a well). We first use a point with coordinates (-2000,4000) and a head of 40 m as the reference point.

```
ref
  -2000 4000 40
```

Solve, grid, and plot the solution (Figure 2.3).

```
solve
grid 50
plot
  d
   [enter]
```

We assume for now that the model closely matches observed heads.

Calculating the head at any point.

We can determine the head at any point in the aquifer through the module CHECK. We type

```
check
```

CZAEM responds with

```
\\\  Module=CHECK              Level=1     Routine=INPUT              ///
<AQUIFER><GIVEN><REFERENCE><WELL><LINSSINK>
<HEAD>(X,Y)<DISCHARGE>(X,Y)<CONTROL><SUMMARY><HELP><RETURN>
```

This is the CHECK module menu. Enter

```
head 1 1
```

CZAEM responds with

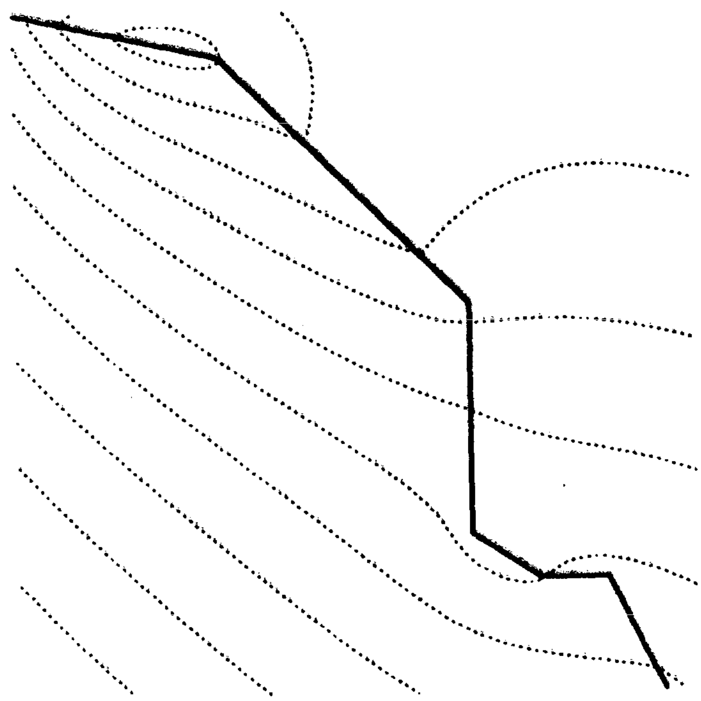

Figure 2.3 *Plot of piezometric contours, well not present,*

```
         X              Y           HEAD
  1.000000E+00   1.000000E+00   3.718284E+01
```

followed by the command line. Enter

```
head -2000 5000
```

CZAEM responds with

```
          x              Y           HEAD
 -2.00000000E+03  5.000000E+03  3.975401E+01
```

Note the heads at these two points for future use. With only uniform flow present, entering either of these heads at their respective locations as the REFERENCE would result in identical solutions. Return to the MAIN module.

```
ret
```

Entering the well.

We now solve the problem with the original reference point and the well present. First, we will reduce the window size so that we may examine more closely the changes due to the well.

```
window -1000 -1000 1000 1000
```

To enter the well, type

```
well
  given
    0 0 1500 0.3
 ret
```

Since the well affects the flow field, we must solve again

```
solve
```

Saving a solution.

It is often desirable to save a solution for later use. The command <SAVE> is used for that purpose and stores all current information in a binary file. We save this solution for retrieval later; enter

```
save
```

CZAEM responds with

```
<SOLUTION><GRID><BOTH><RETURN>
```

To select SOLUTION, type

```
sol
```

CZAEM will request a file name

```
<FILENAME><R>{to abort}
```

Enter the filename

```
ex2.sol
```

If the file `ex2.sol` does not already exist, CZAEM responds with

```
SOLUTION FILE HAS BEEN WRITTEN
PROBLEM:   UNNAMED
```

If the file already exists, CZAEM will offer you a prompt to overwrite the file or abort the command. The name and extension are arbitrary. The directory under which the file `ex2.sol` is placed is CZAEM unless otherwise specified.

In order to view the new solution, enter

```
grid 50
plot
  d
  [enter]
```

Observe the changes in the piezometric contours due to the well (Figure 2.4). Press [enter] to return to the MAIN module.

Influence of the reference point.

We will now examine the effect of the reference point on the solution. First choose the reference point at (1,1) with a head of 37.1828 (these are values that we determined using CHECK).

```
ref
  1 1 37.1828
solve
grid 50
plot
  34 4
  [enter]
```

This plot is shown in Figure 2.5. Comparing Figures 2.4 and 2.5, we see that the influence of the reference point on the piezometric contours is major, because we entered a well near the reference point.

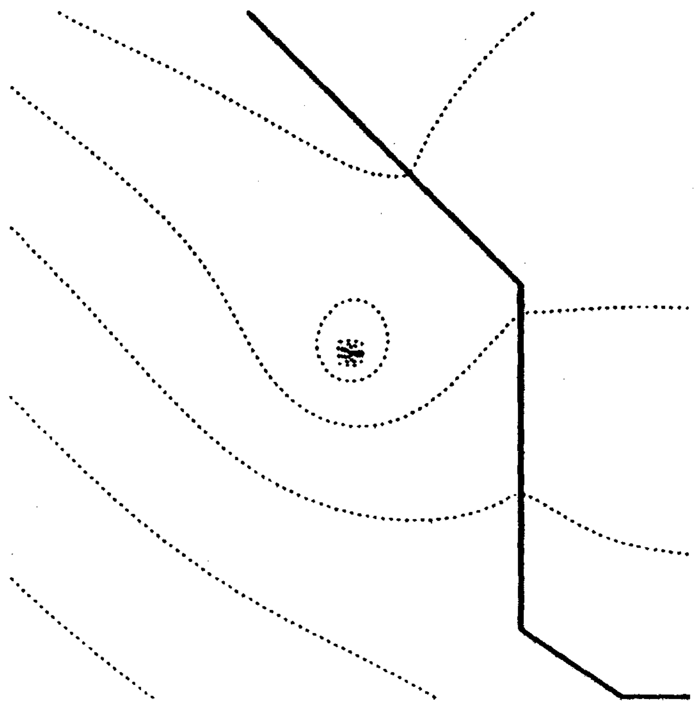

Figure 2.4 *Contours with the well present, reference point at (–2000, 4000).*

Now we see what happens when we enter (-2000,5000) as our reference point with a head of 39.7540 (the second point determined in CHECK)

```
ref
  -2000 5000 39.7540
solve
grid 50
plot
  26 2
  [enter]
```

This plot is reproduced in Figure 2.6 and is nearly identical to the one in Figure 2.4 even though the reference points are different; the influence of the well is insignificant at both reference points. This confirms that the reference point must always be chosen sufficiently far away so that elements in the model do not influence the head at the reference point significantly.

Determining a well's water source using pathlines

We are now prepared to answer the question: will the well capture the river water? We retrieve the original solution and data saved in the file `ex2.sol` by the use of the command <READ>. From the MAIN command line, enter

```
read
```

CZAEM responds with

```
<SOLUTION><GRID><BOTH><DIFGRID><RETURN>
```

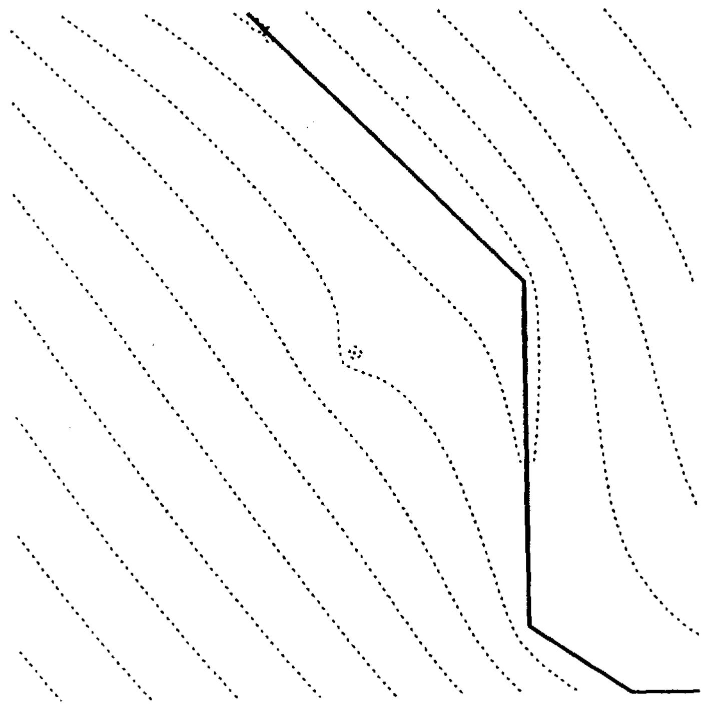

Figure 2.5 *Contours with the well present, reference point at* (1, 1).

Enter

```
solution
```

CZAEM responds with

```
PLEASE ENTER FILENAME; <R> TO ABORT
```

Enter

```
ex2.sol
```

CZAEM responds with

```
SOLUTION FILE HAS BEEN READ
PROBLEM:   UNNAMED
```

CZAEM has read in the binary file with all the elements entered at the time of saving. Since the problem was solved prior to saving, the parameter values have also been read in. CZAEM returns to the MAIN menu after reading in the file.

There are several ways to determine whether the well draws river water in CZAEM here we shall use the technique of tracing the particle pathlines in a backward fashion starting at the well. Enter TRACE by typing

```
trace
```

Streamlines are traced in the direction of flow by default. We set it to backward tracing with the command <BACKWARD ON>. Backward tracing from the well is achieved by the command

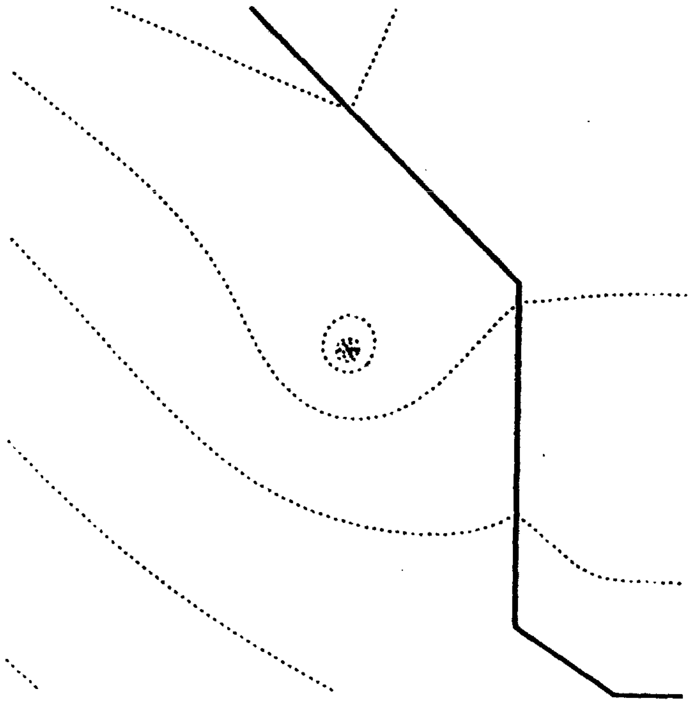

Figure 2.6 *Contours with the well present, reference point at (–2000, 5000).*

<WGENERATE>. Note that to return to forward tracing one must type <BACKWARD OFF>. We must first enter PLOT, or LAYOUT; here we choose PLOT as it will produce the piezometric contours. We enter PLOT exactly as we” did from the MAIN menu.

```
plot
  d
   [enter]
```

CZAEM plots the picture on the screen and gives the following menu:

```
\\\  Module=TRACE;               Level=l     Routine=INPUT            ///
<BASE><SURFACE><COORDINATE><TRACE>[ELEVATION]<BACKWARD>[<ON/OFF>]
<WGENERATE>(#   LINES)[ELEVATION]<WLL><TOL><COMMAND><MENU><RETURN>
{TO BACKSPACE, PRESS < }
```

The cursor appears at the center of the screen (in this *case* directly over the well).

With the cursor positioned at the well, first switch backward tracing on

```
backward on
```

Now the command <WGENERATE> may be used. This command has one required parameter and one optional parameter. The required parameter is the number of pathlines generated from the well and the optional parameter is the vertical elevation in the well from which they will originate. The default elevation is the bottom of the aquifer. We choose the number of traces to be 20 by typing

```
wgen 20
```

You will see pathlines starting from the well and going back toward their original source (Figure 2.7). The well is seen to be drawing some of its water from the river. We conclude that the proposed discharge is not feasible without drawing river water. To return to the MAIN menu and exit CZAEM enter

```
 ret
stop
```

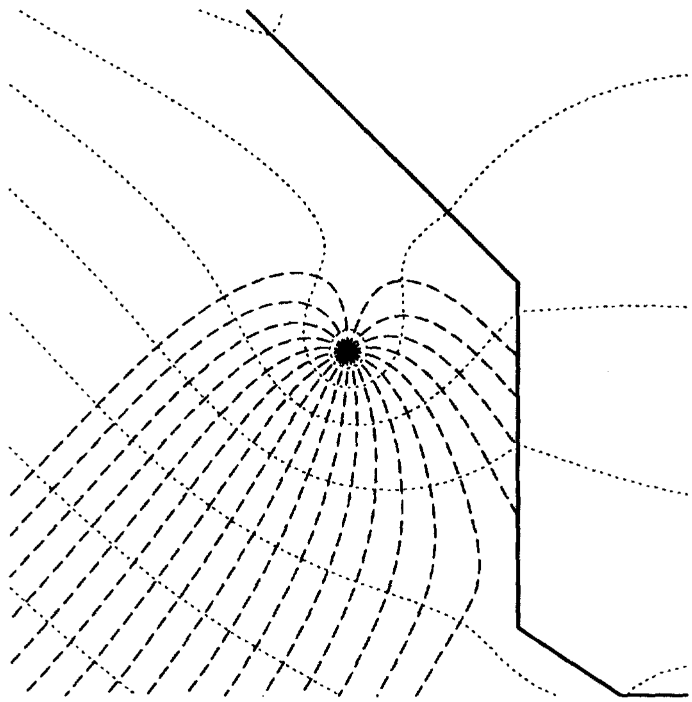

Figure 2.7 *Several pathlines from the well generated by < WGENERATE > begin at the well and end at the line-sank, showing that the well does capture river water.*

EXAMPLE 3. CRITICAL PUMPING LEVEL FOR A WELL

This example expands on the problem presented in Example 2 and introduces the module CAPZONE. We will determine the critical pumping level of the well, defined here as the largest discharge not capturing river water. In Example 2, the well is entered with a discharge of 1500 m^3/day, and is drawing water from the river. We will use <CAPZONE> to view the current solution, then adjust the well discharge until the critical level is reached.

Since the current problem has few elements, it will be sufficient to use <CAPZONE> from the outset to evaluate each well pumping level. For larger problems, it may be more efficient to use <WGEN> or <TRACE> for the first iterations.

Creating capture zones.

Begin by entering CZAEM and reading in the binary file describing Example 2. From the MAIN command line enter

```
read
  solution
  ex2.sol
```

The binary file with all elements entered in Example 2 and the parameter values determined by <SOLVE> has been read in. Enter

```
grid 50
  trace
```

CZAEM responds with

```
\\\  Module=TRACE;                 Level=l    Routine=INPUT             ///
<WINDOW>[(X1,Yl,X2,Y2)/<ALL>/<PUSH>/<POP>]<TOL>[TOLLERANCE]<CURSOR>(<ON>/<OFF>)
<SWITCH><SET><PLOT><LAYOUT><CAPZONE><HELP><RETURN>
```

We enter the module CAPZONE from within TRACE and type

```
capzone
```

CZAEM responds with

```
<D>EFAULT (NUMBER OF LEVELS] <L>AYOUT
(MIN LEVEL [INCREMENT {>0}] [MAX LEVEL]
(MAX LEVEL [DECREMENT {<0}] [MIN LEVEL]
MIN. LEVEL=   2,506159E+01 MAX. LEVEL=   4.225655E+01
```

We can enter the desired levels, request default levels <D>, or just get a layout <L>. For this example enter

```
d
[enter]
```

We are now in the CAPZONE module, and the menu is

```
\\\  Module=CAPUTRE ZONE;                Level=l    Routine=INPUT     ///
<COORDINATE<BASE><SURFACE><WINDOW>[(X1,Yl,X2,Y2)/<ALL>/<PUSH>/<POP>]<WLL>
<SUBZONE><TIMEZONE><SOURCE><NLINE>(LINES)<PAGSE><HELP><COMMAND><RETURN>
<FRONT>[<ON>[VELOCITY  FACTOR]/<OFF>]<WGENERATE>(#  LINES)<COLOR>[COLOR1][2][3]
<BSAVE>(FILE)<BREAD>(FILE){TO BACKSPACE, PRESS < }
```

CZAEM is in graphics mode, and the backspace key is no longer active. It is replaced by the less-than sign (<). We are about to let CZAEM determine the capture zone envelopes for the well and streamlines dividing the capture zone into subzones. Before discussing the meaning of these curves, we will generate them on the screen. Move the cursor over the well and enter the command <SUBZONE>. Since the well is centered in the current window and therefore already coincides with the cursor, we enter

```
subzone
```

CZAEM responds with

```
UNCONFINED:  X,Y,  PHREATIC  SURFACE  4.066071E-02  4.066071E-02  2.551642E+01
CALCULATING SUBZONES PHASE 1:  CREATING INITIAL PATHLINES FROM THE WELL
     10 . . . . . . . . . .
     20 . . . . . . . . . .
     30 .
CALCULATING SUBZONES PHASE 2:  DETERMINING LOCATION OF STAGNATION POINTS
     10 . . . . . . . . . .
     20 . . . . . . . . . .
     30 .
CALCULATING  SUBZONES  PHASE  3:  FILLING  SUBZONE  BUFFERS
     10 . . . . . . . . . .
```

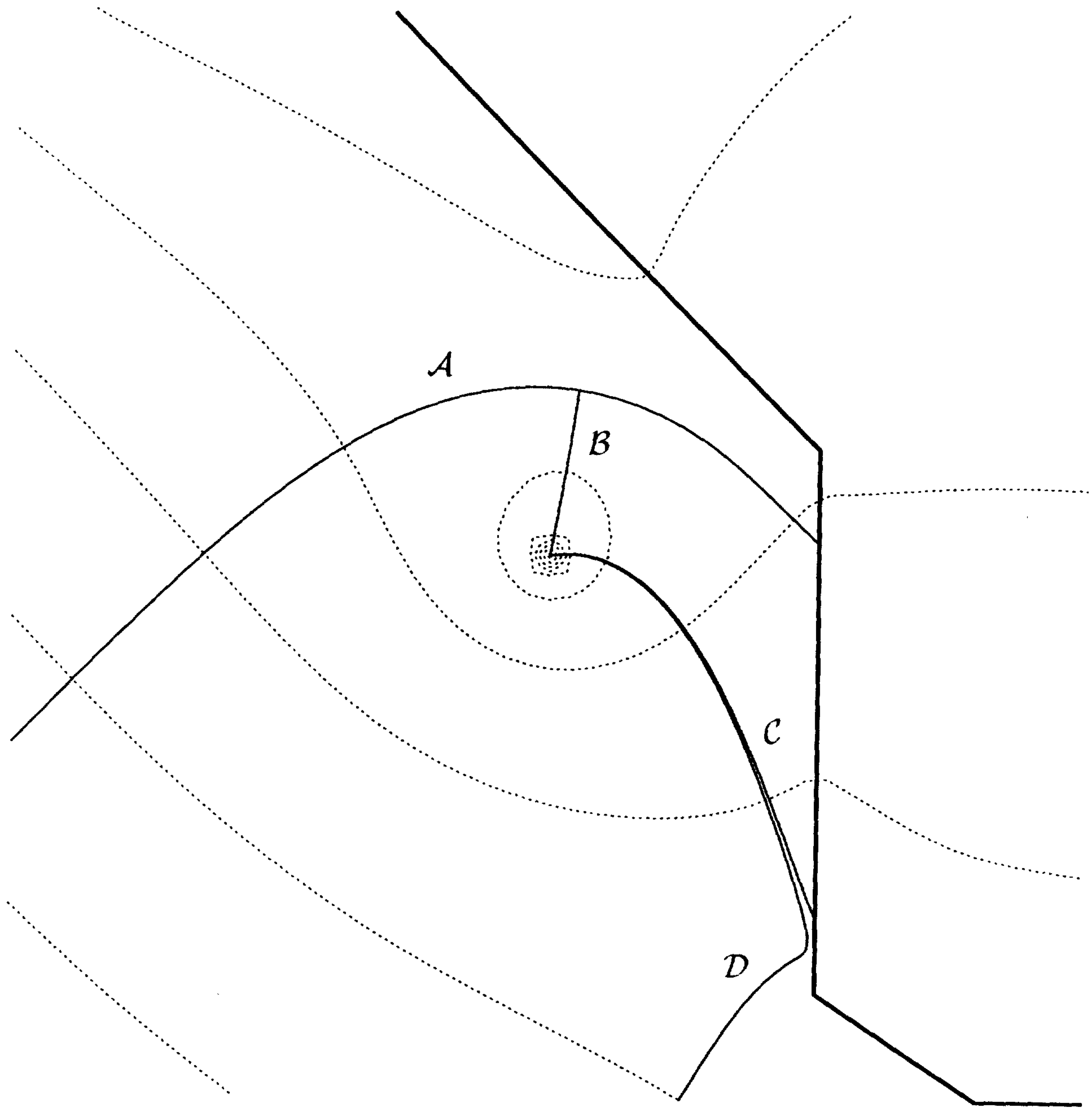

Figure 3.1 *Capture zones generated for* a well *discharge of 1500* m^3/day.

CZAEM computes the capture zone envelope curves and plots them along with all dividing streamlines (Figure 3.1).

Dividing streamlines either pass through stagnation points (points where no flow occurs in any direction) and end at the well, or separate unique source areas for the selected well. The envelope curves bound the entire area supplying water to the well. CZAEM distinguishes each individual element (e. g., a line–sink in a river stretch) as a unique source of water. CZAEM's search for dividing streamlines, envelope curves, and distinct sources terminates at the current window boundary. In order to obtain meaningful results within CAPZONE, the window must be chosen large enough to include all of the important sources and the stagnation points.

The window boundary is identified by CZAEM as the source of any water entering the well originating from far away.

Interpretation of Figure 3.1.

The capture zone envelope for the well consists of envelope curve d, the line–sink, and curve $\mathcal{D}$ below (Figure 3.1). The source area is divided into two subzones, one whose source is the window edge, and one whose source is the line–sink. The source areas are delineated by dividing streamlines $\mathcal{B}, \mathcal{C}$, and $\mathcal{D}$. Curve $\mathcal{C}$ and the upper part of curve $\mathcal{D}$ are intended to be a single dividing streamline distinguishing the two source zones, so why are they plotted distinctly rather than as one? CZAEM tries to plot dividing streamlines starting from stagnation points, which worked for line $\mathcal{B}$. However, the stagnation point which should have been used for drawing lines C and $\mathcal{D}$ is discarded by CZAEM because it is within a tolerance distance of the line-sink; CZAEM plots the nearest dividing streamlines from each source instead. These are separated by l/200'th of the well's discharge, which is generally well within modeling precision. The lower part of *D* is thus inside of the actual envelope curve by less than l/200'th of the well's discharge and can be taken as the working envelope curve.

Determining a well's water source using capture zones.

The amount of water supplied by the river can be found using the command <SOURCE>

```
source
```

CZAEM responds with

```
SOURCE DISTRIBUITON FOR WELL NUMBER 1
SUBZONE NUMBER     SOURCE TYPE        SOURCE NUMBER      % OF WATER
       1        WINDOW BOUNDARY                            79.5
       2        LINE-SINK STRING           5               20.1
PRSSS THE ENTER KEY TO CONTINUE
```

The current pumping level is too high; 20 percent of the well water originates from the river. We will next try a pumping level of 1000 m^3/day. Return to the Well module, reset, enter the well with the new strength, solve, grid, and regenerate the capture zones. Note that <RESET> erases all input data within the current module. This command requires confirmation.

```
  ret
 ret
well
  reset
  yes
  given
    0 0 1000 0.3
 ret
sol
grid 50
tra
  cap
    d
     [enter]
    sub
```

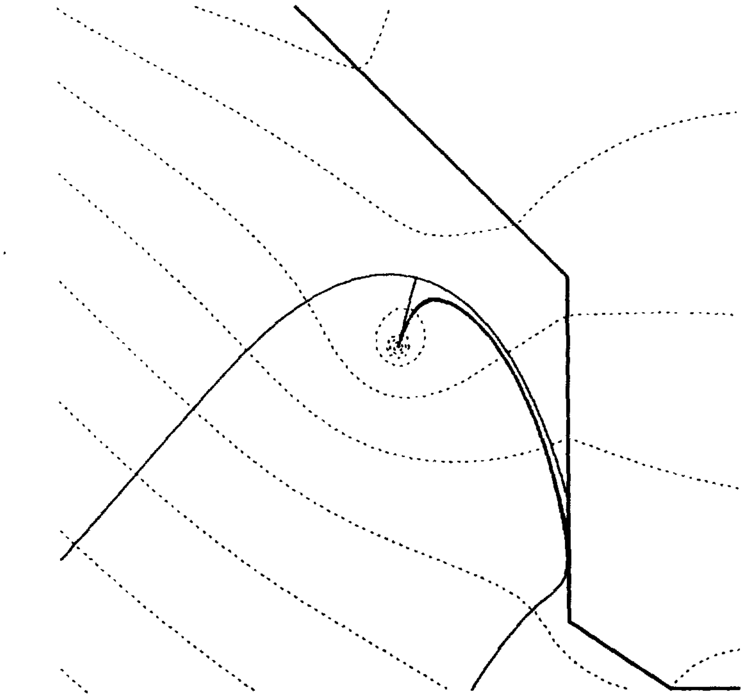

Figure 3.2 *Capture zones generated for a well discharge of 1000 m^3/day.*

At this pumping level, the capture zone still intersects the river (Figure 3.2). Enter

```
source
```

CZAEM will report that about 1.5 percent of the water is coming from the line-sink. We next repeat the above procedure to reset the pumping level to 970 m^3/day. Enter

```
    ret
  ret
well
  reset
  yes
  given
    0 0 970 0.2
  ret
solve
grid 50
trace
  CAPZONE
    d
     [enter]
    sub
```

At this pumping level, the capture zone just misses the river (Figure 3.3). Next try a pumping level of 990 m^3/day. Enter

```
    ret
  ret
well
  reset
  yes
```

```
  given
      0  0  9900.2
 ret
solve
grid 50
trace
  CAPZONE
    d
    [enter]
    sub
```

The capture zone boundary now ends at the line-sink (Figure 3.4); The command< SOURCE> reports that all the water is coming from uniform flow. Enter

```
source
```

What does it mean that the envelope ends at the line-sink but the line-sink is not identified as a source? Recall that CZAEM determines the contributions from each source with a precision of l/200'th of the well's discharge; flow from the line-sink must therefore be less than that amount. No dividing streamlines are drawn to demarcate the source zones since only one source is found. The envelope curve is drawn from the stagnation point toward the line–sink and stops there because CZAEM detects the change in flow direction at the line-sink. As in the first plot, there is no stagnation point recorded at the line–sink, thus the envelope curve is not continued.

We conclude that the critical pumping level is between 970 and 990 m^3/day. Note that this solution is based on an oversimplified representation of the river reach supplying water to the well. In the advanced tutorial lessons (Example 5) we will see that refining the model can change this estimate. The modeling process normally includes successive refinement of the model until changes in the results are within modeling accuracy.

SUMMARY OF PART A

In the first three tutorial exercises we have introduced elementary modeling techniques and the display of capture zones with the following CZAEM commands

```
AQUIFER:    PERMEABILITY, POROSITY, THICKNESS, BASE
GIVEN:      UNIFLOW
REFERENCE
WELL:       GIVEN
LINESINK:   HEAD
SOLVE
CHECK:      HEAD
WINDOW:     X1,Y1 X2,Y2
MAP:        CURVE, POINT, PLOT ON
LAYOUT
GRID
PLOT:       D, L
LAYOUT
TRACE:      TRACE
            PLOT:      WGENERATE, BACKWARDS ON/OFF
            CAPZONS:   SUBZONE, SOURCE
SAVE:       SOLUTION
READ:       SOLUTION
RESET
STOP
```

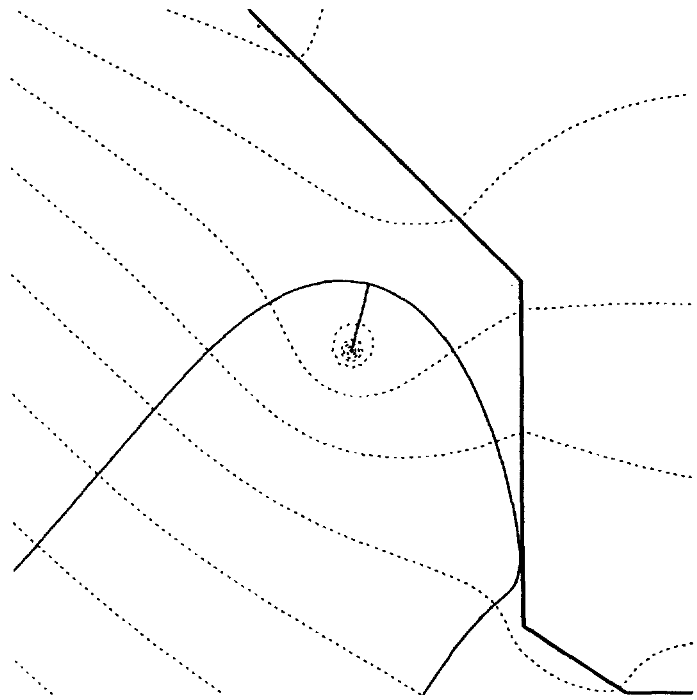

Figure 3.3 *Capture zones generated for a well discharge of 970* m^3/day

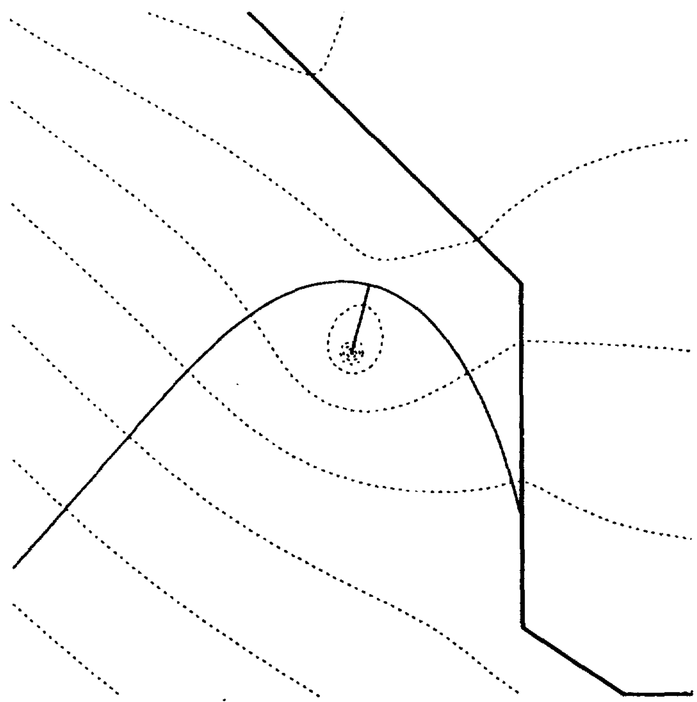

Figure 3.4 *Capture zones generated for a well discharge of 990* m^3/day.

In the remaining examples, we will introduce more advanced modeling techniques, and the following CZAEM commands:

```
GIVEN:      RAIN
LINESINK:   GIVEN,STRING   ON/OFF
CHECK:      AQUIFER,GIVEN,REFERENCE,DISCHARGE,CONTROL,SUMNARY
            WELL:      RANGE
            LINESINK:  RANGE,STRING,  ENDS,  BVAL,  DISCHARGE
WINDOW:     ALL, POP, PUSH
TRACE:      CURSOR ON/OFF
            SET:       MAXSTEP, FRONT ON/OFF, MARKER, TIME
            LAYOUT:    BASE, SURFACE, COORDINATE, WLL, TOL, MENU
            CAPZONE:   COORDINATE, BASE, SURFACE, TIMEZONE, NLINE
                       PAGE, COLOR, BSAVE, BREAD
CURSOR:     LAYOUT:    WLMOVE, LSMOVE
SWITCH:     PREFIX, INPUT/OUTPUT/MESSAGES/ERROR, LOG ON/OFF, CALL,
            BACK
SAVE:       GRID, BOTH
READ:       GRID, BOTH, DIFGRID
PSET:       PRINTER, SCREEN, PALETTE, MOUSE ON/OFF
```

We strongly encourage you to complete the advanced tutorial lessons, but you should now be able to apply CZAEM effectively to many small–scale practical problems as a stand–alone program.

EXAMPLE 4. CONTAMINANT PUMPOUT SYSTEM

A contaminant plume has been identified in a confined aquifer upgradient of a rural subdivision. To avoid contamination of private wells, the contaminant is to be pumped out of the aquifer. Field studies have identified the plume limits and estimated aquifer properties. Three monitoring wells have been installed to evaluate local ground–water flow conditions. A proposed pumpout system is to place a well at coordinates (100,20) of discharge rate 220 m^3/day (Figure 4. 1).

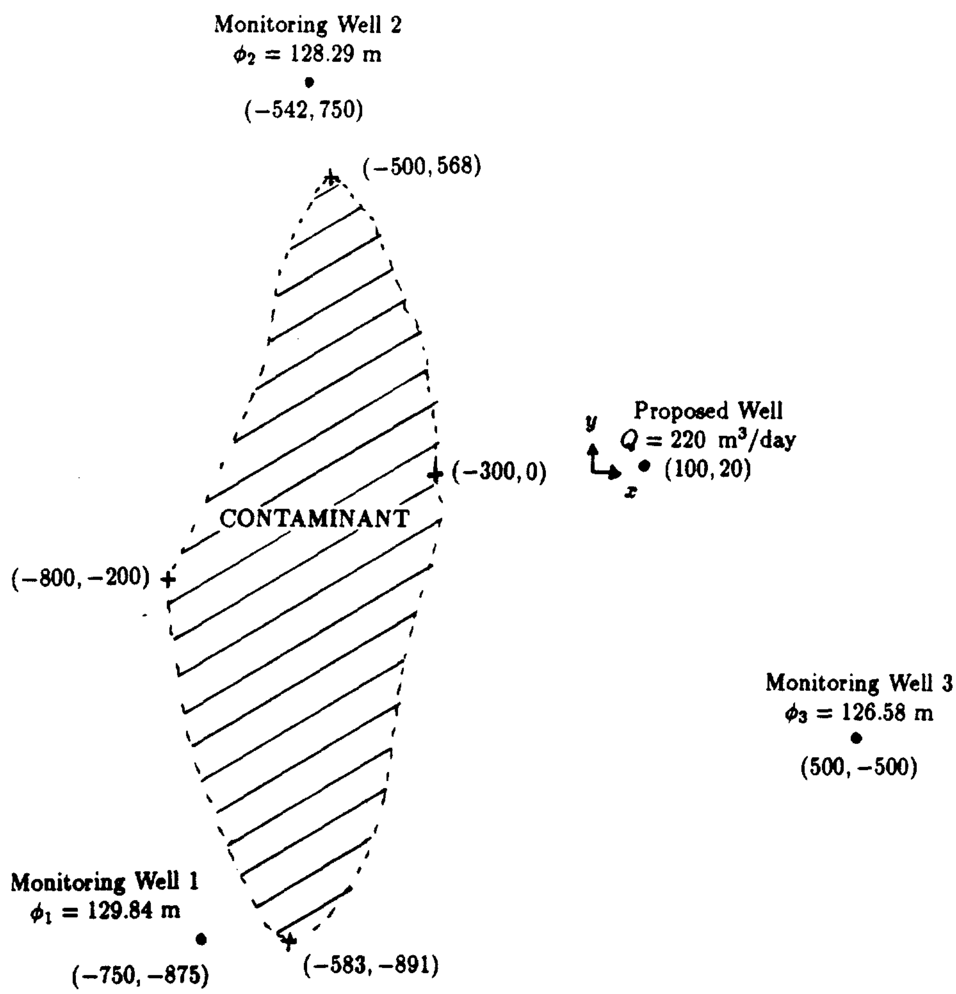

Figure 4.1 *Site map for Example 4.*

An approach for testing the pumpout system design might include:

1. Modeling the existing local ground–water flow as uniform, based on monitoring well informat ion.

2. Adding a discharge well or wells downgradient of the contaminant, strong enough to capture the entire plume.
3. Determining time capture zones to estimate the pumping time required to capture the entire plume assuming no longitudinal dispersion.

The strength of the initial uniform flow may be determined from the monitoring wells as in Example 1. The resuJts follow:

$$Q_x = 0.0966 \ \text{m}^3/(\text{m day})$$
$$Q_y = 0.0259 \ \text{m}^3/(\text{m day})$$
$$Q_\alpha = 0.100 \ \text{m}^3/(\text{m day}) \qquad (\alpha = 15°)$$

To model the existing site conditions, input the aquifer parameters (Figure 4.2) and given strength elements (i.e., uniform flow). Using consistent units of measure, enter

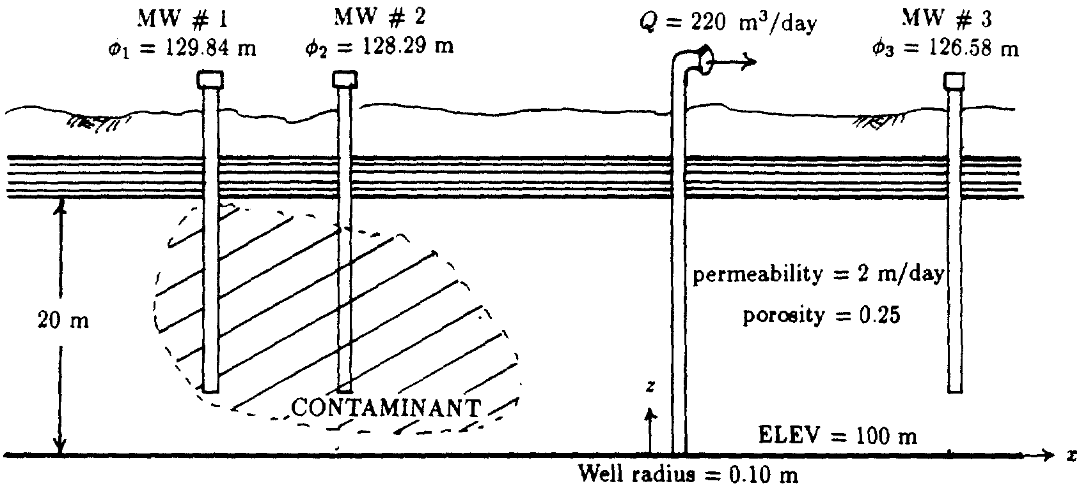

Figure 4.2 *Conceptual model of the aquifer.*

```
aquifer
  perm 2
  thick 20
  base 100
  poro 0.25
 ret
giv
  uni 0.1 15
 ret
```

To complete the model of existing conditions, a reference point where the head is known must be entered. Here, as in Example 1, a good choice is one of the monitoring wells. We will choose MW#1.

```
ref
  -750 -875 129.84
```

We must solve, set a window size, grid, and plot the existing conditions to view the results (Figure 4.3).

```
solve
window -1000 -1000 1000 1000
grid 40
plot
  d 20
  [enter]
```

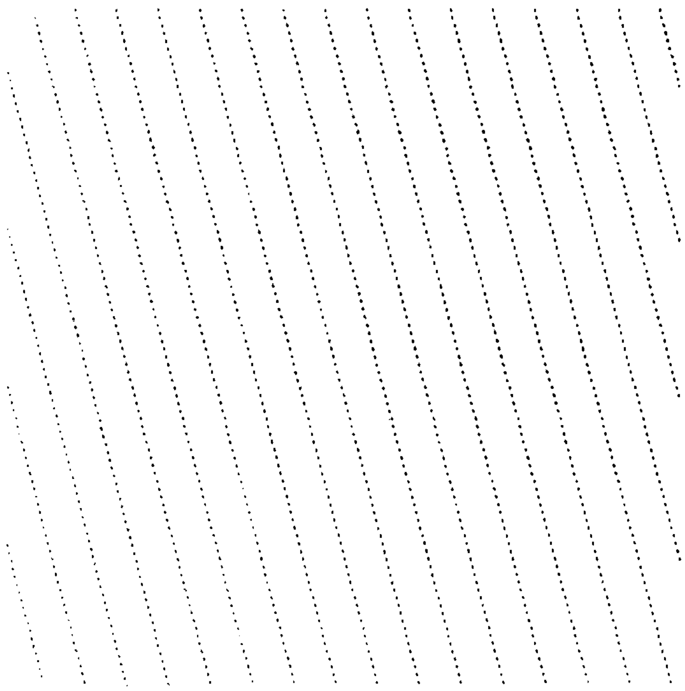

Figure 4.3 *Existing conditions: uniform flow with reference head of 129.84 meters at (–750, –875).*

Obtaining results using CHECK.

At this point it is useful to test our model to make sure that it reflects observed conditions. Modules CHECK and CURSOR provide two means of testing results. Here we will introduce CHECK; CURSOR will be discussed later. The module CHECK allows the user to check input data as well as model results, including point values of head and discharge. We will begin by checking point values, Enter the module by typing

```
check
```

CZAEM responds with

```
\\\  Module=CHECK            Level=l    Routine=INPUT
<AQUIFER><GIVEN><REFERENCE><WELL><LINESINK>
<HEAD>(X,Y)<DISCHARGE>(X,Y)<CONTROL><SUMMARY><HELP><RETURN>
```

A good test for the model is to see whether it reproduces the observed heads at the monitoring wells. Type “head” followed by the coordinates of MW#2:

```
head -542 750
```

CZAEM responds with

```
            X              Y           HEAD
 -5.420000E+02   7.500000E+02   1.282863E+02
```

Now, check the head at MW#3:

```
head 500 -500
```

CZAEM responds with

```
            X              Y           HEAD
  5.000000E+02  -5.000000E+02   1.265788E+02
```

We can also check the discharge at any point in the aquifer. As uniform flow is the only element contained in the current model, discharge will be the same throughout the flowfield. Check the discharge at the origin.

```
discharge 0 0
```

CZAEM responds with

```
 X        , Y            0. 000000E+000. 000000E+00
QX        , QY           9.659258E-02   2.588191E-02
```

The results are consistent with the field data. Commands <REFERENCE>, <AQUIFER>, <GIVEN>, <CONTROL>, <WELL>, and <LINESINK> in module CHECK allow the user to check input data. Enter each command to check your input. Only the first four commands apply to the current model. When you are finished, return to the MAIN menu,

```
ret
```

The model of existing conditions is now complete. To test the proposed pumpout system design, a well must be added near the plume, Ideally, the reference point should be far enough away from the area of interest so that elements added to the model (in this case a well) have a minimal effect on the head at the reference point. Here, the reference point must be moved away from the area of interest. The problem is easily handled in this simple case. Use the above model to check the head far from the plume. A reasonable choice here may be (-2000,-2000).

```
che
  head -2000 -2000
```

CZAEM computes the head at the entered coordinates and responds

```
            X              Y           HEAD
 -2.000000E+03  -2.000000E+03   1.335864E+02
```

Return to the MAIN menu.

```
ret
```

Use the results to set a new reference point at -2000, -2000.

```
ref
  -2000 -2000 133.586
```

CZAEM stores only one reference point. Adding the reference point at -2000,-2000 replaces the previous reference point. Solve, grid, and plot the revised solution (Figure 4.4).

```
solve
grid 40
plot
  d 20
    [enter]
```

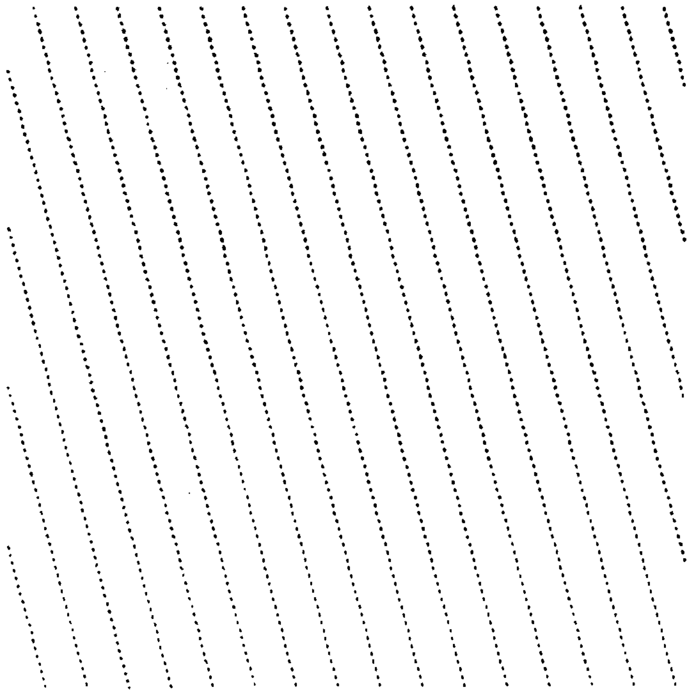

Figure 4.4 *Existing conditions: uniform flow with reference head of 133.586 meters at (–2000, –2000).*

The solution should be exactly the same as the prior solution. To verify this, enter the check module and once again check the heads at the monitoring wells using the same command sequence as before, If the data has been entered correctly, the results will be consistent with the field data.

Now use MAP to identify visually the plume and monitoring wells on the screen. The command <POINT> is used to show the locations of the monitoring wells (Figure 4.1). Field data provide coordinates of points on the perimeter of the plume (Figure 4.1), which are plotted with < CURVE>,

```
map
  plot on
  point
   -750 -875
   -542  750
    500 -500
  curve
   -500  568
   -300    0
   -583 -891
   -800 -200
   -500  568
```

```
ret
```

Check the locations of the input data using the layout command from the MAIN menu.

```
layout
```

The layout of the various elements of the model will appear on the screen without the head contours.

The proposed pumpout system includes a well at coordinates (100, 20) withdrawing 220 m^3/day. To check that the system captures the entire plume, add the well to the model from the MAIN menu by entering

```
well
  giv
   100  20  220  0.1
 ret
```

Solve, and grid the results.

```
solve
grid 40
```

Several methods may be used to check the adequacy of the well. The simplest method is to use the command <TRACE> in the module TRACE to draw forward pathlines from the plume boundary to the well. A second approach is to use <WGENENERATE> in the module TRACE to draw backward pathlines from the well. The approach we will use here is to enter CAPZONE from the module TRACE. Once in module CAP ZONE use the command <SUBZONE> to generate the capture zone envelopes for the well. Input the following sequence

```
trace
  CAPZONE
    d
     [enter]
```

The contoured solution will be plotted on the screen (Figure 4.5).

Move the cursor to the discharge well. Use the [insert] key to reduce the cursor step size. Create the subzones for the well

```
subzone
```

The capture zone envelope will be displayed on the screen, Figure 4.6. The entire plume is captured by the well. The pumpout system appears to be adequate, but we will check conditions at the well for any possible problems. Return to the MAIN module and enter the CHECK module,

```
   ret
 ret
check
  head 100 20
```

CZAEM responds with

```
            X              Y           HEAD
  1.000000E+02   2.000000E+01   1.181211E+02
```

Note that the head at the well is below the elevation of the confining unit; flow near the well is unconfined. CZAEM handles cases of combined confined/unconfined flow directly—the solution is correct. However, you may wish to maintain confined conditions at the well. To achieve this, the discharge of the well must be reduced. The plume may still be captured while maintaining confined conditions by adding a second discharge well downgradient from the first. We will reduce

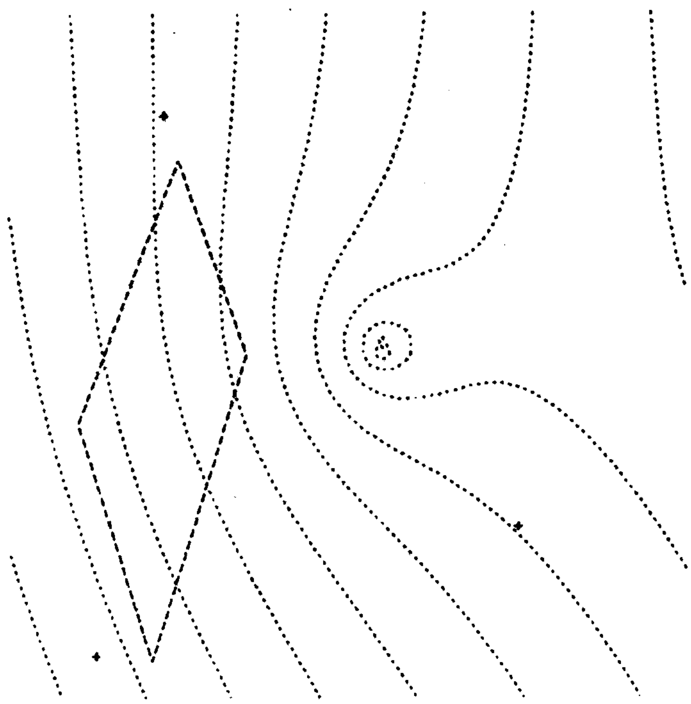

Figure 4.5 *Contours with the well present.*

the discharge of Well 1 to 110 m^3/day and add a second well discharging at the same rate 200 meters downgradient from the first. Return to the MAIN menu and reset Well 1;

```
 ret
well
  reset
  y
  giv
    100 20 110 0.1
```

Well 2 may be added directly at this point

```
    293.2 71.76 110 0.1
 ret
```

Determining capture zones for multiple wells.

We again wish to use the module CAPZONE to determine the capture zone envelopes for the two discharge wells using the command <SUBZONE>, but this time we will use layout and not plot the contours.

```
solve
tra
  cap
    1
    [enter]
```

Move the cursor to the leftmost well (from now on we will refer to the leftmost discharge well as Well 1 and the rightmost discharge well as Well 2).

```
sub
```

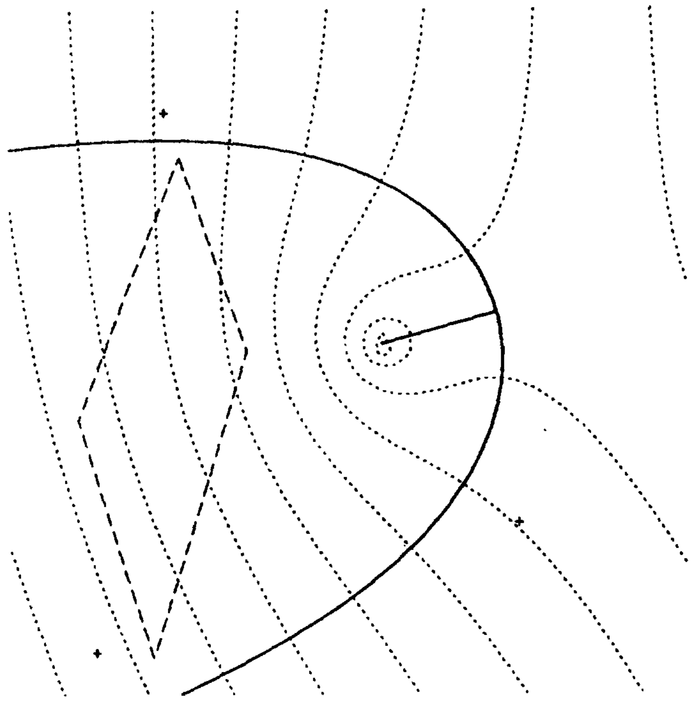

Figure 4.6 *Subzones drawn for the well.*

The capture zone envelope for Well 1 will be recomputed and displayed. Move the cursor to Well 2.

```
sub
```

The capture zone envelope for Well 2 will be displayed (Figure 4.7). Note that the entire plume lies within the combined capture zone envelope for both wells. Return to the MAIN menu and enter module CHECK to see that both wells remain in confined conditions.

Well water travel times.

Additional pertinent information may be obtained from CZAEM Next, we will generate time capture zones for each discharge well to determine how long the wells must operate for their capture zones to reach the plume. A time zone provides the zone of water that a well will capture if operated for a specified period of time. For example, the water at the edge of a five-year time zone will be captured by the well if it pumps continuously for five years. Return to module CAPZONE from the MAIN module.

```
trace
  cap
    1
     [enter]
```

Move the cursor to Well 1 and enter the command <TIMEZONE>

```
time
```

CZAEM responds with

```
CALCULATING  SUBZONES PHASE 1:   CREATING INITIAL PATHLINES FROM THE WELL
    10 . . . . . . . . .
```

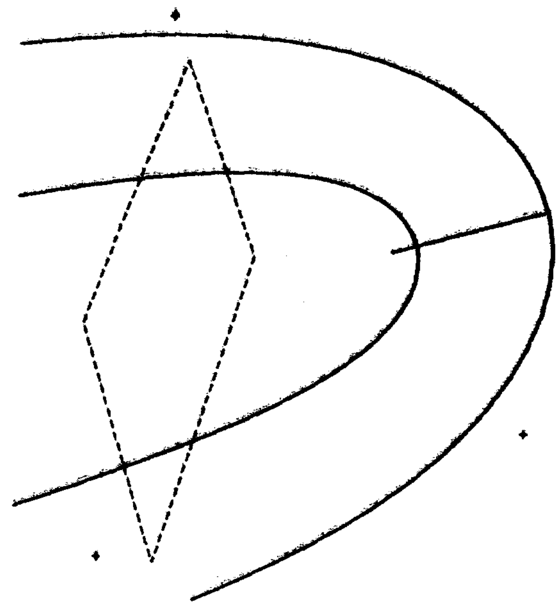

Figure 4.7 *Subzone curves for both wells.*

```
   20 . . . . . . . .
   30 .
CALCULATING  SUBZONES PHASE 2: DETERMINING LOCATION OF STAGNATION POINTS
   10 . . . . . . . .
   20 . . . . . . . .
   30 .
CALCULATING  SUBZONES PHASE 3:  FILLING SUBZONS BUFFERS
   10 . . . . . . . .
ENTER <MINIMUM TIME> [TIME STEP] [MAXIMUM TIME], OR
<R>EDRAW LAST TIME ZONES, OR <D>EFAULT TIME ZONES, OR<E>XIT
MINIMUM  AND  MAXIMUM  TIMES  FOR  CAPTURE  ZONE:  0.00000E+00  4.7S038E+04
```

You may enter <D> for default to generate ten equal increment time zones on the screen. CZAEM determines the increment based on window size. Here we will enter a starting time zone and five increments of twenty years each (7300 days)

```
  7300 7300 36500
```

CZAEM computes and draws the capture zones in 20-year increments. Note that for Well 1, more than 20 years of continuous pumping are required to reach the plume. Move the cursor to Well 2 and repeat

```
time
  7300 7300 36500
```

Twenty-year time zones will be displayed for Well 2 (Figure 4.8). We see that 60 years of continuous pumping are required to reach the plume. The time zones computed so far are based on water velocity. CZAEM allows the user to input a contaminant front velocity as a factor of the water velocity. The velocity factor is capable of describing hydrodynamic dispersion (Strack, 1992) and sorption and must be determined by field studies. Here we will assume a factor of 1.1 has been determined. While in module CAPZONE, set a front velocity factor.

```
front on 1.1
```

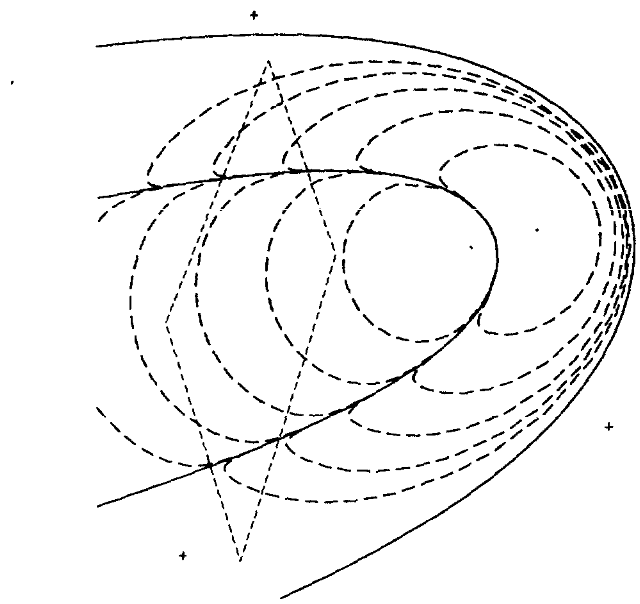

Figure 4.8 *Twenty year time zones for Wells 1 and 2*

Now move the cursor to Well 1 and enter the <TIMEZONE> command.

```
time
  7300 7300 36500
```

New time zones are computed based on the velocity of the front and plotted over the previously computed time zones. Move the cursor to Well 2 and repeat (Figure 4.9). Note that time zones with or without a front factor do not provide information as to how long pumps must operate to capture all of a contaminant; only the time required for the contaminant front to reach the well is provided.

Moving wells in graphics mode.

The pumpout system described here requires long periods of continuous pumping before ever reaching the contaminant. To refine the design, the user may wish to move the discharge wells closer to the plume and/or examine different combinations of wells and discharges. This may be done by resetting the wells as was previously done, or it may be done directly on the graphics screen using the command <WLMOVE> in module CURSOR. Exit both CAPZONE and TRACE, return to the MAIN command line, enter CURSOR, and draw a layout as follows:

```
   ret
 ret
cursor
```

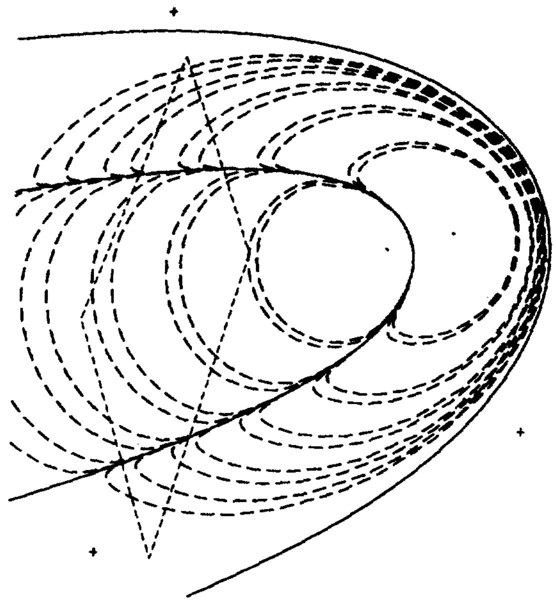

Figure 4.9 *Twenty-year time zones for the fronts, with a front velocity factor of 1.1.*

```
lay
  [enter]
```

Move the cursor to Well 1

```
wlmove
```

CZAEM responds with

```
PLEASE RE-POSITION CURSOR AND PRESS ENTER
```

Move the cursor to the location where you wish to place the well. If the cursor was not originally close to the well, CZAEM will prompt the user to set a new tolerance.

```
WELL NOT FOUND; MOVE CURSOR CLOSER OR RESET TOLERANCE
```

Enter

```
TOL
```

CZAEM responds with

```
PLSASE RE-POSITION CURSOR AND PRESS ENTER
```

Move the cursor one step and enter

```
[enter]
```

A new tolerance is now set and CZAEM responds

```
RTOL=   5.000000E+01
```

Now move the cursor to the well and enter <WLMOVE>

```
Wlmove
```

CZAEM responds with

```
PLEASE RE-POSITION CURSOR AND PRESS ENTER
```

Move the cursor to a new position where you wish to place the well and press enter.

```
[enter]
```

The well is moved to the new position and CZAEM responds with

```
DISCHARGE-SPECIFIED  WELL  NR  1
POSITION CHANGED FROM
  0.100000E+03   0.200000E+02
To
 -0.166633E+03  -0.832S61E+02
CURSOR POSITION (X,Y):   -0.166633E+03  -0.832S61E+02
```

Solve, grid and plot to check the results. Note that <WLMOVE> allows the user to change the well location and discharge simultaneously simply by entering the new discharge following <WLMOVE>. This process may be repeated until an optimal design is obtained.

EXAMPLE 5. DATA MANIPULATION AND MODEL REFINEMENT

Example 5 will build on the model created in Examples 2 and 3. The model will be refined and entered via a data file instead of via the keyboard.

Using input files.

The input file `example5.dat` is included in the CZAEM directory and is listed below:

```
 * input echo off
 ret
win -1000 -1000 1000 1000
aqui
  perm    5
  thick  50
  base    0
  por   0.25
  ret
giv
  uni  0.5  30
  ret
line
  head
    -1500  1500  -600  1300  32
     -600  1300  -200   900  33
     -200   900   200   500  34
      200   500   500   200  35
      500   200   500  -800  37.5
      500  -800   800 -1000  38
      800 -1000  1100  -1000  39
     1100 -1000  1500  -1800  40
  ret
ref
  -2000  4000  40
well
  given
    0 0 1000 0.3
   ret
solve
swi
```

```
end
```

The asterisk (*) indicates a comment statement and CZAEM shall disregard all information to the right of the asterisk on that line. The data file applies to Examples 2 and 3 with a well discharging 1000 m^3/day. To confirm this, start CZAEM and enter module SWITCH from the MAIN command line.

```
switch
```

CZAEM responds with

```
\\\  ROUTINE  SWITCH                                              ///
<PREFIX>[<INPUT/OUTPUT/READ/SAVE/HELP>(PREFIX)]
<INPUT/OUTPUT/MESSSAGES/ERROR>[<ECHO  ON/OFF/APPEND>](FILE  NAME)[LOGICAL  UNIT]
<LOG  ON/OFF>[FILE  NAME][LOGICAL  UNIT]
<CALL>(FILENAME)<BACK><HELP><RETURN>
```

The command PREFIX sets the DOS directory where files are either read or sent. The CZAEM directory is currently the default and is specified by the file `initaem.dat`. The second set of command words in SWITCH dictates how and where to send input data and program feedback. Further information on these features is contained in the help file in this module. When a file is read in, the input and any CZAEM error messages will scroll quickly up the monitor. To record this information to a file, enter

```
log on example5.log
```

This creates a transcript of all information displayed on the screen (aside from graphics) which may be consulted after exiting or when using PAUSE from the MAIN menu. If the command LOG ON is not followed by a file name, the information is sent to the file `log.dat` by default. To read in the data file, enter either

```
call example5.dat
```

or

```
ret
swi example5.dat
```

Both of these command sequences accomplish the same. It is important to do only one or the other, otherwise the data will be superimposed. We must RESET from the MAIN command line before calling in the same data file the second time. Try reading in the data both ways. Also, remove the asterisks on the first two lines and read in the file to see the effects of the command INPUT ECHO OFF. Note that INPUT ECHO OFF is disabled after reading each file and only the input is not displayed (the solve response is still shown on the monitor).

Saving grid files.

Enter <GRID> 50 and plot. Notice that the results are the same as in Example 3 where the data were entered manually. After viewing, enter c SAVE>; save the current grid by typing

```
save
  grid
```

CZAEM responds with

```
<FILENAME><R>{to  abort}
```

Enter the filename

```
sol1.g50
```

The filename is arbitrary and the extension (.g50) reflects the number of grid points chosen.

Now we will refine the model elements. Recall that head-specified line-sinks approximate a constant head boundary along each line segment by specifying the head at the midpoint and determining a constant discharge rate along the segment. The results are approximate as the head matches only at the midpoint. To refine the model we divide the long line–sink nearest the well into several smaller head-specified line–sinks. This provides more control points and a better approximation along the bank. Field data provides the new information. Exit CZAEM and replace the line–sinks by editing the data file `example5.dat` with the following:

```
line
 string on
  head
    -1500  1500  -600  1300  32
     -600  1300  -200   900  33
     -200   900   200   500  34
      200   500   400   300  34.7
      400   300   500  -100  35.5
      500  -100   500  -300  36.0
      500  -200   500  -325  36.5
      500  -325   500  -400  37.0
      500  -400   470  -500  37.2
      470  -300   480  -600  37.3
      460  -600   500  -700  37.4
      500  -700   530  -800  37.8
      530  -800   600  -900  38.0
      600  -900   800 -1000  38.2
      800 -1000  1100 -1000  39
     1100 -1000  1500 -1800  40
  ret
```

Save the file with the new data, enter CZAEM and read in the file with the <SWITCH> command.

```
switch  exemple5.dat
```

A command present in the data file which has not yet been explained is the <STRING ON> command in the module LINESINK. Line–sinks may act as sources to a well (Example 3) and subzones will be computed for each line–sink segment. This requires much computational time and generates data which may not be of interest. For example, each line segment will be identified as an individual source; often a user will only be interested in the total amount of water pumped from a river, not the amount pumped from small segments. The <STRING ON> command is used to link line–sink segments together which will then act as a single source in subzone computations.

Comparing grids.

Enter <Grid> 50 and plot the results in the module CAP ZONE. Create subzones and note that the well no longer draws river water at a discharge of 1000 m^3/day (Figure 5.1). Refining the line-sinks has improved our model and we can now determine a safe pumping level more accurately. The subzone boundary has changed significantly due to the refinements, but the user may wish to know the extent to which heads have changed in the refined model.

Return to the command line of the MAIN module and enter the module READ. We will contour the difference between the original model and the refined model by entering

```
read
```

CZAEM responds with

```
<SOLUTION><GRID><BOTH><DIFGRID><RETURN>
```

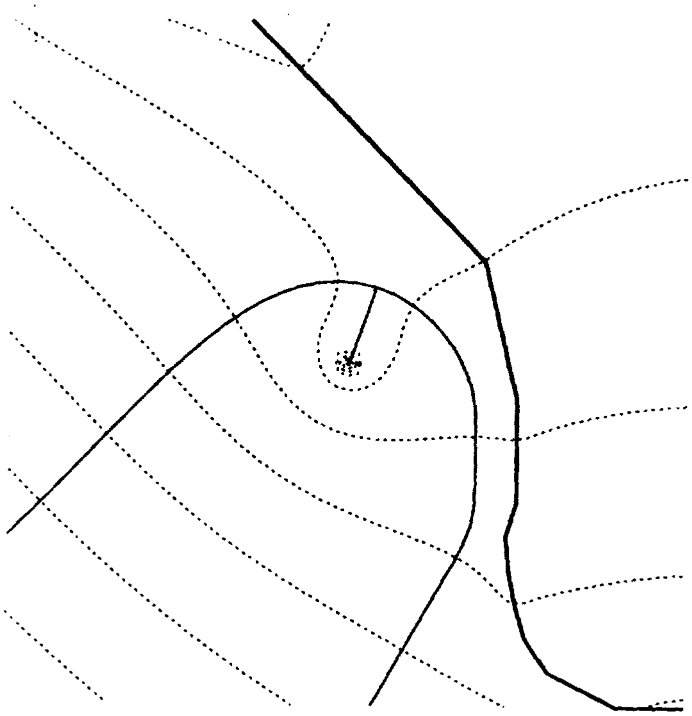

Figure 5.1 *Case of Example 3 with refined line-sinks.*

enter

```
difgrid
```

CZAEM responds with

```
PLEASE ENTER FILENAME; <R> TO ABORT
```

enter the filename of the grid previously saved

```
so1l.g50
```

CZAEM responds with

```
GRIDFILE HAS BEEN SUBTRACTED FROM CURRENT GRID
```

and control returns to the MAIN command line. Enter the module PLOT and CZAEM responds with

```
<D>EFAULT[NUMEER   OF   LEVELS]<L>AYOUT
 (MIN LEVEL [INCREMENT {>0}] [MAX LEVEL]
 (MAX LEVEL [DECREMENT {<0}] [MIN LEVEL]
MIN. LEVEL=  -9.516754E-01 MAX. LEVEL=   9.555435E-02
```

These numbers represent the minimum and maximum head differences between the two models. Contour the difgrid by entering

```
d 10
```

and observe the graphical results (Figure 5.2). We see that the greatest difference in head occurred at the river where the contour lines are concentrated the most (here the head is approximately 1

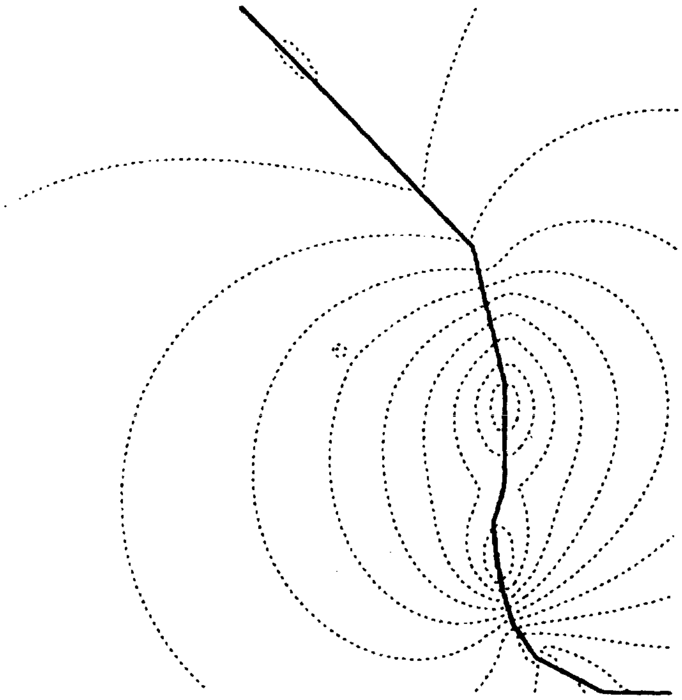

Figure 5.2 *Refined line-sink grid minus the original line-sink grid.*

meter less in the refined model than in the original model). When using DIFGRID to examine head differences, both the number of grid points and the window size must be the same between models.

Obtaining results using the cursor in CAPZONE.

Several additional options exist within module CAPZONE to check results. Regrid the original solution from the MAIN command line and enter the module CAPZONE. Position the cursor over the well and enter

```
coordinate
surface
base
```

and CZAEM responds with

```
  2.235174E-05   2.235174E-05
UNCONFINED:  X,Y,  PHREATIC  SURFACE  2.235174E-05  2.235174E-05  2.924427E+01
X,Y,BASE      2.235174E-05   2.235174E-05   0.000000E+00
```

respectively. Now return to TRACE and enter

```
cursor off
```

This moves control from the cursor to the keyboard. Enter CAPZONE and generate a plot of the solution (grid again if you wish to see piezometric contours instead of difference contours). SURFACE and BASE may still be used to check data, but the commands must be followed by the coordinates of the point to be checked. Check the phreatic surface elevation at coordinates (500, 500). Enter

```
surface 500 500
```

CZAEM responds with

```
UNCONFINED: X,Y, PHREATIC SURFACE 0. 000000E+00 0. 000000E+00 2.924426E+01
```

Note that SUBZONE, TIMEZONE, and WGENERATE may also be used in CURSOR OFF mode by following the command with coordinates of the well of interest.

Validity of Solutions.

Sometimes a solution appears to be correct when observing the graphics, but may not be valid. A clear example of this is a well which pumps the water table below the aquifer base or below the actual vertical extent of the well. Checking the validity of a solution is always necessary, CHECK, CURSOR, SURFACE, BASE, and COORDINATE have already been introduced as methods of checking a solution. Here we will introduce CONTROL in the module CHECK, Note that CONTROL appears in check levels 1 and 2. CONTROL allows the user to check input and computed values at control points. Entering CONTROL from check level 1 will produce a listing of all control point coordinates, specified heads, and computed heads. Large differences between specified and computed values indicate erroneous results. Return to the MAIN command line and enter the module CHECK. Enter CONTROL and observe CZAEM'S response. Now, enter check level 2 by entering LINESINK and CONTROL. Only the line-sink control points are listed. The CONTROL command is also located within REFERENCE in the CHECK module.

EXAMPLE 6. DATA FILE AND GRAPHICS CONTROL

A city located adjacent to a large river is expanding its corporate boundaries and developing an industrial park. The city maintains two water supply wells each operating at 100 million gallons per year; the existing wells are inadequate to handle new demands. Three new wells are proposed, and their locations have been determined previously. The city wishes to enforce land–use zoning near the proposed well–field to protect its water supply from contamination. The existing and proposed well–fields are to be modeled and time zones delineated to aid in zoning decisions.

Accessing multiple data files contiguously.

Data files have been compiled for the model using an ASCII editor and are included in the CZAEM directory. While data files can always be created in this manner, they can also be produced with the assistance of the Geographic Analytic Element Pre-processor (GAEP) developed by Kelson et. al., 1993. The data files and descriptions follow:

`map.dat`	contains township and range lines, corporate boundaries, and proposed industrial park limits;
`line.dat`	contains line-sinks which model the major river and tributary near the city;
`exist.dat`	contains aquifer parameters, rain, and existing well data; and
`well.dat`	contains proposed well information.
`call.dat`	contains call commands to the preceding data files.

Use of the data files will be taught by example. The user is encouraged to examine and evaluate each data file line by line and to run the example by using `call.dat` and by calling each data file individually. The model area is larger than previous examples, consisting of 12 townships. Township boundaries are included in the `map.dat` file. Consistent English units (feet, days) are used in this problem.

From the MAIN command line, enter the module SWITCH and read in the data

```
call call. dat
```

The `call.dat` file includes calls to `map.dat`, `line.dat`, and `exist.dat`. All data will scroll past the screen and control will return to the keyboard at the MAIN command line. All elements for reproducing existing conditions have been read in. Solve, grid the solution, and plot the model of existing conditions (Figure 6.1).

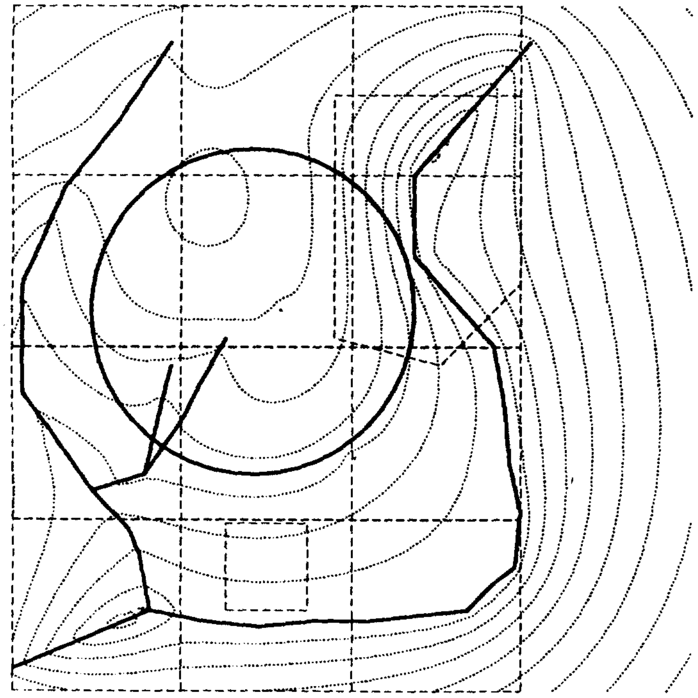

Figure 6.1 *Model of existing conditions (plot; d 10).*

Entering rainfall.

All elements in the model of the existing conditions have been discussed previously except for <RAIN>. The RAIN element models a constant infiltration rate over a circular area; the user must provide centroid coordinates, a radius over which the infiltration acts, and an infiltration rate in units of length per time. The circle in Figure 6.1 shows the area of infiltration. <RAIN> is contained in the module GIVEN. The <RAIN> command for the present model may be found in data file `exist.dat`. Note that <RAIN> by itself creates a mound of water in the northwest portion of the model.

Window manipulation and saving capture zone and time zone boundaries.

The proposed conditions may now be evaluated. Return to the module SWITCH and call the data file containing the proposed well information.

```
call
 well.dat
```

The data are read and control is returned to the keyboard at the MAIN command line. Solve and grid the solution (Figure 6.2).

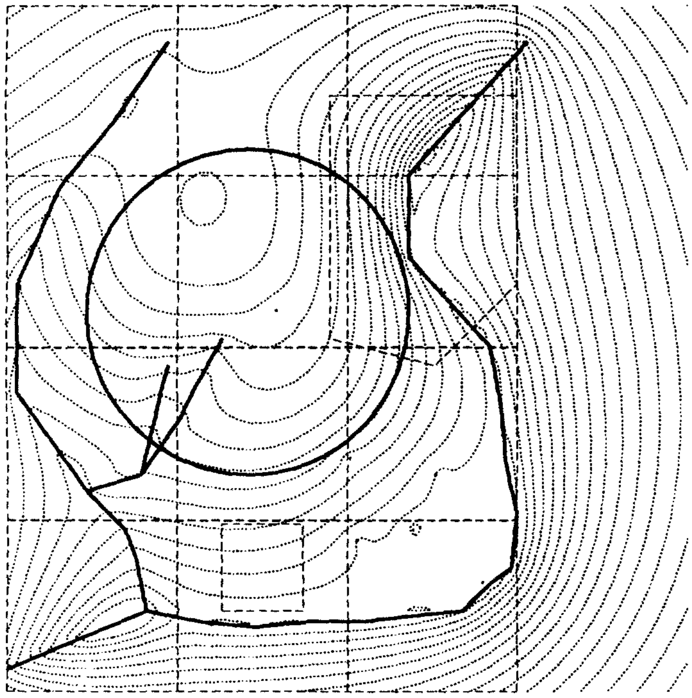

Figure 6.2 *Model of proposed conditions (plot; 780 5).*

Within module CAPZONE move the cursor to the northernmost well and enter <SUB>. CZAEM responds with

```
CALCULATING SUBZONES PHASE 1:  CREATING INITIAL PATHLINSS FROM THE WELL
CALCULATING SUBZONES PHASE 2:  DETERMINING LOCATION OF STAGNATION POINTS
CALCULATING SUBZONES PHASE 3: FILLING SUBZONE BUFFERS
CAPTURE ZONES CAN NOT BE CREATED:
   NO STAGNATION POINTS FOUND IN THE WINDOW, CHANGE WINDOW SIZE
```

The scale of the current window is too large to evaluate the stagnation point caused by the well. To produce a subzone, we must reduce the window size. First, store the current window plot with the <WIN PUSH> command. Enter

```
win push
```

The <WIN PUSH> command stores the current window in a stack; the <WIN POP> command recalls the last window which has been stored in the stack. Now, reduce the window size with the <WLL> command. Position the cursor at the lower left corner of the township containing the well. Enter

```
wll
```

CZAEM responds with

```
PLEASE REPOSITION CURSOR AND PRESS ENTER OR ANY OTHER KEY TO ABORT
```

Move the cursor upward and to the right. The cursor will drag a box with a lower left hand corner at the initial position of the cursor. Move the cursor until the box encloses the area of interest (the area in which you would expect the subzone to be created - in this case, the entire township containing the well) and press enter. The new window will be zoomed in on and a layout will be displayed. Before creating the subzone with the <SUB> command, enter

```
bsave
```

The <BSAVE> command opens a file which stores all computed subzone and time zone boundaries. CZAEM responds with

```
<FIIENAME><R>to abort
```

Enter the filename

```
well.bnd
```

All subzones created will be saved in `well.bnd` until the user leaves module CAPZONE or enters the <PAGE> command. Leaving CAPZONE closes the file; entering <PAGE> erases the file. The saved file may be recalled by the <BREAD> command. Now, move the cursor to the well and create the subzone with the <SUB> command. When the subzone is created, return to the large scale window by entering

```
win pop
```

The original large-scale window will appear with the subzone drawn around the northernmost well. Now, instead of using <WLL> to create a smaller window around the remaining four wells, use the <WINDOW> command. Enter

```
windov 34000 22000 87000 75000
```

The new window containing the four remaining wells will appear with a layout. Create subzones for each well. This time we will return to a large–scale window by using the <WIN ALL> command. Enter

```
win a1l
```

A large–scale window which includes all elements will appear with the subzones included (Figure 6.3). The shapes of the subzones appear in teardrop form and are finite, In this model, rain is the only source of water in the area of interest.

Recall that subzone computations end at the border of the window in which they are computed. As a result, subzone boundaries may be incomplete when viewed within a larger window.

Recall that <BSAVE> was entered before creating any subzones, but we have not yet needed <BREAD>. Computed boundaries will remain on screen until the module CAPZONE is left or the <PAGE> command is used. To demonstrate the use of <BREAD> exit CAP ZONE and TRACE. Reset the window size

```
window 0 0 130000 130000
```

Enter CAPZONE and plot the layout. Note that the proper layout appears, but the subzones are no longer present. To reproduce the subzones, read the boundary file `well.bnd`.

```
bread
```

CZAEM responds with

```
<FILENAME> <R>to abort
```

Enter the filename

```
well.bnd
```

The subzones are displayed on the screen. Now create time zones for each well on which the city will base land–use planning.

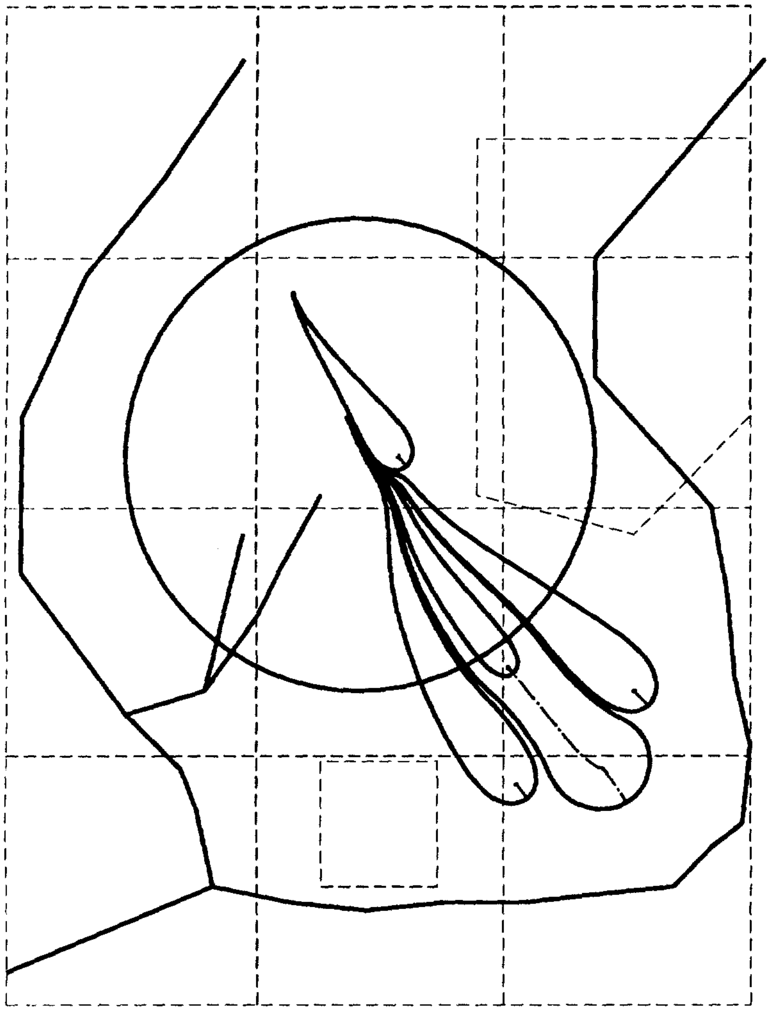

Figure 6.3 *Well-jield subzones.*

Obtaining a hardcopy of graphical output.

To obtain a hardcopy of Figure 6.1, we must route the output to a printer instead of the screen. When CZAEM was installed on your computer, you were prompted for the type of printer device you use. It is assumed here that you chose a postscript device and therefore will create a postscript file instead of directly accessing a printer. This operation is done in the module PSET. Return to the MAIN module and enter PSET.

```
    ret
  ret
pset
```

CZAEM responds with the command line

```
\\\ ROUTINE SET PLOT MODE                                              ///
<PRINTER><SCREEN><DRIVER><PALETTE>(NUMBER)<MOUSE>(<ON>/<OFF>)<HELP><RETURN>
```

To print, type

```
  printer
ret
plot
  d 10
   [enter]
   [enter]
   [enter]
```

This will create a postscript file of the plot called **plot.ps**. CZAEM sends all the graphics to the file instead of the screen. To redirect graphical output to the screen, enter

```
pset
  screen
```

To produce the hardcopy, exit CZAEM and print by typing

```
  ret
stop
print plot.ps
```

Note that no plot appears on the screen as graphical output is redirected to the file. This poses a difficulty in creating plots in TRACE and CAPZONE, where the cursor is used to identify wells or starting points of streamlines.

To obtain hardcopies of streamline traces and capture zones, we first create the plots with the screen as the graphical output device and record our input onto a file. We then direct graphical output to the printer and retrace our steps to produce the plot using the recorded input file as a guideline. In this way we can locate the cursor at desired locations without seeing it on the screen. We turn the cursor off prior to creating the printer file, and manually enter the coordinates of where to begin trace lines or capture zones.

To create the plot on the printer of the subzone boundaries for the well at (6.4e4,4.3e4) for the window 34000220008700075000, enter the following commands:

```
window 34000 22000 87000 75000
grid 50
pset
  printer
  ret
trace
  cursor off
  capzone
    d
     [enter]
     [enter]
    6,4e4 4.3e4 subzone
    ret
  ret
stop
```

Entering the coordinates 6.4e4,4.3e4 in front of the subzone command has the same effect as moving the cursor to the well at that location. The hardcopy is produced in the same manner as before.

The remaining commands in PSET are as follows. The command <PALETTE> followed by the number 1, 2, 3, or 4 results in different combinations of line colors in graphical output. The command <MOUSE> will enable or disable the use of a mouse for cursor movement in graphics mode. If your PC supports a mouse, CZAEM defaults the command MOUSE to ON unless otherwise specified in the file **`initaem.dat`**. For consistency with this tutorial, the line 'mouse off' was placed in the file. To default to MOUSE ON, remove the indicated line in the **`initaem.dat`** file. The command <DRIVER> is explained in the ASCII file read. me in the CZAEM directory.

REFERENCES

Kelson, V. A., H. M. Haitjema, S.R. Kraemer, 1993. GAEP: a geographlc preprocessor for ground-water flow modeling, *Hydrological Science & Technology, 8(1–4): 74–83*.

Strack, O.D.L. *Groundwater Mechanics,* Prentice Hall, Englewood Cliffs, N. Y., 1989.

Strack, O. D. L., 1992: A mathematical model for dispersion with a moving front in groundwater, *Water Resources Research, 28* (11), 2973-2980.

USEPA 1994. Program documentation for WhAEM Wellhead Analytic Element Model), Robert S. Kerr Environmental Research Laboratory, Ada, OK, in press.

COMMAND SUMMARY

Command	Description	Page(s)
Aquifer	input module for aquifer parameters	6,12,30
permeability	Hydraulic conductivity in [L/T]; default is 1.0	6
thickness	Thickness of the aquifer; default is 1.0	6
base	Elevation of the aquifer base; default is 0.0	6
porosity	Effective porosity; default is 0.3	6
reset	Clears all the input data in module AQUIFER; resets to default values	24
help	Extended help for the module AQUIFER	
return	Exit to the MAIN menu	5-6
Given	Input module for uniform flow and infiltration	6-7
uniflow	Uniform far field component	7
rain	infiltration or evaporation rate at the top of the aquifer in [L/T]	46
reset	Clears all the input data in module GIVEN	24
help	Extended help for the module GIVEN	
return	Exit to the MAIN menu	5-6,7-8
Reference	Enter the reference point parameters	8,15,17-18,32-33
Well	Input module for wells	10,16,34-35
given	Well with given discharge	10,16
reset	Clear all the well input data	24,35
help ‘	Extended help for the module WELL	
return	Exit to the MAIN menu	5-6,10
Linesink	Input module for line-sink	13-15,42
given	Line-sinks with given discharge (per unit length of the line-sink)	14
head	Line-sinks with head specified at the midpoint	14
string	Make a series of line-sinks to be treated as one source in CAPZONE	42
tolerance	Tolerance used for joining the nodes of line-sinks when STRING is ON	39
reset	Clear all the line-sink input data	24
help	Extended help for the module LINESINK	
return	Exit to the MAIN menu	5-6,14
Solve	Solve the current problem	8,10,17
Check	Check the solution and the input data	15,31,45
aquifer	Check module for aquifer parameters	32
summary	General information on aquifer	
return	Exit to the CHECK menu	5-6,32
given	Check module for uniform flow and infiltration parameters	32
summary	General information on uniform flow and infiltration	
uniflow	General information on uniform flow	
rain	General information on rainfall	

Check			
	help	Extended help for GIVEN commands	
	return	Exit to the CHECK menu	5-6,32
reference		Check module for reference point parameters	32-33,45
	control	Comparison of the condition at the reference point with the computed value	45
	return	Exit to the CHECK menu	5-6
well		Check module for well parameters	32
	summary	General information on wells	
	range	Specify the start and end well numbers to be checked	
	input	Display locations and radii of all wells	
	control	Display the control point conditions and the computed, values for the wells	45
	help	Extended help for WELL commands	
	return	Exit to the CHECK menu	5-6
linesink		Check module for line-sink parameters	32
	summary	General information on line-sinks	45
	range	Specify the start and end line-sink numbers to be checked	
	string	Displays all the string information	
	ends	Display end coordinates of line-sinks	
	bval	Display boundary conditions of line-sinks	
	discharge	Display discharges of the line-sinks	
	control	Display the control point conditions and the computed values for the line-sink	45
	help	Extended help for LINESINK commands	
	return	Exit to the CHECK menu	5-6
head		Display the head value at a point	15,32,34
discharge		Display the discharge components at a point	32
control		Comparison of conditions at the control points with computed values	32,45
summary		General information about all the modules	
help		Extended help for the module CHECK	
return		Exit to MAIN menu	5-6,32
Window		Set the viewing area;	8,10,46-48
		WINDOW ALL sets the viewing area to include ALL elements;	48
		WINDOW PUSH saves the window setting and	47
		WINDOW POP retrieves the window settings (in the order in which they were saved via PUSH);	47,48
		WINDOW without any options displays the current viewing area	
Map		Input module for a map or diagram of the modeled area	11,33
curve		Begin entry of curve coordinates	11,33
point		Begin entry of point coordinates	33
plot		Turn display of the map ON or OFF	11
reset		Clear all the MAP input	24

Map				
	help		Extended help for the module MAP	
	return		Exit to MAIN menu	5-6
Layout			Plot all the elements within the current window on the screen	15,34
Grid			Compute head values at the nodes of a mesh; used by PLOT to create head contours	8
Plot			Plot the contours computed by grid on the screen	9
Trace			Determine streamlines or capture zones	10,19
	window		See extended help for this command	
	tolerance		Tolerance used for determining which well the cursor is on	39
	cursor		See extended help for this command	44
	switch		Input/output operations	40-41,42,45
		prefix	Specify DOS path for the input and output files	41
		input	Read a data file. With ECHO, copy input to a file	41
		output	Write output to a file. With ECHO copy output to a file	
		messages	Write messages to a file. With ECHO copy messages to a file	
		error	Write errors to a file. With ECHO copy errors to a file	
		log	Create a log of all input/output operations	41
		call	Read a data file	41,45-46
		back	Return control to an input file from SWITCH	
		help	Extended help for the module SWITCH	41
		return	Exit from SWITCH module	5-6
	set		Set TRACE options	
		maxstep	Set the maximum step size for tracing the particle pathlines	
		backward	Set pathlines to be trace in the backward direction	19
		front	Activate computation of solute front; requires an optional velocity factor multiplied by the average velocity to compute the front position.	37-38
	marker		See extended help for this command	
		help	Extended help for SET commands	
		return	Exit to the TRACE menu	5-6
	plot		Plot the piezometric contours and allow user to trace pathlines	10,20
		base	Display base of the aquifer at the cursor location	44
		surface	Display surface of the aquifer at the cursor location	44
		coordinate	Display coordinates of the cursor location	44
		trace	Determine and display streamline through cursor location	10,34
		backward	Enable backward tracing of pathlines	19-20
		wgenerate	Generate a specified number of pathlines from a well by backward tracing	19-20,34
		wll	Set the lower left corner of the new window	47
		tol	Set the tolerance for well identification graphically	39
		command	Display command words	14

Trace			
	menu	Exit to the TRACE menu	5-6
	return	Exit to the MAIN menu	5-6,21
layout		Display layout of elements and allow user to trace pathlines	20
	base	Display base of the aquifer at the cursor location	44
	surface	Display surface of the aquifer at the cursor location	44
	coordinate	Display coordinates of the cursor location	44
	trace	Determine and display streamline through cursor location	10-11,34
	backward	Enable backward tracing of pathlines	19-20
	wgenerate	Generate a specified number of pathlines from a well by backward tracing	19-20,34
	wll	Set the lower left corner of the new window	47
	tol	Set the tolerance for well identification graphically	39
	command	Display command words	14
	menu	Exit to the TRACE menu	5-6
	return	Exit to the MAIN menu	5-6,21
capzone		Draw capture zones for a well	22,34,35,44
	coordinate	Display coordinates of the cursor location	44
	base	Display base of the aquifer at the cursor location	44
	surface	Display surface of the aquifer at the cursor location	44
window		See extended help for this command	
	wll	Set the lower left corner of the new window	47
	subzone	Create subzones for the well at the cursor position	22,34,35-36,46-48
	timezone	Create time zones for the well at the cursor position	36-38
	source	List the sources contributing water to the well	24,26
	nline	Specify number of pathlines to be used to determine the capture zones	
	page	Clear the screen and erase BSAVE file contents	
	help	Extended help for CAPZONE commands	
	command	Display the CAPZONE commands	14
	ret urn	Exit to the TRACE menu	5-6
	front	Set the velocity factor for the solute front used in drawing the time zones	37-38
	wgenerate	Generate a specified number of pathlines from a well by backward tracing	19-20,34
	color	Specify colors for different line types; COLOR1: dividing streamlines COLOR2: time zones, COLOR3: subzone envelopes.	
	bsave	Specify a file into which subsequent capture zone boundaries will be saved	48
	bread	Clear screen, Read BSAVEd file, and draw capture zone boundaries	48
help		Extended help for the module TRACE	
return		Exit to the MAIN menu	5-6

Cursor			Enter CURSOR module for graphical data retrieval	31,38
	tolerance		Set the tolerance with which the cursor can detect an element	39
	switch		input/output operations	40-41,42,45
		prefix	Specify DOS path for the input and output files	41
		input	Read a data file. With ECHO, copy input to a file	41
		output	Write output to a file. With ECHO copy output to a file	
		messages	Write messages to a file. With ECHO copy messages to a file	
		error	Write errors to a file. With ECHO copy errors to a file	
		log	Create a log of all input/output operations	41
		call	Read a data file	41,45,46
		back	Return control to an input file from SWITCH	
		help	Extended help for the module SWITCH	41
		return	Exit from SWITCH module	5-6
	plot		Plot the piezometric contours and activate cursor	
		coordinates	Display the coordinates of the cursor location	44
		head	Display the head at the cursor location	
		discharge	Display the discharge at the cursor location	
		tolerance	Set the tolerance with which the cursor can detect an element	39
		wlmove	Move a well and optionally change its discharge; also identify a well by its number	38-40
	lsmove		See extended help for this command	
		wll	Set the lower left corner of the new window	47
		command	Display the command words in the module CURSOR	14
		menu	Exit to the CURSOR menu	5-6
		return	Exit to the MAIN menu	5-6
	layout		Display layout of elements and activate cursor	
		coordinates	Display the coordinates of the cursor location	44
		head	Display the head at the cursor location	
		discharge	Display the discharge at the cursor location	
		tolerance	Set the tolerance with which the cursor can detect an element	39
		wlmove	Move a well and optionally change its discharge; also identify a well by its number	38-40
	lsmove		See extended help for this command	
		wll	Set the lower left corner of the new window	47
		command	Display the command words in the module CURSOR	14
		menu	Exit to the CURSOR menu	5-6
		return	Exit to the MAIN menu	5-6
	help		Extended help for CURSOR commands	
	return		Exit to the MAIN menu	5-6
Help			Extended help for the command words	
Switch			Enter SWITCH module	40-41,42,45
	prefix		Specify DOS path for the input and output files	41

Switch		
input	Read a data file. With ECHO, copy input to a file	41
output	Write output to a file. With ECHO copy output to a file	
messages	Write messages to a file. With ECHO copy messages to a file	
error	Write errors to a file. With ECHO copy errors to a file	
log	Create a log of all input/output operations	41
call	Read a data file	41,45,46
back	Return control to an input file from SWITCH	
help	Extended help for the module SWITCH	41
return	Exit from SWITCH module	5-6
Save	Save a solution or grid in binary format for future use	17,41
Read	Reset the program and retrieve a solution or grid	18-19,42-43
Pause	Pause from CZAEM to access DOS	41
Reset	Clears the program of all the input data	24,41
Pset	Sets the graphical output	49-51
printer	Sends graphical output to the printer or a file	50
screen	Sends graphical output to the screen	50
driver	see read.me file for details	
palette	Sets the color attributes of the screen (NUMBER= 1,2,3 or 4)	
mouse	Turns the mouse on or off	51
help	Extended help for the module PSET	
return	Exit from the PSET module	5-6
stop	Exit the program	12

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