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Hydrologic Study of Illinois Beach State Park

by ADRIAN P. VISOCKY

ILLINOIS STATE WATER SURVEY

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CONTENTS

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HYDROLOGIC STUDY OF ILLINOIS BEACH STATE PARK

by Adrian P. Visocky

ABSTRACT

The study area, including Illinois Beach State Park, is a 6.7-square-mile strip of land along Lake Michigan near the Wisconsin border. Roadway and basement flooding at the park lodge have been a problem in recent years. A hydrologic study to gather groundwater, stream, and Lake Michigan water level data and water samples, as well as precipitation records, from January 1975 to April 1976 was undertaken. The data are presented in tables, graphs, and maps.

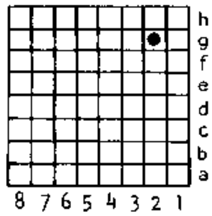
Surface drainage is impeded when barrier bars are built by the lake at the mouths of the major streams: Lake Michigan Tributary, Kellogg Ravine, Bull Creek, and Dead River. Periodically, breakthrough events occur which allow the streams to drain. Drainage is poorest in the park area from Wadsworth Road southward. Data show that Bull Creek is effectively rerouted south to Dead River rather than through its natural channel northward under Wadsworth Road. Channelization of Bull Creek directly south to Dead River might be a solution to both roadway flooding and long-term ponding in Dead River. Groundwater dissolved solids ranged between 301 and 1076 milligrams per liter (mg/l), and Dead River dissolved solids ranged between 196 and 491 mg/l. No major hydrologic problems are anticipated in the northward expansion of the park.

INTRODUCTION

Illinois Beach State Park, located along the shores of Lake Michigan east of Zion, is a popular recreational site for the people of northeastern Illinois and southern Wisconsin. As described in the park brochure, "the beach, the large expanses of marsh and prairie vegetation, the abundant wildlife, the migratory birds, the dunes and its location on Lake Michigan combine to make the dunes area a unique natural resource for the people of Illinois." With its lakefront location, however, the park is not without its problems. A receding shoreline, eroded by high Lake Michigan levels of recent years, has resulted in sometimes severe property damage, not only in the park but along much of the lake shore north of Chicago. High water table levels have resulted in basement flooding of the park lodge. Roadways are often flooded in low sections during heavy storms. Northward expansion of the park is in progress, and there is some concern that the same problems will occur in the northern part of the area. This study is intended to gather hydrologic data which hopefully will be of use in determining the causes of existing problems and possibly in anticipating future problems in the northern extremities of the park.

Instrument Location System

Piezometers and staff gages described in this report are given P- and S- designations for identification, but their locations are given in the standard State Water Survey form by township, range, and section. The location number consists of five parts: county abbreviation (LKE), township (T), range (R), section, and coordinates within the section. Sections are divided into rows of 1/8-mile squares. Each 1/8-mile square contains 10 acres and corresponds to a quarter of a quarter of a quarter section. A normal section of 1 square mile contains 8 rows of 1/8-mile squares; an odd-sized section contains more or fewer rows. Rows are numbered from east to west and lettered from south to north as shown in the diagram. The location shown is LKE 46N12E-10.2g.



Lake County
T46N, R12E
Section 10

Acknowledgments

The author wishes to express his gratitude to Mrs. Nancy F. Gangler who made weekly trips from the State Water Survey Warrenville office to the study area to collect the data and water samples. Special thanks are due also to Curtis R. Benson and John Mende, also of the Warrenville office, for their assistance in installing and maintaining the necessary instrumentation. Appreciation is expressed to George R. Boyd and James A. Harry for designing and fabricating special field equipment; to Laurel M. Henley and Arthur H. Bodenschatz for analyzing the water samples; to Mrs. Karen A. Kabbes for keypunching and Robert A. Sinclair for processing field data for correlation analysis; to Robert E. Needham and his staff of park rangers for their generous cooperation and assistance to our field personnel; and to the Johns-Manville Corporation for allowing access through their property to the southern extremities of the park.

The report was prepared under the general supervision of Dr. William C. Ackermann, Chief of the State Water Survey, and John B. Stall, Head of the Hydrology Section. Much appreciation goes to Richard J. Schicht for his technical review of the report, to James P. Gibb for several stimulating discussions, to Mrs. Becky J. Howard and Mrs. Betty A. Dowling for typing the original manuscript, to Mrs. J. Loreena Ivens and Mrs. Patricia A. Motherway for final editing, to Mrs. Suzi O'Connor for preparing the camera-ready copy, and to John W. Brother, Jr., and William Motherway, Jr., for their work in preparing the illustrations.

STUDY AREA AND METHODS

Description of Study Area

General Features

The study area is a 6.7-square-mile strip of land along Lake Michigan, extending from the Wisconsin border 7 miles south to the Johns-Manville Corporation plant, east of Waukegan (figure 1). The width of the study area from the shoreline to the bluff is about one mile, varying perhaps 10 to 15 percent. The general area has been described in recent geologic studies (Hester and Fraser, 1973; Fraser and Hester, 1974) as a "beach ridge complex" in which simultaneous erosional and aggradational processes cause the system to be transitory and highly mobile.

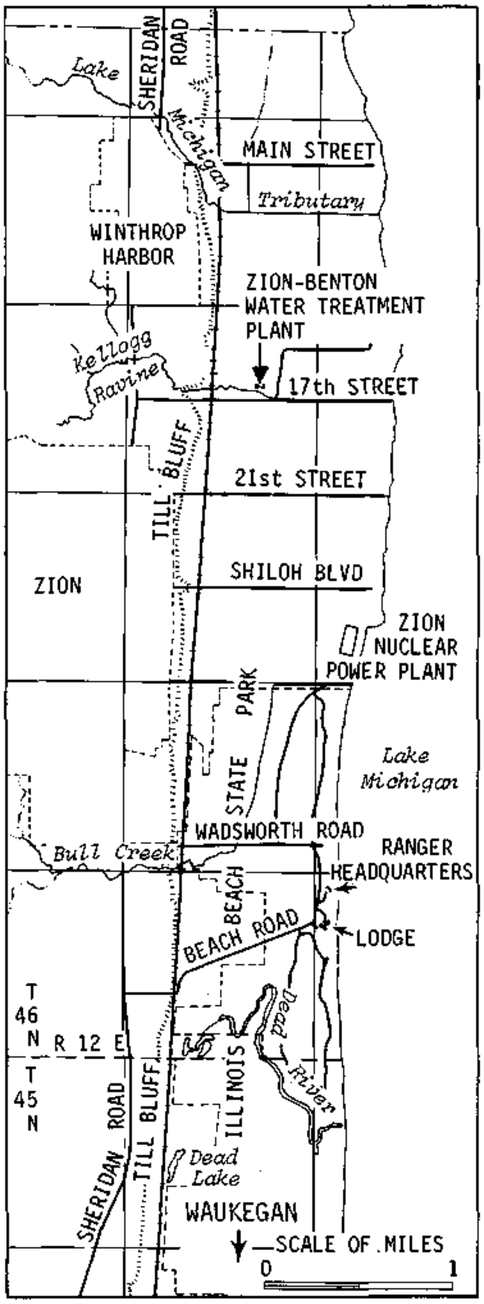


Figure 1. Physical features of study area

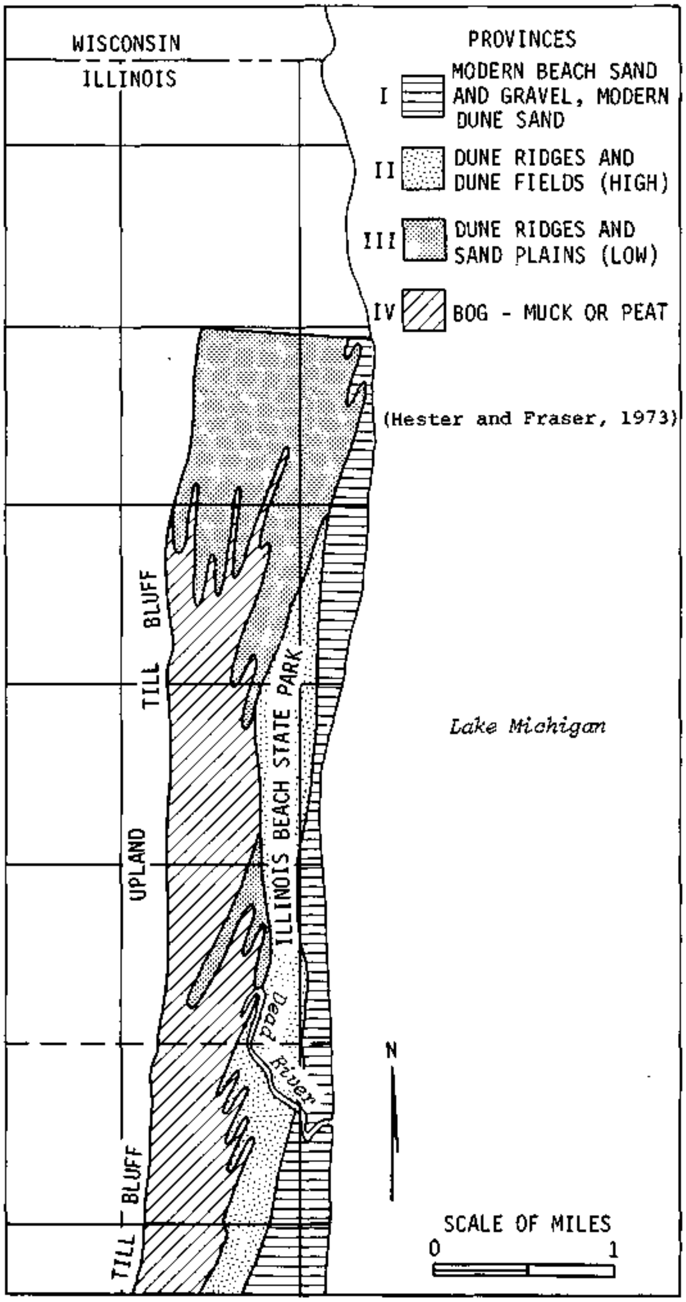


Figure 2. Geologic province map

Hester and Fraser (1973), for example, describe changes in the shoreline over an 83-year period (1872-1955) in which considerable shoreline erosion took place north of 21st Street and deposition added to the beach south of Dead River. Between 21st Street and the Dead River outlet the shoreline has remained essentially unchanged.

The beach ridge complex is bounded on the west by a glacial till bluff which stands 50 to 60 feet above the average level of the study area. The subaqueous portion of the complex extends some 1.5 miles out into Lake Michigan. According to Hester and Fraser (1973) the complex is composed morphologically of several environments. Those observed in the subaerial portion include beach ridges, dune ridges, sand plains, and marshes (figure 2). The complete sand body is elongate north to south and prismatic east to west and is as much as 35 feet thick (figures 3 and 4). The material comprising the subaerial portion of the complex is, for the most part, a fine sand, with the coarsest material along the beach and finest material westward in the marsh areas.

Vegetation in the study area varies with the geologic environment, progressing from sparse vegetation along the shore to many sand-binding plants (scrub oak and pine forests) along the dune ridges, to the sand plains with many varieties of grasses, and finally to the large marsh areas dominated by cattails and bulrushes (figures 5-7).

The southern half of the area comprises Illinois Beach State Park, a 1917-acre site purchased by the state in 1948. According to the park brochure (State Department of Conservation) the area south of Beach Road (approximately the southern half of the park and the southern quarter of the study area) was dedicated in 1964 as the first Illinois nature preserve. The brochure states, "Many species of ducks, geese, gulls, shore birds and occasionally a bald eagle, osprey, or peregrine falcon can be seen during the spring and fall migrations."

Topographic relief is minimal, with ridges and hummocky sand plains standing 2 to 5 feet above adjacent marsh areas. One ridge at the Park Ranger Station has about 10 feet of local relief.

Precipitation, measured 6.5 miles southwest of the park lodge at Radio Station WKRS, averages 32.63 inches per year.

Surface Drainage

Runoff from the bluff and study area to Lake Michigan is accomplished by three streams shown in figure 1: Lake Michigan Tributary at Winthrop Harbor, Kellogg Ravine between Winthrop Harbor and Zion, and Bull Creek just south of Zion. During heavy storm periods a fourth stream — Dead River — routes much of the Bull Creek flow southward and drains the nature preserve. Most of the year Dead River is simply a ponded stream for which drainage into the lake is impeded by a barrier bar, a continuous wave-produced beach deposit shown in figure 8, at its mouth. Actually, during dry weather baseflow periods, all of the streams become blocked at their mouths.by barrier bars, and Lake Michigan Tributary dries up for several months *(see figure 20).*

Nature and Purpose of Study

Recent high Lake Michigan stages have caused considerable erosional damage along beaches and shoreline bluffs north of Chicago. The shoreline of the beach ridge complex which extends from Kenosha, Wisconsin, to Waukegan, Illinois, is undergoing extensive erosion with resultant loss of property (figure 9) and abandonment of homes (figure 10). A recent problem of high groundwater levels which has manifested itself in basement flooding at the park lodge has also been tentatively ascribed to the high lake levels. An alternative judgment places the blame on the poor drainage in the nature preserve area. Whatever the cause, similar problems could plague the park expansion now in progress (plans call for extending the park northward to the state line).

Another problem for park officials is roadway flooding during periods of heavy rainfall. Prominent trouble spots occur along Wadsworth Road at the Bull Creek drainage culvert and along Beach Road at the Dead River culverts.

In order to resolve the causative factors of existing problems and to anticipate future difficulties associated with expansion efforts, a better understanding of the hydrology of the

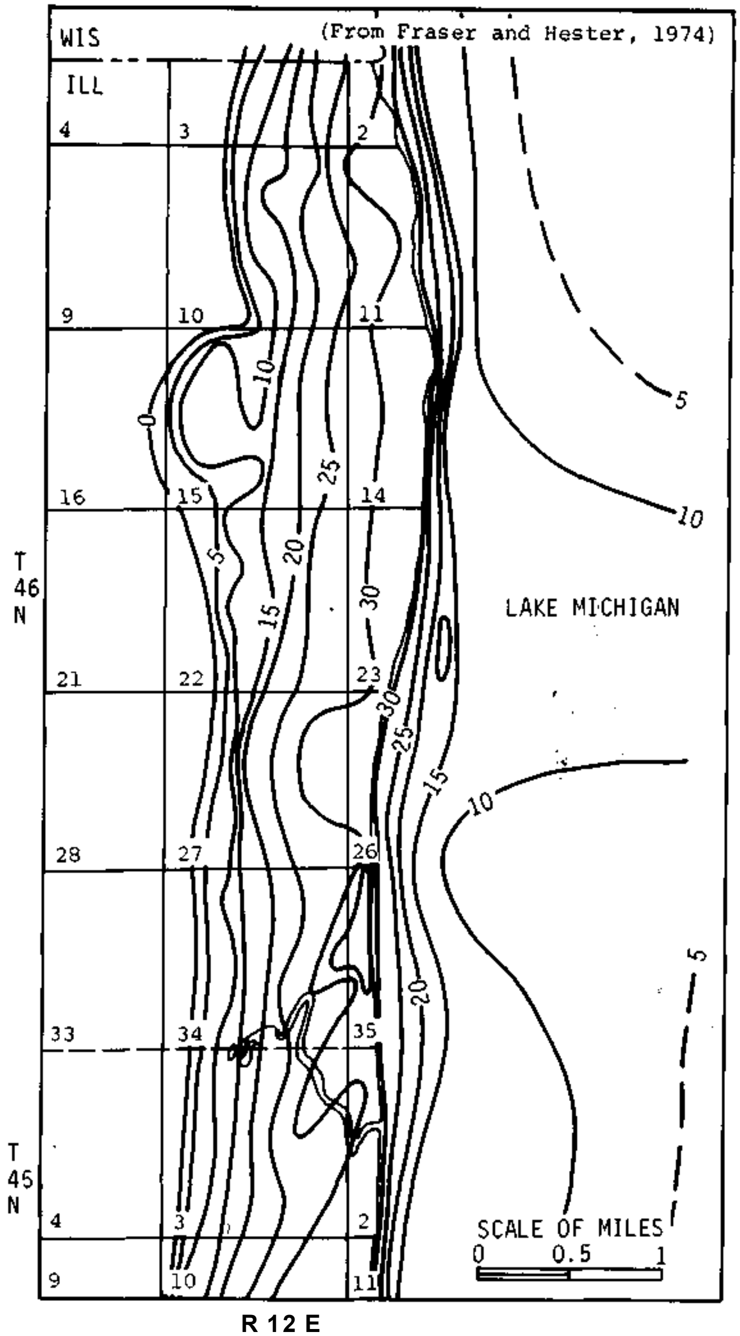


Figure 3. Isopach map of sand body showing contours in feet of thickness

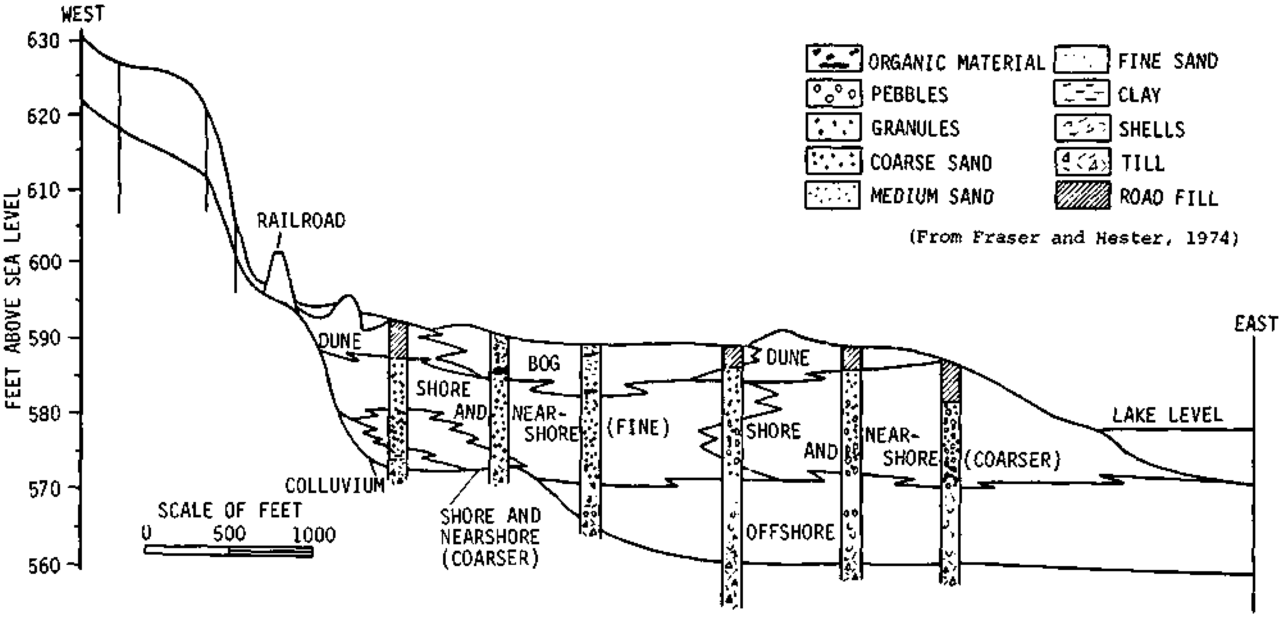


Figure 4. East-west cross section through sand body along Wadsworth Road

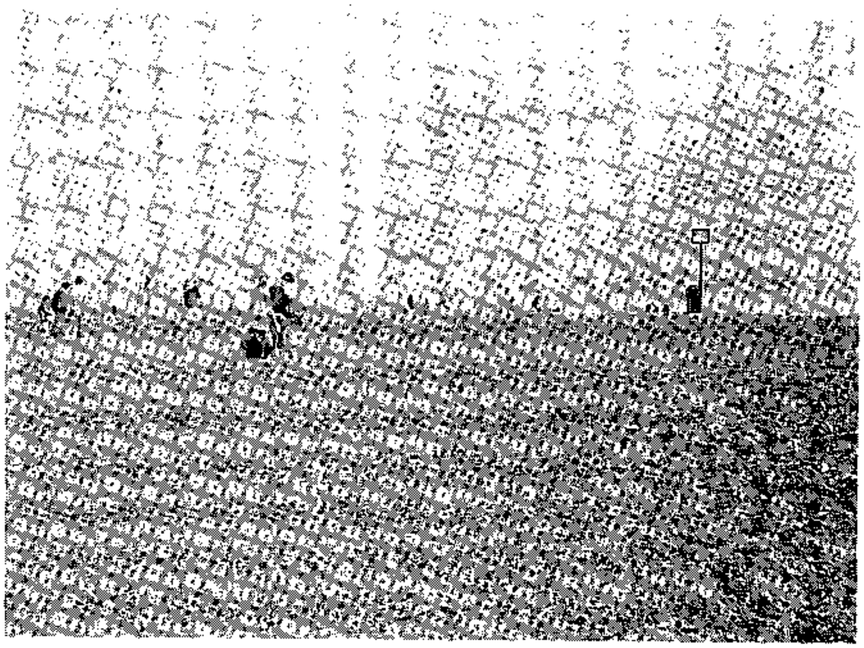


Figure 5. View of beach at end of Wadsworth Road

Figure 6. Dune ridge south of P-17

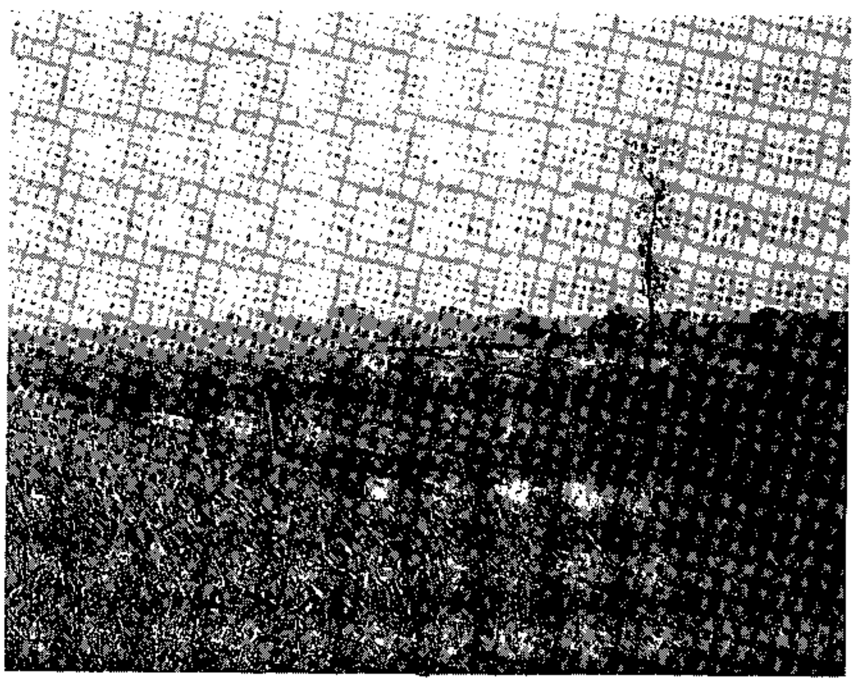


Figure 7. View from P-18, looking northeast across marsh toward wooded dunes

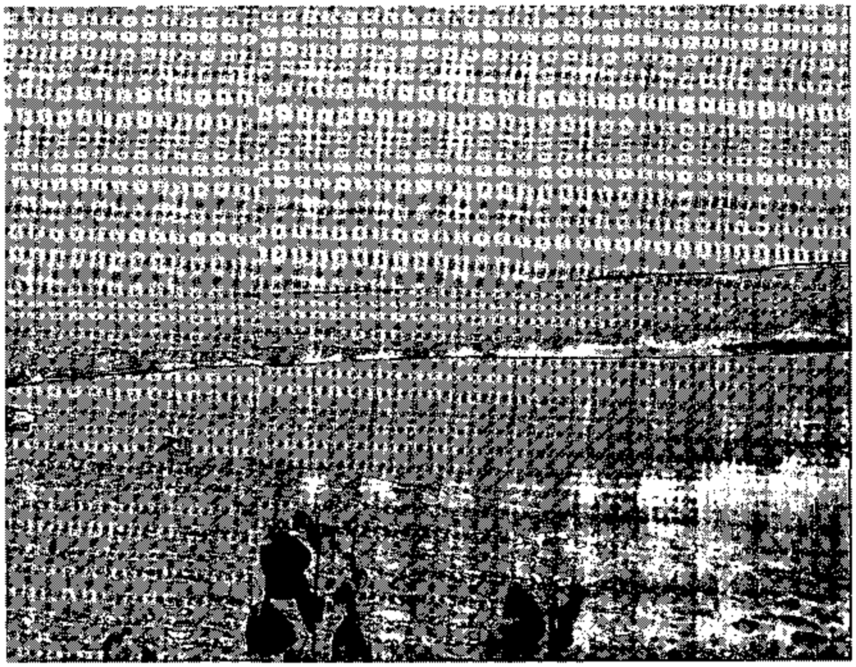


Figure 8. Barrier bar across mouth of Dead River at lake

park is needed. The purpose of this investigation has been to monitor selected hydrologic elements including precipitation, groundwater and surface water stages, Lake Michigan stages, and water quality variation within the area, and to use the resulting data to aid in determining the interrelationships of these elements.

Instrumentation

Piezometers

Instrumentation of the study area commenced in December 1974 when a contract was implemented to drill 1 well and 18 piezometers. This work was completed by mid-December. Piezometers, driven to depths of 5 to 25 feet, consisted of 1.25-inch diameter galvanized pipe attached to 30-inch long, 10 slot, Johnson well points. Figure 11 shows piezometer locations, and table 1 summarizes their depths and other pertinent information. Piezometers 9, 10, and 11 were clustered 2 feet apart (figure 12), midway along the south side of Wadsworth Road and were driven to depths of 5, 15, and 25 feet, respectively, in order to sample and monitor vertical variations in groundwater quality and water levels. Threaded, removable caps were screwed to the top of the piezometers.

Figure 11 shows piezometers located along easily accessible roads in such arrays as to survey four sections across the study area. Additional piezometers (P-16, P-17, and P-18) were placed at available sites within the nature preserve. Limited accessibility precluded a more widespread distribution of monitoring sites within the marshy portions of that area. Access to P-18 was through the Johns-Manville Corporation property at the south edge of Illinois Beach State Park.

Piezometer depths were selected to monitor and sample the approximate midpoint of

Figure 9. Destroyed road at 21st Street and lake

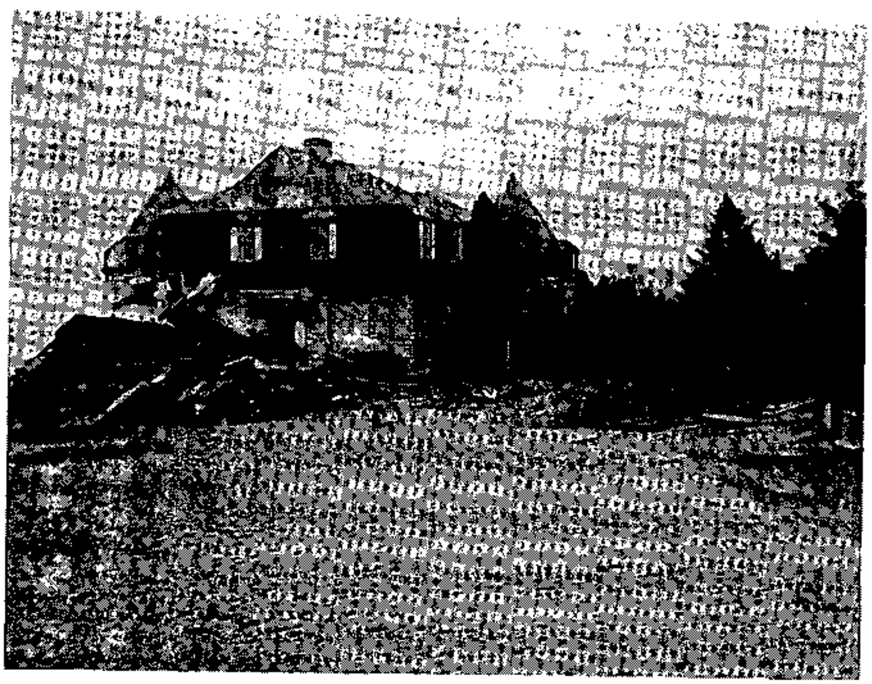


Figure 10. Abandoned house east of Winthrop Harbor

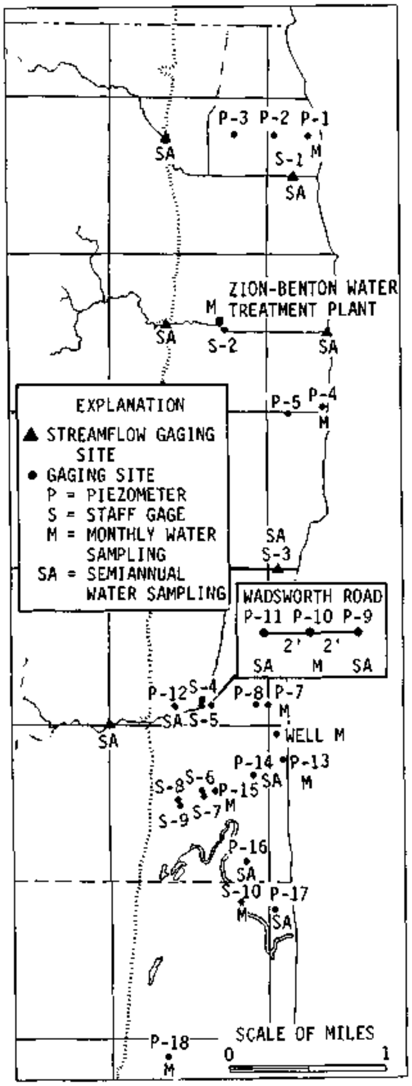


Figure 11. Location of instrumentation for data collection

the aquifer thickness, as shown in figure 3. Depths of piezometers P-9, P-10, and P-11 were selected to monitor the aquifer at its 20 percent depth, 60 percent depth, and and at its bottom, respectively.

Table 1. Monitoring Sites for Groundwater and Surface Water Stages

Groundwater data

Location	*Piezometer*	*Depth (ft)*	*Measuring point elevation (msl)*
LKE 46N12E-			
11.6g	P-1	15	585.85
11.8g	P-2	15	587.55
10.2g	P-3	10	588.31
14.6a	P-4	15	587.96
23.7h	P-5	15	588.06
15.3a	P-6	12	587.86
26.8b	P-7	15	587.05
27.1b	P-8	15	588.28
27.3b	P-9	5	588.37
27.3b	P-10	15	588.09
27.3b	P-11	25	588.11
27.5a	P-12	10	594.20
35.8h	Recorder well	35	594.25
35.8g	P-13	17	587.58
34.1f	P-14	15	586.74
34.3e	P-15	12	586.36
34.2b	P-16	15	589.60
LKE 45N12E-			
2.8g	P-17	15	589.95
10.6h	P-18	15	588.30

Surface water data

Location	*Staff gage*	*Reference point elevation* (msl)*
LKE 46N12E-		
11.7d	S-1	585.00
15.3e	S-2	587.41
26.8h	S-3	585.50
27.4b	S-4	588.79
27.4b	S-5	589.15
34.4e	S-6	586.02
34.4e	S-7	585.92
34.5e	S-8	585.87
34.5e	S-9	586.38
LKE 45N12E-		
3.2h	S-10	586.43

*Reference point is 3.00-inch mark on gages and point of red arrow at S-2

NOTE: All data were recorded weekly with the exception of the recorder well which was measured continuously.

Recorder Well

One of the aims of the study was to investigate the relationship between near-shore groundwater stages and those of Lake Michigan. A continuous, automatic water-level recorder was therefore installed on a 35-foot deep well, drilled through the aquifer near the Park Ranger's Headquarters *(see figure 1).* The site selection was based chiefly on considerations of security, since vandalism could not be adequately curtailed elsewhere. The well construction features included a 5-inch diameter steel casing set to a depth of 20 feet and a 4-inch diameter,

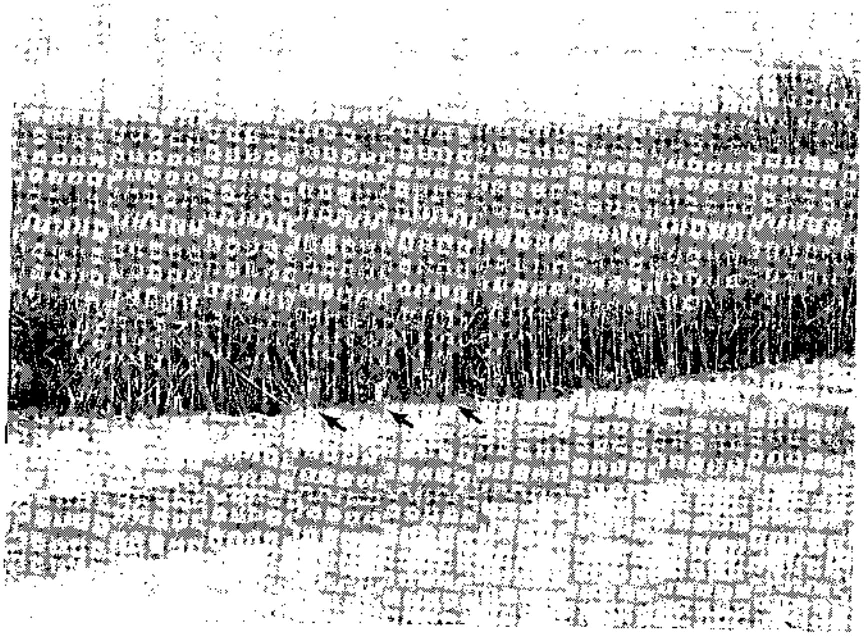


Figure 12. Piezometers 9, 10, and 11 along Wadsworth Road

Figure 13. Recorder well instrumentation

10 slot PVC screen from 20 feet to 35 feet. The recording equipment consisted of a Keck water-level sensor in combination with a Stevens Type F recorder fitted with 1:1 float gears and weekly time gears. The recorder well instrumentation is shown in figure 13.

Staff Gages

Surface water stages were monitored with staff gages installed at nine sites. An additional site (S-2) along Kellogg Ravine was not suitable for the installation of a staff gage, therefore, measurements at that site were made from a marked datum on the downstream edge of a bridge. Staff gages were installed along the three major streams, at the old bridge crossing Dead River, and in pairs on opposite ends of three road culverts beneath Wadsworth Road and Beach Road. The purpose of the paired gages was to test the effectiveness of the culverts as drains or, conversely, to test the effect of the roadways as dams in retarding drainage within the park. Figure 14 shows a typical staff gage installation.

Monitoring and Sampling

Water Levels

Groundwater and surface water stages were measured on a weekly basis, and the field data were converted to mean sea level elevations. Elevations of measuring points and reference marks were surveyed by a registered land surveyor in April 1975. Daily mean groundwater stages were read off the recorder well charts; unfortunately, battery and short-circuit problems hampered data collection at the recorder well, which accounts for numerous breaks in that hydrograph *(see figure 19).* Occasionally, poor weather made the access road to the Dead River area impassable and prevented data collection at P-16, P-17, and S-10.

Lake Michigan Stages

Lake Michigan stages are continuously monitored by a remote controlled digital recorder network operated by the National Oceanic and Atmospheric Administration of the U.S. Department of Commerce in Detroit, Michigan. Daily mean stages at two of the network recorder sites closest in proximity to the study area — Milwaukee, Wisconsin, and Calumet Harbor, Illinois — were furnished to the author by the National Oceanic and Atmospheric Administration. The daily mean stage for the study area was taken to be the average of the daily values at those two sites.

Precipitation

Daily precipitation data were obtained from the weather station operated by Waukegan radio station WKRS, located 3 miles west-southwest of the Waukegan Post Office and 6.5 miles southwest of the Illinois Beach State Park lodge. Although not as conveniently located, the Waukegan station was sufficiently close to provide useful precipitation data for the study and was a welcome alternative to the maintenance and security problems inherent with an unattended raingage installation.

Streamgaging

On April 23, 1975, a field crew from the U.S. Geological Survey Subdistrict Office in Oak Park, Illinois, conducted a series of stream discharge measurements at the request of the

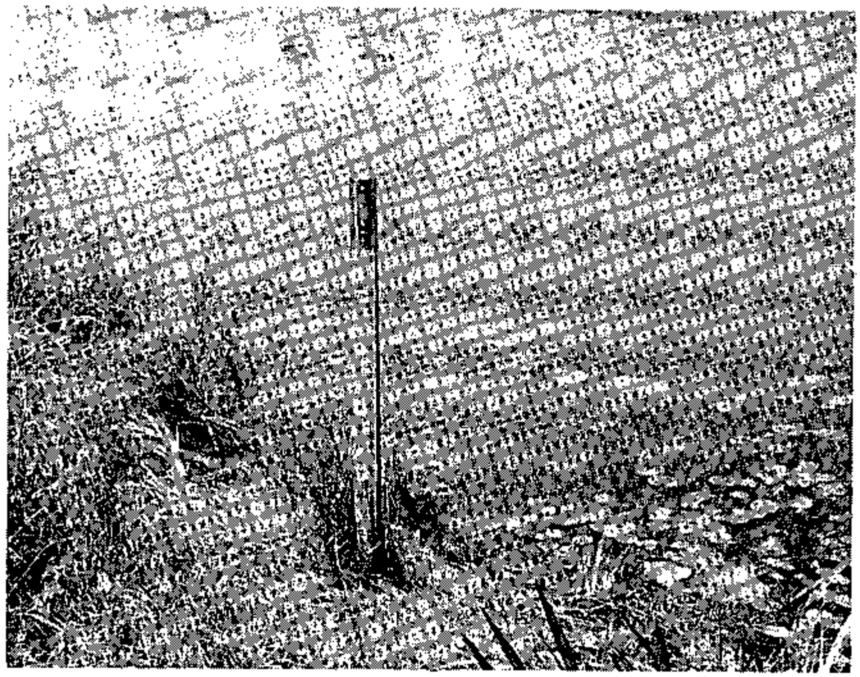


Figure 14. Staff gage 10 at Dead River. Trench had to be cut from gage to water due to extremely low stage

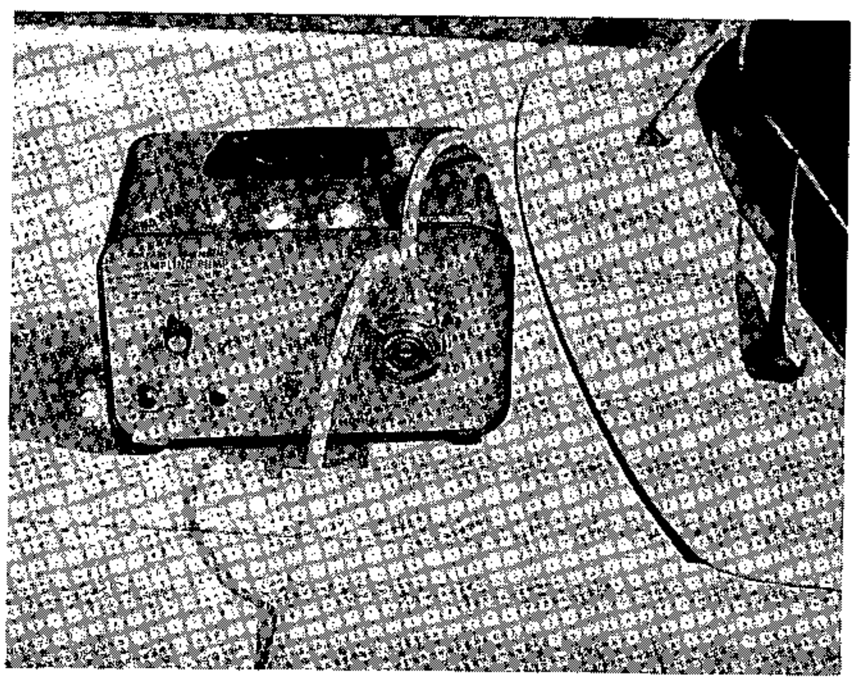


Figure 15. Water sampling pump

author *(see table 10).* Measurements were taken at both bluff (inflow) and beach (outflow) points for all three streams in order to detect gains or losses during throughflow. Another set of measurements was also planned for the fall low-flow period but was cancelled when it became apparent that flows would be either zero or affected by barrier bars.

Water Samples

One-quart water samples were collected at 23 sites (16 groundwater and 7 surface water) at the beginning of the study and during July 1975. Monthly samples were collected at 9 groundwater sites and at S-10 on Dead River. In addition, a monthly gallon sample of Lake Michigan water was collected from the raw water intake line at the Zion-Benton Township Water Treatment Plant along 17th Street near Camp Logan.

Samples taken from the recorder well and from piezometers were collected with a portable Masterflex sampling pump equipped with a 670 milliliters per minute (ml/min) pump head (figure 15). During the winter of 1974-1975 freezing in P-6, P-10, P-11, and P-15 prevented both sampling and measurement. A 3-foot steel rod with a chisel end was later fashioned for the piezometers and was used successfully during the second winter of study in breaking through ice buildups.

All water samples were analyzed at the Survey Chemistry Laboratory.

RESULTS AND OBSERVATIONS

Water Levels

Groundwater Levels

Hydrographs summarizing groundwater levels measured during the 16 months from January 1975 through April 1976 are presented in figure 16. Seasonal effects are observable on most of the hydrographs, although not as strongly at observation sites close to the lake. Minimum depths to water below land surface ranged from 0.8 feet above ground at P-15 on March 19, 1975, to 8.94 feet at the recorder well on April 4, 1975. Maximum depths to water ranged from 2.63 feet at P-6 on October 8, 1975, to 11.01 feet at the recorder well on February 4, 1976. Maximum and minimum levels and fluctuations at each site are summarized in table 2. Fluctuations ranged from 1.76 feet at P-4 along the shore, to 3.74 feet at P-12 near the bluff.

Water level contours drawn from the recorder well and piezometer data during the spring high and autumn low periods are shown in figures 17 and 18. It is evident from the slope of the water table in both maps that groundwater movement is toward the lake, with the gradient being steeper near the bluff than near the shore. The head gradient is inversely related to the thinning of the aquifer toward the bluff. Also evident in both maps is the local southward groundwater movement into the nature preserve area and the extreme flattening of the gradient in the marshy portions of that area caused by standing water. Although the lower concentration of data observation points is in the northern portion of the study area, water table contours in that portion seem to indicate a relative flattening of the flow gradient in the vicinity of Camp Logan. As will be discussed in a later section, Fraser and Hester (1974) reported that the near shore facies portion of the sand body in that area (the shallowest portion) is coarser than elsewhere. It is not compelling evidence, but it does offer a possible explanation for the local flattening of the gradient. The apparent water table high at the bluff near Wadsworth Road cannot be traced northward along the bluff because of the relative sparseness of data control points. However, its position relative to Bull Creek suggests that streamflow may locally affect groundwater levels.

Effect of Precipitation. In general, groundwater levels (with the exception of seasonal trends) do not correlate well with precipitation events. Precipitation and water level hydrographs (figures 16 and 19) show slight-to-moderate delayed responses of water levels to rainfall, especially during periods of low evapotranspiration. During high evapotranspiration periods only the largest rainfall events evoke noticeable rises in groundwater levels and then only after some time lag. The weekly versus daily frequencies in the collection of water level and rainfall data no doubt influence the correlation since response to rainfall at the recorder well appears to be greater than at the piezometers.

Vertical Variation. Water levels were measured in three piezometers (P-9, P-10, and P-11) set 2 feet apart and driven to depths of 5, 15, and 25 feet, respectively, in order to detect vertical head variations in the marsh area. In most cases the weekly water levels were either identical or were within 0.02 foot of one another. In 16 out of 27 instances where vertical head differences of 0.03 to 0.19 foot were measured, the higher water levels in the shallowest piezometer (P-9) were attributable to precipitation events occurring just prior to measurement. Thus, essentially no vertical head differences existed at the site during nearly 90 percent of the field investigation.

Stream Stages

Figure 20 shows surface water hydrographs constructed from weekly observations at the 10 staff gages, from January 1975 through April 1976. Seasonal effects were quite noticeable for all surface water levels. Eight of the 10 hydrographs indicate summer and fall periods in which the staff gages were completely out of water. Table 3 summarizes observed maximum and minimum stages at the 10 sites. As with groundwater stages, most surface water stages showed the greatest degree of correlation with rainfall events during late fall through early spring.

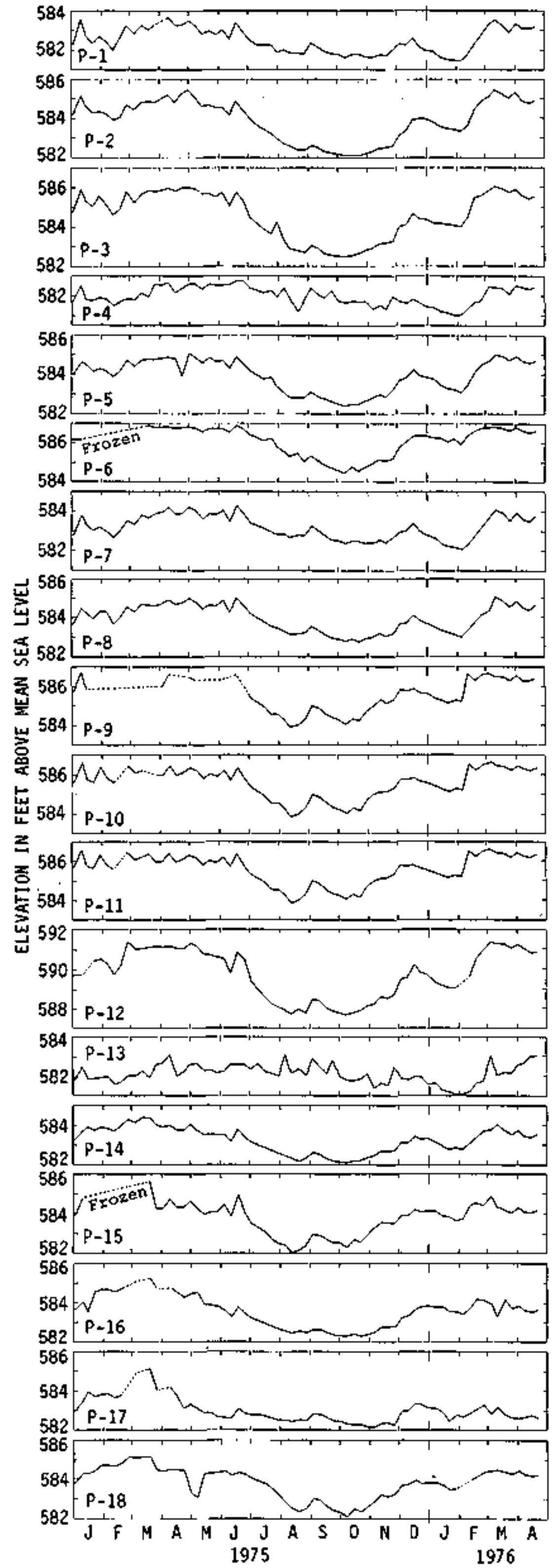


Figure 16. Groundwater stage hydrographs

Table 2. Range of Water-Level Fluctuations at Monitoring Sites

Piezometer	Land surface datum	Low: Depth below surface (ft)	Low: msl	Low: Date	High: Depth below surface (ft)	High: msl	High: Date	Fluctuation (ft)
P-1	585.10	3.64	581.46	2/4/76	1.43	583.67	4/9/75	2.21
P-2	587.10	5.03	582.07	10/8/75	1.64	585.46	4/30/75	3.39
P-3	387.91	5.43	582.48	10/8/75	1.86	586.05	3/10/76	3.57
P-4	587.51	6.51	581.00	1/28/76	4.75	582.76	6/25/75	1.76
P-5	587.41	5.00	582.41	10/8/75	2.34	585.07	4/30/75	2.66
P-6	587.11	2.63	584.48	10/8/75	0.20	586.91	3/19/75	2.43
P-7	586.60	4.49	582.11	2/4/76	2.30	584.30	6/18/75	2.19
P-8	587.08	4.32	582.76	10/22/75	2.02	585.06	3/10/76	2.30
P-9	587.52	3.65	583.87	8/12/75	0.81	586.71	1/10/75	2.84
P-10	587.49	3.65	583.84	8/12/75	0.88	586.61	3/4/76	2.77
P-11	587.16	3.32	583.84	8/12/75	0.55	586.61	3/4/76	2.77
P-12	593.80	6.12	587.68	10/8/75	2.38	591.42	2/26/75	3.74
P-13	587.12	6.06	581.06	{1/28/76 2/4/76}	4.01	583.11	4/9/75	2.05
P-14	585.84	3.73	582.11	10/8/75	1.45	584.39	{3/12/75 3/19/75}	2.28
P-15	584.86	2.81	582.05	8/12/75	0.80	585.66	3/19/75	3.61
P-16	589.10	6.80	532.30	{10/8/75 10/22/75}	3.82	585.28	3/19/75	2.98
P-17	589.45	7.30	582.15	11/5/75	4.34	585.11	3/19/75	2.96
P-18	587.40	5.29	582.11	10/8/75	2.22	585.18	3/19/75	3.07
Recorder well	592.50	11.01	581.49	2/4/76	8.94	583.56	4/4/75	2.07

Table 3. Observed Maximum and Minimum Surface Water Stages

Staff gage	Maximum: msl	Maximum: Date	Minimum: msl	Minimum: Date	Fluctuation (ft)
S-1	584.01	2/26/75	Dry	Sep-Oct 1975	
S-2	585.96	6/25/76	582.25	12/17/75	3.71
S-3	584.56	3/4/76	582.18	10/29/75	2.38
S-4	587.77	2/19/75	Dry	Jun 1975-Jan 1976	
S-5	587.20	3/4/76	Dry	Jun 1975-Jan 1976	
S-6	585.68	2/26/75	Dry	Jul-Nov 1975	
S-7	585.68	2/26/75	Dry	Jul-Nov 1975	
S-8	585.65	2/26/75	Dry	Aug-Oct 1975	
S-9	585.66	2/26/75	Dry	Aug-Oct 1975	
S-10	585.68	3/19/75	580.4*	Feb-Mar 1976	5.3*

*Estimated

Fifteen breakthrough events (emptying of ponded streams as a result of breaching or destruction of barrier bars) were also noticeable from the hydrographs for S-l, S-2, S-3, and S-10. Each event is identified as a sharp drop in stream stage either following a rainfall event or a gradual building in stage *(see table 4).* A discussion of the implications of these phenomena follows.

Effect of Barrier Bars. One of the most intriguing phenomena observed during the study was the natural process response mechanism involved in the interaction between streams and barrier bars built up at their point of discharge to Lake Michigan. Barrier bars are also known

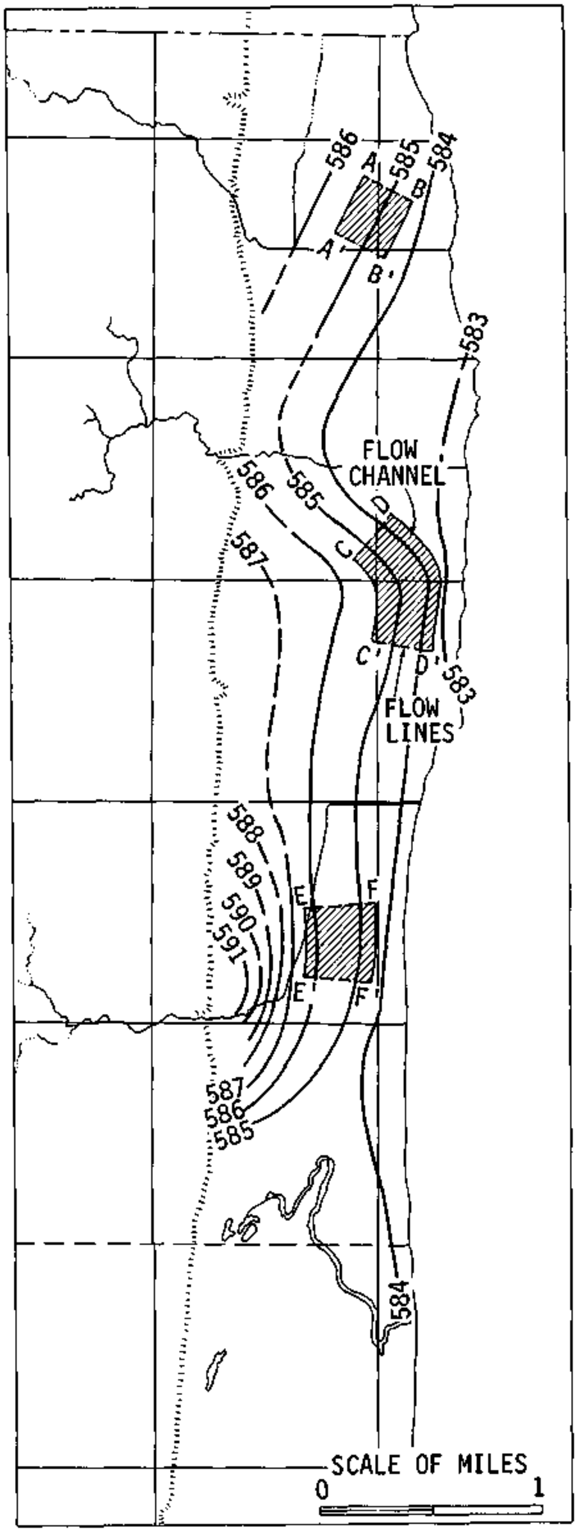


Figure 17. Water table configuration, April 9, 1975

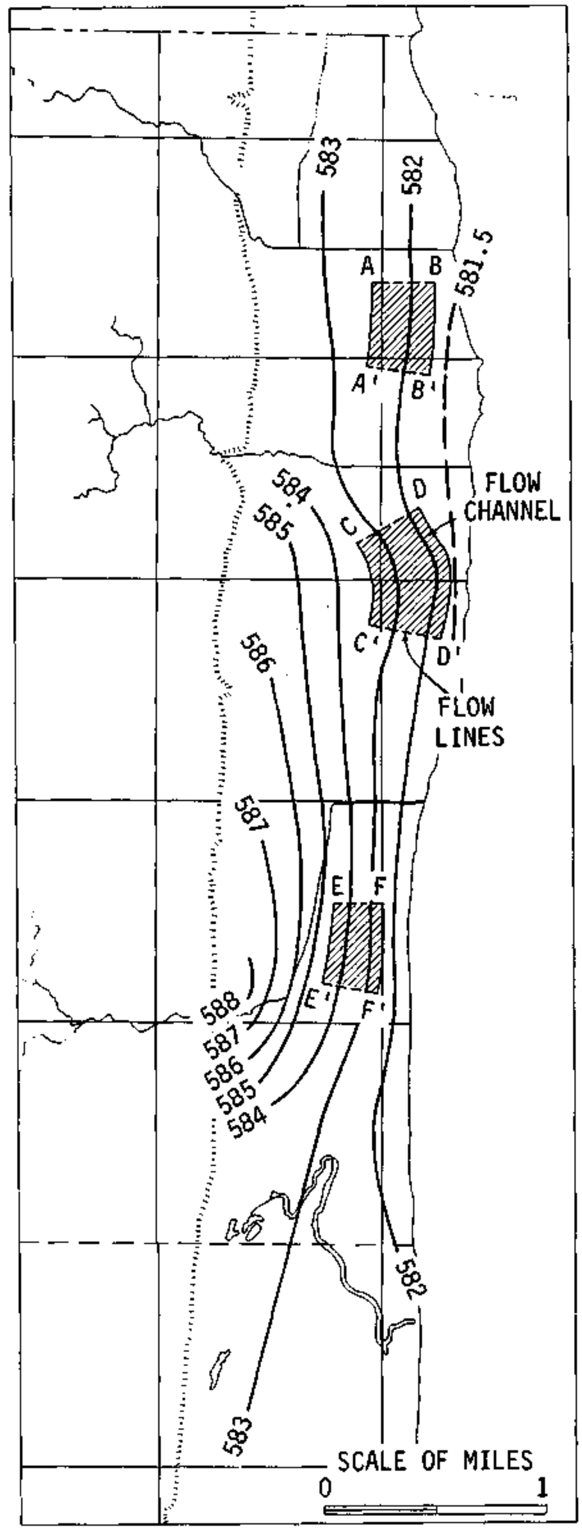


Figure 18. Water table configuration, November 5, 1975

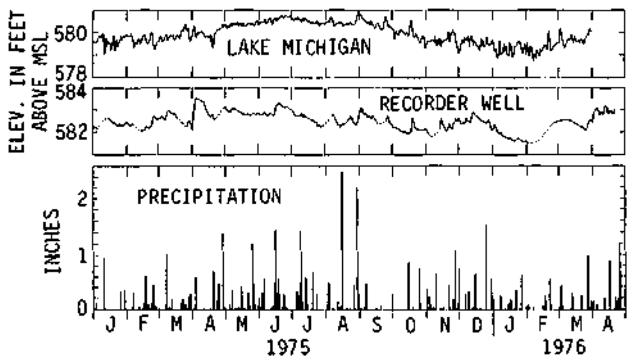


Figure 19. Hydrographs of Lake Michigan, recorder well stages, and precipitation data

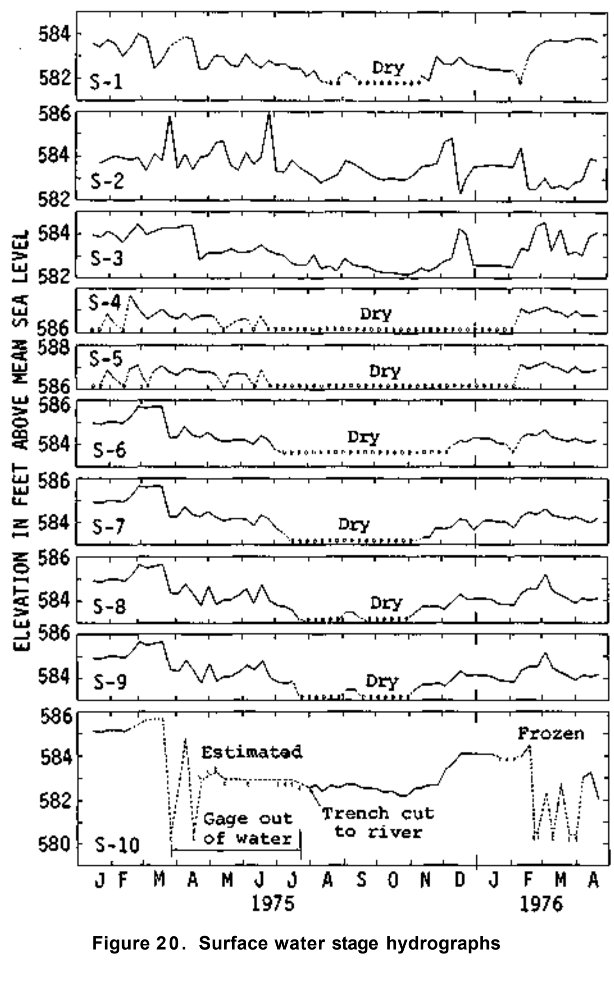


Figure 20. Surface water stage hydrographs

along the southern California coast, where intermittent streams are blocked off from the sea during dry weather (Grant, 1948). Grant concluded from his study of beach aggradation and degradation that " . . . a high water table accelerates beach erosion, and conversely a low water table may result in pronounced aggradation of the foreshore." This conclusion had been discussed in an earlier report by Grant (1946) and corroborated in an earlier laboratory experiment by Bagnold (1940) and by later field studies of Emery and Foster (1948), Isaacs and Bascom (1949), Duncan (1964), and Harrison (1969).

Grant (1948) observed that during the spring, when flow began in the intermittent streams, the runoff was initially impounded behind the bar. When a large volume of runoff was involved, a rapid rise of the impounded water occurred and a channel was cut to the sea. However, when the rise of the impounded water proceeded more slowly and allowed a concomitant rise of the beach water table to develop, subsequent large waves accelerated beach erosion locally and removed the beach bar. Figures 21 and 22 show barrier bars at the mouth of Kellogg Ravine completely and partially destroyed, respectively.

Thus, it appears that two possible mechanisms are available to the streams for breaching the barrier bars: channelization and/or overtopping during high-volume storm discharge, and wave erosion accelerated by a high water table following a gradual rise in impoundment level. Precipitation records and stage hydrographs for S-l, S-2, S-3, and S-10 in figures 19 and 20 indicate that in 11 of the 15 breakthrough events that occurred during the study, relatively large storms (0.5 inch or more) did precede or occur at the times of the breakthrough events. Water table hydrographs from nearby piezometers indicate that the average adjacent groundwater stage was at or above that in the stream in only 7 of the 15 events.

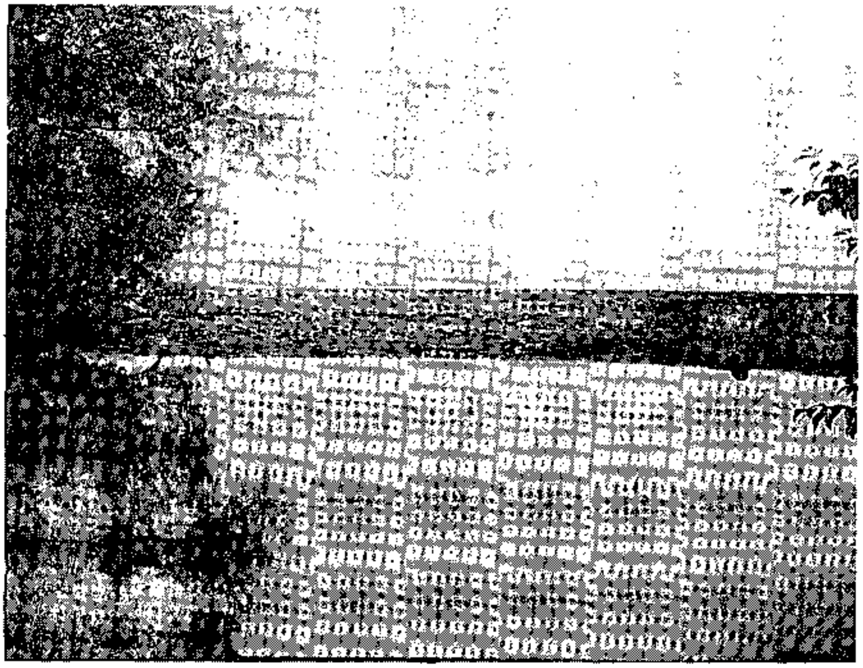


Figure 21. Kellogg Ravine outlet completely blocked by barrier bar

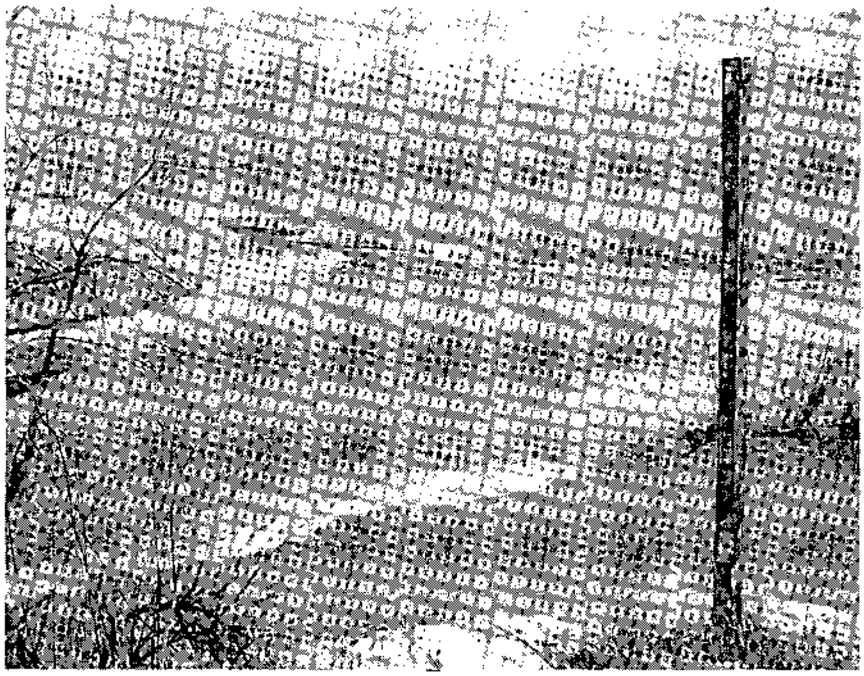


Figure 22. Kellogg Ravine outlet partially blocked by barrier bar

Table 4. Barrier Bar Breakthrough Events during Study

Staff gage	*Date of preceding high stage*	*Stream stage (msl)*	*Lake stage (msl)*	*Stage difference Δs (ft)*	*Stream stage decline (ft)*	*Decline/Δs*
S-1	3/5/75	583.79	579.60	4.19	1.37	0.33
(Lake Michigan Tributary)	4/16/75	583.79	579.74	4.05	1.40	0.34
S-2	3/26/75	585.79	580.16	5.63	2.40	0.43
(Kellogg Ravine)	6/25/75	585.96	580.78	5.18	2.61	0.50
	12/10/75	584.80	579.38	5.42	2.55	0.47
	2/11/76	584.42	579.16	5.26	1.90	0.36
S-3	4/16/75	584.42	579.74	4.68	1.57	0.34
(Bull Creek)	12/23/75	584.02	579.63	4.39	1.42	0.32
	3/4/76	584.56	579.92	4.64	1.33	0.29
	3/18/76	584.24	579.60	4.64	1.14	0.25
S-10	3/19/75	585.68	579.74	5.94	5.2*	0.88*
(Dead River)	4/9/75	584.80	580.02	4.78	4.3*	0.90*
	2/18/76	584.46	579.42	5.04	4.0*	0.79*
	3/4/76	582.33	579.92	2.41	1.9*	0.79*
	3/18/76	582.78	579.60	3.18	2.3*	0.74*

•Estimated

Personal communication with Robert Needham, Head Ranger at the park, and information provided to field personnel by other rangers during the study, indicate that breakthroughs tend to be of the overtopping-channelization type and are often quite spectacular, in that the resultant discharge sends muddy water as far as a mile into the lake. In addition, the nature of the multiple-event breakthroughs at Dead River, alternating with rapid rebuilding of the barrier bar, are suggestive of the overtopping-channelization mechanism. It would seem inconsistent with the above mentioned studies by Grant and others that a barrier bar could so quickly be rebuilt (in as little as 15 minutes or so, according to Needham) under the high water table mechanism. Available information suggests, therefore, that a mechanism of wave erosion related to the water table was not an important factor influencing the majority of breakthrough events during the study.

Table 4 summarizes breakthrough events which occurred in Lake Michigan Tributary, Kellogg Ravine, Bull Creek, and Dead River, as evidenced by stage data at S-l, S-2, S-3, and S-10, respectively. Since the events occurred sometime between weekly field visits, the dates shown in the table are those of the high stages preceding the events. Stage declines are the losses of stage as measured by the field visits preceding and after the events.

It is of interest to observe in table 4 the ratio of *decline/*Δs for each event. While the data are admittedly sparse, they suggest that a more or less consistent value or range of this ratio appears to hold for each of the streams. In other words at a given stream outlet, when a breakthrough event occurs, the stream cuts into the barrier bar to a depth such that the stage difference between the stream and lake is reduced by a constant amount. In a study of geologic processes responsible for beach phenomena, Krumbein (1963) conceptualized a model which showed among other things that beach material factors (grain diameter, sorting, stratification, mineral composition) are important process elements in determining beach erosion or aggradation. He observed that these properties show fairly strong gradients between the plunge point (turbulent zone in which waves break) and the beach berm.

Figure 23 is a schematic map constructed by Krumbein (1963) by measuring the sand penetrability at a number of points and drawing contours. His map shows that the softest part of the beach is at the berm crest, and that firmness increases rapidly toward the water's edge. Figure 23 suggests a possible explanation for the observation that the *decline/As* ratio is relatively constant for a given stream outlet. If, as we have discussed, the overtopping-channelization mechanism is operative, it may be that the eroding stream carves its way down through the softer material at the berm of the barrier and, as its carving energy gradually diminishes, ultimately crosses material of a firmness sufficient to resist further erosion. At such a point stream discharge would decline until the stream stage reached that of the resistant bar material, and flow would stop until regenerated by further storm events (of course, in the meantime the lake waves would be busily reconstructing the eroded bar).

Fraser and Hester (1974) showed that the beach deposits tend to be coarser in the vicinity of Lake Michigan Tributary and Bull Creek outlets than at the Kellogg Ravine outlet, and that they are finer still at the Dead River outlet (figure 24). Grain sizes shown in figure 24 are given in phi (ø) units, which are logarithmic equivalents of the millimeter scale. Table 5 gives the conversion from millimeters to phi units. Given that finer materials would erode more easily than coarser ones, this could help to explain the relative size of the *decline/*Δ*s* ratios at these sites. For example, at the Lake Michigan Tributary and Bull Creek outlets, where the beach material is coarser than at the other sites, breakthrough flows cannot erode as deeply as elsewhere — hence the lower *decline/*Δ*s* ratio at those sites.

Lake Michigan

Daily average stages of Lake Michigan at Illinois Beach State Park are given in figure 19. Daily stages were calculated as the average of daily mean stages at Calumet Harbor, Illinois, and Milwaukee, Wisconsin,

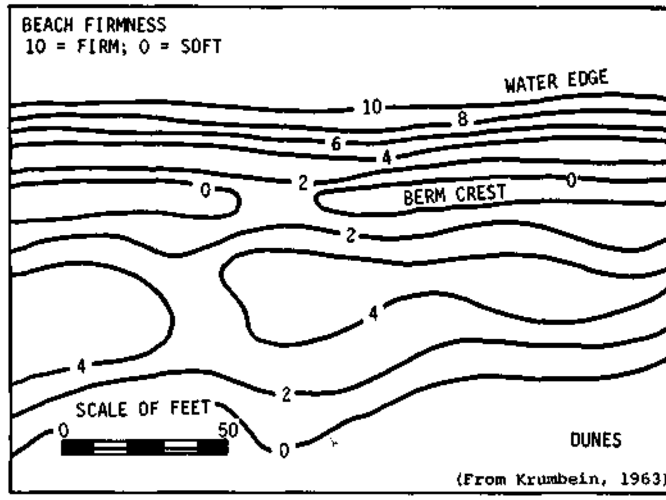


Figure 23. Schematic map of beach firmness

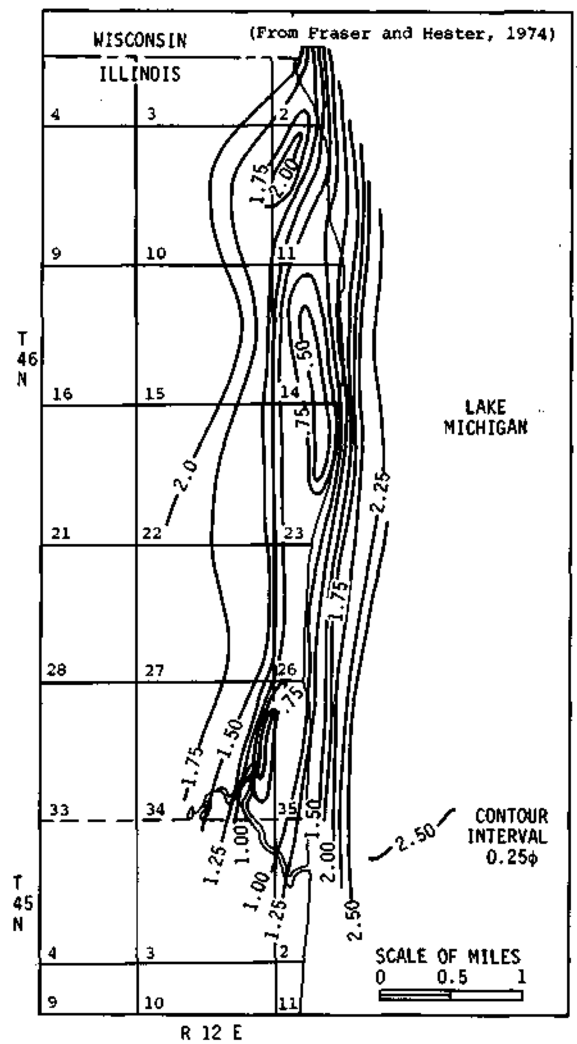


Figure 24. Isolith map of shore-nearshore facies

that are recorded by the National Oceanic and Atmospheric Administration, Lake Survey Center, Detroit, Michigan. From January 1975 through April 1976 the daily lake stage ranged from 578.70 feet (International Great Lakes Datum, IGLD 1955) on February 7, 1976, to 580.92 feet on August 31, 1975. Between 1970 and 1974 Lake Michigan monthly levels fluctuated between 578.61 feet and 581.09 feet IGLD (NOAA, 1972-1975) so that 1975-1976 levels were not significantly different from those of the previous 5 years.

Table 5. Conversion from Millimeters to Phi Units*

mm	*ϕ*	*Size class*
64	-6.0	Pebble
16	-4.0	Pebble
4	-2.0	Pebble
		Granule
2	-1.0	Very coarse sand
1	0.0	Coarse sand
0.50	1.0	Medium sand
0.25	2.0	Fine sand
0.125	3.0	Very fine sand
0.0625	4.0	Silt

(from Fraser and Hester, 1974)

Correlations

High groundwater stages in the vicinity of Illinois Beach State Park lodge have been the source of basement flooding problems in recent years. One of the aims of the current study, therefore, was to gain insight into the relationship between groundwater levels, lake levels, and stream stages in order to evaluate the role each element plays in local problems and to anticipate problems associated with future northward expansion of the park. To this end a number of correlations were made in which data from selected piezometers were compared with Lake Michigan and stream stages.

Groundwater versus Lake Michigan. Water levels from the recorder well and selected near-shore piezometers were compared with lake stages for the same dates (figure 25). Computer correlations are summarized in table 6. The results indicate that, generally, the closer one is to the shore the more closely related are the groundwater and lake levels. Data from P-4 and P-13, located approximately 125 feet and 200 feet, respectively, from the shore, have much better correlations with data from Lake Michigan than do those from P-1, P-7, P-14, P-16, and P-17, located 350, 500, 1150, 1500, and 550 feet from the shore. Thus, while lake-level fluctuations do not always have observable counterparts in near shore piezometers, near shore groundwater head gradients are forced to make adjustments to these fluctuations in order to maintain flow continuity. Such adjustments of necessity affect water levels locally.

A detailed correlation of daily water levels was available from the recorder well data and is plotted in figure 26. The well is located approximately 325 feet from the shore. The massed data had a correlation coefficient of 0.531. An attempt was made to sort out some of the scatter by grouping data according to groundwater temperature as determined from monthly water samples.

Table 6. Correlation Matrix for Selected Observation Points

	Lake	*S-10*	*P-1*	*P-4*	*P-7*	*P-10*	*P-13*	*P-14*	*P-15*	*P-16*	*P-17*	*P-18*
Lake	1.000											
S-10	-0.530	1.000										
P-1	0.148	0.641	1.000									
P-4	0.679	-0.034	0.724	1.000								
P-7	0.359	0.498	0.934	0.839	1.000							
P-10	-0.308	0.770	0.755	0.336	0.657	1.000						
P-13	0.766	-0.200	0.531	0.864	0.657	0.070	1.000					
P-14	-0.222	0.931	0.818	0.370	0.724	0.908	0.150	1.000				
P-15	-0.339	0.884	0.685	0.265	0.600	0.970	-0.016	0.924	1.000			
P-16	-0.331	0.944	0.674	0.189	0.548	0.854	-0.023	0.948	0.912	1.000		
P-17	0.150	0.928	0.194	0.223	0.195	0.057	0.235	0.087	-0.025	0.000	1.000	
P-18	0.147	0.927	0.206	0.237	0.208	0.069	0.249	0.098	-0.019	0.003	1.000	1.000

NOTE: Coefficients have been rounded to three places

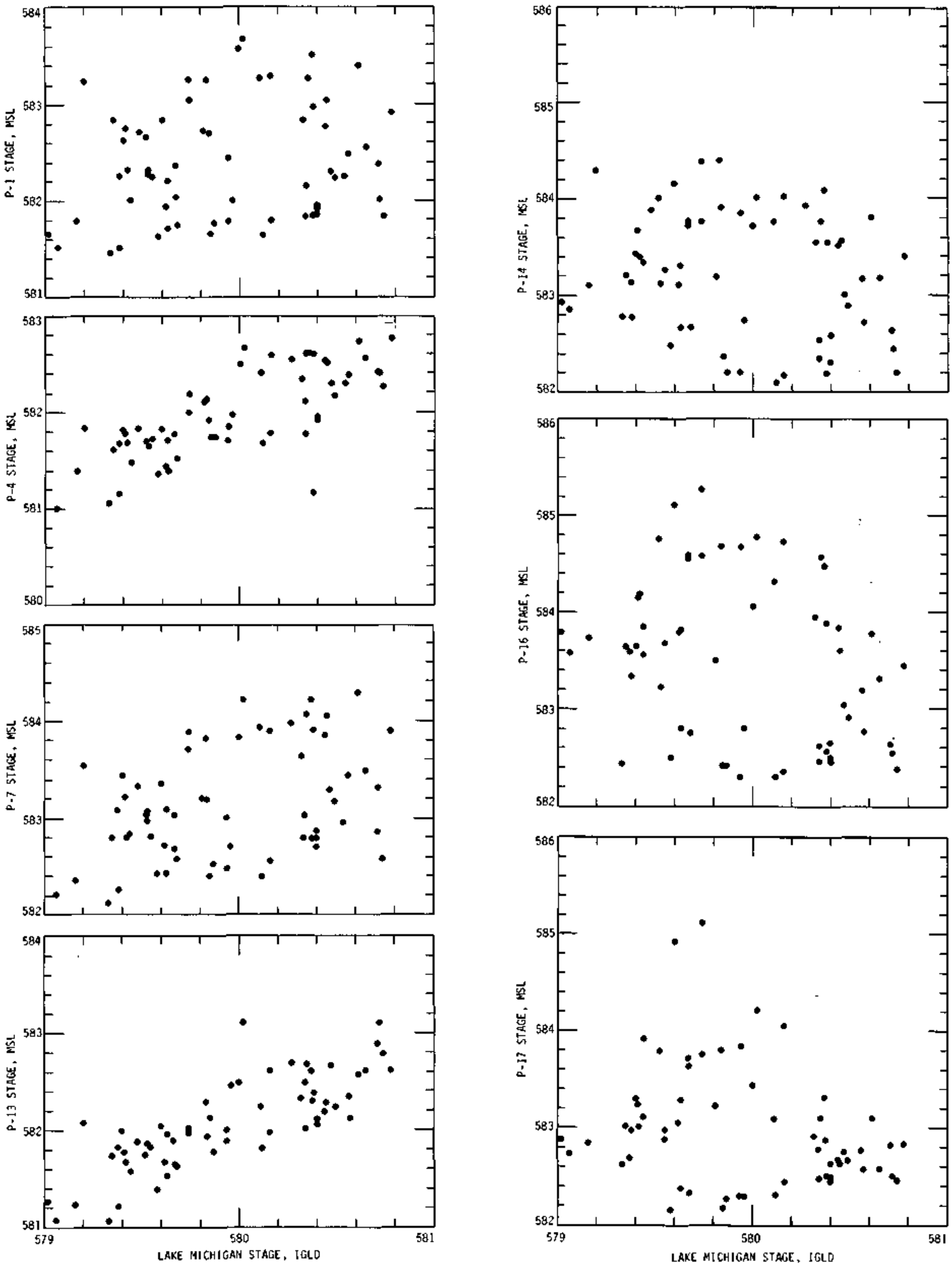


Figure 25. Correlations of groundwater and Lake Michigan stages

Table 7. Groups and Correlations of Recorder Well and Lake Michigan Water Levels

Group	*Period*	*Correlation*
1	Dec 1974–Mar 1975, Jan and Mar 1976	0.585
2	Apr and May 1975	-0.207
3	Jun 1975	0.692
4	Jul and Oct 1975	0.744
5	Aug and Sep 1975	0.509
6	Nov and Dec 1975	0.007
7	Feb 1976	0.388

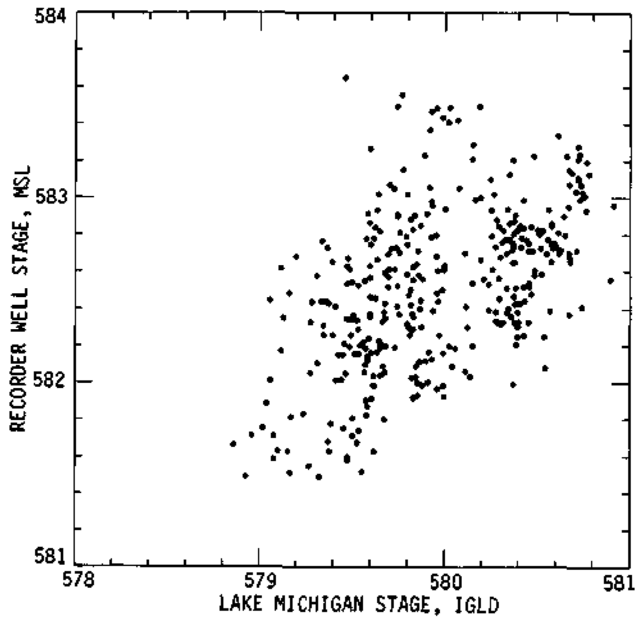


Figure 26. Correlation of recorder well and Lake Michigan stages

It was hypothesized that viscosity differences might account for some of the data scatter. Seven groupings were selected (table 7). Although three of the groups showed improvement in data correlation, four groups showed significant losses in correlation and the overall results are, therefore, inconclusive. No attempt was made at further data grouping.

Groundwater versus Surface Water. As noted earlier, groundwater levels to not appear to be closely tied to surface water stages in the northern half of the study area (see hydrographs of P-1 to P-6 and S-1 and S-2). A much closer relationship is evident in the southern half, especially south of Wadsworth Road.

Figure 27 shows water levels from selected groundwater hydrographs plotted versus surface water levels at stream location S-10 on Dead River. The piezometers were selected by comparison with those in figure 25, in order to demonstrate the relative effect of the marshy Dead River area versus that of Lake Michigan in affecting groundwater stages. (A complete correlation matrix is given in table 6.) One can readily observe, for example, the strong relationship of groundwater levels at P-14, P-16, and P-17 with Dead River stages, whereas those at P-7 are only slightly related and those at P-13 are unrelated.

These correlations, then, support the previous discussion relating groundwater and Lake Michigan stages in that, as one approaches the shore, groundwater levels become less dependent on marsh stages and more so on those of the lake. At some point the marsh becomes insignificant in comparison to the lake, and it is thus a crucial point in considering the cause of high groundwater levels near the park lodge. The lodge is located between 250 to 550 feet from the shore and is much closer to P-13 than to P-14. Thus, evidence points to groundwater levels at the front portion of the lodge being influenced more by Lake Michigan than by ponded marsh water.

Groundwater Properties

Aquifer Test

An aquifer test (Walton, 1962) was conducted for the city of Zion by Ranney Method Water Supplies, Inc., on November 19-22, 1952. A group of wells (figure 28) located along the lake shore near Shiloh Boulevard was used. The generalized logs of the wells are given in figure 29.

The effects of pumping well A-P were measured in observation wells A-S-l, A-S-2, A-N-l, A-E-l, A-E-2, and A-E-3. Lake Michigan stages were also measured throughout the test.

Pumping was conducted at a rate of 99 gallons per minute (gpm) for the 72-hour test, and the accumulated hydrograph data are shown in figure 30. Drawdowns, adjusted for dewatering, were computed from the hydrographs after 5 3 hours, prior to the large change in lake stage, and were plotted against distance from the pumped well on semilog graphs, as shown in figure 31. The transmissivity (capacity of a unit width of the aquifer to transmit water) determined from data for the observation wells parallel to the lake was 58,000 gallons per day per foot (gpd/ft), and the hydraulic conductivity (rate of water flow across a unit cross-sectional portion of the aquifer and equal to the transmissivity divided by the saturated aquifer thickness) was 290 gallons per day per square foot (gpd/sq ft). (The aquifer thickness was assumed to be 20 feet at the time.) Water level data and later studies by Hester and Fraser (1973) and Fraser and Hester (1974) indicate that the saturated thickness of the sand at the test site is more correctly about 30 feet.

For the purposes of this study, an average hydraulic conductivity of 1933 gpd/sq ft was used. Since the data were influenced by the recharge effect of the lake, no accurate calculation of the water table storage coefficient (specific yield) could be made. Specific yield, expressed as a fraction, is the volume of water drained from a unit volume of the aquifer per unit decline in head (or, conversely, that stored in a unit volume of the aquifer per unit rise in head).

Specific Yield Estimates

Estimates of specific yield were made by analyzing rainfall events and their

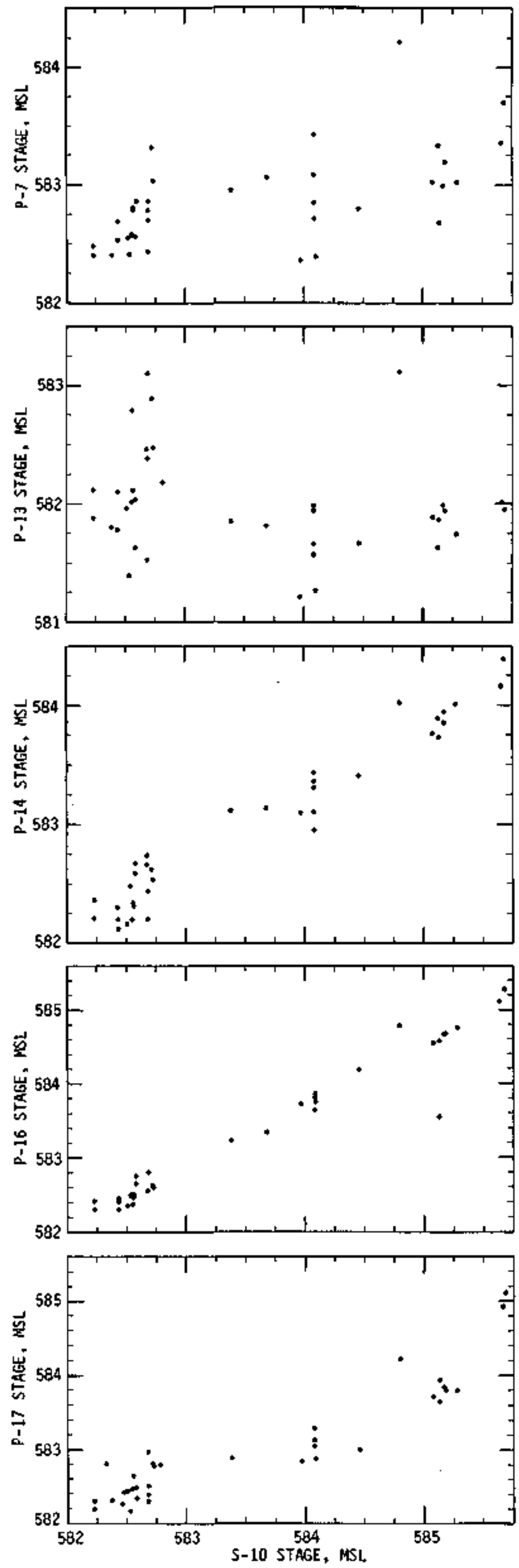


Figure 27. Correlations of groundwater and S-10 stages

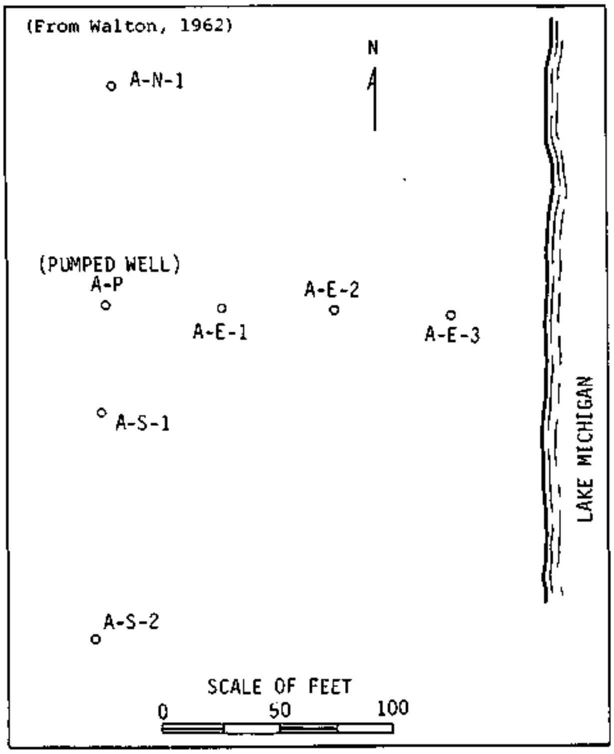


Figure 28. Array of wells used in aquifer test, November 19-22, 1952

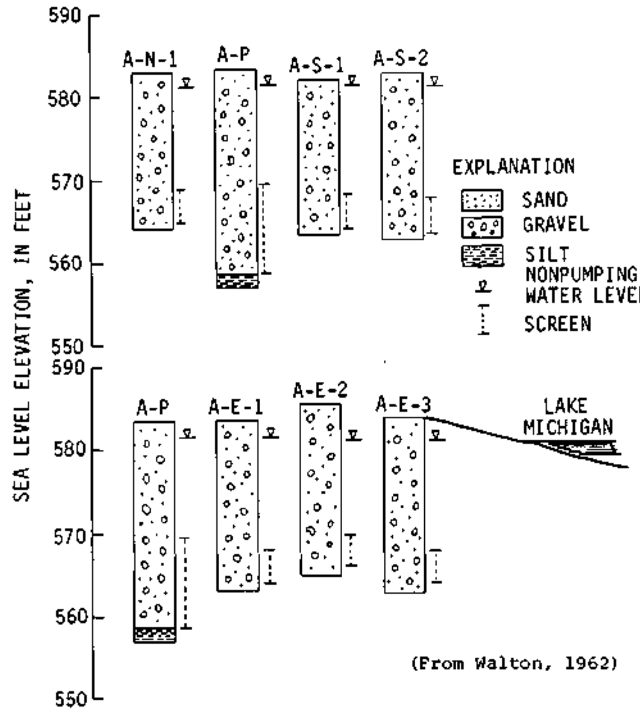


Figure 29. Generalized logs of wells used in aquifer test

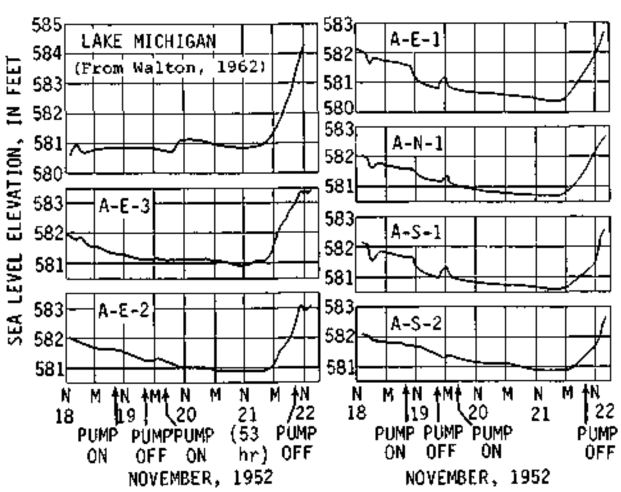


Figure 30. Accumulated hydrographs for aquifer test, November 19-22, 1952

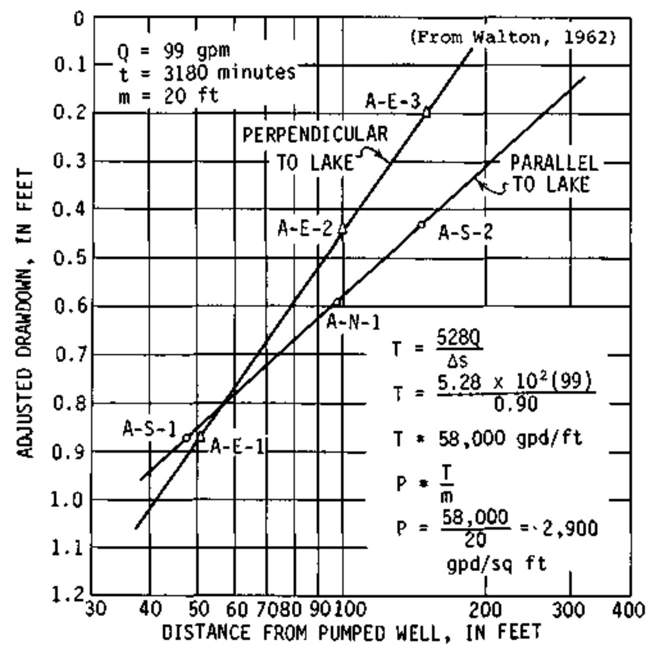


Figure 31. Original semilogarithmic analysis of aquifer test data

Table 8. Summary of Specific Yield Computations

Period	Precipitation (in)	P (ft)	Rise in groundwater stage G (ft)	Specific yield Y
2/23-25/75	0.62	0.052	0.47	0.11
3/6-9/75	1.12	0.093	0.50	0.19
3/27-28/75	0.24	0.02	0.21	0.10
4/1-4/75	0.64	0.053	0.61	0.09
4/23-30/75	1.94	0.162	0.51	0.32
5/5-7/75	0.56	0.047	0.25	0.19
12/5-7/75	0.26	0.022	0.31	0.07
2/25-3/5/76	3.11	0.259	1.24	0.21
3/26-30/76	1.19	0.099	0.47	0.21
Average				0.16

corresponding water level changes at the recorder well. Data for analysis were selected from periods of the year in which evapotranspiration effects were negligible (table 8). During such periods specific yield was computed from the relationship:

$$Y = P/G \tag{1}$$

where Y is specific yield (a fraction) and P and G are, respectively, precipitation and groundwater stage rise, both in feet. For nine selected periods the average value of specific yield was 0.16.

Recharge from Precipitation

The major source of recharge to the sand aquifer at Illinois Beach State Park is precipitation. Recharge from this source occurs irregularly both in time and space. Most recharge occurs during the wet spring months when evapotranspiration is small and soil moisture is rapidly replenished by frequent rains. During the dry summer and fall months evapotranspiration and soil moisture requirements essentially preclude precipitation from any but the largest storms percolating downward to the water table. Recharge during winter months when the ground is frozen is also normally quite small.

The amount of recharge to an aquifer can often be estimated by flow net analysis (Walton, 1962). The procedure involves determining the difference in groundwater flow crossing successive water table contours between two limiting flow lines and applying the results to the following equation:

$$R = [(Q_2 - Q_1) \pm \Delta h_t SA(2.1 \times 10^8)]/A \tag{2}$$

where:

- R = rate of recharge, in gpd/sq mi
- $Q_2 - Q_1$ = difference in groundwater flow crossing successive contour lines between limiting flow lines, in gpd
- Δh_t = average rate of water level rise or fall in flow area between successive contours and limiting flow lines, in ft/day
- S = coefficient of storage (or water table specific yield), fraction
- A = area of flow between successive contours and limiting flow lines, in sq mi

Q_1 and Q_2 are computed from Darcys Law:

$$Q = TIL \tag{3}$$

where:

- Q = quantity of groundwater flowing through a given cross section, in gpd
- T = transmissivity, in gpd/ft
- I = hydraulic gradient at flow cross section, fraction
- L = length of flow cross section, in ft

Water table contours were drawn from water levels as measured during the spring high (April 9) and fall low (November 5) periods in 1975 (figures 17 and 18, respectively). Flow channels were selected on each map at three general sites in order to have a comprehensive sampling for the study area. For each flow channel Δh_t was assumed to be the average seasonal fluctuation in water levels divided by the period of rise (5 months for April) or decline (7 months for November). The specific yield was uniformly assumed to be 0.2 for all cases. Recharge rates were computed at each flow channel for both maps, and a net yearly average recharge rate at each flow channel was then calculated from the 'wet' (April 9) and 'dry' (November 5) data, weighted by time factors of 5 months and 7 months, respectively. Table 9 summarizes the results of the flow net analyses. Negative values indicate dry weather loss of water from storage.

Table 9. Summary of Flow Net Analyses

(In gallons per day per square mile)

Flow channel	Wet season recharge rate	Dry season storage loss	Net yearly average recharge
A-A[1] to B-B[1]	1,209,000	-425,000	256,000
C-C[1] to D-D[1]	1,188,000	-47,400	467,000
E-E[1] to F-F[1]	657,000	-97,300	217,000

The average recharge rate for the study area, from table 8, was estimated to be 313,000 gpd/sq mi in 1975. Precipitation at the Waukegan Radio Station, WKRS, totaled 37.26 inches during 1975, a departure from normal of +4.63 inches or +12 percent.

Recharge from Streams

A second, although probably minor, source of recharge to the sand aquifer is that of infiltration from the three principal streams which cross the area from the bluff to the lake. During spring high-flow periods stream stages may temporarily be higher than those of the adjacent water table, allowing seepage losses to occur in streamflow. Most of the year, however, stream stages are generally at or below groundwater stages, and groundwater flow locally is toward the streams. Streamgage measurements made by the U.S. Geological Survey on April 23, 1975 *(see table 11)* indicated that Lake Michigan Tributary experienced a net loss in flow of 2.79 cubic feet per second (cfs) between the bluff and the lake, whereas Kellogg Ravine appeared to have a net gain of 0.3 cfs. Although the flow in Bull Creek near the lake was 7.92 cfs less than at the bluff, it is believed that the difference was caused by a change in flow regime near Wadsworth Road which routed flow southward toward Dead River.

Since Dead River is ponded most of the year by barrier bars, it acts as a temporary catchment for diverted Bull Creek flow which may average approximately 2.9 cfs during the year *(Water for Illinois, a Plan for Action,* 1967). Drainage occurs following barrier bar breakthrough events *(see table 4).* Thus, on a year-round basis, the only relatively important contribution to recharge from streams in the study area is that in the temporary storage which takes place in Dead River. This storage has the effect of flattening out the water table and reducing flow gradients in the nature preserve area of the park *(see figures 17 and 18).*

Streamflow

Average Runoff

Because the U.S. Geological Survey does not maintain gaging stations on the three principal streams in the study area, the average streamflow is not known. Crest-stage gages have, until 1974 and 1972, respectively, been maintained by the USGS at bluff sites on both Kellogg Ravine and Winthrop Harbor. A list of reported maximum discharges for recent years is given in table 10 (U.S. Geological Survey, 1966-1975).

Records of flow at 150 locations throughout Illinois show that a latitudinal variability in runoff does exist across the state *(Water for Illinois, a Plan for Action,* 1967), and estimates have been made of average runoff on a regional basis. In the Lake County area of Illinois average run-

Table 10. Maximum Discharges for Kellogg Ravine and Lake Michigan Tributary, 1965-1974

(Discharges in cubic feet per second)

Year	Kellogg Ravine	Lake Michigan Tributary
1965	200	
1966		95
1967		51
1968	123	39
1969		355
1970		145
1971	395	134
1972	605	282
1973	117	
1974	320	

off is estimated to be 0.65 cfs/sq mi. Drainage areas at the bluff for Lake Michigan Tributary, Kellogg Ravine, and Bull Creek were determined from 7.5 minute topographic maps to be 1.5, 5.0, and 4.5 sq mi, respectively. Average runoff for these streams, therefore, is estimated to be 0.98, 3.28, and 2.92 cfs, respectively.

Streamgaging

On April 23, 1975, a field crew from the U.S. Geological Survey Subdistrict Office in Oak Park, Illinois, conducted streamflow measurements for the three streams mentioned above. Streamflow was determined both at the bluff and near the lake. The results are summarized in table 11.

As shown in table 11, Lake Michigan Tributary showed a net loss of flow of 2.79 cfs as it traversed the study area, whereas Kellogg Ravine showed a slight increase of 0.3 cfs. As mentioned previously, Bull Creek showed an apparent loss in flow of 7.92 cfs, although it is believed that this is merely the reflection of a major routing change which takes place as Bull Creek enters the study area.

Table 11. U.S. Geological Survey Streamflow Measurements, April 23, 1975

(Streamflow in cubic feet per second)

	Lake Michigan Tributary	Kellogg Ravine	Bull Creek
At bluff	3.25	10.0	9.86
Near lake	0.48	10.3	1.94
Net flow	-2.79	+0.3	-7.92*

•Loss believed caused by rerouting of flow rather than by seepage

100-Year Floods

In March 1975 the Governors Task Force on Flood Control issued guidelines for estimating 100-year flood flows in urbanizing regions of northeastern Illinois. Known as the State Standard Procedure, it is based on a regression analysis using 30 gaged, urbanizing basins in northeastern Illinois. Equations were developed for two subregions in the six county area. The equation recommended for that portion which includes the study area is:

$$Q_{100} = 57.67\ A^{0.76}\ S^{0.43}\ (1 + Au)^{0.94} \quad (4)$$

where:

Q_{100} = the estimated 100-year discharge of a stream, in cfs
A = drainage area, in sq mi
S = main channel slope, in ft/mi, as determined from elevations at points 10 and 85 percent of the distance along the channel from the point of interest to the basin's divide
Au = urban area, as a fraction, occupied by housing developments, playgrounds, shopping centers, industrial plant sites, research parks, extensive rail and air facilities, and other appropriate features

Input data for applying equation 4 to Lake Michigan Tributary, Kellogg Ravine, and Bull Creek were taken from the 7.5 minute Zion Quadrangle topographic map, and the computed flows were weighted to available local gage data. Q_{100} was determined for each stream at the point where it leaves the bluff and enters Illinois Beach. A summary of input data and the computed Q_{100} for each of the three streams is given in table 12.

Table 12. Estimated 100-Year Flood Flows Entering Illinois Beach

Stream	*Drainage area (sq mi)*	*Channel slope (ft/mi)*	*Proportion of urban area (fraction)*	*100-Year storm flow (cfs)*
Lake Michigan Tributary	1.5	47	0.4	412
Kellogg Ravine	5.0	32	0.7	1285
Bull Creek	4.5	66	0.7	1609

Bull Creek—Dead River System

The 7.5 minute Zion Quadrangle topographic map and a detailed (1 inch = 200 ft) topographic map prepared from aerial surveys (Chicago Aerial Survey, 1973) indicate that Bull Creek enters Illinois Beach State Park approximately 500 feet south of Wadsworth Road, enters a marshy area in which the stream channel loses much of its definition, and, at a point roughly one-third of the way into the park, crosses under Wadsworth Road, heading north. At 29th Street Bull Creek turns eastward as a drainage ditch and continues in that direction toward the lake.

Evidence collected during the present study, however, indicates that for most of the year, Bull Creek's flow is entirely routed in a southerly direction, diffusing through the marsh to Dead River. Even during spring flow, evidence from streamgaging suggests that 7.92 cfs or 80 percent of an inflow of 9.86 cfs was routed south and that only 1.94 cfs flowed through Bull Creek north of Wadsworth Road.

Staff Gage Evidence. Hydrographs of water levels observed at S-4 and S-5 *(see figure 20)* indicate that from June 1975 through January 1976 Bull Creek did not flow under Wadsworth Road at all, and yet the hydrograph for S-3 indicated flow in the drainage ditch portion of the channel, especially at times of large rainfall events. Data for the other staff gages in the nature preserve, S-6 through S-10, show patterns similar to that at S-3, indicating responses to precipitation throughout the long dry period at S-4 and S-5.

Water level data collected at staff gages not only present direct evidence of rerouting through hydrograph analysis, as shown, but also are revealing in correlation analysis. Figure 32 shows data from S-4 and S-5 plotted against S-3. Correlations are poor, as evidenced both by the data plot and by the low correlation coefficients (0.22 and 0.39, respectively). Similar results are seen in figure 3 3 where data from S-5 are correlated with those from S-6 and S-8 in the nature preserve. Correlation coefficients of 0.31 and 0.38, respectively, confirm the poorness of the relationships seen in the data plots. A complete correlation matrix of data for all of the staff gages in the area is presented in table 13.

As was noted in the similarity of hydrograph patterns between S-3 data and S-6, S-7, S-8, S-9, and S-10, their correlation coefficients (0.51, 0.64, 0.70, 0.67, and 0.66, respectively)

Table 13. Correlation Matrix for Data from Selected Staff Gages

	S-3	*S-4*	*S-5*	*S-6*	*S-7*	*S-8*	*S-9*	*S-10*
S-3	1.000							
S-4	0.218	1.000						
S-5	0.394	0.717	1.000					
S-6	0.511	0.266	0.307	1.000				
S-7	0.636	0.263	0.302	0.982	1.000			
S-8	0.704	0.316	0.386	0.939	0.945	1.000		
S-9	0.668	0.317	0.384	0.908	0.927	0.972	1.000	
S-10	0.655	0.088	−0.014	0.674	0.693	0.727	0.719	1.000

NOTE: Coefficients have been rounded to three places

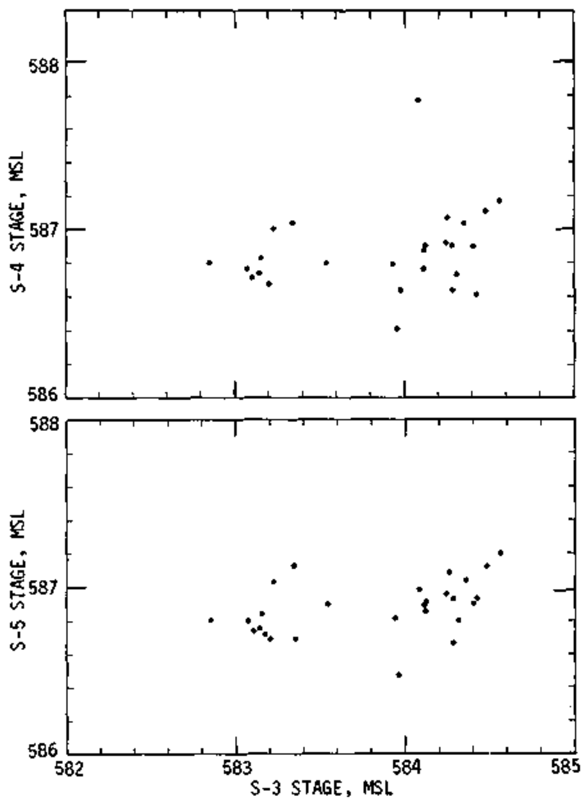


Figure 32. Correlation of S-4 and S-5 data with those at S-3

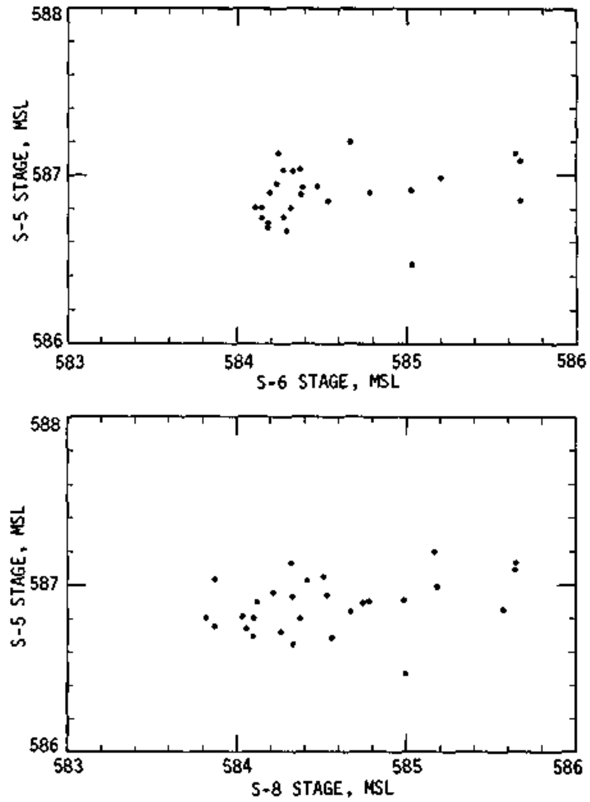


Figure 33. Correlation of S-5 data with those at S-6 and S-8

also show a moderate relationship between water stages. Apparently, activity which affects stream stages at S-3 (precipitation) also does so in the nature preserve. The culvert under Wadsworth Road (site of S-4 and S-5) is not an important drainway, as indicated by the low correlation coefficients relating these two gages with all of the other gages.

Water Sample Evidence. Analyses of water samples collected on July 23, 1975, and on February 18, March 25, and April 7, 1976, provide a second source of evidence supporting the assumption that Bull Creek flows southward to Dead River. On each of these dates water samples were taken from Bull Creek at the bluff and the beach (S-3) sampling sites, and from Dead River at S-10. A comparison of their chemical analyses was made to examine their similarity.

A convenient technique for comparing waters is to categorize a sample by the relative proportions of its major constituents which are plotted graphically. One form of this technique is known as the Piper trilinear diagram (Hem, 1959), in which cation and anion equivalent proportions are plotted on their respective triangular fields and their intersecting projected point is then located on a diamond-shaped field in the upper center of the graph. Figures 34 through 37 show Piper trilinear plots made from the analyses for each of the sampling dates. Projected points in the diamond field show that water from Dead River is much more like that at Bull Creek bluff than is water sampled at S-3. This similarity is also noted in the anion field and in all but the July 23, 1975, samples in the cation field.

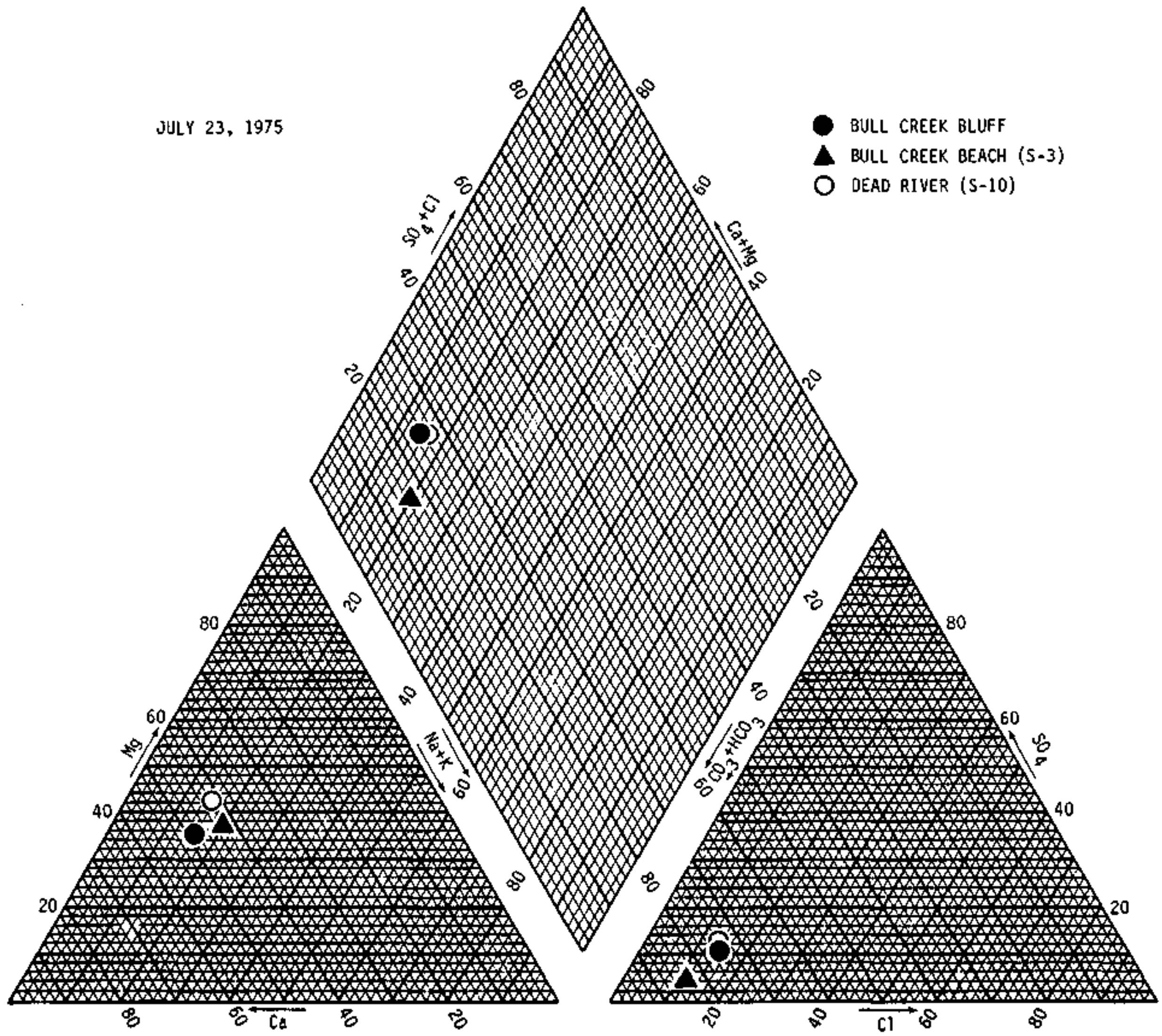


Figure 34. Piper diagram for July 23, 1975

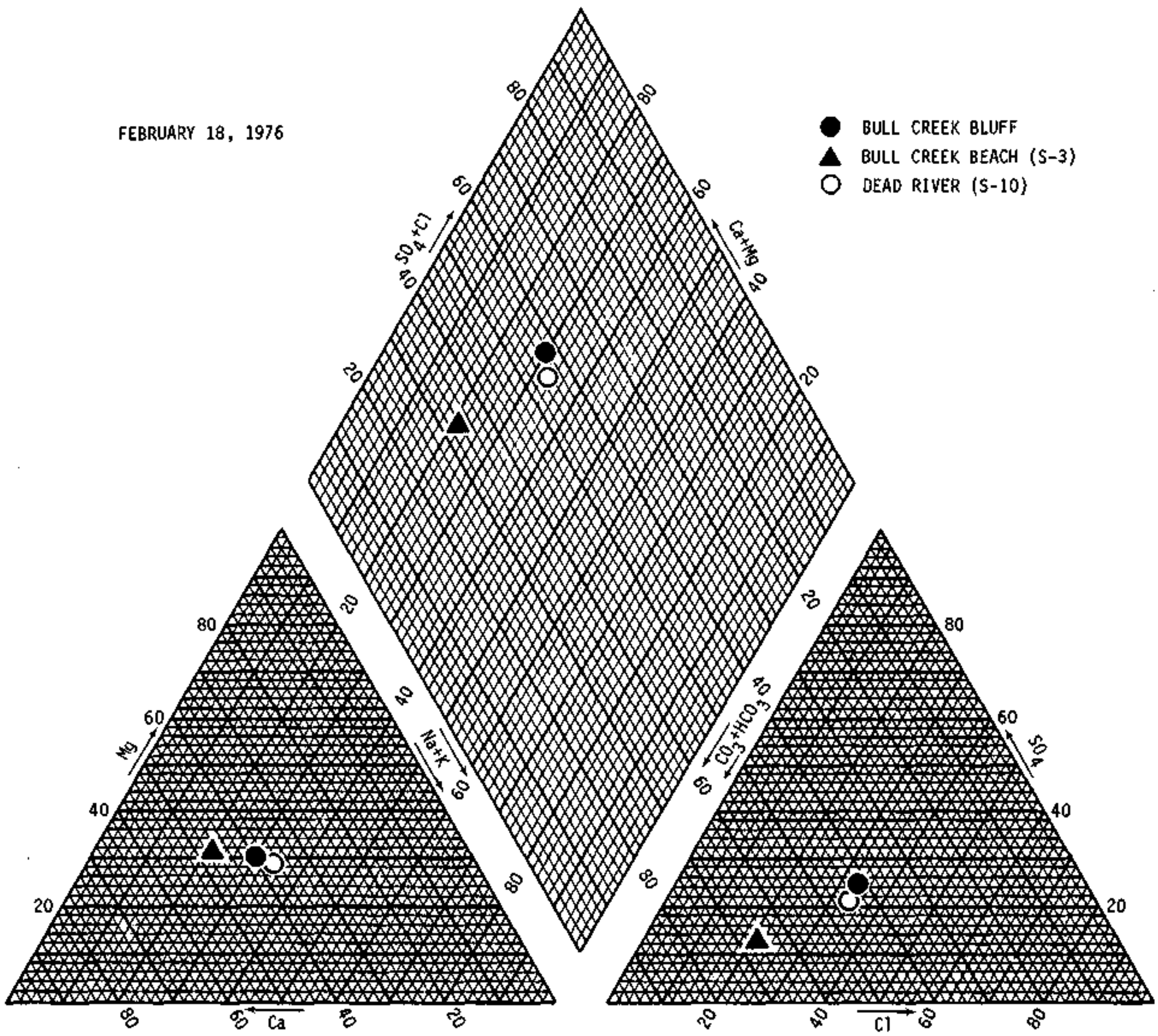


Figure 35. Piper diagram for February 18, 1976

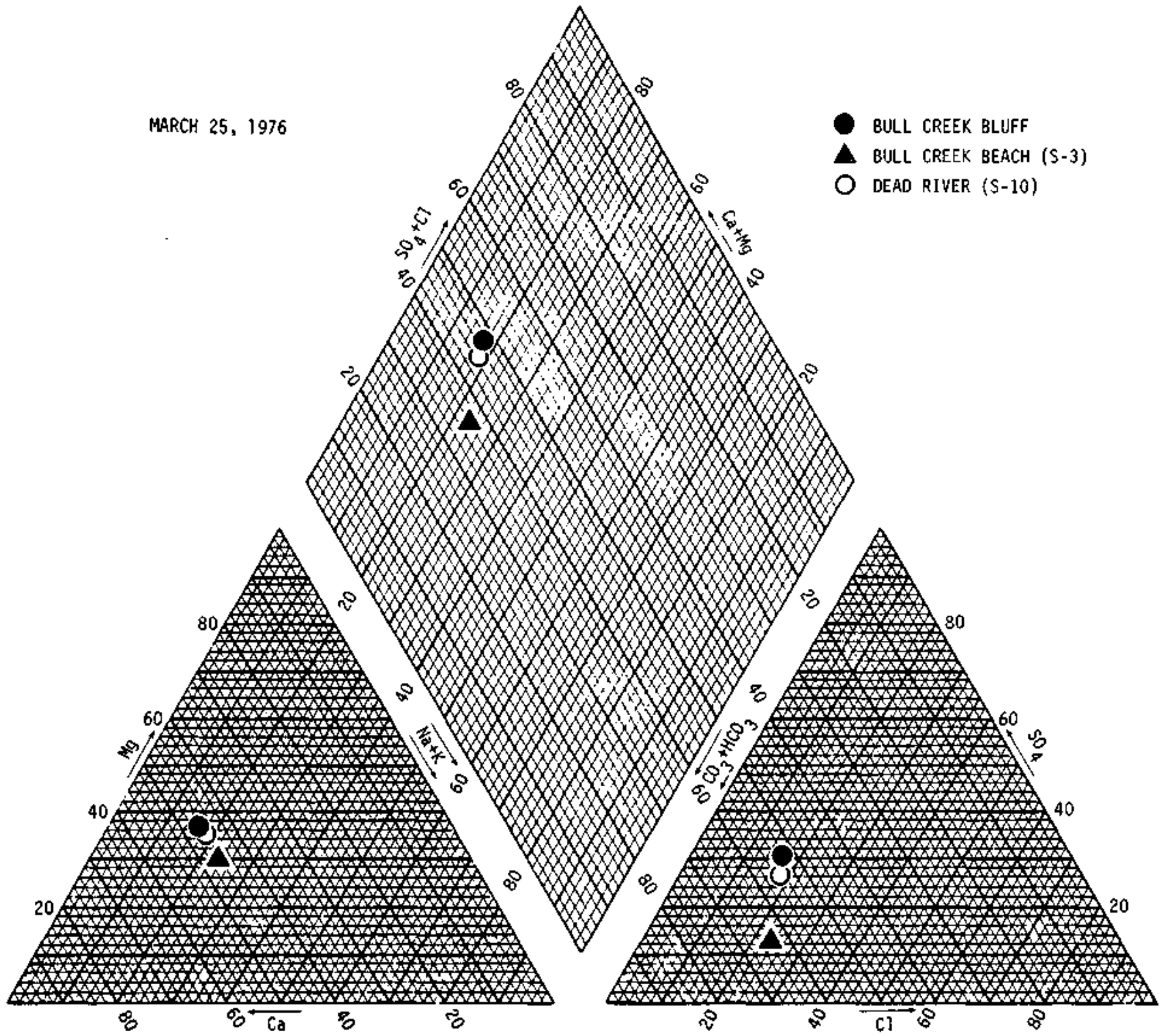


Figure 36. Piper diagram for March 25, 1976

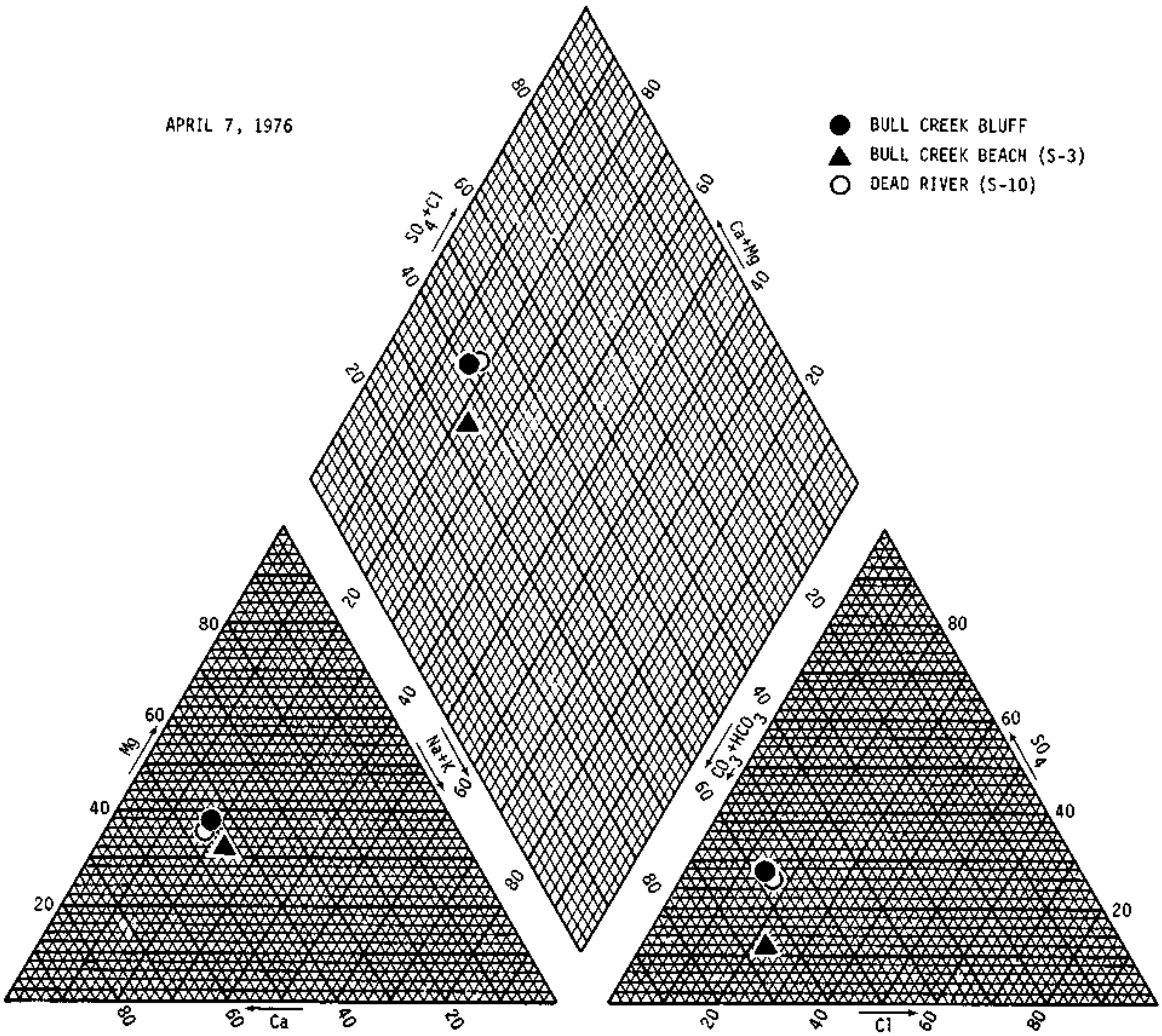


Figure 37. Piper diagram for April 7, 1976

Water Quality

From January 1975 to April 1976, 156 groundwater samples and 33 stream samples were collected in the study area. In addition, 16 samples of Lake Michigan water were collected from the raw water line at the Zion-Benton Township Water Treatment Plant. A complete summary of analyses made of the 205 total water samples is presented in the appendix. Table 14 shows ranges and mean values for alkalinity, hardness, and total dissolved solids for the monthly samples.

Total dissolved solids of groundwater samples ranged between 301 and 1076 milligrams per liter (mg/l) and hardness varied from 152 to 595 mg/l. Dead River mineral quality was generally much better; total solids and hardness ranged from 196 to 491 mg/1 and from 114 to 342 mg/1, respectively. Lake Michigan samples showed a high degree of consistency in that the range of both total dissolved solids and hardness was small (148 to 204 mg/1 and 132 to 148 mg/1, respectively).

Groundwater quality varied unpredictably both in time and space (figures 38 and 39). Chemical quality did not appear to be related to proximity to the lake; however, there is evidence that chlorides of both calcium and sodium have higher concentrations along Wadsworth Road as a result of road salt applications during winter. The plot of total dissolved solids from P-10 (figure 38) indicates a seasonal nature of total solids concentration. Peak values of 680 and 723 mg/1 were observed in January 1975 and February 1976, respectively. Corresponding chloride peaks were 160 and 205 mg/1, respectively. Figure 39 shows total dissolved solids and chlorides from P-7. Unusually high values for both parameters occurred in January 1975 and were followed by nearly proportionate declines and smaller peaks during the following December. Since road salt applications do not extend that far along Wadsworth Road, another, though indirect, cause for the anomalously high chlorides and total solids has been hypothesized. The indirect source is believed to be one or both of two drainage ditches within 100 feet of P-7 which collect the runoff from approximately 11.5 acres of parking area across Wadsworth Road. It is possible that the road salts carried onto the parking area by cars, trucks, and campers and subsequently washed off by rains into the ditches are concentrated enough to seep into the permeable materials as a slug.

Groundwater temperatures — unlike the chemical parameters — exhibited easily discernible areal distributions (figures 40 and 41) as well as seasonal fluctuations (figure 42). A temperature gradient exists across the sand body and is seen to reverse itself from summer to winter. Ground-

Table 14. Ranges and Mean Values of Selected Chemical Characteristics of Water
(Chemical constituents in milligrams per liter)

	Alkalinity (as $CaCO_3$)		Hardness (as $CaCO_3$)		Total dissolved solids	
	Mean	*Range*	*Mean*	*Range*	*Mean*	*Range*
P-1	350	310-388	381	352-430	454	395-523
P-4	276	256-310	297	254-328	460	379-539
P-6	243	154-286	226	152-264	415	305-468
P-7	289	202-372	330	194-595	628	432-1076
P-10	213	166-260	298	244-384	496	387-723
P-13	236	210-266	275	210-380	459	369-604
P-15	273	220-320	278	220-342	359	301-443
P-18	331	212-420	345	218-512	458	304-729
Well	320	284-382	349	308-388	417	357-463
S-10	204	78-316	258	114-342	363	196-491
Lake	112	100-124	138	132-148	168	148-204

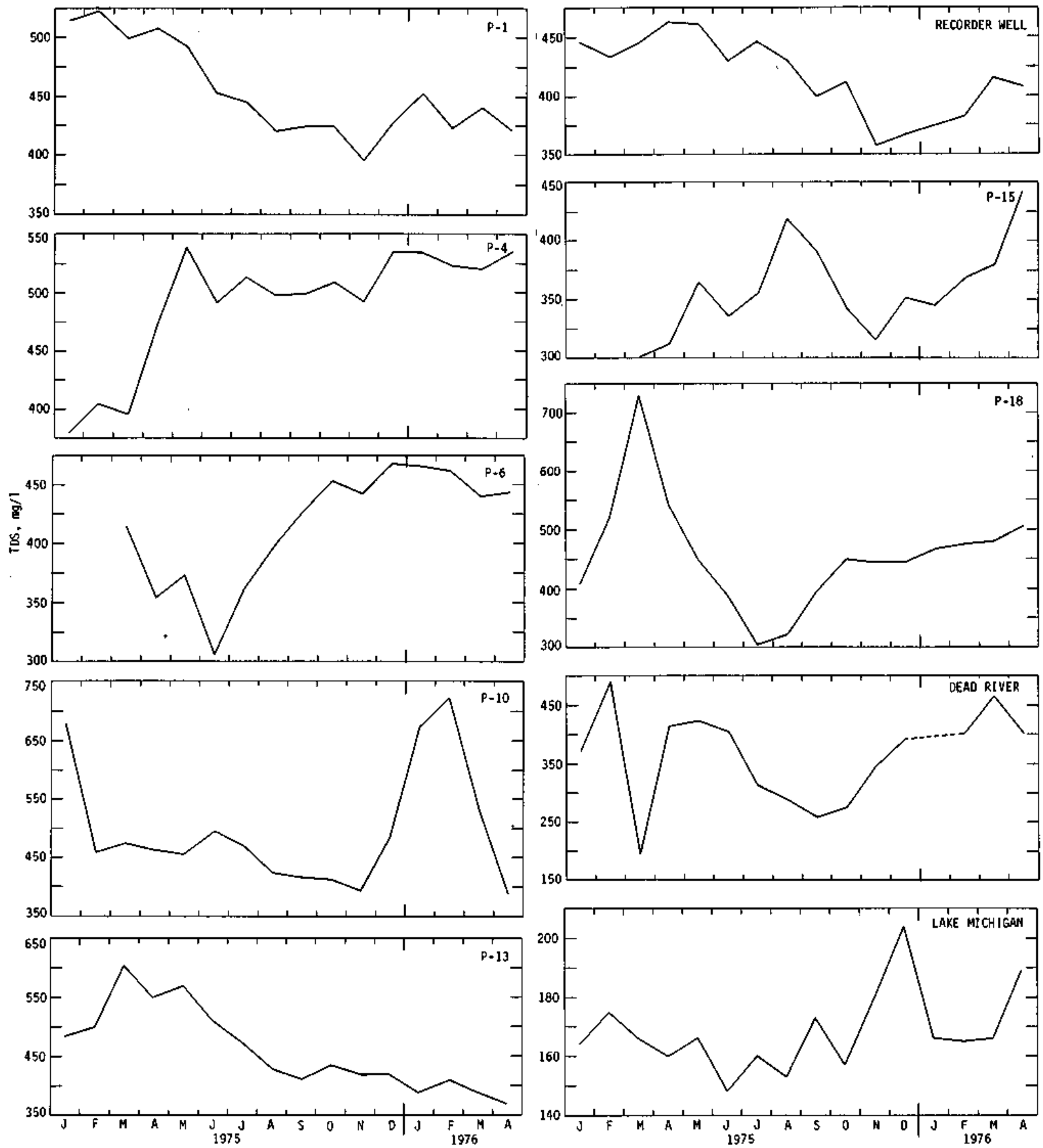


Figure 38. Total dissolved solids concentration at monitoring sites

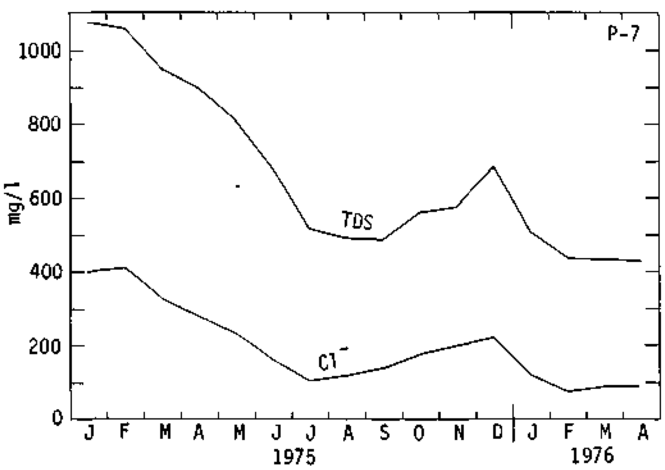


Figure 39. Variation of chlorides and total dissolved solids at P-7

water is recharged by water that is usually higher (summer) or lower (winter) than the prevailing average ground temperature. The recharge water is thus subsequently cooled or warmed as it flows toward the lake, creating a temperature gradient. Temperatures of Dead River and Lake Michigan samples also exhibited seasonal effects, but those from the lake also showed secondary cycles superposed on the seasonal cycles because of the twice-yearly overturn effect common in large lakes.

Water samples were collected at the three clustered piezometers (P-9, P-10, and P-11) in January and July 1975 in order to see what, if any, vertical variation in water quality existed in that portion of the study area. In January 1975 these samples indicated that the mid-depth piezometer (P-10) had significantly higher chlorides and dissolved solids than did the shallow (P-9) and deep (P-11) piezometers. Temperature was also higher at P-10 (42.5°F) than at P-9 (39°F) and P-11 (40.5°F). The July 1975 samples showed that both chloride and sulfate were highest at the mid-depth, but alkalinity, hardness, and dissolved solids all decreased in concentration with depth, and temperature was lowest at the mid-depth. Since water level data from these piezometers did not indicate a significant vertical groundwater movement (nor, therefore, a chemical transport mechanism), differences in chemical quality with depth can most likely be ascribed to the differences in lithologic character of the various strata penetrated at the three depths *(see figure 4).*

CONCLUSIONS

As a result of this study various hydrologic elements have been quantified, the interrelationships of these elements within the study area have been determined, the chemical nature of groundwater and surface water has been identified, and certain conclusions as to current and anticipated problems have been made. These results and conclusions are summarized below.

1) Although the water table fluctuated an average of 2.7 feet, it ranged from 0.8 ft above ground to 11.01 feet below ground in various locations of the study area. Maximum and minimum fluctuations of 3.74 and 1.76 feet were observed at P-12 and P-4, respectively.

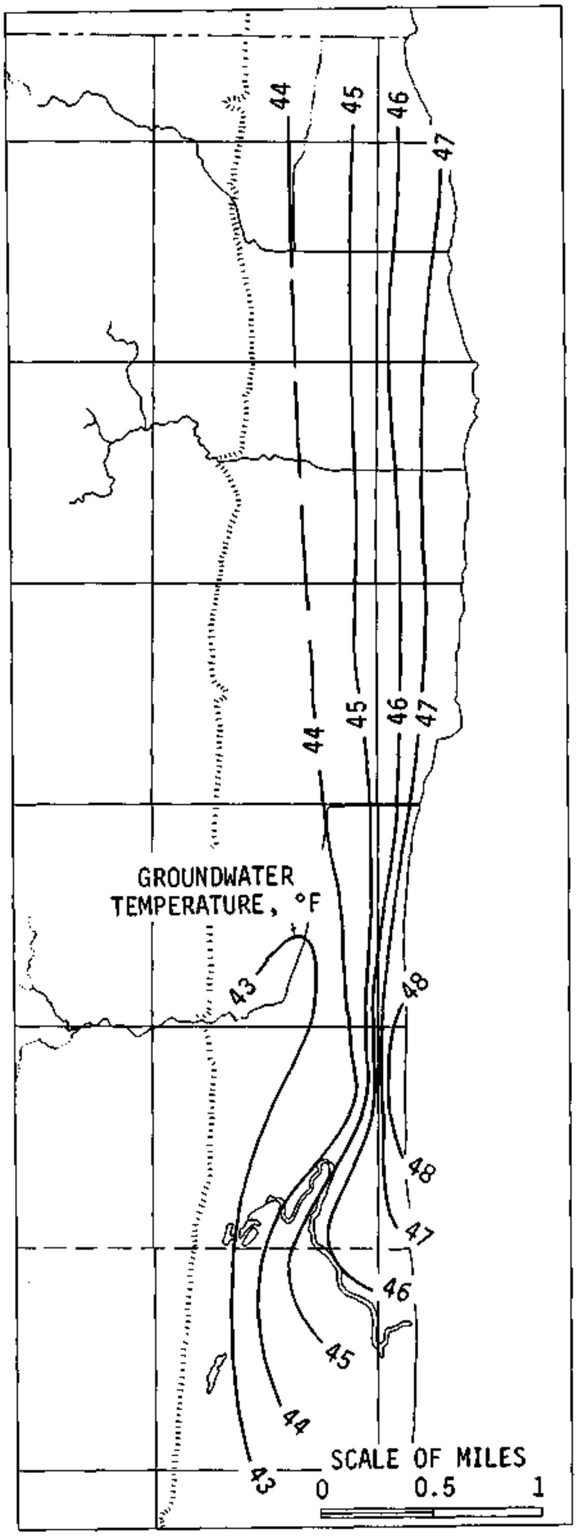


Figure 40. Groundwater temperature variation, January 1975

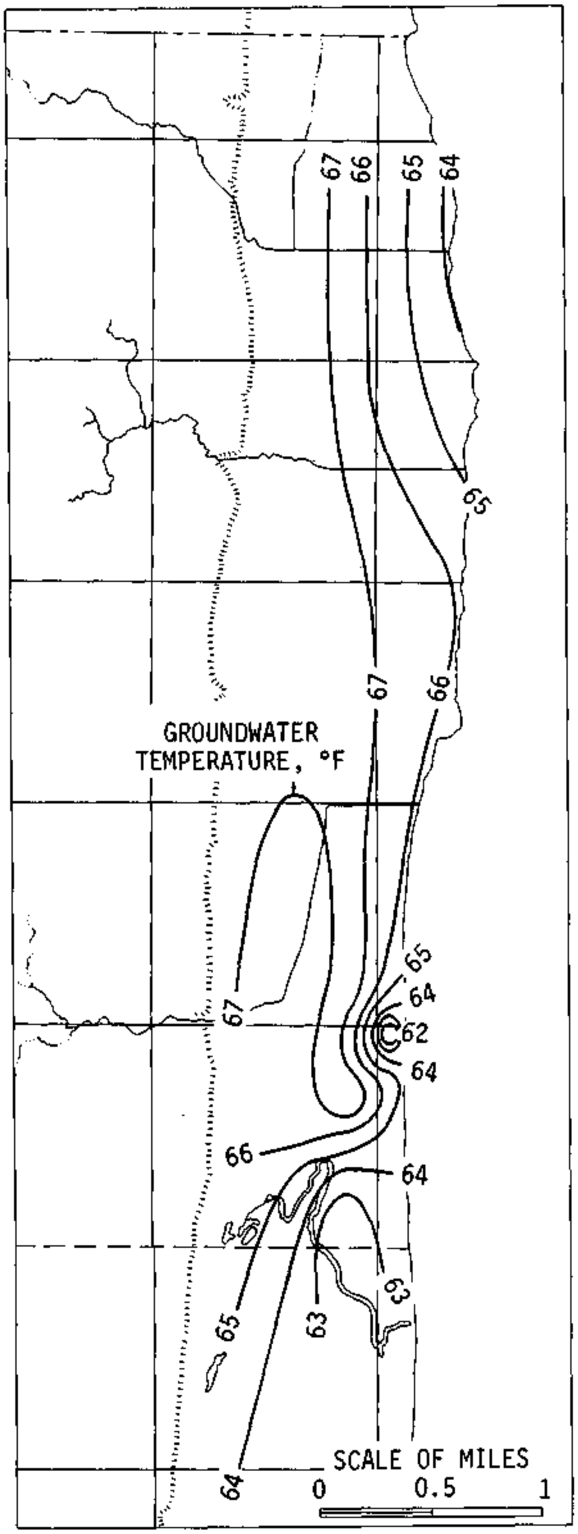


Figure 41. Groundwater temperature variation, July 1975

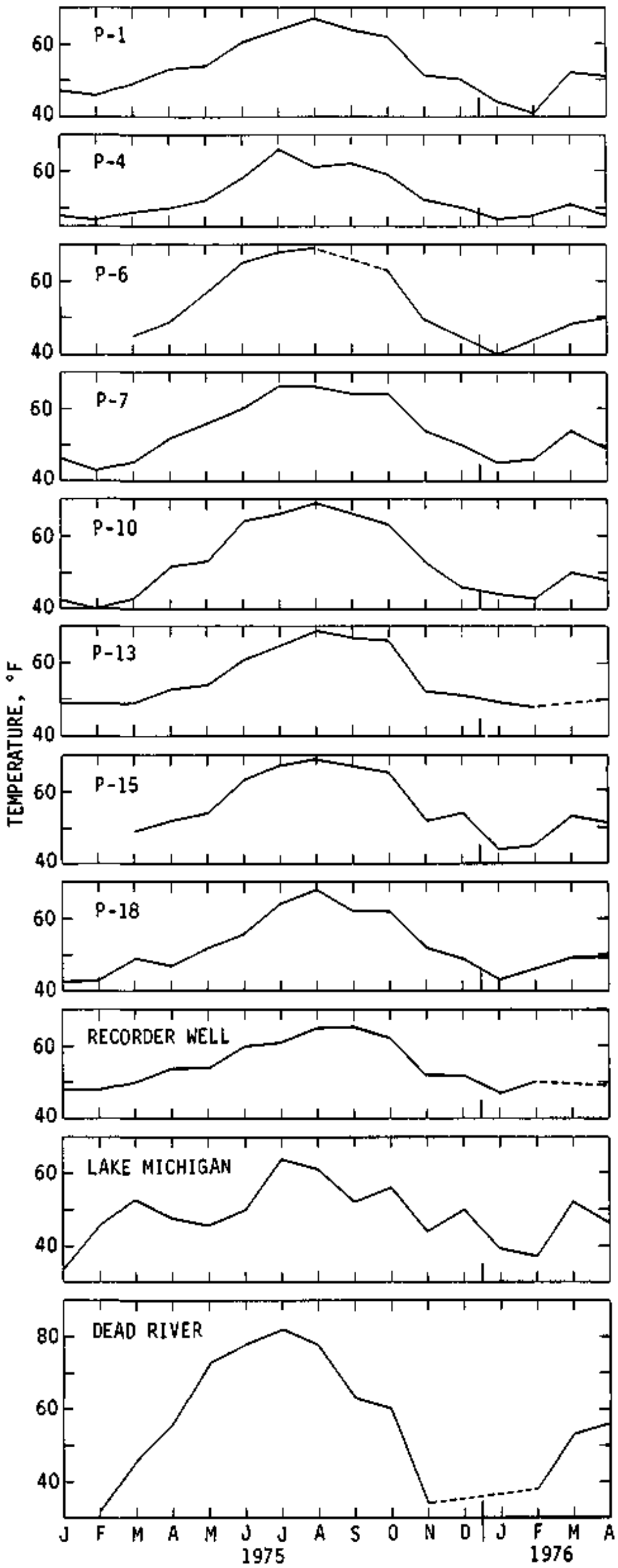


Figure 42. Groundwater temperature at monitoring sites

2) The water table exhibits a variable head gradient from the bluff to Lake Michigan, being steeper near the bluff where the aquifer is thinner. The gradient becomes quite flat in the marshy nature preserve area.

3) Groundwater levels do not generally correlate well with precipitation events; water levels show only slight-to-moderate delayed response to rainfall, especially during periods of low evapotranspiration.

4) Hydrographs for P-9, P-10, and P-ll show no conclusive evidence of vertical groundwater movement in that portion of the marsh.

5) Surface water stages show noticeable seasonal trends, with 8 of the 10 gages out of water during the summer and fall.

6) Staff gage hydrographs for S-1, S-2, S-3, and S-10 sites indicated at least 15 breakthrough events: two on Lake Michigan Tributary, four on Kellogg Ravine, four on Bull Creek, and five on Dead River. Most breakthrough events appeared to be caused by an overtopping-channelization mechanism, suggesting that a wave erosional mechanism related to the water table was not an important factor.

7) Breakthrough data seem to indicate that the *decline/As* ratio is more or less constant for each stream. It is suggested that this might be a function of beach firmness as described by Krumbein (1963).

8) Lake Michigan stages observed during the study (578.70-580.92 ft IGLD) were not significantly different from those of the previous 5 years.

9) Groundwater levels are not closely

related to stream stages in the northern half of the area. In the southern half, particularly south of Wadsworth Road, a close relationship between these data does exist because of the influence of the extensive marsh area around Dead River.

10) The correlation of groundwater levels with Lake Michigan stages improves as one approaches the lake shore, the coefficient reaching a value of 0.766 at P-13. Evidence suggests that the water table near the park lodge is more strongly affected by lake levels than by those of Dead River.

11) The average hydraulic conductivity, based on an earlier well test and subsequent geologic interpretation of aquifer thickness, was determined to be 1933 gpd/sq ft. An average value of 0.16 for specific yield was calculated from rainfall and recorder well data.

12) The major source of recharge to the sand aquifer is precipitation. From flow net analysis the average recharge rate was estimated to be 313,000 gpd/sq mi in 1975, a year in which precipitation was 12 percent greater than normal. On a year-round basis the only relatively important contribution to recharge from streams is that of the temporary storage which takes place in Dead River during ponded periods.

13) Based on an average runoff rate of 0.65 cfs/sq mi the runoff for Lake Michigan Tributary, Kellogg Ravine, and Bull Creek, where they enter the park, is estimated to be 0.98, 3.28, and 2.92 cfs, respectively. With the State Standard Procedure as the basis for computation, the estimated 100-year flood flows for these streams are 412, 1285, and 1609 cfs, respectively.

14) Staff gage evidence and water analyses both indicate conclusively that Bull Creek, upon entering the park, is effectively routed southward in a diffuse overland flow to the Dead River catchment and does not flow northward in its natural channel. The culvert which carries only peak flows under Wadsworth Road is, therefore, not an important drainway. Roadway flooding at the culvert site is caused by the relatively small size of the culvert (24 inches) in comparison to the storm inflow volumes, and no doubt some of the flooding problem could be alleviated by the construction of larger or additional culverts. Perhaps a more desirable and overall more efficient alternative, however, would be that of channeling Bull Creek at a point just inside the park and routing it more directly southward to Dead River. Further modification of the culverts under Beach Road would no doubt be required in order to accommodate the increased flow. The latter alternative would also have the effect of giving Dead River the necessary flow volume to breach the barrier bar at its mouth and reduce the storage time of ponded Dead River water.

15) Groundwater quality is quite variable in time and space. Total dissolved solids observed during the study ranged from 301 to 1076 mg/l while hardness ranged from 152 to 595 mg/1. Calcium and sodium chloride have higher concentrations along Wadsworth Road because of road salt applied during winter months. Mineral concentrations were generally lower in Dead River; dissolved solids and hardness there ranged from 196 to 491 mg/1 and from 114 to 342 mg/1, respectively. Groundwater temperatures exhibited seasonal fluctuations and a gradient which was warmer toward the lake in winter and cooler in summer.

16) It is impractical to be specific in suggesting possible trouble spots to anticipate as the park expands northward; however, one can make certain general comparisons between conditions in the north and south. For one, surface drainage does not appear

to be nearly the problem in the north that it is in the south. No extensive marshy areas appear as in the nature preserve. The water table, however, is shallow, as in the southern half, and water-free basements will be maintained only by dewatering. Of course the latter problem will be aggravated at any near shore site because of the influence of the lake. Groundwater quality would appear to be a bit better than that along Wadsworth Road but not as good as in the nature preserve (P-14 to P-17).

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APPENDIX. Monthly Analyses of Water Samples

(Chemical constituents in milligrams per liter)

	Fe	Ca	Mg	Na	K	NO_3	Cl	SO_4	Alkalinity (as $CaCO_3$)	Hardness (as $CaCO_3$)	Total dissolved minerals	Temperature (°F)
January 1975												
P-1	4.2					0.9	21	63.6	384	404	515	47
P-3	1.6					1.1	6	83.7	190	248	328	44.5
P-4	4.6					0.7	47	1.6	290	280	379	48
P-7	5.0					0.5	400	59.9	352	595	1076	46.5
P-8	2.2					0.5	170	66.0	304	200	691	44.5
P-9	17					0.6	50	133.5	268	334	532	39
P-10	2.8					0.5	160	99.4	250	340	680	42.5
P-11	1.5					0.8	49	129.6	162	274	423	40.5
P-12	4.3					0.6	92	35.4	460	496	649	43
P-13	7.3					0.4	125	38.3	244	340	484	49
P-14	1.8					0.3	56	33.7	294	258	440	44
P-16	1.6					0.5	3	17.1	244	250	282	46.5
P-17	0.1					0.6	6	33.5	214	252	281	46
P-18	6.7	74.8	26.9	23.9	4.6	1.8	28	1.2	336	298	408	42.5
Well	4.9	86.4	33.7	19.6	1.8	1.4	35	23.9	334	354	446	48
Lake Michigan Tributary												
Bluff	1.3	78.4	36.1	26.0	1.8	19.3	43	97.3	230	344	478	32
S-1	7.2	84.4	32.5	6.2	1.8	1.6	3	82.1	274	344	412	
Kellogg Ravine												
Bluff	0.7	87.2	35.1	35.2	2.7	26.7	65	106.6	224	362	532	32
Beach	1.2	83.2	34.2	35.1	2.0	22.4	64	83.1	232	348	514	34.5
Bull Creek												
Bluff	0.4	93.6	43.9	91.3	2.5	2.7	133	139.7	280	414	688	
S-3	2.9	98.4	36.1	36.8	4.3	2.0	59	66.6	328	394	547	35
S-10	0.6	54.4	34.2	25.2	3.6	1.2	33	46.7	240	276	373	
Lake	0.5	37.2	10.9	5.6	1.2	1.5	8	23.9	104	138	164	34
February 1975												
P-1	5.2					0.5	20	59.0	388	408	523	46
P-4	5.2					0.7	60	2.9	284	282	404	47
P-7	5.7					0.5	410	53.3	348	526	1058	43
P-10	1.6					0.4	59	88.7	236	272	458	40
P-13	9.4					0.5	150	34.8	226	344	499	49
P-18	9.3					1.1	50	7.6	420	376	521	43
Well	2.2					0.5	29	29.8	332	350	433	
S-10	0.5	80.0	34.7	39.3	4.7	6.2	60	108.4	224	342	491	32
Lake	0.3	38.4	11.2	6.7	1.6	1.5	10	25.1	108	142	175	46
March 1975												
P-1	11	102	40.0	14.7	2.7	0.5	20	58.8	388	420	499	49
P-4	7	67.2	21.0	47.0	8.4	0.6	66	9.1	272	254	395	49
P-6	2.3	66.4	23.0	48.0	3.2	1.1	92	3.1	244	260	415	45
P-7	4.6	110	47.3	170.0	4.6	0.4	330	61.7	336	470	949	45
P-10	0.2	68.8	36.6	30.3	2.1	0.0	54	85.4	242	322	474	43
P-13	7.5	92.8	36.1	72.6	4.8	0.4	180	39.3	244	380	604	49
P-15	0.4	44.0	26.8	21.2	2.1	0.3	25	16.0	220	220	301	45
P-18	15	133	43.9	43.5	5	1.7	80	191.9	308	512	729	49
Well	0.4	85.6	37.6	13.1	1.5	0.6	28	40.7	324	368	445	50
S-10	0.9	27.2	11.2	21.9	2.7	1.1	34	34.8	78	114	196	46
Lake	0.4	37.6	11.7	7.3	1.3	1.4	13	22.4	114	142	166	53

(Continued on next page)

APPENDIX. *(Continued)*

(Chemical constituents in milligrams per liter)

	Fe	Ca	Mg	Na	K	NO_3	Cl	SO_4	Alkalinity (as $CaCO_3$)	Hardness (as $CaCO_3$)	Total dissolved minerals	Temperature (°F)
April 1975												
P-1	1.5	104.0	41.5	15.4	2.7	0.6	19	54.3	384	430	508	53
P-4	4.8	73.6	26.4	53.6	9.2	0.6	79	30.9	276	292	473	50
P-6	2.3	56.8	18.6	44.7	2.8	1.0	45	1.0	250	218	354	49
P-7	1.4	94.4	45.8	168	3.9	0.1	280	52.5	336	424	898	52
P-10	0.5	71.2	35.6	37.8	1.9	0.1	51	76.1	260	324	463	52
P-13	14	78.4	32.2	74.7	4.5	1.1	146	38.7	256	328	550	53
P-15	2.6	48.8	26.8	22.8	2.0	0.5	25	14.4	230	232	312	52
P-18	14	99.2	35.1	39.1	3.8	1.8	53	99.8	300	392	542	47
Well	0.3	92.8	37.1	13.0	1.6	0.3	29	47.1	328	384	463	54
S-10	1.4	69.6	30.8	26.8	2.4	1.4	42	81.7	202	300	416	56
Lake	0.3	37.6	11.2	6.5	1.3	1.3	11	23.2	114	140	160	48
May 1975												
P-1	1.4	99.2	42.4	16.2	2.9	0.5	19	47.5	384	422	492	54
P-4	7.1	81.6	26.4	65.0	10.8	0.7	98	57.4	268	312	539	52
P-6	2.6	61.6	21.0	40.3	3.2	1.1	52	7.6	244	240	373	57
P-7	2.3	86.4	42.4	147	3.6	0.2	235	48.5	338	390	812	56
P-10	0.2	64.0	41.5	39.3	1.6	0.5	61	78.6	254	330	456	53
P-13	9.8	78.4	33.7	74.2	3.9	0.2	138	39.1	266	334	569	54
P-15	5.7	70.4	25.9	23.4	1.8	0.5	25	8.0	296	282	365	54
P-18	9.2	80.0	29.3	31.2	3.6	0.8	44	72.2	254	320	448	52
Well	0.4	91.2	39.0	13.2	1.4	0.3	34	45.3	332	388	462	54
S-10	0.8	72.0	34.2	25.0	2.1	2.5	40	55.1	266	320	424	73
Lake	0.1	36.0	10.7	5.4	1.2	0.9	10	22.6	112	134	166	46
June 1975												
P-1	1.1	92.8	42.9	16.6	2.7	0.3	19	40.7	378	408	453	61
P-4	3.5	76.8	24.4	58.2	8.6	0.2	82	46.9	264	292	491	58
P-6	0.6	46.4	16.1	28.0	2.9	0.6	72	11.1	154	182	305	65
P-7	1.6	76.0	37.1	124	3.5	0.2	165	40.1	372	342	684	60
P-10	0.2	66.4	34.2	55.0	1.7	0.2	79	95.9	214	306	494	64
P-13	2.6	73.6	31.3	72.5	4.0	0.1	115	37.2	264	312	509	61
P-15	4.0	69.6	24.4	22.4	2.5	0.4	23	17.3	270	274	336	63
P-18	6.5	73.6	25.4	28.4	3.2	0.6	35	42.6	258	288	389	56
Well	0.7	91.2	37.6	14.7	1.6	0.2	34	45.0	320	382	430	60
S-10	0.7	64.0	29.8	38.6	2.8	0.7	36	66.9	242	282	406	78
Lake	0.0	34.8	11.4	4.7	1.1	1.9	9	23.7	106	134	148	50
July 1975												
P-1	5.0	83.2	45.4	17.8	2.8	0.5	18	34.4	368	394	445	64
P-3	2.2	81.6	30.3	8.4	2.0	0.6	16	102.4	212	328	401	67
P-4	2.5	73.6	27.8	66.5	12.0	0.4	91	51.0	268	298	514	66
P-6	0.9	51.2	20.6	48.2	3.0	0.5	83	17.3	180	212	361	68
P-7	1.3	64.0	30.3	83.0	3.1	0.5	105	26.5	296	284	518	66
P-8	1.5	76.8	27.8	206	4.9	0.3	285	70.8	298	306	891	67
P-9	13	81.6	27.4	68.9	2.4	0.2	43	85.8	324	316	541	69
P-10	0.3	49.6	35.0	61.6	1.9	0.5	85	101.0	196	268	472	66
P-11	0.3	32.8	43.3	48.2	3.0	0.4	54	94.4	192	260	424	70
P-12	2.9	91.5	43.7	49.8	2.5	0.7	115	47.9	324	408	567	67
P-13	0.8	58.4	32.2	67.4	4.1	0.3	100	26.1	256	278	472	65
P-14	1.0	54.4	24.0	38.4	2.3	0.4	13	24.1	274	234	328	68

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APPENDIX. *(Continued)*

(Chemical constituents in milligrams per liter)

	Fe	*Ca*	*Mg*	*Na*	*K*	NO_3	*Cl*	SO_4	*Alkalinity (as* $CaCO_3$*)*	*Hardness (as* $CaCO_3$*)*	*Total dissolved minerals*	*Temperature (°F)*
P-15	2.7	65.6	26.9	22.4	2.5	0.7	23	26.5	268	274	356	67
P-16	1.5	56.0	23.0	1.5	0.9	0.3	0	15.6	220	234	247	62
P-17	0.2	18.4	26.8	1.4	0.6	0.0	2	24.9	126	152	161	63
P-18	1.9	54.8	19.8	25.8	3.1	0.8	27	21.8	212	218	304	64
Well	5.7	88.0	35.6	17.7	1.6	0.6	36	30.0	340	366	446	61
Lake Michigan Tributary												
Bluff	2.1	70.4	33.2	16.4	2.6	1.9	19	74.7	238	312	394	73
S-1	2.4	53.6	31.7	8.6	1.9	2.0	3	22.2	244	264	292	83
Kellogg Ravine												
Bluff	3.4	48.0	20.4	16.3	3.6	1.2	23	24.7	180	204	277	78
Beach	3.6	63.2	26.9	19.9	2.8	0.7	31	45.7	220	268	352	81
Bull Creek												
Bluff	1.8	86.4	38.1	28.8	4.3	0.7	41	48.5	320	372	472	77
S-3	1.2	76.8	40.0	30.5	18.3	1.7	36	20.6	394	356	475	77
S-10	0.4	45.6	28.7	20.0	1.3	1.5	25	34.4	200	232	313	82
Lake	0.3	36.0	11.2	5.3	1.3	2.0	9	24.1	110	136	160	64
August 1975												
P-1	0.9	75.2	42.4	18.3	3.0	0.5	17	31.7	344	362	421	67
P-4	2.4	73.6	25.4	69.5	13.2	0.8	92	52.2	256	288	498	61.5
P-6	0.5	40.8	23.8	76.6	4.4	0.8	96	18.3	202	200	397	69
P-7	0.4	52.8	31.1	83.5	3.2	0.6	120	19.3	260	260	493	66.5
P-10	0.2	43.2	34.2	57.1	1.6	0.8	76	88.9	176	248	425	69
P-13	0.2	36.8	34.0	67.2	4.4	0.6	98	15.6	236	232	429	69
P-15	3.7	78.4	33.2	23.2	2.4	0.9	22	32.9	320	332	419	69
P-18	4.5	60.0	23.0	23.2	2.8	1.3	40	9.1	232	244	321	68
Well	2.0	80.8	37.6	16.2	1.6	0.8	35	34.4	316	356	430	65
S-10	1.0	40.0	25.3	15.8	0.8	1.4	24	30.6	188	204	288	77.5
Lake	0.3	36.0	10.2	4.8	1.0	1.2	8	21.4	100	132	153	61
September 1975												
P-1	0.9	68.8	46.8	17.2	3.3	1.2	18	35.8	348	364	424	64
P-4	2.3	66.4	27.8	65.6	13.7	1.1	91	51.6	264	280	499	62
P-6	0.5	25.8	42.4	77.1	3.8	1.4	100	19.1	224	212	427	
P-7	0.5	48.0	33.1	88.0	3.7	1.0	138	25.1	236	256	491	64
P-10	0.2	40.8	34.5	52.2	1.9	0.8	70	95.4	168	244	417	66
P-13	0.2	36.0	32.6	72.0	5.0	0.4	92	20.6	228	224	411	67
P-15	3.7	72.8	31.7	21.3	2.4	0.8	18	42.6	296	312	391	67
P-18	8.8	76.8	26.4	26.9	3.0	1.6	40	3.1	300	300	396	62
Well	0.2	72.0	35.1	17.3	0.6	0.4	34	38.3	284	324	399	65
S-10	0.2	40.0	24.3	16.8	1.2	1.6	20	31.7	168	200	258	63
Lake	0.3	35.2	11.7	6.4	1.3	2.1	9	24.1	112	136	173	52
October 1975												
P-1	0.8	78.4	42.0	17.2	3.3	0.4	16	38.1	348	368	424	62
P-4	2.7	66.4	28.7	65.1	14.5	0.8	88	53.1	256	284	509	59
P-6	0.6	49.2	27.0	78.9	3.6	0.9	102	14.6	250	234	453	63
P-7	0.5	50.4	33.6	96.3	3.8	0.3	177	23.7	218	264	560	64
P-10	Tr.	39.2	35.5	48.3	1.6	0.2	65	92.8	168	244	413	63
P-13	0.2	38.0	23.8	70.6	5.2	0.3	102	24.3	236	234	434	66
P-15	0.5	52.4	31.9	21.5	2.4	0.5	19	21.8	272	262	343	65
P-18	11	86.4	30.2	28.4	3.1	1.2	40	4.1	356	340	456	62

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APPENDIX. *(Continued)*

(Chemical constituents in milligrams per liter)

	Fe	*Ca*	*Mg*	*Na*	*K*	NO_3	*Cl*	SO_4	*Alkalinity (as $CaCO_3$)*	*Hardness (as $CaCO_3$)*	*Total dissolved minerals*	*Temperature (°F)*
Well	1.8	76.4	34.8	18.3	1.3	0.4	39	19.1	312	334	412	62
S-10	0.2	38.4	27.2	14.9	1.1	0.5	24	36	176	208	274	60
Lake	0.1	34.4	11.2	6.2	1.4	1.6	9	22.8	112	132	157	56
November 1975												
P-1	0.2	69.6	44.4	16.2	3.3	0.6	16	43.6	324	356	395	51
P-4	3.1	74.4	27.4	65.1	13.6	0.8	92	54.1	264	298	492	52
P-6	2.5	62.8	26.1	72.0	2.9	1.5	104	2.7	270	264	442	49
P-7	0.7	53.6	35.1	107	4.2	0.3	200	24.1	202	278	574	54
P-10	0.2	43.2	36.0	47.5	1.9	0.4	64	94.0	166	256	394	53
P-13	0.4	44.0	30.6	71.2	4.9	0.6	94	26.5	226	236	418	52
P-15	1.4	40.8	34.5	25.1	2.8	0.7	17	20.4	254	244	316	52
P-18	9.2	90.4	31.7	28.2	3.5	1.7	36	1.0	372	356	445	52
Well	0.1	66.0	34.9	19.2	1.8	0.9	33	18.1	284	308	357	52
S-10	0.2	48.8	33.6	23.8	2.7	1.0	33	59.9	200	260	345	34
Lake	0.9	37.6	10.7	6.5	1.2	2.5	10	20.4	110	138	180	44
December 1975												
P-1	0.3	68.0	44.4	16.4	2.9	0.4	18	56.0	318	352	428	50
P-4	2.1	77.6	29.3	62.8	12.7	0.3	98	62.3	272	314	536	50
P-6	4.3	60.0	24.9	72.5	2.2	0.9	100	3.5	278	252	468	45
P-7	0.6	72.8	31.7	128	3.9	0.2	220	26.9	274	312	685	50
P-10	1.0	61.6	36.6	49.1	1.8	0.3	73	96.1	228	304	485	46
P-13	0.1	57.2	29.4	58.3	4.5	0.5	84	28.2	252	264	419	51
P-15	2.4	52.8	37.6	24.5	2.4	0.6	19	43.0	276	286	352	54
P-18	12	91.2	30.0	28.4	3.0	1.6	36	0.0	384	351	445	49
Well	1.4	74.4	31.7	18.3	1.5	0.5	23	9.1	326	316	367	52
S-10	1.7	59.2	29.8	33.6	3.2	3.3	54	87.2	182	270	392	33
Lake	0.5	38.8	10.5	5.8	1.6	6.3	11	25.3	112	140	204	50
January 1976												
P-1	2.0	69.6	44.4	28.1	2.9	0.5	36	54.3	318	356	453	44
P-4	2.2	76.0	30.3	65.6	11.1	0.6	92	47.3	300	314	534	47
P-6	3.9	62.4	25.9	73.3	2.4	1.5	94	2.9	286	262	466	40
P-7	2.0	56.0	25.4	99.3	3.4	0.4	122	20.1	280	244	511	45
P-10	0.8	72.8	46.3	102	2.1	0.4	205	88.9	232	372	674	44
P-13	1.1	54.8	24.2	55.8	3.6	0.4	75	26.1	230	236	389	49
P-15	3.9	49.2	35.3	26.8	2.3	0.7	19	29.2	272	268	346	44
P-18	12	92.0	32.7	28.4	2.8	1.6	36	1.6	382	364	466	43
Well	0.4	76.0	33.2	14.5	1.4	0.5	17	21.2	316	326	374	47
Lake	0.2	37.6	11.2	6.8	1.2	2.0	10	22.4	116	140	166	39
February 1976												
P-1	2.7	67.2	44.9	17.1	3.3	0.5	17	57.2	314	352	423	41
P-4	2.0	74.4	30.8	69.1	10.7	0.8	98	41.6	290	312	523	48
P-6	4.2	62.4	25.4	72.3	2.8	1.6	96	1.6	276	260	462	44
P-7	0.5	44.0	20.4	86.6	3.7	1.2	76	14.6	260	194	437	46
P-10	1.2	78.4	45.8	116	3.0	0.6	205	98.7	252	384	723	43
P-13	1.2	55.2	23.0	60.8	4.0	1.6	78	27.6	228	232	408	48
P-15	1.9	47.6	39.2	28.3	2.8	1.0	21	39.5	272	280	368	45
P-18	11	92.0	32.7	29.3	3.4	1.2	37	1.2	380	364	475	46
Well	1.8	78.4	34.7	11.1	1.5	0.4	17	32.5	312	338	382	50

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APPENDIX. *(Concluded)*

(Chemical constituents in milligrams per liter)

	Fe	Ca	Mg	Na	K	NO_3	Cl	SO_4	Alkalinity (as $CaCO_3$)	Hardness (as $CaCO_3$)	Total dissolved minerals	Temperature (°F)
Bull Creek												
Bluff	2.1	63.2	28.8	52.6	2.7	15.3	93	92.8	166	276	469	41
S-3	1.7	56.8	22.0	26.8	3.5	3.9	43	34.4	192	232	349	36
S-10	0.6	54.4	25.4	53.8	3.4	5.7	84	74.1	158	240	403	38
Lake	0.3	38.8	12.4	6.6	1.4	2.0	10	23.4	124	148	165	42
March 1976												
P-1	2.1	68.0	44.4	19.3	3.3	0.6	18	60.7	310	352	441	52
P-4	3.5	73.6	29.3	67.7	9.1	0.6	102	31.9	288	304	521	51
P-6	2.1	36.0	15.1	109	2.9	1.6	85	1.6	272	152	440	48
P-7	1.7	54.0	22.3	77.7	4.0	0.4	88	17.9	260	226	435	54
P-10	2.6	70.8	31.5	65.0	2.0	0.6	100	128.2	184	306	537	50
P-13	0.3	47.6	23.6	59.4	3.9	0.4	81	25.1	212	216	387	50
P-15	2.1	54.0	38.3	26.6	2.7	0.8	22	48.5	272	292	380	53
P-18	13	97.6	34.2	28.8	3.0	1.1	41	13.4	384	384	480	49
Well	1.5	82.4	34.2	10.7	1.4	0.5	32	33.3	298	346	416	51
Bull Creek												
Bluff	1.4	81.2	38.3	33.1	2.0	4.3	52	126.7	232	360	507	52
S-3	1.3	82.0	33.3	43.4	7.5	7.8	71	53.3	278	342	494	49
S-10	0.9	74.0	34.4	32.7	2.6	1.5	52	102.0	222	326	465	53
Lake	0.3	36.0	10.8	6.7	1.3	2.3	10	23.9	114	134	166	49
April 1976												
P-1	2.9	67.6	44.6	16.1	3.2	1.3	17	55.5	310	352	421	51
P-4	4.1	79.6	29.5	71.4	8.8	1.1	112	25.1	310	320	535	48
P-6	3.1	52.8	21.5	76.1	2.8	1.3	94	2.3	268	220	443	50
P-7	1.2	52.0	24.0	76.9	3.8	0.7	88	16.3	262	228	432	49
P-10	1.9	56.8	25.4	38.8	2.5	0.4	48	88.5	176	246	387	48
P-13	0.4	44.8	23.8	58.7	3.9	0.0	80	21.6	210	210	369	50
P-15	5.0	63.2	44.9	26.1	2.7	1.1	23	66.9	306	342	443	51
P-18	14	103.2	38.1	28.6	3.1	1.4	39	8.8	416	414	505	49
Well	3.1	81.6	34.7	12.0	1.6	0.4	33	30.4	296	346	408	49
Bull Creek												
Bluff	7.7	84.4	39.3	31.2	1.9	6.0	47	115	250	372	503	51
S-3	1.2	80.8	34.2	43.1	6.9	7.1	71	51.8	282	342	483	56
S-10	0.6	67.2	30.8	28.4	2.7	2.1	43	88.4	202	294	401	56
Lake	0.6	39.2	11.2	9.2	1.5	3.8	13	28.0	120	144	189	46