GROUND-WATER FLOW PATTERNS AND WATER BUDGET OF A BOTTOMLAND FORESTED WETLAND, BLACK SWAMP, EASTERN ARKANSAS

By Gerard J. Gonthier and Barbara A. Kleiss

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.40	millimeter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
mile (mi)	1.609	kilometer
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
inch per year (in/yr)	25.40	millimeter per year
square foot (ft^2)	0.09294	square meter
square mile (mi^2)	2.590	square kilometer
acre-foot (acre-ft)	1,233	cubic meter
pound per square inch (lb/in^2)	6.895	kilopascal

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8x°C)+32$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929

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Abstract

The U.S. Geological Survey, working in cooperation with the U.S. Army Corps of Engineers, Waterways Experiment Station, collected surface-water and ground-water data from 119 wells and 13 staff gages from September 1989 to September 1992 to describe ground-water flow patterns and water budget in the Black Swamp, a bottomland forested wetland in eastern Arkansas. The study area was between two streamflow gaging stations located about 30.5 river miles apart on the Cache River. Ground-water flow was from northwest to southeast with some diversion toward the Cache River. Hydraulic connection between the surface water and the alluvial aquifer is indicated by nearly equal changes in surface-water and ground-water levels near the Cache River. Diurnal fluctuations of hydraulic head ranged from more than 0 to 0.38 feet and were caused by evapotranspiration. Changes in hydraulic head of the alluvial aquifer beneath the wetland lagged behind stage fluctuations and created the potential for changes in ground-water movement. Differences between surface-water levels in the wetland and stage of the Cache River created a frequently occurring local ground-water flow condition in which surface water in the wetland seeped into the upper part of the alluvial aquifer and then seeped into the Cache River. When the Cache River flooded the wetland, ground water consistently seeped to the surface during falling surface-water stage and surface water seeped into the ground during rising surface-water stage. Ground-water flow was a minor component of the water budget, accounting for less than 1 percent of both inflow and outflow. Surface-water drainage from the study area through diversion canals was not accounted for in the water budget and may be the reason for a surplus of water in the budget. Even though ground-water flow volume is small compared to other water budget components, ground-water seepage to the wetland surface may still be vital to some wetland functions.

INTRODUCTION

Wetland areas in the lower Mississippi River Valley are being significantly reduced. Turner and others (1981) estimated that 16 percent of southern bottomland forests were lost in the United States from 1940 to 1975. Wetlands are destroyed primarily so the land may be used for agriculture or urban development. Wetlands perform many functions including the maintenance of wildlife, improvement of water quality, and the control of flooding (Gregory and others, 1991). An additional bottomland forested wetland function is the recharge of surface water into the alluvial aquifer (Novitzki, 1978; Siegel, 1988).

In 1987, the U.S. Army Corps of Engineers, Waterways Experiment Station began a multidisciplinary wetlands research study. The study was designed to consider physical, biological, and chemical aspects of a bottomland forested wetland ecosystem and included assessment of hydrology, sedimentation, fisheries, spatial information, vegetation, water quality, and wildlife of the Black Swamp, eastern Arkansas. The major objectives of the study were to better understand the bottomland, forested wetland systems of the lower Mississippi River Valley and to use the information obtained to aid in the evaluation of the functions of this wetland type. The Waterways Experiment Station conducted many of the studies including surveying ecology and monitoring sedimentation rates. Ouachita Baptist University collected water-quality data. The U.S. Geological Survey, in cooperation with the Waterways Experiment Station, collected surface-water, ground-water, and sedimentation data as part of the multidiscipline effort.

Literature Review

Very little information is available in the literature about ground-water flow and ground-water/surface-water interaction within bottomland forested wetlands. What little information that exists does provide some important initial findings. Gavenciak and Lindtner (1988) determined that "fluctuations of groundwater table are synchronous with fluctuations of surface-water level" in the "floodplain forests" in the vicinity of the Danube River in former Czechoslovakia. Their biweekly soil-moisture measurements down to the water table for a 7-month period provide evidence for ground-water/surface-water interaction. Mitsch and others (1977) attempted to determine the ground-water component of a water budget for Heron Pond located next to the Cache River, southern Illinois. Very limited water-level data indicated that ground-water flow conditions changed from before spring flooding to after spring flooding. Data were not sufficient to calculate the ground-water component of the water budget for Heron Pond. McKay and others (1979) detected changes in vertical ground-water flow direction in a ridge and swale complex near the main channel of the Mississippi River in southern Illinois. The data were "not sufficient to allow an assessment of the role of ground water in the budget." McKay and others (1979) provided soil borings information that was used in the development of the Black Swamp water budget. It is the intent of the Black Swamp study to improve upon the cursory information about ground-water flow and ground-water/surface-water interaction within bottomland forested wetlands provided by previous studies.

Purpose and Scope

The purpose of this report is to describe ground-water flow patterns and the water budget of a bottomland forested wetland, Black Swamp, in eastern Arkansas. Ground-water flow patterns include ground-water/surface-water interaction. The water budget was developed to determine the proportion of the water budget that was ground-water flow in a bottomland forested wetland within the lower Mississippi River Valley. The scope of the report includes the collection of surface-water and ground-water heads from 119 wells and 13 staff gages, and interpretation of the data. This report discusses findings from the monthly measurements collected from September 1989 to September 1992 (table 1) plus more frequent measurements including continuous records.

Table 1. Measurement dates of water levels at wells and staff gages in Black Swamp during the study period

[--, no measurements; *, measurements were made at less than 30 percent of the 119 wells and 13 staff gages normally measured]

Month	1989	1990	1991	1992
1	--	January 22-26	January 7-10*	January 6-10
2	--	February 12-16	January 28-31	February 10-14
3	--	March 12-16	March 4-8	March 9-13
4	--	April 23-27	April 8-12	April. 6-10
5	--	May 21-25	May 13-17	May 4-8
6	--	June 18-22	June 3-7	June 8 -10
7	--	July 16-20	July 8-12	July 13-17
8	--	August 20-24	August 12-16	August 23-25
9	September 11-15*	September 10-14	September 9-13	September 20-23
10	--	October 15-19	October 28-31	--
11	--	November 5-9	November 18-22	--
12	December 11-15	December 3-7	December 16-20	--

Description of the Study Area

The study area was in Woodruff County, eastern Arkansas, approximately 60 mi southwest of Jonesboro, Ark., 65 mi east-northeast of Little Rock, Ark., and 72 mi west of Memphis, Tenn. (fig. 1). The Black Swamp wetland is bottomland, forested wetland contained within the small alluvial valley of the Cache River. The Black Swamp usually is forested but a small portion of the area was cleared for agriculture. Agricultural land use is prevalent on the upland of the alluvial plain and is adjacent to the bluffs bounding Black Swamp wetland. A large portion of the small alluvial valley of Cache Bayou is used for agriculture.The Black Swamp study area included the union of the area where wells monitored for water levels were located, and the extent of a drainage area used to develop the water budget. Some wells used to study ground-water flow patterns were located outside of the drainage area.

The study area was located in a regional lowland called the Mississippi Alluvial Plain (Fenneman, 1938), herein referred to as the alluvial plain. General alluvial deposition has left terraces of different land-surface altitudes. Two land types are treated separately in this report: (1) lowland adjacent to the Cache River and Cache Bayou, and (2) the upland of the alluvial plain. The lowland is 10 to 20 ft lower in altitude than the upland of the alluvial plain and comprises small alluvial valleys within the alluvial plain. The small alluvial valleys harbor the Cache River and Cache Bayou and were created by the larger St. Francis and Black Rivers in prehistoric times. Lowland on either side of a tributary to the Cache River, the Cache Bayou, merges with the Black Swamp wetland near the southernmost gaging station. Land-surface altitude of the lowland areas, excluding the Cache River channel, range from 175 ft above sea level at the southernmost gaging station to 205 ft at the northernmost gaging station. Land-surface altitude of the upland of the alluvial plain ranges from 185 ft at the southernmost wells used in this study to 232 ft at Nubbin Ridge, which runs parallel to Highway 17. The lowland and upland of the alluvial plain are separated by moderately sloping bluffs 10 to 20 ft in height. The bluffs are about 1.5 mi from either side of the Cache River.

Land-surface altitude within the Black Swamp wetland varies about 3 ft. The Cache River channel is 3 to 5 ft lower than the surrounding wetland. Some wetland areas often are associated with abandoned meander channels or traces of small streams and are inundated by stagnant pools for 10 to 12 months a year. Some areas near the bluffs are inundated by water impounded by beaver dams or poor local drainage. Better drained areas also are inundated by Cache River floods for up to 5 months a year. Patterson, Ark., is situated on a broad area in the lowland, herein referred to as the intermediate land around Patterson, about 5 ft higher than the rest of the lowland and rarely is flooded.

The Black Swamp drainage area, for which the water budget was developed, is the drainage area between two primary streamflow gaging stations located about 30.5 river miles apart on the Cache River. One gaging station, located at the Highway 64 bridge crossing the Cache River at Patterson, Ark., monitors surface water entering the Black Swamp drainage area. The other gaging station, located at a county bridge crossing the Cache River 4.5 mi west-northwest of Cotton Plant, Ark., monitors surface water leaving the Black Swamp drainage area. Drainage areas for the inflow and outflow gaging stations are about 1,040 mi^2 and 1,170 mi^2, respectively. The Black Swamp drainage area between these gaging stations is 127.8 mi^2. Upland of the alluvial plain comprises 61.7 mi^2 (48 percent) of the drainage area, and the Black Swamp wetland, adjacent small alluvial valleys, and intermediate land around Patterson comprise 66.1 mi^2 (52 percent) of the drainage area (fig. 1).

The climate for Black Swamp is subtropical to near temperate. Annual rainfall in the area averages 48.8 in. (Freiwald, 1985) and is heaviest from November to May. Evapotranspiration averages about 38.6 in. The average monthly temperature ranges from 40 °F in January to 81 °F in July (National Oceanic and Atmospheric Administration, 1990).

The Cache River is a pool and riffle stream. Stage frequently rises and falls over 10 ft in an annual cycle. Surface-water discharge ranges from no flow to over 10,000 ft^3/s. In the drainage area, small tributaries do not contribute significant discharge to the Cache River except when rice farmers drain their fields in late summer. Dikes and diversion canals commonly are used to control inundation during floods of agricultural land that extends into the wetland and diverts water from surface-water bodies during the summer in the southwestern part of the drainage area.

Much of the area known as Black Swamp has become a U.S. Fish and Wildlife refuge, and the area has been designated as a RAMSAR site, which is an

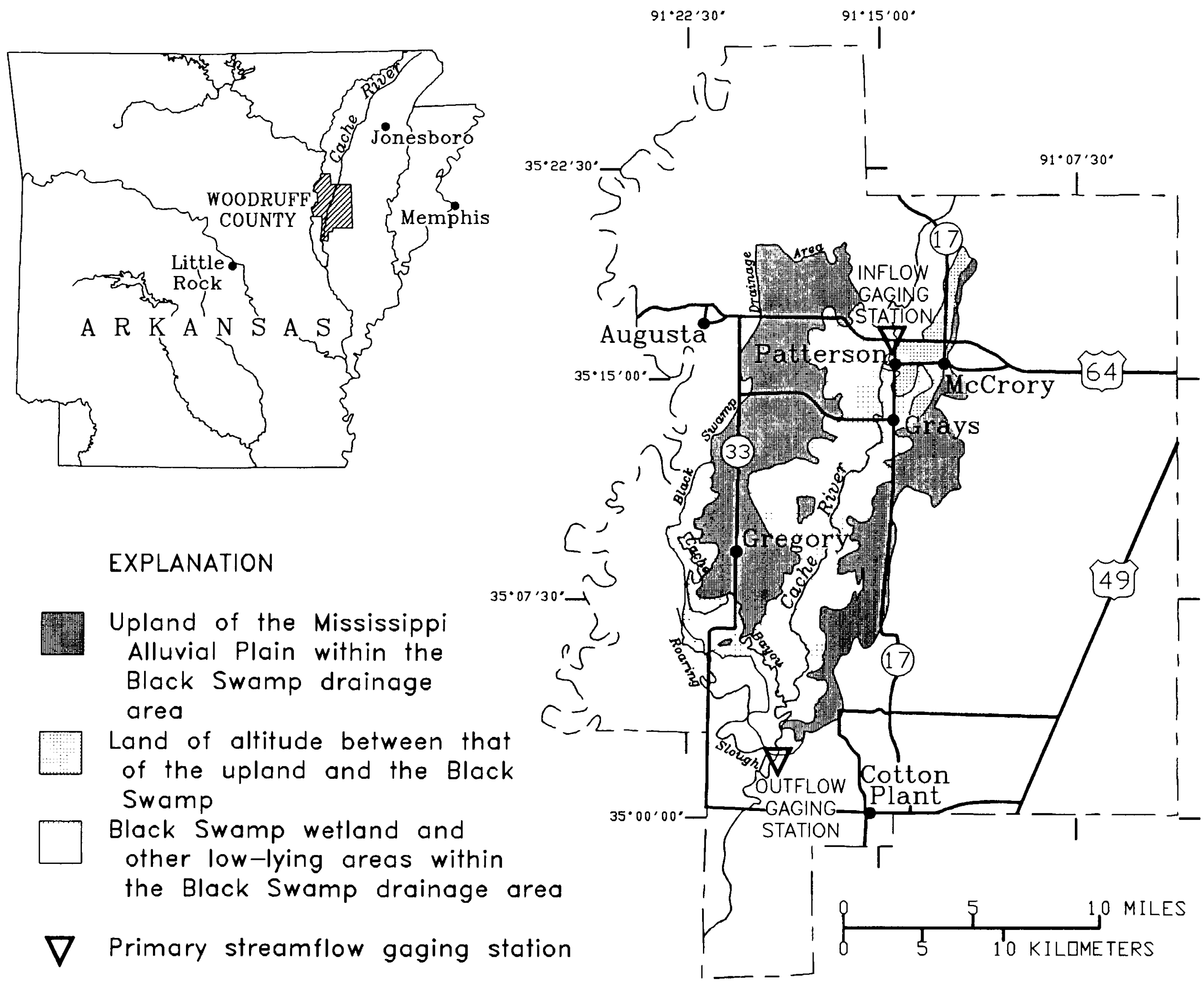


Figure 1. Location of study area.

internationally recognized wetland of critical ecological importance. Soils are hydric and are under undrained conditions within the Black Swamp wetland. Tree species vary according to frequency of inundation. Bald cypress (*Taxodium distichium* L.) and tupelo gum (*Nyssa aquatica* L.) dominate the abandoned meanders or stream traces of the lower wetland. Overcup oak (*Quercus lyrata* L.), bitter pecan (*Carya aquatica* L.), willow oak (*Quercus phellos* L.), and nuttall oak (*Quercus nuttallii* L.) are prevalent in the slightly higher areas of the wetland. Water oak (*Quercus nigra* L.) is prevalent in areas 3 to 15 ft higher than the wetland.

Geologic Description

The alluvial plain lies within a large structural trough called the Mississippi embayment, herein referred to as the embayment, which extends 600 mi from the southern tip of Illinois to the Louisiana coast. The alluvial plain attains a maximum width of about 125 mi in central Arkansas (Ackerman, 1989). Geologic units of Tertiary age and older dip toward the axis of the Mississippi embayment with a southward component of dip following the southward plunge of the axis (Hosman and others, 1968) (fig. 2).

In the embayment, alluvial deposits of Quaternary age, which comprise the Mississippi River Valley alluvium, herein referred to as the alluvium, lie unconformably on the eroded surface of the geologic units of Tertiary age and older. This erosional surface generally dips to the south and locally undulates (Saucier, 1994). Most of the geologic units in contact with the base of the alluvium are unconsolidated sand, silt, and clay beds of Tertiary age.

Six geologic sections were constructed from drillers' logs to show the lithology and distribution of the alluvium deposits of Quaternary age in Woodruff County. Most of the drillers' logs were from previously constructed wells. Additional drillers' logs created when wells were constructed for this study also were used. The traces of the geologic sections are shown in figure 3 and the geologic sections are presented in figures 4-9.

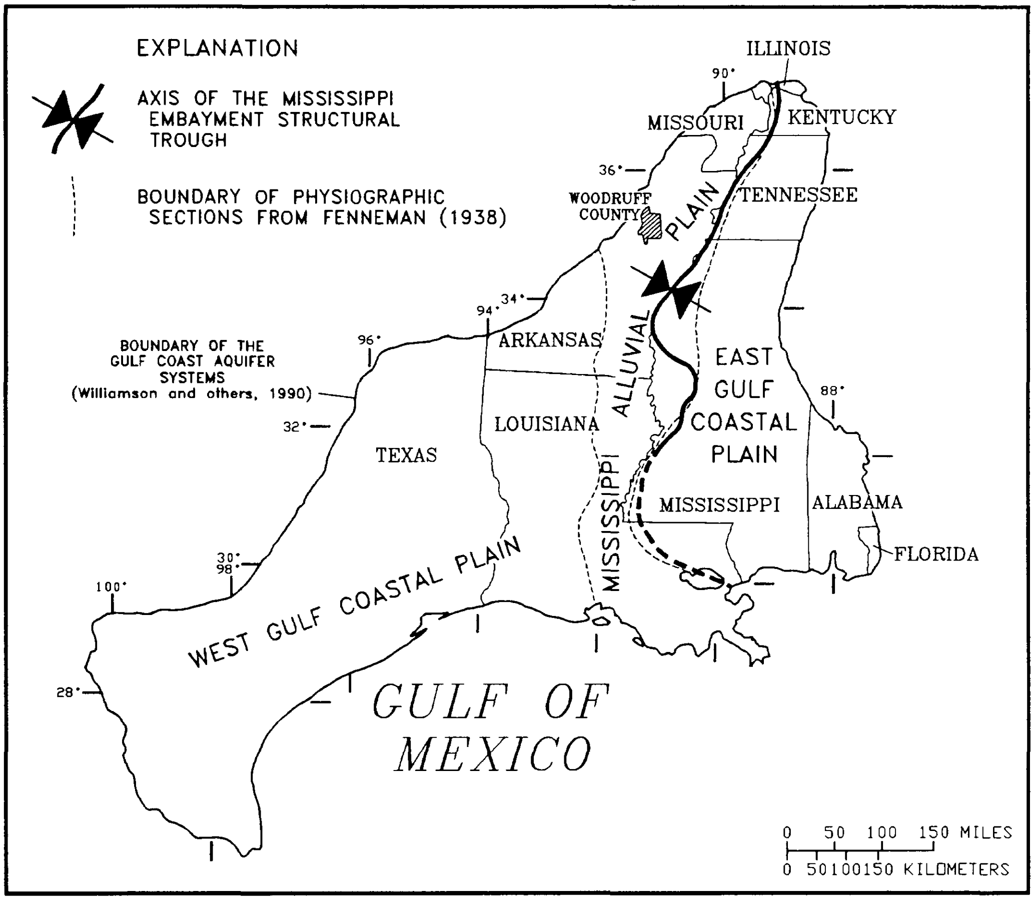


Figure 2. Location of structural and physiographic setting in the region of the study area.

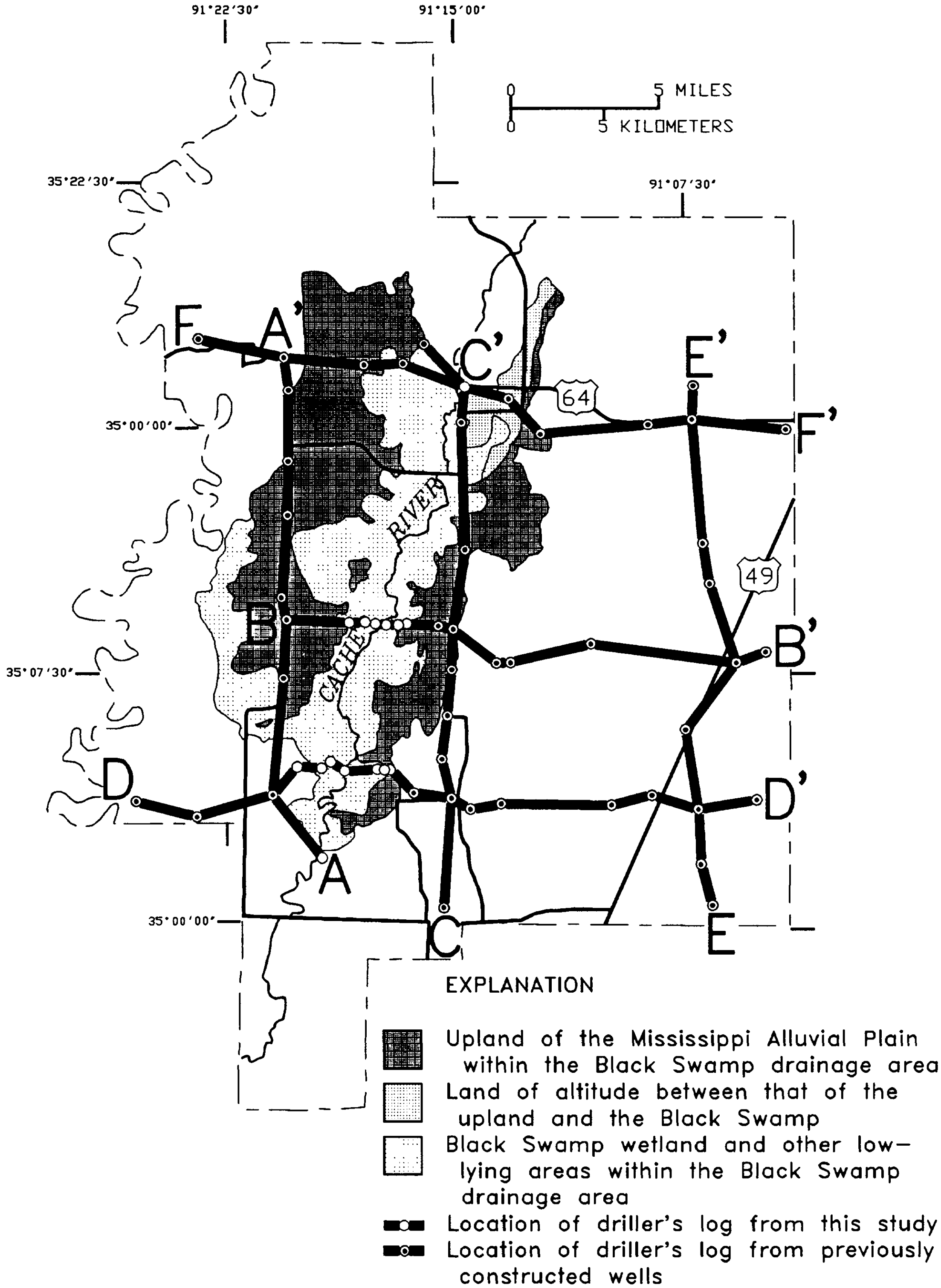


Figure 3. Locations of geologic sections A-A' through F-F' in Woodruff County, Arkansas.

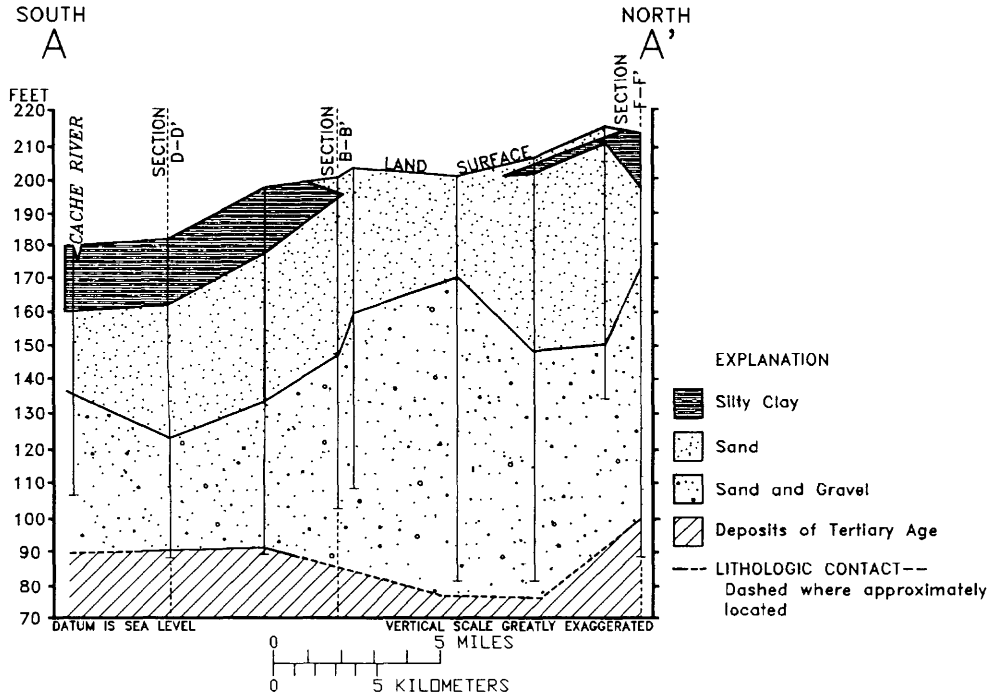


Figure 4. Geologic section A-A'.

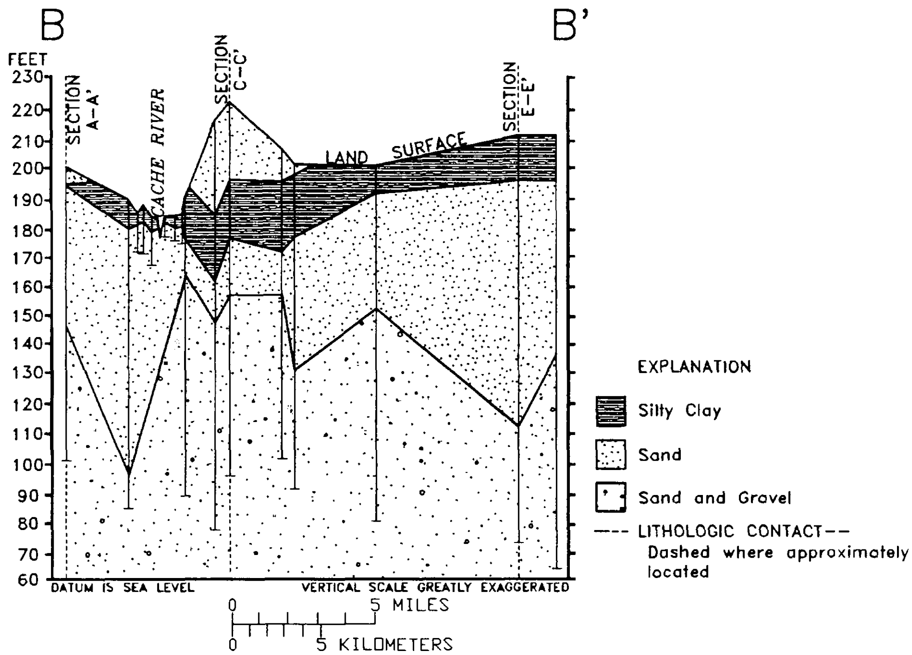


Figure 5. Geologic section B-B'.

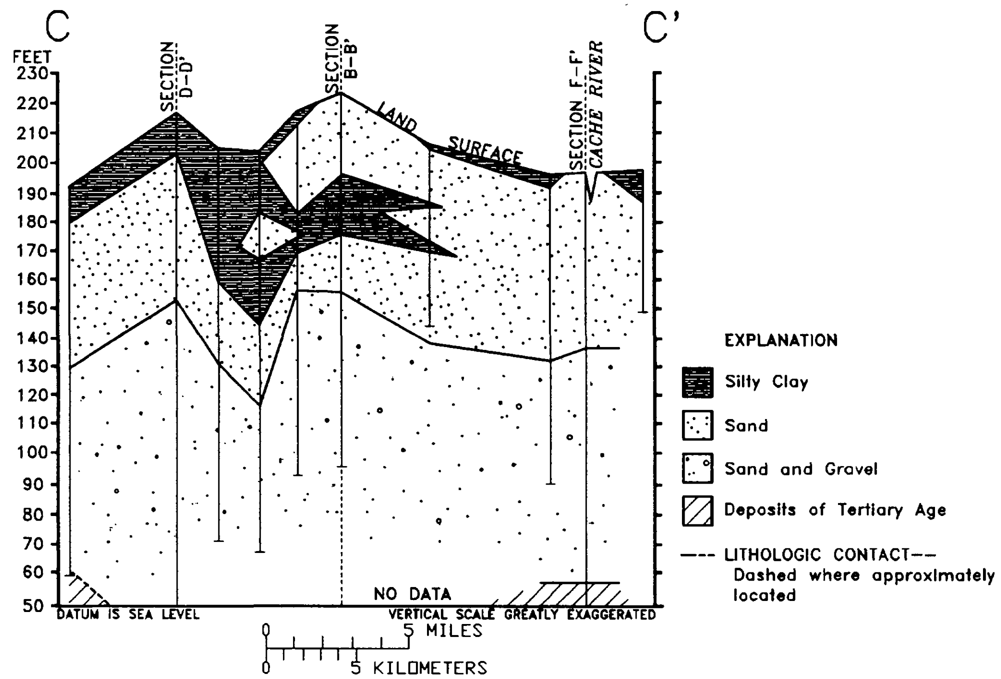


Figure 6. Geologic section C-C'.

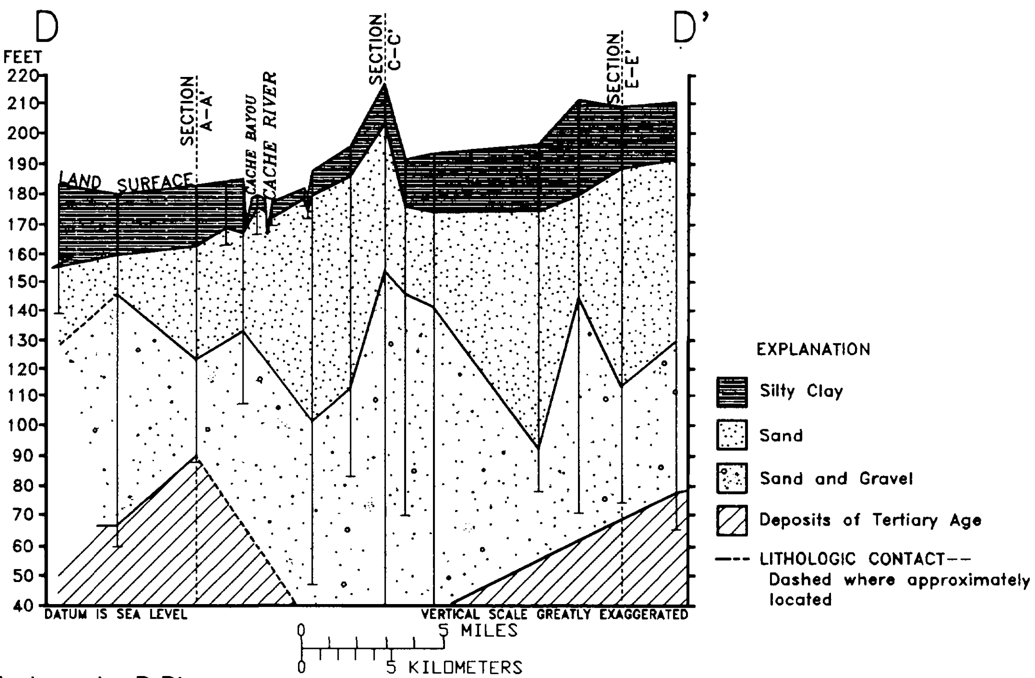


Figure 7. Geologic section D-D'.

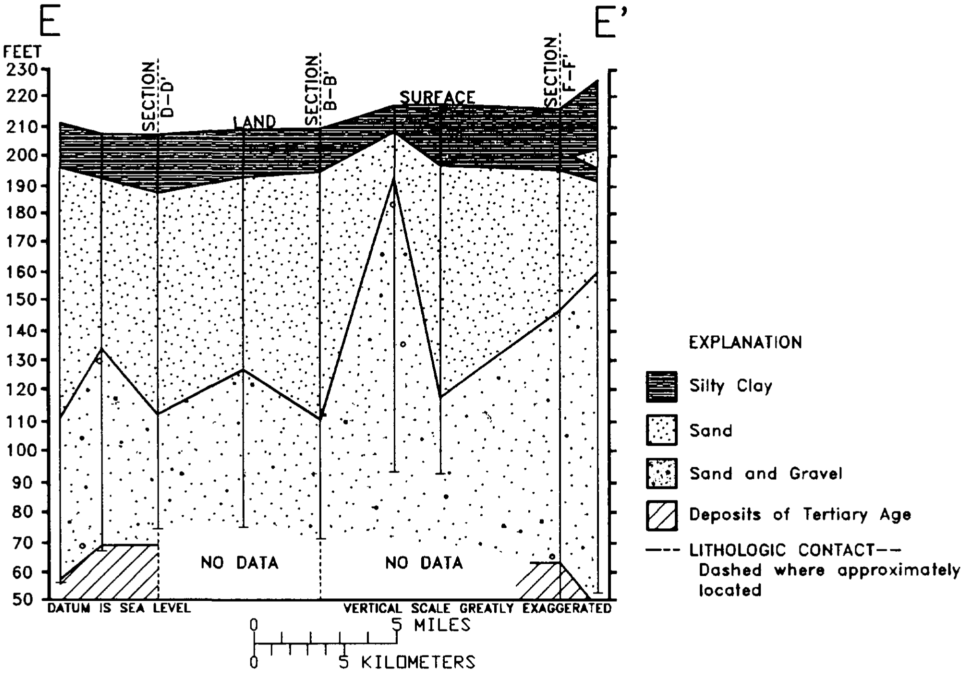


Figure 8. Geologic section E-E'.

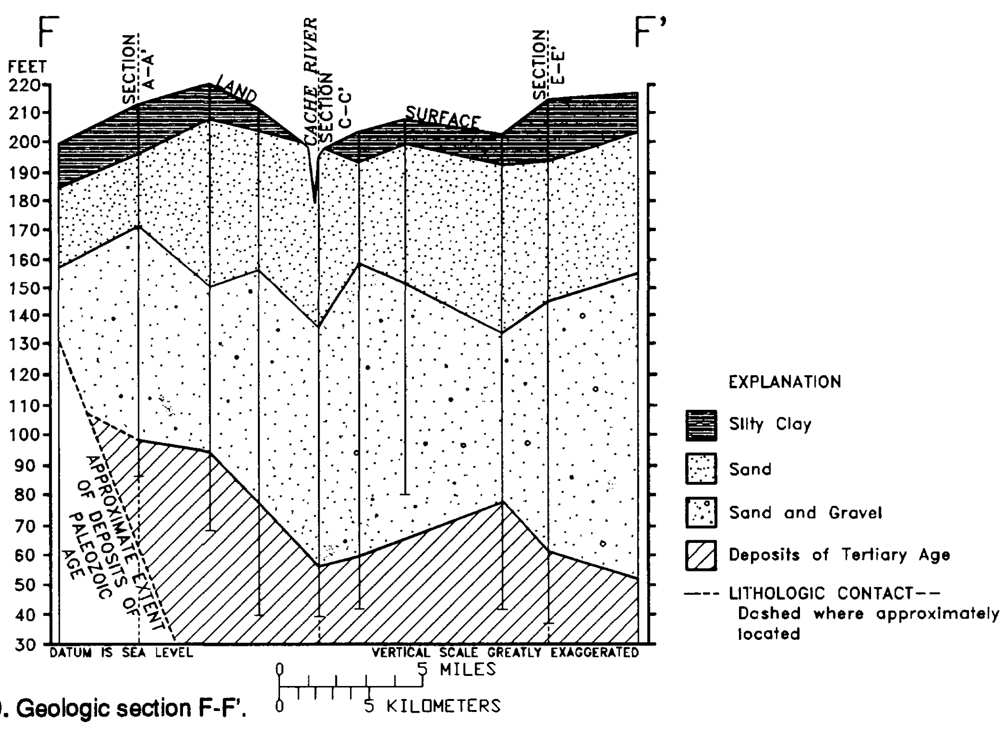


Figure 9. Geologic section F-F'.

The base of the alluvium is about 90 to 150 ft in depth and consists of sand and gravel (figs. 4-9). At many locations the base of the alluvium mainly consists of a gravel layer about 3 ft thick. Maximum grain size is 4 in. at the base of the alluvium and decreases upward. At some locations sand mixed with gravel is within 30 ft of the land surface, but it mostly occurs below a depth of 30 ft. Sand mixed with gravel usually is at depths from 50 to 150 ft. In many locations the alluvium also contains blackened wood chips that usually are rounded and are more than 0.33 in. in diameter. Thickness of the blackened wood chip deposit varies considerably over short distances. Sand of medium- to fine-grain size and of "salt and pepper" color exists at depths from 10 to 100 ft. The "pepper" color is caused by the presence of fine, sand-grain sized pieces of blackened wood chips or plant matter in the white sand. The surficial deposit overlying the sand at most locations within the Black Swamp drainage area consists of clay and silt and usually is 5 to 30 ft thick, but is absent at some locations where fine- to medium-grain sand deposit is at the surface (figs. 4, 6, and 9).

Hydrogeology

The alluvium consists of two distinct but gradational lithologies; clays and silts overlie coarse sands and gravels that decrease in grain size toward the surface (Ackerman, 1989). The sand and gravel from the eroded surface of the deposits of Tertiary age and older to the base of the surficial silty clay deposits form the basal Mississippi River Valley alluvial aquifer, herein referred to as the alluvial aquifer. The low permeability clays and silts form the overlying Mississippi River Valley confining unit, herein referred to as the confining unit.

The alluvial aquifer produces a great volume of water for irrigation. The alluvial aquifer is bounded by the extent of the sand or sand and gravel, which ranges in thickness from about 70 to 150 ft. Horizontal hydraulic conductivity (Kh) values for the alluvial aquifer range from 90 to 400 ft/d (Krinitzsky and Wire, 1964; Newcome, 1971) and have a geometric mean of about 205 ft/d (Ackerman, 1989). The horizontal hydraulic conductivity is much larger than the vertical hydraulic conductivity (Kv); the Kh/Kv ratio can exceed 100 (Williamson and others, 1990). Although discussion in this report emphasizes the lower and upper parts of the alluvial aquifer, the alluvial aquifer is a single hydrogeologic unit.

The confining unit consists mostly of silt and clay that confines the alluvial aquifer and impedes vertical ground-water flow into or out of the alluvial aquifer (Krinitzsky and Wire, 1964). The confining unit generally is about 5 to 25 ft thick in the Black Swamp drainage area; however, the unit is absent in the parts of the upland of the alluvial plain and in the intermediate land around Patterson near the Highway 64 bridge over the Cache River (figs. 4, 6, and 9). Laboratory determinations of horizontal hydraulic conductivity for clay to silty sand texture samples of the confining unit range from 1×10^{-4} to 5×10^{-1} ft/d (Ackerman, 1989, p. 16); these values are near the minimum horizontal hydraulic conductivity values for clayey, silty substrate in other wetlands (Siegel, 1988; Andrews, 1978; O'Brien, 1977). Vertical hydraulic conductivity values from other studies range from 7.10×10^{-5} ft/d (McKay and others, 1979) to 1.30×10^{-1} ft/d for "black muck" (O'Brien, 1977).

Cuttings obtained during the construction of wells within the wetland indicate that the top 1 ft is a soil zone riddled with macropores. During the drilling of one well, water was trickling out of a small hole in the side of the drill hole, clearing the side of the hole, and rapidly pouring into the well. Vertical hydraulic conductivity of the top 1 ft probably is near that of gravel (250 ft/d). Beneath the zone of macropores, the confining unit is silty or sandy clay and consistently is 4 to 8 ft thick. The bottom of the confining unit relatively quickly grades into clayey sand. The silty or sandy clay probably has a hydraulic conductivity similar to that of McKay and others (1979), and a value of 1.51×10^{-3} ft/d is used in this report. For this report, based on drillers' logs, the confining unit in the Black Swamp is assumed not to be fully penetrated by macropores. Field observations indicate that the Cache River breaches the confining unit and has a riverbed comprised of a mixture of silt and sand.

DATA-COLLECTION METHODS AND DESCRIPTION OF SITES

Ground-water flow patterns in the Black Swamp were studied from five different perspectives: (1) areal distribution of head in the upper part of the alluvial aquifer using shallow wells, (2) areal distribution of head in the lower part of the alluvial aquifer using deep wells, (3) general vertical distribution of head along two transects perpendicular to the Cache River using wells and staff gages, (4) vertical distribution of head at ground-water-flow study sites along two transects, and (5) comparison of highly localized vertical head between a shallow well and an adjacent staff gage in a nested site.

Data from 119 wells and 13 staff gages were obtained for this study. Sixty-one wells were pre-existing privately owned wells; 58 wells were constructed specifically for this study. Of the 61 pre-existing wells, 54 were used for irrigation, 6 were unused, and 1 was domestic. Many of the wells constructed for this study are nested with each other or a pre-existing well. Selected well nests, herein referred to as nested sites, specifically designed to study ground-water/surface-water interaction in the Cache River or wetland are named in table 2.

For the study, 23 wells were drilled with a hydraulic rotary system that used a 3-blade 6-in. drag bit, and 35 wells were augured. Most of the wells were constructed with screens that were relatively short compared to overall well depth so that the wells could be used as piezometers. The exception is shallow well S55. After the well was drilled, water was injected into the casing to flush drilling mud away from the screen. Clean sand was poured around the well screens, and bentonite pellets were poured around the well casing.

Wells ranging in depth from 2.3 to 140 ft were screened in the alluvium. Eight wells were screened in the confining unit (fig. 10) and the other 111 wells were screened at various depths in the alluvial aquifer (figs. 11 and 12; and table 2). Wells and staff gages were monitored at least monthly (table 1); wells and

Table 2. Description of wells used to study Black Swamp

[ft, foot; in., inch; N, nested site; L, log available; B, bored or augered; USGS, well drilled specifically for the Black Swamp study; U, unused; TB, well is on Transect B-B'; --, unreported, unavailable, or not applicable; CR, continuous recorder data available; TD, well is on Transect D-D'; Y, hydraulic rotary; H, domestic; GW, data used to calculate flow through the wetland confining unit; I, irrigation; GR, data used to calculate flow through the bed of the Cache River; Z, well destroyed during study period]

Well name	Name of selected nested site	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Altitude of land surface above sea level (ft)	Depth of well below land surface (ft)	Drillers' log	Length of openings (in.)	Diameter of casing (in.)	Construction	Primary use of water	Comments
				Wells open to the confining unit							
C13	N4	350906	911753	183.73	3.40	L	24	2.00	B, USGS	U	TB
C16	N5	350906	911721	184.64	5.30	--	36	1.25	B, USGS	U	TB
C18	N6	350905	911722	179.89	3.50	L	24	2.00	B, USGS	U	TB
C20	N7	350858	911655	182.99	2.30	L	24	2.00	B, USGS	U	CR, TB
C24	N100	350901	911618	183.80	3.30	L	24	2.00	B, USGS	U	TB
C40	N8	350454	911854	178.85	3.50	L	24	2.00	B, USGS	U	TD
C42	N9	350442	911821	177.88	5.00	L	24	2.00	B, USGS	U	CR, TD
C45	N12	350444	911658	178.56	3.60	L	24	2.00	B, USGS	U	TD
				Wells open to the upper part of the alluvial aquifer							
S1	--	351334	911619	192.15	18.50	--	--	1.25	--	U	--
S2	--	351333	911522	195.20	24.60	--	--	2.00	B, USGS	U	--
S3	--	351330	911450	189.39	13.00	--	60	1.25	B, USGS	U	--
S4	--	351253	911550	194.19	14.00	--	60	1.25	B, USGS	U	--
S5	--	351241	911442	190.41	11.40	--	60	1.25	B, USGS	U	--
S6	--	351058	911503	200.71	20.70	--	60	1.25	B, USGS	U	--
S7	--	351047	911740	197.08	16.70	--	120	1.25	Y, USGS	U	--
S8	--	351028	911726	190.05	10.00	--	60	1.25	B, USGS	U	--
S9	--	350953	911545	191.88	23.60	--	60	1.25	B, USGS	U	--
S10	--	350930	911826	185.02	14.20	--	60	1.25	B, USGS	U	--
S11	--	350916	0912036	200.00	23.70	--	--	1.25	B	H	--

Table 2. Description of wells used to study Black Swamp--Continued

[ft, foot; in., inch; N, nested site; L, log available; B, bored or augered; USGS, well drilled specifically for the Black Swamp study; U, unused; TB, well is on Transect B-B'; --, unreported, unavailable, or not applicable; CR, continuous recorder data available; TD, well is on Transect D-D'; Y, hydraulic rotary; H, domestic; GW, data used to calculate flow through the wetland confining unit; I, irrigation; GR, data used to calculate flow through the bed of the Cache River; Z, well destroyed during study period]

Well name	Name of selected nested site	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Altitude of land surface above sea level (ft)	Depth of well below land surface (ft)	Drillers' log	Length of openings (in.)	Diameter of casing (in.)	Construction	Primary use of water	Comments
S12	N4	350906	911753	182.89	11.00	L	24	2.00	B, USGS	U	GW, TB
S14	--	350907	911745	187.04	16.00	L	24	2.00	B, USGS	U	TB
S15	N5	350906	911721	184.44	9.35	--	60	1.25	B, USGS	U	GW, TB
S17	N6	350905	911722	180.16	11.00	L	24	2.00	B, USGS	U	GW, TB
S19	N7	350858	911655	182.97	6.20	L	24	2.00	B, USGS	U	GW, CR, TB
S21	--	350902	911636	183.94	9.90	L	24	2.00	B, USGS	U	TB
S22	--	350839	911631	198.05	21.90	--	120	1.25	Y, USGS	U	--
S23	N100	350901	911618	183.65	10.30	L	24	2.00	B, USGS	U	TB
S25	--	350902	911606	187.97	35.50	L	60	4.00	Y, USGS	U	TB
S26	--	350902	911606	188.50	29.10	L	60	4.00	Y, USGS	U	TB
S27	--	350802	912004	198.13	18.85	--	120	1.25	Y, USGS	U	--
S28	--	350750	911841	184.46	20.00	--	12	1.25	B, USGS	U	--
S29	--	350750	911841	185.59	10.00	--	12	1.25	B, USGS	U	--
S30	--	350750	911841	185.98	10.00	--	12	1.25	B, USGS	U	--
S31	--	350750	911841	187.45	30.00	--	12	1.25	B, USGS	U	--
S32	--	350559	912007	185.34	16.85	--	120	1.25	Y, USGS	U	--
S33	--	350559	912007	185.36	19.20	--	120	1.25	Y, USGS	U	--
S34	--	350511	911834	181.39	10.00	--	60	1.25	B, USGS	U	--
S35	--	350513	911718	196.48	27.00	L	120	4.00	Y, USGS	U	--
S36	--	350509	911717	193.42	19.60	--	120	1.25	Y, USGS	U	--
S37	--	350446	912012	183.34	13.80	--	120	1.25	Y, USGS	U	TD
S38	--	350404	911918	185.09	35.60	L	60	4.00	Y, USGS	U	TD
S39	N8	350454	911854	178.81	14.00	L	24	2.00	B, USGS	U	GW, TD
S41	N9	350442	911821	177.41	8.00	L	24	2.00	B, USGS	U	GW, CR, TD
S43	N11	350444	911712	180.56	5.30	L	24	2.00	B, USGS	U	GW, TD
S44	N12	350444	911658	178.50	8.30	L	24	2.00	B, USGS	U	GW, TD
S46	--	350445	911652	186.97	33.00	L	60	4.00	Y, USGS	U	TD
S47	--	350349	911701	190.22	14.00	--	60	1.25	B, USGS	U	--
S48	--	350209	911918	180.57	32.30	L	60	4.00	Y, USGS	U	--
S49	--	350152	911904	183.65	14.40	--	120	1.25	Y, USGS	U	--
S50	--	350148	912047	179.47	16.90	--	120	1.25	Y, USGS	U	--
S51	N10	350506	911753	186.19	17.50	--	60	1.25	B, USGS	U	--
S52	--	350353	912014	182.70	13.60	--	60	1.25	B, USGS	U	--
S53	--	351636	911536	198.13	14.50	--	--	2.00	--	U	--
S54	--	351349	911823	200.45	18.90	--	--	1.25	--	U	--
S55	--	350148	912047	178.96	9.50	--	108	1.25	Y, USGS	U	--
Wells open to the lower part of the alluvial aquifer											
D1	--	351641	911943	216.00	--	--	--	--	--	I	--
D2	--	351640	911910	214.00	--	--	--	--	--	I	--

Table 2. Description of wells used to study Black Swamp--Continued

[ft, foot; in., inch; N, nested site; L, log available; B, bored or augered; USGS, well drilled specifically for the Black Swamp study; U, unused; TB, well is on Transect B-B'; --, unreported, unavailable, or not applicable; CR, continuous recorder data available; TD, well is on Transect D-D'; Y, hydraulic rotary; H, domestic; GW, data used to calculate flow through the wetland confining unit; I, irrigation; GR, data used to calculate flow through the bed of the Cache River; Z, well destroyed during study period]

Well name	Name of selected nested site	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Altitude of land surface above sea level (ft)	Depth of well below land surface (ft)	Drillers' log	Length of openings (in.)	Diameter of casing (in.)	Construction	Primary use of water	Comments
D3	--	351611	911411	194.64	63.30	L	60	4.00	Y, USGS	U	GR
D4	--	351611	911338	201.03	--	--	--	--	--	I	GR
D5	--	351337	912027	202.59	--	--	--	--	--	I	--
D7	--	351330	911621	200.20	--	--	--	4.00	--	I	GR
D8	--	351345	911358	196.90	--	--	--	--	--	U	GR
D9	--	351328	911251	210.09	140.00	--	--	8.00	Y	I	--
D10	--	351252	911701	194.84	--	--	--	--	--	I	--
D11	--	351233	912052	200.82	--	--	--	--	--	I	--
D12	--	351047	911740	196.94	100.00	--	--	--	--	I	--
D13	--	351028	911830	192.56	--	--	--	--	--	I	--
D14		351035	911412	226.05	--	-	--	--	--	I	--
D15		350907	911019	199.91	--	-	--	--	--	I	--
D16		350905	911812	188.79	111.00	L	60	4.00	Y, USGS	U	TB
D17	--	350905	911812	189.26	50.00	L	60	4.00	Y, USGS	U	GR, TB
D18	--	350902	911606	188.31	65.50	L	60	4.00	Y, USGS	U	GR, TB
D19	--	350901	911505	212.35	67.00	--	--	6.00	--	I	TB
D20	--	350858	911434	218.65	81.00	--	--	6.00	--	I	TB
D21	--	350857	911416	222.31	--	--	--	6.00	--	Z	--
D22	--	350839	911631	198.09	--	--	--	--	--	I	--
D23	--	350802	912004	198.36	--	--	--	--	--	I	--
D24	--	350805	911854	195.97	--	--	--	--	--	I	--
D25	--	350819	911435	220.58	--	--	--	14.00	Y	I	--
D26	--	350700	911648	197.34	--	--	--	--	--	I	--
D27	--	350559	912007	185.56	--	--	--	--	--	I	--
D28	--	350520	911834	186.67	--	--	--	--	--	I	GR
D29	--	350509	911717	193.30	120.00	--	--	6.00	--	U	GR
D30	--	350442	912136	186.12	--	--	--	--	--	I	TD
D31	--	350446	912012	183.43	--	--	--	--	--	I	TD
D33	--	350443	911921	185.27	80.00	L	60	4.00	Y, USGS	U	TD
D34	--	350445	911652	187.32	75.80	L	60	4.00	Y, USGS	U	TD
D35	--	350440	911635	194.79	--	--	--	10.00	--	I	TD
D36	--	350441	911554	201.52	--	--	--	8.00	--	I	TD
D37	--	350452	911503	217.18	--	--	--	--	--	I	--
D38	--	350422	912012	184.50	--	--	--	12.00	--	I	--
D39	--	350403	911546	194.63	--	--	--	6.00	--	I	--
D40	--	350354	912125	184.26	--	--	--	--	--	I	--
D41	--	350310	911746	186.09	--	--	--	--	--	I	--
D42	--	350219	912045	181.88	--	--	--	--	--	I	--
D43	--	350220	912002	172.05	--	--	--	--	--	I	GR
D44	--	350208	912102	179.00	--	--	--	--	--	I	--

Table 2. Description of wells used to study Black Swamp--Continued

[ft, foot; in., inch; N, nested site; L, log available; B, bored or augered; USGS, well drilled specifically for the Black Swamp study; U, unused; TB, well is on Transect B-B'; --, unreported, unavailable, or not applicable; CR, continuous recorder data available; TD, well is on Transect D-D'; Y, hydraulic rotary; H, domestic; GW, data used to calculate flow through the wetland confining unit; I, irrigation; GR, data used to calculate flow through the bed of the Cache River; Z, well destroyed during study period]

Well name	Name of selected nested site	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)	Altitude of land surface above sea level (ft)	Depth of well below land surface (ft)	Drillers' log	Length of openings (in.)	Diameter of casing (in.)	Construction	Primary use of water	Comments
D45	--	350148	912047	179.00	119.00	--	--	6.00	--	I	--
D46	--	350152	911904	183.51	--	--	--	--	--	I	GR
D47	--	350152	911735	185.70	--	--	--	--	--	I	--
D48	--	351031	912350	190.00	--	--	--	--	--	I	--
D49	--	350745	912423	187.00	--	--	--	--	--	I	--
D50	--	350613	912347	185.00	--	--	--	--	--	I	--
D51	--	350451	912448	183.00	--	--	--	--	--	I	--
D52	--	350216	912603	180.00	--	--	--	--	--	I	--
D53	--	350059	912257	175.00	--	--	--	--	--	I	--
D54	--	351602	910739	207.00	--	--	--	--	--	I	--
D55	--	351537	910917	206.00	--	--	--	--	--	I	--
D56	--	351318	910848	201.00	--	--	--	--	--	I	--
D57	--	351230	910857	203.00	--	--	--	--	--	I	--
D58	--	351045	910827	202.00	--	--	--	--	--	I	--
D59	--	350950	910914	202.44	--	--	--	--	--	I	--
D60	--	350758	919756	196.00	--	--	--	--	--	I	--
D61	--	350651	910755	196.00	--	--	--	--	--	I	--
D62	--	350455	919744	198.00	--	--	--	--	--	I	--
D63	--	350336	919720	211.00	--	--	--	--	--	I	--
D64	--	350151	919854	204.00	--	--	--	--	--	I	--
D65	--	350649	911444	218.05	59.30	--	--	2.00	--	U	--
D66	--	350209	911918	185.00	64.60	L	--	4.00	Y, USGS	Z	Casing breached

staff gages in more critical areas of the Black Swamp were more frequently monitored. Well and staff gage altitudes above sea level were surveyed within 0.01 ft. Water levels in wells were measured with a steel tape using the method described by Stallman (1968). Data were stored in the Ground Water Site Inventory (GWSI) and Automatic DAta Processing System (ADAPS) data bases of the U.S. Geological Survey. Wells screened in the alluvial aquifer have been separated into two categories based on their depth. Wells less than 36 ft deep (fig. 11), herein referred to as shallow, are considered open to the upper part of the alluvial aquifer whereas wells greater than 36 ft deep (fig. 12), herein referred to as deep, are considered open to the lower part of the alluvial aquifer. The 36-ft limit is somewhat arbitrary. All pre-existing wells are assumed to have fairly long screens. Though the exact depth of the irrigation wells usually was not reported, interviews with well drillers and owners, indicate that irrigation wells penetrated most of the alluvial aquifer. Of the six unused wells, three were shallow and three were deep. The one domestic well was shallow. Of the 58 wells constructed for this project, 51 were shallow and 7 were deep. Forty-seven shallow wells were measured to study the interactions between the upper part of the alluvial aquifer and the surface whereas 64 deep wells were monitored to study ground-water flow in the more permeable lower part of the alluvial aquifer.

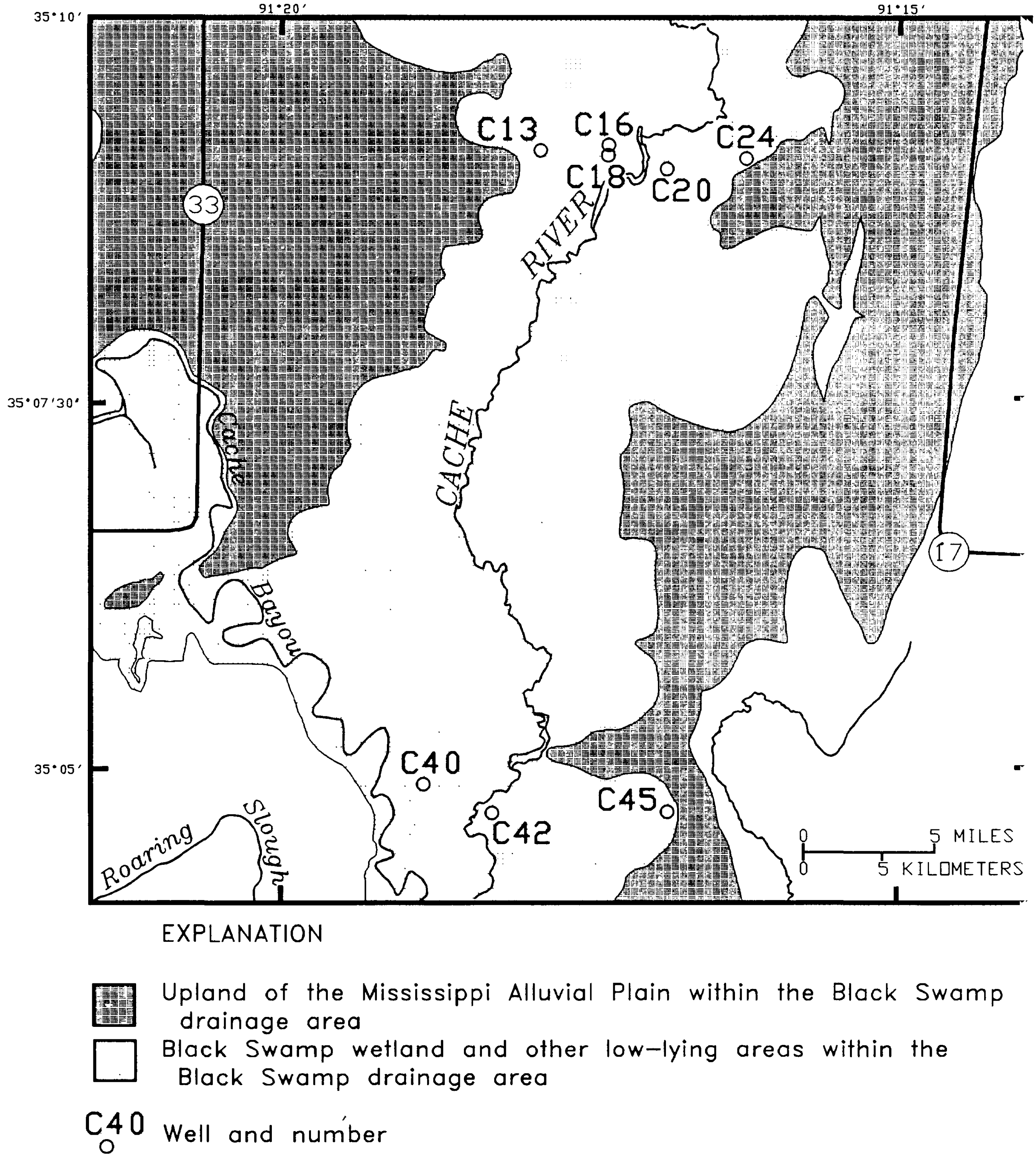


Figure 10. Location of monitoring wells open to the Mississippi River Valley confining unit.

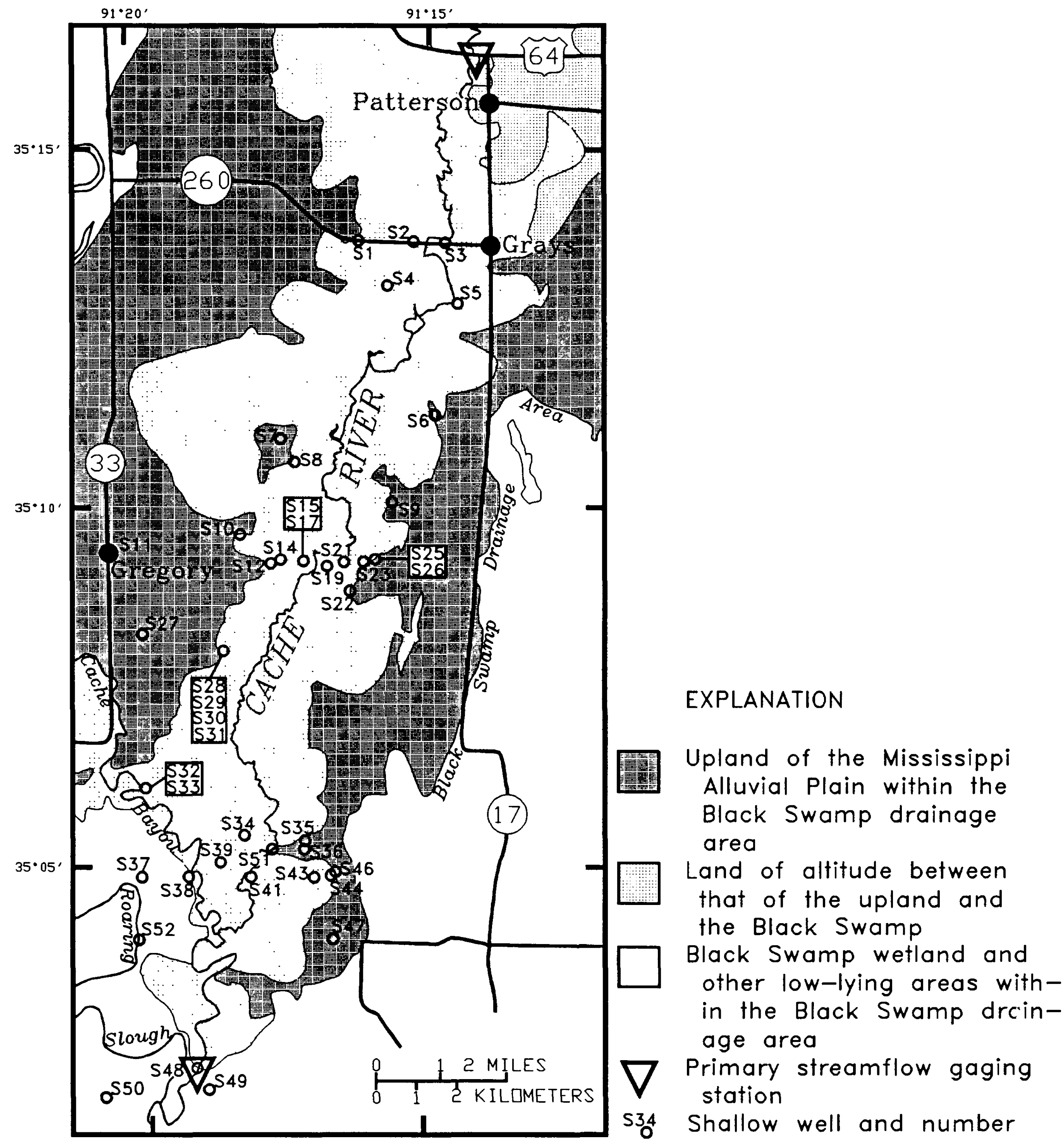
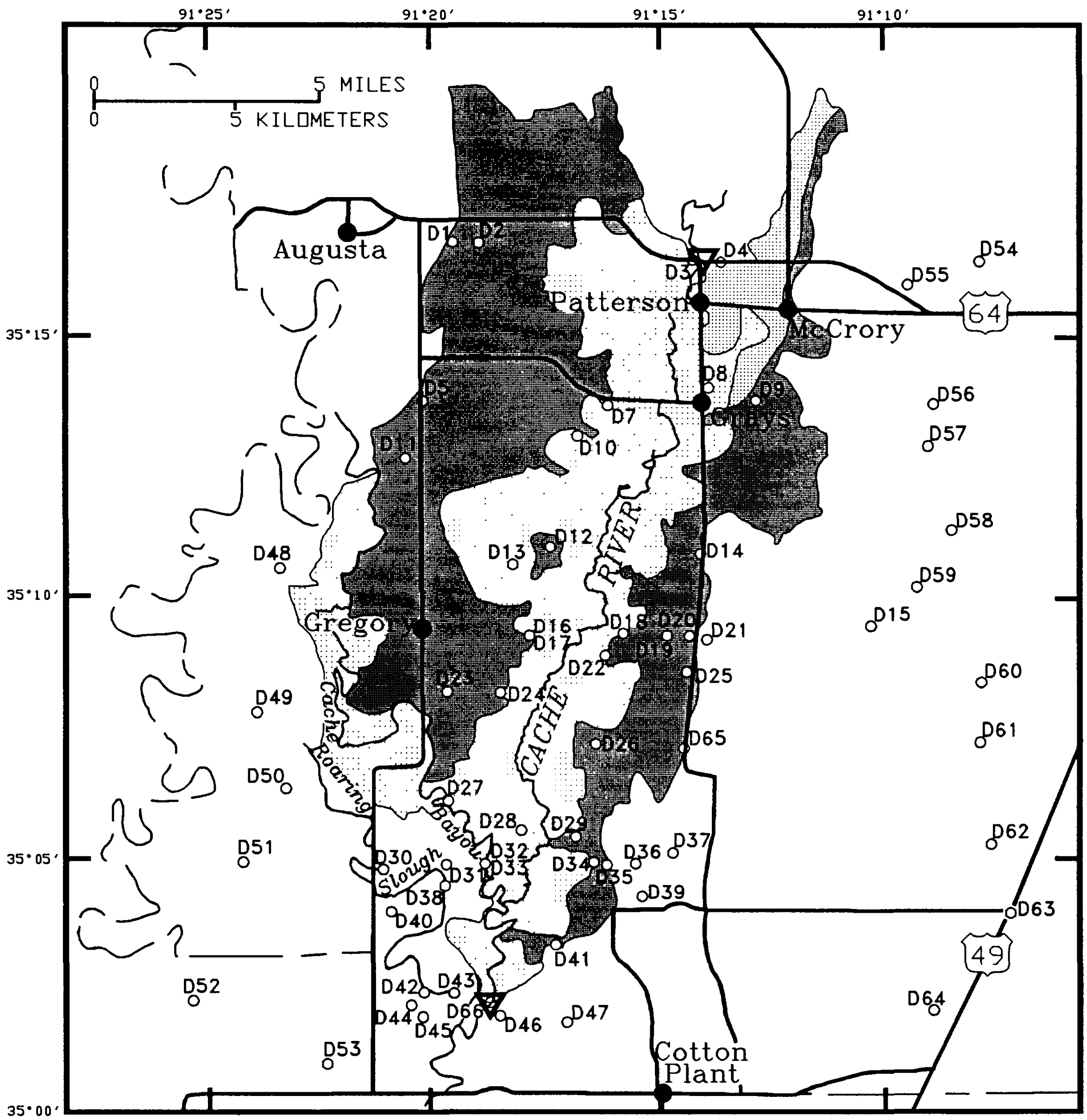


Figure 11. Location of monitoring wells open to the upper part of the Mississippi River Valley alluvial aquifer.



EXPLANATION

Upland of the Mississippi Alluvial Plain within the Black Swamp drainage area

Land of altitude between that of the upland and the Black Swamp

Black Swamp wetland and other low-lying areas within the Black Swamp drainage area

▽ Primary streamflow gaging station

D53 Deep well and number

Figure 12. Location of monitoring wells open to the lower part of the Mississippi River Valley alluvial aquifer.

Some deep wells were located in a large area east of the Black Swamp drainage area.

Staff gages were used to monitor surface-water levels in the Cache River and in the wetland (fig. 13, table 3). Daily surface-water discharge and stage of the Cache River were measured at the two primary gaging stations (G1 and G13) using conventional U.S. Geological Survey methods. Cache River stage also was measured at three other staff gages between the two primary gaging stations (G2, G5 and G10). Stage in the wetland was measured at eight other staff gages.

Wells and staff gages were concentrated along two transects (B-B' and D-D') perpendicular to the Cache River (fig. 14) in order to study ground-water/surface-water interaction from a cross-sectional perspective. Transect B-B' crosses the Cache River east of Gregory, Ark., and Transect D-D' crosses the Cache River about 7 river miles downstream or 5 straight-line miles south of Transect B-B'. Transect B-B' consists of 5 staff gages and 19 wells ranging in depth from 2.3 to 111 ft (fig. 15), and Transect D-D' consists of 4 staff gages and 16 wells ranging in depth from 3.5 to 100 ft (fig. 16). Individual well response times, local topography, well locations upstream or downstream from the traces of transects, and water levels in nearby wells must be considered to assess the ground-water flow pattern beneath a location in the wetland.

Ten nested sites were constructed for the specific purpose of studying ground-water/surface-water interaction in the wetland (table 4, fig. 14). Nested sites usually were comprised of a staff gage, a well open to the confining unit (2.3 to 5.3 ft), and a well open to the top of the alluvial aquifer (5.3 to 17.5 ft) (fig. 17). Nested sites N10 and N11 did not have a well open to the confining unit, and nested site N100 had limited use because it did not have a staff gage. Ground-water/surface-water interactions in the Cache River were studied using nested site N10. Beginning about halfway through the study period, measurements were made inside and outside of well casings

Table 3. Description of staff gages used to study Black Swamp

[*, primary gaging station; --, not applicable; D, daily streamflow; S, daily stage; M, monthly measurements only; N, selected nested site; wooded wetland, flooded 1 to 5 months per year (contains oak and bitter pecan); relatively high wooded wetland, flooded on average once per year; lower wooded wetland, almost always inundated with stagnant water (contains Bald Cypress and Tupelo Gum); C, partial continuous water-level record exists for this staff gage; poorly drained wooded wetland, sometimes inundated with stagnant water due to impoundments but not as low in altitude as lower wooded wetland]

Gage name	Name of selected nested site	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds	Datum of gage above sea level (feet)	Available data	Hydrologic setting
G1*	--	351613	911419	182.96	D, S	Cache River at the U.S. Highway 64 bridge, Patterson, Ark.
G2	--	351330	911509	201.44	M	On the State Highway 260 bridge over the Cache River, 1 mile west of Grays, Ark.
G3	--	350907	911800	185.65	M	On a bridge (since destroyed) over water impounded by a beaver dam.
G4	N4	350906	911753	182.66	M	Wooded wetland.
G5	N5	350908	911718	176.74	M	The end of a canal directly connected to the Cache River. Near relatively high wooded wetland.
G6	N6	350905	911722	178.80	M	At the edge of lower wooded wetland.
G7	N7	350858	911655	181.20	C	Wooded wetland 720 feet from the Cache River bank.
G8	N8	350454	911854	179.15	M	Poorly drained wooded wetland (staff gage disappeared during the study period).
G9	N9	350442	911821	177.13	C	Wooded wetland 180 feet from the Cache River bank.
G10	N10	350507	911755	165.94	S	Cache River at James Ferry.
G11	N11	350444	911712	178.98	M	At the edge of lower wooded wetland.
G12	N12	350444	911658	177.97	M	At the boundary between wooded wetland and lower wooded wetland.
G13*	--	350205	911920	164.17	D, S	Cache River at a county road bridge, 4.5 miles west-northwest of Cotton Plant, Ark.

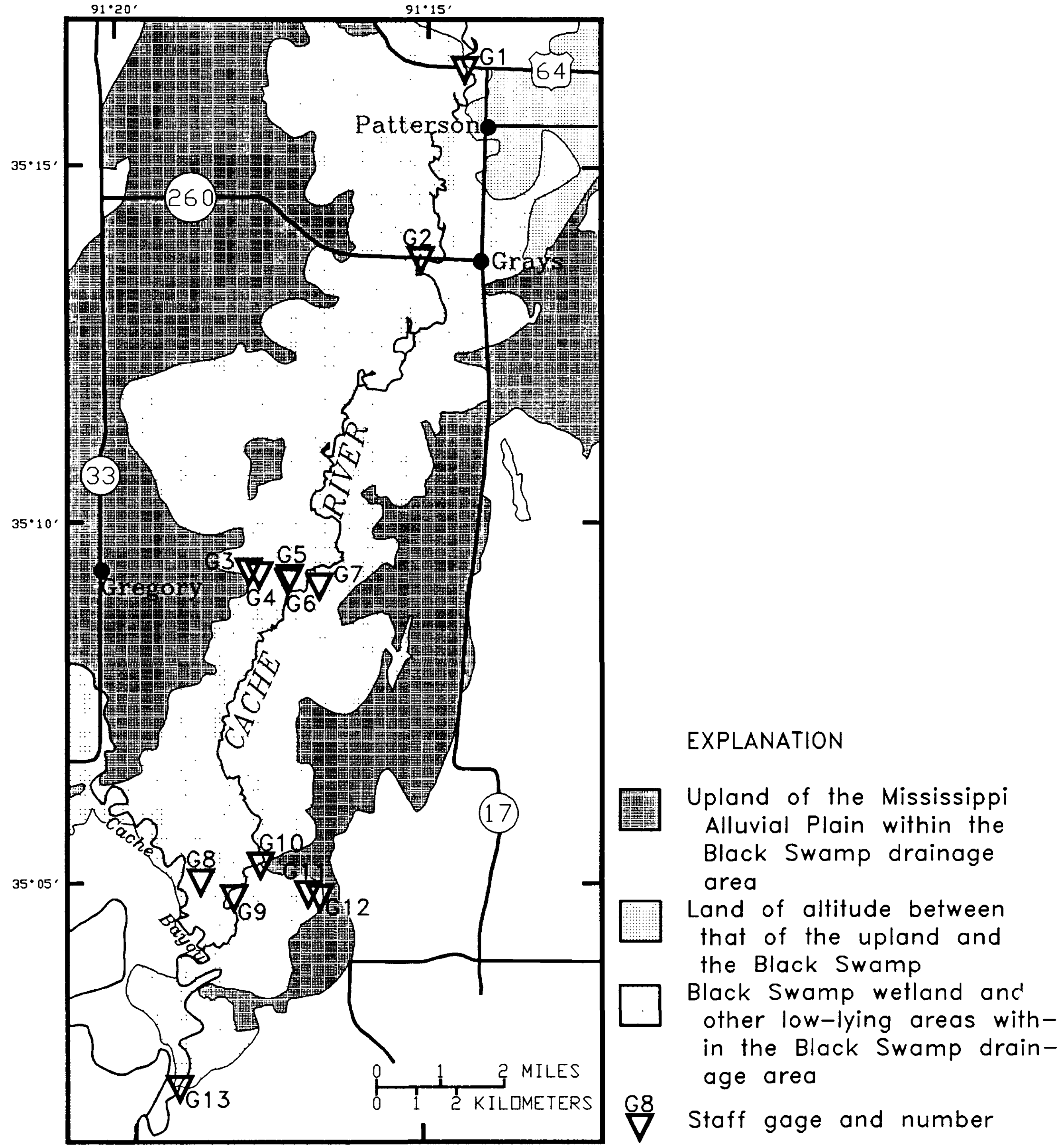
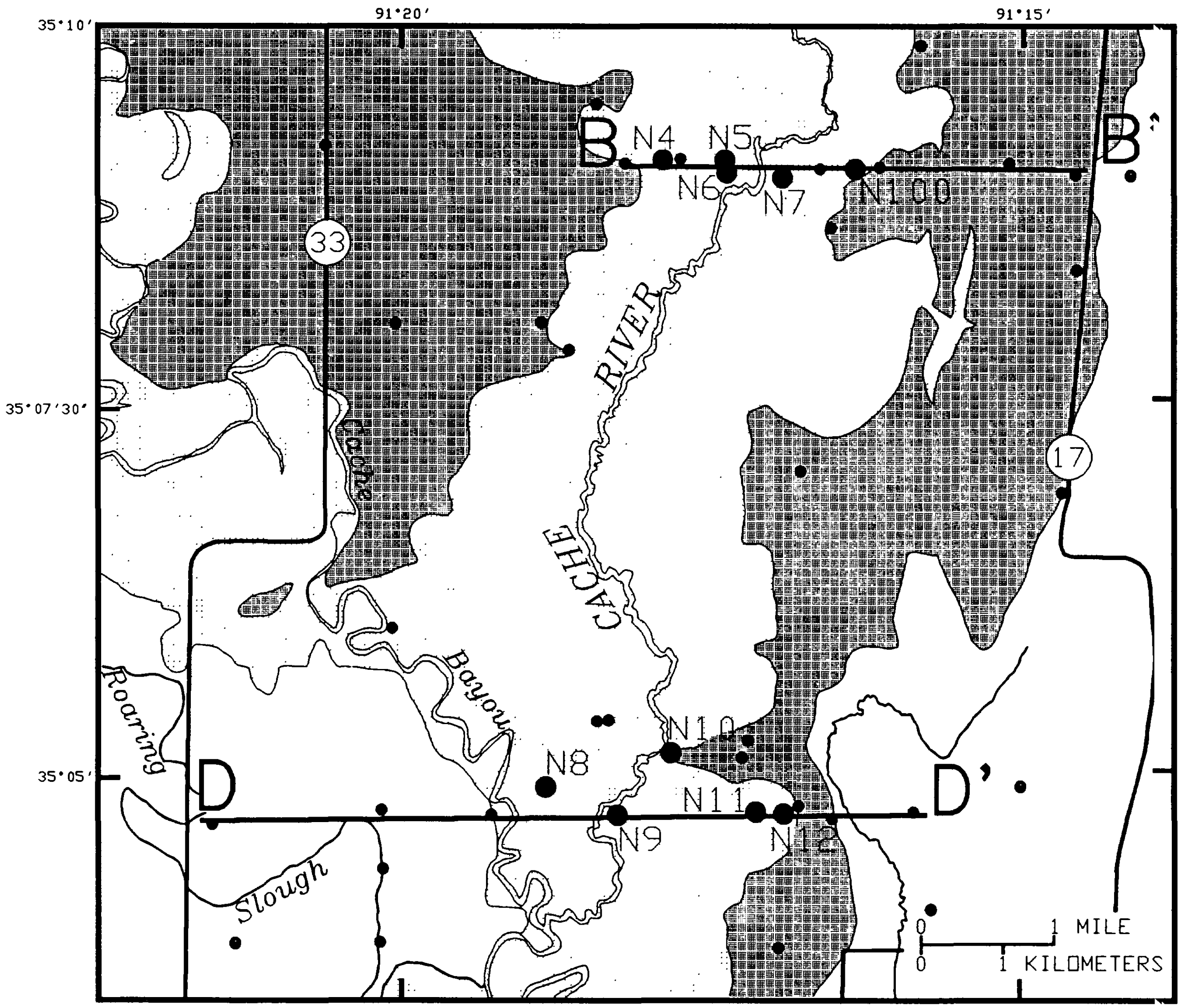


Figure 13. Location of staff gages.



EXPLANATION

Upland of the Mississippi Alluvial Plain within the Black Swamp drainage area

Black Swamp wetland and other low-lying areas within the Black Swamp drainage area

N8 Nested site and number

Well

Trace of transect

Figure 14. Location of nested sites and Transects B-B' and D-D'.

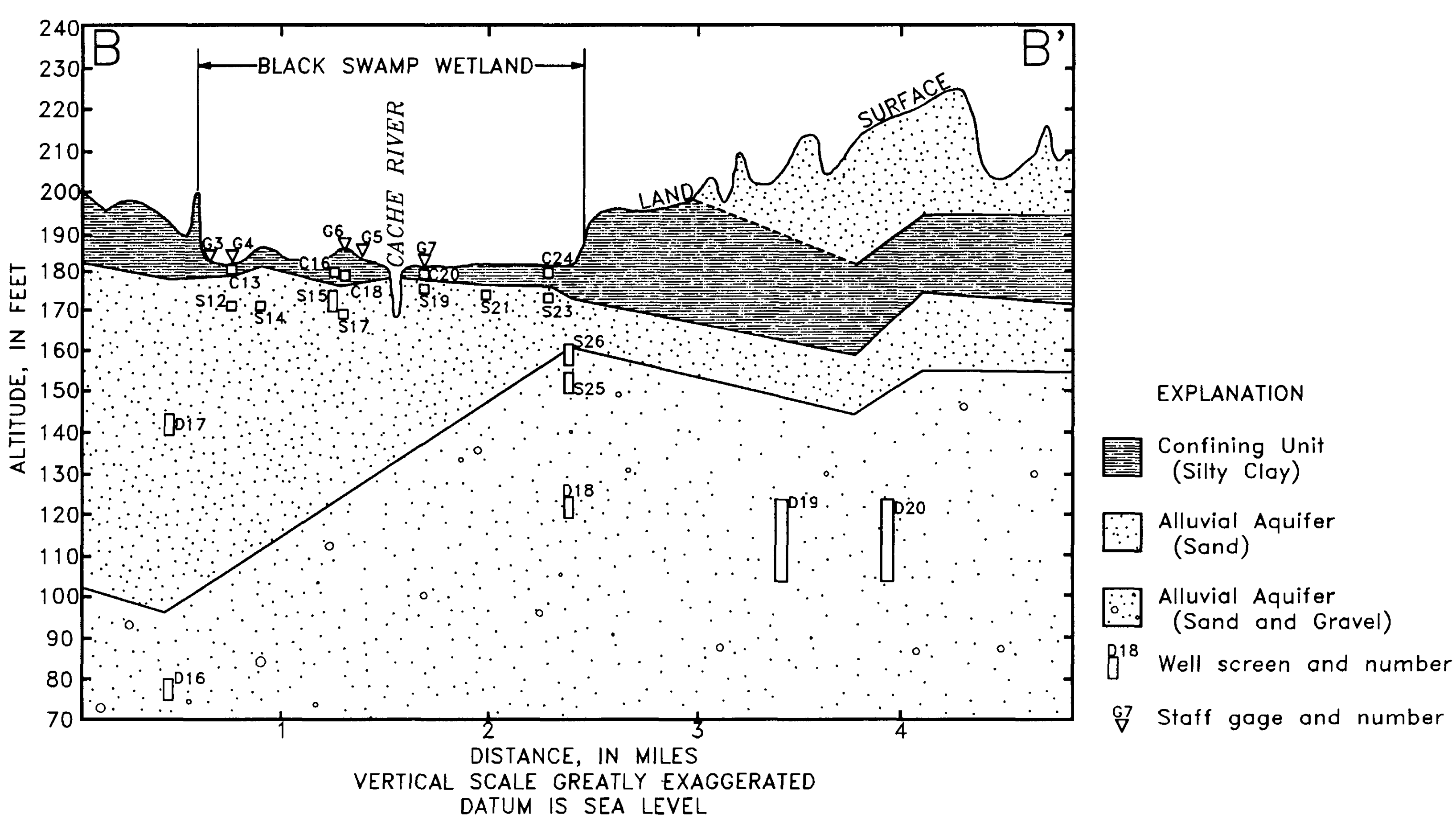


Figure 15. Location of well screens and staff gages along Transect B-B'.

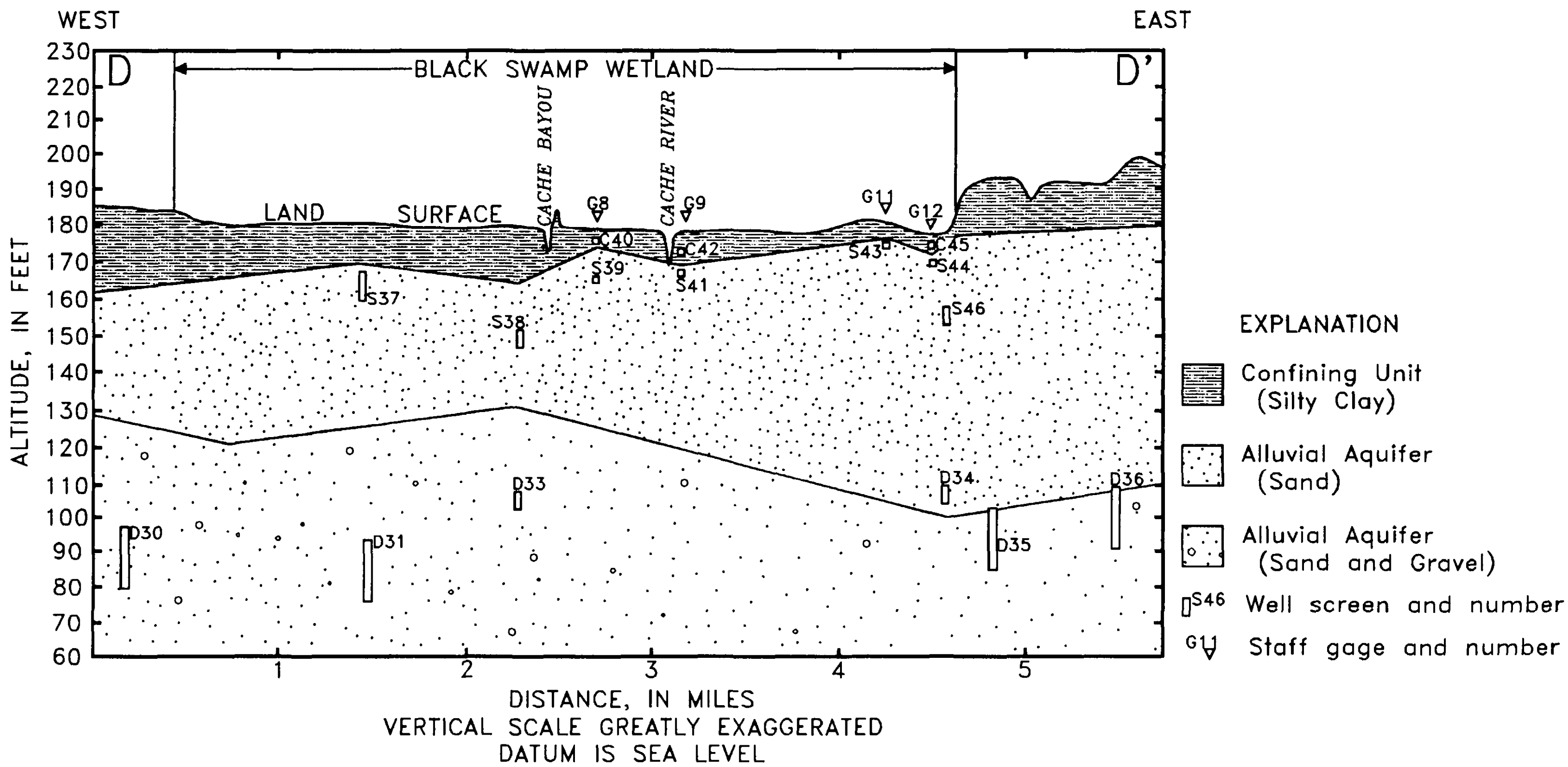


Figure 16. Location of well screens and staff gages along Transect D-D'.

Table 4. Description of nested sites used to study ground-water/surface-water interaction in Black Swamp

[wooded wetland, flooded 1 to 5 months per year (contains oak and bitter pecan); relatively high wooded wetland, flooded on average once per year; lower wooded wetland, almost always inundated with stagnant water (contains Bald Cypress and Tupelo Gum); poorly drained wooded wetland, sometimes inundated with stagnant water due to impoundments but not as low in altitude as lower wooded wetland; --, not available; upland of the alluvial plain, flooded on average once per 5 years]

Site name	Staff gage	Well open to the confining unit	Well open to the top of the alluvial aquifer	Hydrologic setting
N4	G4	C13	S12	Wells and staff gage in a wooded wetland.
N5	G5	C1	S15	Wells on relatively high wooded wetland. Staff gage at the end of a canal directly connected to the Cache River.
N6	G6	C18	S17	Wells and staff gage at the edge of lower wooded wetland.
N7	G7	C20	S19	Wells and staff gage in wooded wetland 720 feet from the Cache River bank. Continuous recorders installed.
N8	G8	C40	S39	Wells and staff gage in poorly drained wooded wetland.
N9	G9	C42	S41	Wells and staff gage in wooded wetland 180 feet from the Cache River bank. Continuous recorders installed.
N10	G10	--	S51	Well at the edge of the upland of the alluvial plain, Cache River bank at James Ferry. Staff gage at Cache River at James Ferry.
N11	G11	--	S43	Well in wooded wetland surrounded by lower wooded wetland. Staff gage at the edge of lower wooded wetland.
N12	G12	C45	S44	Wells and staff gage at the boundary between wooded wetland and lower wooded wetland.
N100	--	C24	S23	Wells in poorly drained wooded wetland.

when the nested sites were inundated. The second measurement of surface-water altitude outside the well casing was useful in cross-checking water-level measurements. Ground-water-flow study sites are centered at nested sites and include neighboring wells.

Continuous recorders were installed at nested sites N7 and N9. At each of these two nested sites, a 10 ft high platform was constructed. A waterproof box was mounted at the top of the platform and a 2-in. stilling well was mounted on the side of the platform. The waterproof box housed the battery, basic data recorder, and the pressure-transducer junction boxes. The stilling well had 2 ft of slotted casing just above the land surface and 8 ft of casing above the slotted casing and protected the transducer. The pressure transducers were operated for two periods: March 21, 1991, to August 9, 1991, and November 25, 1991, to October 9, 1992. A solar panel and voltage regulator were installed onto the battery near the end of the first period. Each pressure transducer has a range of 0 to 5 lb/in^2 and was connected to a vented cable that was used to correct variations in atmospheric pressure. The vented cables terminated in the waterproof box and were connected through a junction box to the basic data recorder (BDR) and power supply. The BDR was programed to instruct the transducers to make water-level measurements at a specified interval and to send the information to the BDR where the data were recorded and stored. Water-level-measurement frequency ranged from 30 minutes to 3 hours. Steel-tape water-level measurements were made at the two nested sites in order to calibrate pressure-transducer readings. Pressure transducer accuracy was about $\pm$ 0.05 ft during the first operating period and $\pm$ 0.0[illegible] ft during the second operating period. A more detailed discussion concerning pressure transducer accuracy was presented by Gonthier (1994). During visits, data were transferred from the BDR to a lap top computer. Visits were made, on average, every 14 days during the first operating period and every 18 days during the second operating period. Time between visits ranged from 4 days to 1 month.

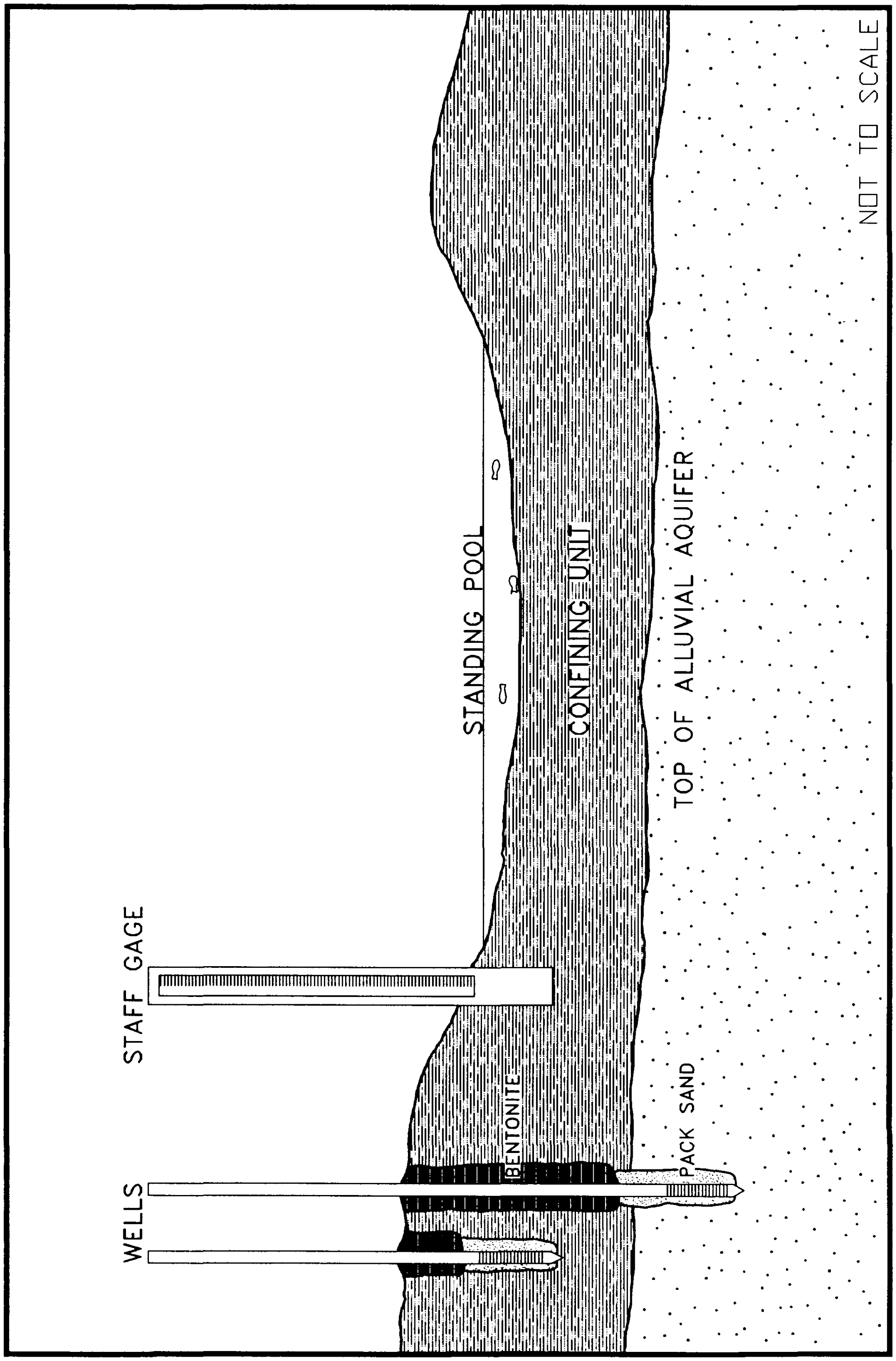


Figure 17. Diagram of a nested site.

GROUND-WATER FLOW PATTERNS

Ground-water and surface-water heads were used to interpret the ground-water flow patterns in the alluvial aquifer underlying the Black Swamp. The study of ground-water flow patterns included the study of ground-water/surface-water interaction.

Areal Head Distribution

Hydraulic heads (potentiometric levels) in the upper part of the alluvial aquifer generally were 10 to 12 ft higher in the northwestern part of the study area than in the southern part (fig. 18). The highest heads in the upper part of the alluvial aquifer were at the northernmost available wells, about 4 mi southwest of Patterson, Ark., and ranged from 187 to 192 ft above sea level. The lowest heads were at a shallow well about 1 mi west-southwest of the outflow gaging station and ranged from 172 to 179 ft above sea level.

The general distribution of horizontal head gradients in the upper part of the alluvial aquifer was similar for all months from September 1989 to July 1991. Flow in the upper part of the alluvial aquifer usually was toward the Cache River. Local variations in the head were apparent where there was a relatively high density of shallow wells. A cone of depression of the potentiometric surface in the southwestern part of the study area occurred in the upper part of the alluvial aquifer about one-fourth of the time.

Hydraulic heads in the lower part of the alluvial aquifer generally were 16 to 18 ft higher in the northwestern part of the study area than in the southern part of the study area and as much as 28 ft higher in the northwestern part of the study area than at a persistent cone of depression in the southwestern part of the study area (fig. 19). The highest heads in the lower part of the alluvial aquifer were 2 mi southeast of Augusta, Ark., in the northwesternmost available wells, and ranged from 190 to 196 ft above sea level. The lowest heads in the lower part of the alluvial aquifer were less than 1 mi west-northwest of the outflow gaging station and ranged from 161 to 171 ft above sea level.

The general distribution of horizontal head gradients in the lower part of the alluvial aquifer was similar for all months from September 1989 to July 1991. Flow in the lower part of the alluvial aquifer was similar to flow in the upper part of the alluvial aquifer and was from northwest to southeast for much of the study area. Ground water moved past the Cache River in the area of Nubbin Ridge and thence southeastward. Ground-water flow in the northern part of the study area near the Patterson gaging station usually was toward the Cache River. Flow in the southwestern part of the study area was toward the cone of depression west of the Cache River. Ground water appears to radially move away from the upland of the alluvial plain in the western and northwestern parts of the drainage area.

The cause of the cone of depression in the southwestern part of the study area is unknown. Reported pumpage in the area of the cone of depression is not greater than in any other area (fig. 20). Pumpage for 1991 (fig. 20) was similar to that for 1990 and 1992. Almost all pumpage locations in figure 20 represent irrigation wells (T.W. Holland, U.S. Geological Survey, oral commun., 1992). Pumpage at the cone of depression was less than pumpage about 4 mi to the northeast where there is no cone of depression (fig. 19). Differences in the lithology and aquifer characteristics of the southwestern part of the study area, in particular lower aquifer transmissivity, could contribute to a cone of depression. The large concentration of fine-grain sediment in abandoned meanders of Cache Bayou, Roaring Slough, and Little Clear Lake may create a barrier to horizontal flow. Pumpage near barriers to horizontal flow would likely lower water levels because of less than normal horizontal flow of ground water towards the area, thus creating a cone of depression. However, more lithologic data are needed to test this hypothesis.

Vertical Head Distribution

Hydraulic heads generally were higher along Transect B-B' than along Transect D-D'. Heads along Transect B-B' ranged from 175.8 ft above sea level in the lower part of the alluvial aquifer on the east end to 185.3 ft above sea level in the lower part of the alluvial aquifer on the west end. Heads along Transect B-B' in the upper part of the alluvial aquifer on the east end ranged from 178.8 to 185.1 ft above sea level, and on the west end ranged from 180.2 to 184.8 ft above sea level. Cache River stage at Transect B-B' ranged from 178.2 to 185.3 ft above sea level. Heads along Transect D-D' ranged from 172.6 ft above sea level in the lower part of the alluvial aquifer beneath Cache Bayou to 184.4 ft above sea level in the upper part of the alluvial aquifer near the Cache River. Cache River

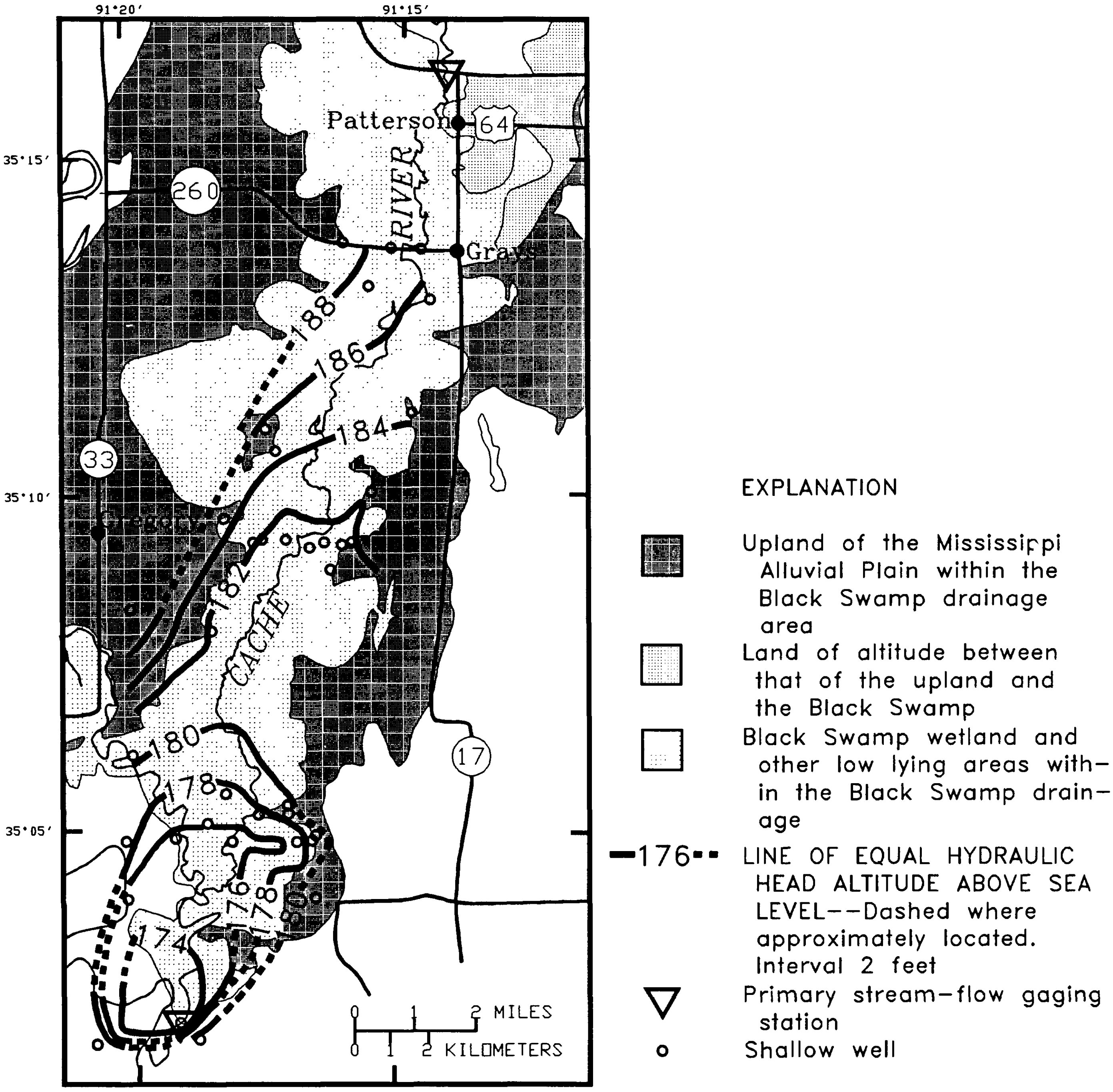
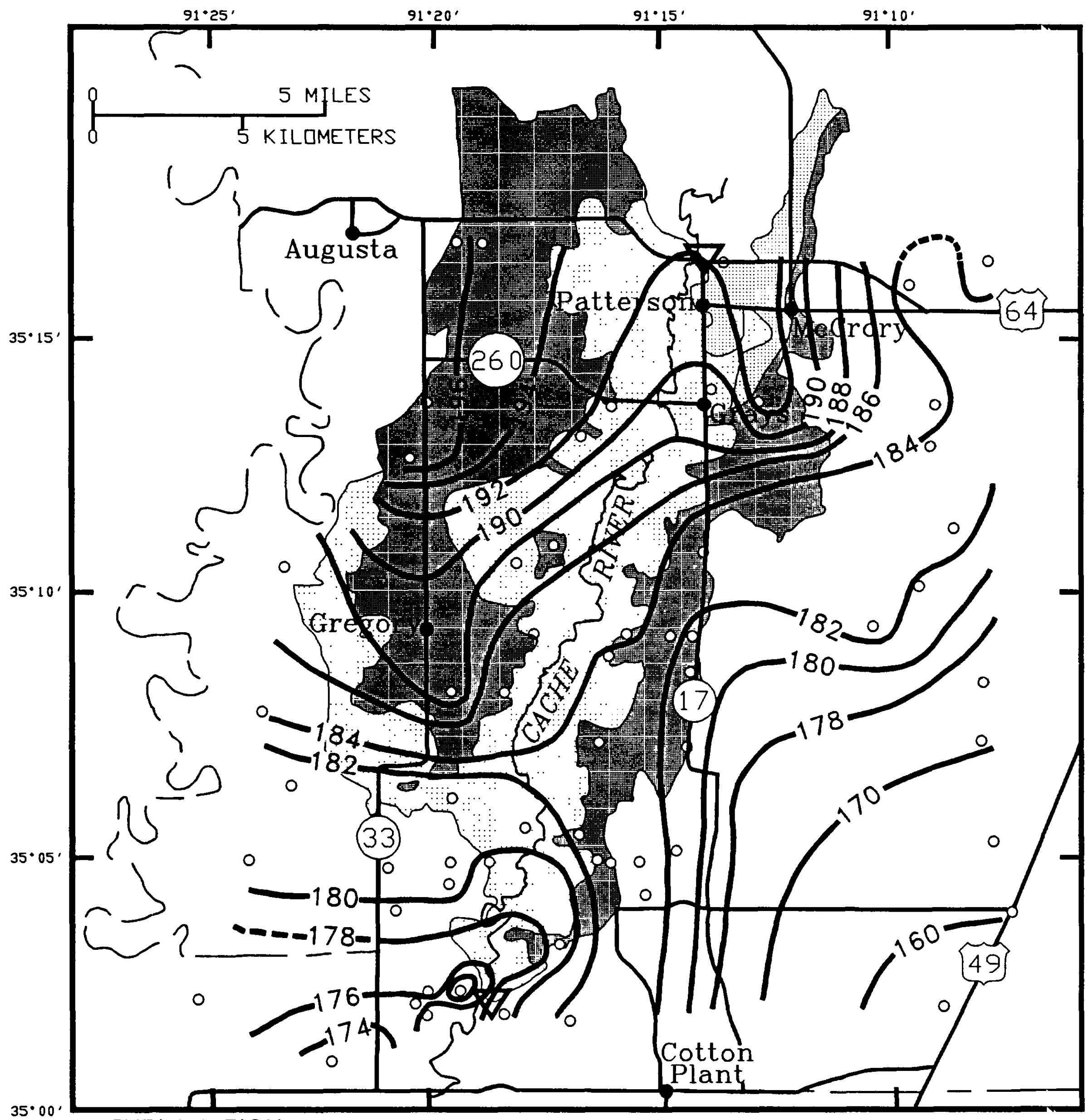


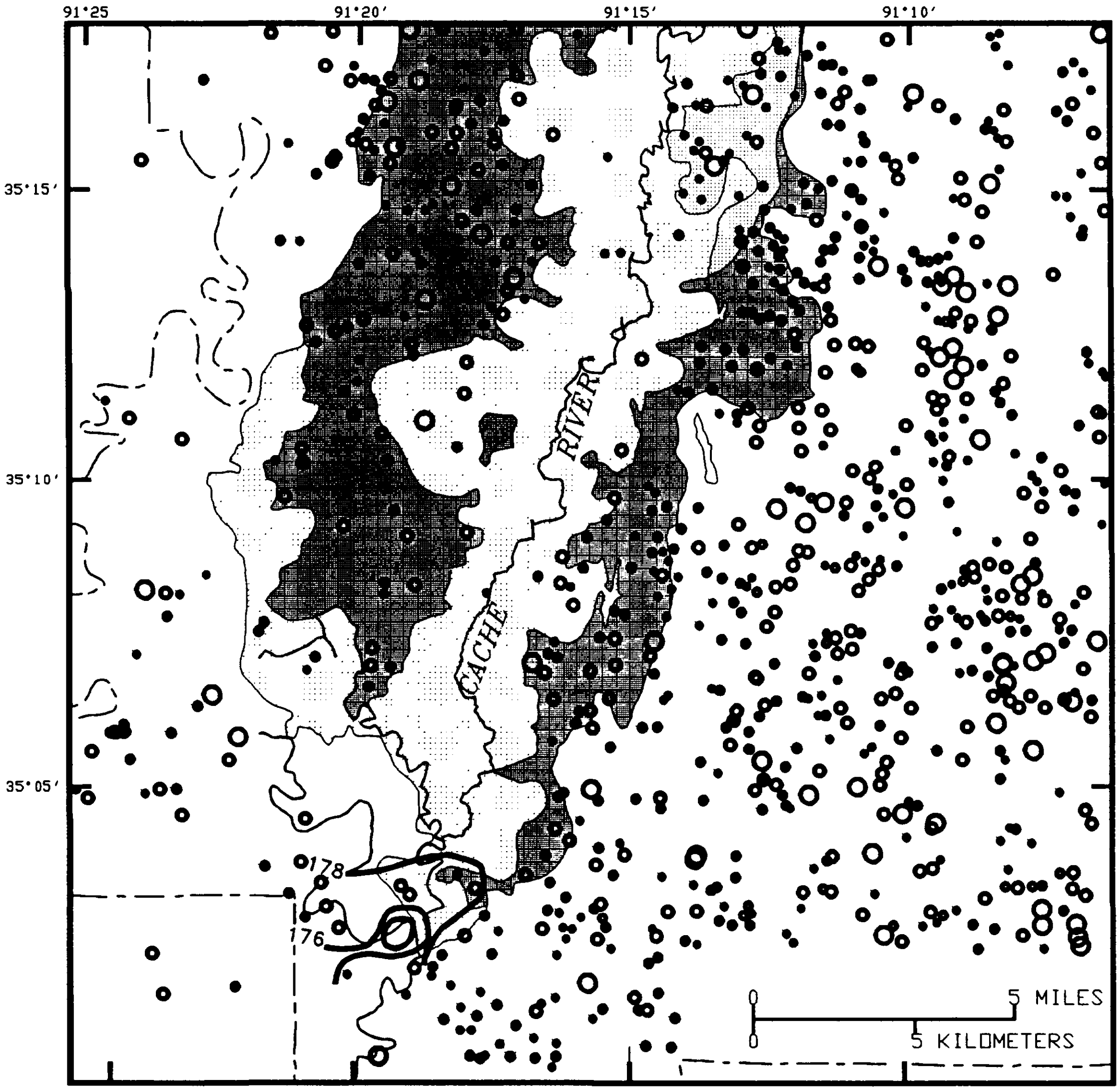
Figure 18. Hydraulic head in the upper part of the Mississippi River Valley alluvial aquifer, Black Swamp, July 8-12, 1991.



EXPLANATION

- Upland of the Mississippi Alluvial Plain within the Black Swamp drainage area
- Land of altitude between that of the upland and the Black Swamp
- Black Swamp wetland and other low lying areas within the Black Swamp drainage area
- —176-- LINE OF EQUAL HYDRAULIC HEAD ALTITUDE ABOVE SEA LEVEL--Dashed where approximately located. Interval, in feet, is variable
- ▽ Primary stream-flow gaging station
- o Deep well

Figure 19. Hydraulic head in the lower part of the Mississippi River Valley alluvial aquifer, Black Swamp, June 3-7, 1991.



EXPLANATION

Upland of the Mississippi Alluvial plain within the Black Swamp drainage area

Land of altitude between that of the upland and the Black Swamp

Black Swamp wetland and other low-lying areas within the Black Swamp drainage area

Line of equal hydraulic head in the lower part of the alluvial aquifer near the cone of depression in the southern part of the study area

Pumpage from the alluvial aquifer, 1991 (in acre-feet)

- Less than 100
- 100 to 200
- 200 to 400
- Greater than 400

Figure 20. Location of ground-water pumpage points during 1991 compared to the location of the cone of depression during June 3-7, 1991, Mississippi River Valley alluvial aquifer, Black Swamp.

stage at Transect D-D' ranged from 174.3 to 183.8 ft above sea level.

Vertical head gradients near land surface along Transects B-B' and D-D' changed orientation often from December 1989 to September 1992 (figs. 21-26). Orientation of head gradients generally was either downward from the Cache River and wetland to the lower part of the alluvial aquifer or upward from the lower part of the alluvial aquifer to the Cache River and wetland. Generally, ground-water flow in May 1990 was from the lower part of the alluvial aquifer towards the Cache River (figs. 21 and 22) when the Cache River was receding following a 4-month flood. General flow from the lower part of the alluvial aquifer towards the Cache River occurred 25 out of 35 times during measurement along Transect B-B' and 4 out of 34 times during measurement along Transect D-D'. Generally, ground-water flow in October 1990 was down from the wetland and the Cache River to the lower part of the alluvial aquifer (figs. 23 and 24) after a dry summer and during a flood on the Cache River. General flow from the Cache River and wetland towards the lower part of the alluvial aquifer occurred 5 out of 35 times during measurement along Transect B-B' and 17 out of 34 times during measurement along Transect D-D'. Generally along Transect B-B', ground-water flow in September 1991 was up towards the Cache River on the west side and down away from the Cache River on the east side (fig. 25). Along Transect B-B' general flow was up towards the Cache River on the west side and down away from the Cache River on the east side during 5 of 35 times of measurement; along Transect D-D' general flow was up towards the Cache River on the east side and down away from the Cache River on the west side during 13 out of 34 times of measurement. General ground-water flow conditions often were not the same for both transects. During September 1991 general ground-water flow along Transect D-D' was away from the Cache River and toward the lower part of the alluvial aquifer west of Cache Bayou (fig. 26).

Ground water seeped onto the wetland surface at the ground-water-flow study sites, on the average, 31 percent of the time when hydraulic head increased from the surface to the lower part of the alluvial aquifer (table 5). Ground water seeped onto the wetland surface at the ground-water-flow study sites along Transects B-B' and D-D', on the average, 32 and 30 percent of the time, respectively. An example of ground-water seepage to the surface in May 1990 on the east side of the wetland along both Transects B-B' and D-D' is indicated in figures 21 and 22, respectively where water levels in wells generally increased with increasing depth from the confining unit into the alluvial aquifer. The greatest number of ground-water flow study sites, in the wetland, to have ground water seeping to the surface at the same time was seven (78 percent) during the measurement time in May 1992. Ground water seeped into the wetland at all four ground-water-flow study sites along Transect B-B' during the measurement times in August 1991 and May 1992. Ground-water seepage occurred more often into the Cache River channel than onto the surface of the surrounding wetland.

Ground water seeped to the ground-water-flow study sites in the Cache River channel, on the average, 58 percent of the time when hydraulic head increased with distance from the river (table 6). Ground water seeped into the channel at the two transects most during the month of May. Ground-water seeped to the ground-water-flow study sites in the Cache River channel at Transects B-B' and D-D', on the average, 71 and 44 percent of the time, respectively. An example of ground-water seepage in May 1990 into the Cache River channel along Transect B-B' is indicated in figure 21 where water levels in wells generally increased with distance from the river.

Surface water seeped into the ground at the ground-water-flow study sites in the wetland along both Transects B-B' and D-D', on the average, 67 percent of the time when hydraulic head decreased from the surface to the lower part of the alluvial aquifer (table 5). An example of surface-water seepage into the ground in October 1990 along both Transects B-B' and D-D' is indicated in figures 23 and 24 where water levels in wells decrease with increasing depth from the confining unit into the alluvial aquifer. The greatest number of ground-water-flow study sites, in the wetland, that had surface water seeping into the ground at the same time was all nine (100 percent) during the measurement time in October 1990. Surface water seeped into the ground at all four ground-water-flow study sites along Transect B-B' 7 out of 35 times during measurement, and most often occurred during the month of November. Surface water seeped into the ground at all five ground-water-flow study sites along Transect D-D' 12 out of 34 times during measurement, and most often occurred during the month of December. Months with the least surface-water seepage into the ground are the same months with the most ground-

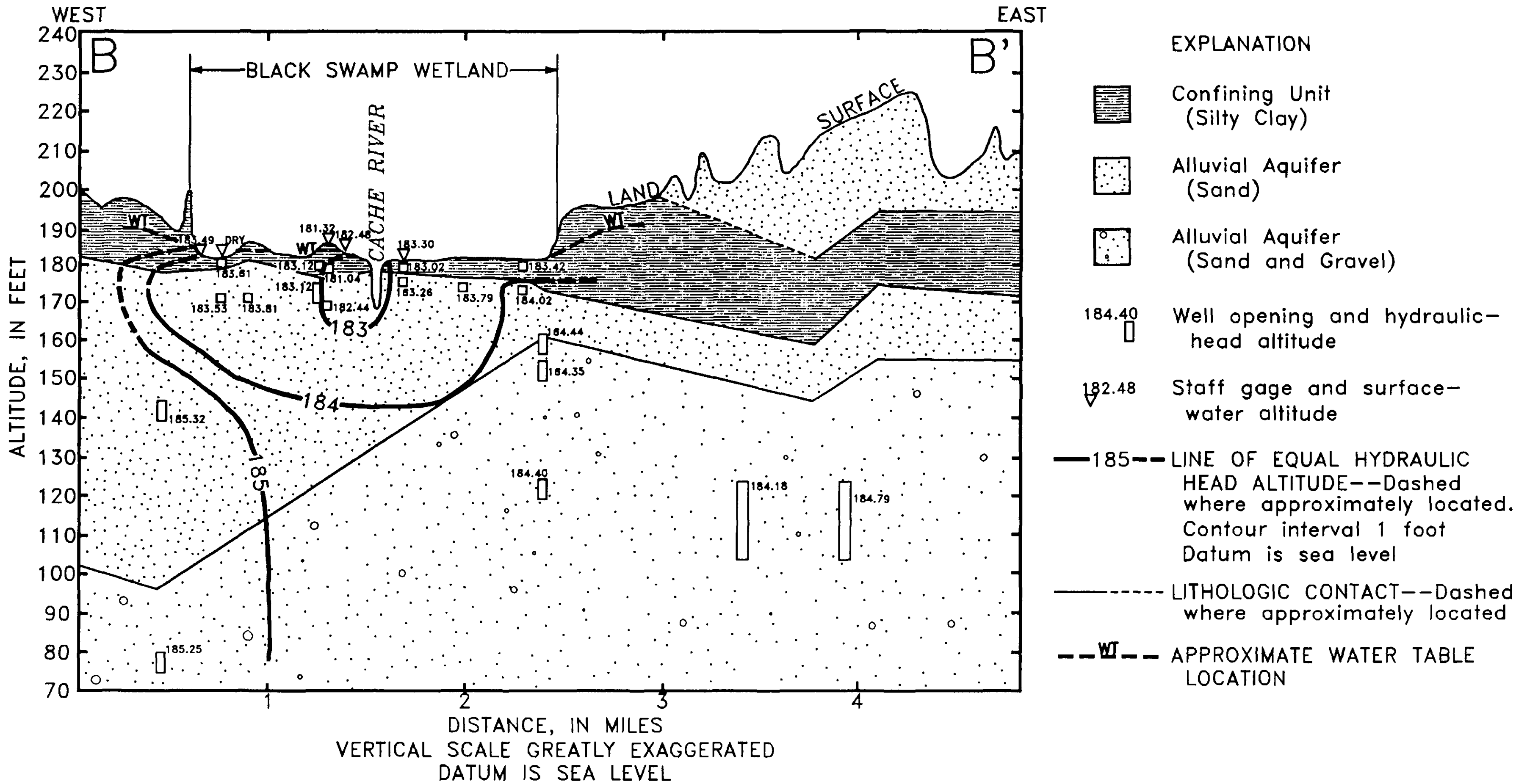


Figure 21. Transect B-B' through Black Swamp showing vertical head distribution after a 4-month flood, May 21-25, 1990.

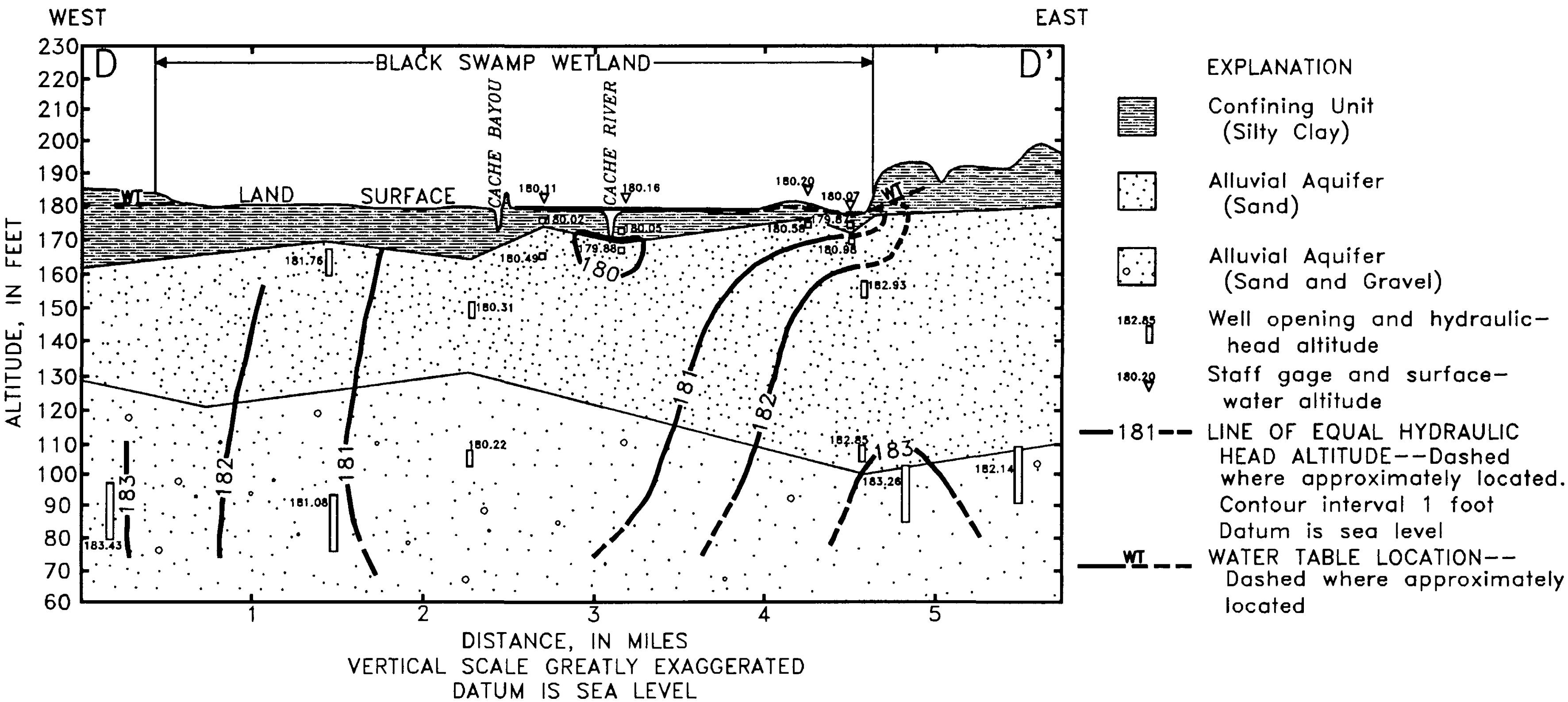


Figure 22. Transect D-D' through Black Swamp showing vertical head distribution after a 4-month flood, May 21-25, 1990.

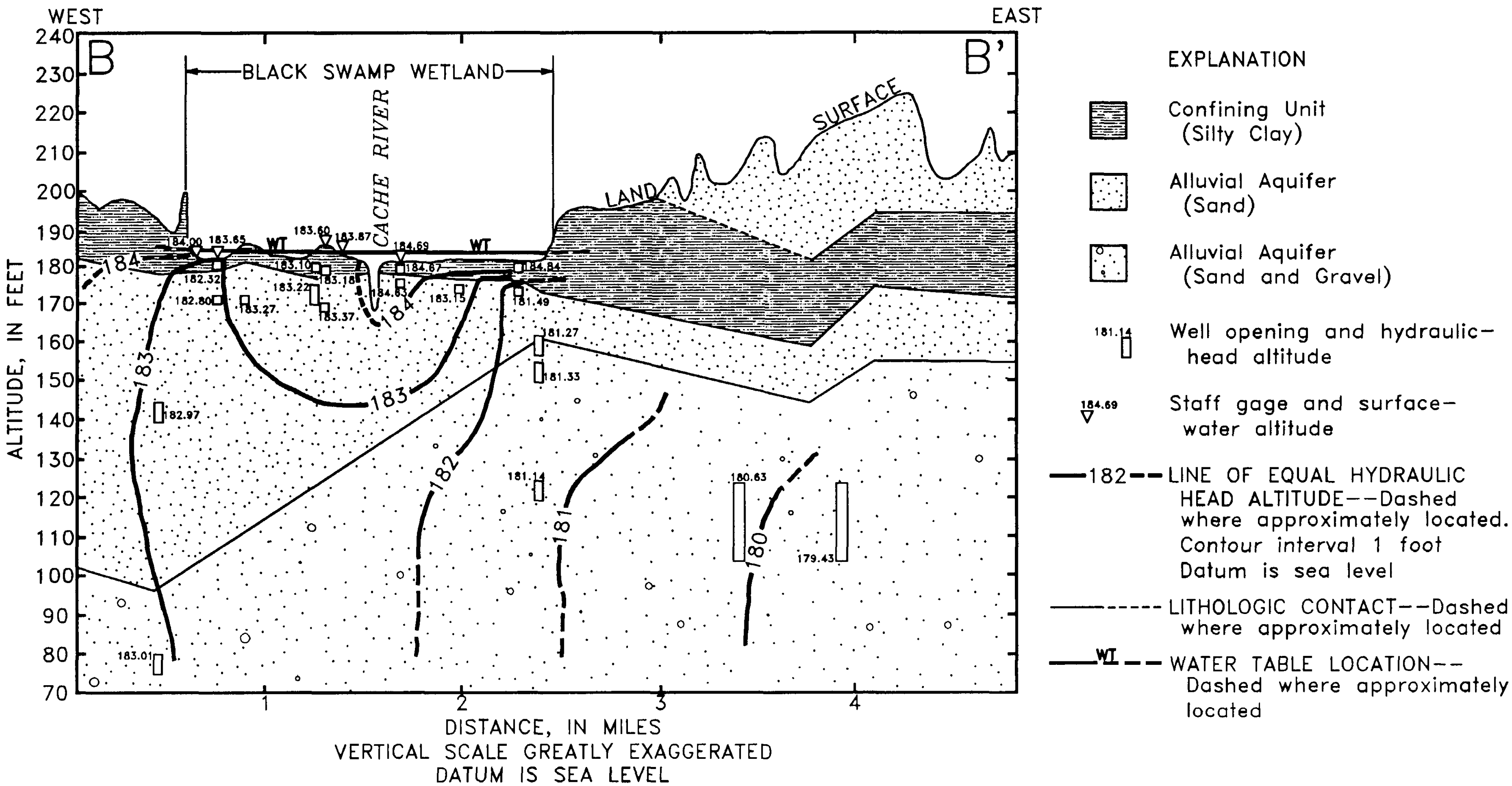


Figure 23. Transect B-B' through Black Swamp showing vertical head distribution during a flood after a dry summer season, October 15-19, 1990.

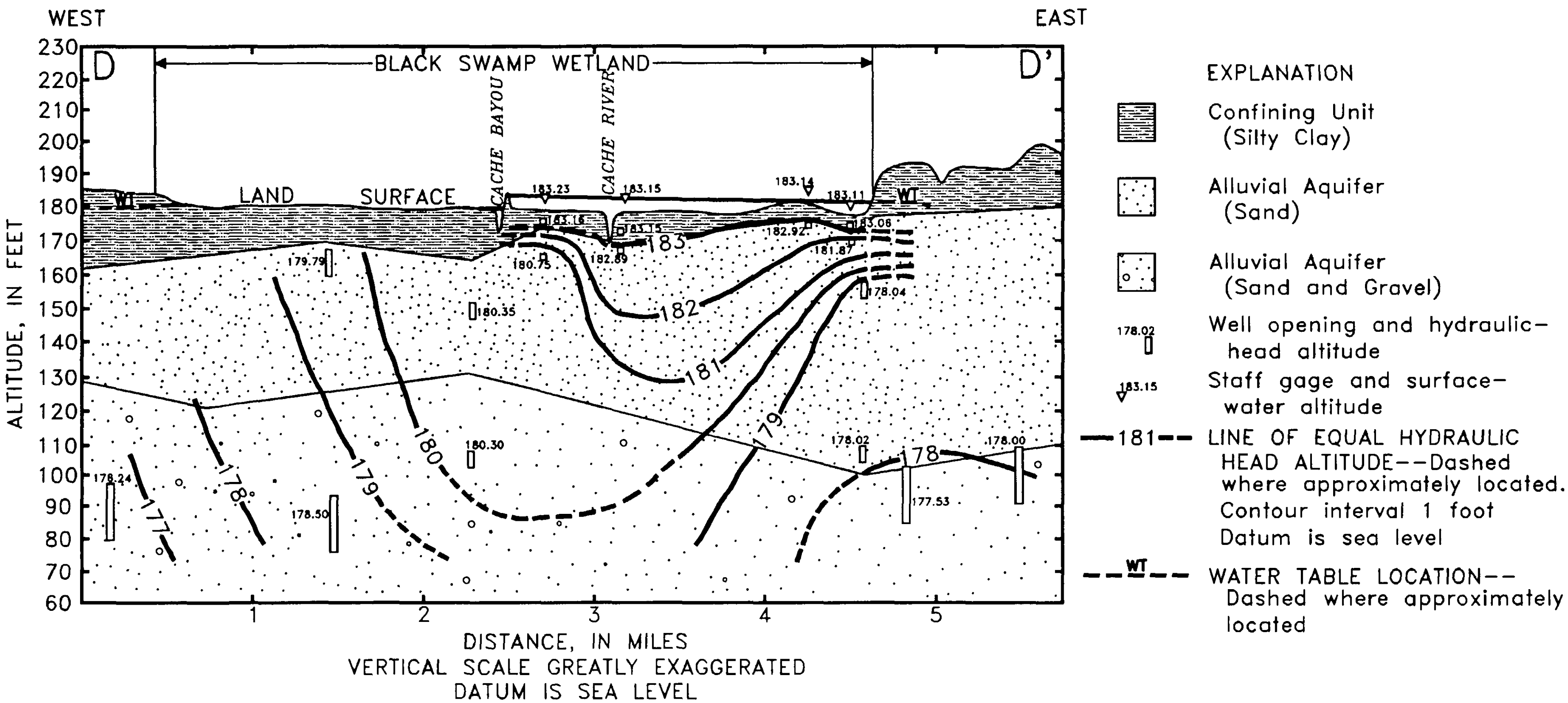


Figure 24. Transect D-D' through Black Swamp showing vertical head distribution during a flood after a dry summer season, October 15-19, 1990.

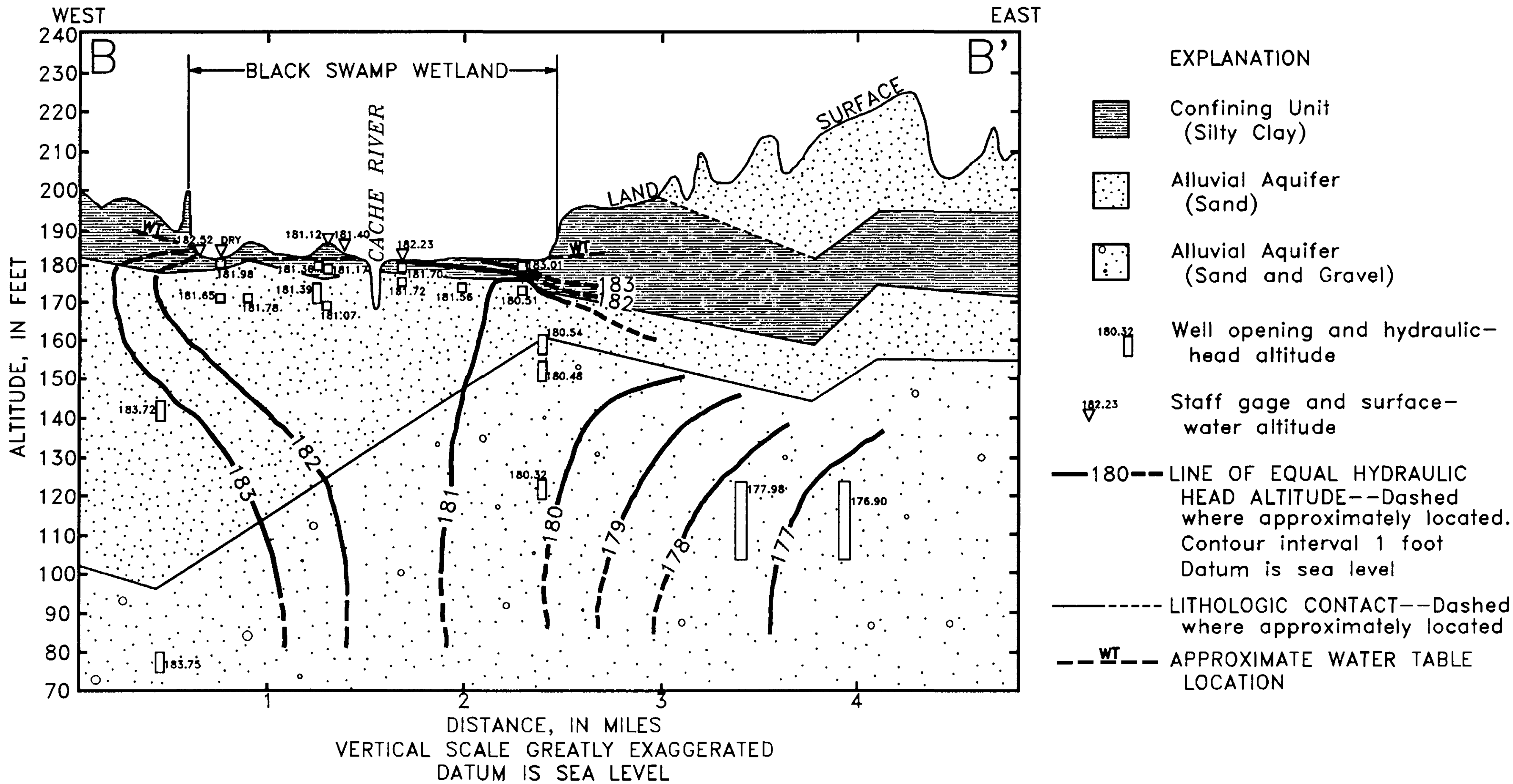


Figure 25. Transect B-B' through Black Swamp showing vertical head distribution, September 9-13, 1991.

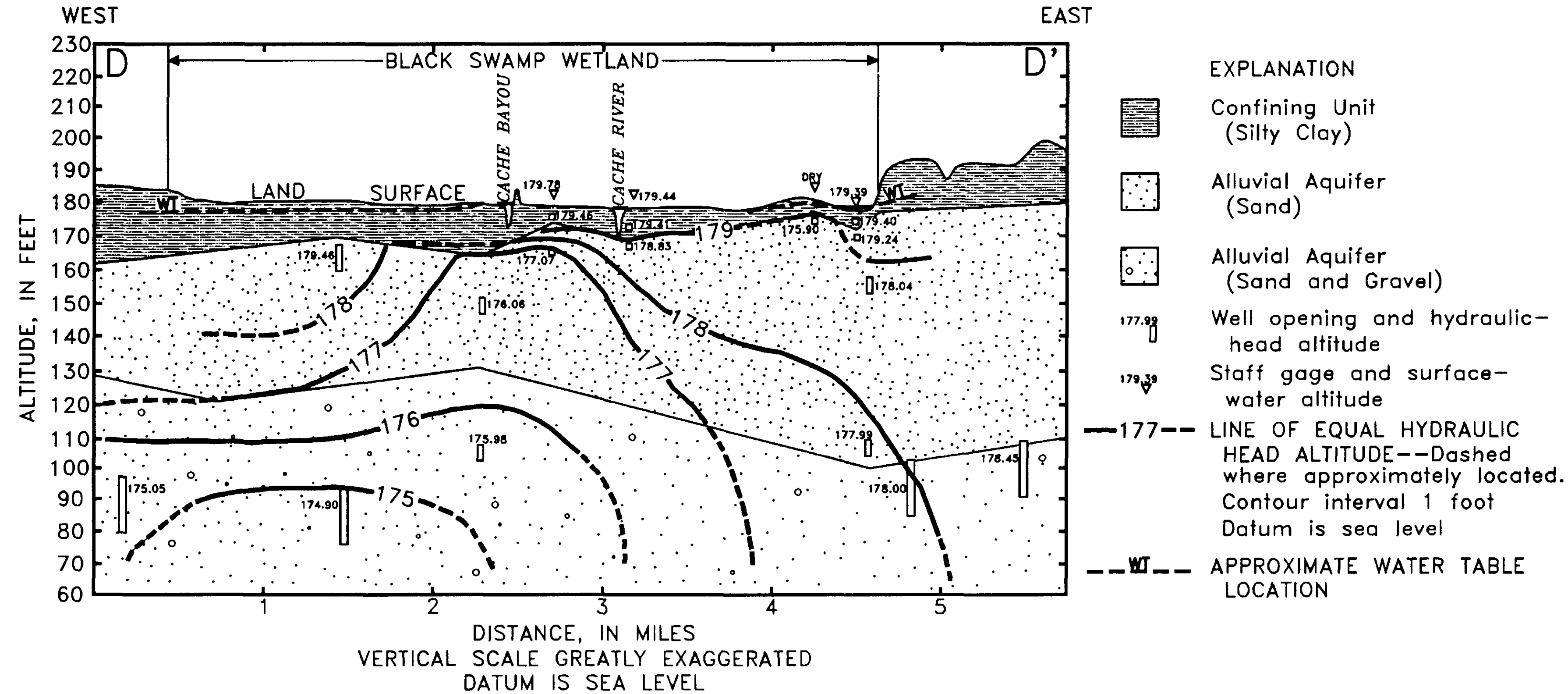


Figure 26. Transect D-D' through Black Swamp showing vertical head distribution, September 9-13, 1991.

Table 5. Percentage of available ground-water flow study sites in the wetland that had ground-water seepage to the surface (discharge) and surface-water seepage into the ground (recharge) during December 1989 to September 1992

[N, maximum number of ground-water flow study sites in the wetland along the transect; Discharge, ground-water seepage onto the wetland surface; Recharge, surface-water seepage down into the ground; Other, no vertical ground-water flow; *, N = 4 for Transect D-D'; --, N = 0 for Transect D-D']

Date	Transect B-B' (N = 4)			Transect D-D' (N = 5)			Both transects (N = 9)		
	Discharge	Recharge	Other	Discharge	Recharge	Other	Discharge	Recharge	Other
December 11-15, 1989	25	75	0	0	100	0	11	89	0
January 15-19, 1990*	25	75	0	0	100	0	13	87	0
January 22-26, 1990	50	50	0	0	100	0	22	78	0
February 12-16, 1990	25	75	0	0	100	0	11	89	0
March 12-16, 1990	25	75	0	0	100	0	11	89	0
April 23-27, 1990	50	50	0	40	60	0	44	56	0
May 21-25, 1990	50	50	0	80	20	0	67	33	0
June 18-22, 1990	25	75	0	40	60	0	33	67	0
July 16-20, 1990	0	100	0	60	40	0	33	67	0
August 20-24, 1990*	50	25	25	25	75	0	37	50	13
September 10-14, 1990	50	50	0	0	100	0	25	75	0
October 15-19, 1990	0	100	0	0	100	0	0	100	0
November 5-9, 1990	0	100	0	20	80	0	11	89	0
December 3-7, 1990	25	75	0	0	100	0	11	89	0
January 28-31, 1991	50	25	25	0	100	0	22	67	11
March 4-8, 1991	25	75	0	40	60	0	33	67	0
April 8-12, 1991	25	75	0	20	80	0	22	78	0
May 13-17, 1991*	50	50	0	75	25	0	63	37	0
June 3-7, 1991	50	50	0	40	60	0	44	56	0
July 8-12, 1991	50	50	0	60	40	0	56	44	0
August 12-16, 1991	100	0	0	0	100	0	44	56	0
September 9-13, 1991	50	50	0	20	80	0	33	67	0
October 28-31, 1991	25	75	0	20	80	0	22	78	0
November 4, 1991	25	75	0	--	--	--	--	--	--
November 18-22, 1991	0	100	0	0	100	0	0	100	0
December 16-20, 1991	25	75	0	0	100	0	11	89	0
January 6-10, 1992	25	75	0	60	40	0	44	56	0
February 10-14, 1992	0	100	0	20	80	0	11	89	0
March 9-13, 1992	0	100	0	80	20	0	44	56	0
April 6-10, 1992	25	75	0	60	40	0	44	56	0
May 4-8, 1992	100	0	0	60	40	0	78	22	0
June 8-10, 1992	25	75	0	60	40	0	44	56	0
July 13-17, 1992*	50	50	0	25	75	0	37	63	0
August 23-25, 1992	0	100	0	60	40	0	33	67	0
September 20-23, 1992	25	75	0	40	60	0	33	67	0
Average	32	67	1	30	67	3	31	67	2

Table 6. Ground-water seepage into the Cache River channel (discharge) and surface-water seepage down into bed of the Cache River (recharge) at Transects B-B' and D-D', and the percentage of the two ground-water flow study sites in the Cache River channel under ground-water discharge and recharge conditions during December 1989 to September 1992

[N, maximum number of ground-water flow study sites in the Cache River channel along the transect; Discharge, ground-water seepage into the Cache river; Recharge, surface-water seepage down into the bed of the Cache River; Other, ground water seeps out one bank of the Cache River while surface water seeps into the opposite bank; yes, ground-water flow condition is present; no, ground-water flow condition is absent; --, N = 0 for Transect D-D']

Date	Channel at Transect B-B' (N=1)			Channel at Transect D-D' (N=1)			Channel at both transects (N=2)		
	Discharge	Recharge	Other	Discharge	Recharge	Other	Discharge	Recharge	Other
December 11-15, 1989	yes	no	no	yes	no	no	100	0	0
January 15-19, 1990	yes	no	no	no	yes	no	50	50	0
January 22-26, 1990	no	no	yes	no	yes	no	0	50	50
February 12-16, 1990	no	yes	no	no	yes	no	0	100	0
March 12-16, 1990	yes	no	no	no	yes	no	50	50	0
April 23-27, 1990	yes	no	no	no	yes	no	50	50	0
May 21-25, 1990	yes	no	no	yes	no	no	100	0	0
June 18-22, 1990	yes	no	no	yes	no	no	100	0	0
July 16-20, 1990	yes	no	no	no	no	yes	50	0	50
August 20-24, 1990	no	yes	no	no	yes	no	0	100	0
September 10-14, 1990	no	no	yes	no	yes	no	0	50	50
October 15-19, 1990	no	yes	no	no	yes	no	0	100	0
November 5-9, 1990	yes	no	no	yes	no	no	100	0	0
December 3-7, 1990	yes	no	no	no	yes	no	50	50	0
January 28-31, 1991	no	yes	no	no	yes	no	0	100	0
March 4-8, 1991	yes	no	no	yes	no	no	100	0	0
April 8-12, 1991	yes	no	no	no	yes	no	50	50	0
May 13-17, 1991	yes	no	no	yes	no	no	100	0	0
June 3-7, 1991	yes	no	no	yes	no	no	100	0	0
July 8-12, 1991	yes	no	no	yes	no	no	100	0	0
August 12-16, 1991	no	no	yes	no	yes	no	0	50	50
September 9-13, 1991	no	no	yes	no	yes	no	0	50	50
October 28-31, 1991	yes	no	no	no	yes	no	50	50	0
November 4, 1991	no	yes	no	--	--	--	--	--	--
November 18-22, 1991	yes	no	no	no	yes	no	50	50	0
December 16-20, 1991	yes	no	no	no	yes	no	50	50	0
January 6-10, 1992	yes	no	no	yes	no	no	100	0	0
February 10-14, 1992	yes	no	no	yes	no	no	100	0	0
March 9-13, 1992	yes	no	no	yes	no	no	100	0	0
April 6-10, 1992	yes	no	no	yes	no	no	100	0	0

Table 6. Ground-water seepage into the Cache River channel (discharge) and surface-water seepage down into bed of the Cache River (recharge) at Transects B-B' and D-D', and the percentage of the two ground-water flow study sites in the Cache River channel under ground-water discharge and recharge conditions during December 1989 to September 1992--Continued

[N, maximum number of ground-water flow study sites in the Cache River channel along the transect; Discharge, ground-water seepage into the Cache river; Recharge, surface-water seepage down into the bed of the Cache River; Other, ground water seeps out one bank of the Cache River while surface water seeps into the opposite bank; yes, ground-water flow condition is present; no, ground-water flow condition is absent; --, N = 0 for Transect D-D']

Date	Channel at Transect B-B' (N=1)			Channel at Transect D-D' (N=1)			Channel at both transects (N=2)		
	Discharge	Recharge	Other	Discharge	Recharge	Other	Discharge	Recharge	Other
May 4-8, 1992	yes	no	no	yes	no	no	100	0	0
June 8-10, 1992	yes	no	no	no	yes	no	50	50	0
July 13-17, 1992	no	yes	no	no	yes	no	0	100	0
August 23-25, 1992	yes	no	no	yes	no	no	100	0	0
September 20-23, 1992	yes	no	no	yes	no	no	100	0	0
Total (percent)	71	17	12	44	53	3	58	35	7

water seepage to the surface. Downward surface-water seepage occurred less often into the bed of the Cache River than into the wetland surface.

Surface water seeped at the ground-water-flow study sites into the bed of the Cache River channel, on the average, 35 percent of the time when hydraulic head decreased with distance from the river (table 6). Surface water seeped into the bed of the Cache River at the two transects most during the months of August and October. Surface water seeped into the bed of the Cache River at Transects B-B' and D-D', on the average, 17 and 53 percent of the time, respectively. An example of surface-water seepage into the bed of the Cache River along Transect B-B' and Transect D-D' occurred in October 1990 and is indicated in figures 23 and 24 where water levels in wells generally decreased with increasing distance from the river.

Surface water seeped into one bank of the Cache River while ground water simultaneously seeped to the surface of the other bank of the Cache River during 5 of the 69 measurements (7 percent). Simultaneously opposing seepage directions on the banks of the Cache River occurred four out of the five times in late summer.

Surface water that seeped down into the ground at the ground-water-flow study sites in the wetland then flowed toward the Cache River or the lower part of the alluvial aquifer. Water that seeped through the wetland confining unit on Transect B-B' most often flowed toward the Cache River, whereas water that seeped through the wetland confining unit on Transect D-D' most often continued down toward the lower part of the alluvial aquifer. Water seeped through the wetland confining unit and then flowed toward the Cache River 28 percent of the time on both Transects B-B' and D-D' or 49 and 10 percent of the time along Transects B-B' and D-D', respectively. Simultaneous surface-water seepage into the wetland surface and ground-water seepage to the east bank of the Cache River on Transect B-B' occurred May 1990 (fig. 21) when wetland surface-water levels were higher than heads in the upper part of the alluvial aquifer, which were higher than water levels in the Cache River. Surface water seeped into the ground at the ground-water-flow study sites and continued downward toward the lower part of the alluvial aquifer 39 percent of the time on both Transects B-B' and D-D' or 18 and 57 percent of the time along Transects B-B' and D-D', respectively. An example of surface-water seepage from the wetland surface to the lower part of the alluvial aquifer on the east side of the wetland on Transect B-B' occurred October 1990 and is indicated in figure 23.

Ground-water flow in the lower part of the alluvial aquifer along both transects was horizontal. Along Transect B-B', ground-water flow in the lower part of the alluvial aquifer was from the west to the east for all 35 measurement times. Along Transect D-D', ground-water flow in the lower part of the alluvial aquifer was toward a zone of convergence (a location of minimum head along the transect) located west of the Cache River (figs. 22 and 26). In October 1990, this zone of convergence likely was west of the study area. In

November and December 1991, this zone of convergence subsided. A zone of divergence (a location of maximum head along the transect) formed east of the Cache River along Transect D-D' during 14 of about 30 months (data for that part of Transect D-D' are available for 30 months) causing ground-water flow in the eastern part of Transect D-D' to move east instead of west toward the zone of convergence (fig. 22). The changes in flow direction along Transect D-D' are suspected to be caused by pumpage in the alluvial aquifer and to some extent by fluctuations in Cache River stage. The zone of convergence west of the Cache River is suspected to be the intersection of Transect D-D' with the cone of depression (fig. 19).

Ground-Water/Surface-Water Interaction

A hydraulic connection between the surface water in Black Swamp or the Cache River and the alluvial aquifer is indicated by simultaneous and nearly equal changes in surface-water and ground-water levels near the Black Swamp wetland. Wells screened just beneath the confining unit in the wetland had water-level fluctuations that were similar to stage fluctuations of the Cache River (fig. 27). Well S41 (fig. 27) is only 170 ft east of the Cache River and had water-level fluctuations that corresponded closely with changes in stage during floods and low flows. Because of the proximity of well S41 to the Cache River, the water level in the well may be responding with stage fluctuations directly through the bed of the Cache River or through the confining unit. Well S44 (fig. 28) also is in the wetland but is about 1.3 mi from the Cache River. Because of the large distance of well S44 from the Cache River, the water level well S44 should be responding more to stage fluctuations through the confining unit than the water level in well S41. Water-level changes in well S44 corresponded closely to stage fluctuations of the Cache River during floods but water levels did not decline much below the land surface during low flow on the Cache River. Shallow wells screened in the confining unit (C42 and C45) (figs. 29 and 30) had water-level fluctuations similar to those of adjacent wells (S41 and S44, respectively).

Wells screened in the lower part of the alluvial aquifer and near the Cache River had water-level changes that corresponded similarly to changes in stage of the Cache River (fig. 31) except during the growing season when water levels drew down in response to pumpage. Water-level fluctuations in deep wells farther than about 2.5 mi from the Cache River were not very similar to stage fluctuations of the Cache River. Water-level fluctuations in deep wells were smaller and occurred later than stage fluctuations of the Cache River as distance from the well to the river increased. Rapid decreases in water levels in deep wells likely were caused by nearby pumpage. Well S48 is the deepest well (32.3 ft) that is close (90 ft) to the Cache River in the southern part of the study area. Water-level fluctuations in well S48 were similar to stage fluctuations of the Cache River (fig. 31) except during the growing season when water levels drew down in response to pumpage. Well D41, 1.1 mi from the Cache River, had water-level fluctuations similar to stage fluctuations of the Cache River, though with a subdued and delayed response (fig. 32) except during the growing season when water levels drew down in response to pumpage. Well D36, 2.4 mi from the Cache River, had water-level fluctuations that tended to respond to cumulative antecedent stage conditions rather than to individual floods and low flows (fig. 33). Wells D37 and D60, 2.8 and 10 mi from the Cache River, respectively, had water levels that responded to the wet season and summer pumpage and not to individual floods and low flows on the Cache River (figs. 34 and 35).

Ground-water seepage to the surface and surface-water seepage to the ground within the wetland tend to occur during specific surface-water conditions of the Cache River. Ground water from the upper part of the alluvial aquifer most often seeps to the wetland surface in the latter phase of floods when stage of the Cache River is falling (figs. 36 and 37). Surface water most often seeps into the upper part of the alluvial aquifer in the early phase of floods when stage of the Cache River is rising.

During five floods from November 1991 through May, well S41 screened in the top of the alluvial aquifer (S41) had water levels lower than surface water during rising surface waters (surface-water seepage to the ground) and usually had water levels higher than surface water during falling surface waters (ground-water seepage to the surface; fig. 36). During the first flooding event, surface water seeped into the ground about 12 days after the crest on December 15, 1991. During the four following flooding events, seepage reversal from downward to upward occurred within 2 days after the crests. Water levels in the well

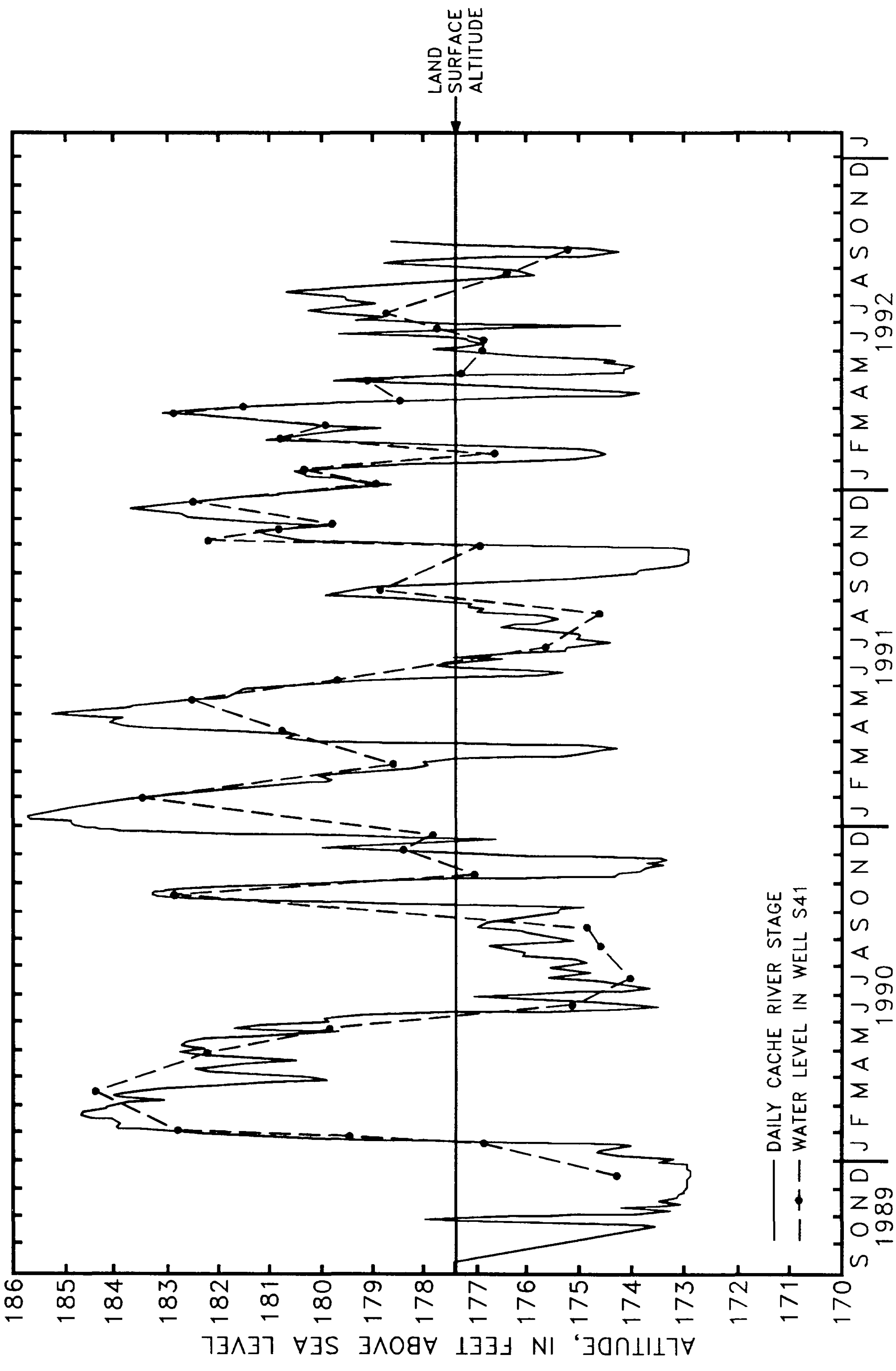


Figure 27. Relation of water level in well S41 with stage of the Cache River at staff gage G10.

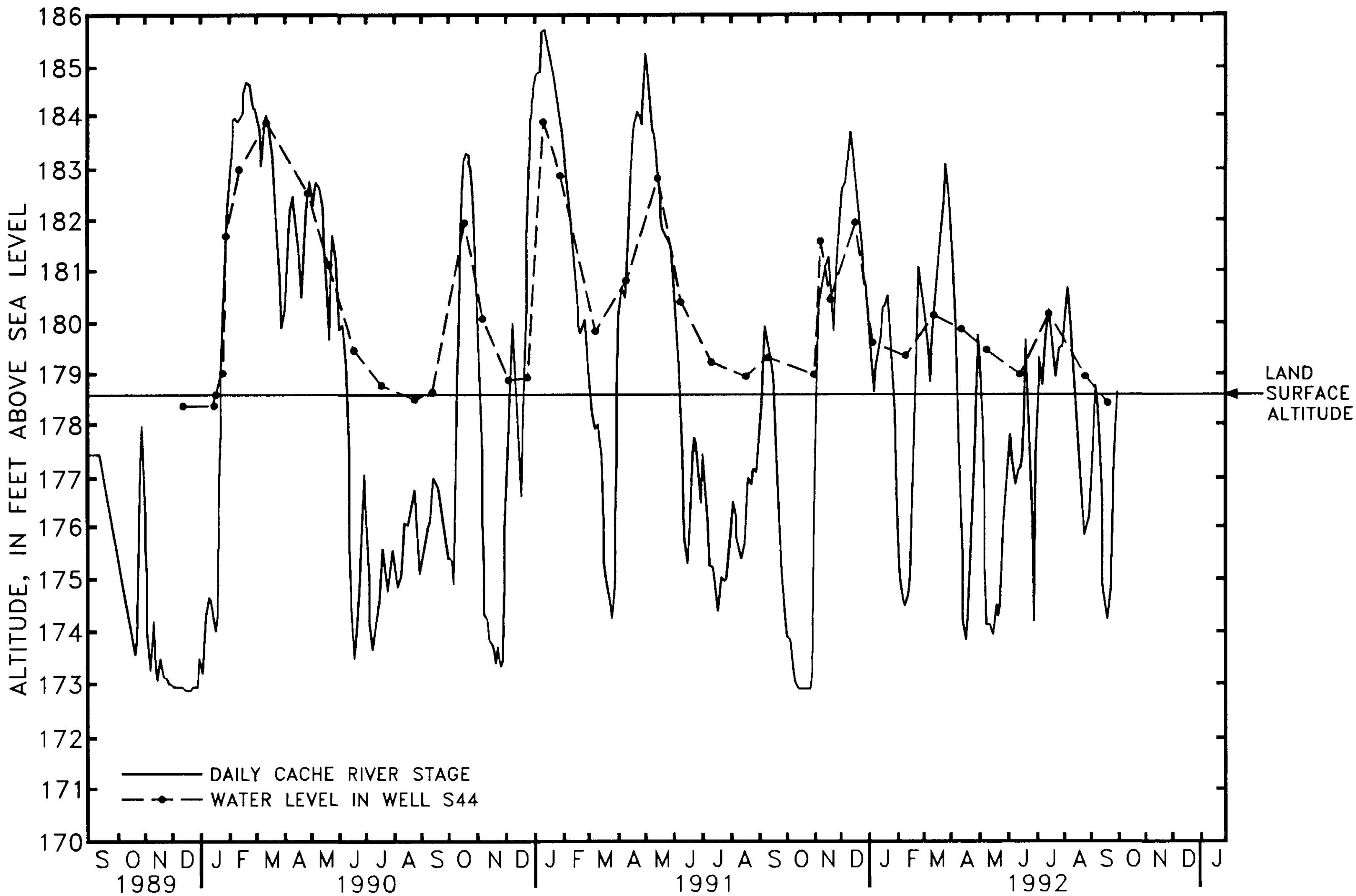


Figure 28. Relation of water level in well S44 with stage of the Cache River at staff gage G10.

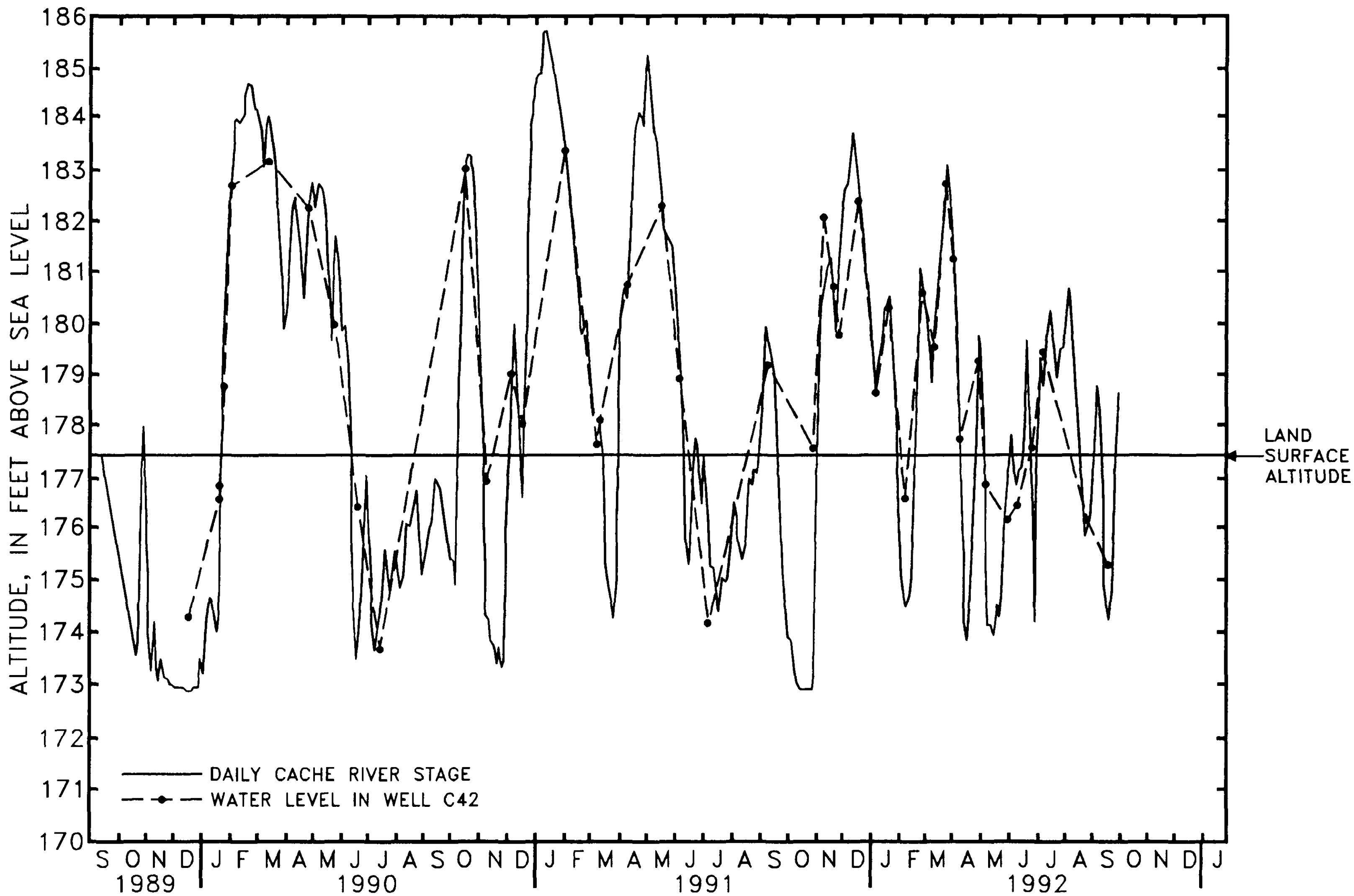


Figure 29. Relation of water level in well C42 with stage of the Cache River at staff gage G10.

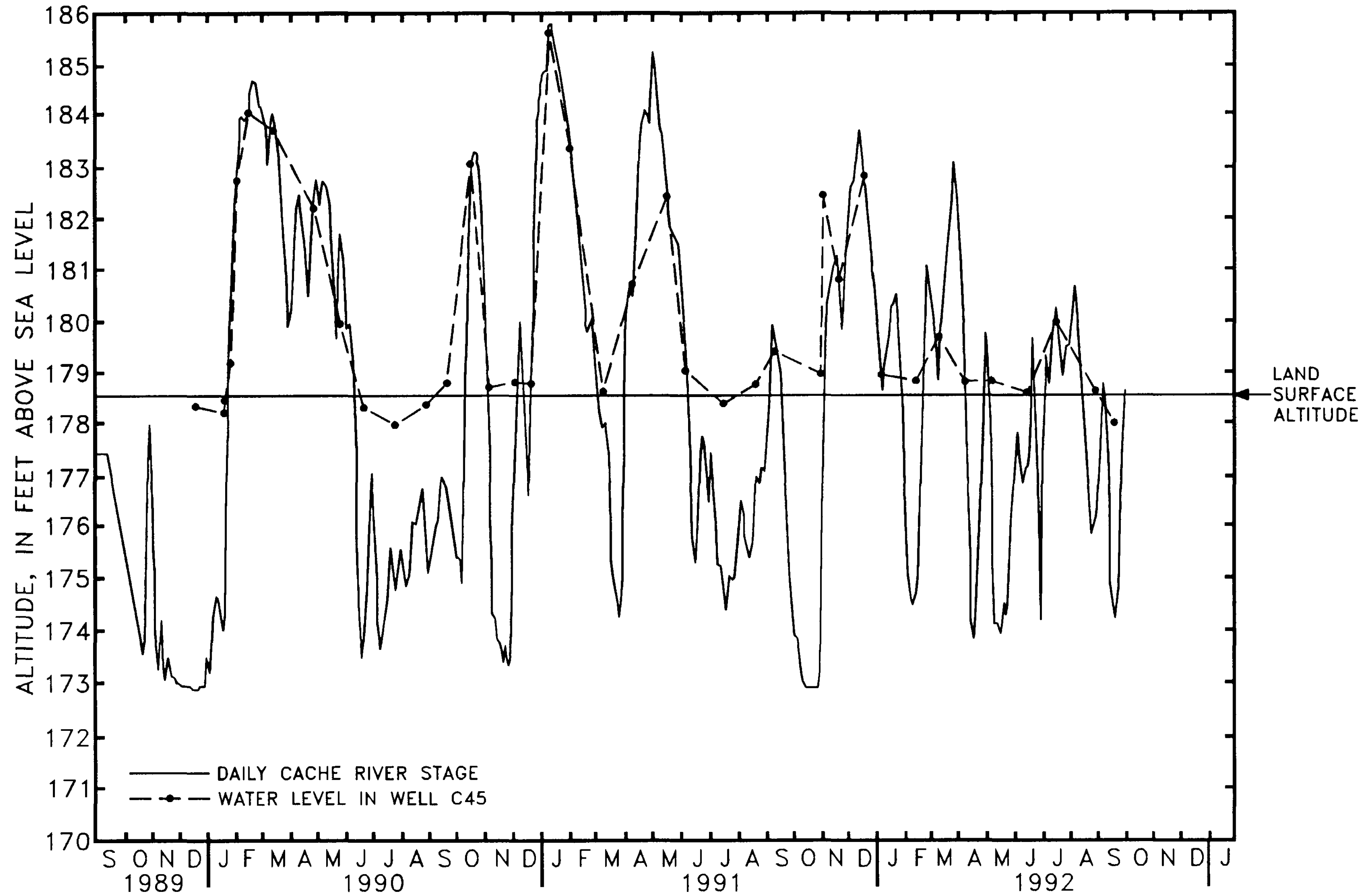


Figure 30. Relation of water level in well C45 with stage of the Cache River at staff gage G10.

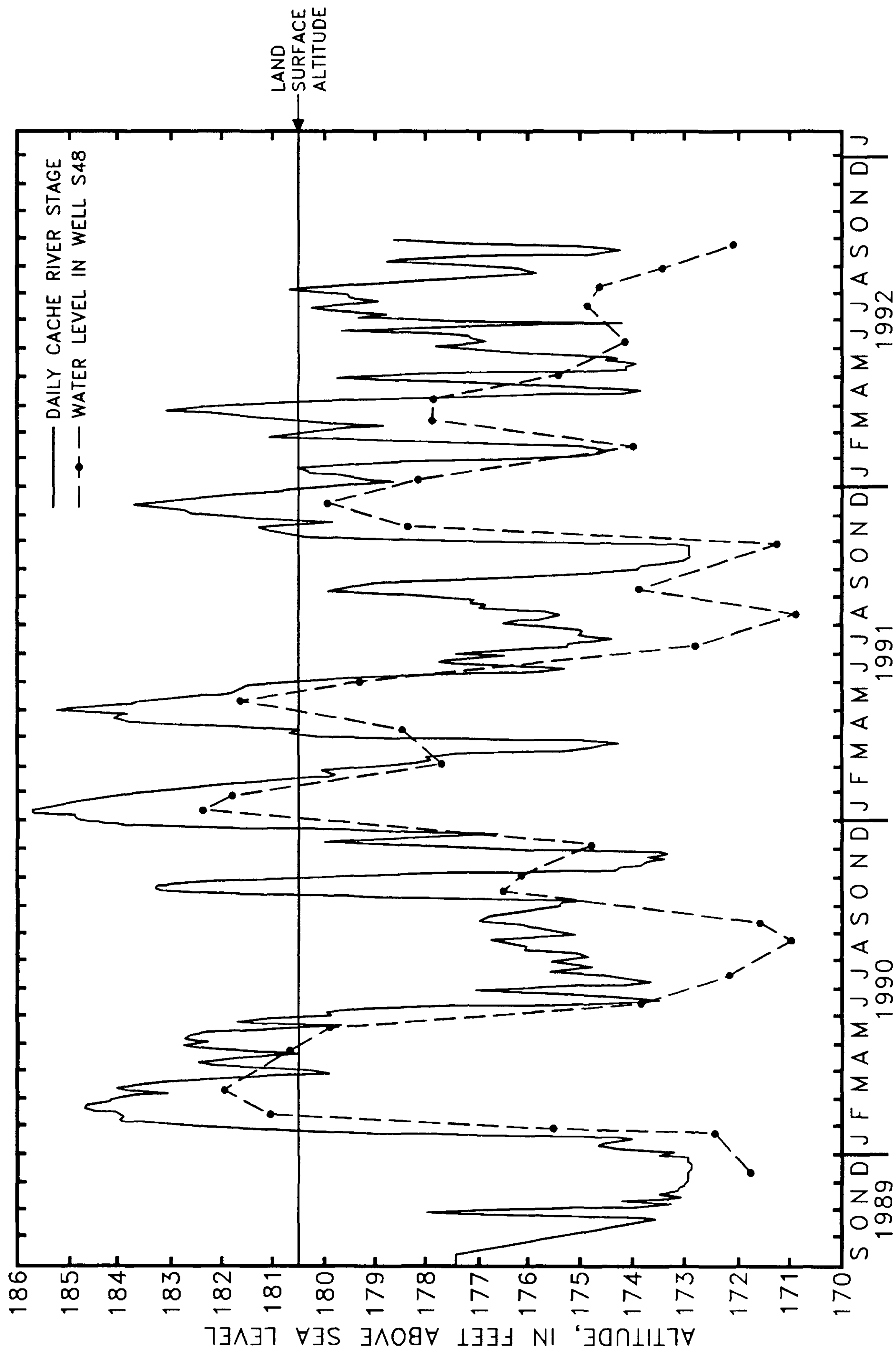


Figure 31. Relation of water level in well S48 with stage of the Cache River at staff gage G10.

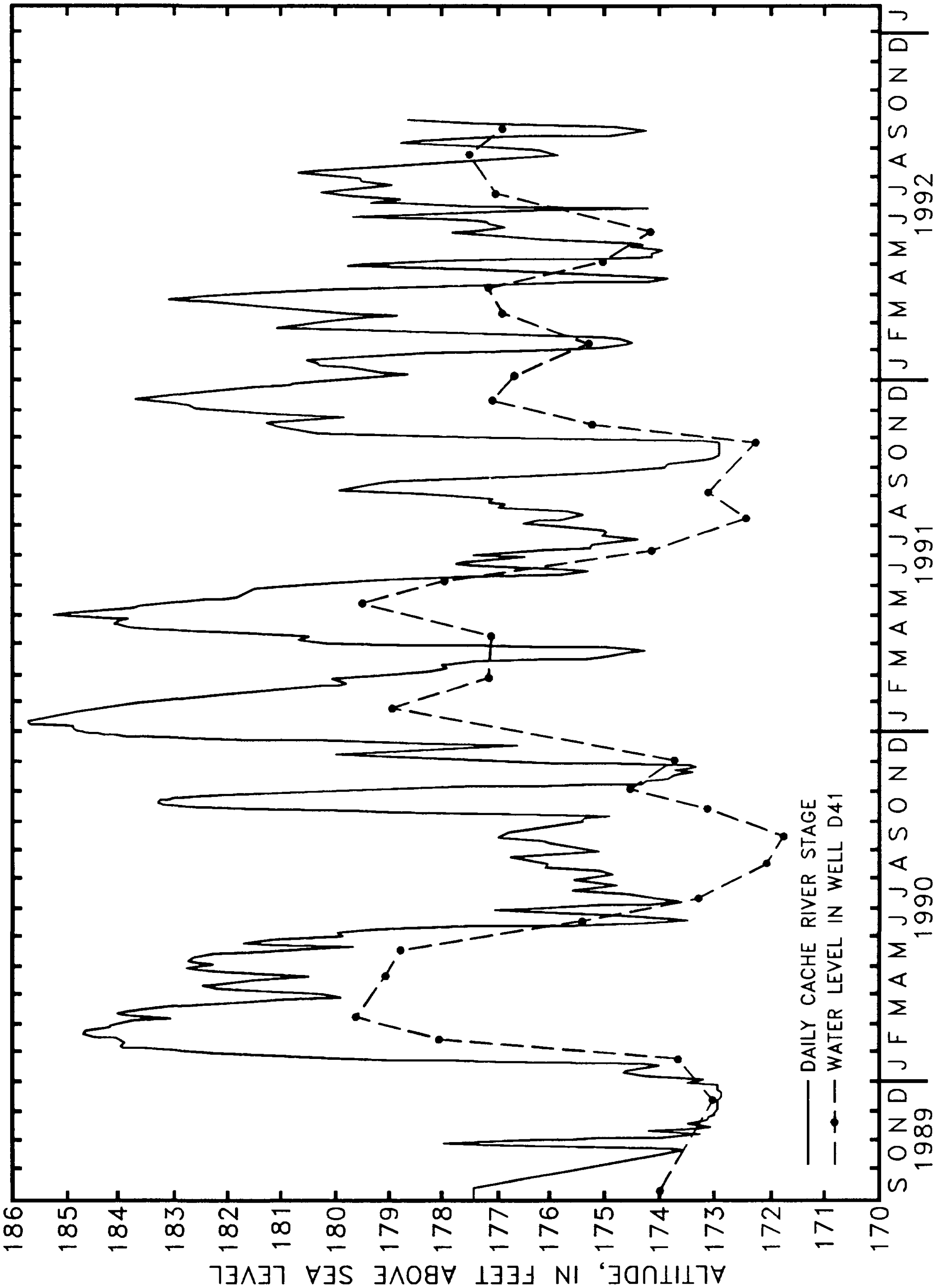


Figure 32. Relation of water level in well D41 with stage of the Cache River at staff gage G10.

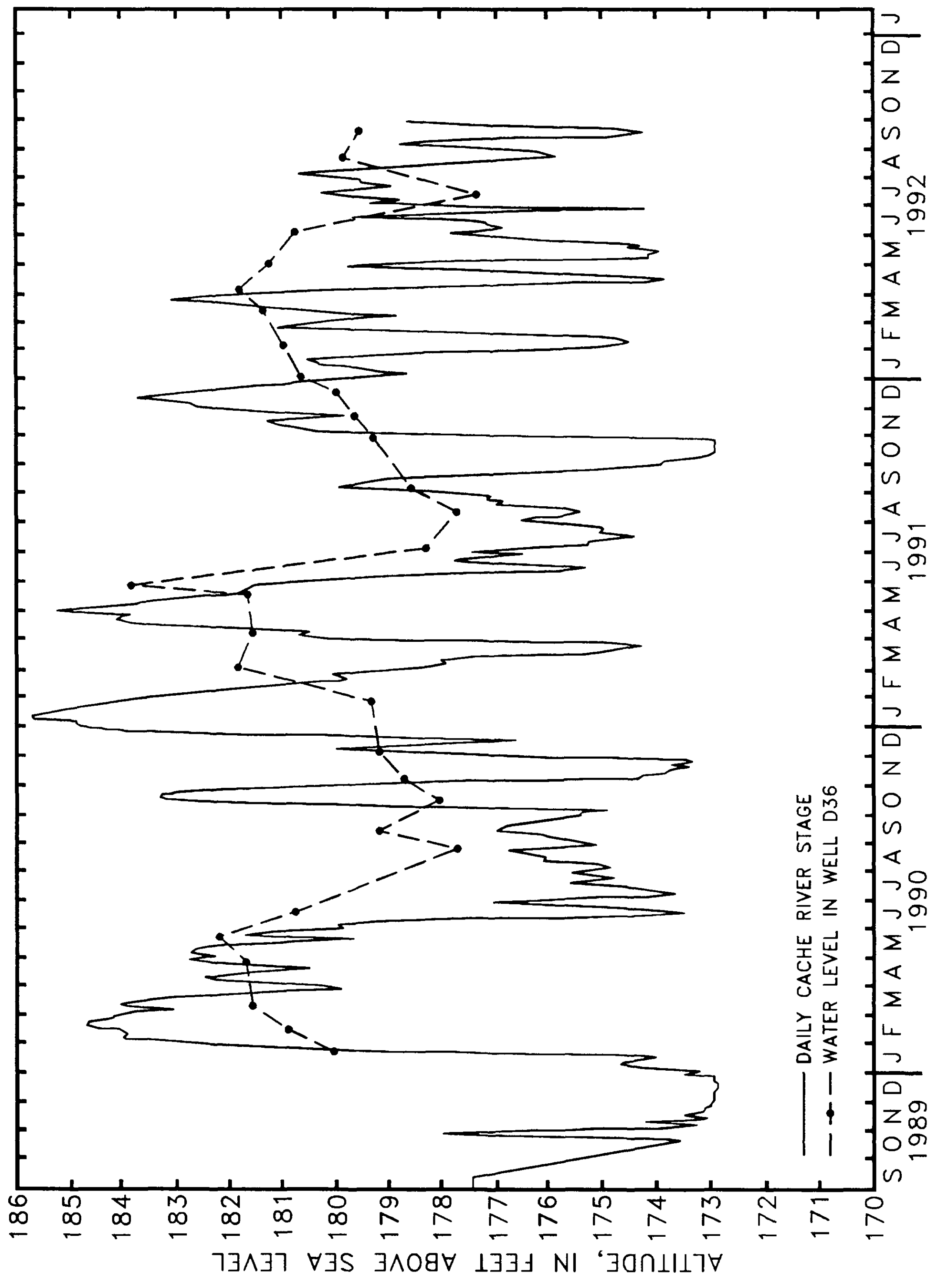


Figure 33. Relation of water level in well D36 with stage of the Cache River at staff gage G10.

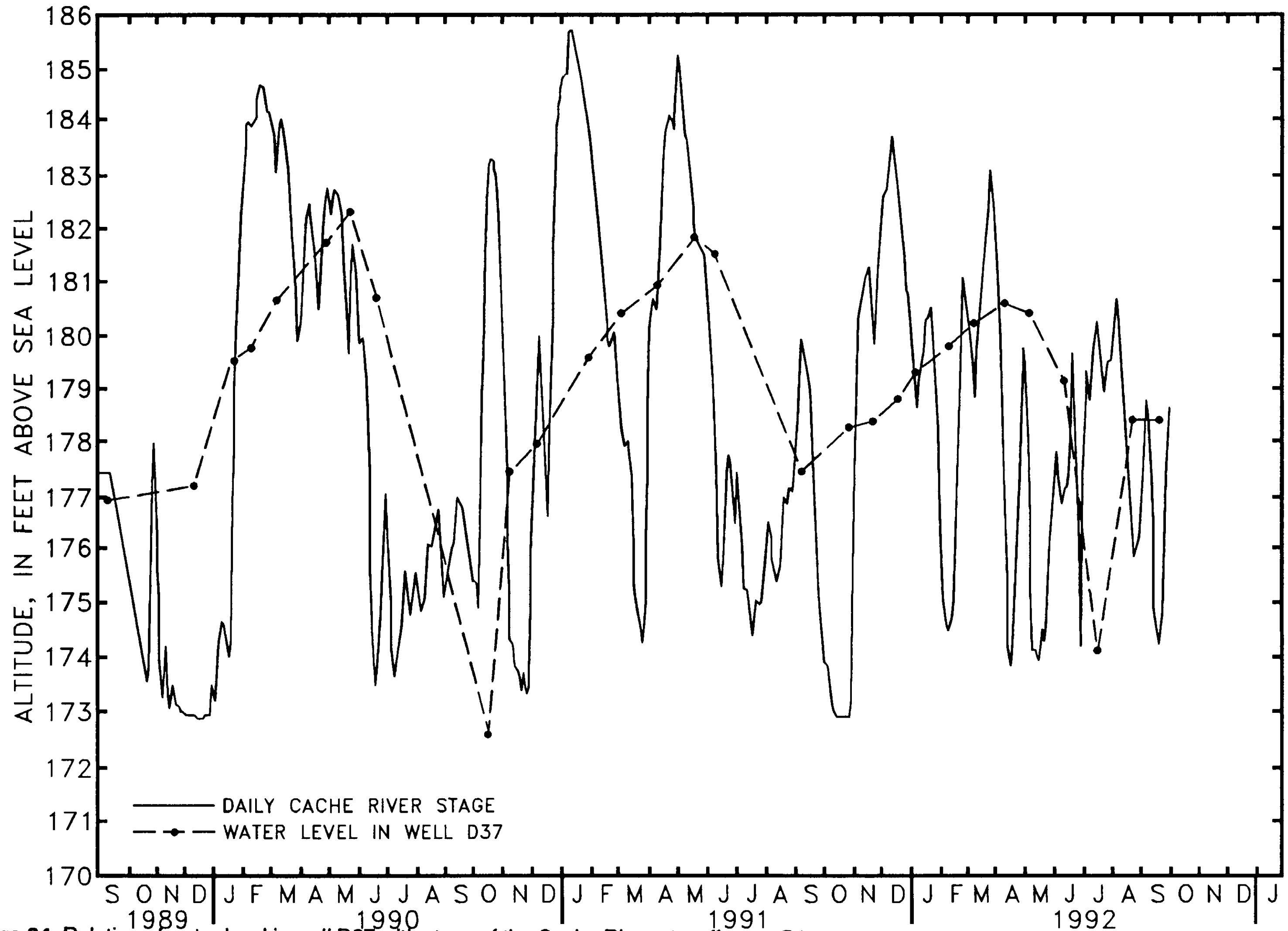


Figure 34. Relation of water level in well D37 with stage of the Cache River at staff gage G10.

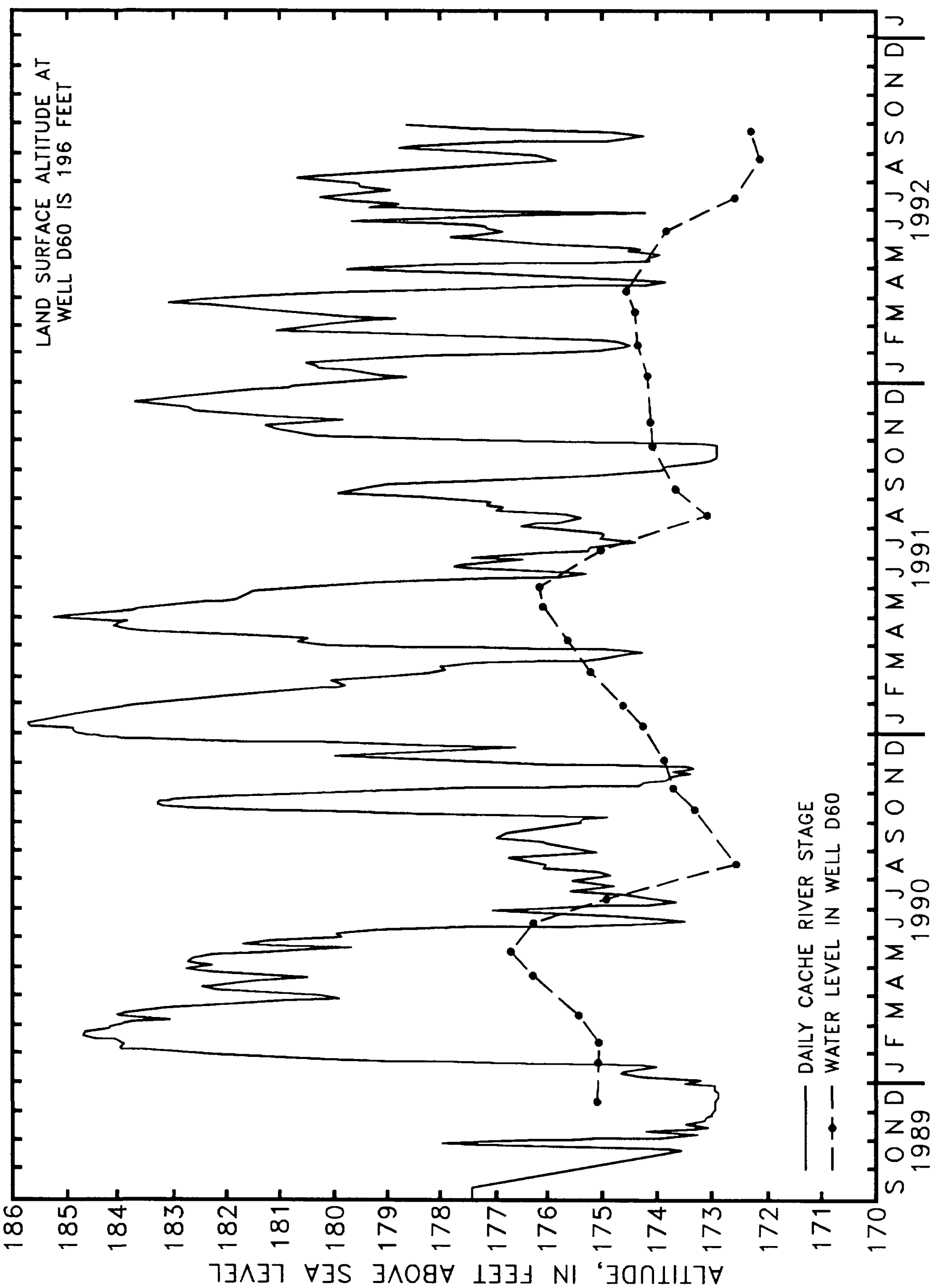


Figure 35. Relation of water level in well D60 with stage of the Cache River at staff gage G10.

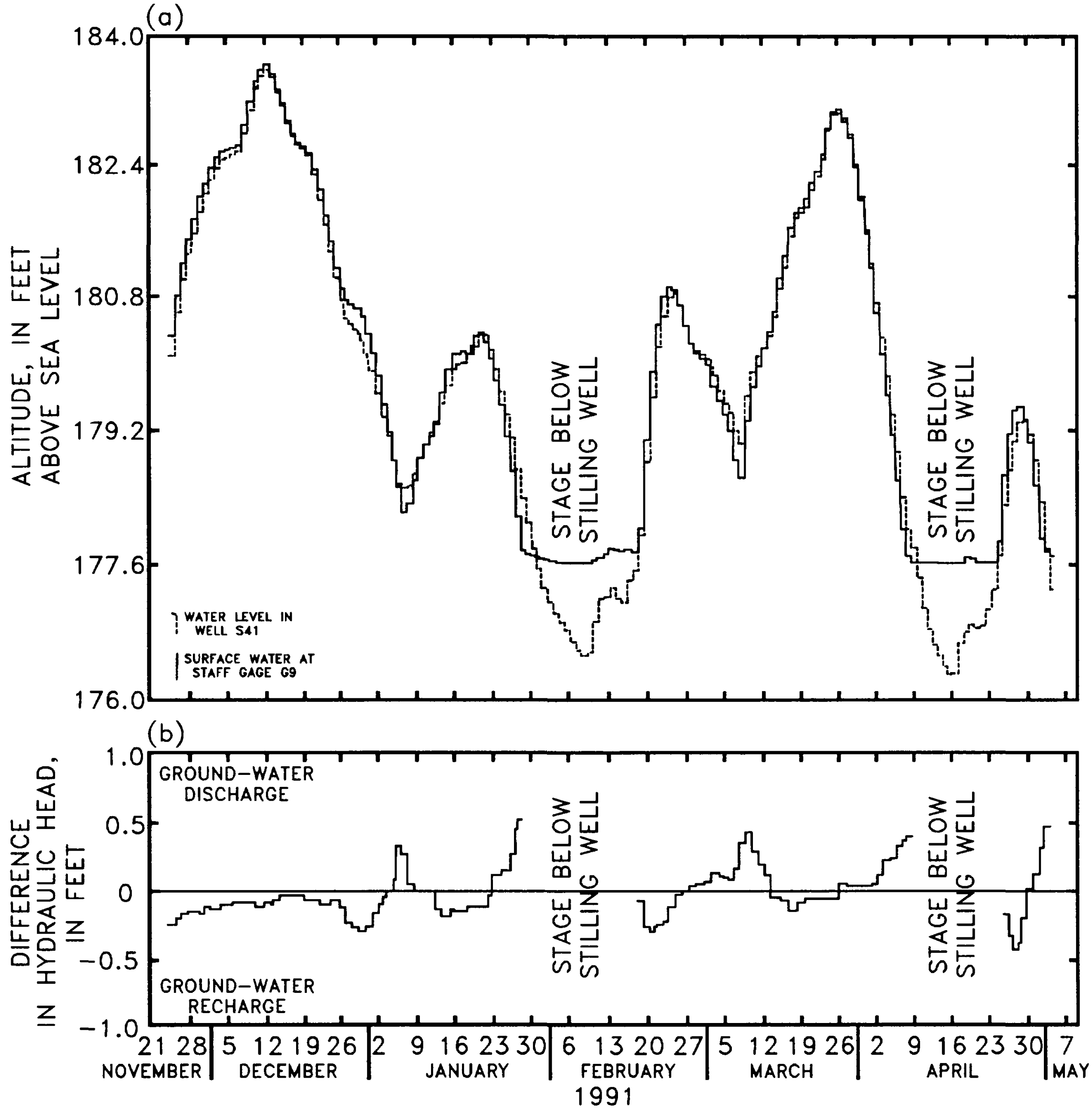


Figure 36. Comparison of ground- and surface-water levels at nested site N9, November 21, 1991, to May 7, 1992.

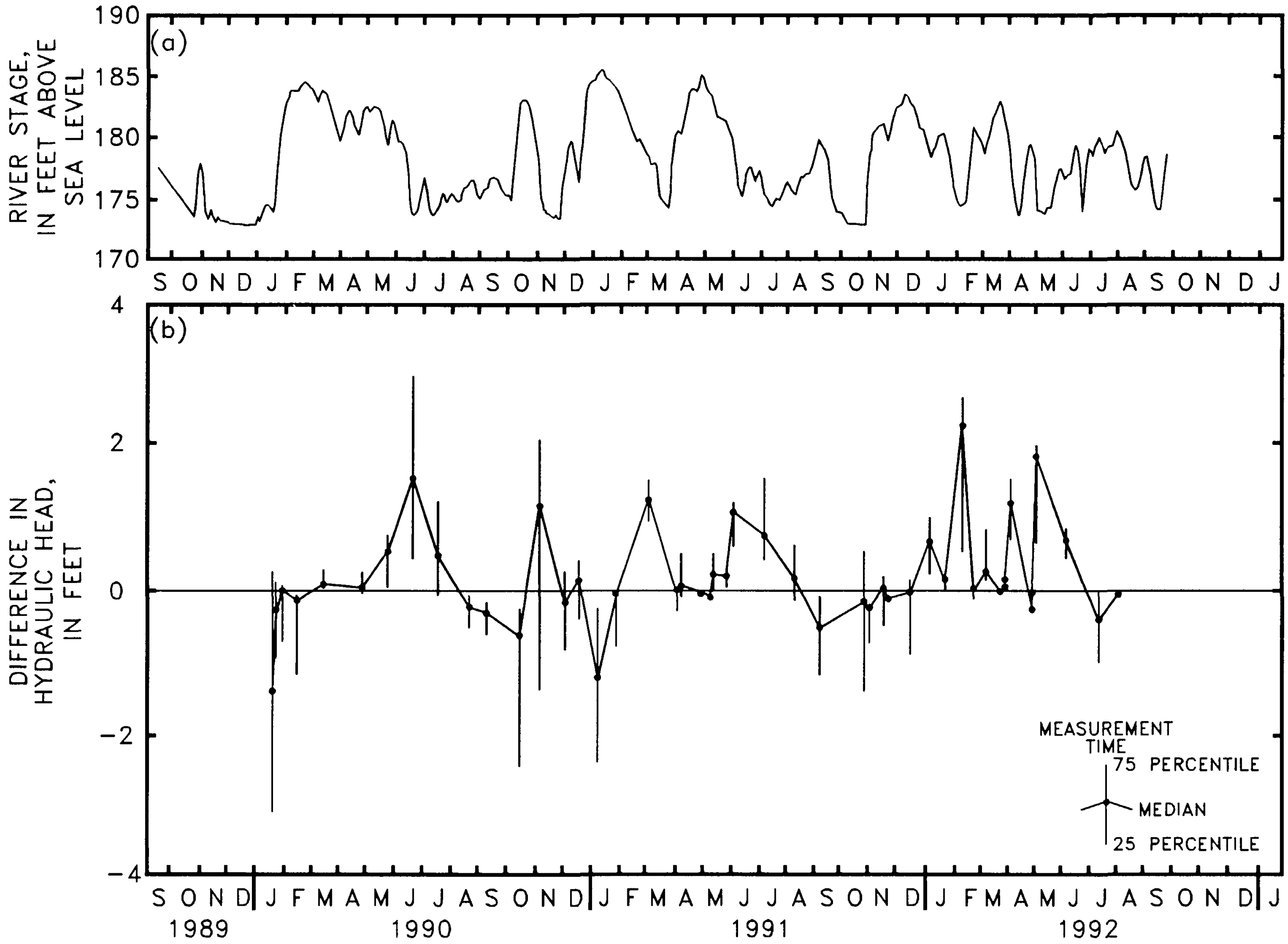


Figure 37. Comparison of hydraulic-head differences from nested sites with stage of the Cache River, January 19, 1990, to August 7, 1992.

screened to the confining unit (C42) did not indicate systematic seepage reversals. Nested site N7 containing continuous recorder data was not inundated often enough to have stage data to compare well water levels.

Surface-water seepage into the ground during rising surface-water levels and ground-water seepage to the surface during falling surface-water levels are indicated by a compilation of simultaneous surface- and ground-water measurements at up to nine nested sites. For each nested site of each measurement time, the difference between surface-water and ground-water level, herein referred to as difference in hydraulic head, was calculated. The lowest medians in the differences in hydraulic head of the nested sites (surface-water seepage into the ground) occurred during January 19, 1990, October 16, 1990, January 9, 1991, September 11, 1991, and July 17, 1992, all during predominantly rising surface-water levels on the Cache River. The highest medians in the differences in hydraulic head of the nested sites (ground-water seepage to the surface) occurred during June 19, 1990, November 6, 1990, March 5, 1991, June 6, 1991, February 12, 1992, April 8, 1992, and May 6, 1992, all during predominantly falling surface-water levels on the Cache River. The average difference in hydraulic head for all 46 measurement times indicates a net seepage of ground water to the surface during the study period. High variance during many measurement times decreases the certainty of whether net seepage of ground water to the surface or net surface-water seepage into the ground actually occurred throughout Black Swamp.

Evaporation Effects on Ground-Water Levels

Diurnal fluctuations of hydraulic head occurred from May to August 1991 and from April to October 1992 in all four shallow wells that were installed with continuous recorders (S19, C20, S41, and C42; fig. 38). Heads fluctuate in a sinusoidal pattern with a wavelength that averages 24 hours; heads reach a daily maximum after sunrise and a daily minimum near sunset. In the summer, daily maximums and minimums usually occurred about 9:00 a.m. and 9:00 p.m. Central Standard Time (CST), respectively. Progressively through autumn, maximums shifted from 11:00 a.m. to as late as 3:00 p.m. and minimums usually occurred about 7:00 p.m. CST. Lower average daily heads were associated with higher amplitudes in fluctuations. Amplitudes of diurnal head fluctuations generally were from more than 0 to 0.38 ft and generally were largest in late summer (table 7). Continuous recorder equipment was removed from the wells in August 1991. Diurnal fluctuations were undetectable by November 25, 1991, when continuous records were reinstalled. Continuous recorders were removed again in October 1992; consequently, the extent of diurnal fluctuations was not determined during the fall of 1991 and 1992. Continuous recorders were reinstalled in September 1993 and diurnal fluctuations barely were detectable by November 9, 1993. Diurnal fluctuations during floods were not detected, and small amplitude fluctuations were unapparent during precipitation.

Table 7. Average amplitude of diurnal fluctuations of head, in feet, from continuous-recorder data during selected times, Black Swamp

[--, dry well]

Date[1]	Nested site N7		Nested site N9	
	S19	C20	S41	C42
May 28-30, 1991	0.09	0.08	0.03	0.00
June 22-27, 1991	.19	.16	.06	.11
July 12-19, 1991	.23	--	.18	.01
August 1-8, 1991	.32	--	.16	--
April 22-23, 1992	.13	.13	.02	.02
May 8-17, 1992	.19	.13	.05	.04
June 13-15, 1992	.20	.13	.07	.06
July 8-26, 1992	.28	.28	.03	.03
August 13-19, 1992	.18	.16	.05	.05
September 5-9, 1992	.38	--	[2].02	[2].02
October 5-7, 1992	.24	--	.01	.06

[1]Rain days not included.
[2]Diurnal fluctuations of head are out of daily phase by 180 degrees.

Continuous recorders detected sudden increases in head up to 2.5 ft, which occurred during rainfall recorded by the National Oceanic and Atmospheric Administration (fig. 39). Rainfall induced increases in head possibly are caused by two phenomena during infiltration: (1) an increase in vadose air pressure from an inverted water table (the Lisse effect), and (2) the quick transfer of the capillary fringe to the water table (the Wieringermeer effect) (Gerla, 1992; Heliotis and DeWitt, 1987).

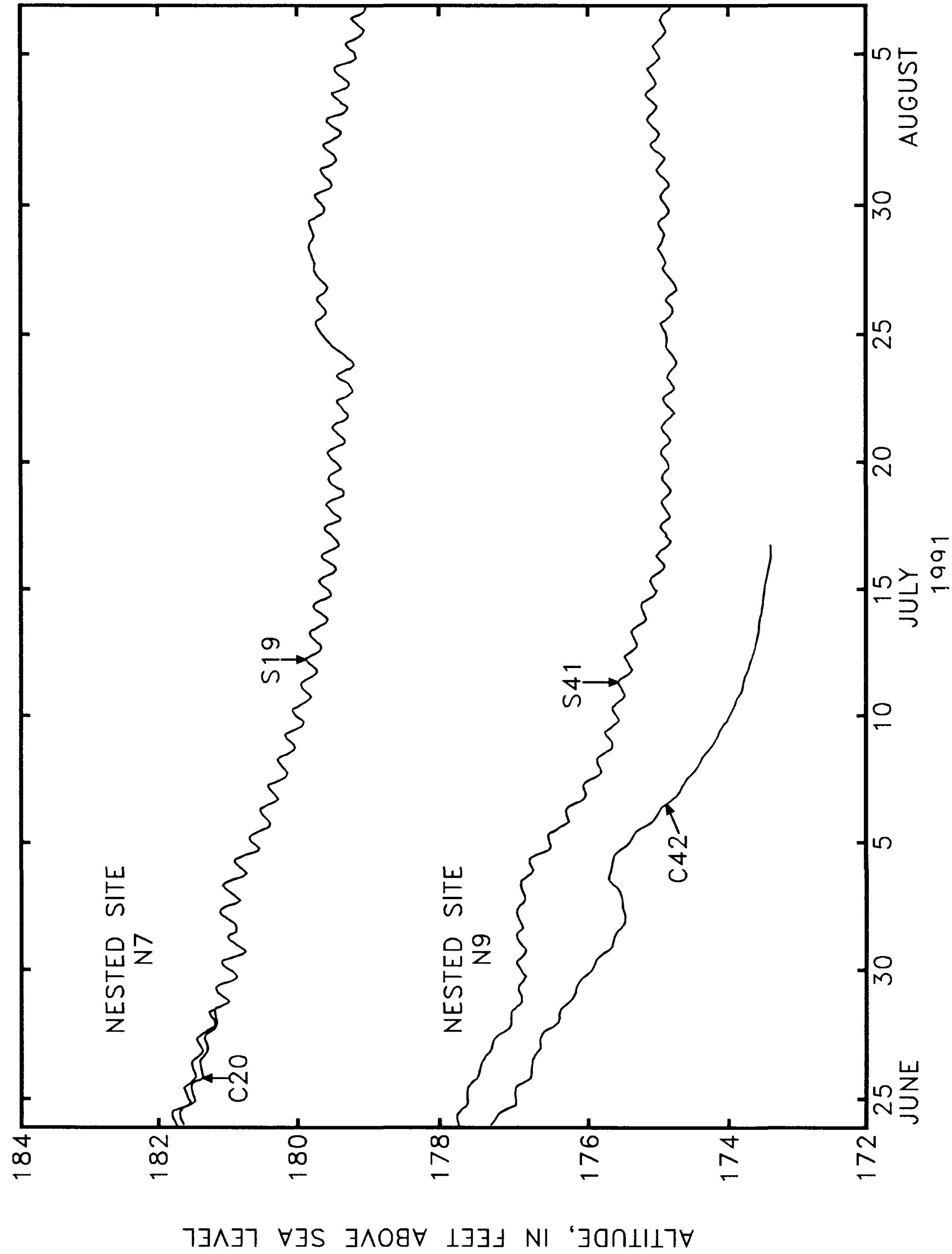


Figure 38. Diurnal fluctuations of head in wells installed with continuous recorders, June 24 to August 7, 1991.

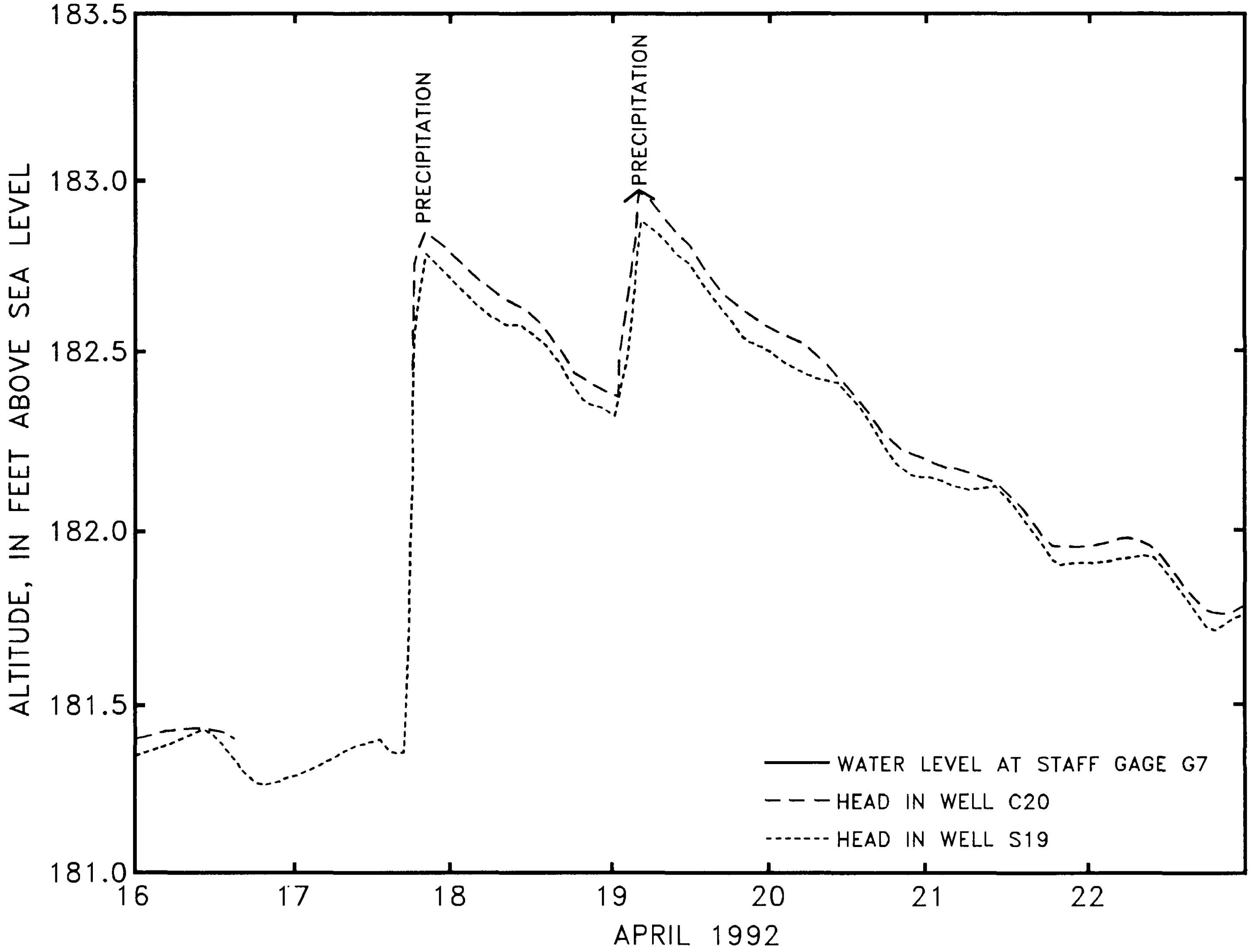


Figure 39. Hydraulic-head fluctuations during precipitation events, April 17 and 19, 1992, at nested site N7.

Diurnal fluctuations of head are caused by the two opposing influences on ground water surrounding the wells: (1) uptake of ground water by evapotranspiration decreases heads in the upper part of the alluvial aquifer during the day, and (2) flow from the lower part of the alluvial aquifer to the upper part increases heads at night. Flow from the lower part of the alluvial aquifer to the upper part occurs day and night but only increases head in the upper part of the alluvial aquifer at night. Evapotranspiration rates have been successfully calculated from diurnal fluctuations (White, 1932; Gerla, 1992). A small sample of calculations of evapotranspiration rates based on diurnal fluctuations in the Black Swamp appeared to correlate to calculations of evapotranspiration based on temperature (Thornthwaite and others, 1944). But because of the sparse data, diurnal fluctuations were not used in the water budget.

Diurnal fluctuations in head beneath the confining unit indicate that the confining unit does not impede plants from getting water from beneath the confining unit. Wells S19 and S41, screened in the top of the alluvial aquifer, had diurnal fluctuations larger than wells C20 and C42, screened in the confining unit (during 1991 and 1992, p-value = 0.05). Well S19, completed beneath 6 ft of confining unit, had diurnal fluctuations larger than well C20 screened in the confining unit (p-value = 0.03).

Conceptual Model of the Black Swamp and the Alluvial Aquifer

The hydraulic-head fluctuations of the alluvial aquifer lag behind stage fluctuations and result in changes in hydraulic-head gradients that create the potential for changes in general ground-water movement. Based on studies of vertical distribution of head at different scales, ground-water seepage to the surface is associated with falling stage and surface-water seepage into the ground is associated with rising stages. From the largest scale perspective--general ground-water movement along an entire transect--flow from the lower part of the alluvial aquifer to the wetland or to the Cache River (ground-water discharge) tends to occur when antecedent Cache River stage was much higher, and flow from the surface to the lower part of the alluvial aquifer (ground-water recharge) tends to occur when antecedent river stage was much lower. Differences between surface-water levels of impounded water in the wetland and stage of the Cache River below its banks complicate the matter by adding a frequently occurring local ground-water flow condition in which surface water in the wetland seeps down into the upper part of the alluvial aquifer and then seeps into the Cache River. When the Cache River flooded the wetland, nested sites consistently followed a pattern of ground-water seepage onto the wetland surface during falling surface-water stage and surface-water seepage down into the wetland during rising surface-water stage. When the river stage was below the altitude of the wetland, different nested sites responded differently to falling and rising surface-water levels depending on three heads: (1) wetland surface-water level, (2) stage of the Cache River, and (3) hydraulic head in the lower part of the alluvial aquifer. This is probably one reason there are high variances in differences in hydraulic head measured from a group of nested sites. In the simple setting where the Cache River is flooding the wetland, the larger the scale of the alluvial aquifer considered, the more time is required for the alluvial aquifer to respond to stage fluctuations. Vertical ground-water flow direction in the shallow parts of the alluvial aquifer beneath the wetland is a result of stage changes in previous days. But general ground-water flow between the lower part of the alluvial aquifer and the wetland and Cache River may be because of stage changes in previous months.

Greater frequency of ground-water seepage to the surface at Transect B-B' than at Transect D-D' may be caused by a combination of pumpage, differences in the lithology of the alluvial aquifer, and downward infiltration of rainfall in upland of the alluvial plain near Transect B-B'. Increased pumpage, all other factors being constant, will decrease frequency of ground-water seepage to the surface. Differences in the lithology of the alluvial aquifer will cause some locations to be more affected by pumpage than other locations. Preferential infiltration of rainfall in upland areas where the confining unit is absent may allow hydraulic heads to be high and induce ground-water seepage to the surface in nearby lowlands.

WETLAND WATER BUDGET

The hydrologic-budget equation of the Black Swamp is based on the conservation of mass, namely that a change in surface-water volume for a given time period is equal to the sum of the water inflows and outflows. The water budget in this report considers surface-water storage in the drainage area between the inflow and outflow gaging stations. Errors in the hydrologic-budget components are important to the interpretation of a final hydrologic budget (Winter, 1981). These errors are represented in the following form of the hydrologic-budget equation as modified by Sacks and others (1992):

$$\Delta S \pm \epsilon_{\Delta S} = -SO \pm \epsilon_{SO} + SI \pm \epsilon_{SI} + P + \epsilon_{P} - E \pm \epsilon_{E} + W \pm \epsilon_{W} + GR \pm \epsilon_{GR} - I \pm \epsilon_{I} + GW \pm \epsilon_{GW} \quad (1)$$

where,

ΔS is the change in surface-water storage for a specific time period, in inches;

SO is volume of surface-water flow through the outflow gaging station during the specific time period, in inches;

SI is volume of surface-water flow through the inflow gaging station during the specific-time period, in inches;

P is precipitation during the specific time period, in inches;

E is evapotranspiration during the specific time period, in inches;

W is the volume of ground-water pumpage during the specific time period, in inches;

GR is the net volume of ground-water flow from the alluvial aquifer into the Cache River through the riverbed during the specific time period, in inches;

I is infiltration of precipitation on the upland of the alluvial plain into the lower part of the alluvial aquifer during the specific time period, in inches;

GW is the net volume of ground-water flow from the alluvial aquifer into the wetland through the confining unit during the specific time period, in inches; and

e is the error in the calculation of each budget component during the specific time period, in inches.

Water volume of components SO, SI, W, GW, and GR is divided by the drainage area in order to convert volume into equivalent inches. Daily surface-water discharge at gaging stations, hydraulic conductance values in literature, ground-water and surface-water heads from the 119 wells and 13 staff gages, drillers' logs, and water-use data were used to calculate surface-water and ground-water components. Weather data from the National Oceanic and Atmospheric Administration monthly reports and annual Arkansas Agricultural Statistics were used to estimate precipitation and evapotranspiration. Calculations of individual components of the hydrologic budget of the Black Swamp drainage area are discussed below.

Change in Storage

The start and end dates of the water budget study period were selected when the Cache River stage was low and the wetland was relatively dry to minimize the change and error of the storage component. On January 17, 1990, and September 21, 1992, the Cache River was within its banks. Change in stage ranged from -4.21 ft at the Cotton Plant gaging station (G13) to +2.00 ft at the Transect B-B' staff gage (G5). A change in volume of water stored in the Cache River from January 17, 1990, to September 21, 1992, can be estimated from the change in stage at the five gages and the Cache River dimensions (width and length). The river width for the stages on January 17, 1990, and September 21, 1992, was about 100 ft (A.P. Hall, U.S. Geological Survey, oral commun., 1994). The Cache River can be separated into four segments bounded on both ends by two gaging stations. The change in storage for each segment would be the average change in stage of the two gaging stations, times the river width, times the length of the reach of the river segment "i":

$$\Delta S_i = \left(\frac{\Delta B_{Di} + \Delta B_{Ui}}{2}\right) \times R \times \left(\left(M_{Ui} - M_{Di}\right) \times 5280\right) \quad (2)$$

where,

Δ is the change in a value from January 17, 1990, to September 21, 1992;

S_i is the storage of river segment i, in cubic feet;

B_{Di} is the stage of the gaging station on the downstream end of river segment i, in feet above sea level;

B_{Ui} is the stage of the gaging station on the upstream end of river segment i, in feet above sea level;

R is the width of the river (100 ft);

M_{Ui} is the river mile of the gaging station on the upstream end of river segment i; and

M_{Di} is the river mile of the gaging station on the downstream end of river segment i.

Table 8 lists the data used to calculate the change in storage including the length of the river reach for each segment. Change in storage was calculated to be 1,520,000 ft^3. This converts to 0.01 in. (0.005 rounded to the nearest hundredth of an inch) indicating that change in storage from January 17, 1990, to September 21, 1992, was minimal.

Surface-Water Inflow And Outflow

Daily surface-water discharge measurements, from the Patterson and Cotton Plant gaging stations, were used to calculate surface-water inflow and surface-water outflow, respectively. Thirteen surface-water discharge measurements, made at each of the inflow and outflow gaging stations during the study period, were used with standard rating curves to calculate daily average surface-water discharge from daily average stage. The total surface-water discharge for the Patterson and Cotton Plant gaging stations for the study period was 1.216×10^{11} and 1.409×10^{11} ft^3 of river water, respectively. The volumes convert into 409.53 in. of surface-water inflow and 474.49 in. of surface-water outflow. The net surface-water flow is 64.95 in. out of the study area.

Estimated error for individual inflow and outflow surface-water discharge measurements is 8 and 5 percent, respectively (A.P. Hall, U.S. Geological Survey, oral commun., 1994). Combined error for all 13 daily surface-water discharge measurements would be approximately $\frac{1}{\sqrt{13}}$ times the error for individual inflow and outflow surface-water discharge measurements (Ott, 1988). Estimated error for the inflow and outflow surface-water discharge for the study period based on 13 daily surface-water discharge measurements would be 8 and 5 percent divided by square root of 13 or 2.22 and 1.39 percent, respectively. Estimated error, in inches, of inflow and outflow is then 9.09 and 6.60 in., respectively.

Precipitation

Data from 19 NOAA precipitation stations surrounding the Black Swamp were used to determine the total amount of precipitation within the Black Swamp drainage area (table 9) (National Oceanic and Atmospheric Administration, 1990; 1991; 1992). Contour maps of monthly precipitation, using the 19 NOAA sites, were made for each of the 33 months that comprise the study period. An example for November 1990 is shown in figure 33. For the first and last months (January 1990 and September 1992) only precipitation for the part of the month during the study period was mapped and contoured. Monthly precipitation contour positions, within the Black Swamp drainage area for each month, were used to estimate the average monthly precipitation within the drainage area

Table 8. Values of Cache River stage and dimensions used to calculate the change in storage from January 17, 1990, to September 21, 1992

[ΔB, is the change in stage at a gaging station; ΔS, is the change in the volume of water in the Cache River]

Gaging station	Stage (feet above sea level) January 17, 1990	Stage (feet above sea level) September 21, 1992	Change in stage (ΔB, feet)	Cache River segments (by gaging stations)	Cache River segment length (miles)	ΔS (cubic feet)	ΔS (inches)
G1	186.51	187.66	1.15				
				G1 to G2	6.2	1,228,000	0.004
G2	186.63	186.23	-.40				
				G2 to G5	9.4	3,971,000	.013
G5	177.00	179.00	2.00				
				G5 to G10	7.2	4,334,000	.015
G10	174.03	174.31	.28				
				G10 to G13	7.7	-8,009,000	-.027
G13	175.59	171.38	-4.21				
				TOTAL	30.5	1,520,000	.005 (0.01)

for that month. In November 1990 (fig. 40), for example, the 4.00-in. contour line crosses the extreme northwestern part of the study area. About 10 percent of the drainage area had 4.00 in. of precipitation during November 1990. The 3.50-in. contour crosses a larger part of the northwestern part of the drainage area and is near the southwestern boundary of the drainage area. Precipitation recorded at Beedeville, Brinkley, Madison, and Wynne indicates that precipitation in the eastern part of the drainage area probably was not much lower than 3.50 in. About 30 percent and the remaining 60 percent of the drainage area had 3.50 and 3.40 in. of precipitation during November 1990, respectively, based on the position of the 3.50-in. contour and precipitation recorded at Beedeville, Brinkley, Madison, and Wynne. The average monthly precipitation for the drainage area is calculated as the sum of the precipitation amounts weighted for the area that they represent or (0.1 x 4.00 in.) + (0.3 x 3.50 in.) + (0.6 x 3.40 in.) = 3.49 in.

Table 9. National Oceanic and Atmospheric Administration (NOAA) weather station data used to calculate the water budget of the Black Swamp drainage area

Station	Precipitation data	Temperature data
BATESVILLE L & D 1	yes	yes
BEEDEVILLE 4 NE	yes	yes
GEORGETOWN	yes	no
JONESBORO 4 N	yes	yes
NEWPORT	yes	yes
SEARCY	yes	yes
CABOT 4 SW	yes	yes
AUGUSTA 2 NW	yes	no
BRINKLEY	yes	yes
CLARENDON	yes	yes
DES ARC	yes	yes
HELENA	yes	yes
KEO	yes	yes
MADISON 1 NW	yes	no
MARIANNA 2 S	yes	yes
ST CHARLES	yes	yes
STUTTGART	yes	no
STUTTGART 9 ESE	yes	yes
WYNNE	yes	yes

The total precipitation for the Black Swamp drainage area during the study period was estimated, based on monthly precipitation maps, to be 157.72 in. (table 10). This compares favorably to the estimate (158.45 in.) based on a precipitation map that contains the total precipitation during the study period at nine NOAA sites around Black Swamp. In light of the similarity of the estimates between the 33 monthly precipitation maps and the total precipitation map (0.73 in.), the error for the precipitation value is estimated to be about 1 in.

Evapotranspiration

Evapotranspiration was calculated based on temperature data from 15 NOAA sites around Black Swamp (table 9). Average temperature during a given time period (usually 1 month) was used to calculate the potential evapotranspiration within the drainage area based on the Thornthwaite equation (Thornthwaite and others, 1944):

$$U = pc\left(\frac{10t}{TE}\right)^a \qquad (3)$$

where,

U is potential evaporation for the given time period, in centimeters;

p is the coefficient for the period of time, where p = 0.53 for 1 day, or p = 1.6 for 1 month;

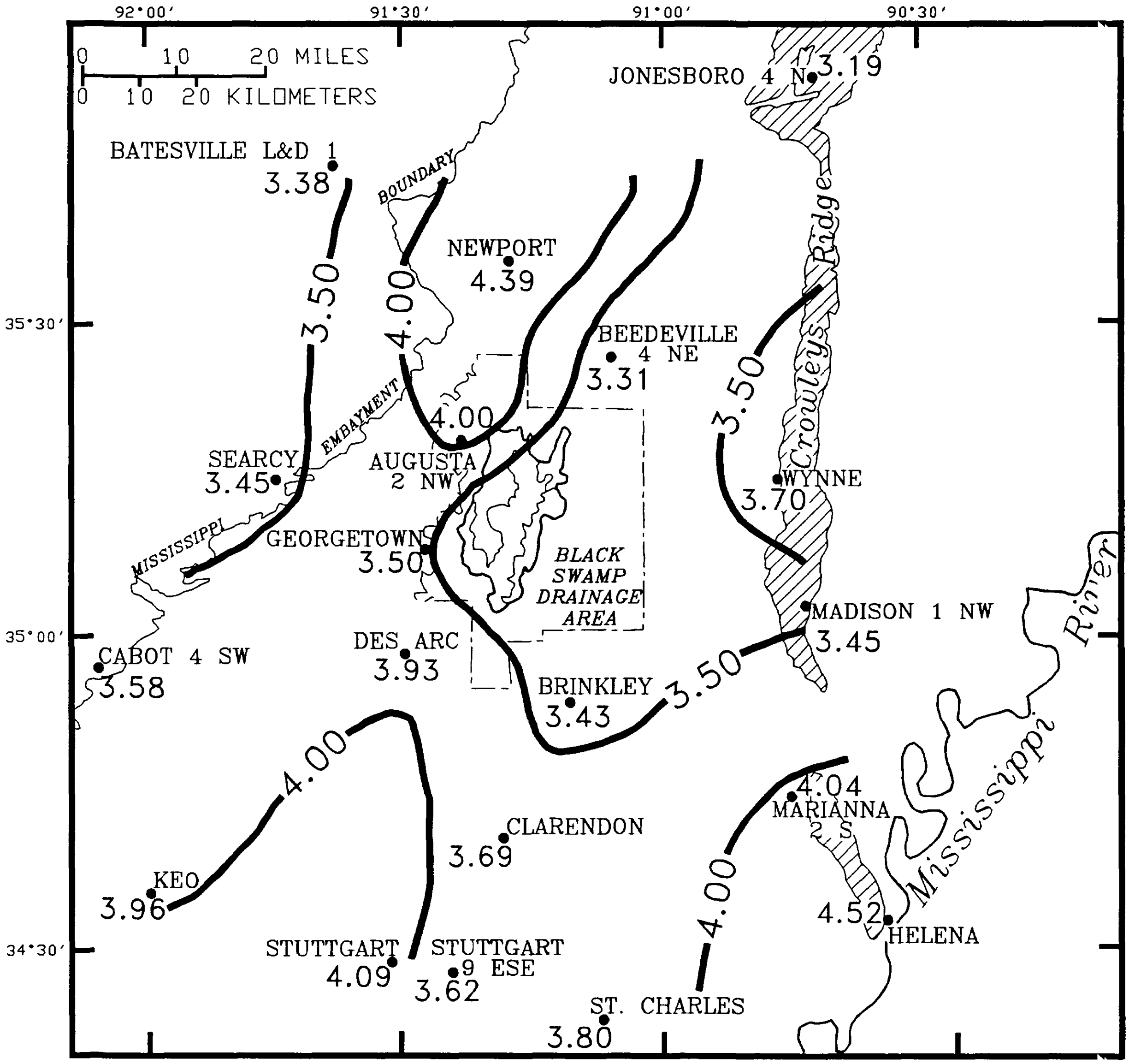
c is a correction factor close to 1.00 by Criddle (1958) that takes into account the difference in the number of days of each month and the difference in day length by latitude and season;

t is the average temperature for the given time period, in degrees Celsius;

TE is the temperature-efficiency index, being equal to the sum of 12 monthly values of heat index $i = \left(\frac{t}{5}\right)^{1.514}$ where t is the 30-year mean temperature for the month, in degrees Celsius; and

a is $6.75\times10^{-7}\,(TE)^3 + 0.0000771\,(TE)^2 + 0.01792TE + 0.49239$.

The TE value used for Black Swamp was 78.0. TE of the two NOAA sites of Stuttgart 9 ESE and Newport was calculated to be 78.36 and 76.74, respectively. The Black Swamp drainage area is located between these two NOAA sites with Stuttgart 9 ESE being located 40 mi to the south and Newport being located 33 mi to the north. Thornthwaite values of



EXPLANATION

—4.00– – PRECIPITATION CONTOUR—Dashed where approximately located. Contour interval 0.5 inch

NEWPORT 4.39 NOAA weather station and inches of precipitation

Figure 40. Precipitation in the region of the Black Swamp drainage area during November 1990.

potential evaporation are not sensitive to changes in TE except at temperatures above 25 °C and were most sensitive to changes in TE at 27.8 °C, which occurred in July 1990. At that temperature, a change in TE of 1.62, which is the difference in TE between Stuttgart 9 ESE and Newport, causes a change in Thornthwaite calculated monthly evaporation of 0.34 in. At 15 °C, a change in TE of 1.62 causes a change in Thornthwaite calculated monthly evaporation of -0.04 in.

Average monthly temperatures in the Black Swamp drainage area were calculated using contour maps of temperature in the same manner as contour maps of precipitation (fig. 33). The monthly temperatures at 15 NOAA sites were used to estimate the temperature of the upland of the alluvial plain within the drainage area. The temperature in the Black Swamp wetland was modified to take into account the high moisture content. Temperatures in the Black Swamp were assumed to lag slightly behind NOAA station temperatures because of the relatively high percentage of water in the wetland. The extent of wetland temperature modifications were based on qualitative field observations; wetland temperatures in table 10 are on average, 0.18 °C cooler than upland temperatures. Average monthly temperatures of the upland of the alluvial plain and wetland within the Black Swamp drainage area are listed in table 10.

Monthly potential evapotranspiration values of upland and wetland were calculated based on the Thornthwaite equation and average monthly temperatures of the upland and wetland (table 10). The total potential evapotranspiration during the study period for the upland and swamp areas is 103.27 and 100.83 in., respectively. Because the Black Swamp wetland is usually moist and the water table is close to the land surface, water is assumed to not be a limiting factor for driving evapotranspiration and that the potential evapotranspiration equals actual evapotranspiration. In the upland area, water becomes a limiting factor, and potential evapotranspiration is expected to be greater than actual evapotranspiration.

Doorenbos and Pruitt (1977) published crop coefficients that correlate "ET_{crop}" with "ET_o":

$$ET_{crop} = k_c \times ET_o \quad (4)$$

where,

ET_{crop} is "the depth of water needed to meet the water loss through evapotranspiration of a disease-free crop, growing in large fields under nonrestricting soil conditions including soil water and fertility and achieving full production potential under the given growing environment."

k_c is the crop coefficient which changes through the growing season of each crop;

ET_o is "the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green-grass cover of uniform height, actively growing, completely shading the ground and not short of water."

ET_o is assumed to be similar to potential evapotranspiration.

Land use in the upland area must be known to calculate the ratio of actual ET to potential ET in the upland area. Most of the upland area within the drainage area was used for agriculture. Less than 5 percent of the upland was wooded and less than 0.1 percent was used for aquaculture. The Arkansas Agricultural Experiment Station (AAES) publishes annual reports of acreage, by county, for soybeans, corn, wheat, cotton, rice and sorghum, and other crops (Arkansas Agricultural Experiment Station, 1991; 1992; 1993). These crops are grown on over 95 percent of the upland of the alluvial plain in Woodruff County. Fifty-three percent of the crops in Woodruff County were irrigated in 1987 according to a federal census. Two assumptions made are: (1) the proportions of acreage for the six crops in Woodruff County are similar to the proportions in the Black Swamp drainage area, and (2) about one-half of the crops were irrigated through the three growing seasons during the study period. AAES also reports seasonal progress of these six important crops. The irrigation crop coefficient (k_c) values of each of the six crops during each month of the crops' growing season were calculated using the methods and k_c values published in Doorenbos and Pruitt (1977). Irrigation (k_c) ranged from 0.51 for wheat just before harvest (June 1990) to 1.17 for cotton during mid season (July 1990). Initial k_c values are the same for all crops when the ground is devoid of vegetation and are

Table 10. Precipitation, temperature, and evapotranspiration data used to calculate the water budget in the Black Swamp drainage area (Thornthwaite and others, 1944)

[k_c, crop coefficients from Doorenbos and Pruitt (1977); --, not applicable]

		Evapotranspiration data								
		Black Swamp wetland		Upland of the Alluvial Plain						Estimated evapo-transpiration of Black Swamp drainage area (inches)
						Crop coefficient				
Date	Precipitation (inches)	Temperature (degrees Celsius)	Potential evapo-transpiration (inches)	Temperature (degrees Celsius)	Potential evapo-transpiration (inches)	Irrigation k_c	Nonirrigation k_c	Total k_c	Estimated evapo-transporation (inches)	
January 1990	5.40	8.67	0.32	8.67	0.32	1.01	1.00	1.01	0.33	0.33
February 1990	5.78	9.72	.79	9.67	.78	1.01	1.00	1.01	.78	.78
March 1990	9.50	11.50	1.28	11.72	1.32	1.02	1.00	1.01	1.33	1.30
April 1990	6.07	14.89	2.12	15.50	2.27	.96	.92	.94	2.14	2.13
May 1990	7.77	19.44	3.74	19.72	3.83	.92	.87	.90	3.44	3.59
June 1990	2.54	26.11	6.25	26.50	6.41	.89	.50	.71	4.53	5.42
July 1990	1.28	27.28	6.86	27.61	7.00	.91	.29	.62	4.33	5.63
August 1990	1.78	26.39	6.10	26.67	6.21	.97	.42	.71	4.42	5.29
September 1990	3.18	24.22	4.67	24.33	4.71	.96	.74	.86	4.03	4.36
October 1990	8.59	15.61	2.05	15.44	2.01	.75	.77	.76	1.52	1.79
November 1990	3.49	13.22	1.36	13.11	1.34	.76	.77	.76	1.02	1.20
December 1990	8.60	6.61	.40	6.28	.37	.95	.95	.95	.35	.38
January 1991	5.42	3.39	.13	2.78	.09	1.00	1.00	1.00	.09	.11
February 1991	2.43	7.33	.48	7.78	.53	.99	.99	.99	.53	.50
March 1991	2.90	11.94	1.36	12.50	1.47	1.01	1.00	1.01	1.48	1.42
April 1991	13.94	16.17	2.44	17.50	2.80	1.01	1.00	1.01	2.82	2.62
May 1991	4.90	22.56	4.84	23.33	5.14	0.92	0.93	0.92	4.75	4.80
June 1991	3.68	26.11	6.25	26.50	6.41	.78	.65	.72	4.61	5.46
July 1991	1.50	27.39	6.90	27.94	7.15	.87	.62	.75	5.38	6.17
August 1991	4.78	26.22	6.04	26.39	6.10	.99	.68	.84	5.15	5.61

Table 10. Precipitation, temperature, and evapotranspiration data used to calculate the water budget in the Black Swamp drainage area (Thornthwaite and others, 1944)–Continued

[k_c, crop coefficients from Doorenbos and Pruitt (1977); –, not applicable]

		Evapotranspiration data								
		Black Swamp wetland		Upland of the Alluvial Plain						Estimated evapo-transpiration of Black Swamp drainage area (inches)
						Crop coefficient				
Date	Precipitation (inches)	Temperature (degrees Celsius)	Potential evapo-transpiration (inches)	Temperature (degrees Celsius)	Potential evapo-transpiration (inches)	Irrigation k_c	Nonirrigation k_c	Total k_c	Estimated evapo-tranaporation (inches)	
September 1991	1.88	22.94	4.25	22.78	4.19	.90	.76	.83	3.50	3.89
October 1991	7.72	17.61	2.52	17.50	2.50	.65	.63	.64	1.60	2.08
November 1991	4.16	9.17	.72	8.72	.66	.97	.97	.97	.64	.68
December 1991	5.66	7.44	.49	7.00	.44	1.00	1.00	1.00	.44	.47
January 1992	2.38	5.00	.25	4.44	.21	1.00	1.00	1.00	.21	.23
February 1992	2.65	9.06	.69	9.22	.72	.98	.97	.98	.70	.70
March 1992	7.56	10.94	1.17	11.38	1.25	.96	.95	.96	1.20	1.18
April 1992	2.75	15.94	2.38	16.38	2.50	.73	.69	.71	1.78	2.09
May 1992	3.40	19.83	3.87	20.44	4.08	.89	.87	.88	3.59	3.74
June 1992	5.37	23.89	5.35	24.33	5.53	.90	.81	.86	4.74	5.06
July 1992	6.70	26.78	6.64	27.06	6.76	.96	.76	.87	5.85	6.26
August 1992	3.39	23.67	5.05	23.78	5.09	.94	.67	.81	4.14	4.61
September 1992	.57	23.61	3.07	23.61	3.07	.79	.55	.68	2.08	2.59
Total	157.72	--	100.83	–	103.27	--	–	--	83.48	92.45

a function of ET_0 and the recurrence interval of precipitation or irrigation events. Non-irrigated upland areas were assumed to have initial k_c values. Upland potential ET was calculated from equation 3, and recurrence interval of precipitation events was determined from NOAA monthly reports (National Oceanic and Atmospheric Administration, 1990; 1991; 1992). Initial (nonirrigation) k_c values ranged from 0.29 during the hot and dry month of July 1990 to 1.00 during eight cool and wet months. Monthly k_c values for nonirrigated, irrigated, and a weighted average of both (total) are listed in table 10. The total monthly k_c values were multiplied by the monthly potential evapotranspiration value for the upland calculated from equation 3. Total actual evapotranspiration for the upland during the study period is calculated to be 83.48 in. or 19.79 in. less than the calculated total potential evapotranspiration. Total actual evapotranspiration for the Black Swamp drainage area during the study period would then be the sum of ET values for the wetland and upland weighted for their relative area or 92.45 in.

The Thornthwaite method was used in this study because only temperature data were needed. Relative humidity, wind speed, and insolation play very important roles in the process of evapotranspiration. Sensitivity of Thornthwaite's calculated evapotranspiration to temperature increases with increasing temperature. At 10 °C a change in monthly temperature of 1 °C will cause a change in calculated evapotranspiration of about 0.4 in. At 25 °C a change in monthly temperature of 1 °C will cause a change in calculated evapotranspiration of 0.7 in. A sufficiently large drainage area and number of months of estimated temperature minimized the temperature error in the same manner as the estimation of total precipitation. Problems in calculating k_c values included different proportions of crops within the Black Swamp drainage area compared to the whole county, different proportion of land being irrigated compared to the proportion reported by the 1987 census, and unknown k_c values for nonirrigated crops.

Ground-Water Pumpage

Water-use data in Arkansas are collected from farmer interviews and stored in the Site Specific Water Use Data System (SSWUDS). These data include ground-water pumpage and well locations. More than 90 percent of the water used is being reported in Arkansas, and steps have been taken to ensure accuracy (T.W. Holland, U.S. Geological Survey, oral commun., 1994). Water-use data for all wells within the Black Swamp drainage area were retrieved for the years of 1990 through 1992 to determine the total amount of ground water pumped onto the surface of the study area. Less than 5 percent of the pumpage occurs outside of the growing season (T.W. Holland, U.S. Geological Survey, oral commun., 1994) so that the total pumpage for 1992 is close to the value of pumpage prior to the end of the study period (September 21, 1992). The water-use retrieval indicated that a total of 117,315 acre-ft of ground water was pumped into the Black Swamp drainage area during the study period. Therefore, pumpage is equivalent to 18.64 in. of water over the drainage area.

Ground-Water Flow through the Bed of the Cache River

Ground-water flow through a porous media is calculated based on the equation of Darcy's law:

$$Q = K \times A \times \frac{(H-h)}{L} \quad (5)$$

where,

Q is the volume of ground-water flow through the porous medium per unit time, in cubic feet per day;

K is the permeability of the porous medium, in feet per day;

A is the cross-sectional area of the porous medium, in square feet, or the width of the porous medium, in feet (w) times the length of the porous medium, in feet (l);

H is the hydraulic head on one side of the porous medium, in feet above sea level;

h is the hydraulic head on the other side of the porous medium, in feet above sea level, and;

L is the thickness of the porous medium, in feet.

In this section the porous medium is the bed of the Cache River, w is the width of the bed of the river (100 ft), l is the reach length of a segment of the river, H is the hydraulic head in the lower part of the alluvial aquifer, and h is the stage of the river. Monthly stages at the five gaging stations along the river and monthly water-level measurements from deep wells near each staff gage were used to calculate the hydraulic head difference between the river and the alluvial aquifer (H - h).

Estimation of the conductance value of the bed of the Cache River is prerequisite to the calculation of ground-water seepage into the river. There have been few direct measurements of the conductance of riverbeds. Riverbed conductance usually is set in ground-water models to cause model output to agree with actual water-level data from wells. The only available value for riverbeds in the Mississippi Alluvial Plain is a vertical hydraulic conductivity value used to calibrate a ground-water model by Ackerman (1989) of 1×10^{-2} ft/d and no information is available about the "thickness" of riverbeds. A conceptual model of the bed of the Cache River is proposed based on field observations. In the conceptual model, the riverbed lies between the Cache River and the water supply to the alluvial aquifer. Because of the sandy nature of the riverbank and the relatively slow stream velocity even during flooding, the conceptual model indicates that the bed of the Cache River is comprised of two layers: a 3-ft-thick layer of the bed of the Cache River (L_R) with a vertical hydraulic conductivity of 1×10^{-1} ft/d, and an underlying 55-ft-thick layer of the alluvial aquifer (L_A) with a hydraulic conductivity of 10 ft/d. The equivalent conductance (C) of these two layers is:

$$C = \frac{1}{\left(\frac{1}{C_R} + \frac{1}{C_A}\right)} \qquad (6)$$

where,

C_R is the conductance of the 3-ft-thick bed of the Cache River or $\frac{K_R}{L_R} = \frac{1 \times 10^{-1}}{3} = 0.0333$ day^{-1}, and;

C_A is the conductance of 55-ft-thick layer of the alluvial aquifer or $\frac{K_R}{L_A} = \frac{10}{55} = 0.1818$ day^{-1}.

From equation 6, C equals 0.0282 day^{-1}.

Ground-water seepage into the Cache River was calculated by segments similar to the calculation of the change in storage (ΔS) discussed in a previous section. Each of four river segments were bounded on both ends by two gaging stations. Hydraulic head in the lower part of the alluvial aquifer was monitored at all five gaging stations. The average rate of ground-water flow, for the study period, through a segment of the riverbed to the Cache River is given by:

$$GR_i = \left(\frac{(H_{Di} - h_{Di}) + (H_{Ui} - h_{Ui})}{2}\right) \times C \times R \times ((M_{Ui} - M_{Di}) \times 5{,}280) \qquad (7)$$

where,

GR_i is the average rate of ground-water flow for the study period through segment "i" of the bed of the Cache River into the Cache River, in cubic feet per day;

H_{Di} is the average hydraulic head, for the study period, in the lower part of the alluvial aquifer beneath the downstream end of river segment i, in feet above sea level;

h_{Di} is the average stage, for the study period, of the Cache River at the downstream end of river segment i, in feet above sea level;

H_{Ui} is the average hydraulic head, for the study period, in the lower part of the alluvial aquifer beneath the upstream end of river segment i, in feet above sea level;

h_{Ui} is the average stage, for the study period, of the Cache River at the upstream end of river segment i, in feet above sea level;

C is the conductance of the bed of the Cache River (0.0282 day^{-1});

R is the river width (100 ft)

M_{Ui} is the river mile of the upstream end of river segment i; and

M_{Di} is the river mile of the downstream end of river segment i.

This equation is similar to the one used to calculate the change in storage from January 17, 1990, to September 21, 1992.

Average values of stage at the five gaging stations and hydraulic head beneath the gaging stations (table 11 and equation 7) are used to calculate the average rate of ground-water seepage, for the study period, into each of the four river segments. At the southernmost river segment between the James Ferry and Cotton Plant gaging stations surface water actually seeped through the bed of the Cache River into the alluvial aquifer at an average rate of 94,300 ft^3/d. The

Table 11. Values of average Cache River stage and hydraulic head in the lower part of the alluvial aquifer and dimensions used to calculate the average ground-water seepage into the Cache River from January 17, 1990, to September 21, 1992

[Conductance of the bed of the Cache River is 0.0282 day^{-1}. h, is the average stage of the Cache River at a gaging station; H, is the average head in the lower part of the alluvial aquifer near a gaging station; GR, is the volume of ground-water flow through the bed of the Cache River; -, surface water is seeping downward into the bed of the Cache River]

						Ground-water seepage to the Cache River (GR)		
Gaging station	Average stage of the Cache River (h, feet)	Average hydraulic head in the lower part of the alluvial aquifer (H, feet)	Average hydraulic head difference (H-h, feet)	Cache River segments (by gaging station)	Cache River segment length (miles)	Average (cubic feet per day)	Total (cubic feet)	Total (inches)
G1	190.86	191.31	0.45					
				G1 to G2	6.2	126,864	124,200,000	0.42
G2	186.84	189.15	2.31					
				G2 to G5	9.4	299,310	293,025,000	.93
G5	181.29	183.20	1.91					
				G5 to G10	7.2	139,448	136,519,000	.45
G10	178.83	179.53	.70					
				G10 to G13	7.7	-94,341	-92,360,000	-.31
G13	175.46	173.11	-2.35					
				TOTAL	30.5	471,281	461,384,000	1.55

other three river segments experienced ground-water seepage into the Cache River at average rates, listed from upstream to downstream, of 126,900; 299,300; and 139,400 ft^3/d, respectively. The net volume of ground-water flow into all four segments of the Cache River for the 979-day study period was 461,383,600 ft^3 or an equivalent of 1.55 in. of water to the drainage area.

The accuracy of the estimate of ground-water seepage into the Cache River in percent is probably very poor. The uncertainty in the conductance value is a main source of possible error. The hydraulic conductivity value of 1×10^{-1} ft/d is an upper limit estimation. If a value of 1×10^{-2} ft/d were used for the 3-ft layer, ground-water seepage into the river would have only been 0.18 in. for the whole study period. Adding another 3 ft to this layer would cause calculated ground-water seepage into the river to only be 0.09 in. The downstream river segment between staff gages G10 and G13 probably also has lower hydraulic conductivity than the other river segments creating the likelihood that GR is closer to the sum of the ground-water seepage into the upper three river segments. The poor accuracy will probably not hurt the water budget because GR is so small compared to the larger components of surface-water inflow and outflow, precipitation, evapotranspiration, and ground-water pumpage.

Infiltration

In this report, infiltration is the recharge of precipitation on the land surface into the alluvial aquifer. Precipitation that infiltrates to recharge the alluvial aquifer does not contribute to surface-water outflow. Infiltration data in eastern Arkansas comes in the form of calibration values of ground-water models. Ackerman (1989; fig. 33) simulated a predevelopment value in the vicinity of Black Swamp drainage basin, of about 1 in/yr. Broom and Lyford (1981) achieved calibration with an infiltration value of 0.4 in/yr, except in areas west of the Cache River where a value of 2 in/yr was used. Ackerman (1990) simulated a 1987-pumpage value in the vicinity of the Black Swamp drainage basin of 1.4 in/yr. Infiltration probably is greatest where the confining unit is absent in the upland area. The low wetland areas within the bluffs are discussed as ground-water flow across the confining unit in a later section. About 20 percent of the upland area or about 10 percent of the Black Swamp drainage area has the confining unit absent (Gonthier and Mahon, 1994). If the infiltration rate in the absent confining unit area (12.3 mi^2) is 2 in/yr and the remaining 80 percent of the upland area (49.4 mi^2) is 1.4 in/yr, then the infiltration rate in the drainage area (127.8 mi^2) is 0.73 in/yr. For the whole study period, total infiltration would be 1.97 in.

The infiltration data come from calibration of models on a scale much larger than the Black Swamp drainage area or absent confining unit areas. Infiltration can be higher within the absent confining unit areas than is mentioned here.If the infiltration rate in the absent confining unit area is 10 in/yr and the remaining 80 percent of the upland area is 1.2 in/yr, then the infiltration rate in the drainage area is 1.43 in/yr or 3.84 in. during the study period.

Ground-Water Flow through the Wetland Confining Unit

Ground-water flow volume through the wetland confining unit at a given location for the study period can be calculated using:

$$GW_{NS} = C \times \Delta H \times X \times 979 \tag{8}$$

where,

GW_{NS} is the net flow or seepage of ground water to the wetland surface at nested site NS for the study period (979 days), in feet;

C is the conductance of the wetland confining unit $\frac{K}{L}$ (the vertical hydraulic conductivity divided by the thickness) at the nested site in day^{-1};

ΔH is the average difference in hydraulic head at the nested site when ground-water/surface-water interaction is occurring, in feet, and;

X is the proportion of time during the study period when ground-water/surface-water interaction could occur at the nested site.

Ground-water and surface-water heads from eight nested sites were used to determine the difference in hydraulic head (ΔH) between the upper part of the alluvial aquifer and the surface water or land surface in the wetland. ΔH is similar to (H - h) in equation 5 except that a special case is made when the land surface is not inundated, but hydraulic head level is higher than the land surface. In this case, ΔH equals the hydraulic head minus the land-surface altitude. Otherwise, ΔH equalled the hydraulic head minus the surface-water level. Hydraulic head of the alluvial aquifer was never below the bottom of the confining unit while the land surface was inundated. Average hydraulic head difference ranged from -1.21 ft at N8 to 0.76 ft at N5 (table 12). Hydraulic head difference at any given time of measurement ranged from -3.09 ft at N8 on January 19, 1990, to 2.40 ft at N5 on June 19, 1990.

Based on field observations during drilling, the top 1 ft of sediment has a high hydraulic conductivity due to macroporosity. The rather tight clay below the zone of macropores is the actual confining unit for the wetland and is assumed to have a value of hydraulic conductivity of 1.51 x 10^{-3} ft/d. Confining unit thickness ranges from 2 ft at N11 to 9 ft at N9.

Ground-water/surface-water interaction can only occur when either the land surface is inundated or hydraulic head in the alluvial aquifer is above land-surface altitude. Only visits that included all wells and staff gages in the entire study area (33 monthly visits, table 1) were used to determine the proportion of time that ground-water/surface-water interaction could occur during the study period. Only when ground-water/surface-water interaction could occur were the conductance C and average difference in hydraulic head ΔH used to calculate the flow at ground water through the wetland confining unit. A difference in hydraulic head must exist before ground-water/surface-water interaction actually occurs. The proportion of time that ground-water/surface-water interaction could occur during the study period at a nested site ranged from 12 percent for N4 to 94 percent for N6.

An average 0.11 in. of ground water seeped into the wetland during the study period (table 12). Net surface-water seepage into the ground for the study period occurred at four of the eight well nest sites. At site N8, surface-water seepage through the wetland confining unit into the alluvial aquifer was 1.63 in. Net ground-water seepage to the surface for the study period occurred at the other four well nest sites. At site N5, ground-water seepage onto the wetland surface was 1.97 in.

Table 12. Values used to calculate the net ground-water seepage from the upper part of the alluvial aquifer onto the wetland surface from January 17, 1990, to September 21, 1992

[Vertical hydraulic conductivity of the confining unit is 1.51×10^{-3} feet per day. Average net ground-water seepage is not corrected for local ground-water flow. ΔH, average difference in hydraulic head between the surface and ground water at a nested site; L, thickness of the confining unit at a nested site; C, conductance of the confining unit at a nested site; discharge, ground-water seepage onto the wetland surface; X, the proportion of time that ground-water/surface-water interaction could occur at a nested site during the study period; -, (excluding exponents) on average surface-water levels were higher than ground-water levels and net surface-water seepage into the ground occurred]

Nested site	Average difference in hydraulic head (ΔH, feet)	Confining unit thickness (L, feet)	Confining unit conductance (C, day^{-1})	Average daily discharge (feet per day per square foot)	X	Net discharge (inches per square foot)
N5	0.76	6	2.52×10^{-4}	1.91×10^{-4}	0.879	1.97
N6	.31	8.5	1.77×10^{-4}	5.54×10^{-5}	.939	.61
N11	.10	2	7.55×10^{-4}	3.10×10^{-5}	.394	.24
N7	.01	3	4.03×10^{-4}	6.38×10^{-6}	.455	.03
N8	-1.2	4	3.77×10^{-4}	4.58×10^{-4}	.303	-1.63
N4	-.25	4	3.78×10^{-4}	-9.31×10^{-5}	.121	-.13
N12	-.12	5	3.02×10^{-4}	-3.61×10^{-5}	.727	-.31
N9	-.06	9	1.68×10^{-4}	-4.70×10^{-6}	.485	-.06
AVERAGE						0.11

Accuracy in the calculation of ground-water seepage into the wetland is limited by the high standard deviation in values (1.01 in.) compared to the average value (0.11). Evidence is statistically insufficient to determine whether net surface-water seepage into the ground or ground-water seepage into the surface occurred in the wetland though more surface water seeped into the ground near Transect D-D' and more ground water seeped to the surface near Transect B-B'. Water flow through the wetland confining unit consists of three components mentioned earlier: (1) ground-water discharge, (2) ground-water recharge, and (3) local ground-water flow. Local ground-water flow is part of other components in the wetland water budget such as SO, P, and W because surface water in the wetland still ends up as surface water (in the Cache River). Preliminary results indicate that the volume of water associated with ground-water discharge, ground-water recharge, and local ground-water flow during the study period are 0.56, 0.33, and 0.12 in., respectively. Excluding 0.12 in. of local ground-water flow makes the value of ground-water discharge through the wetland confining unit closer to 0.23 in. in the wetland (66.1 mi^2) or 0.12 in. in the drainage area (127.8 mi^2). Ground-water seepage values will not create a large problem with the wetland water budget because these values are nearly insignificant compared to the larger components of surface-water inflow and outflow, precipitation, evapotranspiration, and ground-water pumpage.

Adding the Components of the Black Swamp Water Budget

The error values in equation 1 e_S, e_{SO}, e_{SI}, e_P, e_E, e_W, e_{GR}, e_I, and e_{GW} are not known. Equation 1 can then be modified to:

$$e_{TOT} = -SO + SI + P - E + W + GR - I + GW - \Delta S \qquad (9)$$

where, e_{TOT} is the sum of all errors. Ideally, all errors should be close to zero. Therefore, e_{TOT} should be close to zero. All components were calculated prior to estimation of e_{TOT}. The summation of all components indicates that there is a surplus of 18.64 in. (table 13). Pumpage volume being the same as the surplus is considered a coincidence. A significant volume of pumpage flows into the Cache River and is lost to evapotranspiration so that pumpage can not make up all of the 18.64 in. of surplus. The summation of the four largest components, SO, SI, P, and E being very close to zero (0.31) also is considered coincidence because the other components (including pumpage) can not be discounted. Actual pumpage may be even larger than reported pumpage increasing the surplus. If we use the greater value of infiltration (3.84) the e_{TOT} would be 16.77 in. Any other modification of component values would be calibrations to balance the water budget. E and SI - SO could be increased 5 and 4 in., respectively, and still be within their error margin while decreasing the surplus to about 8 in. But a better way to account for the surplus is to consider the possibility of unmeasured surface-water outflow. Farmers have built many surface-water diversion canals near the southwestern boundary of the drainage area. A significant volume of water possibly is leaving the system unmeasured. Some of these drainage canals are seen along the roadside. Assuming that two canals with a 50 ft^2 cross section area removed 5.54×10^9 ft^3 (18.64 in.) of surface water from the drainage area during only 25 percent of the study period, velocity in the canal would only be 2.62 ft/s or nearly 1.8 mi/hr. Flow velocities this high are commonly in diversion canals (A.P. Hall, U.S. Geological Survey, oral commun., 1994).

Table 13. Water volumes of components used to calculate the water budget of the Black Swamp drainage area from January 17, 1990, to September 21, 1992

[in., inch; -, water volume is leaving the drainage area; +, water volume is entering the drainage area; ?, estimated error is uncertain; <, less than; NA, not applicable]

Water budget component	Symbol in equations 1 and 9	Volume of water (in.)	Estimated error (in.)
Surface-water outflow	SO	-474.49	7
Surface-water inflow	SI	+409.53	9
Precipitation	P	+157.72	1
Evapotranspiration	E	-92.45	5?
Pumpage	W	+18.64	1?
Ground-water flow through the bed of the Cache River	GR	+1.55	<1
Infiltration	I	-1.97	1.5?
Ground-water flow through the wetland confining unit	GW	+.12	1
Change in storage	ΔS	-.01	<1
Net sum of all actual errors	e_{TOT}	+18.64	NA

Ground-water flow was a minor component of the water budget. Infiltration, the principle outflow ground-water component, made up 0.35 percent of the total outflow, and ground-water seepage through the bed of the Cache River and the wetland confining unit, the principle inflow ground-water components, made up 0.26 percent of the total inflow. All three ground-water components lacked information concerning parameters used to calculate water volumes and true values of these component may be plus or minus one order of magnitude. Even if the proportion of the water budget that is ground-water flow in terms of water volume is small compared to other water budget components, ground-water seepage to the surface may still be important to vital wetland functions.

SUMMARY

The U.S. Geological Survey, working in cooperation with the U.S. Army Corps of Engineers, Waterways Experiment Station, collected surface-water and ground-water data from 119 wells and 13 staff gages from September 1989 to September 1992 to describe ground-water flow patterns and water budget in the Black Swamp, a bottomland forested wetland in eastern Arkansas. The study area is located in Woodruff County in a regional lowland called the Mississippi Alluvial Plain. The lowland is 10 to 20 feet lower in altitude than the upland of the alluvial plain and comprises small alluvial valleys within the alluvial plain. The Black Swamp wetland is bottomland forested wetland contained within the small alluvial valley of the Cache River. Agricultural land use is prevalent on the upland of the alluvial plain surrounding the Black Swamp.The Black Swamp drainage area, for which the water budget was developed, is the drainage area between two streamflow gaging stations located about 30.5 river miles apart on the Cache River. The Black Swamp drainage area between these gaging stations is 127.8 mi^2. Alluvial deposits of Quaternary age, which comprise the Mississippi River Valley alluvium underlie the Black Swamp. The alluvium consists of two distinct but gradational lithologies; clays and silts of the Mississippi River Valley confining unit overlie coarse sands and gravels of the Mississippi River Valley alluvial aquifer that decrease in grain size toward the surface. The confining unit impedes the flow of water between the surface and the alluvial aquifer. The Cache River breaches the confining unit and has a riverbed comprised of a mixture of silt and sand.

Ground-water flow patterns in the Black Swamp were studied from five different perspectives: (1) areal distribution of head in the upper part of the alluvial aquifer using shallow wells, (2) areal distribution of head in the lower part of the alluvial aquifer using deep wells, (3) general vertical distribution of head along two transects perpendicular to the Cache River using wells and staff gages, (4) vertical distribution of head at ground-water-flow study sites along the two transects, and (5) comparison of highly localized vertical head between a shallow well and an adjacent staff gage in a nested site. Monthly measurements of surface-water and ground-water head were collected plus more frequent measurements including continuous records.

Hydraulic heads in the upper part of the alluvial aquifer generally were 10 to 12 ft higher in the northwestern part of the study area than in the southern part. Hydraulic heads in the lower part of the alluvial aquifer generally were 16 to 18 ft higher in the northwestern part of the study area than in the southern part of the study area and as much as 28 ft higher in the northwestern part of the study area than at a persistent cone of depression in the southwestern part of the study area. The general distribution of horizontal head gradients in the alluvial aquifer was similar for all months from September 1989 to July 1991. Ground-water flow was from northwest to southeast for much of the study area except near the Cache River where flow sometimes was towards the Cache River.

Vertical head gradients near land surface along two transects within the Black Swamp and perpendicular to the Cache River changed orientation often from December 1989 to September 1992. Orientation of head gradients generally was either downward from the Cache River and wetland to the lower part of the alluvial aquifer or upward from the lower part of the alluvial aquifer to the Cache River and wetland. Ground water seeped to the surface at the ground-water-flow study sites in the wetland and in the Cache River channel, on the average, 31 and 58 percent of time, respectively. Surface water seeped downward at the ground-water-flow study sites into the wetland surface and into the bed of the Cache River, on the average, 67 and 35 percent of the time, respectively. Ground water seeped out one bank of the Cache River and surface water seeped into the opposite bank, on the average, 7 percent of the time. Surface water seeped into the ground at the ground-water-flow study sites in the wetland and then flowed toward the Cache River, on the average, 28 percent of the time, and toward the lower part of the alluvial aquifer, on the average, 39 percent of the time.

A hydraulic connection between the surface water in Black Swamp or the Cache River and the alluvial aquifer is indicated by simultaneous and nearly equal changes in surface-water and ground-water levels near the Black Swamp wetland. Water-level fluctuations in deep wells closer than 2.5 mi from the Cache River were similar to stage fluctuation except during the growing season when water levels drew down in response to pumpage. Water-level fluctuations in deep wells farther than about 2.5 mi from the Cache River were not very similar to stage fluctuations of the Cache River and responded to the wet season and summer pumpage and not to individual floods and low flows on the Cache River.

Diurnal fluctuations of hydraulic head occurred in all four shallow wells that were installed with continuous recorders. Amplitudes of diurnal head fluctuations generally were from more than 0 to 0.38 ft and generally were largest in late summer. Diurnal fluctuations of head are caused by uptake of ground water by evapotranspiration. Diurnal fluctuations in head beneath the confining unit indicate that the confining unit does not impede plants from getting water from beneath the confining unit.

The hydraulic-head fluctuations of the alluvial aquifer lag behind stage fluctuations and result in changes in hydraulic-head gradients that create the potential for changes in general ground-water movement. Differences between surface-water levels of impounded water in the wetland and stage of the Cache River complicate the matter by adding a frequently occurring local ground-water flow condition in which surface water in the wetland seeps down into the upper part of the alluvial aquifer and then seeps into the Cache River. When the Cache River is flooding the wetland, nested well sites consistently follow a pattern of ground-water seepage to the surface during falling surface-water stages and surface-water seepage into the ground during rising surface-water stages. When the river stage is below the altitude of the wetland, different nested sites respond differently to falling and rising surface-water levels depending on three heads: (1) wetland surface-water level, (2) stage of the Cache River, and (3) hydraulic head in the lower part of the alluvial aquifer.

The hydrologic-budget equation of the Black Swamp is based on the conservation of mass--that a change in surface-water volume for a given time period is equal to the sum of the water inflows and outflows. Daily surface-water discharge at gaging stations, hydraulic conductance values in literature, ground-water and surface-water data from the 119 wells and 13 staff gages, drillers' logs, and water-use data were used to calculate surface-water and ground-water components. Weather data from the National Oceanic and Atmospheric Administration monthly reports and annual Arkansas Agricultural Statistics were used to estimate precipitation and evapotranspiration. The budget was calculated for the period from January 17, 1990, to September 21, 1992, when change in storage was minimal (0.01 in.). Surface-water inflow and outflow were 409.53 and 474.49 in., respectively. Precipitation and evapotranspiration were 157.72 and 92.45 in., respectively. Ground-water pumpage, flow through the bed of the Cache River, infiltration, and flow through the wetland confining unit were 18.64, 1.55, 1.97, and 0.12 in., respectively. The summation of all components indicates that there is a surplus of 18.64 in. The surplus may be caused by surface-water diversion canals draining water away from the drainage area unmeasured. Even if the proportion of the water budget that is ground-water flow in terms of water volume is small compared to other water budget components, ground-water seepage to the surface may still be important to vital wetland functions.

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