PROBLEMS OF RISING GROUND-WATER LEVELS IN URBAN AREAS WITH SPECIAL REFERENCE TO THE LOUISVILLE, KENTUCKY AREA

By Douglas V. Whitesides, Robert J. Faust, and Douglas D. Zettwoch

---

U.S. GEOLOGICAL SURVEY

Water Resources Investigations Report 83-4233

Prepared in cooperation with

THE KENTUCKY GEOLOGICAL SURVEY
UNIVERSITY OF KENTUCKY

Louisville, Kentucky

1983

UNITED STATES DEPARTMENT OF THE INTERIOR

WILLIAM P. CLARK, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
Water Resources Division
Room 572 Federal Building
600 Federal Place
Louisville, KY 40202

Copies of this report can be purchased from:

Open-File Services Section
Western Distribution Branch
U.S. Geological Survey
Box 25425 Federal Center
Lakewood, CO 80225
Telephone: (303) 234-5888

CONTENTS

ILLUSTRATIONS

TABLE

CONVERSION FACTORS

For use of readers who prefer to use metric units, conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
gallon per minute (gal/min)	0.0630	liter per second (L/s)
million gallon per day (Mgal/d)	0.0438	cubic meter per second (m^3/s)
inch (in.)	25.40	millimeter (mm)
inch per year (in/yr)	25.40	millimeter per year (mm/yr)
mile (mi)	1.609	kilometer (km)

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, called NGVD of 1929, is referred to as sea level in this report.

PROBLEMS OF RISING GROUND-WATER LEVELS IN URBAN AREAS WITH SPECIAL REFERENCE TO THE LOUISVILLE, KENTUCKY AREA

by Douglas V. Whitesides, Robert J. Faust, and Douglas D. Zettwoch

ABSTRACT

Rising ground-water levels are a problem in many urban areas in the United States because of the potential damage to man-made structures such as basements, foundations, utility lines, and septic tank systems. A decrease in ground-water withdrawals, above average precipitation, recharge from irrigation water, and leaky water lines and sewers are some of the causes of water level rises in cities such as San Bernardino, California; Greely and Fort Collins, Colorado; New York City boroughs of Brooklyn and Queens; and Louisville, Kentucky. Dewatering is necessary in many urban areas to maintain water levels below structures.

The ground-water rise in the alluvial aquifer underlying Louisville, Kentucky, in the 1970's was in response to above average precipitation and a decrease in ground-water withdrawals. The rising trend decreased in 1979 and by 1981 the water levels were stabilizing at 25 to 45 feet below land surface in the downtown area. Basements are generally 20 to 25 feet below land surface and some utility lines are as much as 40 feet below land surface in this area. Because of the shallow depth to water, any resumption of the upward trend would require preventive measures such as selective dewatering.

INTRODUCTION

Rising ground-water levels can cause damage in urban areas if the rise is great enough to inundate man-made structures. In many instances, because of the development of marginal land, seasonal or climatic rises in the water table may be sufficient to affect structures. In other instances, a combination of natural and man-made factors may contribute to a rise that causes damage. When recharge to the aquifer exceeds discharge, the net increase in storage causes a rise that can generally be attributed to one or more of the following reasons:

1. Increased recharge to the aquifer due to:

   a. Above average precipitation
   b. Lower heads in the aquifer than in nearby rivers, lakes, and reservoirs
   c. Increased return flow from irrigation
   d. Injection wells
   e. Leaking from deep artesian wells
   f. Leaking from water mains and sewers (when water table is below lines)

2. Decreased discharge from the aquifer due to:

   a. Reduction or cessation of pumping
   b. Blocking of natural-discharge areas
   c. Repair of well casings, water mains, and sewers (when water table is above these facilities)
   d. Decreased return flow from irrigation

Inundation of man-made structures can cause damage to basements and other subgrade structures, foundations, utility lines, and septic tank systems. Control of ground-water levels generally requires selective pumping, but installation of drain tiles and ditches may alleviate certain problems. This report gives an overview of the problem of rising ground-water levels in selected urban areas of the United States and describes a rise that occurred in Louisville.

Examples of problem areas in the United States were provided by offices of the U.S. Geological Survey, for their respective States. Water-level data for the Louisville example were collected as part of the basic network of observation wells measured by the U.S. Geological Survey in cooperation with the Kentucky Geological Survey.

Selected Urban Areas Affected by Rising Ground-Water Levels

Alaska--Fairbanks, Alas. has problems with rising ground-water levels (Gordon, Nelson, written commun., 1982) when the Tanana River and Chena River are in flood stage for several days or occasionally when the Chena Slough, which is a discharge area for ground water, is blocked by ice. Ground water seepage has damaged several homes and commercial buildings. Water levels in Fairbanks are discussed in a report by Nelson (1978).

Arizona--Rising ground-water levels have caused problems in the Yuma and Benson areas of Ariz. (J. Man, written commun., 1982). The high levels in Yuma are caused by irrigation. The high levels in Benson are believed to be a result of leakage from deteriorating casings in abandoned wells that tap a deep artesian aquifer. The saturation of fine-grained deposits near land surface has resulted in structural damage to buildings, streets, and sidewalks.

California--Part of the area in the vicinity of San Bernardino, Calif. has high ground-water levels that must be pumped to prevent flooding and other problems (E. J. McClelland, written commun., 1982). Early in the 1940's, ground-water development for agriculture and below normal precipitation resulted in the lowering of the water table and the drying of some swamps. This swamp land was then developed as commercial and industrial sites. Decline in the use of ground water and increased recharge since the late 1960's has caused the water table to rise near land surface again in the reclaimed swamps. Besides the flooding and damage to structures, there is concern about possible soil liquefaction during an earthquake which could cause catastrophic failure of building foundations.

The City of Sacramento, Calif. which is located on the flood plains of the Sacramento and American Rivers has problems with rising ground-water levels during wet years when river stages remain high for extended periods (G. L. Bertoldi, written commun., 1983). Basements in older multiple-story business and office buildings must be pumped to prevent flooding. Also, homes with basements in some residential areas are equipped with sump pumps to handle seepage caused by high water levels.

Water-logging occurs in irrigated areas of the Central Valley of California. Although this is mainly an agricultural area, towns such as Stocton, Tracy, Modesto, Merced, Colusa, and Williams suffer from the effects of waterlogging due to irrigation.

Colorado--Probably one of the earliest documentations of high ground-water levels was given by Boyd (1897, p. 80) who reported that the towns of Greely and Fort Collins, when settled, had no problems with wet cellars. However, after irrigation had been going on for three of four years, water started to rise in some of the cellars and to discharge at land surface in some of the lower lying areas. Drain tiles were installed to alleviate the problem.

The Greely area was also alluded to by P. L. Schneider, Jr. (written commun., 1983) who reported that a shallow water table exists in the alluvial deposits along streams and rivers in the Boulder-Fort Collins-Greely area and this would be a potential control on the use and location of construction and excavation projects in parts of the Front Range Urban Corridor. This water table, which ranges from land surface to 50 feet below land surface, underlies approximately 400 mi^2 (square miles). It is maintained above natural levels by the infiltration of irrigation water that is diverted into the basin from streams and reservoirs in the Colorado and Laramie River basins.

Kentucky--Ground-water levels showed a steeply rising trend in the alluvial aquifer underlying Louisville, Ky. during the 1970's. This rise was in response to decreasing withdrawals of ground-water and above average precipitation, and it brought water levels to within a few feet of some existing structures in the downtown area. This rise is discussed in the body of this report.

New York--Problems of high ground-water levels in New York City have been documented in reports by Soren (1976) and Buxton and others (1981). According to Buxton (written commun., 1983) ground-water flooding problems have been evident in parts of the New York City boroughs of Brooklyn and Queens, for more than 30 years. Problems developed because deep subway lines and basements were constructed during the period 1920-40 when the water table had been drawn down below sea level. Since then, ground-water withdrawals have stopped because of saltwater encroachment and water levels have recovered to near predevelopment levels. The Metropolitan Transportation Authority is permitted to pump as much as 31 million gallons per day for dewatering. The dewatering, however, complicates operations of sewage treatment plants. The sewer system carries both untreated sewage and storm-water runoff and during times of heavy precipitation the treatment plants are unable to process all the inflow and untreated sewage is discharged to tidewater. Ground water discharge to the sewer system during these times adds to problems of the treatment plants.

Buffalo, N.Y. did have some problems locally with high ground-water levels. According to Roger M. Waller (written commun., 1983) pumping from two mine shafts ceased in 1976 after 50 years of pumping. Some homes built in the area near the mine shafts, when ground-water levels had been depressed by pumping, began to have basement-flooding problems after the water levels recovered to their pre-pumping levels. Trenches were constructed leading from the affected areas to existing drainage systems or to storm-sewer systems to alleviate the problem.

Pennsylvania--Ground-water levels in Philadelphia, Pa. are strongly controlled by the water and sewer systems (G. N. Paulachok, written commun., 1983). Leakage from water pipes and sewers is a source of recharge when the water levels are below the utility lines. However, infiltration to leaky sewers prevents the ground-water levels from rising much above the sewers during any rising trend. A rising trend could be a problem if the existing leaky sewers are replaced by ones that are relatively watertight. Some dewatering is required in central and southern Philadelphia to protect subway tunnels and building foundations.

Need for Water-Level Data

Because of the potential harm of high ground-water levels, monitoring is important in providing background data, detecting trends, developing an understanding of the aquifer system, and for implementing water-management decisions. This is especially true for alluvial aquifers that are hydraulically connected to a river. An increase in river stage can trigger rapid rises of several feet in ground-water levels at distances of several hundred feet from the river. These rapid rises occurring on top of already dangerously high ground-water levels can be very damaging and the suddeness of the rise allows very little lead time for preventive action.

Water-Management Decisions in Problem Areas

Decisions in areas threatened by high ground-water levels generally involve methods of protecting structures or ways of controlling a rising water-level trend. Newer buildings, in problem areas such as Louisville, Ky., have been designed to withstand high ground-water levels. However, most decisions will involve ways of maintaining the ground-water levels to a safe position below structures that were not designed for high ground-water levels. These decisions generally require sophisticated, quantitative analyses to assess the various stresses on the aquifer system. The accuracy of the answers from these analyses depends on the validity of the technique and the quantity and accuracy of the data used.

Ground-Water Rise--Louisville, Kentucky Example

The U.S. Geological Survey in cooperation with the Kentucky Geological Survey, monitors water levels in Kentucky. A potentially harmful rising trend of water levels in the alluvial aquifer underlying Louisville (fig. 1) was detected in the 1970's. The rise was particularly steep during the 1970's when ground-water withdrawals were decreasing and precipitation was above normal. Kernodle and Whitesides (1977) predicted that if the steep rising trend continued the water table would be within 20 feet of land surface in some places by 1982. Ground water at this depth could cause damage to some subsurface structures in Louisville.

The rising trend started to flatten in 1979 and by 1981 the water table appeared to stabilize and fluctuate seasonally in response to precipitation, and to changes in evapotranspiration. Water levels in 1982 were at depths ranging from 25 to 45 feet below land surface in downtown Louisville and 10 to 55 feet below land surface in southwest Jefferson County. Normal seasonal fluctuations range from 2 to 10 feet in wells in the alluvial aquifer. The highest level generally occurs in May and the lowest in December or January.

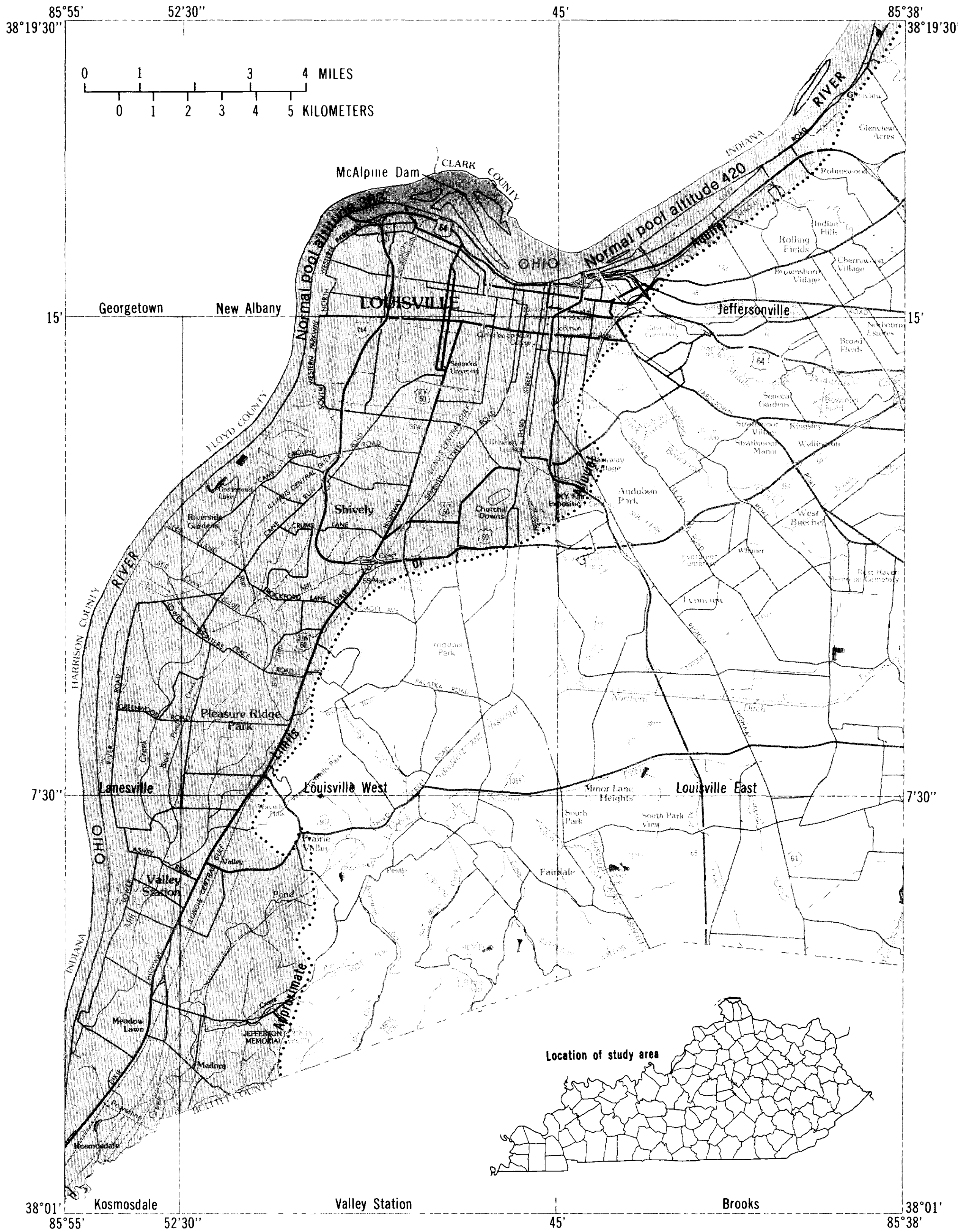


Figure 1.-- Location of alluvial aquifer in the Louisville area, Jefferson County, Kentucky.

HYDROGEOLOGY

The alluvial aquifer underlying Louisville is glacial outwash consisting mostly of sand and gravel, that is as much as 130 feet in thickness in some areas. The upper part generally contains more sand and silt and less gravel. The glacial outwash is overlain by 15 to 30 feet of flood-deposited sand, silt, and clay (fig. 2). The alluvial aquifer is underlain by bedrock consisting of limestone and shale.

The alluvial aquifer is recharged by downward percolation of precipitation and by movement of water from the underlying and flanking bedrock. It also receives recharge from the Ohio River when the river stage is above the water table. This can happen because of a rise in river stage due to increased runoff or, as shown in figure 2, because of a lowering of the water table below the river stage due to withdrawals of ground water through wells. Recharge is also derived from leaking water and sewer lines, from septic tank systems, and from injection wells.

Water is removed from the aquifer by natural discharge to the Ohio River and by withdrawals through wells. Under natural or no pumping conditions, the gradient of the water table and the movement of ground water is towards the river except during high river stages (fig. 2). Pumping can lower the ground-water levels and reverse the natural gradient so that water is induced to move from the river into the aquifer. This has occured in the past and could happen again if withdrawals exceed the recharge to the aquifer. However, pumping from the aquifer had practically stopped in the downtown area by 1980.

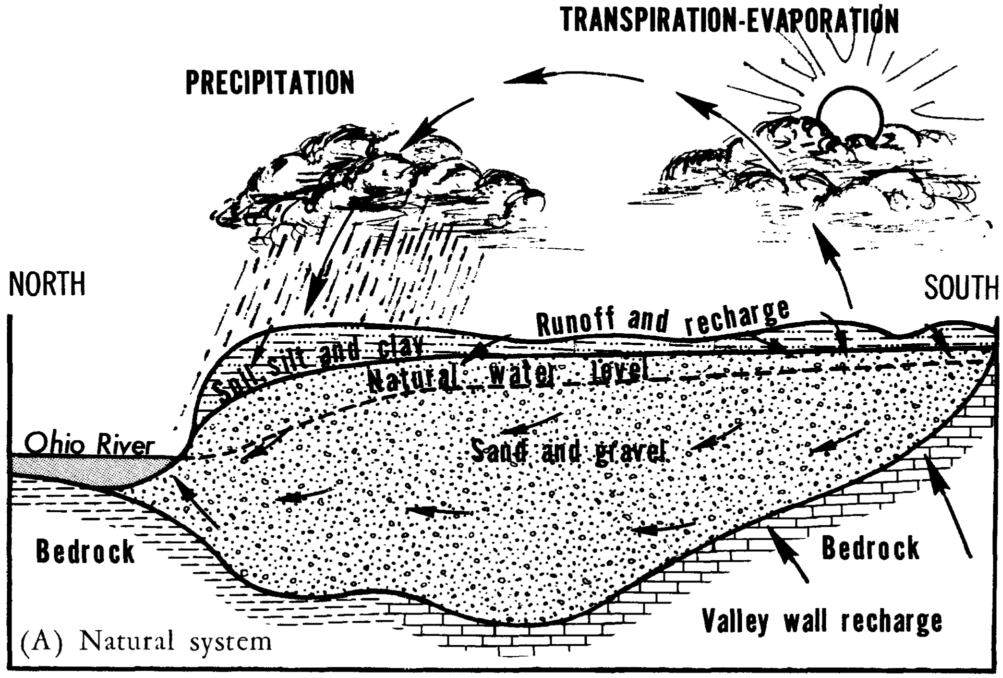
GROUND-WATER LEVELS

Long-Term Changes

The U.S. Geological Survey, in cooperation with the Kentucky Geological Survey, monitors water levels in wells at sites shown in figure 3. Records for some of these began in 1935 and provide a history of long-term changes. Hydrographs of wells A2, C2, and C6 (fig. 4) show that ground-water levels declined in the early 1940's and remained depressed until about 1970 when a dramatic rise or recovery began.

Areal Changes

The altitudes of ground-water levels in 1962 and in 1982 are shown in figures 5 and 6. The year 1962 was chosen for comparison because Bell (1966) described and mapped the water levels in 1962. The cross sections (fig. 7) show the rise in the downtown area (section A-A') and the industrial area of west Louisville (section B-B') (see fig. 3 for traces of sections). The contour maps (figs. 5 and 6) show the shape of the potentiometric surface in 1962 and 1982. If these two contour maps are superimposed and the differences between contour lines are plotted and contoured, a water-level change map results (fig. 8) that illustrates the magnitude and extent of the water-level rise.



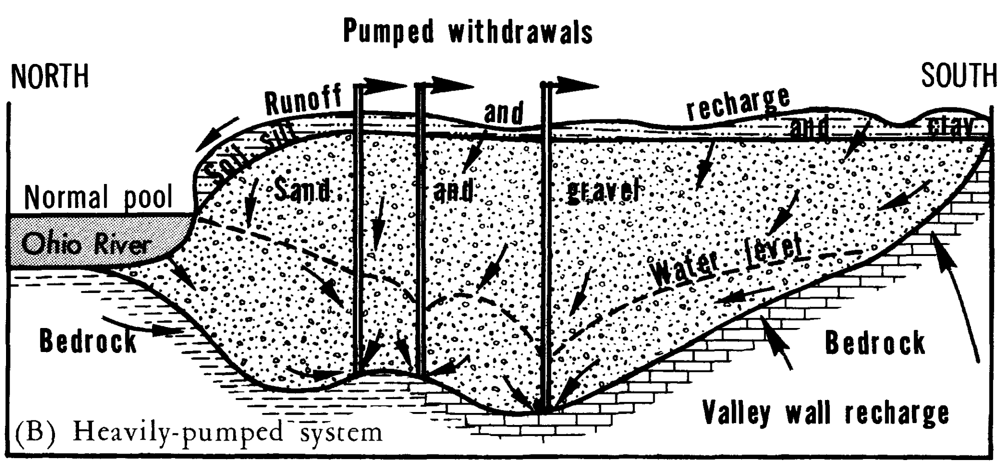
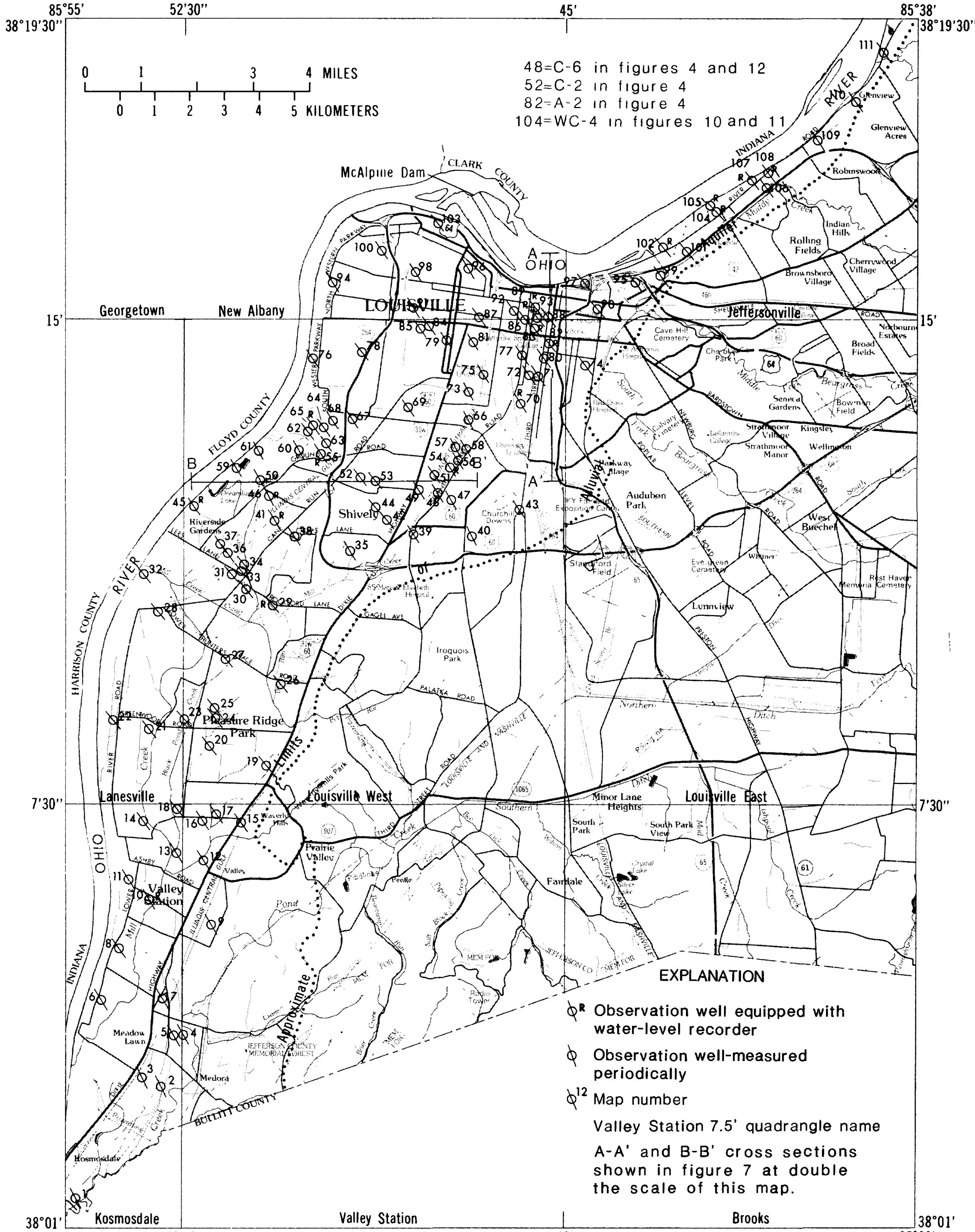


Figure 2.-- Generalized profile of alluvial aquifer underlying downtown Louisville. A, Natural system showing gradient of water table towards the Ohio River; B, Heavily-pumped system showing gradient of water table away from the Ohio River.



Base from U.S. Geological Survey

Figure 3.-- Location of observation wells in Louisville and Jefferson County area.

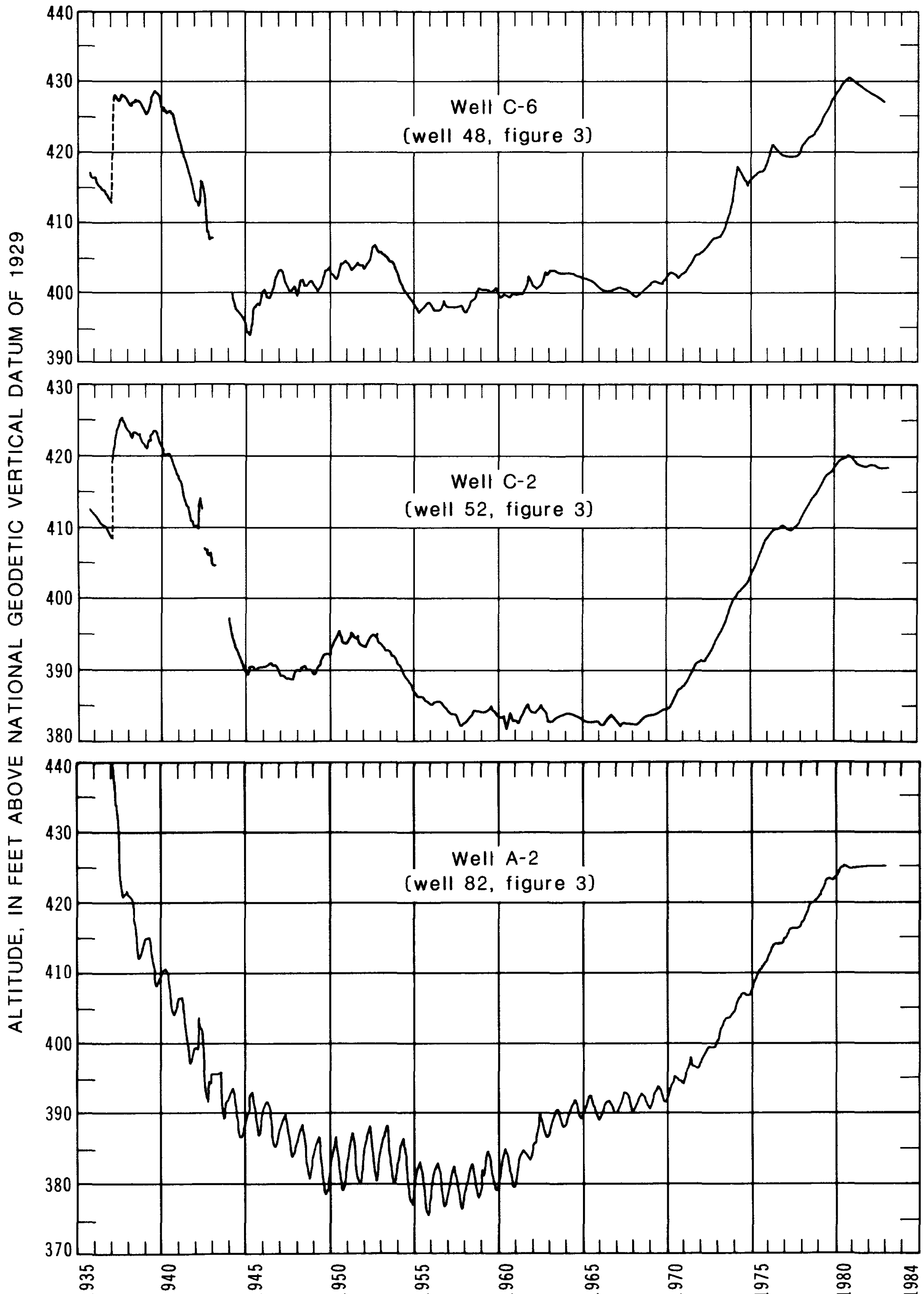


Figure 4.-- Hydrographs of wells showing rise in water levels in the 1970's.

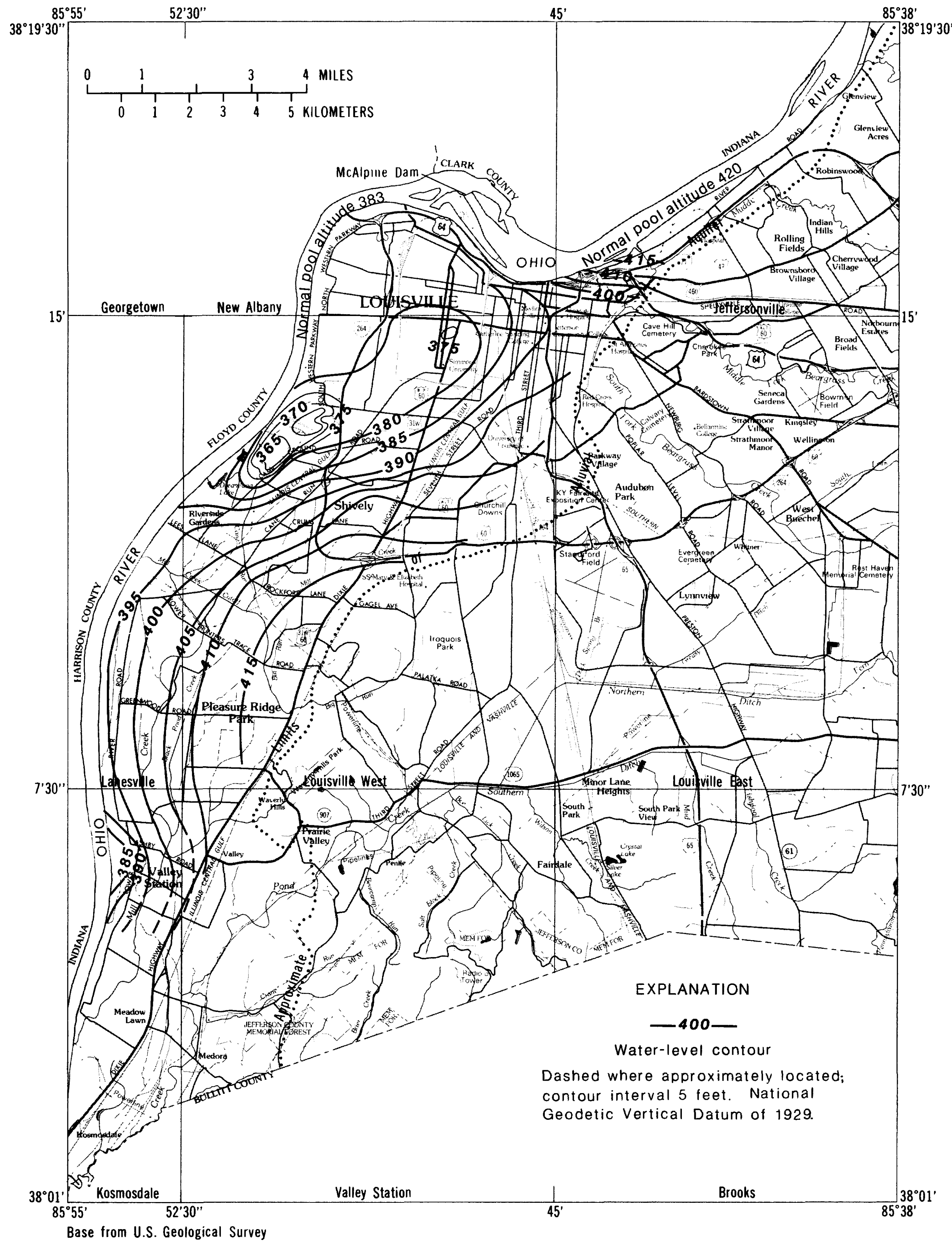


Figure 5.-- Altitude of the water table beneath the flood plain of the Ohio River in the Louisville area, December 1962. (modified from Bell E.A., 1966)

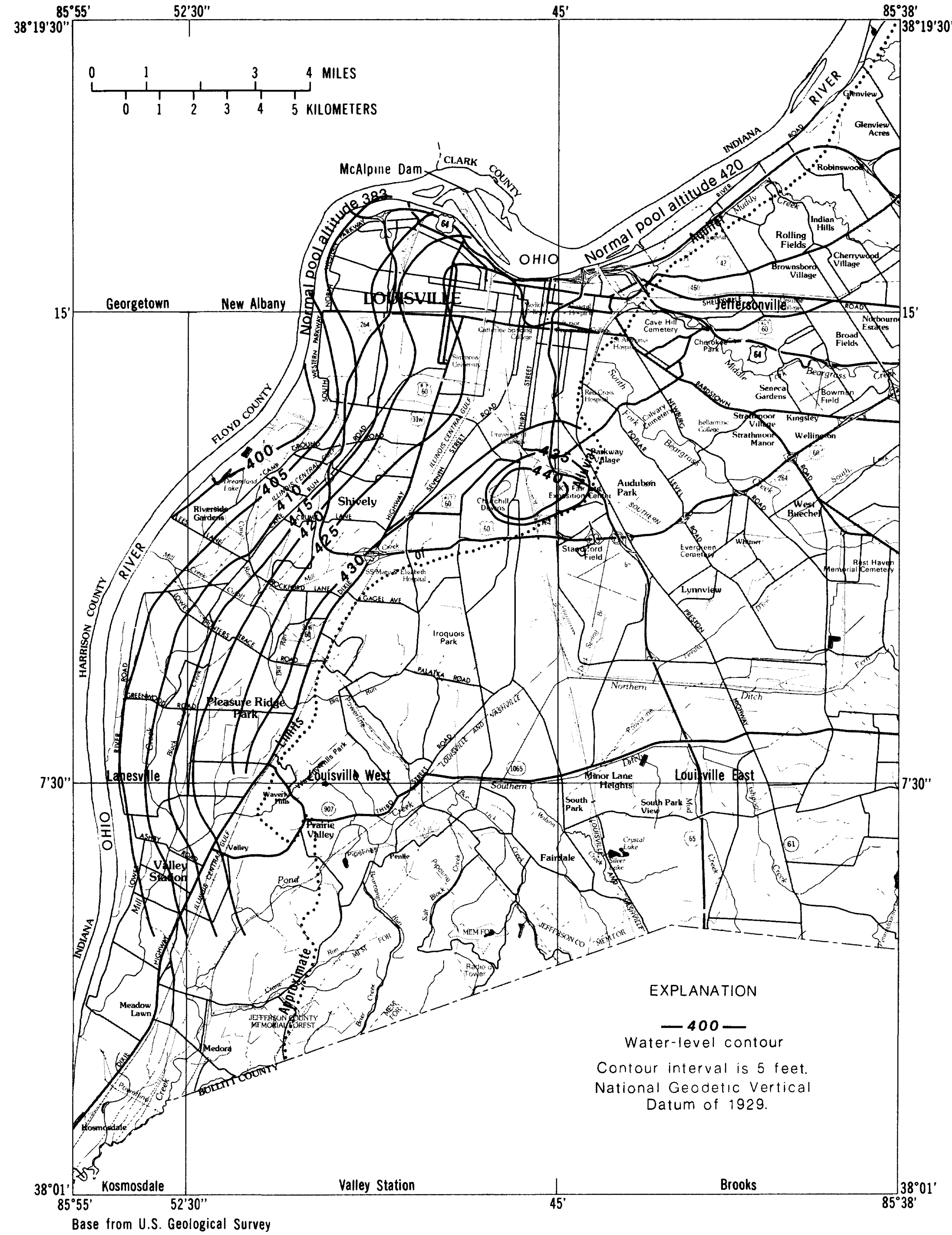
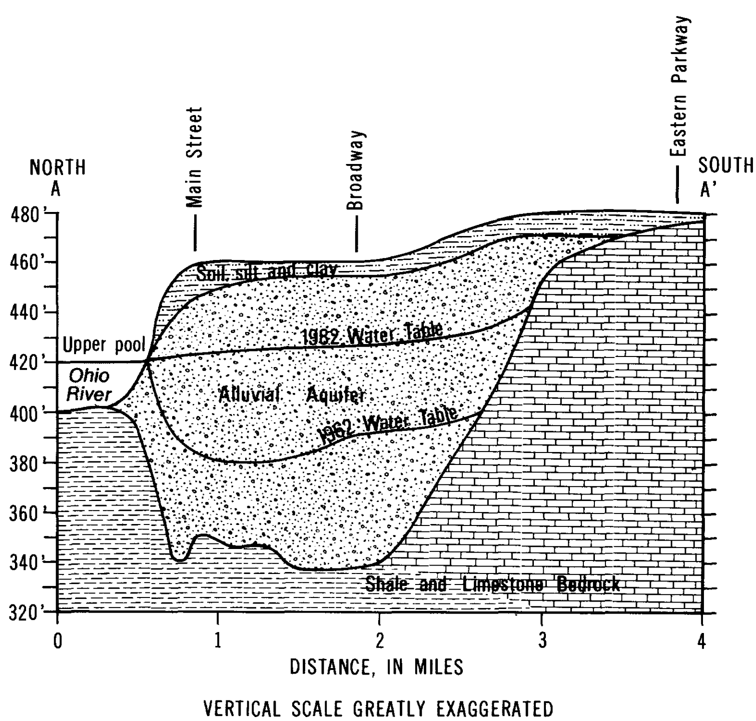
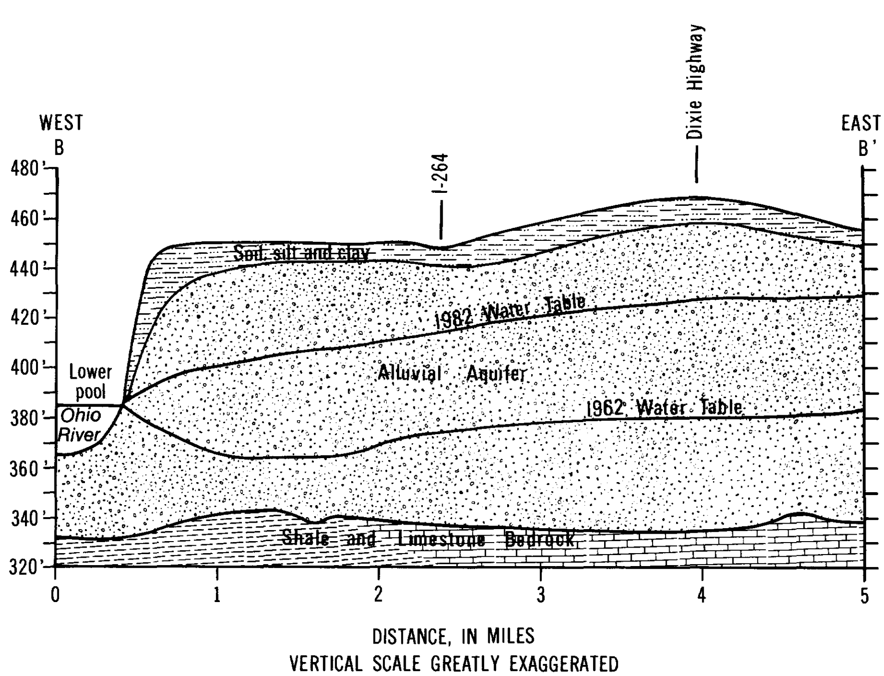


Figure 6.-- Altitude of the water table beneath the flood plain of the Ohio River in the Louisville area, April 1982.



Generalized profile of downtown Louisville area, Ohio River upper pool above McAlpine Dam and water table for 1962 and 1982



Generalized profile of south Louisville area, Ohio River lower pool below McAlpine Dam and water table for 1962 and 1982

Figure 7.--Generalized profiles of water levels in downtown and west Louisville. See figure 3 for trace of sections.

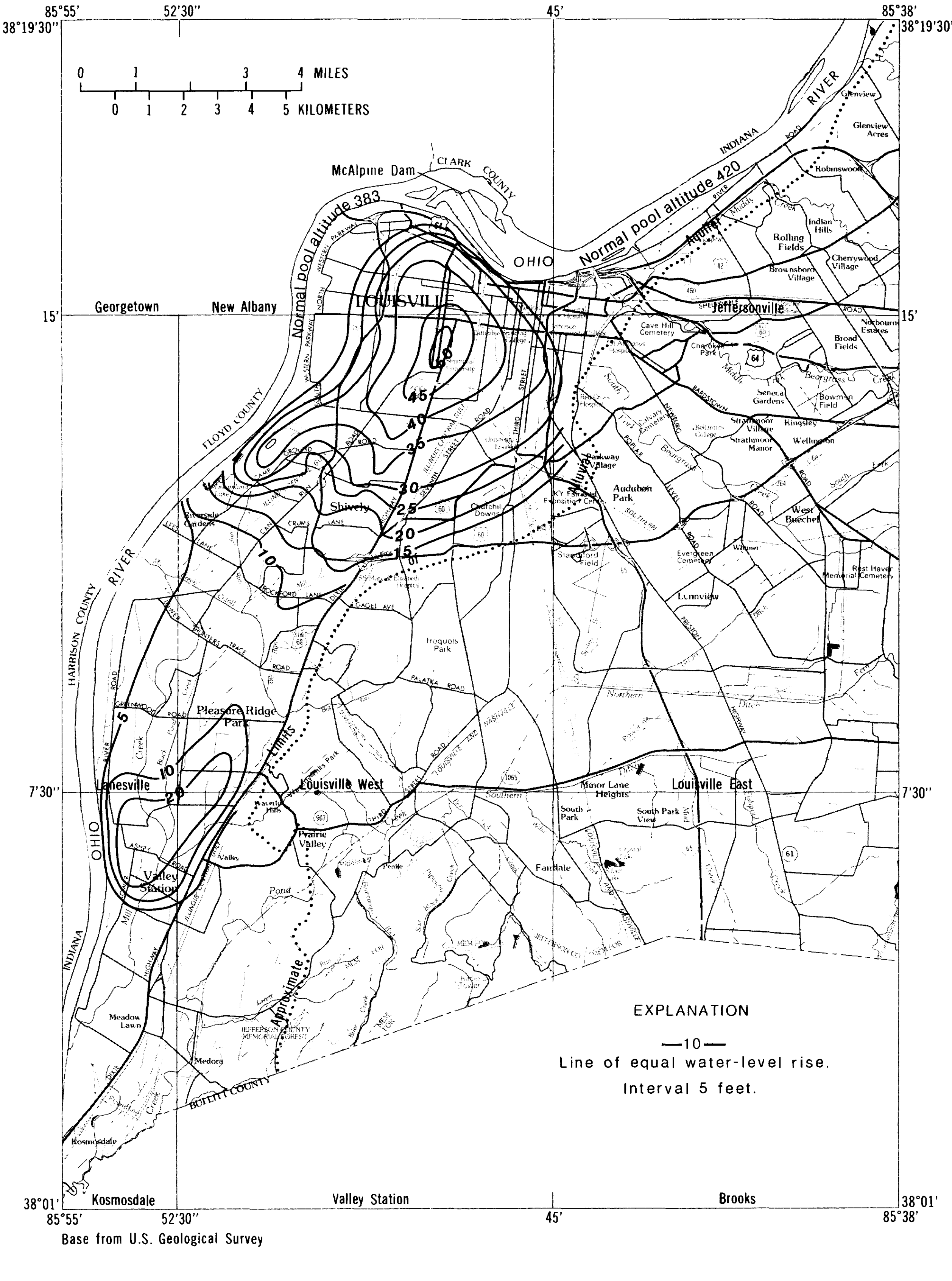


Figure 8.-- Magnitude and extent of water-level rise between 1962 and 1982.

Problems of Rising Water Levels

There are several problems associated with rising ground-water levels. A major problem is the additional stress on basements and other subgrade structures that were not designed for high ground-water levels. Seepage of water into these structures is also a problem. Basements and subbasements are generally 20 to 25 feet below land surface and some utility lines are as much as 40 feet below land surface in the downtown area. The bearing capacity of some foundations is reduced by high ground-water levels. Differential compaction could occur in some geologic material, such as clay lenses, if the material were saturated by rising ground-water levels and later drained by declining water levels. The reduced bearing capacity of foundations and differential compaction of geologic materials could cause differential settlement of buildings. This could cause structural damage to buildings and break utility lines at their point of attachment to buildings. Underground utility lines such as gas, electric, water, sewer, and communication lines could also be damaged by high ground-water levels. Damage to subgrade structures and utility lines would be more likely to occur in the downtown area because of their concentration and because, for most of the area, water levels are less than 35 feet below land surface (fig. 9).

Relation to Ohio River

Hydrographs of wells close to the Ohio River do not show any long-term trends up or down. Instead they reflect the normal pool stages of the river as shown in figure 10. In contrast, wells away from the river (fig. 4) show the decline and subsequent rise in water levels for the period 1935-82 in response to pumping and precipitation.

Hydrographs of wells close to the Ohio River show short-term reactions of several feet in a few days to changes in river stages. This has been observed in many wells and has been described in reports by Grubb (1974) and Kernodle (1977). The U.S. Geological Survey has collected data on natural water levels (no pumping effects) from pairs of wells located on a line approximately normal to the river at several sites including the four shown in figure 11. Well number 1 at each of these sites was located close to the river and well number 2 at some distance from the river. Data for the four sites are listed in table 1 for a rise in river stage that occurred in April 1970. No pair of wells was used for downtown Louisville because water levels were affected by pumping in 1970. The hydrographs of the ground-water levels are similar to that of the river except the peaks are dampened and time lag increases with distance from the river as shown by the hydrographs for site 3 in figure 11. However, as seen in table 1, the rise in ground-water levels can be several feet in wells hundreds of feet from the river. The magnitude will depend on the rise in river stage and hydraulic properties of the streambed and aquifer. These responses to river stage are an important consideration where ground-water levels are already near subsurface structures.

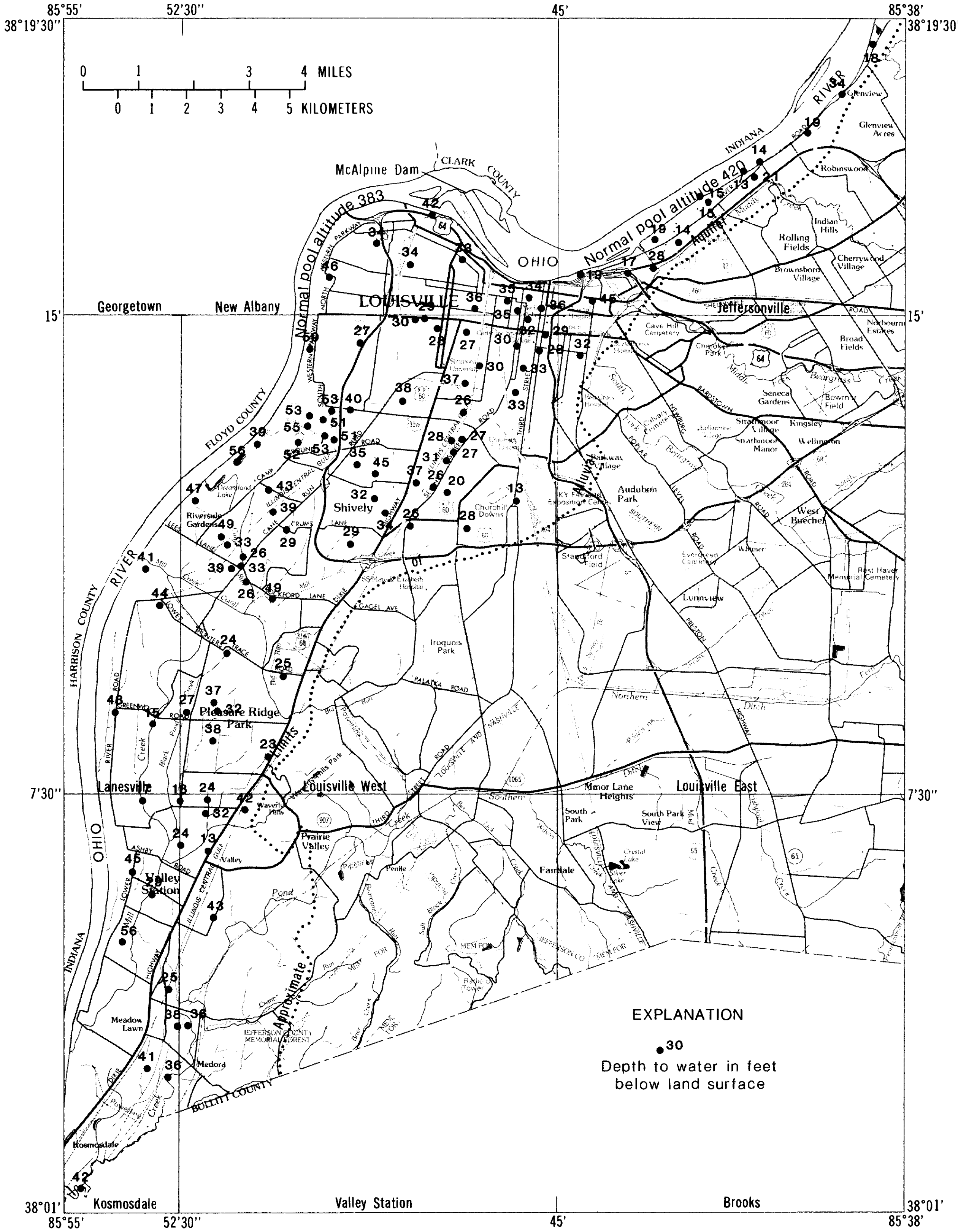


Figure 9.-- Water levels below land surface in October 1982.

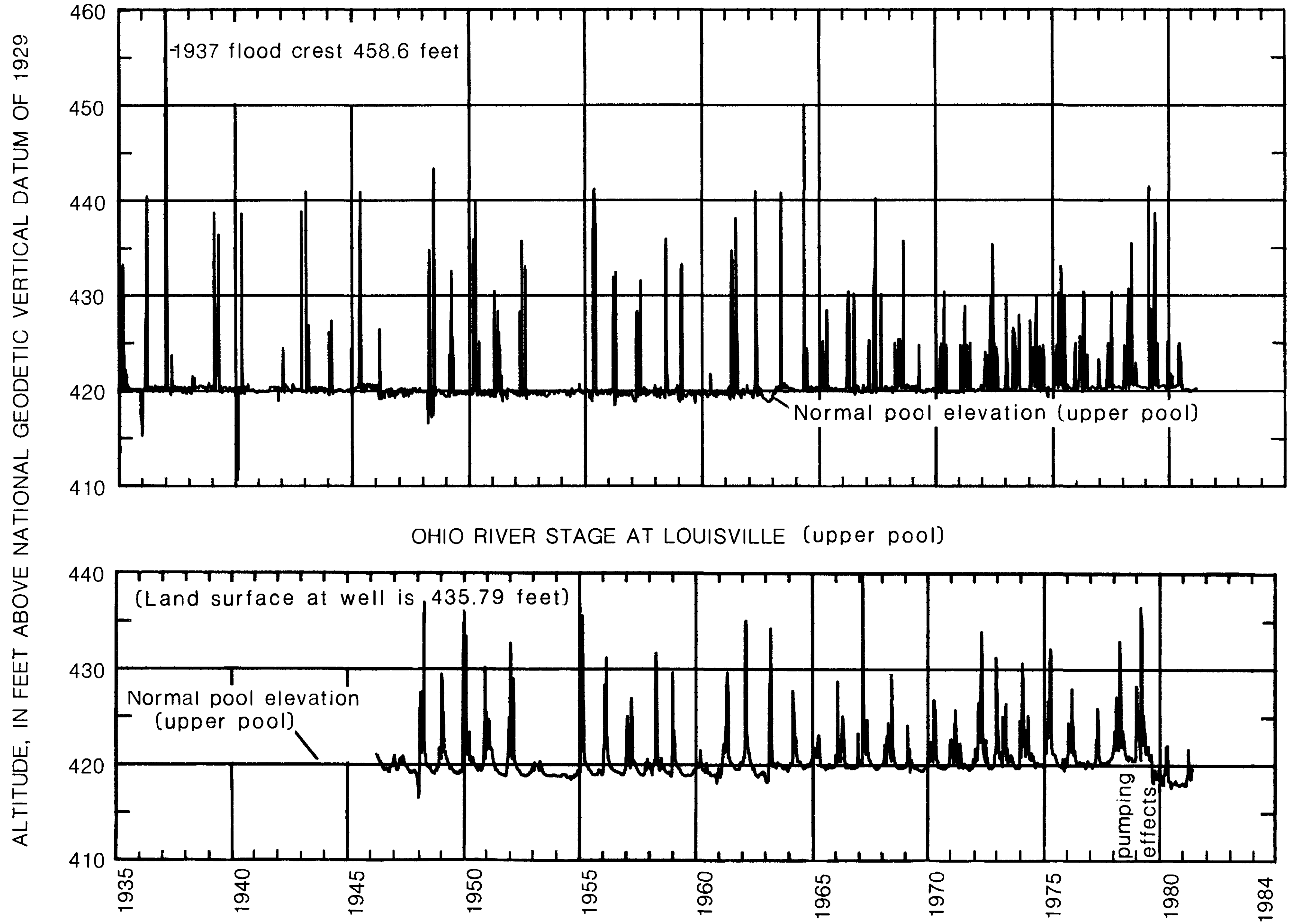


Figure 10.-- Hydrograph of City of Louisville well WC-4, at River Road and Zorn Avenue and stage of Ohio River at Louisville.

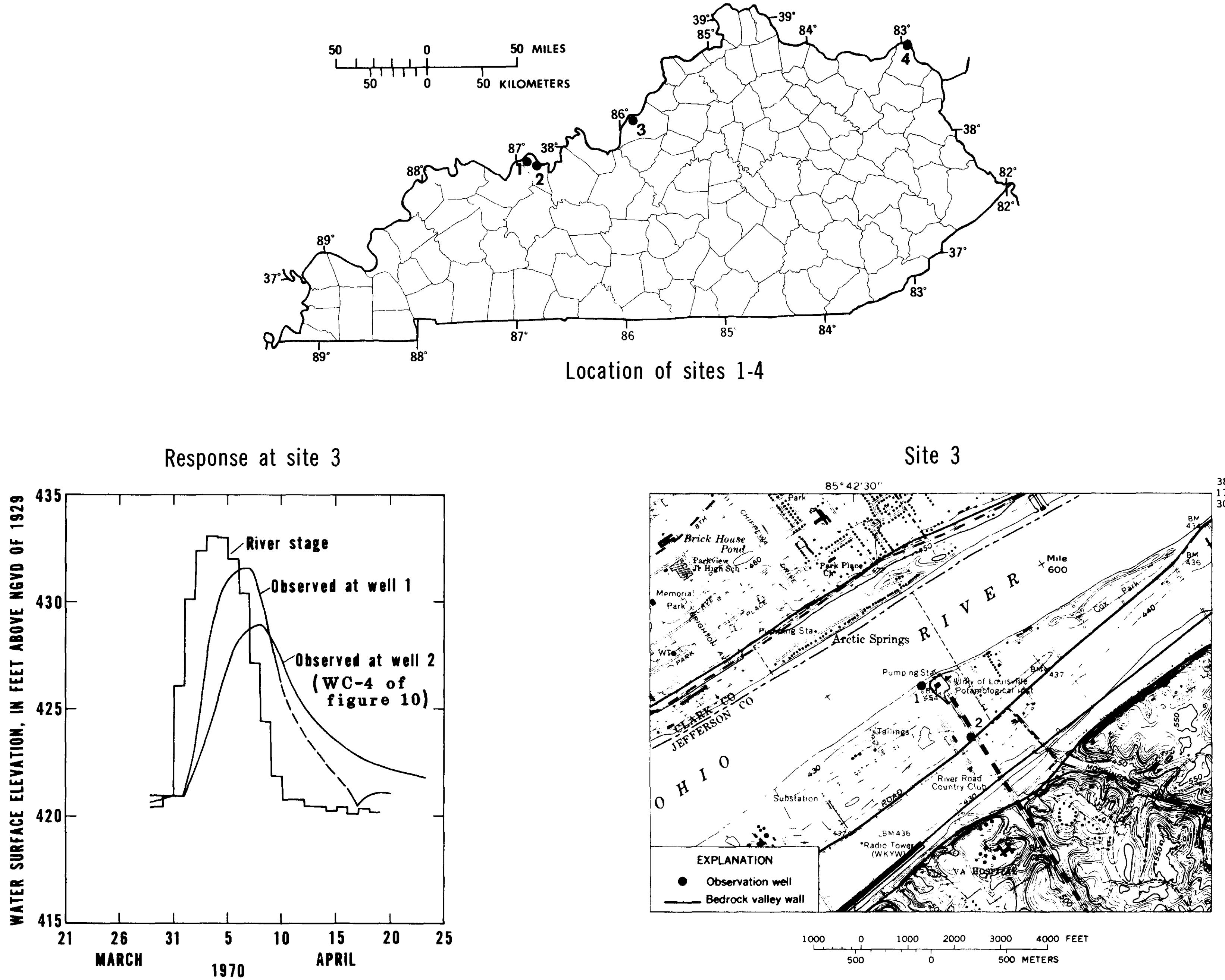


Figure 11.-- Location of paired well sites and typical response to rise in river stage, at site 3.

Table 1.--Water-level rises in wells in response to a rise in river stage, April 1970

Site	Normal pool altitude[1]	Ohio River flood peak[1]	Day of month
1	358	386	5
2	358	392	6
3	420	433	4
4	485	520	5
	Well 1		
	Water-level rise in feet	Distance from river[2]	Date of peak
1	16	50	9
2	15	100	9
3	11	100	7
4	13	125	6
	Well 2		
	Water-level rise in feet	Distance from river[2]	Date of peak
1	13	760	10
2	12	1,094	11
3	8	1,600	8
4	5	975	8

[1] Normal pool altitudes and flood peaks given in feet above National Geodetic Vertical Datum of 1929.
[2] Distance in feet at normal pool stage.

Causes of Rise

There were a number of interrelated causes for the rise in ground-water levels, but the overall cause was that recharge to the aquifer exceeded discharge during the rise. A hydrograph of well C-6 (fig. 12) is typical of many wells in the Louisville area for the period 1935-82. A comparison of the water level with precipitation and pumping data (fig. 12) shows that major fluctuations, such as the decline in the 1940's and the rise in the 1970's, reflect major changes in precipitation and pumping. For example, heavy pumping and below average rainfall caused a large decline in the early 1940's whereas decreased pumping and above average precipitation in the 1970's caused a large rise.

A cumulative departure curve (fig. 12) shows how much a measured quantity is above or below the average value of the measured quantity for a given period of time. The cumulative departure curve for precipitation shows a maximum deficit of about 43 inches in 1969. However, this deficit was made up in the period 1970-79 by above average precipitation. This period coincides with the steep rise in ground-water levels. Because water levels had started to rise slightly before 1970 when there was still a large deficit in precipitation, it appears the decreasing withdrawals triggered a rise in ground-water levels that was accelerated in the 1970's by above-average precipitation.

PRECIPITATION

The cumulative departure of precipitation from the average for the period 1935-82 and the well hydrograph (fig. 12) show a correlation between precipitation and ground-water levels. The closeness of this correlation cannot be determined directly because pumpage effects are superimposed on ground-water levels. Nevertheless, the correlation may be good enough so that a cumulative departure curve for precipitation records starting in 1873 (fig. 13), which is much longer than the record for ground-water levels, may give a more historical view of the present trends and possible magnitude of changes.

The cyclic nature of the long-term cumulative departure curve is obvious and it illustrates the upward trend or "wet period" that correlates with the rapidly rising ground-water levels between 1970 and 1979. The below-average precipitation in 1980 and 1981 may represent a reversal in this upward trend or only a temporary pause in the general upward cycle of the curve. Only time will reveal this. However, it should be noted that the "wet period" between 1969 and 1979 is 20 inches less than the maximum of the upward trend between 1873 and 1885. This would lead to the conclusion that ground-water levels could rise above the 1982 levels because precipitation records show sustained wet periods can be both wetter and longer than the 10 years between 1969 and 1979.

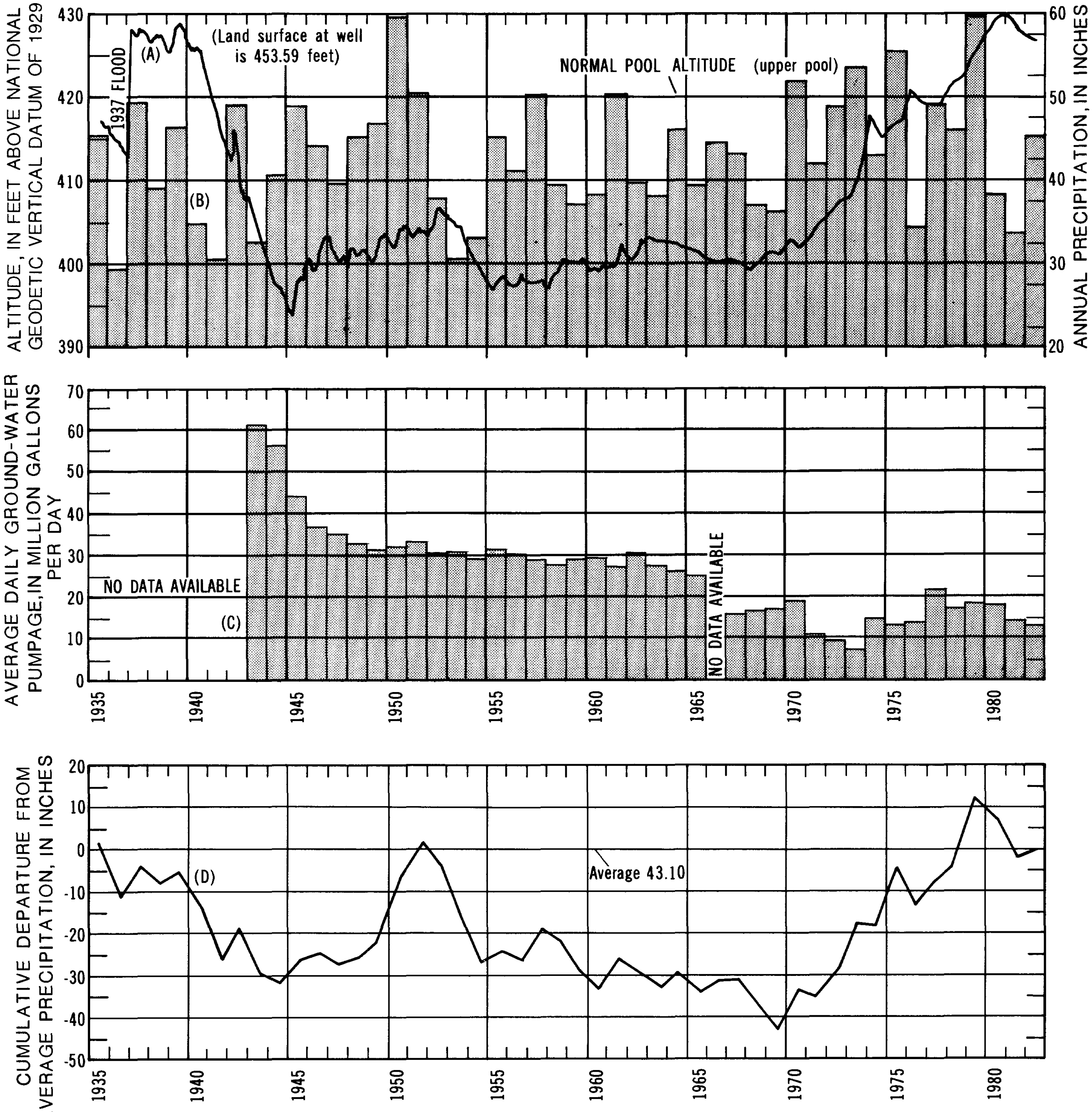


Figure 12.-- Relation of ground-water level to pumpage and precipitation.

(A) Water-level hydrograph for well C-6 (Well 48 in figure 3).
(B) Bar graph of annual precipitation.
(C) Estimated average daily ground-water pumpage 1943 through 1982.
(D) Cumulative departure from average precipitation at Louisville, 1935-82.

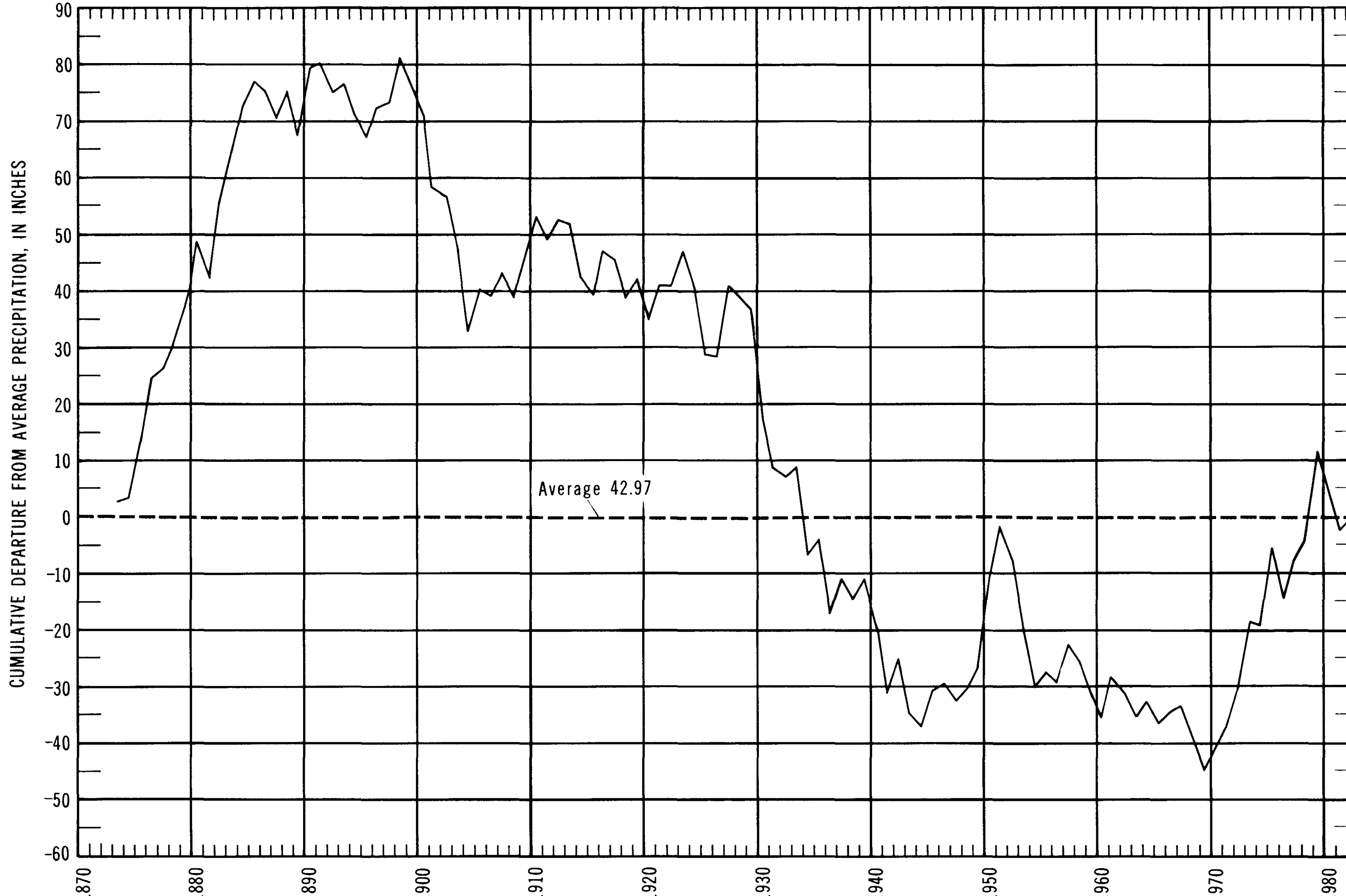


Figure 13.-- Cumulative departure from average precipitation at Louisville, 1873-1982.

PREVENTIVE MEASURES

Pumping

Pumping from the alluvial aquifer is the most feasible preventive response to the potential problem of rising ground-water levels in the Louisville area. Most of the older buildings still have wells in their basements which could be used to lower ground-water levels. Also, industries could be encouraged to use some ground water for water supplies or for heating and cooling. This would accomplish dewatering, and would be a beneficial use of ground water.

Predicting Pumping Rates to Control Water Levels

A study by Geraghty and Miller, Inc., (1979) determined the feasibility of lowering ground-water levels in the downtown Louisville central business district. They estimated that ground-water levels in this area could be controlled by pumping 2 to 4 Mgal/d (million gallons per day) from a small number of properly located wells. This would require a maximum of 10 wells, pumped at a continuous rate of about 300 gal/min (gallons per minute) each.

Another study by Hagerty and Lippert (1982, p. 222) presented the following equation for predicting an average ground-water level:

$$GWL = 386.8 + 0.156 \Sigma \Delta PUMP + 0.109 \Sigma \Delta PREC$$

where

GWL = average ground-water level, in feet

PUMP = cumulative departure from mean for pumping rate (decrease in rate represents a positive change), in million gallons per day

PREC = cumulative departure from mean for precipitation, in inches

The development of this equation was based on an assumption of an equilibrium condition between 1951-65 when pumping was reported to average 29.8 Mgal/d and precipitation averaged 41.27 inches per year. Also, a closed system was assumed whereby precipitation, as inflow, and pumping, as outflow, were the only stresses on the system. Idealized relations such as this, while useful, cannot furnish some answers that may be needed for effective management. For example, short term but large changes occur in ground-water levels near the river in response to high river stages. The above equation cannot evaluate these rises.

More sophisticated hydrologic tools, such as calibrated digital models, are required to assess and predict the effects of several simultaneous stresses on an aquifer system. A calibrated digital model can help answer such questions as: What withdrawals would be needed to maintain water levels below structures?, What withdrawals would be feasible if ground-water use resumed in the downtown area?, How much and how far from the river would a high river stage affect ground-water levels and what effect would extended wet or dry periods have on ground-water levels?

SUMMARY

Ground-water levels have rising trends because of natural and man-made reasons such as above average precipitation, application of irrigation water, leaking from deep artesian wells, leaking from water mains and sewers, and decreases in ground-water withdrawals. These rises can be damaging in urban areas when the rises reach structures such as basements, underground utility lines, and septic tank systems. Examples of urban areas that have problems with rising ground water are San Bernardino, Calif.; Greely and Fort Collins, Colo.; New York City boroughs of Brooklyn and Queens; and Louisville, Ky.

Ground-water levels have risen more than 30 feet in parts of the alluvial aquifer in Louisville and southwest Jefferson County during the past 20 years. The rate of the rise accelerated during the 1970's when ground-water withdrawals were decreasing and precipitation was above normal. This caused some concern that the levels could rise to a point where buildings and underground utilities in downtown Louisville would suffer damage.

Measurements made since 1980 indicate the rising trend has flattened and the water table is again fluctuating with the seasons. However, an extended period of above-average precipitation could possibly trigger another rise in ground-water levels, and certainly, high river stages will cause quick rises in ground-water levels near the river. Continued monitoring of the water levels is needed to observe responses of ground-water levels to natural and man-made stresses.

Because of the nearness of the ground-water levels to man-made structures, the ability to predict and monitor responses of ground-water levels to stresses is necessary for optimum management of ground-water resources. Technology exists to simulate complex ground-water systems with computer models that can assess and predict the effects of several simultaneous stresses on an aquifer system.

REFERENCES

Bell, E. A., 1962, The ground-water situation in the Louisville area, Kentucky, 1945-61; Kentucky Geological Survey, series 10, Information Circular 10, 24 p.

----- 1966, Summary of hydrologic conditions of the Louisville area, Kentucky: U.S. Geological Survey Water-Supply Paper 1819-C, 36 p.

Bell, E. A., Kellogg, R. W., and Kulp, W. K., 1963, Progress report on the ground-water resources of the Louisville area, Kentucky, 1949-55: U.S. Geological Survey Water-Supply Paper 1579, 49 p.

Boyd, David, 1897, Irrigation near Greely, Colorado: U.S. Geological Survey Water-Supply Paper 9, 90 p.

Buxton, Herbert T., Soren, Julian, Pasnor, Alex, and Shernoff, Peter K., 1981, Reconnaissance of the ground-water resources of Kings and Queens Counties, New York: U.S. Geological Survey Open-File Report 81-1186, 55 p.

Caye, W. C., 1939, Ground-water well report 1937-38: Commissioners of Sewerage of Louisville, Kentucky, 24 p.

Commissioners of Sewerage of Louisville, Kentucky, 1942, Final report of Commissioners of Sewerage of Louisville: Commissioners of Sewerage of Louisville, Kentucky, 894 p.

Geraghty and Miller, Inc., 1979, Physical, geochemical and hydrologic constraints affecting the engineering feasibility of alternatives for utilizing ground water as a source of energy for heating and/or cooling buildings in downtown Louisville, Kentucky, 71 p.

Grubb, H. F., 1974, Simulated drawdown for selected well field in the Ohio River alluvial aquifer: U.S. Geological Survey Water-Resources Investigation 2-74, 45 p.

Grubb, H. F., and Zehner, H. H., 1973, Aquifer diffusivity of the Ohio River alluvial aquifer by the floodwave response method: U.S. Geological Survey Journal of Research, v. 1, no. 5, p. 597-601.

Guyton, W. F., 1944, Artificial recharge of ground-water resources with water from city's surface supply at Louisville, Kentucky: U.S. Geological Survey Open-File Report, 6 p.

----- 1946, Artificial recharge of glacial sand and gravel with filtered river water at Louisville, Kentucky: Economic Geology, v. 41, no. 6, p. 644-658.

Guyton, W. F., Stuart, W. T., and Maxey, F. B., 1944, Progress report on the ground-water resources of the Louisville area, Kentucky: U.S. Geological Survey Open-File Report, 20 p.

Hagerty D. J., and Lippert, K., 1982, Rising groundwater-problem or resource? Ground Water, v. 2, no. 20, March-April, 1982, p. 217-223.

Hamilton, D. K., 1944, Ground water in the bedrock beneath the glacial outwash in the Louisville area, Kentucky: U.S. Geological Survey Open-File Report, 22 p.

Kernodle, J. M., and Whitesides, D. V., 1977, Rising ground-water level in downtown Louisville, 1972-1977: U.S. Geological Survey Water-Resources Investigations Report 77-92, 24 p.

Lippert, K., 1980, A study of rising ground-water levels in Louisville, Kentucky: University of Louisville, Master of Engineering Thesis, 134 p.

Lusczynski, N. J., 1952, The recovery of ground-water levels in Brooklyn, New York, from 1947 to 1950: U.S. Geological Survey Circular 167, 29 p.
MacCary, L. M., 1955, Map of the Louisville area, Kentucky, showing contours on the bedrock surface: U.S. Geological Survey Hydrologic Investigations Atlas HA-5.
----- 1956, Availability of ground water for domestic use in Jefferson County, Kentucky: U.S. Geological Survey Hydrologic Investigations Atlas HA-8, 5 p.
McMurtrie, H., 1819, Sketches of Louisville and its environs; including, among a great variety of miscellaneous matter, a Florula Louisvillensis: Louisville, Kentucky, 255 p.
Moreland, Joe A., and Leonard, Robert B., 1980, Evaluation of shallow aquifer, in the Helena Valley, Lewis and Clark County, Montana: U.S. Geological Survey Open-File Report 80-1102, 24 p.
Nelson, Gordon L., 1978, Hydrologic information for land-use planning Fairbanks vicinity, Alaska: U.S. Geological Survey Open-File Report 78-959, 47 p.
Price, W. E., Jr., 1964a, Geology and hydrology of alluvial deposits along the Ohio River between southwestern Louisville and West Point, Kentucky: U.S. Geological Survey Hydrologic Investigations Atlas HA-111.
----- 1964b, Geology and hydrology of alluvial deposits along the Ohio River between Prospect and southwestern Louisville, Kentucky: U.S. Geological Survey Hydrologic Investigations Atlas HA-130.
Ray, L. L., 1974, Geomorphology and Quaternary geology of the glaciated Ohio River Valley-A reconnaissance study: U.S. Geological Survey Professional Paper 826, 77 p.
Rorabaugh, M. I., 1946, Ground-water resources of the southwestern part of the Louisville area, Kentucky: U.S. Geological Survey Open-File Report, 39 p.
----- 1956, Ground water in northeastern Louisville, Kentucky, with reference to induced infiltration: U.S. Geological Survey Water-Supply Paper 1360-B, p. 101-169.
Rorabaugh, M. I., Schrader, F. F., and Laird, L. B., 1953, Water resources of the Louisville area, Kentucky and Indiana: U.S. Geological Survey Circular 276, 49 p.
Shoecraft, E. C., Drury, W. R., and McNamee, R. L. 1944, Report on water resources: Underground Water Users Association, Louisville, Kentucky, 131 p.
Soren, Julian, 1976, Basement flooding and foundation damage from water-table rise in the East New York section of Brooklyn, Long Island, New York: U.S. Geological Survey Water-Resources Investigation 76-95, 14 p.
U.S. Geological Survey, Water resources data for Kentucky: U.S. Geological Survey Open-File Report (issued annually).
Walker, E. H., 1957, The deep channel and alluvial deposits of the Ohio Valley in Kentucky: U.S. Geological Survey Water-Supply Paper 1411, 25 p.
Walker, E. H., 1957, An aquifer test in the southwestern part of the Louisville area, Kentucky: U.S. Geological Survey Open-File Report, 41 p.
Whitesides, D. V., Kernodle, J. M., and Leist, David W., 1978, Water levels in observation wells in Kentucky, 1935 through 1976. U.S. Geological Survey Open-File Report 78-129, 156 p.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1984-760-489/190