A DECISION SUPPORT SYSTEM FOR PUMPING TEST ANALYSIS

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Kansas Geological Survey
Open-file Report 90-40

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ABSTRACT

Analysis of pumping tests can be a difficult procedure in all except the most simple situtations. In the last few years a number of computer automated pumping test analysis programs have been developed; however, they generally are not set up to give the user information which can be used to make further decisions regarding the analysis. Usually, the user simply requests that a particular well function be fit either manually or automatically to the input data. After the fit, the program may give a simple measure of the goodness of fit. We have designed an analysis program that gives the user a number of options, with the goal of allowing him to design and analyze the pumping test in an intelligent and logical manner. First of all the program is highly modular so that pieces may be modified or added without undue effort. A number of well functions are available currently and others can be added easily. The program allows a number of variable rate pumping wells and observation wells. A graphics module allows plotting of most any variable of interest either as an x-y plot or a contour plot. The program may be run in either design or analysis mode. The design mode is useful as a guide in planning a test. Several senarios may be tried until one yielding the desired accuracy is obtained or until it becomes apparant that goal cannot be satisfied. In the design mode one can investigate the effect of adding an additional observation well, varying the pumping rate, adding a new pumping well, and varying the number of measurements made in time. In analysis mode the program simply analyzes a given amount of experimental data. However, that data may be analyzed as a whole or as rather arbitrary segments by a number of differnt well functions. In both design and analysis mode the program gives a number of diagnostic results. In addition to giving the usual statistics for the goodness of fit, the program gives a measure of the relative sensitivities of the various parameters and the correlation between pairs of parameters. The most desirable situation is to have high sensitivity to a parameter and little correlation with other parameters. Using this output, one can attempt to maximize sensitivity and minimize correlation in design mode or simply see what the limitations of the present data are in analysis mode. Sensitivity coefficients can be plotted over space and time and are the main tools used to produce a better design. Two general rules for improving the design are: collect data at space and time locations that show high sensitivity, and try to minimize the correlation between the sensitivities of the parameters of interest. In future work we will be attempting to automate some of the general procedures we have learned in an expert system to help the user in selecting an appropriate experimental design and to guide the user in model selection for the best analysis of the experimental data. The capabilities of the current system in providing the user with decision support will be illustrated with a well function incorporating simple aquifer heterogeneity.

INTRODUCTION

We have developed a program (see flow chart below) that allows the user to design and analyze a pumping test in an intelligent and logical manner. A number of well functions are available currently and others can be added easily. The program allows a number of observation wells and variable rate pumping wells. A graphics module allows plotting of almost any variable of interest. The program may be run in either design or analysis mode. Design mode is useful as a guide in planning a test. Several scenarios may be tried until one yielding parameters with the desired accuracy is obtained. In design mode one can investigate the effect of adding an additional observation well, varying the pumping rate, adding a new pumping well, and varying the number of measurements made in time. In analysis mode the program analyzes a given set of test data. In both design and analysis mode the program gives a number of diagnostic results. In addition to the usual statistics for the goodness of fit, the program gives a measure of the relative sensitivities of drawdown to the various parameters and the correlation between pairs of parameters. Two general rules for improving the design are: collect data at space and time locations that show high sensitivity, and minimize correlation between the sensitivities to parameters of interest. The program can be used in design mode to provide decision support to implement these rules. This will be illustrated with an example incorporating simple aquifer heterogeneity.

SENSITIVITY ANALYSIS

Sensitivity analysis is a valuable tool for designing pumping test strategies for the characterization of aquifers. A sensitivity coefficient can be defined for each distinct parameter of an aquifer. Plots of sensitivity coefficients over space and time indicate when and where the maximum sensitivity to a particular parameter is achieved. This information aids in the choice of an appropriate spatial and temporal sampling scheme. Sensitivity coefficients also appear in the conventional reliability analysis, allowing the estimated standard error of the parameters and their correlation to be expressed as a function of sensitivity coefficients. In general, one would like to design a spatial and temporal sampling strategy that minimizes the estimated standard error and parameter correlation. Such a strategy corresponds to sampling in regions of maximum sensitivity while trying to minimize the correlation between sensitivity coefficients.

EXAMPLE

We illustrate how the program can provide decision support by designing and analyzing a pumping test in an alluvial aquifer with a suspected barrier boundary. This example (Figure 1) is directly related to an experimental area where we are currently pursuing aquifer characterization studies. The objective of this example will be to demonstrate how the design phase of the program can be used to choose observation well locations and appropriate times of data collection for the following assumed situation.

T = 9.72 sq. ft./min
S = 0.5 E - 4
Coordinates of Pumping Well (500,500)
Pumping Rate, Q = 500 gal./min. = 67 cu. ft./min.
Boundary at 18 degrees to x axis 485 feet from pumping
    well.
Image-well theory is employed to represent the
    boundary.
Coordinates of Image Well (1423,800)

INITIAL GUESS

We assume that some work has been done in the area so that ballpark estimates are possible. For example, it is usually possible in alluvial environments to infer the approximate boundary location by looking at the surface expression of the valley wall. For initial guesses we use the following data.

Q = 67 cu. ft./min.
T = 10. sq. ft./min.
S = 1.0 E - 4
Coordinates of Pumping Well (500,500)
Coordinates of Image Well (1500,500)
Assume boundary perpendicular to x axis 500 feet from
    pumping well.

This initial estimation of the situation will be used to look at sensitivities and to design the pumping test. The goal is to adequately define T, S, and the boundary location (or image well location). Sensitivity coefficients will be plotted in space and time and this information will be used to design the test. All sensitivities are normalized so they have units of feet, the same as drawdown.

SENSITIVITY TO TRANSMISSIVITY

These maps (Figures 2 and 3) of sensitivity to transmissivity show that the maximum sensitivity occurs near the pumped well. At early time the contours are nearly radially symmetric about the pumping well. At later times the barrier boundary causes significant deformation near the boundary. However, the basic spatial structure of the sensitivity map does not change at times larger than one day.

SENSITIVITY TO STORAGE

The sensitivity to storage starts out at early times being symmetric around the pumping well and having its maximum near the well. Very quickly the sensitivity to storage is affected by the boundary. However, after a few hundred minutes, it is nearly constant in the mapped area. This is illustrated in Figures 4 through 6.

SENSITIVITY TO IMAGE WELL X

The maximum sensitivity to the image well x coordinate occurs at the boundary on the line joining the pumping well and the proposed image well. The basic spatial structure of the map does not change with time; however, the values become nearly constant in time in the mapped area after a few hundred minutes (see Figures 7 and 8).

SENSITIVITY TO IMAGE WELL Y

The maximum sensitivity to the image well y coordinate occurs on the boundary in the upper and lower right-hand corners of the mapped area. The basic spatial structure of the map does not change with time; however, after a few hundred minutes the values are nearly constant in time in the mapped area (see Figure 9).

CHOOSING OBSERVATION WELL LOCATIONS

Given the preceding sensitivity plots, how can we use this information to design the pumping test? Using the simple rule of selecting observation wells near points of maximum sensitivity, we choose the three observation wells shown in Figure 10. One well is placed near the pumping well and will have the greatest sensitivity to transmissivity. Another well is placed near the suspected boundary on the x axis to have greatest sensitivity to the image well x coordinate. The third well is placed in the upper right-hand corner of the mapped area to have greatest sensitivity to the image well y coordinate. A plot of drawdown versus time for each of these observation wells is shown in Figure 11.

OBSERVATION WELL SENSITIVITIES

The plots of sensitivities versus time at the three chosen wells for the four parameters (Figures 12 through 15) show the importance of obtaining good early time data. The main structure of the time dependence has been established by a few hundred minutes. The earliest time measurement shown on the plots is .01 minute, which is reasonable with good equipment. Three of the four sensitivities become constant at large times. The correlation between sensitivities becomes greater as they become constant, so one might expect little improvement in parameter estimation after a few hundred minutes.

RESULTS

The plots of sensitivity versus time (Figures 12 through 15) suggest that a pumping test of one day duration might be sufficient. Hypothetical data for the three selected observation wells is generated using the actual parameters and rounded to the nearest .1 foot (simulating field data), for a one day test. This data is analyzed by the program and a page from the output is reproduced to show the results. The mean square residual of .029 feet is consistent with the data being rounded to the nearest .1 feet. The parameter values and the 95% confidence limits determined from the analysis are shown. The estimated and actual parameter values and percent error are summarized here.

Parameter Values

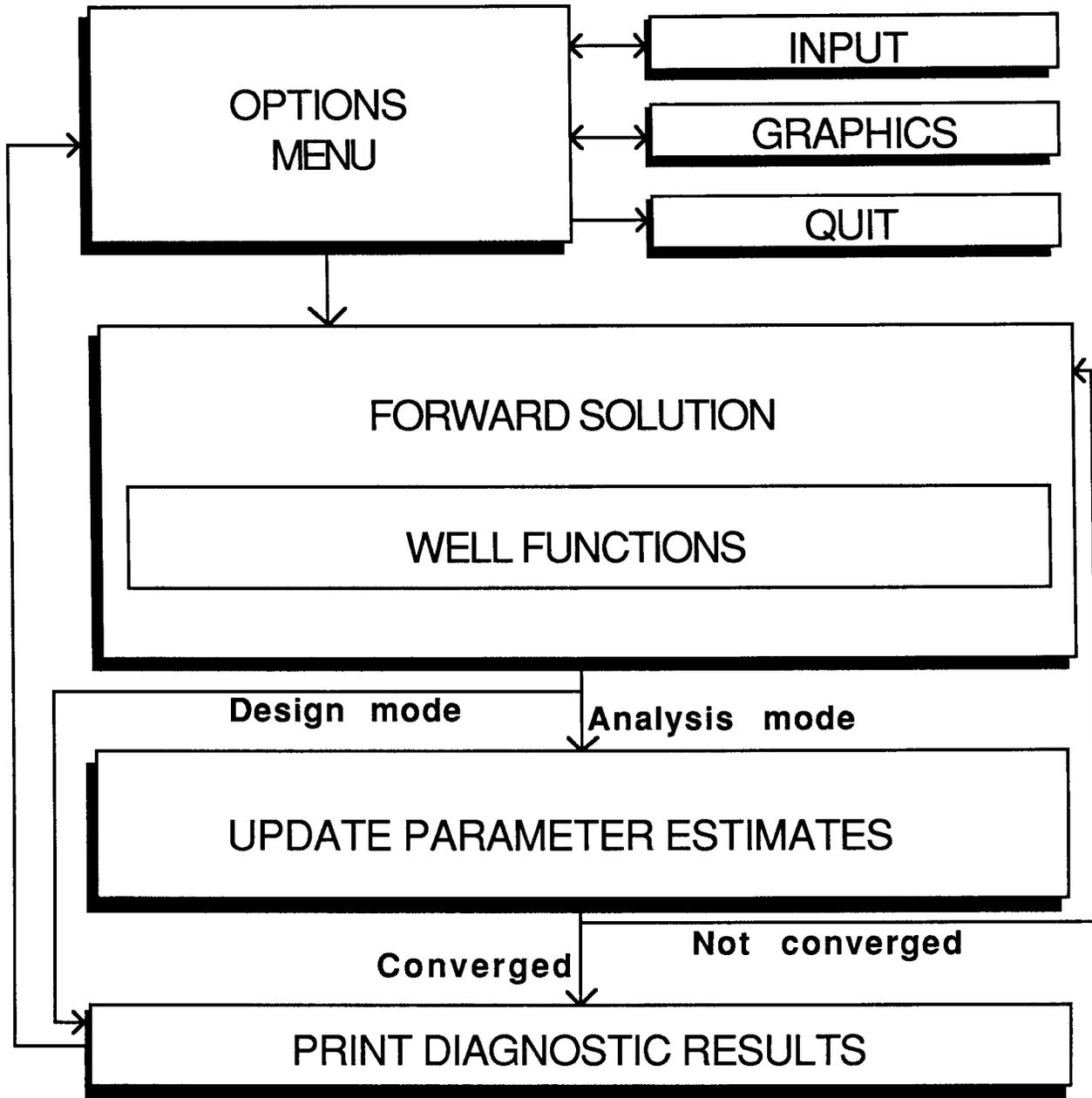|	Actual	Estimated	% Error
T	9.72	9.715	.05%
S	.5 E - 4	.5066E - 4	1.3%
IX	1423	1415	.6%
IY	800	793	.9%

The diagonal elements of the raw crossproducts matrix of normalized sensitivities give a measure of the magnitudes of the parameter sensitivity coefficients for the test. Looking only at this matrix would give the impression that the test is least sensitive to the image well y (IY). However, the sensitivity correlation matrix

11

shows there is significant correlation between the sensitivity coefficients for S and IX. In the final analysis, drawdown is most sensitive to T and least sensitive to S. Increasing the length of the pumping test to five days produces only marginally better results. Wells #1 and #3 alone can be used for the analysis with good results for the parameters. However, using two wells to locate a boundary is not recommended because the plot of sensitivity to image well y coordinate shows zero sensitivity on the line joining the pumping and image wells. Therefore, two wells on this line would produce an indeterminate problem .

CONCLUSIONS

As our need for more detailed descriptions of aquifers increases, pumping tests will play an increasingly important role. Field instrumentation is improving steadily, particularly with the advent of more reliable pressure transducers that can be interfaced directly with personal computers. Sophisticated analysis techniques are needed to keep pace with this improved field technology. We should no longer be satisfied to analyze data with a manual graphical technique after the pumping test has been completed. Pumping tests are expensive to run and every effort must be made to ensure that they produce the maximum amount of information. Ideally, a pumping test analysis program should help design the pumping test from the initial conception, by making a decision support system available to the user. There are usually specific limitations and goals set for pumping tests, such as the maximum pumping rate, maximum number of observation wells, maximum length of the test, and the need to estimate aquifer parameters within a certain accuracy. This is a formidable problem to solve in an optimal manner. We have created a program that makes a decision support system available to the user. The pumping-test design activity is guided by sensitivity analysis. Although an optimal design may not be achieved, one meeting all the limitations and goals of the test can often be found. We have illustrated the program and the decision support system with an example of a pumping test in an aquifer with a simple heterogeneity.

PROGRAM FLOW CHART

```
┌─────────────────┐          ┌──────────────────┐
│                 │◄────────►│      INPUT        │
│    OPTIONS      │          └──────────────────┘
│     MENU        │◄────────►┌──────────────────┐
│                 │          │    GRAPHICS       │
│                 │          └──────────────────┘
│                 │─────────►┌──────────────────┐
└─────────────────┘          │      QUIT         │
        │                    └──────────────────┘
        ▼
┌───────────────────────────────────────────────┐
│                                                │
│           FORWARD SOLUTION                     │
│                                                │
│     ┌───────────────────────────────────┐     │
│     │        WELL FUNCTIONS             │     │
│     └───────────────────────────────────┘     │
│                                                │
└───────────────────────────────────────────────┘
   │                    │
Design mode          Analysis mode
   │                    ▼
   │      ┌───────────────────────────────────────┐
   │      │     UPDATE PARAMETER ESTIMATES         │
   │      └───────────────────────────────────────┘
   │                    │
   │        Converged   │     Not converged
   │                    ▼
   │      ┌───────────────────────────────────────┐
   └─────►│      PRINT DIAGNOSTIC RESULTS          │
          └───────────────────────────────────────┘
```

PROGRAM OUTPUT

```
******************************************************************************
Analysis of the three wells for one day pumping.
MODE: ANALYSIS          TRIAL NUMBER:  1
```

The root mean squared residual is   .2918E-01

The parameter values with approximate 95% confidence intervals are:

Parameter	Value	Lower Bound	Upper Bound
TRANSMISSIVITY	9.715	9.700	9.730
STORAGE COEFFICIENT	.5066E-04	.4967E-04	.5164E-04
X COORD. OF IMAGE PW	1415.	1405.	1425.
Y COORD. OF IMAGE PW	793.1	784.1	802.0

For the following arrays:
Col-Row 1 represents TRANSMISSIVITY
Col-Row 2 represents STORAGE COEFFICIENT
Col-Row 3 represents X COORD. OF IMAGE PW
Col-Row 4 represents Y COORD. OF IMAGE PW

Raw crossproducts matrix of normalized sensitivities:

	1	2	3	4
1	7228.	1210.	2120.	301.8
2	1210.	265.4	503.3	65.05
3	2120.	503.3	1038.	113.2
4	301.8	65.05	113.2	43.59

The reciprocal condition number of the
sensitivity crossproducts matrix is   .7148E-03

Sensitivity correlation matrix:

	1	2	3	4
1	1.000	.8736	.7742	.5377
2	.8736	1.000	.9590	.6048
3	.7742	.9590	1.000	.5323
4	.5377	.6048	.5323	1.000

Covariance matrix of normalized parameter variations:

	1	2	3	4
1	.6357E-06	-.5594E-05	.1373E-05	.3812E-06
2	-.5594E-05	.9643E-04	-.3330E-04	-.1868E-04
3	.1373E-05	-.3330E-04	.1365E-04	.4737E-05
4	.3812E-06	-.1868E-04	.4737E-05	.3247E-04

Parameter correlation matrix:

	1	2	3	4
1	1.000	-.7145	.4660	.8390E-01
2	-.7145	1.000	-.9179	-.3338
3	.4660	-.9179	1.000	.2250
4	.8390E-01	-.3338	.2250	1.000
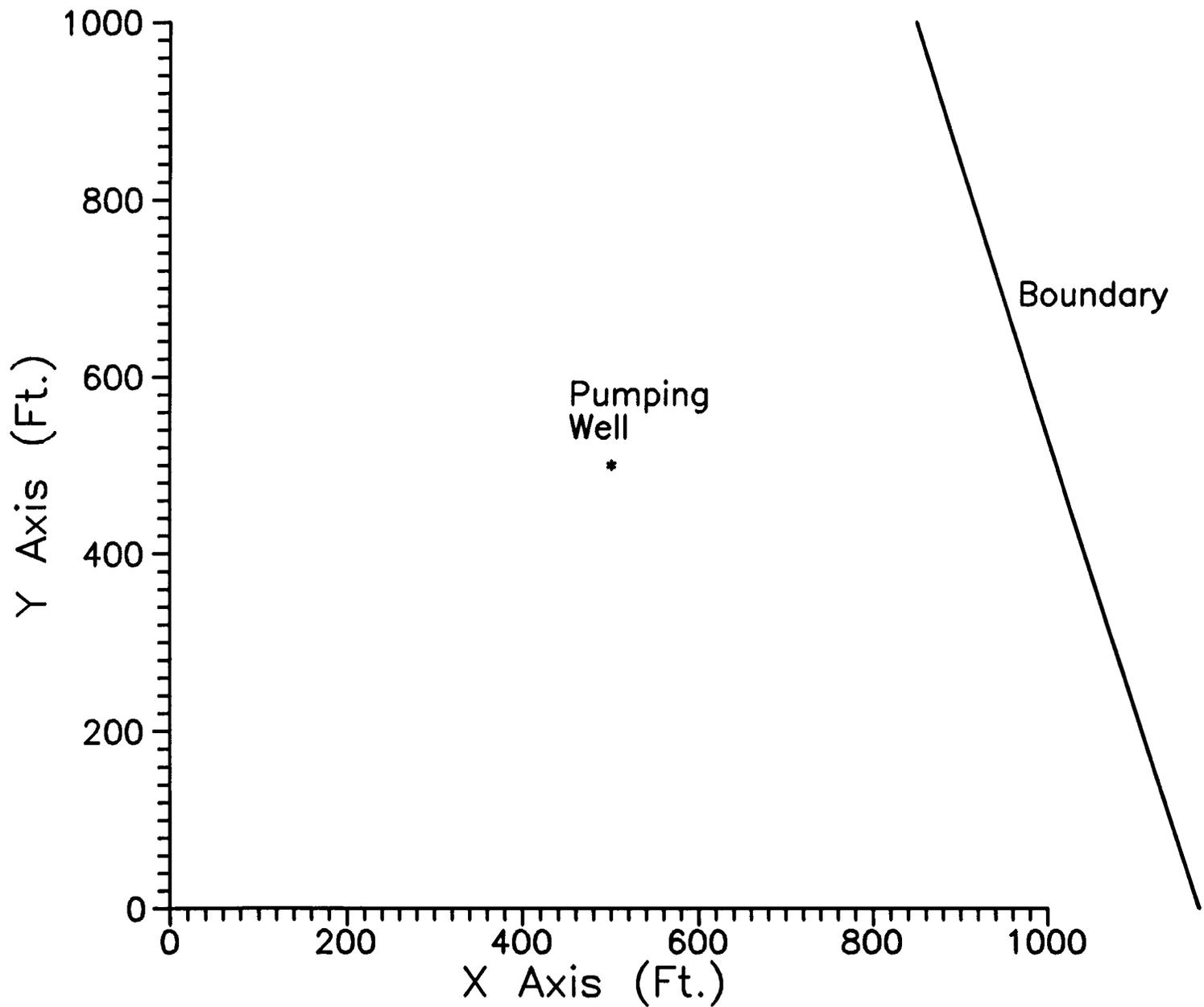
Figure 1.

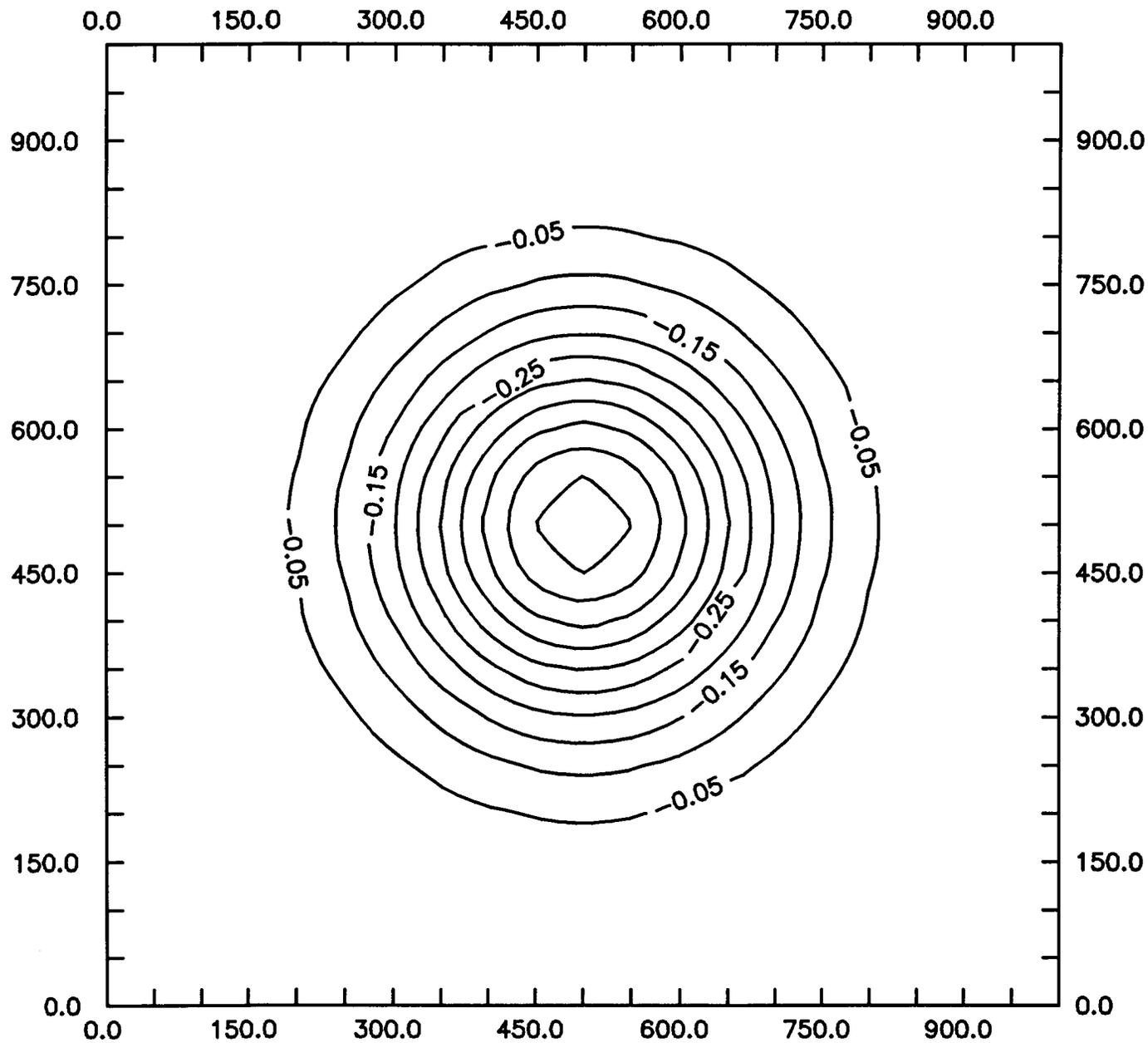Sensitivity to Transmissivity at 1.44 Min.

Figure 2.
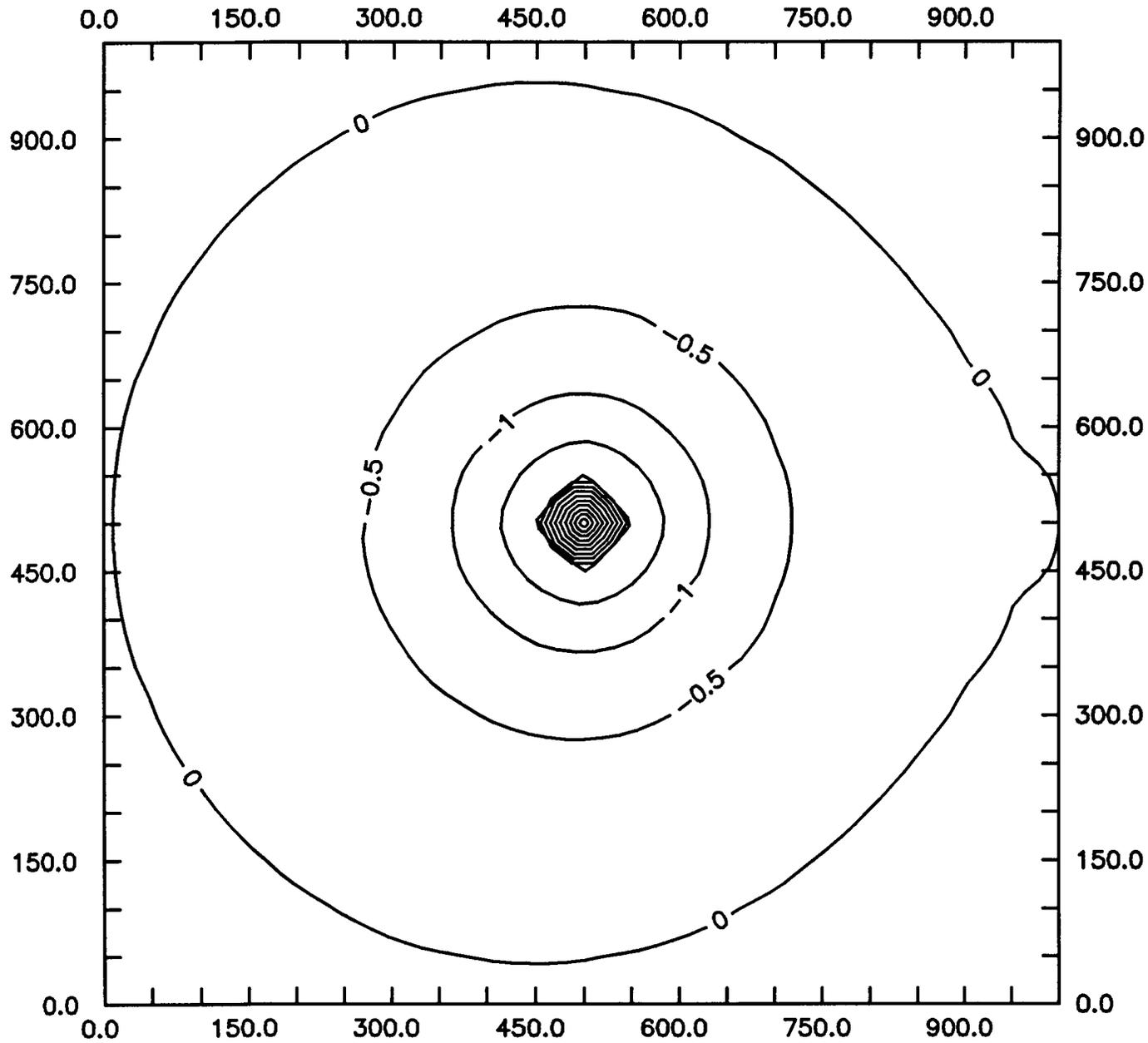
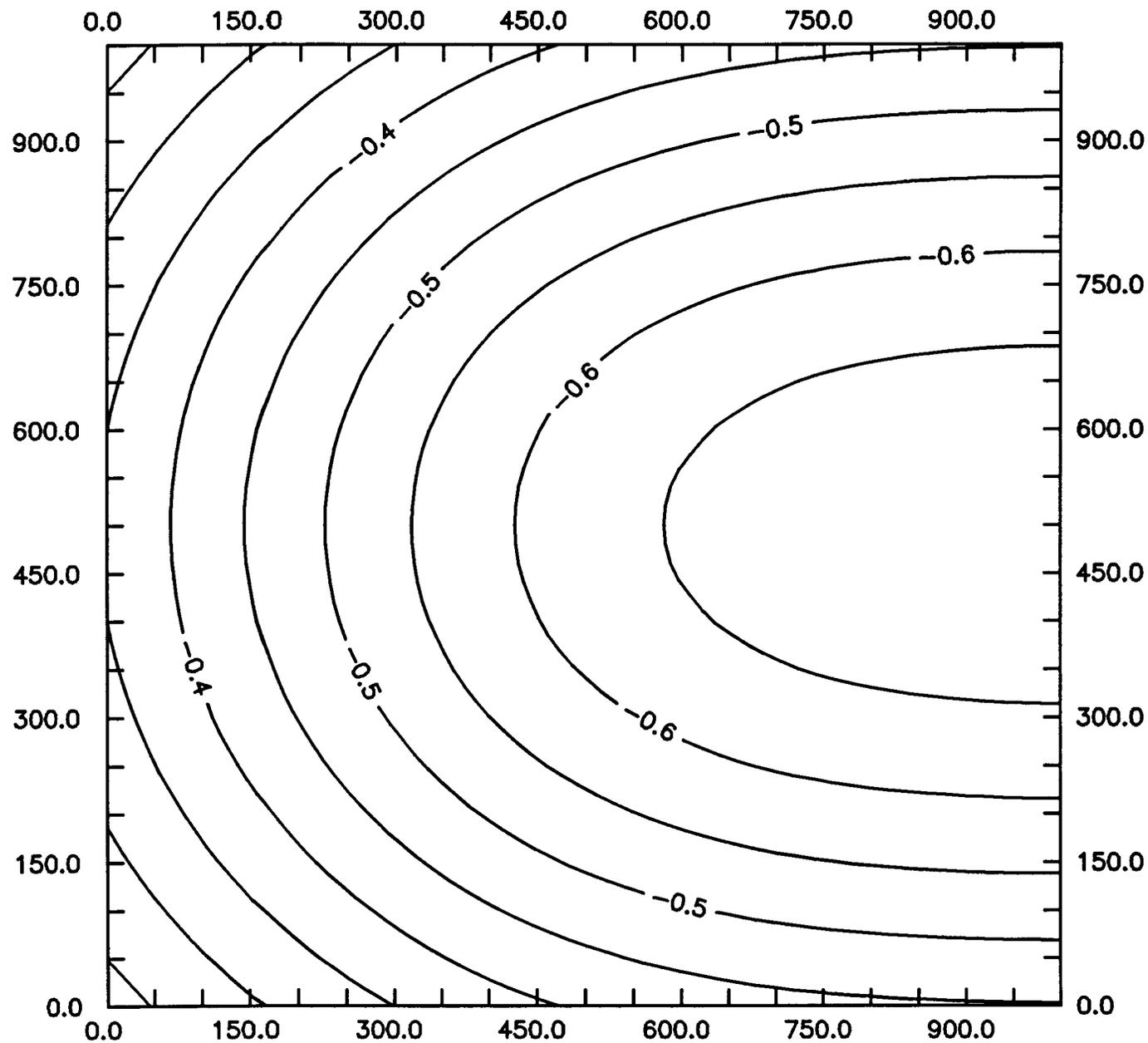Sensitivity to Transmissivity at 1 Day

Figure 3.
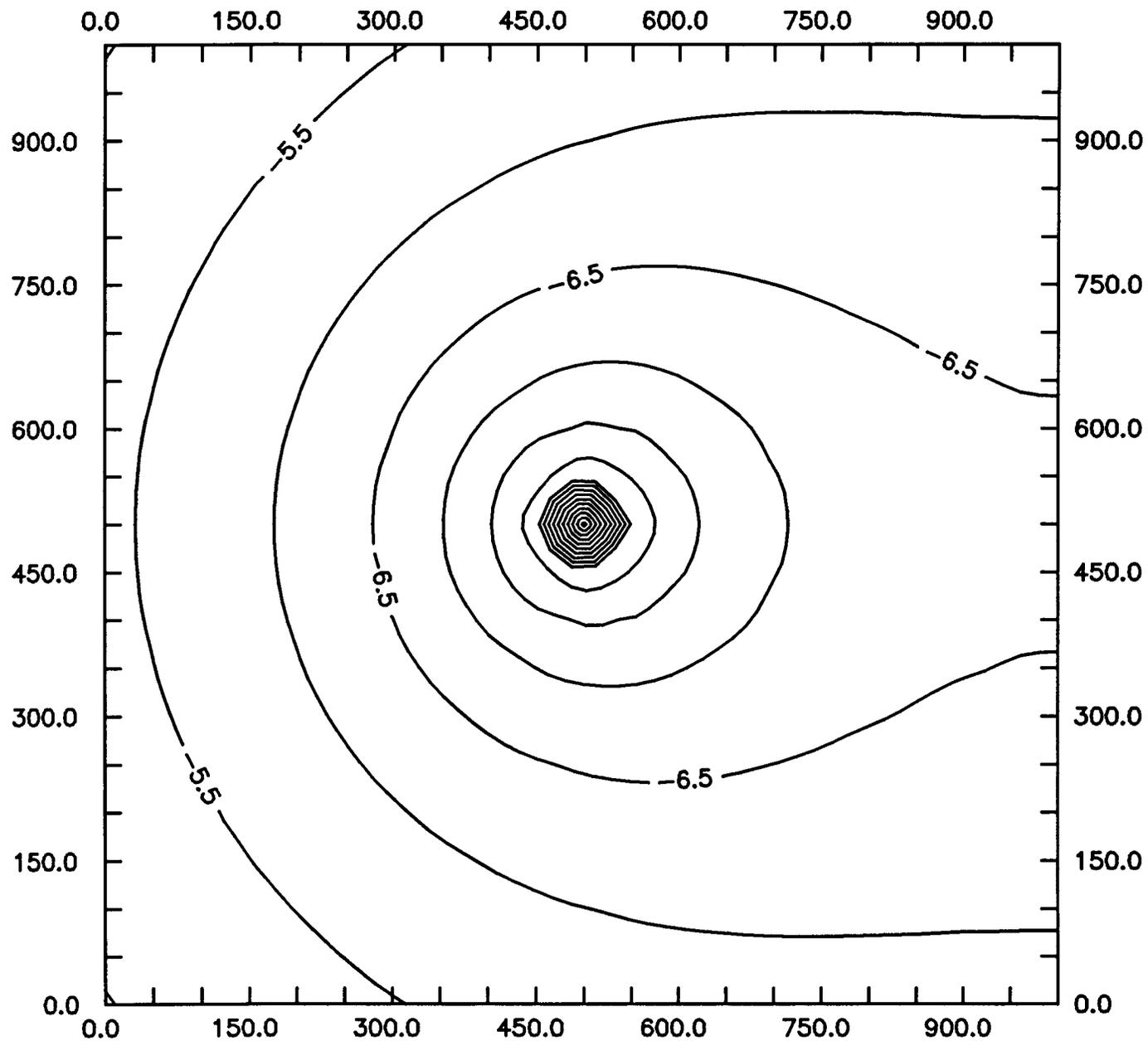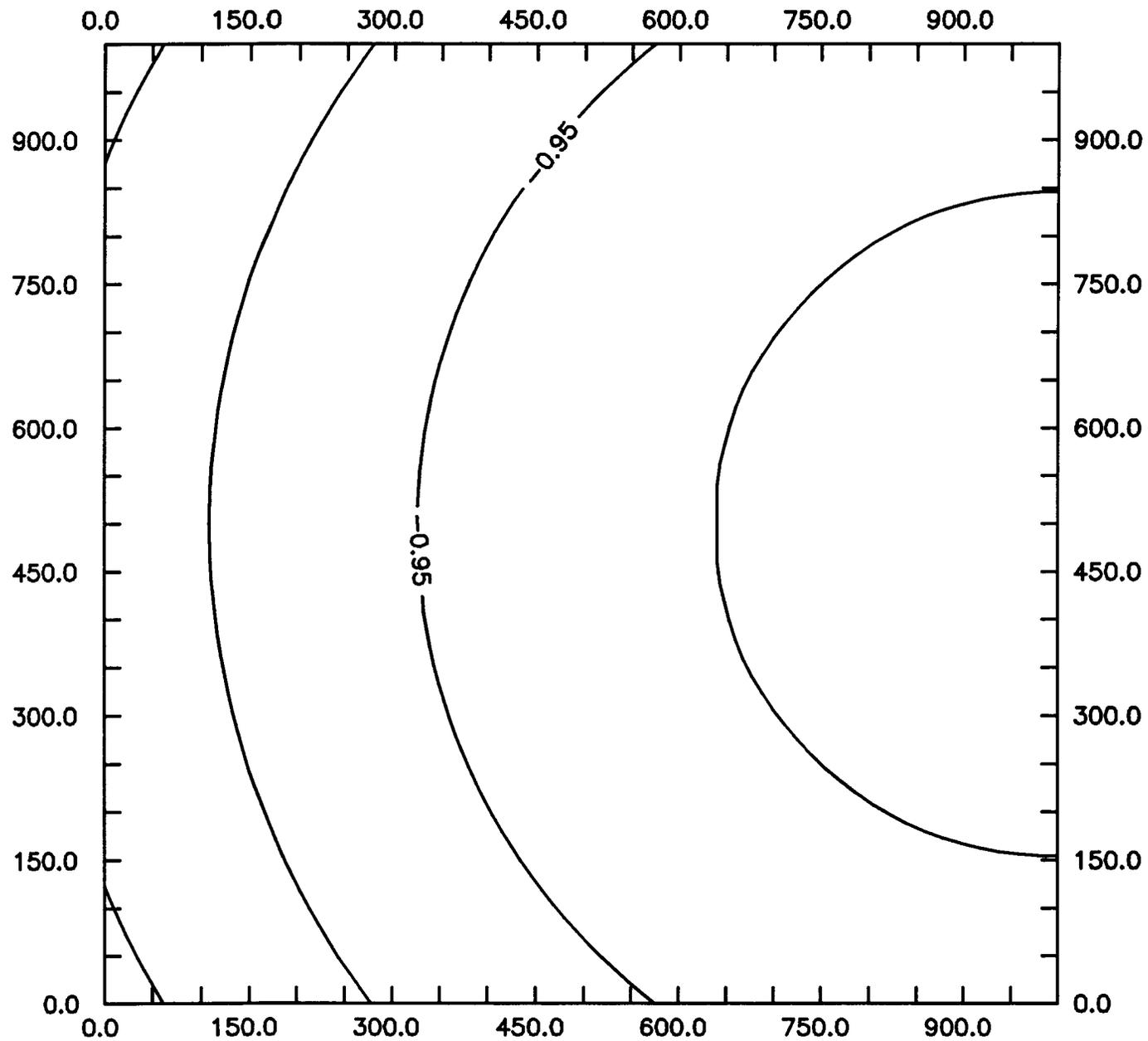
Sensitivity to Storage at .1 Min.

Figure 4.

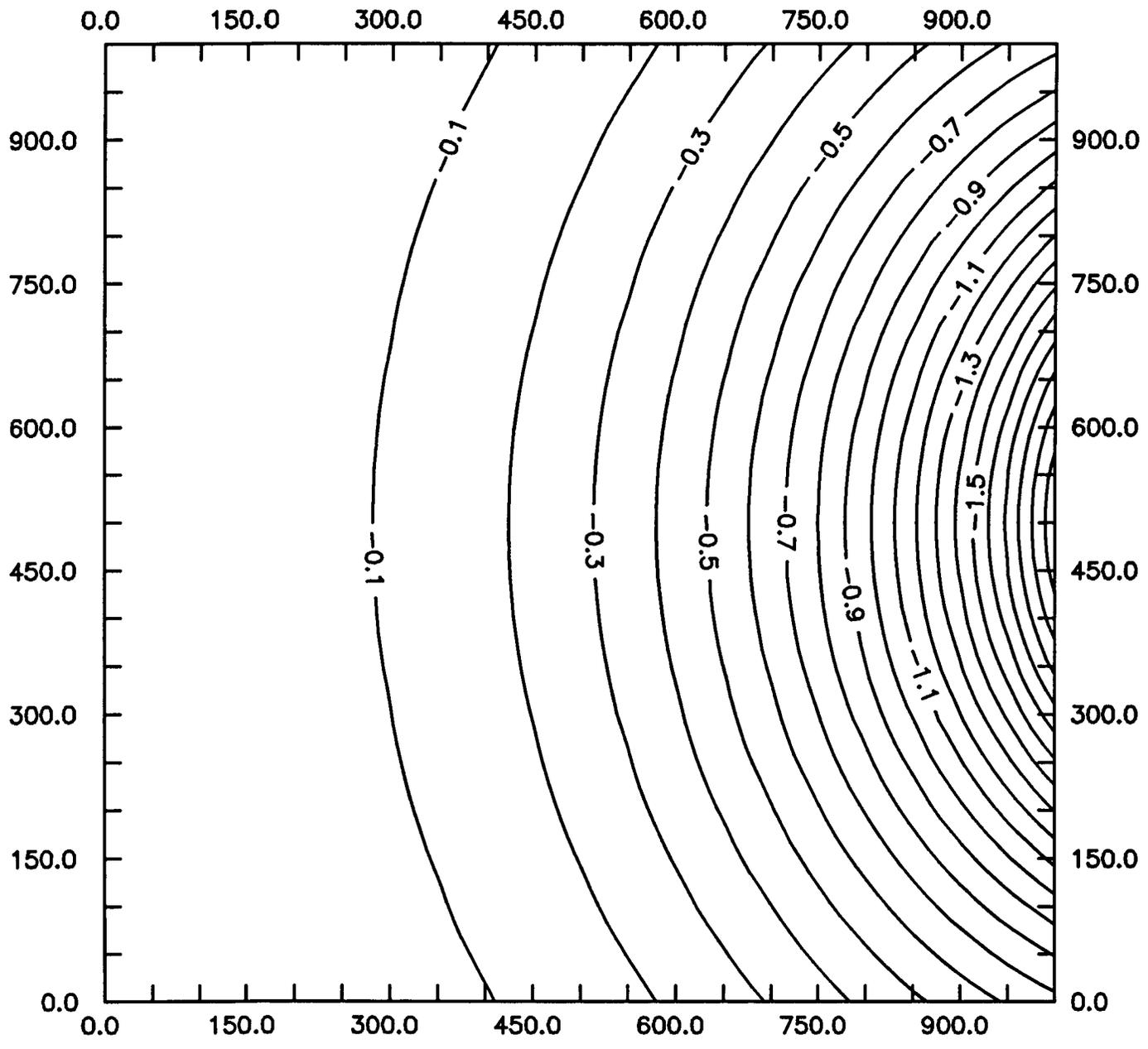Sensitivity to Storage at 1.44 Min.

Figure 5.

Sensitivity to Storage at 14.4 Min.
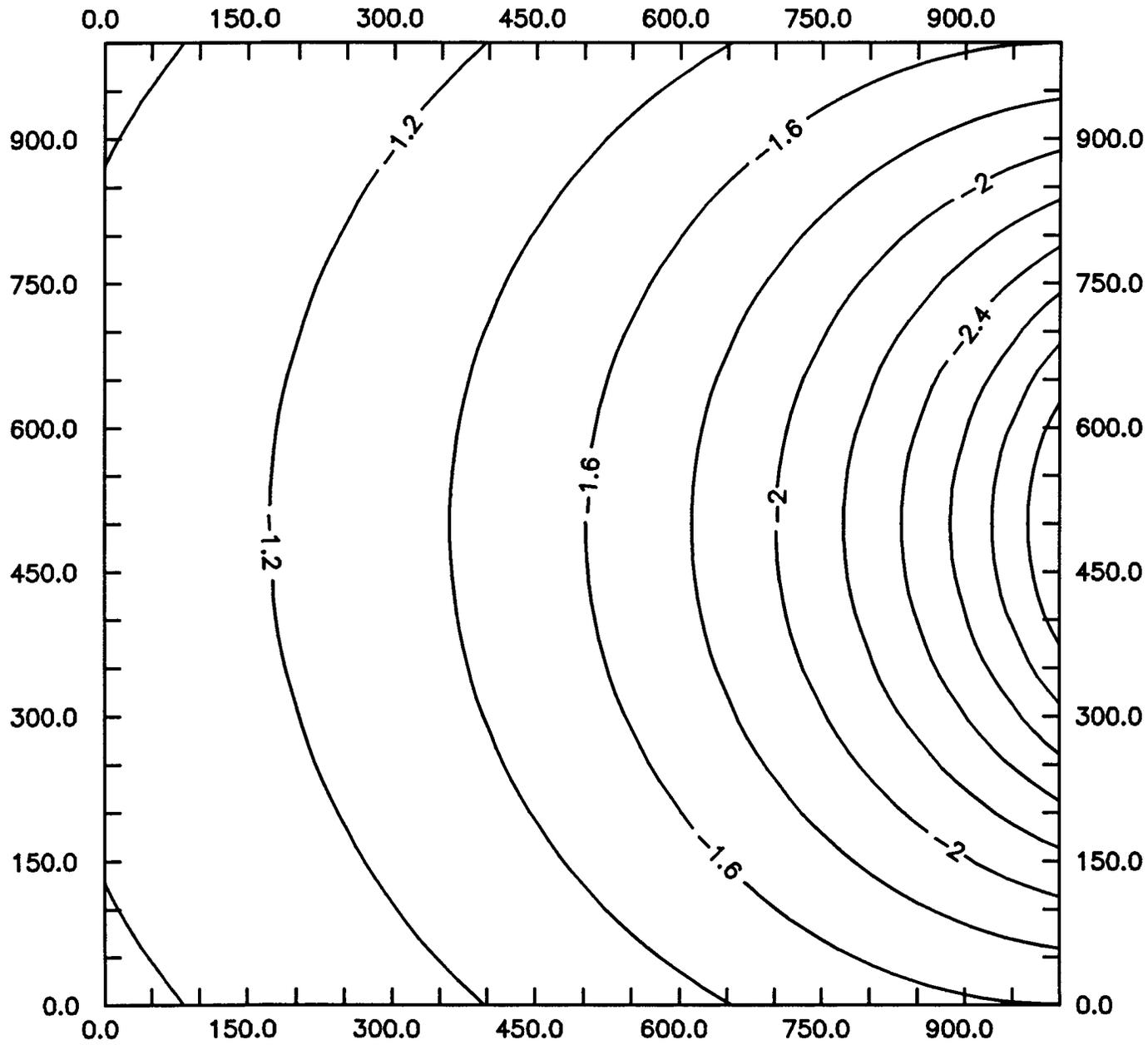
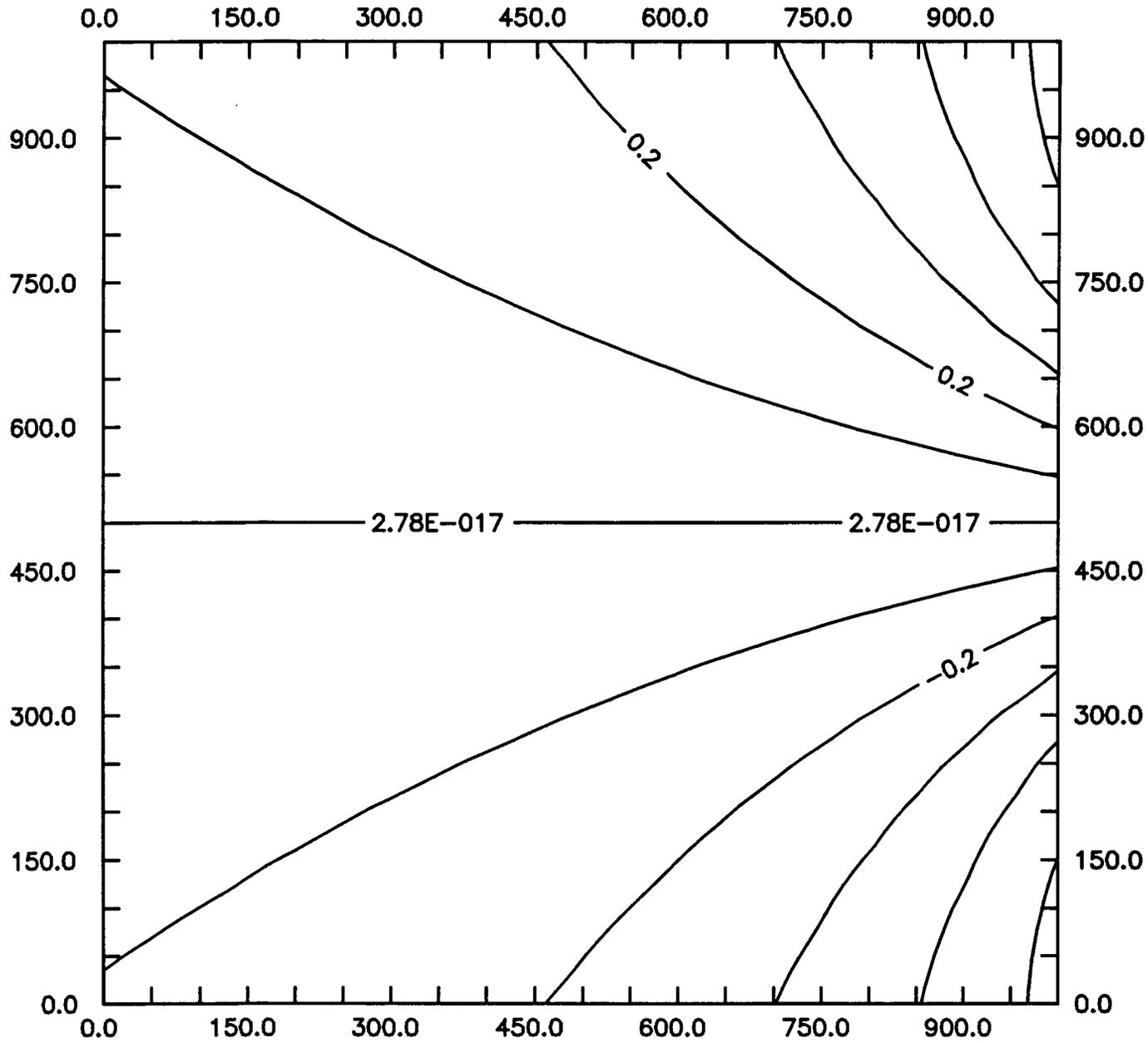Figure 6.

Sensitivity to Image Well X at 1.44 Min.

Figure 7.

Sensitivity to Image Well X at 1 Day

Figure 8.

Sensitivity to Image Well Y at 1 Day
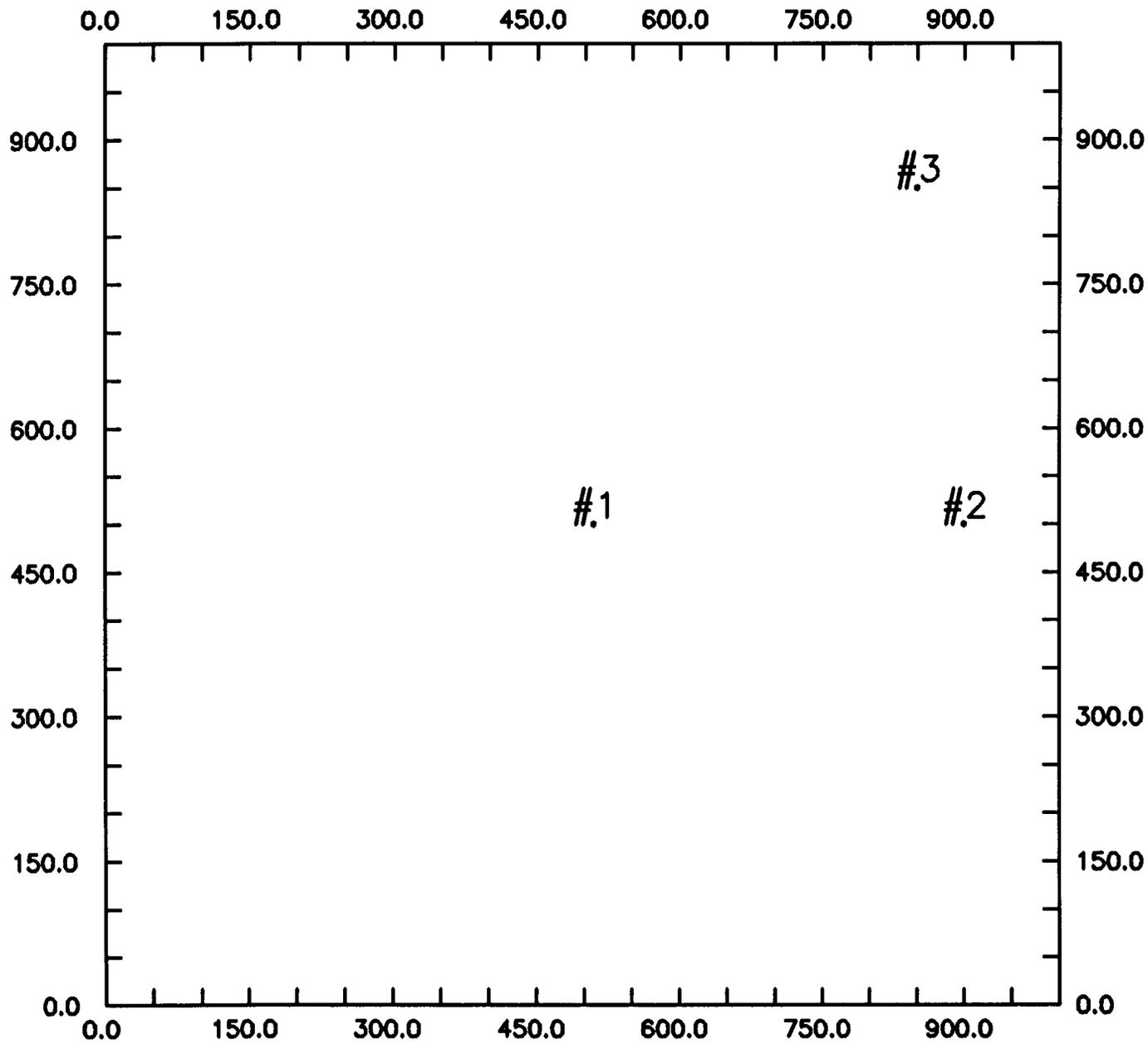
Figure 9.
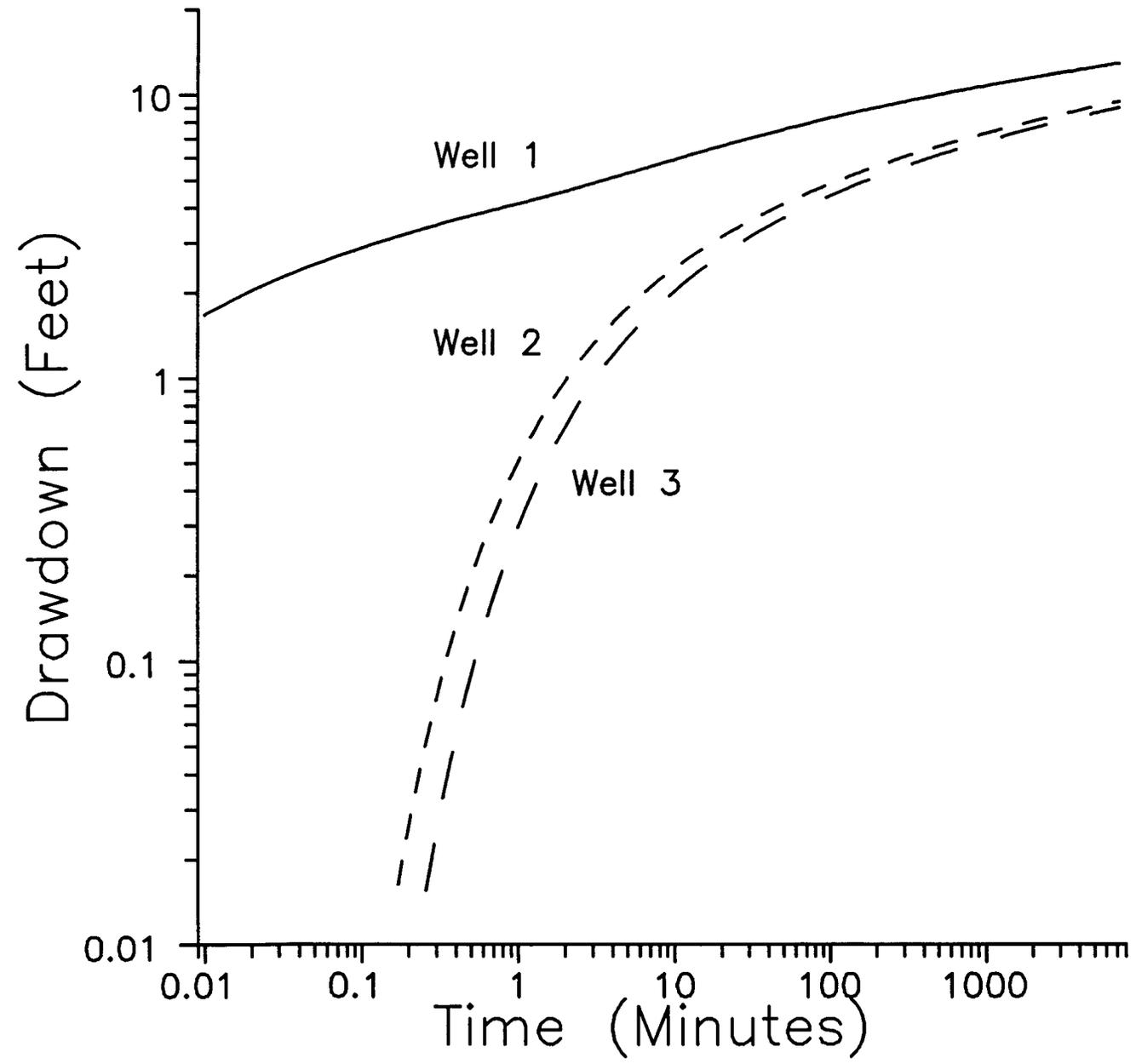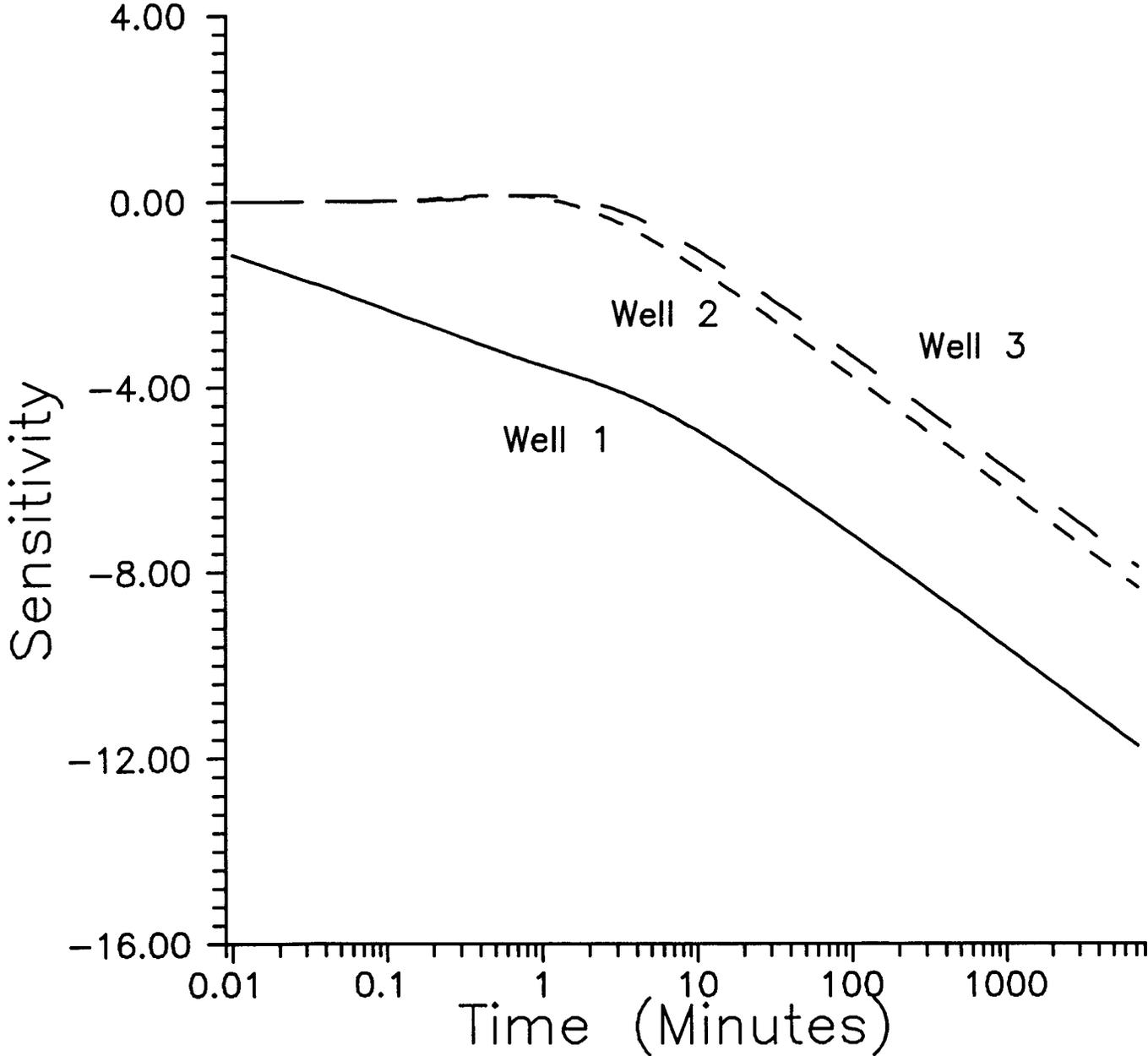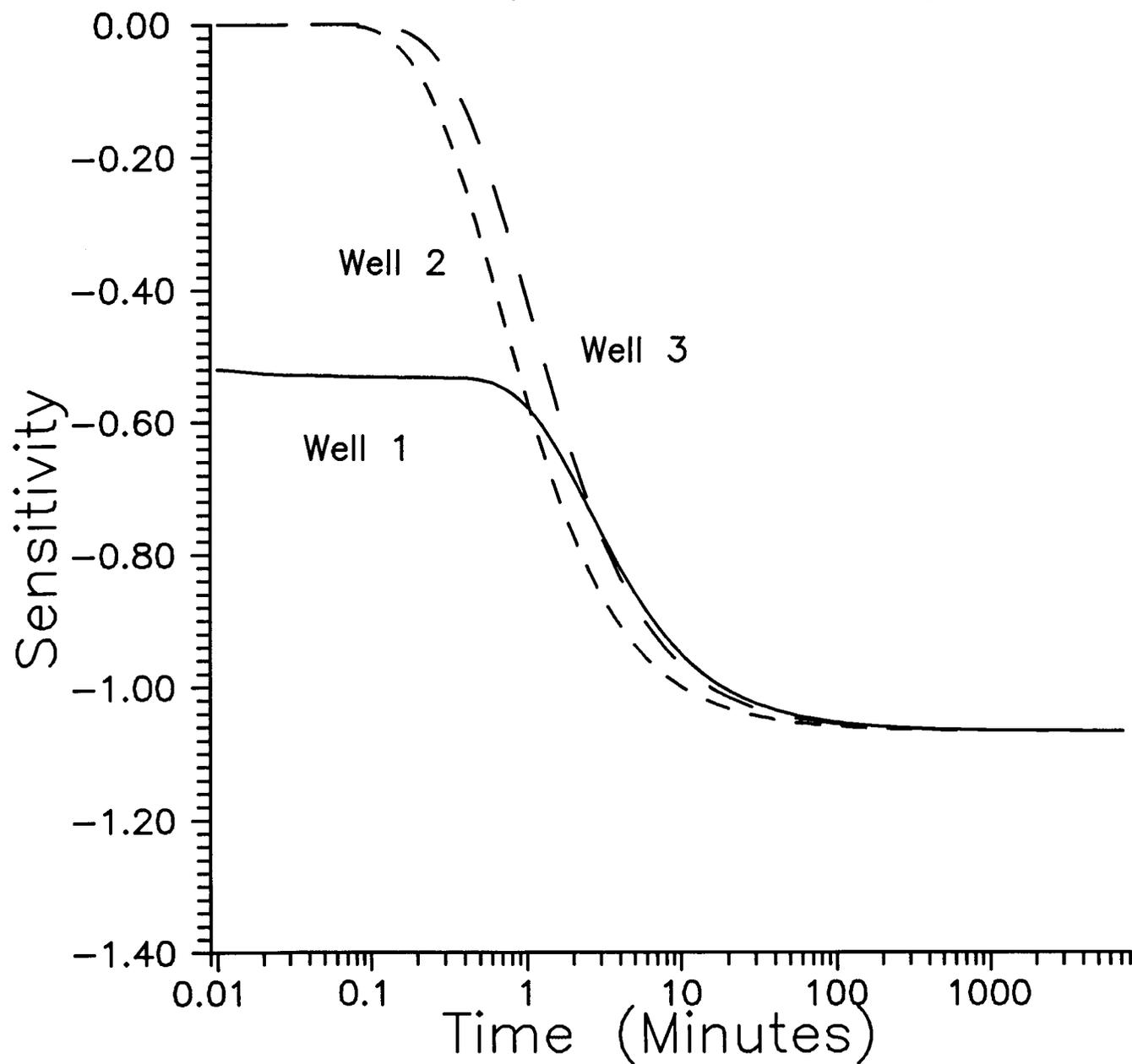
Observation Well Locations

Figure 10.

Figure 11.

Drawdown at the Wells

Figure 12.

Sensitivity to Transmissivity

Figure 13.

Figure 14.

Figure 15.

Sensitivity to Image Well Y

Well 3

Time (Minutes)