SIMULATED DRAWDOWN FOR SELECTED WELL FIELDS IN THE OHIO RIVER ALLUVIAL AQUIFER

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 2-74

Prepared in cooperation with

THE UNIVERSITY OF KENTUCKY
KENTUCKY GEOLOGICAL SURVEY
Wallace W. Hagan
Director and State Geologist

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IN THE OHIO RIVER ALLUVIAL AQUIFER

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UNITED STATES DEPARTMENT OF THE INTERIOR

Rogers C. B. Morton, Secretary

GEOLOGICAL SURVEY

Vincent E. McKelvey, Director

For additional information write to:

U.S. Geological Survey
Room 572 Federal Building
Louisville, Kentucky 40202

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SIMULATED DRAWDOWN FOR SELECTED WELL FIELDS IN THE OHIO RIVER ALLUVIAL AQUIFER

By Hayes F. Grubb

ABSTRACT

Drawdown due to pumping was simulated for three sites in the alluvial aquifer adjacent to the Ohio River by digital modeling techniques. Two well-field arrangements were used at each site. The initial well-field arrangement at each site consisted of three wells located in a line parallel to the Ohio River. The simulated wells were 350 feet (107m) apart and 500 feet (152m) from the river. Pumping was simulated at a rate of 1,500 gal min^{-1} (5,678 1 min^{-1}) for 256 days. The second well-field arrangement allowed comparison of drawdown between the initial well-field arrangement and (a) wells located 350 feet (107m) nearer the river, (b) additional wells, located between the initial well field and the bedrock valley wall and (c) wells located on a line perpendicular to the river rather than parallel to the river. A verification procedure for the digital model based on observed aquifer response to a flood on the Ohio River is included as an appendix.

INTRODUCTION

Since 1960 increased use of ground water from the alluvial aquifer adjacent to the Ohio River in Kentucky has revealed problems of well-field location relative to the river, the bedrock valley wall and other pumping wells. (Whitesides and Ryder, 1969; Whitesides, 1970). Sustained high pumping rates of 500-1,500 gal min^{-1} (1,890-5,680 l min^{-1}) from individual wells in a multiwell system in this aquifer depend upon infiltration of water from the Ohio River.

Optimum location of a well field for this aquifer can be complex and will be determined by several factors such as, (1) hydraulic characteristics of the aquifer, (2) width of the flood plain, (3) physical properties of the stream bed, (4) saturated thickness, which is generally less than 120 feet (36 meters) when the river is at pool stage, and (5) the quantity of water needed.

The purpose of this report is to illustrate, for selected sites in Kentucky, the theoretical response of the alluvial aquifer adjacent to the Ohio River to alternative well-field arrangements. The aquifer response of interest is the lowering of the water level due to pumping, commonly referred to as drawdown. This analysis underscores some basic principles useful to those engaged in developing water supplies from this aquifer.

The aquifer's response to different well-field arrangements was evaluated by a digital ground-water model described by Pinder and Bredehoeft (1968) and by Bredehoeft and Pinder (1970). Use of this model made it possible to consider the effects of all the above-mentioned factors on the decline of water levels due to pumping. Application of this technique, necessitates a verification procedure for the model at each site. The verification procedure is given in the appendix.

This work was done as part of a water-resources investigation program in Kentucky made in cooperation with the Kentucky Geological Survey. The author thanks J. D. Bredehoeft and G. F. Pinder for instruction in the analysis of stream-aquifer systems by digital modeling and for providing a basic computer program to make the necessary computations. The cooperation of landowners who granted permission for installation of test wells and collection of data is gratefully acknowledged.

GENERAL SITE CHARACTERISTICS

The sites selected for this analysis are shown in figure 1. At each site the physical locations of flow boundaries were determined from topographic and bedrock-contour maps. The bedrock valley wall and the bedrock floor on which the sand and gravel occurs are treated as barriers to the flow of water in the sand and gravel aquifer. The generalized relationship of the river to the aquifer, the bedrock valley wall, and the observation wells is shown by figure 2. The river bed is treated as a material of constant hydraulic conductivity which will allow water to flow from the aquifer to the river or from the river to the aquifer depending upon the hydraulic gradient.

The navigational pools that are maintained in the Ohio River during periods of little or no precipitation represent the smallest head on the stream bed. During such periods, commonly existing for 3 or more months each year, water is being discharged from the aquifer to the river in areas unaffected by man. A river condition of pool stage, maintained in the model for the periods of pumping considered below, thus represents the poorest condition for induced infiltration from the river to the aquifer. A pool-stage river condition lasting for 256 days is a severe condition and would be expected to occur infrequently.

In each of the following analyses a uniform hydraulic conductivity was used for the section of aquifer modeled. Stresses outside of the section under consideration were assumed to be negligible. The simulated drawdown in the aquifer does not include that due to well screen losses. Thus the drawdowns observed in real pumping wells will be somewhat greater than those indicated on the following diagrams. Drawdown near the pumping wells was estimated from the relationship of distance to drawdown in the aquifer.

Water temperature is assumed to be the same in the river as in the aquifer. The effects of temperature on water viscosity and flow rates have been discussed by Rorabaugh (1963, p. H53 and H58).

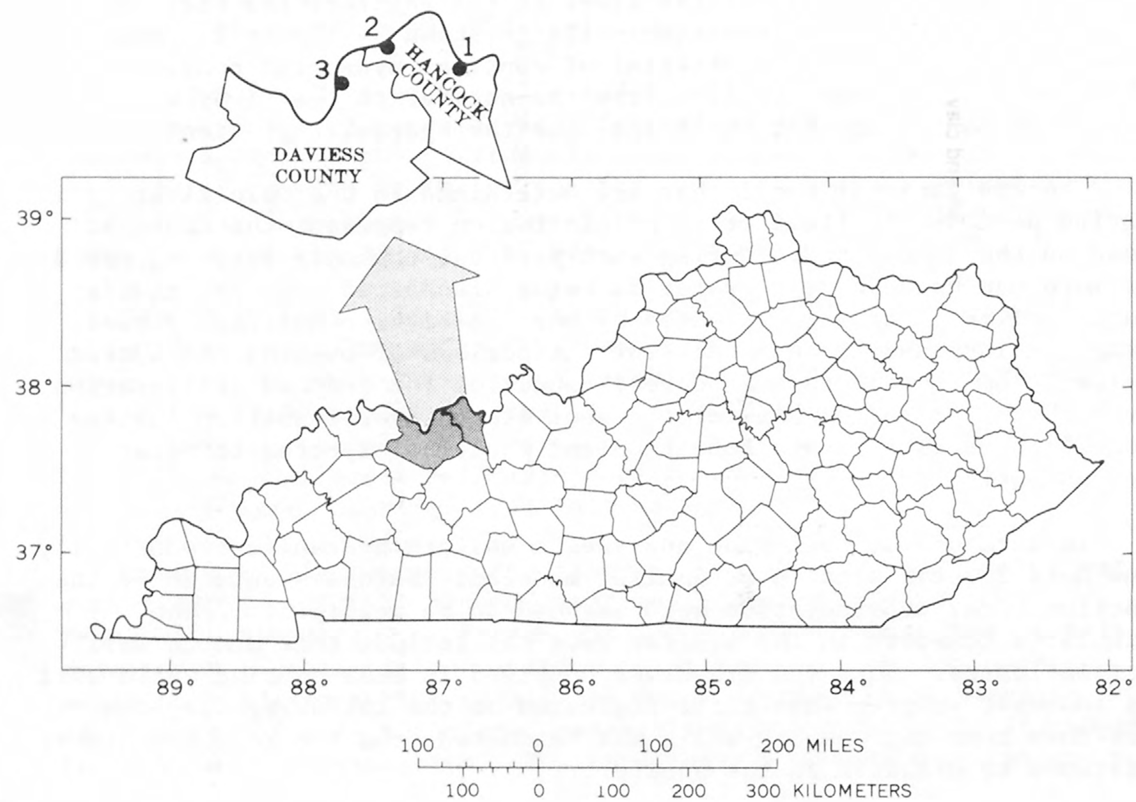

Figure 1 - Location of test sites in Hancock and Daviess Counties, Kentucky.

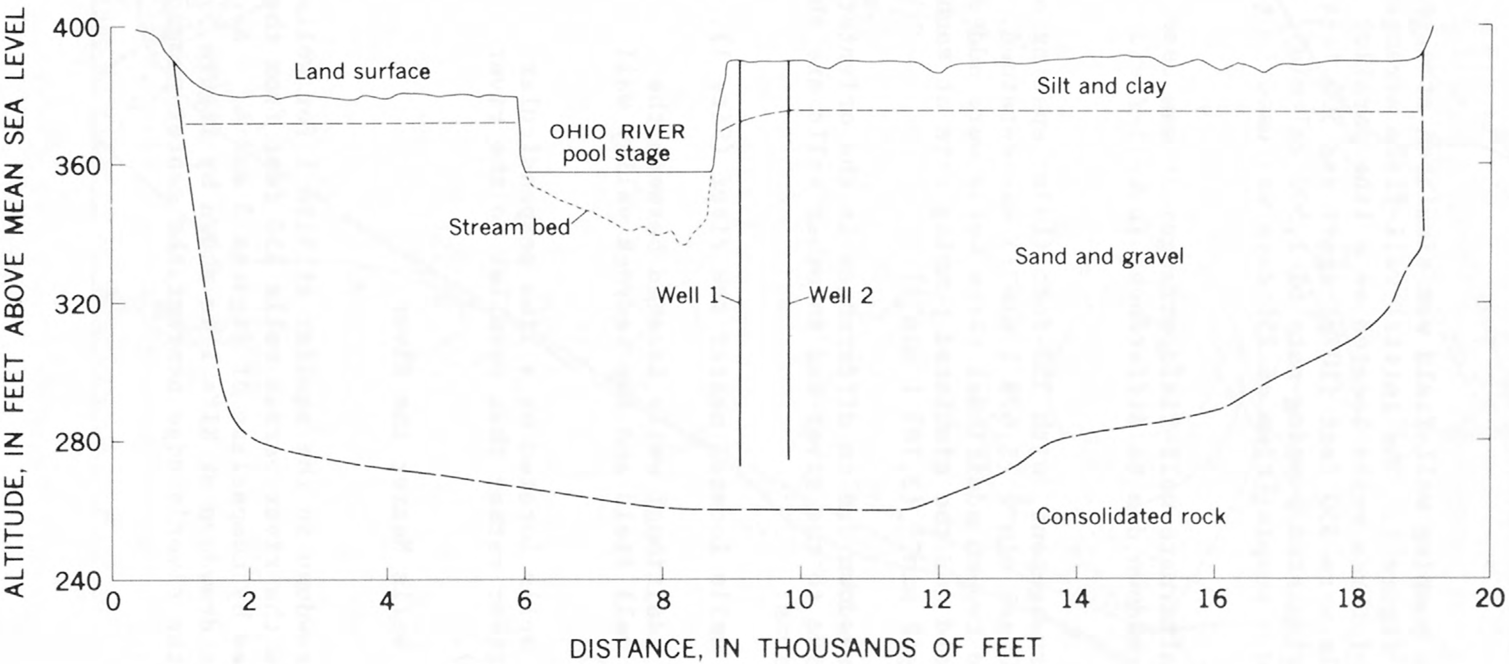

Figure 2 - Generalized cross section at the Singleton site (Site 2).

DRAWDOWN DUE TO ALTERNATIVE PUMPING SCHEMES

Drawdown due to a pumping well field was simulated at each of the three sites shown on figure 1. The initial well-field arrangement at each site consisted of three wells located on a line parallel to the Ohio River. The wells were 350 feet (107m) apart and 500 feet (152m) from the river. A simulated pumping rate of 1,500 gal min^{-1} (5,678 l min^{-1}) per well and a pumping time of 256 days was used in each case.

At each site an alternate well-field arrangement was used to show the differences in drawdown due to differences in well-field arrangement.

The three-well arrangement, with 350-foot (107m) spacing and a pumping rate of 1,500 gal min^{-1} (5,678 l min^{-1}) was retained, except at site two. At site two an additional three wells were added to the hypothetical well field and the simulated pumping rate at each of the six wells was 1,000 gal min^{-1} (3,785 l min^{-1}).

Differences in drawdown due to differences in the orientation of the well field relative to the river and to other wells are shown for the following conditions:

(1) Pumping wells located nearer the river (Site 1).

(2) Pumping additional wells located between the initial well field and the bedrock valley wall (Site 2).

(3) Pumping wells located on a line perpendicular to the river rather than parallel to the river (Site 3).

Wells Nearer the River

Differences in drawdown in the aquifer at Site 1 for wells located 500 feet from the river versus wells 150 feet from the river are shown in plan view by comparison of figures 3 and 4. A cross-sectional view of the drawdown at Site 1 is shown by figure 5. The rate of drawdown at the river's edge nearest the center pumping well is shown by figure 6.

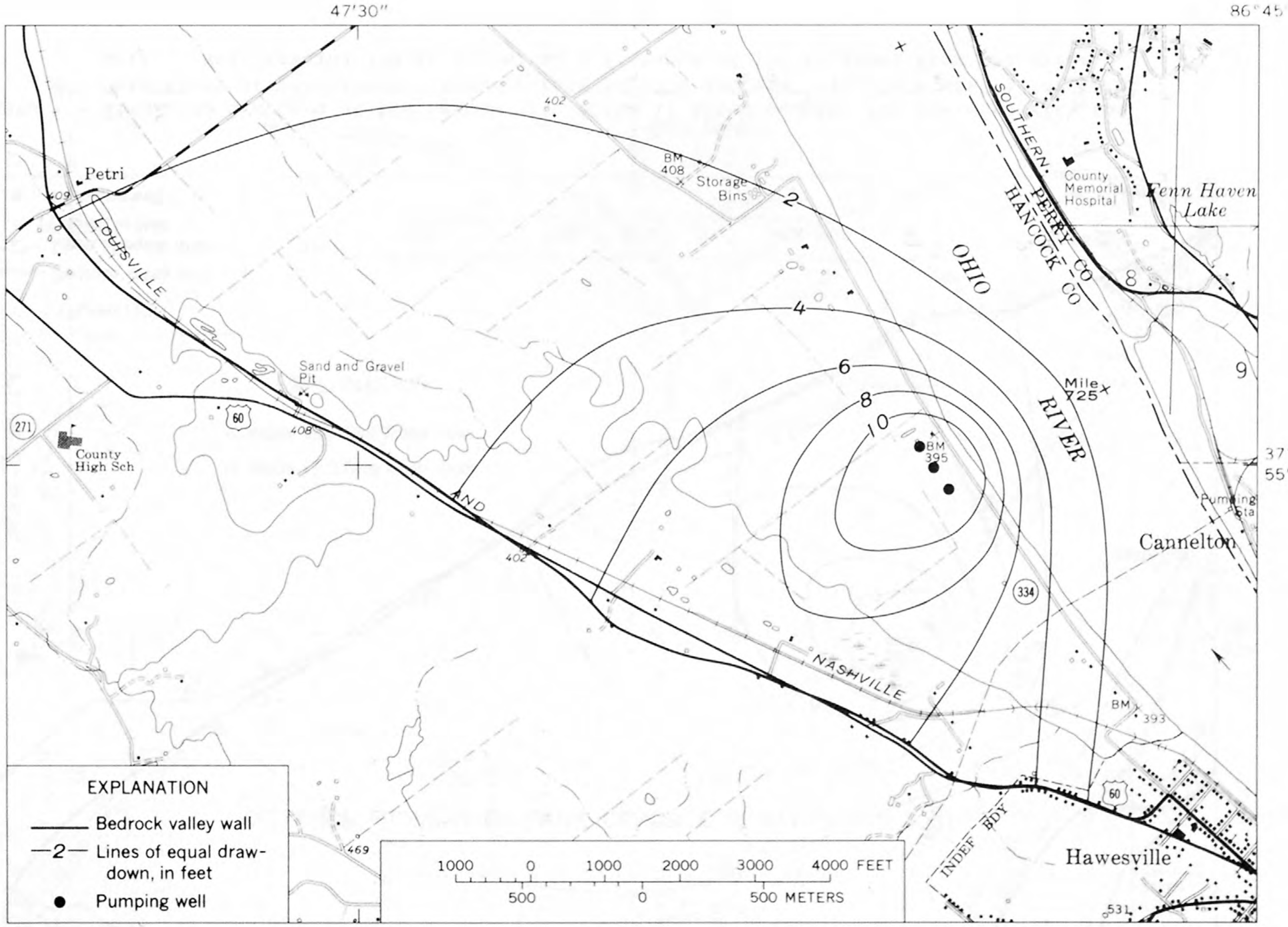

Figure 3 - Simulated drawdown at the Hagman site (Site 1) after pumping for 256 days with the Ohio River at pool stage. Pumpage rate is 1500 gal min^{-1} (5,678 l min^{-1}) for each well. Well spacing 350 ft. (107m) at a distance of 500 ft. (152m) from the river.

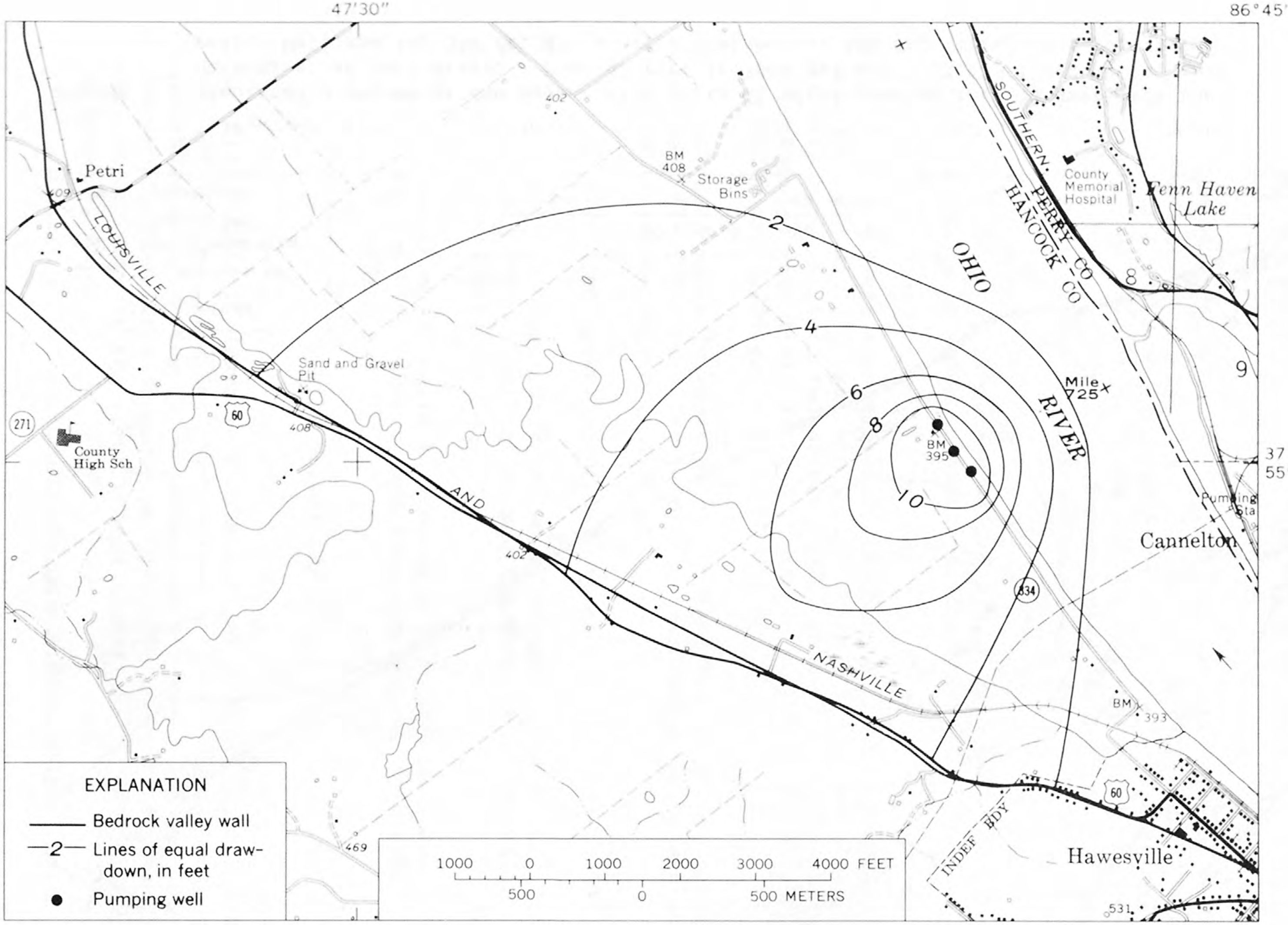

Figure 4 - Simulated drawdown at the Hagman site (Site 1) after pumping for 256 days with the Ohio River at pool stage. Pumpage rate is 1500 gal min^{-1} (5,678 l min^{-1}) for each well. Well spacing 350 ft (107m) at a distance of 150 ft (46m) from the river.

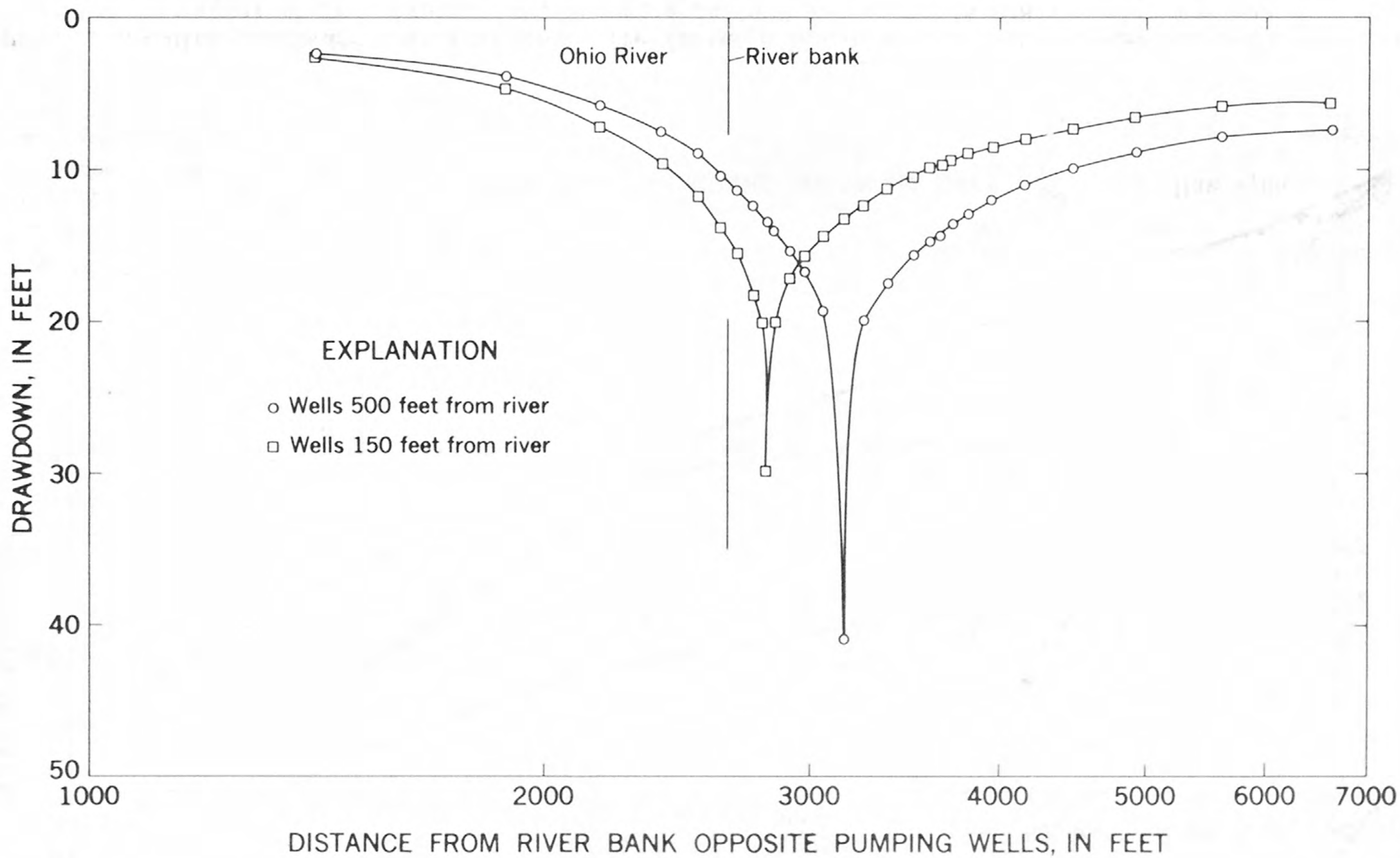

Figure 5 - Drawdown along a line beginning at the river bank opposite the well field and through the center pumping well for Site 1 (Hagman), after pumping for 256 days.

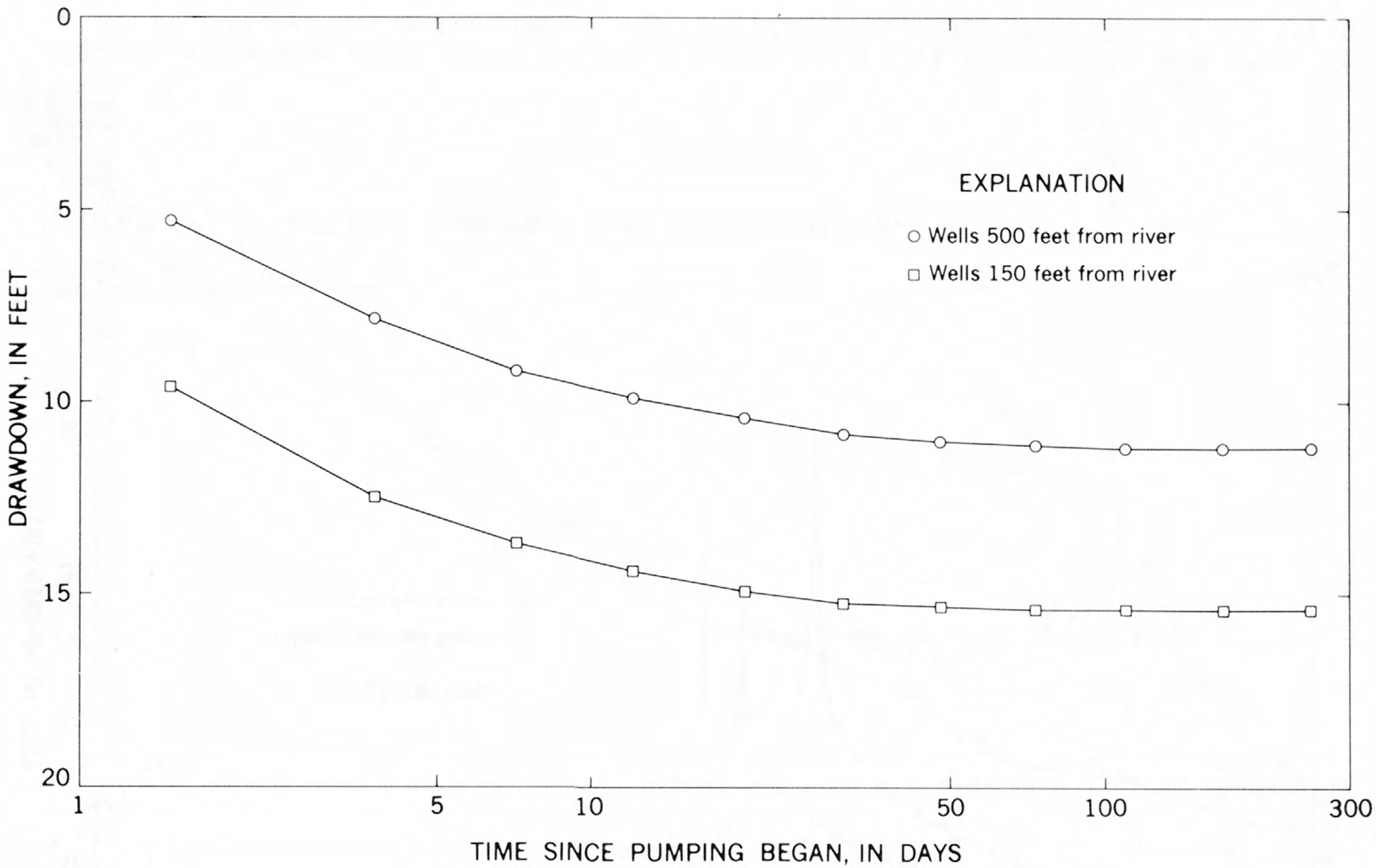

Figure 6 - Simulated drawdown at the river's edge nearest the center pumping well for Site 1 (Hagman) after pumping for 256 days.

Wells Between a Well Field and the Valley Wall

The effects of wells located between a pumping well field and the valley wall at Site 2 are shown in plan view by comparison of figures 7 and 8. A cross-sectional view of the drawdown at this site is shown by figure 9. The rate of drawdown at the river's edge nearest the center pumping well is shown by figure 10.

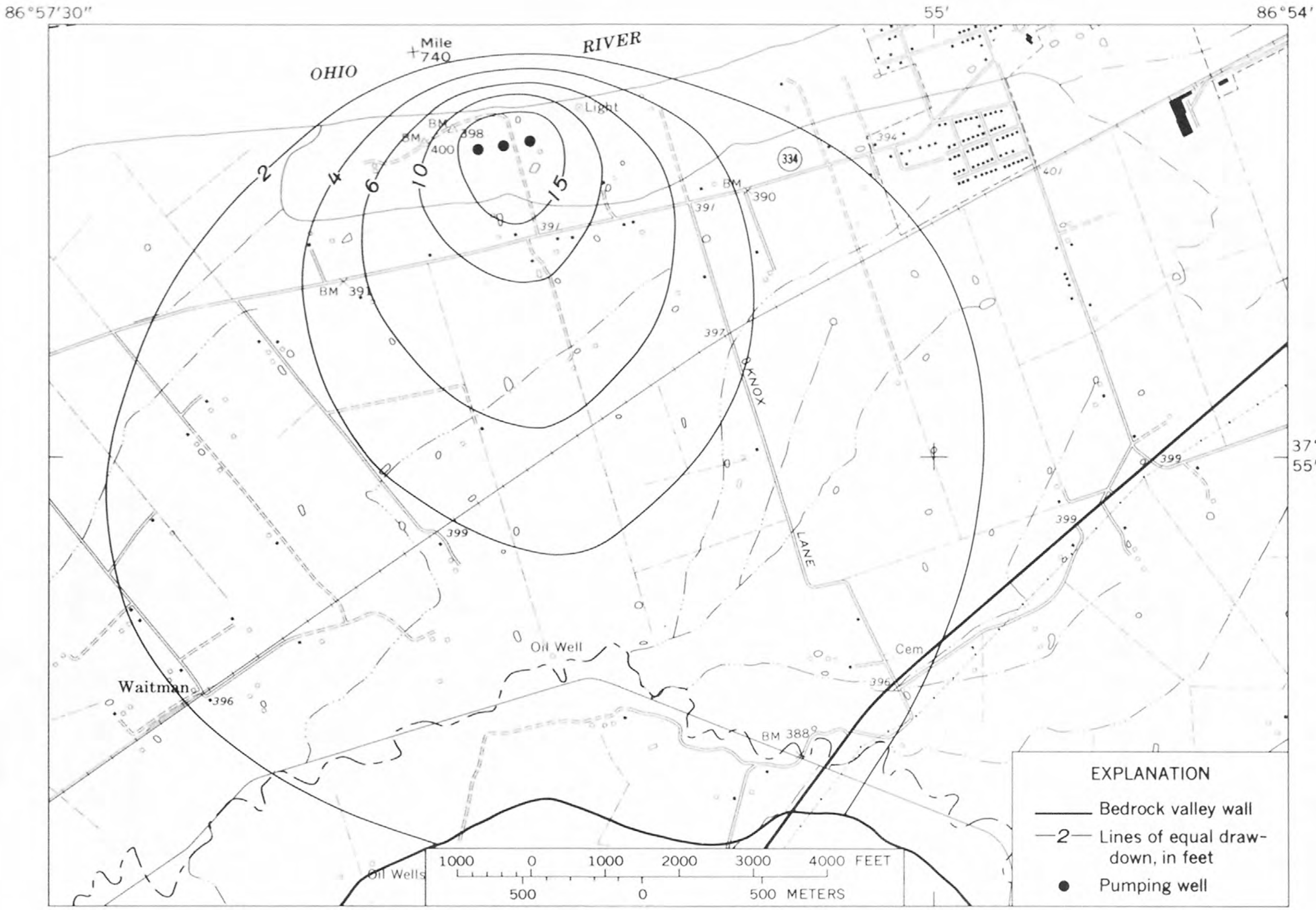

Figure 7 - Simulated drawdown at the Singleton site (Site 2) after pumping for 256 days with the Ohio River at pod stage. Pumpage rate is 1500 gal. min^{-1} (5,678 l min^{-1}) for each well. Well spacing 350 ft (107m) at a distance of 500 ft. (152m) from the river.

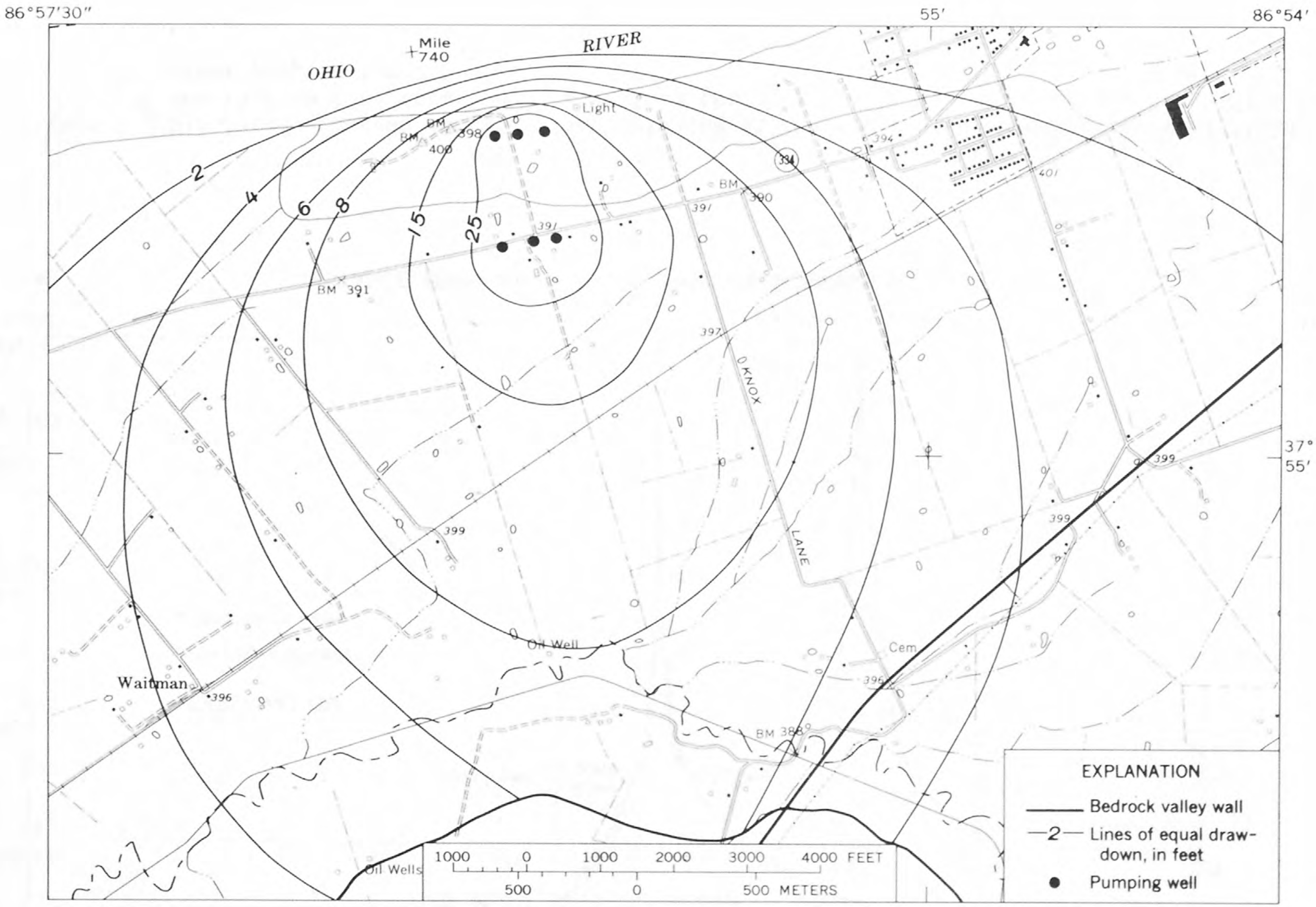

Figure 8 - Simulated drawdown at the Singleton site (Site 2) after pumping for 256 days with the Ohio River at pool stage. Pumpage rate is 1000 gal min^{-1} (3,785 l min^{-1}) for each well. Well spacing 350 ft (107m). One line is 500 ft (152m) from the river and the other line is 1800 ft (549m) from the river.

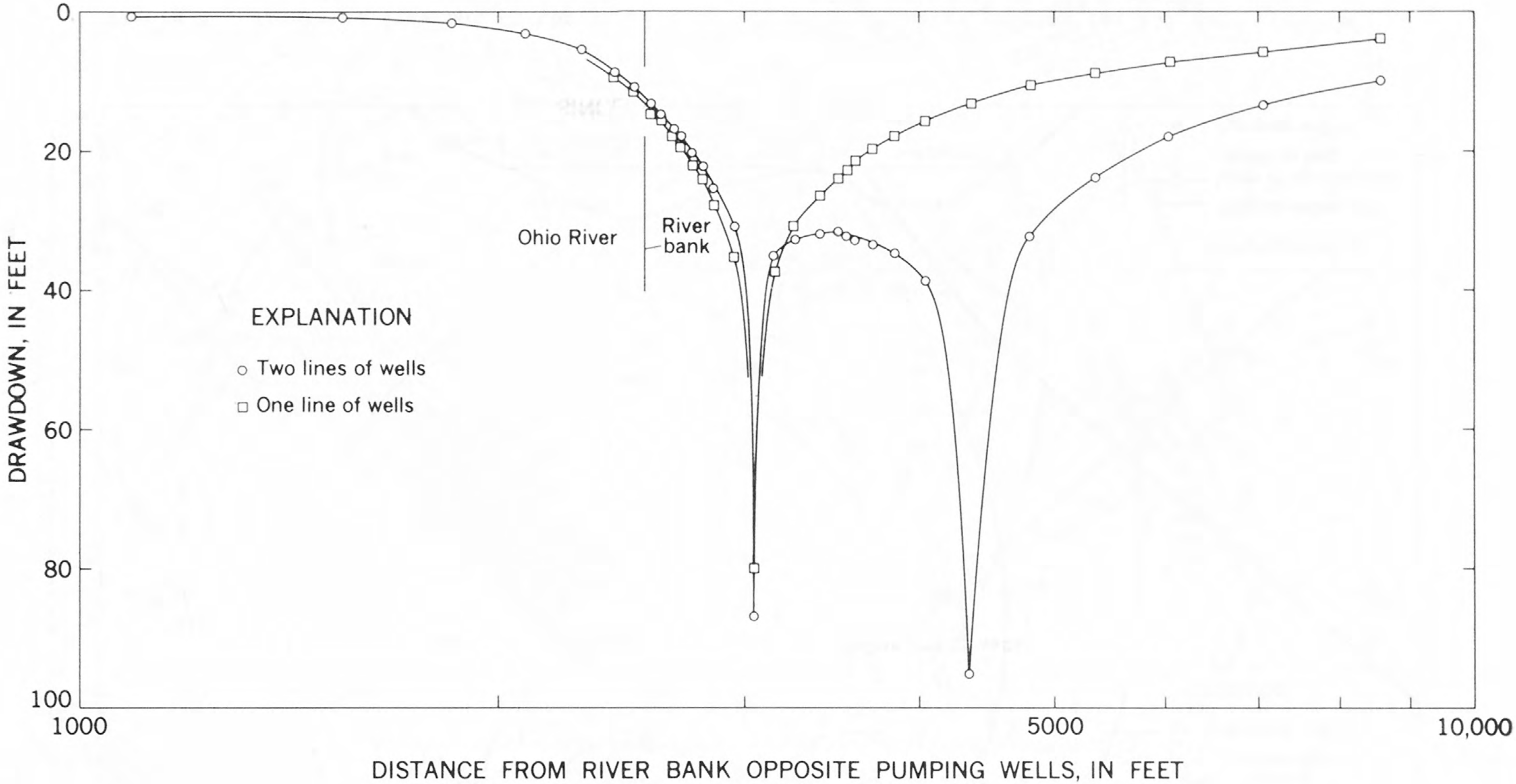

Figure 9 - Simulated drawdown along a line beginning at the river bank opposite the well field and through the center pumping well to the valley wall at the Singleton site (Site 2) after pumping for 256 days.

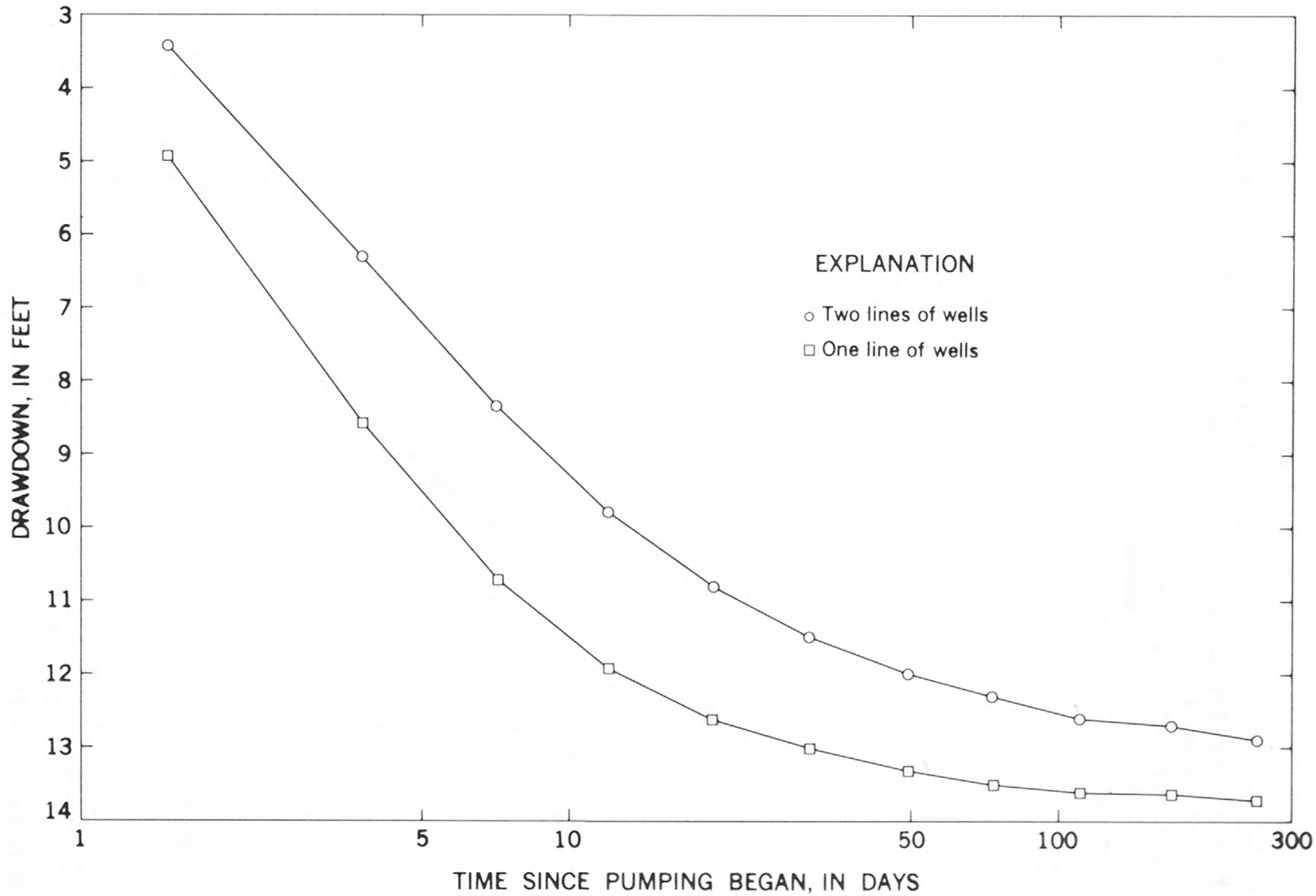

Figure 10 - Simulated drawdown at the river's edge nearest the center pumping well for the Singleton site (Site 2) after pumping for 256 days.

Wells Perpendicular to the River

Differences in drawdown in the aquifer at Site 3 for wells oriented perpendicular to the river versus wells oriented parallel to the river are shown in plan view by comparison of figures 11 and 12. A cross-sectional view of the drawdown at this site is shown in figure 13. The rate of drawdown at the river's edge nearest the center pumping well is shown in figure 14.

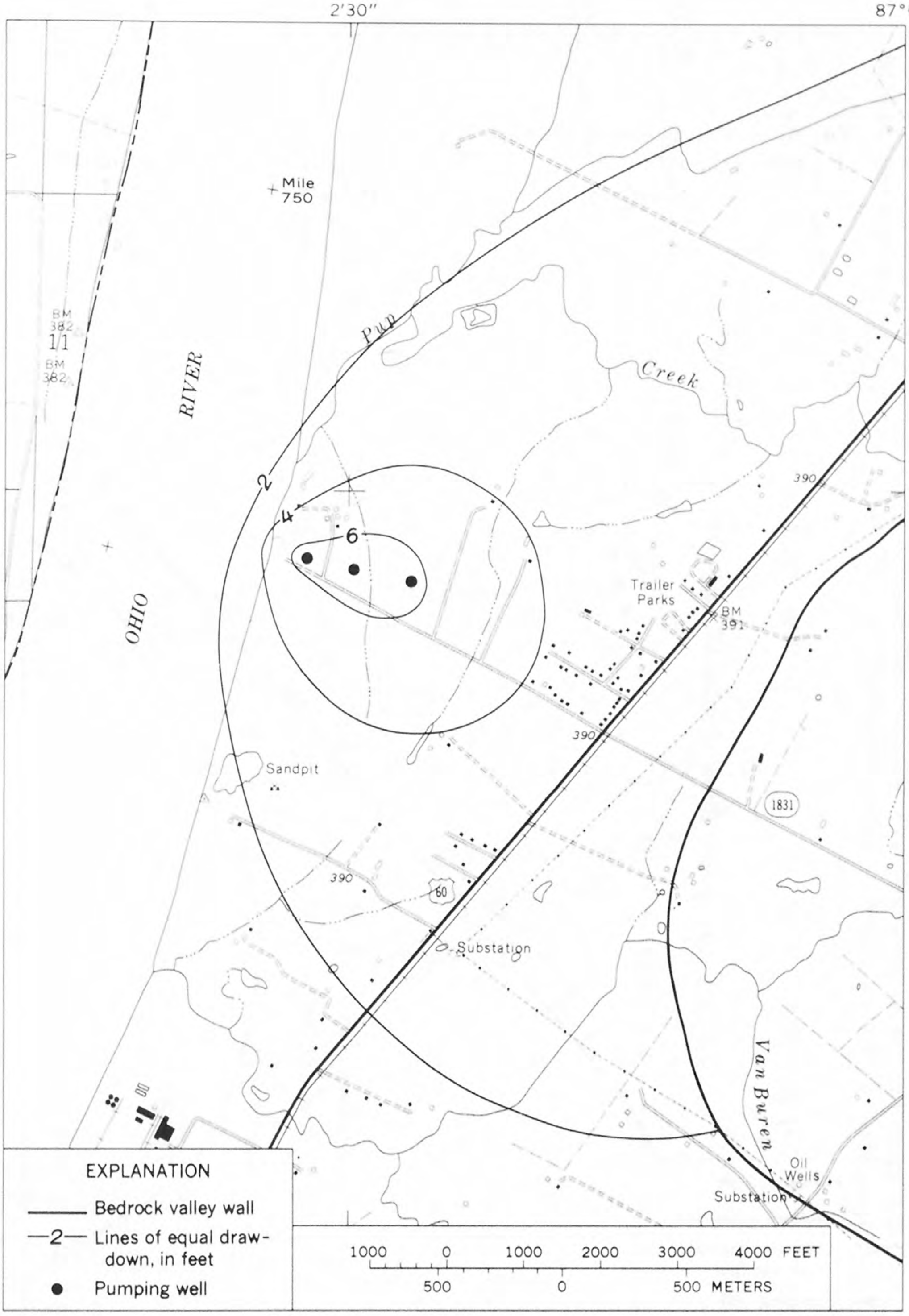

Figure 11 - Simulated drawdown at the Givens site (Site 3) after pumping for 256 days with the Ohio River at pool stage. Pumpage rate is 1500 gal min^{-1} (5,678 l min^{-1}) for each well. Well locations 550 ft (168m), 1130 ft (344m) and 1890 ft (576m) from the river.

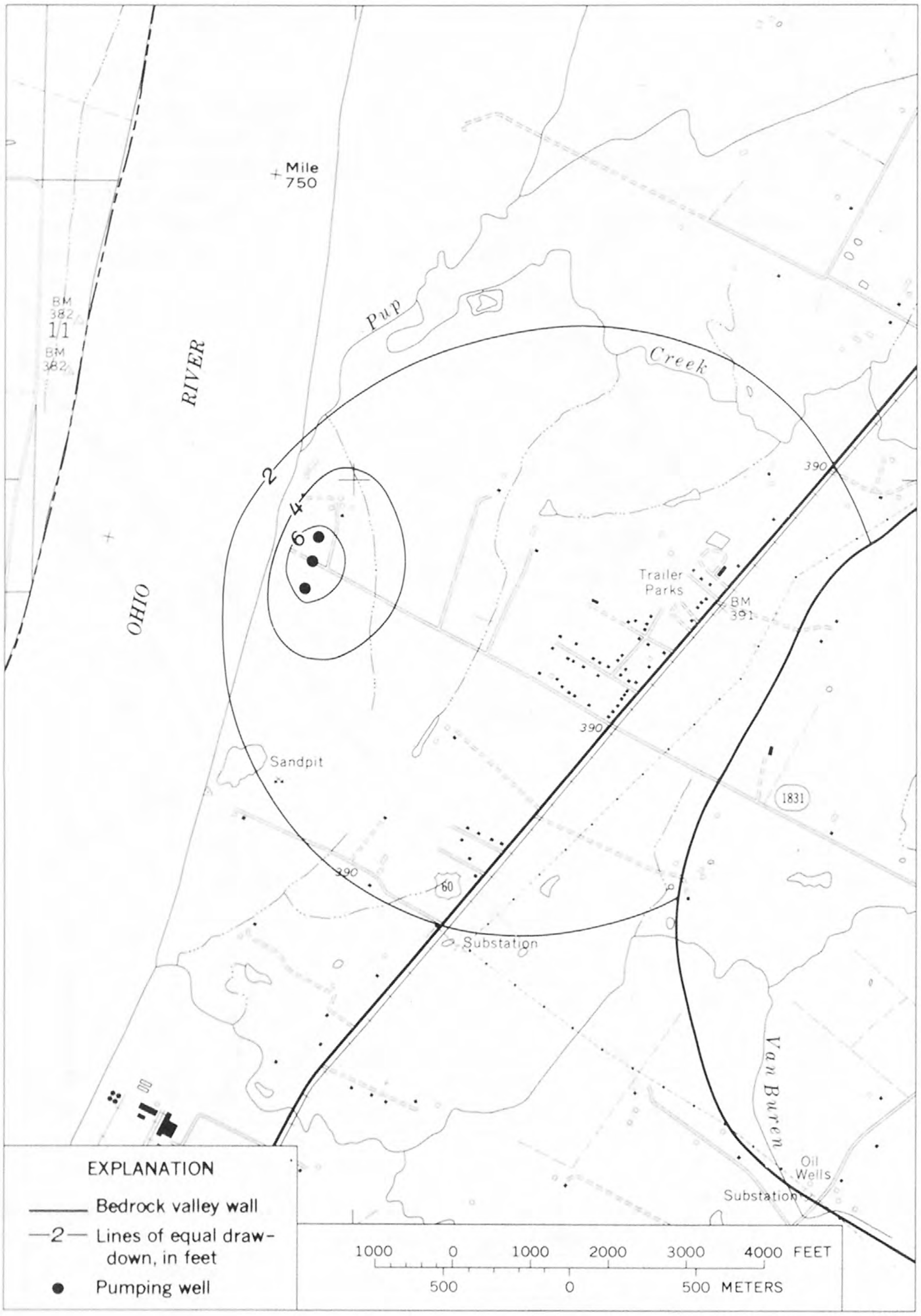

Figure 12 - Simulated drawdown at the Givens site (Site 3) after pumping for 256 days with the Ohio River at pool stage. Pumpage rate is 1500 gal min^{-1} (5,678 l min^{-1}) for each well. Well spacing 350 ft (107m) at a distance of 500 ft (152m) from the river.

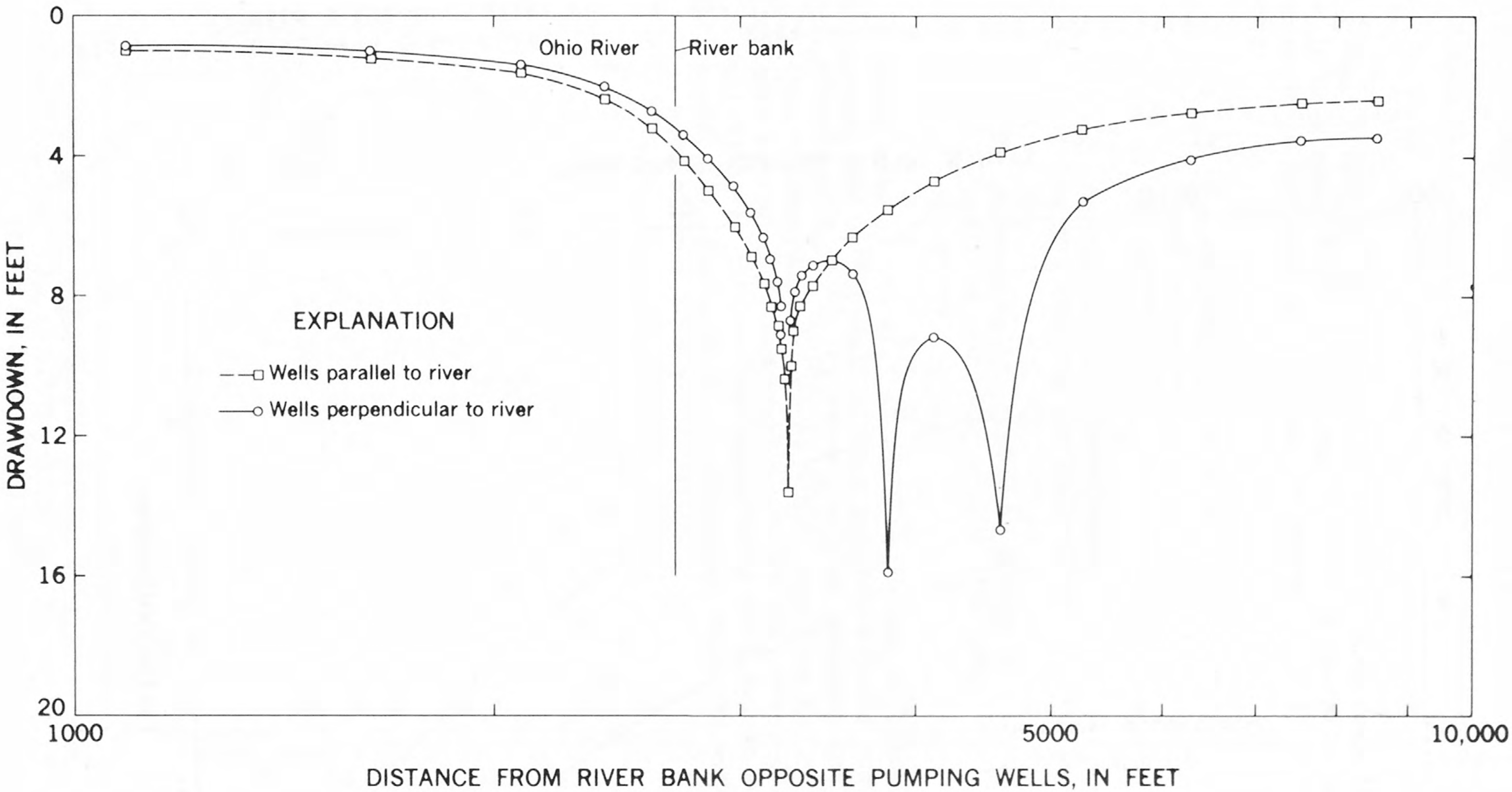

Figure 13 - Simulated drawdown along a line beginning at the river bank opposite the well field and through the center pumping well to the valley wall at Site 3 (Givens) after pumping for 256 days.

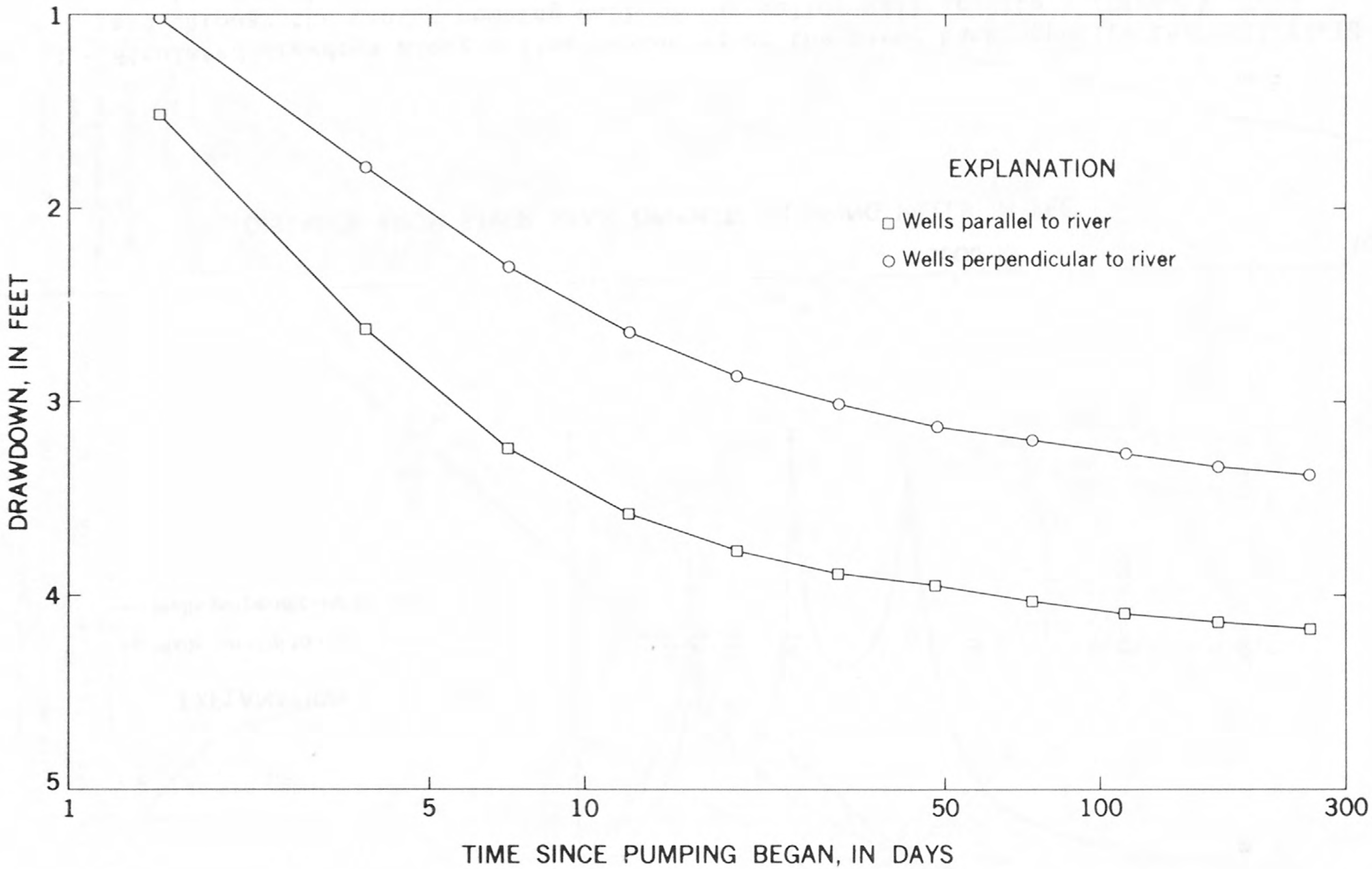

Figure 14 - Simulated drawdown at the river's edge nearest to the center pumping well for Site 3 (Givens) after pumping for 256 days.

SUMMARY AND CONCLUSION

The effects of well field arrangement on drawdown due to pumping wells were shown for three selected sites in the alluvial aquifer adjacent to the Ohio River. The arrangements of wells at these sites were:

(1) Pumping wells located 150 feet from the river versus wells located 500 feet from the river.

(2) Pumping wells located between the initial well field and the bedrock valley wall.

(3) Pumping wells located on a line perpendicular to the river rather than parallel to the river.

Other uses of the digital model which can be considered in the management and development of this aquifer include the following: (1) The effects of fluctuating river stage on drawdown and aquifer yield, (2) The optimum combination of yield, drawdown and well location relative to the river and proposed water use sites, (3) The effects of variations in river-water temperature on drawdown and aquifer yield and, (4) The effects of additional wells in areas where well fields have already been developed.

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APPENDIX

The flow boundaries in the Ohio River valley alluvial aquifer are so complex that a method for solving ground-water problems, such as digital modeling, is almost imperative except for the simplest problem. The limitations of analytical methods and the usefulness of electric analog and digital ground-water models were reviewed by Pinder and Bredehoeft (1968). Owing to the recent advances in solving ground-water problems by digital computer techniques, and the availability for this investigation of a digital computer, this method was selected to evaluate the boundary conditions of the aquifer adjacent to the Ohio River in Kentucky and to simulate the effects of alternative well-field arrangements.

Finite difference approximations of the two-dimensional flow equations in a nonhomogeneous anistropic porous medium were developed by Pinder and Bredehoeft (1968, p. 1077). Pinder (1970) presented a digital computer program which evaluated the finite difference equations by an alternating direction implicit procedure (ADIP). The digital computer program used in this study is essentially the same as that described by Pinder (1970) except, (1) an iterative ADI technique is used to solve the finite difference equations, and (2) leakage from the streambed is approximated by equation 5 of Bredehoeft and Pinder (1970).

Evaluation of flow boundaries for this aquifer requires a knowledge of the following: (1) Location of the impermeable boundaries, (2) Transmissivity (T) (or hydraulic conductivity and saturated thickness of the aquifer), (3) Storage coefficient (S), (4) Location and magnitude of hydraulic stresses upon the aquifer, and (5) Location and hydraulic conductivity of the streambed.

Model Verification

Location of the bedrock valley wall and the elevation of bedrock underlying the sand and gravel aquifer were shown by Gallagher (1964) for the three sites of figure 1. Site 4 (fig. 15) was included in the verification process to allow comparison with the other three sites because data from an aquifer test were available (Rorabaugh, 1956). Bedrock valley wall and bedrock altitude for Site 4 were shown by Price (1964).

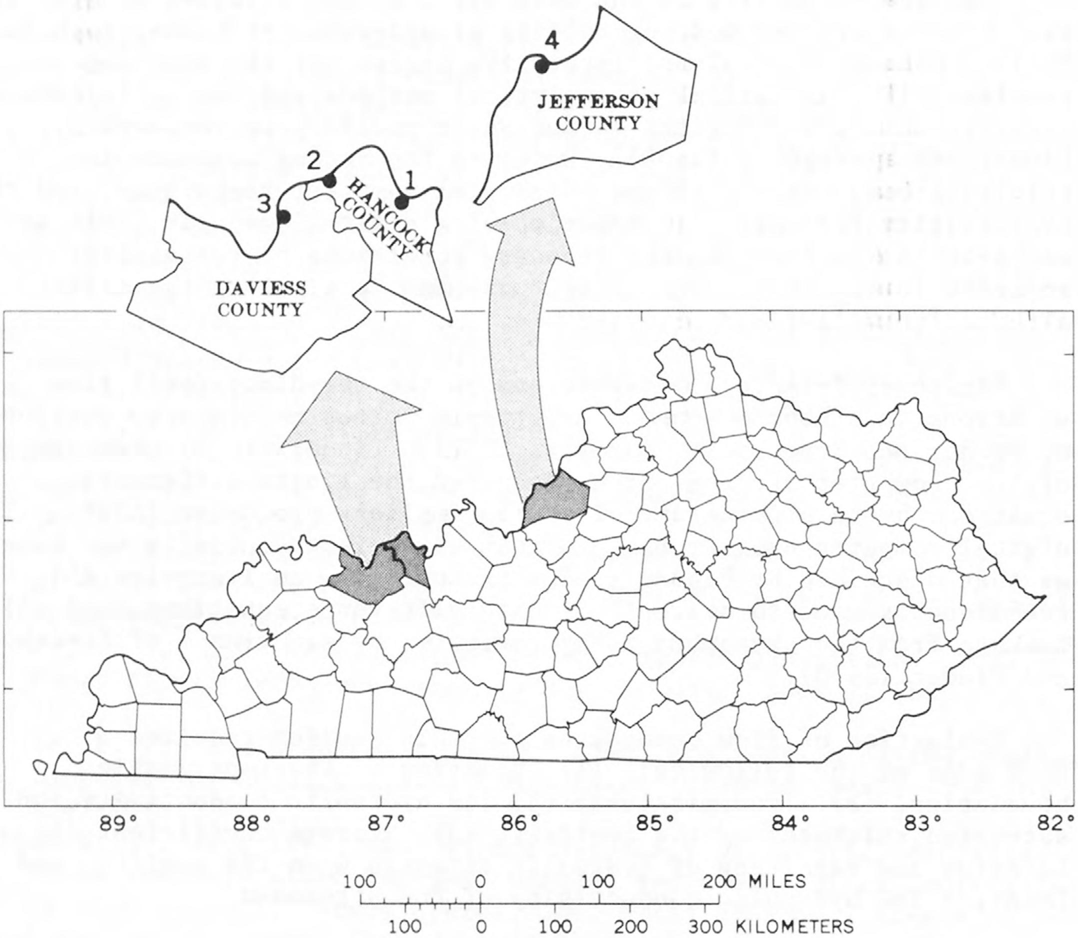


Figure 15 - Location of sites for model verification in the three Kentucky Counties of Jefferson, Hancock, and Daviess.

The width of the aquifer between the river and the bedrock valley wall ranges from about 3,000 feet (914m) at Site 4 to about 10,000 feet (3,048m) at Site 2 (figs. 16-19). Aquifer diffusivity (the ratio of transmissivity to the storage coefficient) was determined at each site by Grubb and Zehner (1973). Based upon lithology, water-level fluctuations, and model response the diffusivity was converted to reasonable T and S values by a trial and error process. For purposes of model verification a flood period was selected in which the stress applied to the aquifer by the flood wave was of such magnitude that the recharge from the bedrock valley wall and the infiltration of precipitation falling on the aquifer could be neglected. A hydraulic conductivity value was assigned to the streambed which was assumed to be 1 foot in thickness and homogeneous. The aquifer's response to the selected flood wave was then simulated and the results compared to the observed aquifer response at wells 1 and 2. The value of streambed hydraulic conductivity was then adjusted until the simulated aquifer response compared favorably with the observed aquifer response at wells 1 and 2.

River stage was determined at each site by a straight line interpolation between an upstream and a downstream gage. For the test case shown in figure 20, where interpolated values were compared with recorded stages at Tell City, errors in the magnitude of the stress applied to the aquifer were less than ± 1 foot (0.3m).

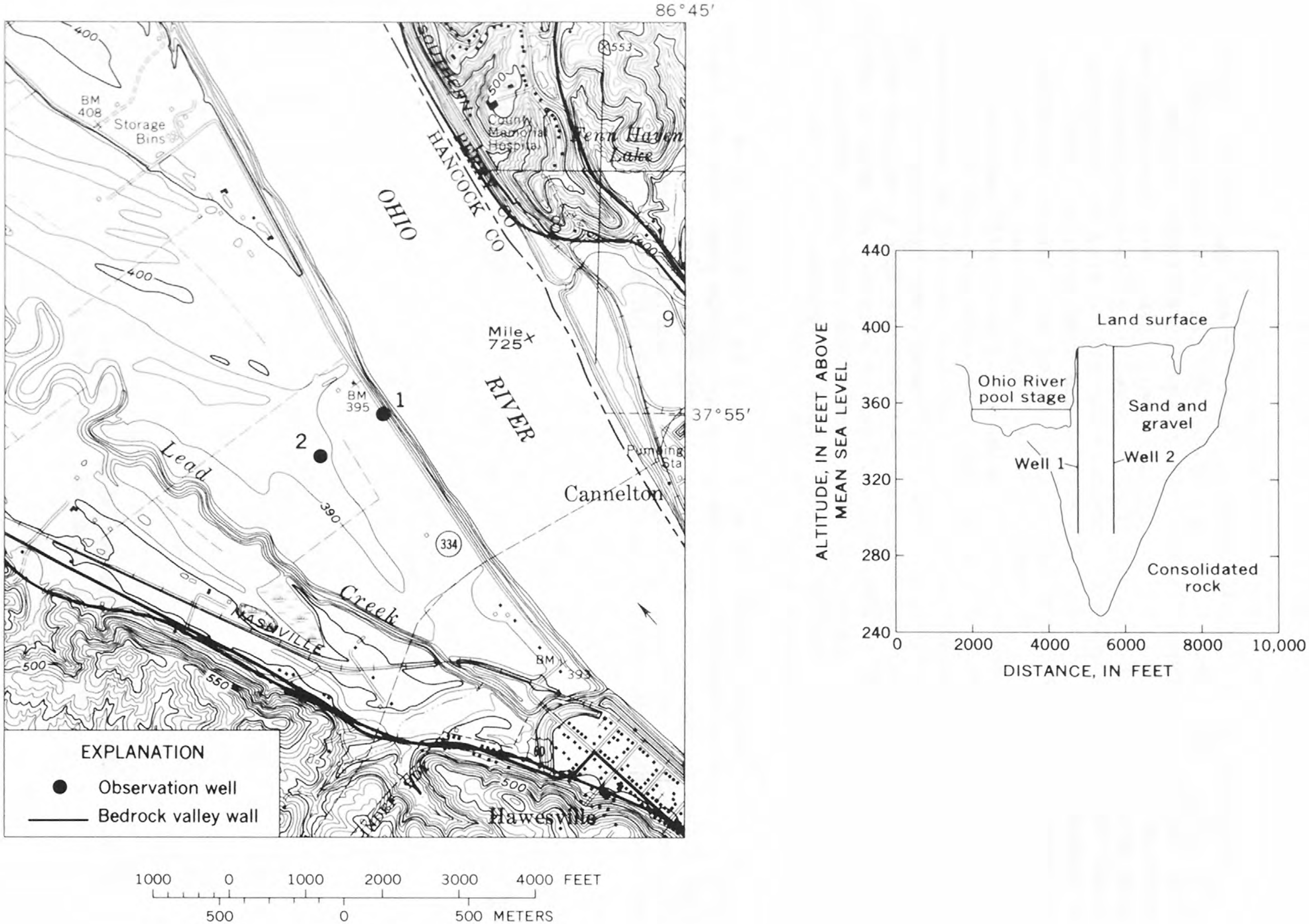


Figure 16 - Location of observation wells and generalized cross section at Site 1 (Hagman).

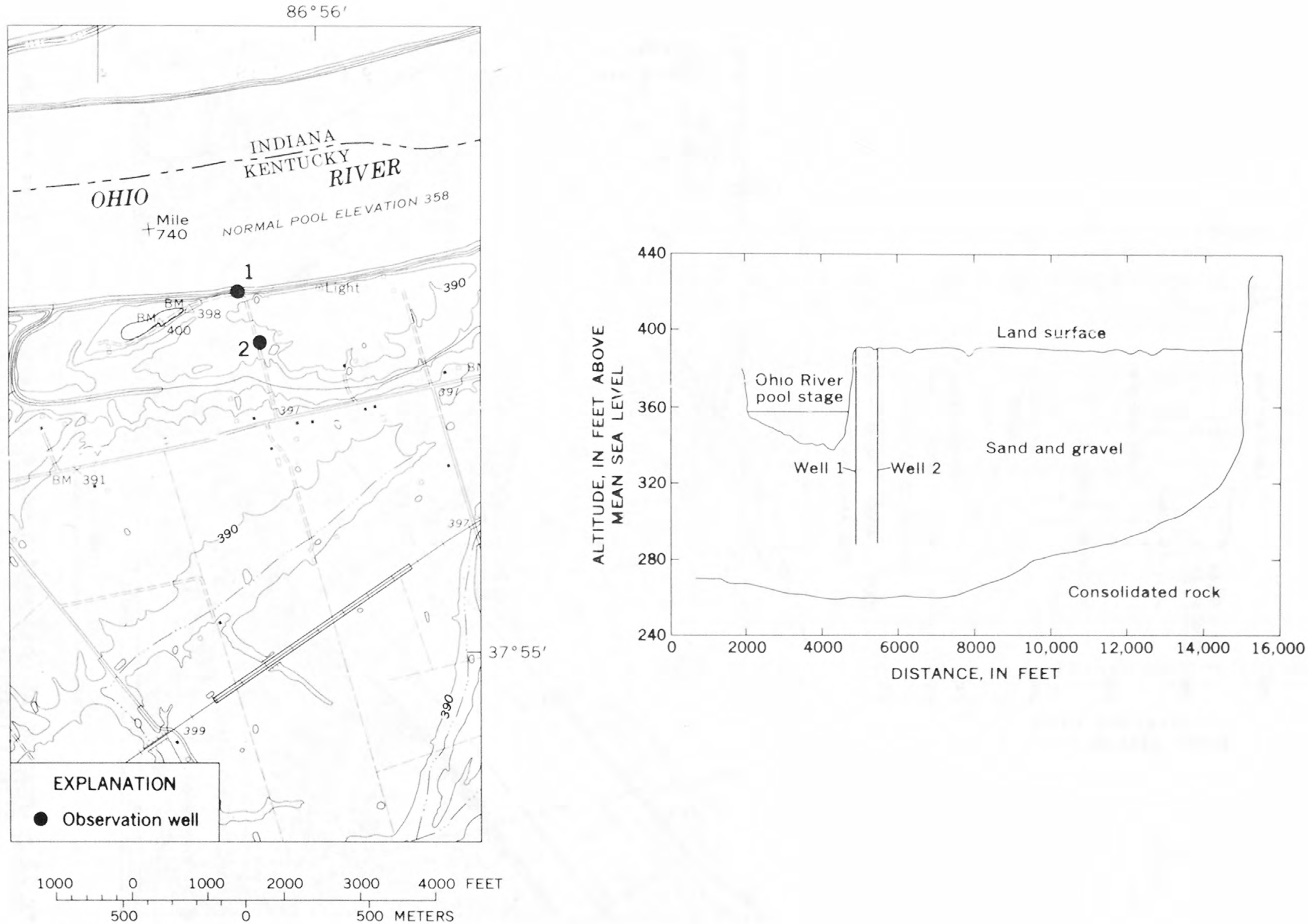
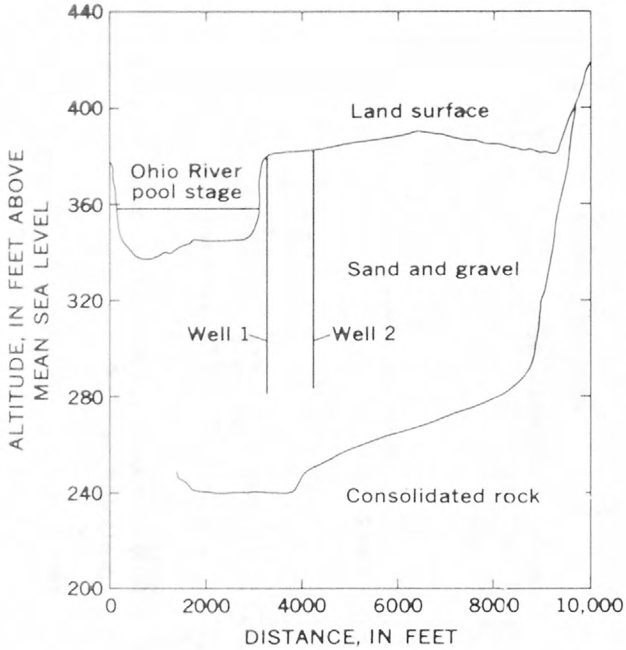


Figure 17 - Location of observation wells and generalized cross section at Site 2 (Singleton).



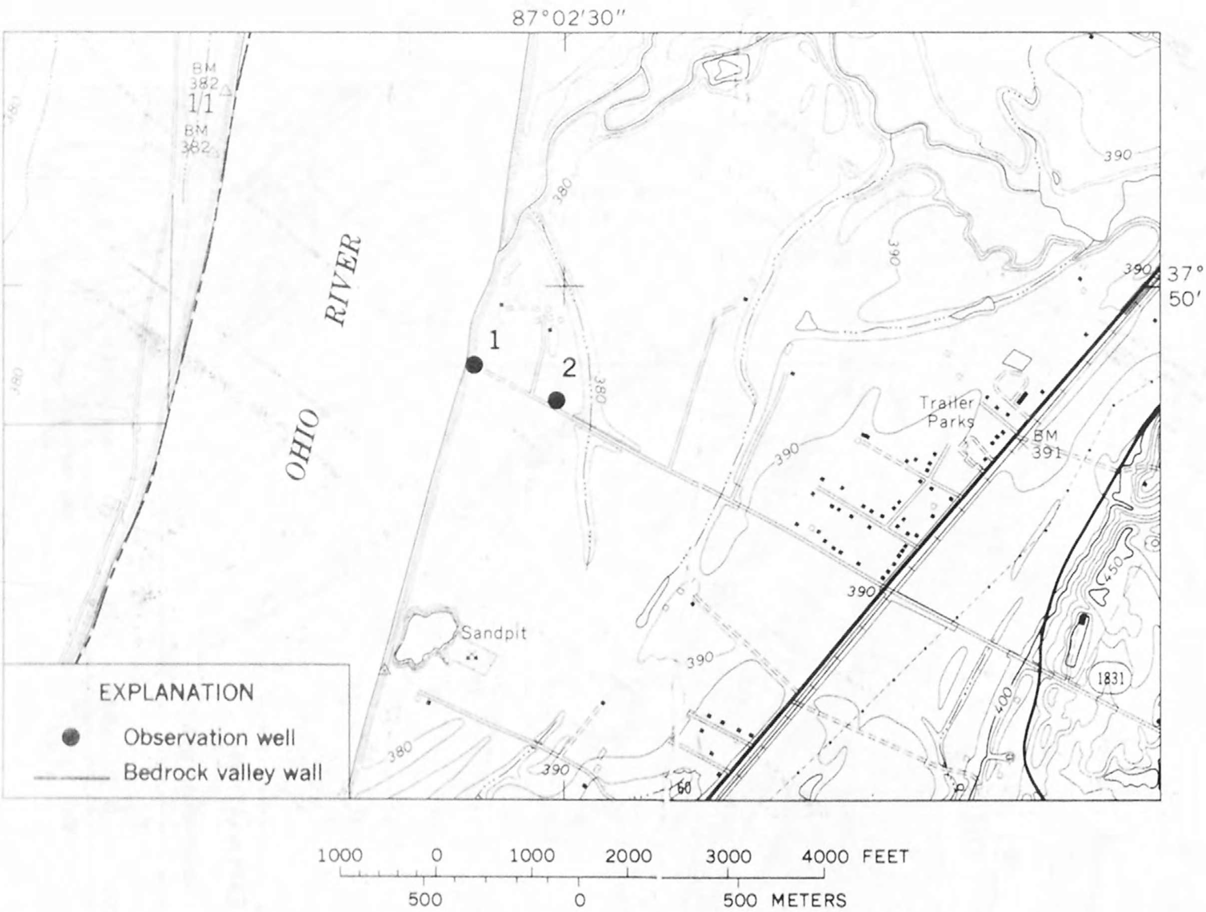


Figure 18 - Location of observation wells and generalized cross section at Site 3 (Givens).

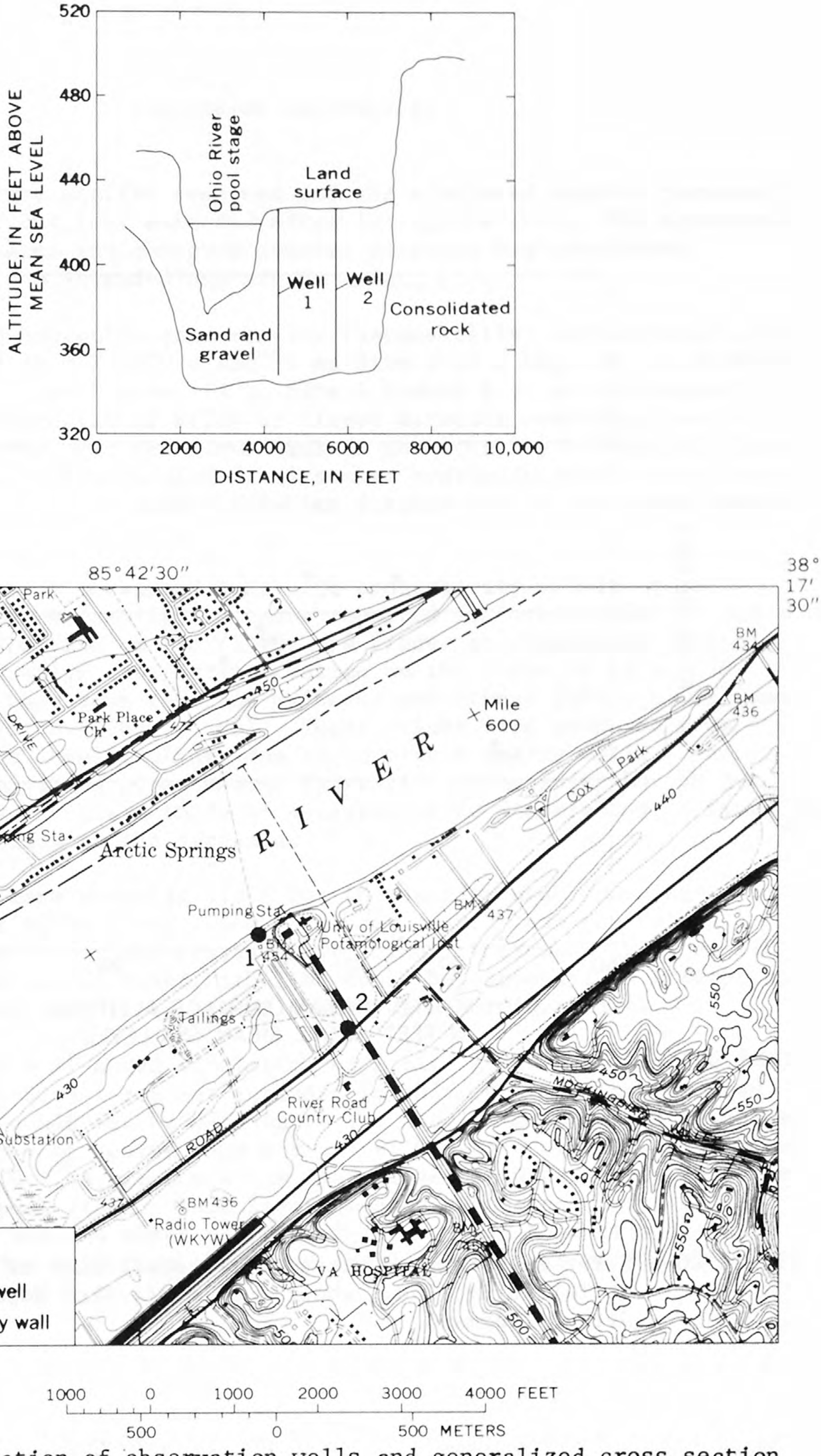


Figure 19 - Location of observation wells and generalized cross section at Site 4 (Louisville Water Company).

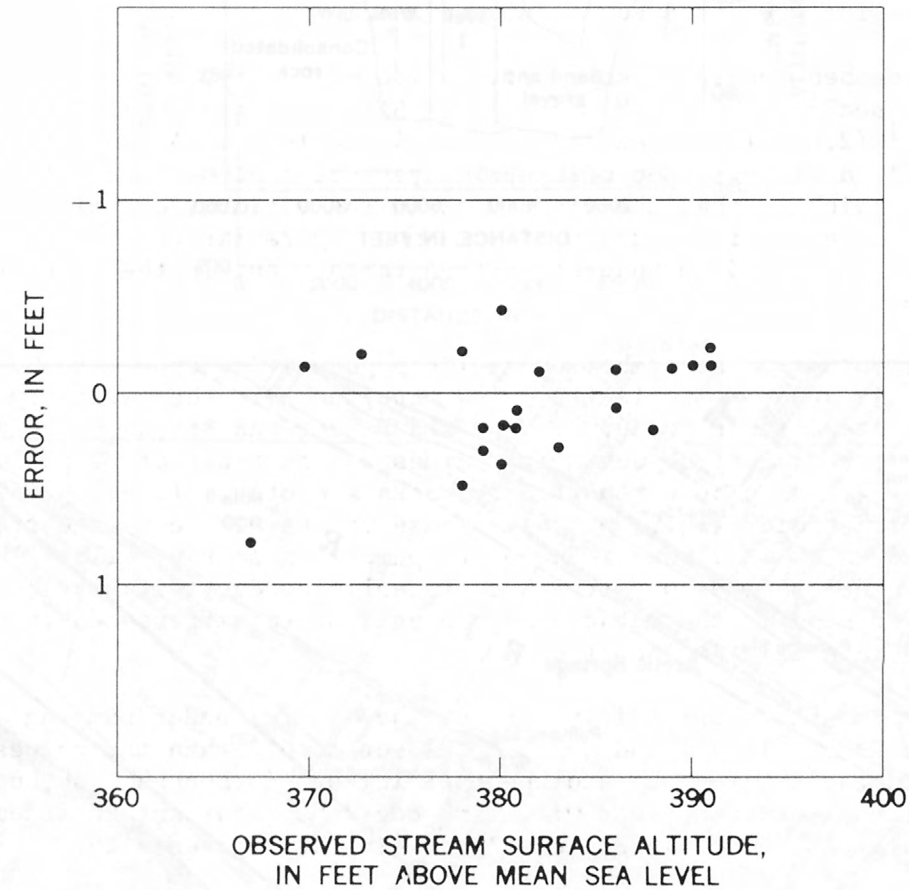


Figure 20 - Error in estimated stream surface altitude of the Ohio River at Tell City, Ind., about 3 miles (4.8km) downstream from Site 1 (Hagman).

Discussion and Results

The observed aquifer response and the simulated aquifer response are shown for the four selected sites in figures 21-24. The agreement between simulated and observed aquifer response was considered adequate for the intended use of the model.

Streambed hydraulic conductivity (permeability) varies from 2.5 X 10^{-7} ft sec^{-1} (2.0 X 10^{-6} m sec^{-1}) at Site 1 to a high of 7.5 X 10^{-6} ft sec^{-1} (2.0 X 10^{-6} m sec^{-1}) at Site 4 (table 1). At the Hagman site (2), a fine-grained silty or clayey material overlying the aquifer thickens near the river bank in the vicinity of well 1. This results in an overestimation of streambed hydraulic conductivity near the river bank and an underestimation farther out in the river toward midstream.

The values of streambed hydraulic conductivity appear to be reasonable and are similar to those reported for other areas by Lin (1973), Trescott and others (1970) and Pinder and Bredehoeft (1968). Streambed hydraulic conductivity values on the order of 10 to 100 times larger have been reported by Weeks and others (1965, p. 49) and Norris and Fidler (1969, p. 45). These values were computed from observed water level declines due to pumping a nearby well. The difference in values of streambed hydraulic conductivity may be due to differences in the methods of analysis or to differences in fine-grained materials in the streambed.

The long-term specific yield for the aquifer under pumping conditions at Sites 1 and 2 may be closer to 0.2 than the values shown in table 2 for the storage coefficient (Rorabaugh 1956, p. 112) Variations in specic yield with time could be important in attempting to simulate optimum yield and well spacing at a given site.

The results of model simulation at a site about 60 miles (96.5km) upstream from Site 1 are not included in this report. The observed water levels could not be matched by the model simulation as described above. A layer of coarse sand and gravel having a storage coefficient greater than 0.2 is present a few feet above the water table when the river is at pool stage. This layer becomes saturated during a flood on the river and the observed rate of increase in head at a distance of 1,000 (305m) feet from the river (well 2) declines markedly.

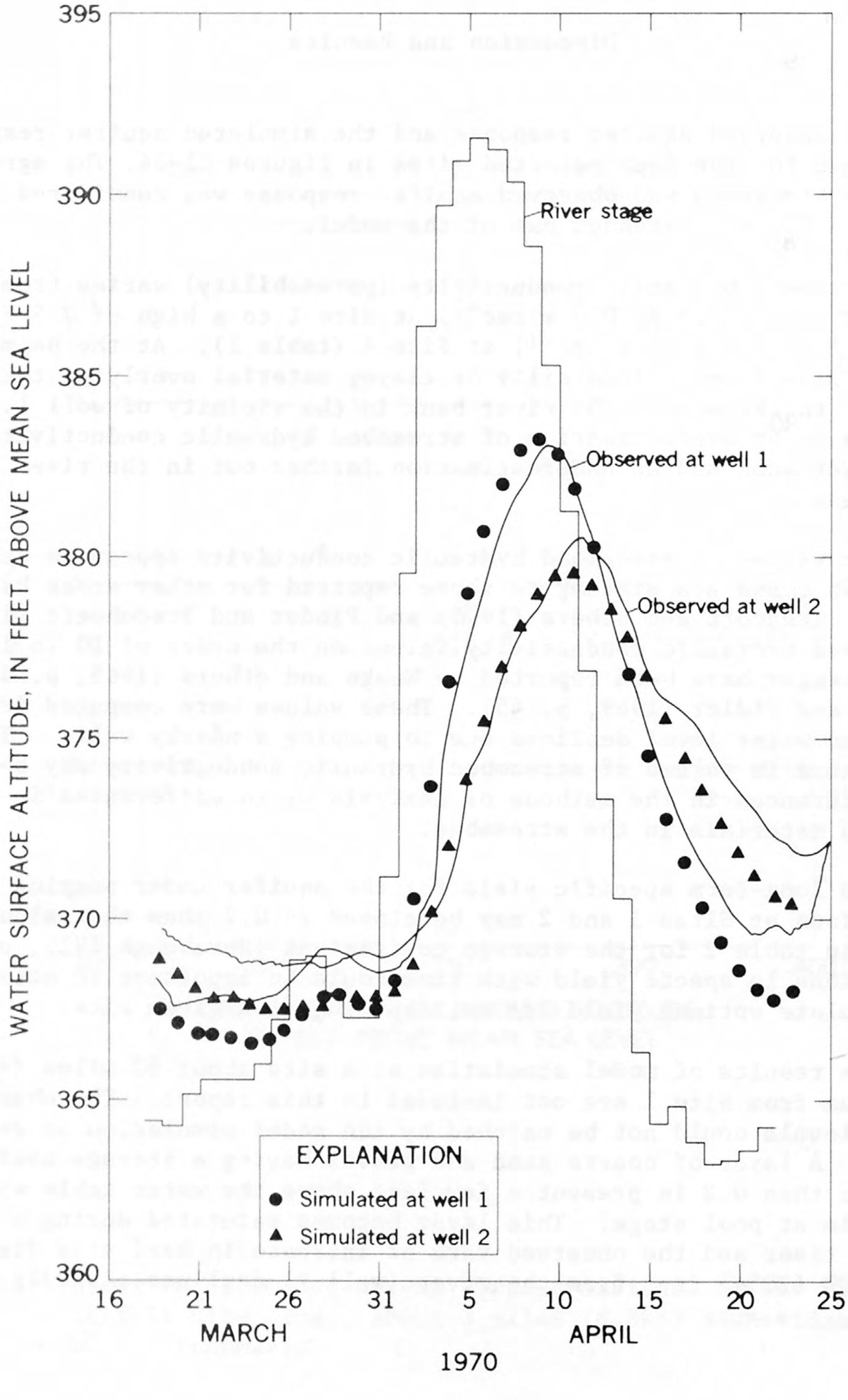


Figure 21 - Observed and simulated water levels, and Ohio River stage at the Hagman Site (1).

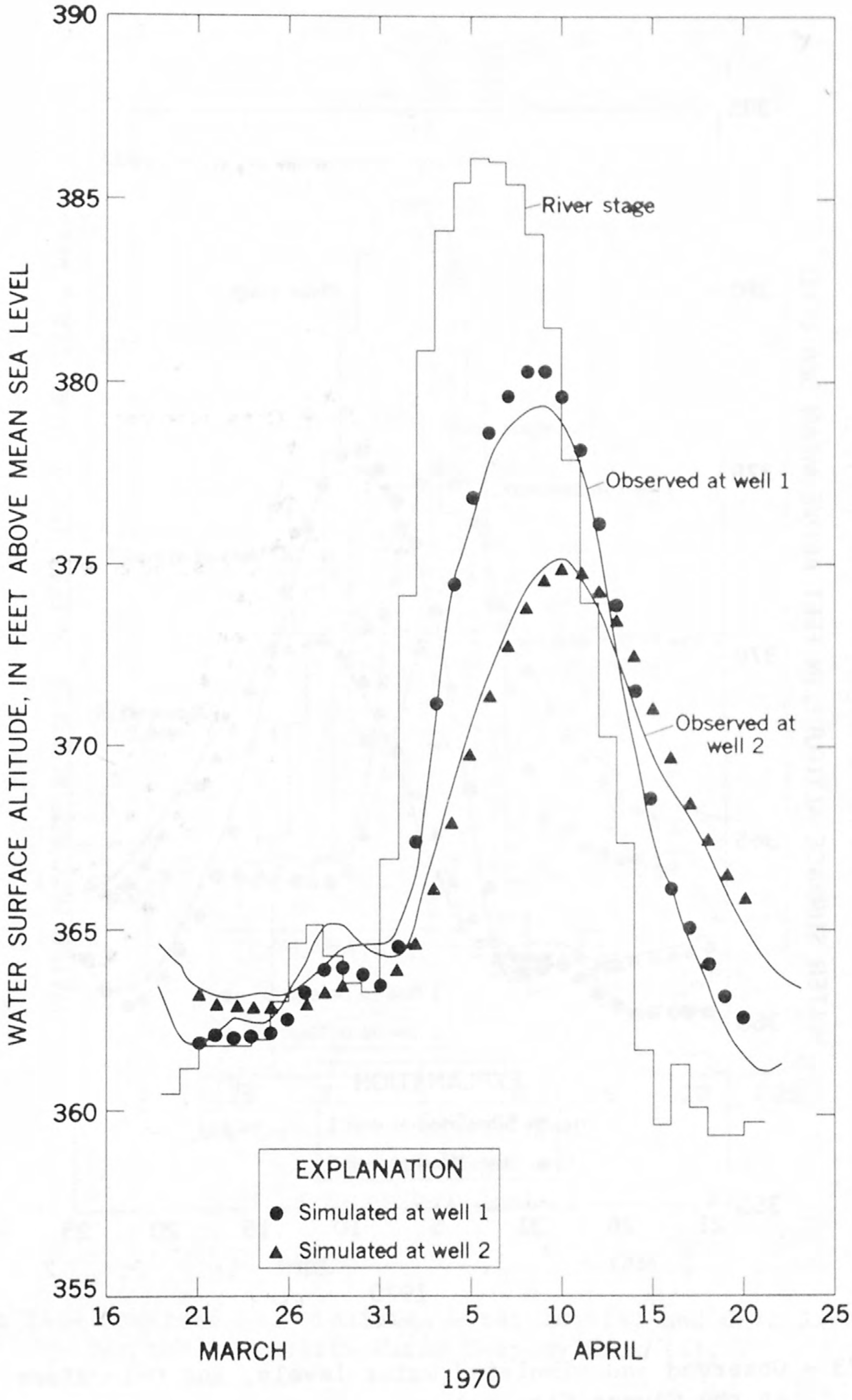


Figure 22 - Observed and simulated water levels, and Ohio River stage at the Singleton Site (2).

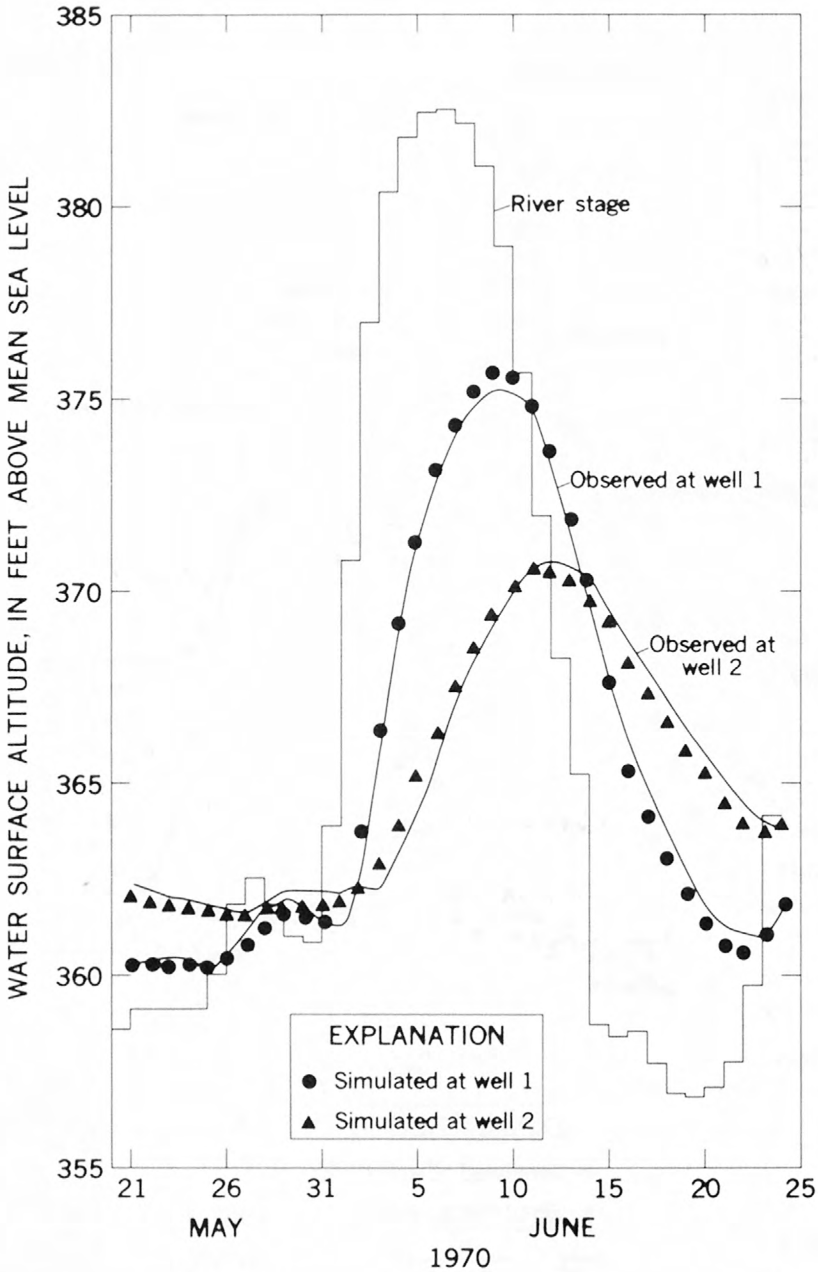


Figure 23 - Observed and simulated water levels, and Ohio River stage at the Givens Site (3).

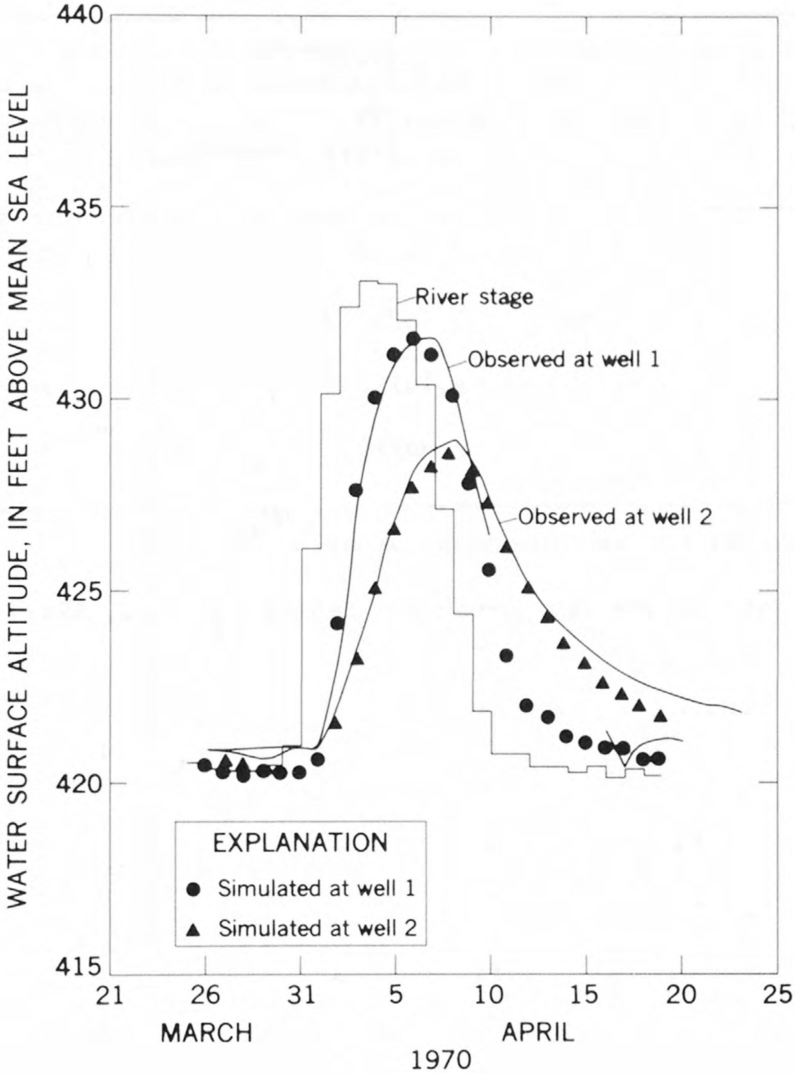


Figure 24 - Observed and simulated water levels, and Ohio River stage at the Louisville Water Company Site (4).

Site number and name	Aquifer[1/]				Stream bed
	Hydraulic[2/] diffusivity $ft^2\ sec^{-1}$	Hydraulic conductivity $ft\ sec^{-1}$	Saturated thickness (feet)	Storage coefficient	Hydraulic conductivity $ft\ sec^{-1}$
1 Hagman..........	8.77	$2.25X10^{-3}$	115	0.03	$2.5X10^{-7}$
2 Singleton.......	2.68	$1.15X10^{-3}$	117	.05	$7.0X10^{-7}$
3 Givens..........	2.79	$4.10X10^{-3}$	136	.20	$2.5X10^{-6}$
4 Louisville Water Co.	10.29	$2.40X10^{-3}$	96	.02	$7.5X10^{-6}$

1/ Terms as defined by Lohman and others (1972).

2/ Diffusivity values from Grubb and Zehner (1973, p. 599).

Table 1.--Aquifer and stream bed characteristics at four sites in the Ohio River alluvial aquifer.

Summary

A digital ground-water model was used to evaluate aquifer and boundary characteristics at four sites in the alluvial aquifer adjacent to the Ohio River in Kentucky. The model was verified by using observed aquifer response to a flood on the Ohio River. At each site data on river stage and water levels, (at two points in the aquifer), during a flood were used in conjunction with the digital model to determine average values of streambed hydraulic conductivity

CONVERSION TABLE

Hydraulic conductivity		Transmissivity	
ft sec^{-1}	m sec^{-1}	ft^2 sec^{-1}	m^2 sec^{-1}
One	0.305	One	0.093
3.28	One	10.76	One

	English	Metric (S. I.)
Length	One foot	0.305 meter
	One mile	1.609 kilometer
Volume	One gallon	3.785 liter
Flow rate	One ft^3 sec^{-1}	0.283m^3 sec^{-1}
	One ft^3 sec^{-1}	1680 l min^{-1}
	One gal min^{-1}	3.785 l min^{-1}

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