Evapotranspiration and the Water Budget of Prairie Potholes in North Dakota

GEOLOGICAL SURVEY PROFESSIONAL PAPER 585-B

Prepared as part of the program of the Department of the Interior for the development of the Missouri River basin

EVAPOTRANSPIRATION AND THE WATER BUDGET OF PRAIRIE POTHOLES IN NORTH DAKOTA

Pothole complex about 1½ miles northwest of Geneseo, Sargent County, N. Dak. The large lake is in the NE¼ of sec. 2, T. 130 N., R. 53 W. Photograph by Shin Koyama, North Dakota State Game and Fish Department, May 3, 1963.

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By JELMER B. SHJEFLO

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CONTENTS

ILLUSTRATIONS

TABLES

EVAPOTRANSPIRATION AND THE WATER BUDGET OF PRAIRIE POTHOLES IN NORTH DAKOTA

By JELMER B. SHJEFLO

ABSTRACT

The mass-transfer method was used to study the hydrologic behavior of 10 prairie potholes in central North Dakota during the 5-year period 1960–64. Many of the potholes went dry when precipitation was low. The average evapotranspiration during the May to October period each year was 2.11 feet, and the average seepage was 0.60 foot. These averages remained nearly constant for both wet and dry years.

The greatest source of water for the potholes was the direct rainfall on the pond surface; this supplied 1.21 feet per year. Spring snowmelt supplied 0.79 foot of water and runoff from the land surface during the summer supplied 0.53 foot. Even though the water received from snowmelt was only 31 percent of the total, it was probably the most vital part of the annual water supply. This water was available in the spring, when waterfowl were nesting, and generally lasted until about July 1, even with no additional direct rainfall on the pond or runoff from the drainage basin. The average runoff from the land surface into pothole 3 was found to be 1.2 inches per year—1 inch from snowmelt and 0.2 inch from rainfall.

The presence of growing aquatic plants, such as bulrushes and cattails, was a complicating factor in making measurements. New computation procedures had to be devised to define the variable mass-transfer coefficient. Rating periods were divided into 6-hour units for the vegetated potholes. The instruments had to be carefully maintained, as water levels had to be recorded with such accuracy that changes of 0.001 foot could be detected. In any research project involving the measurements of physical quantities, the results are dependent upon the accuracy and dependability of the instruments used; this was especially true during this project.

INTRODUCTION

Parts of North and South Dakota, Minnesota, Montana, and Iowa, in the United States, and the Prairie Provinces of Canada contain millions of small craterlike depressions of glacial origin called prairie potholes. These potholes generally contain water, but many of them go dry when precipitation is low.

This study was made during May to October 1960–64 and emphasizes evapotranspiration from potholes filled with emergent aquatic plants. To carry out the study, it was necessary to study the broader subject of where the water in a pothole comes from, where it goes, and the rates at which these movements take place. The report gives the results of the study and describes the instruments and methods used. Other parts of the broader study of prairie potholes are still under investigation.

More information on the hydrologic behavior of prairie potholes is urgently needed. The potholes are vital to waterfowl production, and the region is often referred to as the duck factory of North America. The potholes provide water and habitat for other wildlife also, and in some areas they are a major source of water for livestock. New irrigation projects under consideration in the Dakotas could eventually bring water to an additional 1.5 million acres of land. Much of this land is in the prairie-pothole region, and many potholes would be eliminated by canal construction, drainage systems, and land leveling. It is planned that the waterfowl habitat thus lost will be replaced by lowlands to be flooded in other areas. Construction of small impoundments, dikes, canals, and similar works to maintain and improve wildlife habitat would be done in connection with the irrigation projects. The amount of water required for these undertakings is not known.

The wetlands acquisition programs for wildlife management on both the State and Federal levels would be greatly benefited by a more thorough understanding of the hydrology of prairie potholes. Since a pothole is useful to waterfowl only when it contains water, an understanding of the rates of water loss is necessary in determining its degree of permanence. Water depth, water quality, and type of emerged and submerged vegetation are some of the clues that aid in determining the permanence of a pond, and therefore its usefulness to wildlife. The presence of some forms of aquatic life such as snails, salamanders, and minnows may also be a useful indicator, as such forms may be associated with the more permanent water bodies.

Runoff rates in the prairie-pothole region are difficult to evaluate. Much of the potential drainage area is noncontributing insofar as streamflow is concerned. Since there is practically no streamflow, the hydrology of the prairie-pothole region cannot be evaluated by standard streamgaging methods. A study designed to account for all of the water entering and leaving a basin in this area would necessarily have to measure precipitation, evaporation, transpiration, and seepage. A combination of the mass-transfer method and the water budget appeared to be the best approach and was utilized in this study.

Ten prairie potholes in North Dakota were selected for study. They are on the 70-mile-wide strip of high, rolling prairie land, known as the Coteau du Missouri, that borders the Missouri River on the east.

Of the 10 potholes, 7 contained aquatic vegetation such as hardstem and river bulrush, whitetop, sedge, cattail, watermilfoil, common bladderwort, star duckweed, and grassleaf pondweed. The other three potholes were nearly free of vegetation, except for a ring near the shore.

The presence of growing vegetation and the resultant variation in evapotranspiration rates was indeed a complicating factor in making measurements. Quantities had to be measured with far greater accuracy than originally expected. For example, water levels had to be recorded with such accuracy that changes of only 0.001 foot could be detected.

Also, new computation procedures had to be devised to define the variable rate of evapotranspiration. Rating periods were divided into 6-hour units for vegetated potholes.

In any research project involving the measurements of physical quantities, the results are dependent on the accuracy and dependability of the instruments used. This was especially true during this project, when it was necessary to keep five instruments working mechanically and electrically at all times to properly record the variables. Failure of any instrument for any cause meant a break in the record of evapotranspiration.

Few scientists who are not experienced in the computation procedures used in this project can fully appreciate the necessity for meticulous attention to the details of instrumentation. For this reason, the instruments and computation procedures are described in detail for the benefit of anyone undertaking similar observations.

This project, of which the author was project chief, is part of the larger study of the hydrology of prairie potholes under the supervision of William S. Eisenlohr, Jr. Reports of other projects in the study will be published as chapters of this professional-paper series. The study is part of the Department of the Interior program for the development of the Missouri River basin.

The author acknowledges the assistance given by the U.S. Bureau of Sport Fisheries and Wildlife, the U.S. Soil Conservation Service, the North Dakota State Game and Fish Department, and the North Dakota State Soil Conservation Committee. He also thanks the following landowners and tenants for permitting the work to be done on their land: Otto and George Marten, Drang Opstad, Levadney Brothers, William Puhlman, Dan Zahn, George Wolf, Philip and Emil Walz, and Hugo Mairer.

GENERAL DESCRIPTION OF THE AREA

GEOLOGY

By C. E. Sloan

Most of the prairie potholes in North Dakota are on the Coteau du Missouri, which is defined by the U.S. Geographic Board (1933) as a "narrow plateau beginning in the northwest corner of North Dakota between the Missouri River and River des Lacs and Souris River and running southeast and south, with its southern limit not well defined; and its western escarpment forming the bluffs of the Missouri." Many other definitions have been applied to the Coteau du Missouri; for a discussion see Winters (1967).

The Coteau du Missouri, shown in figure 1, is a topographically high belt of mainly stagnation moraine, but also includes end moraines of several different ice advances. This feature, which is about 20–70 miles wide, extends from Saskatchewan and northeastern Montana to south-central South Dakota. Its northeast-facing escarpment, which forms the approximate boundary between the Great Plains province to the west and the Central Lowland province to the east, is commonly 200–300 feet high in North Dakota (Lemke and others, 1965, p. 17).

The Coteau du Missouri is characterized by hilly topography having moderate to high relief and generally lacking an integrated drainage pattern. The layer of glacial drift that mantles the coteau is several hundred feet thick in places; there are few bedrock outcrops. The prairie potholes are natural depressions in the glacial drift formed mainly as the result of stagnation and melting of glacial ice on the Coteau du Missouri.

The predominant deposit underlying the instrumented potholes of this study is poorly permeable till. The till, which is mainly unsorted and unstratified, consists of about equal parts of clay, silt, and sand, with generally less than 5 percent pebbles, cobbles, and boulders. Interspersed with the till are minor deposits of stratified drift.

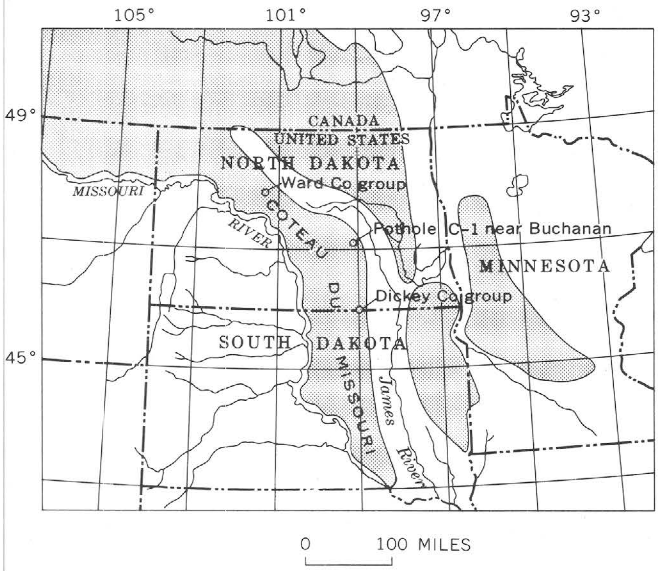

FIGURE 1.—Prairie-pothole region (shaded), showing the Coteau du Missouri and location of the pothole study areas.

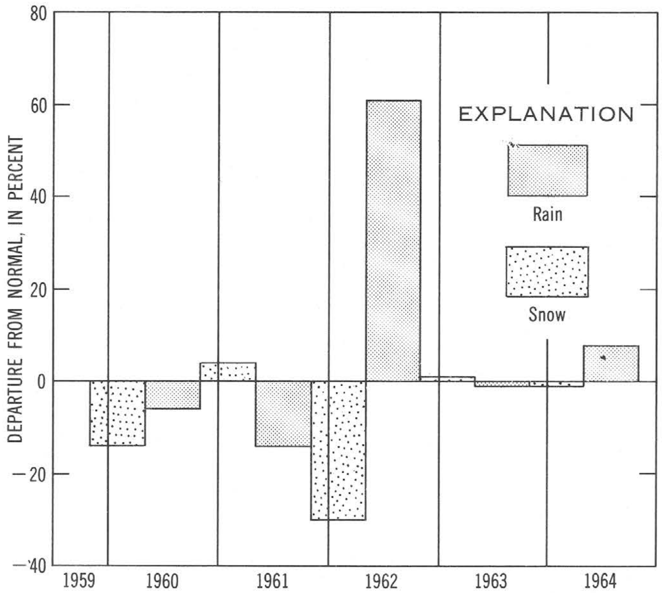

FIGURE 2.—Precipitation departures from normal during the study period, by 6-month periods. Data are from long-term weather records at Max, Jamestown, and Ashley.

Weathering of the till results in oxidation and the development of joints from the surface to depths of generally less than 50 feet. These joints, although poorly developed, provide avenues of vertical seepage. Probably there is some movement of water through the till interstices as well, but little seems to be known about the mechanics of such movement.

CLIMATE

The region has a continental climate—short summers, and long cold winters with characteristic rapid fluctuations in temperatures. It is normal to have several days in the summer with temperatures of 90°F–100°F and many days in the winter when the temperatures are below zero. The average July temperature is about 68°F in Ward County in northwestern North Dakota and about 70°F in Dickey County near the South Dakota border. The average annual lake evaporation is 33 inches, according to Kohler, Nordenson, and Baker (1959).

The average wind speed is about 10 miles per hour. The prevailing winds are from the northwest, but southeast winds are very common during the summer months. Wind speeds are usually highest during the afternoon and lowest at night.

The average annual precipitation ranges from 16 inches in Ward County to 19 inches in Dickey County, according to the U.S. Weather Bureau records. General and prolonged rains occur in the spring; summer precipitation is usually from local thunderstorms, which sometimes are violent and accompanied by wind and hail. Occasionally, several inches of rain may fall in a short period, and such rains are about the only ones that will produce any runoff during the summer and fall.

Precipitation was about 10 percent below normal during the first 2 years of the study and slightly above normal during the last 3 years. The winter of 1961–62 (November–April) and the following open-water season (May–October) was a year of extremes, as is shown in figure 2. The winter precipitation was 30 percent below normal, and the precipitation during the following open-water season was 61 percent above normal. Normally, about 25 percent of the annual precipitation is received during the period November to April.

In spite of the abnormal distribution of precipitation in 1962 when winter precipitation (mostly snow) was 30 percent deficient, runoff from snowmelt was four times greater than it was in either the succeeding or the preceding years when snowfall was above normal. This was partly because there was very little thawing during the winter of 1961–62 so that the snows accumulated, and partly because the accumulated snows melted rapidly in the spring while the ground was still frozen.

The relationship between the amount of precipitation and the amount of runoff and how it is affected by other factors will be discussed further in the section entitled "Runoff."

SELECTION OF POTHOLES FOR STUDY

This project was concerned mainly with the investigation of evapotranspiration; hence, it was desirable to minimize factors which would complicate the study. Therefore, each pothole was selected to meet the following requirements as nearly as possible:

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1. Highly impermeable bottom to minimize seepage losses.
2. No surface inflow except during periods of snowmelt and rainfall.
3. No surface outflow.
4. Surface area of 50 acres or less.
5. Circular or elliptical.
6. Permanent water body except during extreme droughts.
7. Stabilized drainage basin with minimum change because of agricultural or other activities.

In each of the two original study areas, four potholes are within a short distance of each other. One pothole in each group had little or no emergent vegetation, and three had a major part of the water area covered with emergent vegetation. A different type of vegetation was predominant in each pothole.

Finding potholes suitable for the study was difficult. Many that looked promising on topographic maps and aerial photographs, such as those in the upper James River basin, were dry in 1959. The maps and photographs of this area had been made during the wet years of 1950–52, and many of the potholes had dried up during the years that followed. During a drought period, vegetated potholes usually dry up first because they are shallower than clear potholes. Thus, the search was primarily for suitable vegetated potholes.

After spending a few days searching from the main highways and county roads, it became clear that this approach was impractical. Selection of potholes from an airplane flying at 1,500 feet was then tried, and six trips were made before suitable areas were found. Even with a suitable area selected, it was difficult, from the air, to identify it on the small-scale (1:250,000) Army Map Service maps.

A group of potholes was found in Ward County in north-central North Dakota during the fall of 1959, and four which most nearly met the criteria were selected for study. Field examination and test drilling around the potholes showed that the underlying material was mostly clay or till and indicated that seepage rates could be expected to be very low. These potholes were designated 1, 2, 3, and 4. Pothole 3 was clear and the others contained vegetation.

During the summer of 1960, a group of potholes was selected in the Robinson area, Kidder County, but was rejected after test drilling indicated that they were underlain by sand and that seepage rates would probably be too great to meet the requirements for the study.

The study area was enlarged in the fall of 1960 by including a group of potholes near Forbes in Dickey County, in south-central North Dakota. Four potholes which most nearly met the criteria were selected and designated potholes 5, 6, 7, and 8. Pothole 5 was clear and the others contained vegetation.

In 1963, pothole C–1 near Buchanan in Stutsman County was included in the study. This pothole had previously been selected for study by the U.S. Bureau of Sport Fisheries and Wildlife. It was nearly clear except for a ring of bulrushes along the shoreline, as shown in figure 23. Geographically, this pothole provided a link between the two original study areas, which were about 200 miles apart, since it was about midway between them. The Ward County group is 80 miles south of the Canadian border, and the Dickey County group is 2 miles north of the South Dakota State line.

Pothole 5A was also added to the study in 1963. It is a small vegetated pothole 100 feet north of pothole 5. (See fig. 28.) It was selected because it was so close to pothole 5 that the anemometer and precipitation and wind records could be used for both. Their water surfaces are at different elevations. A ground-water observation well was drilled on the ridge between them. An examination of figures 26 and 29 shows that the elevation of the water surface in the ground-water observation well was usually about midway between the elevations of the water surfaces in the two potholes.

MAPS AND PHOTOGRAPHS

The only maps that provided complete coverage of the study areas were Army Map Service quadrangle maps (1:250,000) and North Dakota State Highway planning maps (1:125,000). The AMS quadrangles were used during the reconnaissance flights, and the highway planning maps were used on the ground in locating the potholes and in preparing the station descriptions.

U.S. Geological Survey 7½-minute quadrangle maps were available for the Stutsman County area. The Minot 15-minute quadrangle map shows pothole 2 near Max, and the Benedict 15-minute quadrangle map shows pothole 4 near Max.

The U.S. Soil Conservation Service made a special study of the areas around the Ward and Dickey County potholes and provided soils maps at the beginning of the project.

Large-scale (13 in.=1 mile) aerial photographs of the potholes and surrounding areas, which had been taken in 1953, were obtained from the U.S. Department of Agriculture, Salt Lake City, Utah.

The U.S. Fish and Wildlife Service, Minneapolis, Minn., also made aerial photographs of the area at the beginning of the project, and these were available to the project personnel.

William Sebens, Executive Secretary, North Dakota State Soil Conservation Committee, took aerial photographs in September 1961 and furnished both black-and-white 8- by 10-inch prints and 2- by 2-inch color slides of each pothole.

FLORA AND FAUNA OF THE POTHOLES

The flora and fauna of the potholes are affected by changes in water level in the potholes and to some extent by freezing of the potholes. The chemistry of the water is very important also but this is beyond the scope of this report.

At the beginning of the project, a dry period was in progress, and many of the study potholes went dry during 1960 and 1961. During 1962–64, however, precipitation was locally above normal. Ward County was one area where precipitation was above normal during 1962–64; nevertheless, pothole 3 dried up in the fall of 1964—the first time in at least 25 years. In Dickey County, water levels in most potholes rose about 2 feet in both 1962 and 1964 as a result of accumulation of runoff from intense rains.

These variations in pond levels caused major changes in the vegetation in a number of the potholes. Pothole 1, in Ward County, was about one-fourth covered with vegetation (mostly whitetop) at the beginning of the project, but in June 1961 the pothole dried up. September rains falling on the dry bed caused the whitetop seeds to germinate, and by the time of the first freeze in the fall of 1961, the pothole was completely covered

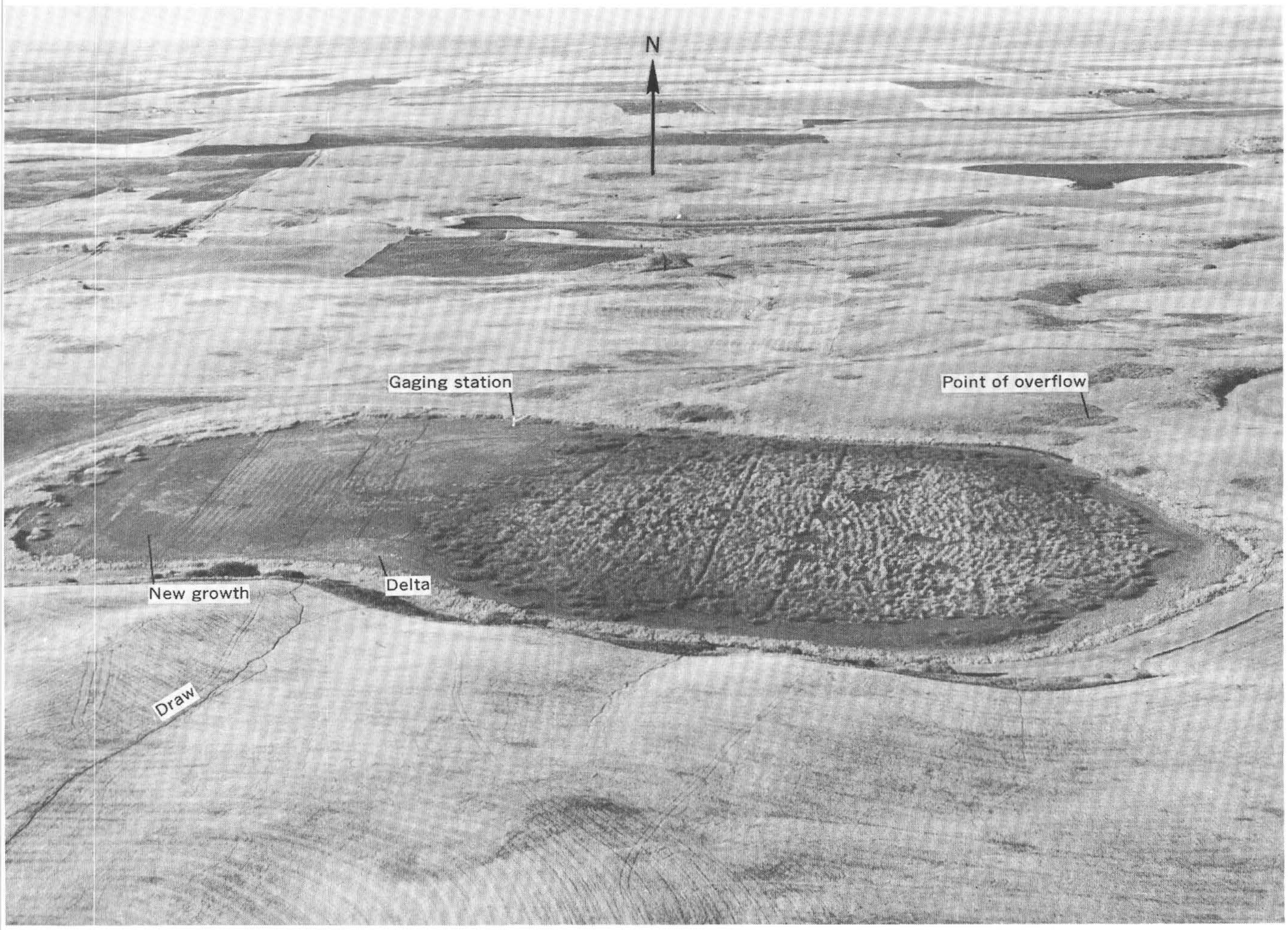

FIGURE 3.—Pothole 2 near Max, N. Dak., September 16, 1961, after it had been dry about 1 month. At low stages, the pothole covered about 30 acres, 18 of which were covered with hardstem bulrush. There was also a ring of cattail and whitetop around the edge. The remaining 12 acres, at the left, stayed clear of vegetation until the fall rains caused cattail seeds to germinate. New growth filled the clear area with plants several inches high before killing frosts occurred. Farming operations during the drought of 1929–39 are clearly indicated by the lines marking the ditches and furrows. There is little evidence of sedimentation, except for the delta on the near side, at the foot of the draw containing a cow trail. The gaging equipment is on the far side of the pothole, and the point of overflow (if any) is in the northeast corner. Photograph by W.P. Sebens, Executive Secretary, North Dakota State Soil Conservation Committee.

with plants several inches high. Pothole 2, shown in figure 3, underwent similar changes.

Pothole 4, in Ward County, and potholes 7 and 8 in Dickey County, dried up in July 1961. At pothole 4, hardstem bulrush was predominant, and no new growth developed; at potholes 7 and 8, vegetation became sparse.

In general, the emergent aquatic plants thrived and remained luxuriant throughout the summer and fall, even in potholes that had dried up. Apparently, potholes support aquatic vegetation if they are shallow and if they go dry occasionally so that the seeds of certain plants can germinate. Most emergent vegetation seems to thrive in swampy low-water conditions, but some types of plants begin to die when water depths exceed about 3 feet.

The peripheral vegetation at all the potholes shifted back and forth as the pond levels rose or fell each year, and this shifting indicated that each type of plant could tolerate only certain depths of water at certain times during the year. When the water in the Dickey County potholes reached depths up to 6 feet after rains in 1964, nearly all the vegetation in the potholes died, so that the potholes became clear except around their periphery.

Pothole 3 was considered to be a clear pothole at the beginning of the project when the pond stage was high. However, as the drought continued and the pond stage became lower, blossoms from the submerged plants (probably watermilfoil and pondweed), which protrude above the water surface, increased and became more noticeable. It is possible that the 2- to 4-inch stems of these plants may act as wicks and transpire water vapor, thereby increasing the evaporation. On the other hand, it was noted occasionally that even when there were fairly large waves on the open water owing to wind, the areas with these submerged floating plants were placid; so these plants may tend to reduce the evaporation loss from the water surface.

Pothole 3 contained numerous 3-inch minnows in the fall of 1959, but they died during the winter. There was about 5 feet of water in the pothole before freezeup, but after about half of it became ice, the oxygen supply in the remaining water apparently was not enough to support the fish. A hole cut through the ice in November 1959 revealed dying minnows that could have been scooped out by the pailful. Pothole 5 contained numerous salamanders during the fall of 1960, but most of them apparently died during the winter of 1960–61, inasmuch as few have been observed there since. There was only about 3 feet of water left in the pond at freezeup time, and the pond froze to the bottom during that winter. White pelicans were frequent visitors at this pothole during 1960 when the salamanders were plentiful, but were rarely seen afterward. Potholes 1, 2, and 6 contained large snails about 1 inch in diameter, and most of the other potholes contained a smaller species of snail.

INSTRUMENTATION

STAGE-GAGING STRUCTURES

The structures for recording water levels in Ward County were built in the fall and winter of 1959. Advantage was taken of the frozen potholes to get heavy construction equipment on the ice to build the stilling wells about 50 feet from shore. First, a section of 48-inch-diameter concrete culvert pipe was set vertically to act as a caisson during construction of the rest of the well. Then, an 11-foot length of 24-inch asbestos-cement pipe was set in the caisson, and the two were anchored together by a concrete footing about 1 foot thick. The whole unit then weighed nearly 2 tons. Intake holes had been drilled and filled with beeswax at 6-inch intervals in a vertical line in the caisson before placement, and a ½-inch intake hole was cut in the asbestos-cement pipe about 0.1 foot above the footing. An instrument shelter was bolted to the top of the asbestos-cement pipe.

To reach the instruments from shore, a plank walkway was constructed 5 feet above water and supported by 2-inch pipes driven into the pothole bed, as shown in figure 4. An outside staff gage was mounted on the side of the asbestos-cement pipe. The water-temperature gage was mounted on a steel pipe driven 6 feet into the pothole bed near the walkway. A tipping-bucket rain gage was mounted near the shore end of the walkway. An anemometer was placed beside the walkway, 10 feet from the gage shelter, on an adjustable standard so that it could be kept at a constant distance of 4 meters above the water surface.

The structures in Dickey County were slightly different because they were installed before freezeup. The

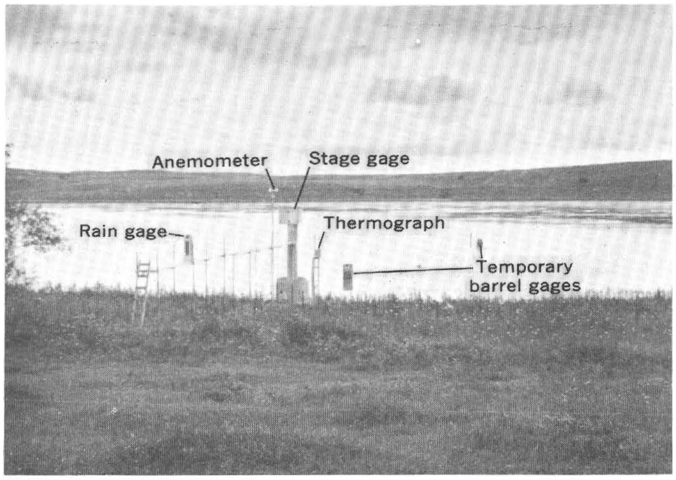

FIGURE 4.—Pothole 3 near Max, showing instruments. Photograph by Roger Pewé, September 13, 1965.

asbestos-cement pipe was set in the bank about 20 feet from the edge of the water. The pipe was connected to the water by 60–80 feet of ¾-inch pipe set 3 feet below the water surface, in a trench excavated by a backhoe. A pump screen was placed on the outer end of the intake pipe to keep out aquatic animals and trash. The screen sometimes became clogged with moss or encrustations.

The outside staff gage, water-temperature recorder, and anemometer were fastened to a cluster of 2-inch pipes driven into the pothole bed near the end of the intake, as shown in figure 5. They were reached by wading or by boat.

A bubble gage was tried at pothole C–1 because the long distance from shore to deep water made an intake too impractical and a walkway too expensive. The bubble gage was replaced by a temporary barrel gage when it was found unsuitable for measuring the small changes in stage that occur.

Temporary gages were installed at potholes 2, 3, 5, and 6 in 1961 when the water levels dropped below the intakes to the established stilling wells. These temporary gages have stilling wells made from 55-gallon steel barrels (fig. 6) with ⅛-inch intake holes in the side. A small metal shelter protected the weekly recorder. A water-temperature gage and an outside staff were mounted nearby on another support.

The stilling wells used in Ward County thawed out quickly in the spring and had good intake action, but they could be tilted or tipped over by ice at high stages. The walkways were difficult to maintain, and the whole structure was subject to heaving and settling due to frost action. At times, the recorded change in stage due to settlement following the spring thaw exceeded the change due to the losses from evapotranspiration and seepage during the period.

The stilling wells used in Dickey County were more stable. They did not heave owing to frost action, but the intake pipes and stilling wells did not thaw out until May, so that the stage data were not recorded during a significant part of the spring season. Swamp gas sometimes accumulated in the intake pipes and interfered with the gage-height record, as did moss and encrustations on the outer end of the intakes.

The temporary barrel-type stilling wells were economical and fairly satisfactory. Materials cost very little, and a gage could be installed in a few hours. Intake action was positive. Additional holes could be punched in the barrel just above the bed ice in the spring to admit runoff from snowmelt. The barrel gages were usually heaved about 0.2–0.3 foot by frost action, but they did not settle back during April and May as did the Ward County gages because they were so light in weight. Of course, the barrel could be damaged by ice in the spring, or submerged by runoff from a heavy rainstorm.

INSTRUMENTS AND THEIR OPERATION

There were many variables to be measured to satisfy both the mass-transfer and the water-budget equations. Each of these variables required a special recording instrument or accessory. Extreme care had to be exercised in setting and maintaining the instruments. Actually, the applicable lag correction for the float on the stage recorder might have been greater than some of the values being defined, and this probably accounts for some of the scatter of the data. Since good rating periods were usually infrequent, it was necessary that all instruments worked properly during these times.

The change in stage of the water surface at the potholes equipped with permanent stilling wells was recorded by a Stevens A35 continuous water-stage recorder, as shown in figure 7. The recorder was geared for 4.8 inches of strip-chart travel per day and a gage-height ratio of 10:12 (10 units change on the chart

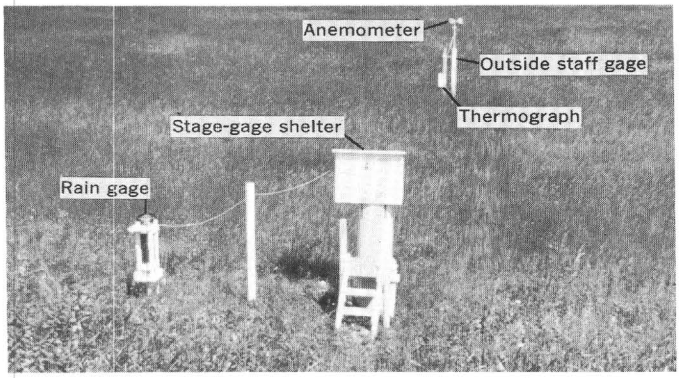

FIGURE 5.—Pothole 8 near Forbes, showing instruments. Photograph by Roger Pewé, September 15, 1965.

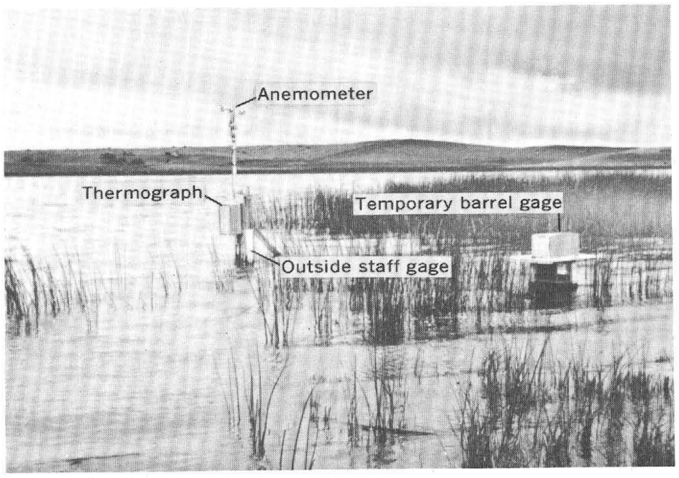

FIGURE 6.—Pothole C–1 near Buchanan, showing the temporary barrel gage, thermograph, anemometer, and staff gage. Photograph by Roger Pewé, September 14, 1965.

equals 12 units change in water level). Auxiliary pens at the margins of the recorder chart recorded wind movement and precipitation. Each 10 miles of wind movement was identified by a pip on a continuous ink line near the right margin of the chart, and each 0.1 inch of rain was identified by a jog in the ink line near the left margin of the chart. The power source for these pen movements was a 9-volt battery. A few of the original batteries were still in service after 5 years. The Stevens A35 recorders operated satisfactorily throughout the 5-year period. The pen seldom gained or lost more than 15 minutes per month. A 12-inch-diameter float provided a stage record for vegetated potholes that could ordinarily be read to the nearest one-thousandth of a foot, but provided a less accurate record for clear potholes, owing to wave action on the float.

To insure a high degree of accuracy at all times in recording the stage in a clear pothole, the average from two or more recording gages installed on opposite sides of the pond might have been used. Ordinarily, this was not necessary because, as is explained later, the mass-transfer coefficient, N, is a constant for an entire open-water season on clear potholes, and there are generally enough calm days to enable accurate N determination.

Levels were run from permanent reference points to the staff gages several times during each season, and corrections were applied as required.

The weekly recorders used with the temporary barrel stilling wells provided good stage records. The wind movement and precipitation continued to be recorded on the regular A35 recorder chart. The weekly recorders were geared for 1.2 inches per day on the time scale and 1 : 1, or direct, recording of gage height. A 10-inch-diameter float was used.

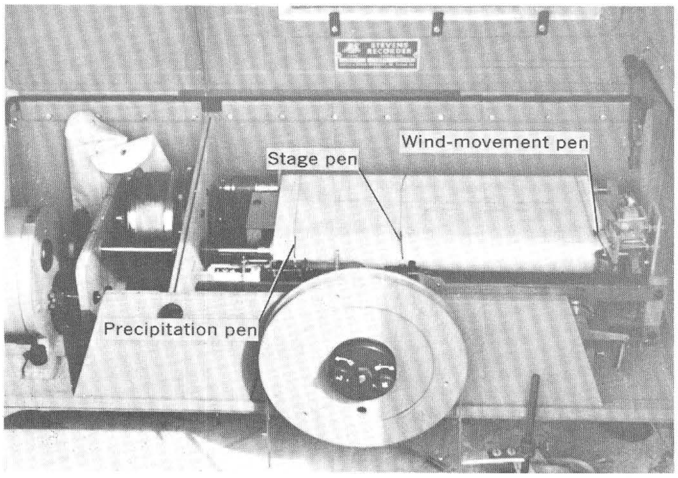

FIGURE 7.—Stevens A35 continuous water-stage recorder with auxiliary marginal pens for recording precipitation and wind movement. Photograph by Roger Pewé, September 13, 1965.

Precipitation was recorded at each of the permanent stilling wells by using a U.S. Weather Bureau standard 8-inch rain gage with a tipping-bucket attachment, as shown in figure 8. The tipping bucket was connected electrically to the auxiliary pen on the Stevens A35 water-stage recorder. The bucket tipped after each 0.1 inch of precipitation was collected and closed a switch that would advance a mechanical counter dial by 1 and cause the left margin pen to jog one step to the right or left. Five jogs to the right and five to the left complete a cycle and represent 1 inch of precipitation.

The tipping-bucket rain gages did not function properly during the first season. Some of the 8-inch collector cans and some of the tipping buckets leaked at the seams and had to be resoldered. The switch had to be carefully centered and adjusted to eliminate double and even triple counts. Multiple counts occurred, for instance, when the cup bounced after the bucket had tipped; on each bounce the electrical circuit was completed. Some of the bumper screws also required adjusting, for sometimes a bucket would tip after receiving only 0.06 or 0.07 inch of water, or would not tip until it had received 0.12 or 0.13 inch of water, or would not tip at all. During the following years, care was taken to level the gages after each field visit so that the buckets would tip properly.

Occasionally, during violent wind storms, the gage support would vibrate enough to cause the bucket to tip.

Evaporation from the collector can was cause for some concern because the recorded precipitation could not be checked by actually measuring the catch. A clear plastic water glass with a small hole drilled in the side near the bottom and charged with a small amount of ground cork was placed in the collector can to provide a

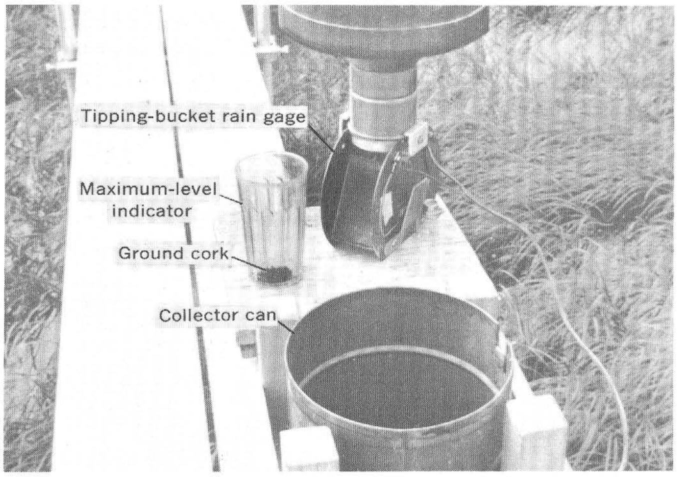

FIGURE 8.—Tipping-bucket rain gage with collector can. Photograph by Roger Pewé, September 13, 1965.

means of checking on the total amount of precipitation. The highwater mark in the water glass was measured with a scale at the time of each visit. The glass was then cleaned and recharged with cork. This aided in verifying the recorded precipitation if there was only one rain, but if it rained two or three times during the week, evaporation from the collector can between rains would prevent an accurate determination.

Hexadecanol crystals were placed in the collector cans in an effort to reduce the evaporation, but this did not seem to help very much. Likewise, two or three drops of light instrument oil in the can would not prevent the evaporation entirely. A $1/10$-inch layer of SAE 10 motor oil was effective, but messy. Possibly this objection could have been overcome if the water had been drained off through a valve near the bottom of the can, but this was not tried.

An inherent shortcoming of the tipping-bucket rain gage is that rains of less than 0.1 inch cannot be detected, and many rains were of this magnitude. Thus, errors in several phases of the computations could have been prevented if a more accurate type of rain gage had been used. The weighing-type rain gages used in other phases of the study were entirely satisfactory. Alter type windshields recommended by the U.S. Weather Bureau were used in connection with the weighing rain gages, but no windshields were used on the tipping-bucket rain gages.

Wind movement was measured by a totalizing anemometer, as shown in figure 9. The instrument has three cups, a mechanical counter, and a dial reading to the nearest one-tenth of a mile. The dial showed the total number of miles of wind movement that had passed the gage. At the end of each 10 miles of wind movement, a switch would close and cause a pen on the right margin of the record chart to make a pip. The anemometer was mounted on an adjustable pipe support so that its height could be reset from time to time to keep it 4 meters above the water surface.

The anemometers performed very well during the period. Occasionally one of the mechanical counters would become stuck and need replacing. Sometimes the counter could be repaired by replacing the "tenths" wheel. Sometimes the ball bearing at the lower end of the shaft would wear flat on one side and need replacing.

Temperature of the water near the surface was obtained by suspending the sensing element of a thermograph a short distance below the water surface. The water-surface temperature was needed to obtain as closely as possible the saturation vapor pressure corresponding to it. The instrument recorded the temperature on a circular chart that was turned by a spring-driven 8-day clock, as shown in figure 10. An alcohol-filled capillary tube 10 feet long connected the recorder to the sensing element, and the current from a 4-volt mercury battery caused a trace on the sensitized chart. The sensing element was attached to a 2-inch-diameter steel pipe and was raised or lowered each week to keep it as near as possible to, but below, the water surface. The sensing element was usually set about 0.1 foot below the water surface during cool weather, when the water loss rate was expected to be low, and 0.2 foot below the surface during hot weather, so that it would remain completely submerged until the next weekly visit. Attaching the sensing element to a float had been found unsatsifactory on other projects because the capillary tube would break due to the continuous motion.

The temperature recorders functioned very well during the 5-year period. Two or three developed leaks at the soldered joint near the sensing element, but these were quickly repaired when returned to the factory.

FIGURE 9.—Totalizing anemometer. Photograph by Roger Pewé, September 13, 1965.

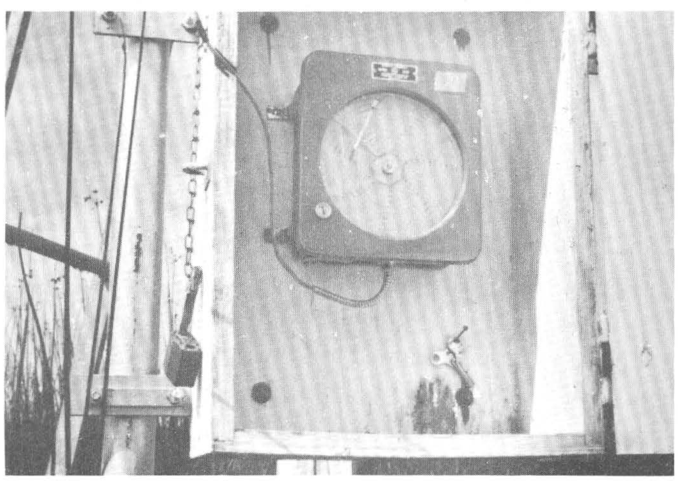

FIGURE 10.—Thermograph for recording water-surface temperature. Photograph by Roger Pewé, September 13, 1965.

The clocks kept almost perfect time and did not require cleaning. The mercury batteries were replaced once a year.

Air temperature and humidity were recorded by single hygrothermographs (fig. 11) centrally located at each group of potholes. The temperature and humidity data were necessary to obtain the vapor pressure of the air. These hygrothermographs were weekly, vertical-drum, 2-pen instruments with a hair element for humidity sensing and a bimetal element for temperature sensing. The instruments performed very well.

During the first year, sling psychrometers were used to determine the relative humidity. However, the readings obtained were suspect because often the only shade available was that from the instrument shelter, and although the operator's hand was in the shade, the thermometer bulbs on the periphery of the sling may have been exposed to direct sunlight at times during operation. The problem was solved by replacing the sling psychrometer with a commercial psychrometer with a built-in battery-driven fan.

The weekly inspections were usually made early in the afternoon when relative humidity was most stable. One disadvantage of inspecting the instrument at this same time every week was that, at the end of the period, the pens were usually found on the metal strip that held the chart in place, so the pens' positions were not being recorded on the chart. This was corrected by replacing the metal strip holder with two rubber bands—one placed near the top of the drum and the other near the bottom. The pens were always read immediately upon opening the door of the instrument shelter. The hair element was cleaned with alcohol, as required, and the pen was set at 95 percent humidity after saturating the element with distilled water.

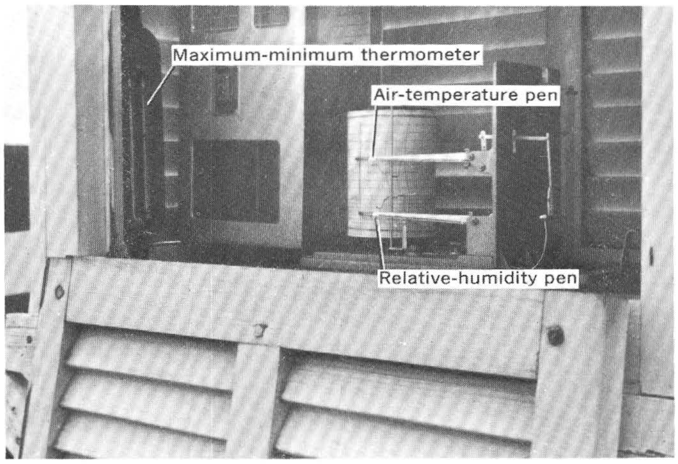

FIGURE 11.—Hygrothermograph for recording air temperature and relative humidity. Photograph by Roger Pewé, September 13, 1965.

GROUND-WATER OBSERVATION WELLS

Wells for observing the ground-water level were located on shore within 100 feet of the edge of each pothole. These wells were developed from original test holes used to determine the type of soil around the potholes. A 1½-inch pipe casing was placed in each test hole. The lower 6–10 feet of this pipe was slotted, and a pack of gravel was placed between the pipe and surrounding ground in the slotted range. Clay was tamped around the upper part of the casing to prevent the entrance of surface water. The casing extended about 1 foot above ground and was capped. The index point was the top of the casing with screw cap removed. The water level in the observation well was determined by measuring the distance from the index point to the water surface with a steel tape. Even though the bottom of most of the wells was at least 10 feet below the bottom of the pond, some of the wells went dry.

Levels were run to the index point several times each year and datum corrections applied if necessary.

Some of the potholes under study became dry during the summer of 1961. Questions arose as to the location of the water table with respect to the root zone, and whether there was any correlation between the water table at the center of the pothole and that in the area immediately surrounding the pothole. Shallow wells were hand augered near the center of each dry pothole and were called water-table wells to distinguish them from the previously established ground-water observation wells in the area immediately surrounding the potholes. During October 1961, water-table wells were established at potholes 1, 2, and 4 in Ward County and 7 and 8 in Dickey County. The wells were cased with 3-inch vent pipe that was perforated in the lower 2 feet, and the hole around the pipe was backfilled with clay and silt to make conditions as natural as possible.

The water-table well at pothole 4 was dry and the ground in the bottom of the well frozen in the spring of 1962. The ground thawed during the latter part of May, and by the end of June the water level in the well had risen 8 feet, so that it was 0.1 foot above the water level in the pond. The water level in the well remained about 0.1 foot higher than the water level in the pond throughout the summer until the pond dried up in mid-September. The water in the well continued to recede so that by the end of the year it was dry again.

VEGETATION GAGES

Two vegetation gages were located on opposite sides of each pothole containing emergent aquatic vegetation. The gages were made of 1- by 6-inch boards painted alternately black and white at 1-foot intervals and mounted on 2-inch-diameter pipe-posts driven into the bed of the pothole.

Color photographs of each vegetation gage were taken regularly from the same location on the shore to aid in determining the height and rate of growth of the plants. Information gained in this manner was found to be too general to be used in plotting graphs showing the rate of growth, but it did indicate when the plants began to grow in the spring, the time of maturity, and the effects of winter kill, droughts, or frosts in the fall.

THERMISTORS

Thermistors were installed in 1964 at several potholes to determine when the ground thawed in the spring. Four thermistor elements set 9 inches apart in a protective rubber tube formed a unit or probe. Small insulated conductor wires connected each of the thermistors to a terminal strip in the gage house. The resistance at each thermistor could then be measured at these terminals by connecting a wheatstone bridge in series and reading the scale. A calibration table was used to translate resistance in ohms to degrees Fahrenheit.

Thermistor probes were placed vertically in the beds of potholes 5, 5A, 6, and C–1 with the top element set 0.1 foot above the bottom of the pothole. This was to determine when the pothole bed thawed and possibly explain the hydrologist's observations of "walking on frost" during most of May and noting "ice in the water-table well" in June, possible "winter kill of vegetation" at times, and "late start"—usually mid-May for growth of hardstem bulrush.

Two other probes were installed on shore—one at pothole 5 was placed with the upper thermistor 5 feet below ground surface to detect deep frost, and one at pothole C–1 with the top of the probe 0.1 foot below ground surface to detect the presence of frost in the upper layers of the soil. These probes were intended to indicate when the ground surface thawed. The date of thawing could be expected to have an effect on surface runoff from snowmelt and indicate when the ground beneath a pond thawed so that seepage could begin.

The thermistor readings have been tabulated and are shown in table 1. They could not be correlated with any of the factors mentioned above.

TABLE 1.—*Thermistor readings, in degrees Fahrenheit, showing ground temperatures in bottom of pond and on shore for certain potholes 1964*

Pothole	Depth of observation (inches)	March	April				May				June				July					August				September					October				November		December
		31	6	14	20	29	6	13	22	27	3	9	16	23	1	7	14	21	28	4	11	18	25	1	8	15	22	29	6	13	20	27	2	18	2
[1] 5A	0	31	33	35	36	41	42	46	51	54	53	55	56	58	63	64	65	55	65	64	56	60	57	60	54	51	48	46	44	46	43	42	45	----	34
	9	31	31	32	32	33	34	38	44	47	48	50	52	53	56	58	60	61	61	60	58	58	56	57	54	52	52	49	47	47	46	45	46	----	38
	18	33	33	33	33	32	33	35	40	43	45	47	49	50	52	54	56	58	58	58	58	56	56	56	55	53	53	50	49	48	47	46	46	----	41
	27	33	33	33	33	33	33	34	38	41	43	45	46	48	49	52	53	55	56	56	56	55	55	55	54	53	52	51	50	48	48	47	46	----	42
[2] 5	60	31	31	31	34	40	42	44	51	52	51	53	54	55	59	60	62	64	64	64	62	61	59	59	56	55	55	53	51	50	49	48	48	----	39
	69	33	33	33	34	39	41	43	48	50	50	52	53	53	56	58	60	62	62	62	62	60	59	58	57	56	56	54	52	51	50	49	49	----	41
	78	33	33	33	34	37	39	42	45	48	48	50	51	52	54	55	57	59	60	60	60	58	58	57	57	56	55	54	52	51	51	49	49	----	41
	87	34	34	34	34	36	39	41	44	46	47	49	50	50	52	54	55	57	58	58	59	58	57	57	56	55	55	54	53	51	51	50	49	----	43
[1] 5	0	30	37	35	38	47	55	53	68	61	59	58	63	75	75	77	75	75	69	73	57	68	59	68	60	54	50	47	45	48	43	44	46	----	35
	9	29	31	32	35	42	48	49	63	59	58	60	61	65	69	71	73	74	71	72	63	66	62	64	58	55	56	51	48	48	47	47	47	----	38
	18	29	32	31	32	36	42	47	56	57	55	58	59	60	66	66	70	71	69	69	65	46	62	62	58	56	57	52	50	49	48	47	47	----	39
	27	32	32	32	32	32	39	44	51	54	53	56	57	58	62	64	66	68	67	66	66	62	62	61	60	57	57	54	52	50	49	48	48	----	41
[1] 6	0	37	34	43	60	61	52	51	63	61	58	61	60	68	70	71	72	72	67	70	58	66	59	65	55	49	47	44	42	43	39	38	----	----	----------
	9	31	32	32	33	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	----	----	----------
	18	32	32	32	32	39	43	45	51	53	51	54	55	56	61	62	64	65	64	63	62	60	60	60	58	55	56	52	50	48	48	47	47	----	43
	27	32	32	32	32	37	49	43	48	51	50	52	53	54	58	59	60	62	62	61	61	59	59	58	57	55	55	53	51	49	49	47	47	----	43
[1] C–1	0	32	38	44	46	54	54	52	67	--	70	61	58	64	77	76	80	76	74	76	56	69	60	62	56	52	55	49	45	50	43	46	46	35	33
	9	28	30	31	34	42	44	46	56	--	56	56	58	58	70	68	71	71	67	67	59	60	55	56	53	50	--	--	--	--	--	--	----	----	32
	18	27	29	30	31	34	38	44	52	--	54	57	58	56	65	66	68	71	69	68	66	63	61	60	58	56	56	52	50	48	48	47	46	42	40
	27	26	29	30	30	30	33	41	48	--	52	55	56	55	61	63	66	67	67	66	65	62	60	60	58	57	56	53	51	49	49	47	47	43	41
[2] C–1	3	------	--	35	38	46	41	46	57	--	59	55	55	59	74	71	77	67	69	63	59	72	57	66	57	53	54	48	48	55	47	47	48	31	21
	12	------	--	34	37	44	44	45	51	--	50	54	54	55	63	63	65	66	63	64	61	61	66	58	55	52	53	49	47	47	45	45	45	38	29
	21	------	--	34	37	42	43	45	48	--	49	52	53	54	59	60	61	64	62	62	61	59	57	57	56	54	54	51	49	48	47	46	46	42	34
	30	------	--	33	36	40	41	43	46	48	50	51	52	56	58	59	61	60	60	60	58	57	56	55	54	54	54	52	50	49	48	47	46	44	37

[1] In pond.
[2] On shore.

FROST HEAVE

Heaving and settling of the wet, spongy ground in and around the potholes due to frost was severe and complicated the study. Although gages were not operated during the winter, levels were run about once per month beginning in February or March to determine the datum corrections prior to, and during, the period of runoff from snowmelt.

Two permanent reference-mark posts were placed near each gage. They were located several feet away from the water's edge on high ground and deep enough so that they were not affected by frost heave. The reference markers were 6-inch-diameter poured-in-place reinforced concrete posts 6 feet long that projected about 0.5 foot above ground. Levels were run from the top of the reference-mark posts to the outside staff gage

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at about monthly intervals to check for changes in gage datum.

Most pothole gages heaved about 0.25 foot during the winter. The only gages that did not heave were the bank installations in Dickey County, which had 8 or 9 feet of backfill around them. The 2-inch pipes driven about 6 feet into the bed of the potholes heaved relatively little—that is, less than 0.1 foot. The heavy gages in Ward County heaved during the winter but settled back in the spring. Figure 12 illustrates graphically the heaving and settling of different types of gages during the study period.

Because the heavy gages settled back to their original positions and the deeply set 2-inch pipes beside them did not move appreciably, it became obvious that by placing an index pointer on the nearby pipe and obtaining the difference in elevation between the gage well and the pipe each week, the amount of settling of the gage well could be roughly observed, as shown in figure 13. These weekly measurements are plotted in figure 13 along with the results of the monthly differential leveling, and agreement is very good. These readings helped to define more closely the proper distribution of the datum corrections applicable during this period when rate of change was the greatest.

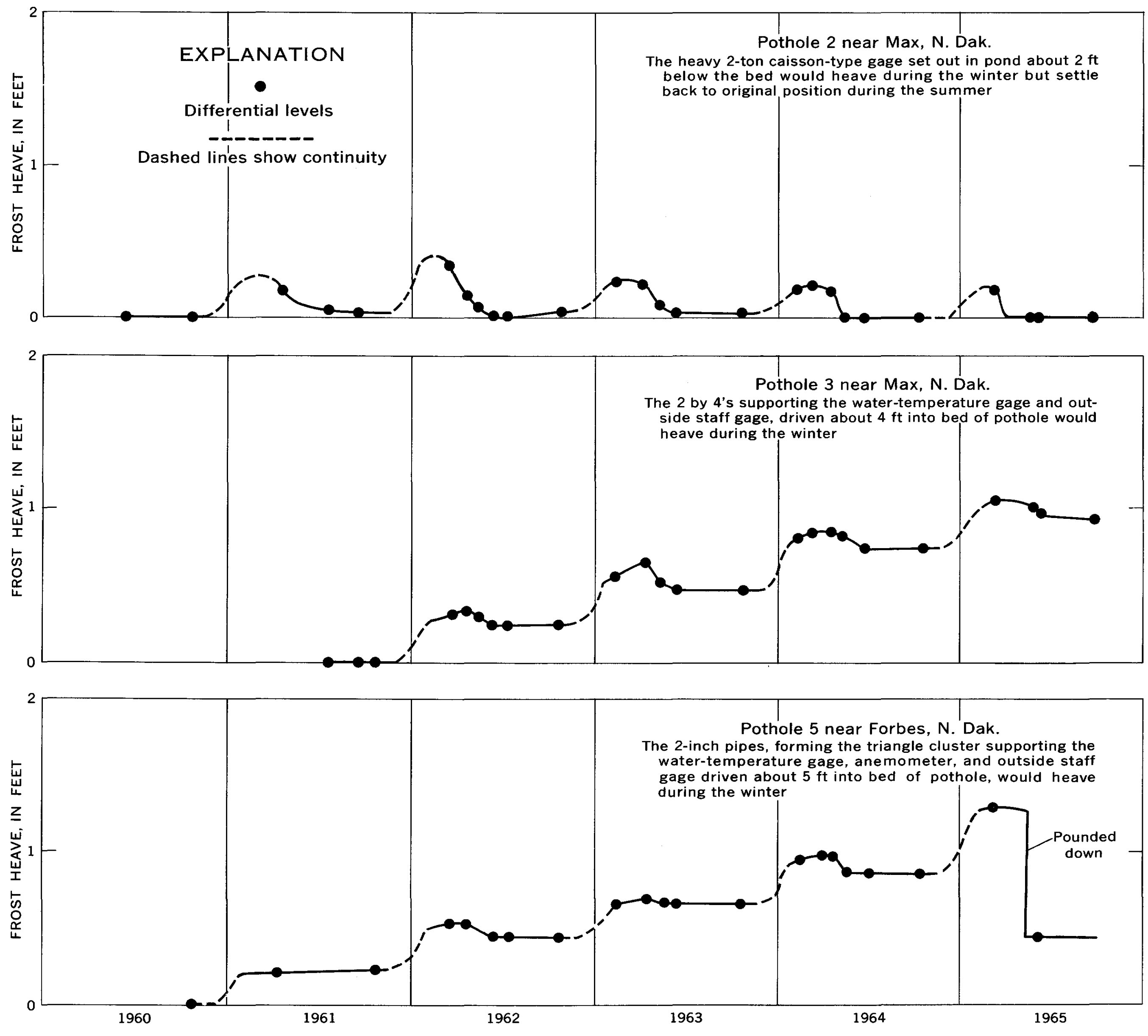


FIGURE 12.—Frost heave for gages of different construction.

To get more detailed information on the settling rate of these heavy gages, intensive leveling was attempted on May 6 and 7, 1963. An accurate gage-height record was needed to compute an N value during May because the settlement of the gage was greater than the water loss during certain periods, and these quantities had to be separated. The plan was to alternate level runs among the four gages in Ward County and measure the amount of settlement continuously for several days. The project was abandoned on the second day when the wind became so strong that the level rod could not be read accurately. A rain (0.16 in.) the first evening at pothole 4 also interfered because it eliminated May 6 and possibly May 7 from being used in the determination of N. The datum corrections found to be applicable as a result of this survey are shown in the following table.

Date	*Time*	*Datum correction, in feet*
	Pothole 1	
May 6	1430	0.049
7	0830	.044
7	1515	.043
7	1740	.042
	Pothole 2	
May 6	1600	0.077
7	1240	.077
7	1625	.073
	Pothole 3	
May 6	1800	0.204
7	1130	.194
7	1540	.188
	Pothole 4	
May 6	1300	0.048
7	1035	.046
7	1435	.045
7	1705	.042

The pothole bottoms often feel quite firm under foot until about mid-May. A 3-inch-diameter cased water-table well in the middle of pothole 4 was found to have ice in it as late as the middle of June some years.

Another type of ice action caused problems in the spring at potholes that had not frozen to the bottom during the winter. The ice in these potholes lifted, or floated, in the spring after snowmelt had added a foot or two of water on top of the ice, and in doing so pulled up the 3-post clusters that supported the instruments, or anything else frozen in the ice, such as horizontal ladder rungs. When the wind shifted this huge ice sheet, everything in the path of the sheet was tipped. Fortunately, not much of this type of ice action occurred because water levels in most potholes remained low, especially in Ward County where the gages were most vulnerable.

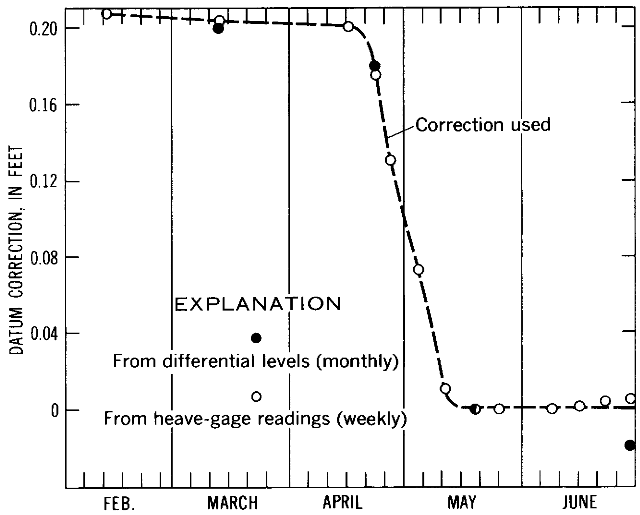


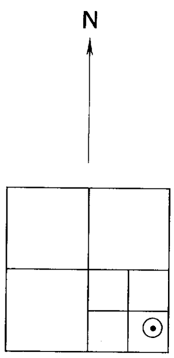
FIGURE 13.—Rate of settlement of the heavy 2-ton gage at pothole 2 during the spring of 1964.

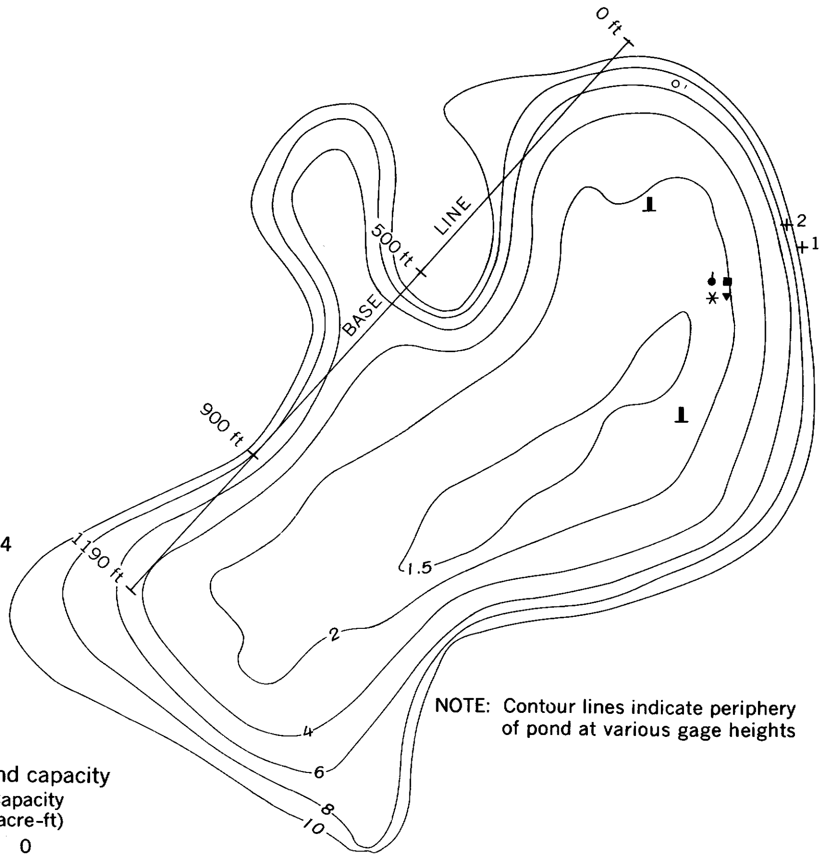
AREA AND CAPACITY OF POTHOLES

Accurate area and capacity tables were needed for evaluation of runoff from the contributing areas as well as for studies involving chemical quality of the water. These tables were prepared for each pothole from detailed topographic maps made by planetable surveying in the area between the water level in the pond and the estimated high-water level, and from soundings at several cross sections of the area under water. A ½-foot contour interval was used for the lowest 5 feet, and a 1-foot contour interval was used at higher levels. The scale used for the maps was usually 1 inch=100 feet.

As a starting point for the field survey, a base line was staked out along one side of the pothole—usually about the same length as the pothole. A reinforced-concrete post marker was set at each end and at midpoint to permanently mark the base line. An old automobile tire, painted white, was placed around the concrete posts so that the farmers would not run into them with their mowers and so that they could be identified on the aerial photographs that were planned. The azimuth of the base line was determined from magnetic north by use of an engineer's transit and then corrected to approximate true north by using declinations as shown on U.S. Geological Survey quadrangle maps of the area. The base line was shown on the topographic map so that similarly oriented extensions of the present survey or resurveys could be made at a later date if needed.

Figures 14–35 are contour maps with skeleton tables of area and capacity, hydrographs of water-level fluctuations and precipitation, and photographs of the potholes.





Skeleton table of area and capacity

Gage height (ft)	Area (acres)	Capacity (acre-ft)
1.48	0	0
2	6.4	2.2
2.5	8.4	5.9
3	9.4	10
4	11	21
5	13	33
6	15	46
7	16	62
8	18	78
9	19	97
10	20	116

Drainage area including pond	76 acres
Ratio of water to land about	1:8
Gage height at point of overflow	12.4 ft

EXPLANATION

■ Water-stage recorder

□ Staff gage

▼ Rain gage

Water-temperature recorder

✳ Anemometer

Hygrothermograph

Vegetation gage

○ Observation well

+1 Reference mark and number

FIGURE 14.—Contour map for pothole 1 with skeleton table of area and capacity.

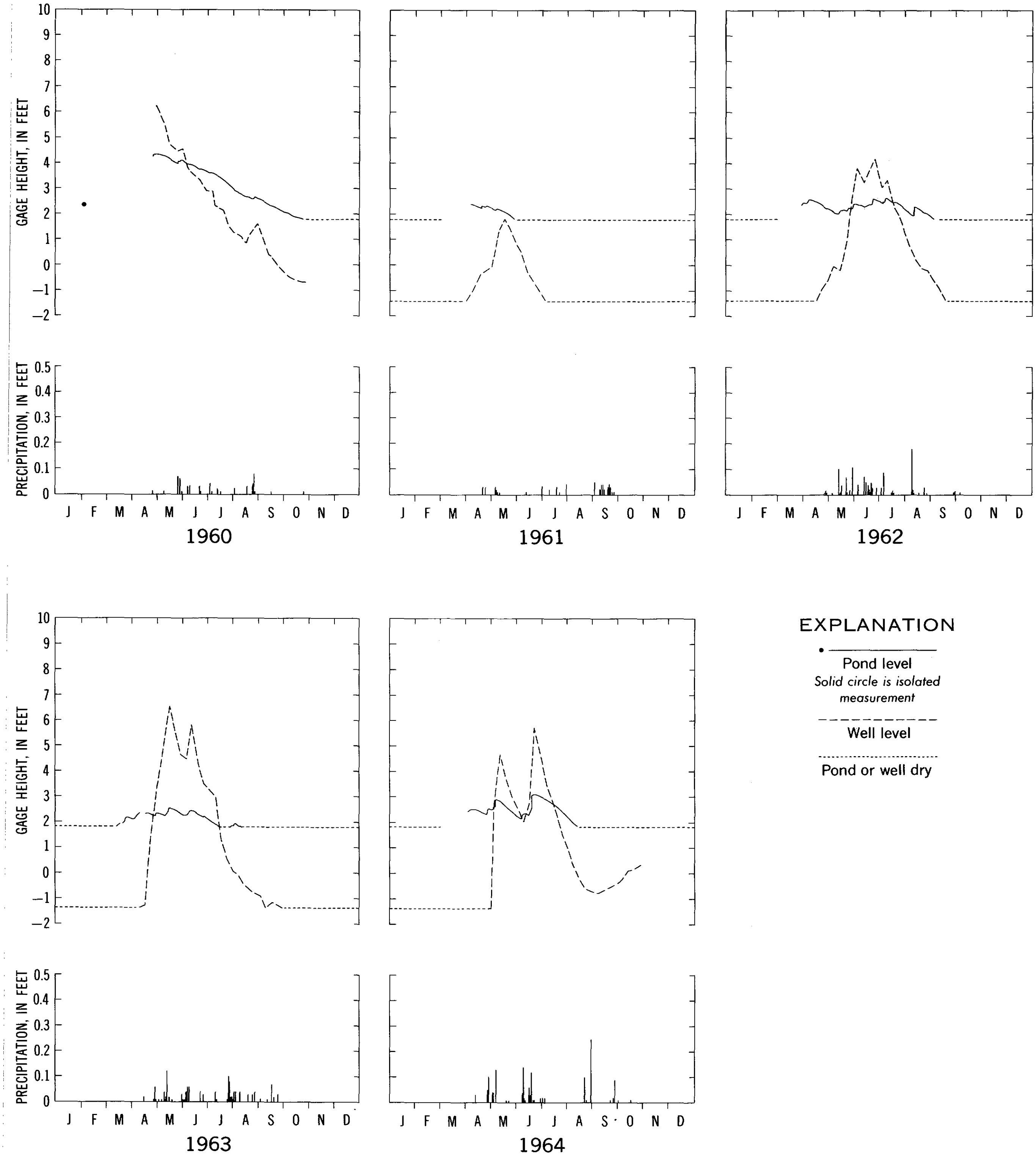
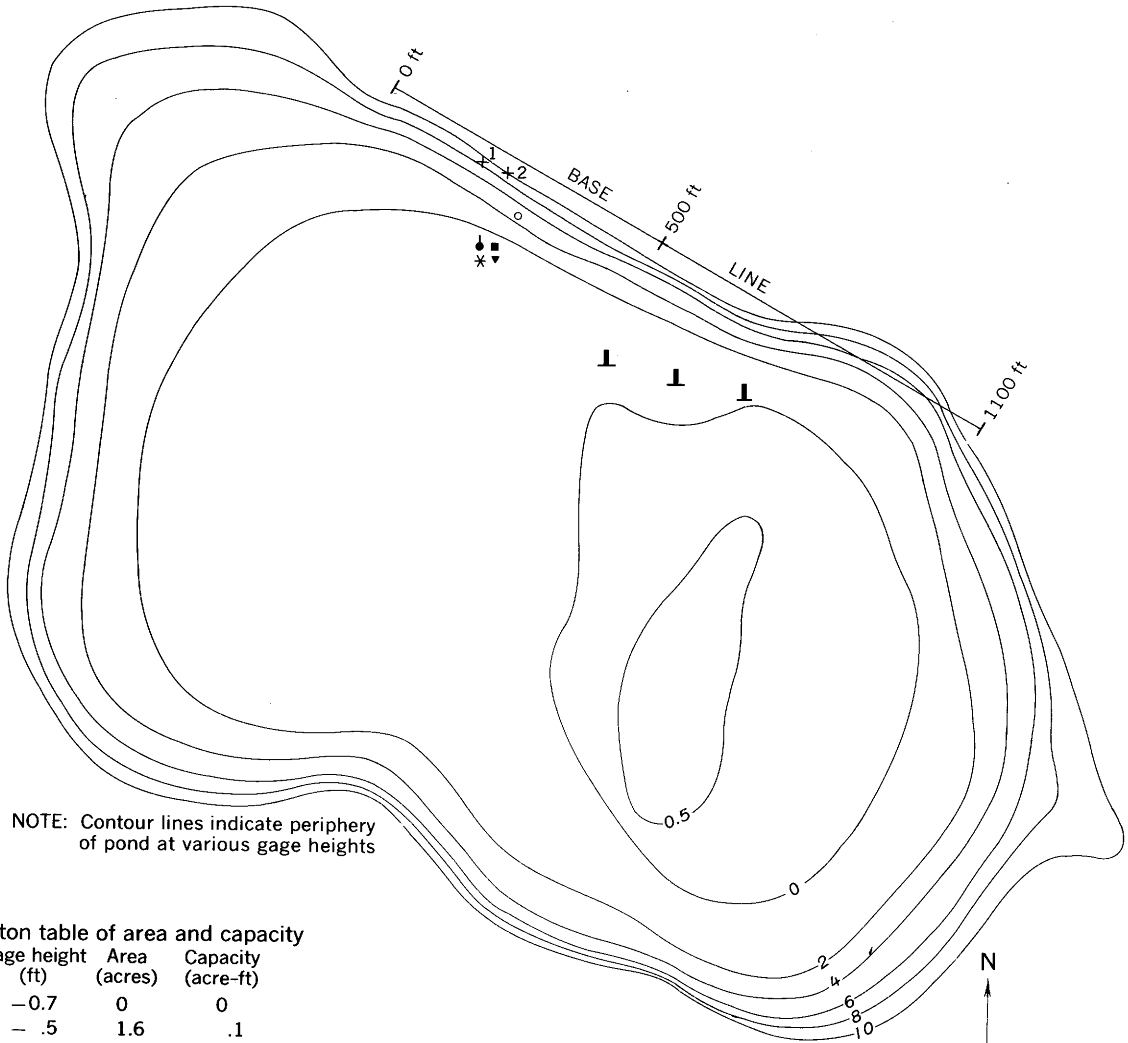


FIGURE 15.—Hydrographs for pothole 1, showing water levels in pond and observation well, and daily precipitation.

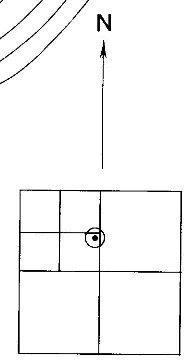


Skeleton table of area and capacity

Gage height (ft)	Area (acres)	Capacity (acre-ft)
−0.7	0	0
− .5	1.6	.1
0	8.4	2.6
.5	15	8.6
1	20	18
2	26	41
3	29	69
4	32	100
5	35	133
6	36	169
7	38	206
8	39	245
9	41	285
10	43	327

Drainage area including pond 223 acres
Ratio of water to land about 1:8
Gage height at point of overflow 16.2 ft

See figure 14 for
explanation of symbols



Center of pothole
SE¼NW¼NW¼ sec. 9
T. 152 N., R. 83 W.

FIGURE 16.—Contour map for pothole 2 with skeleton table of area and capacity.

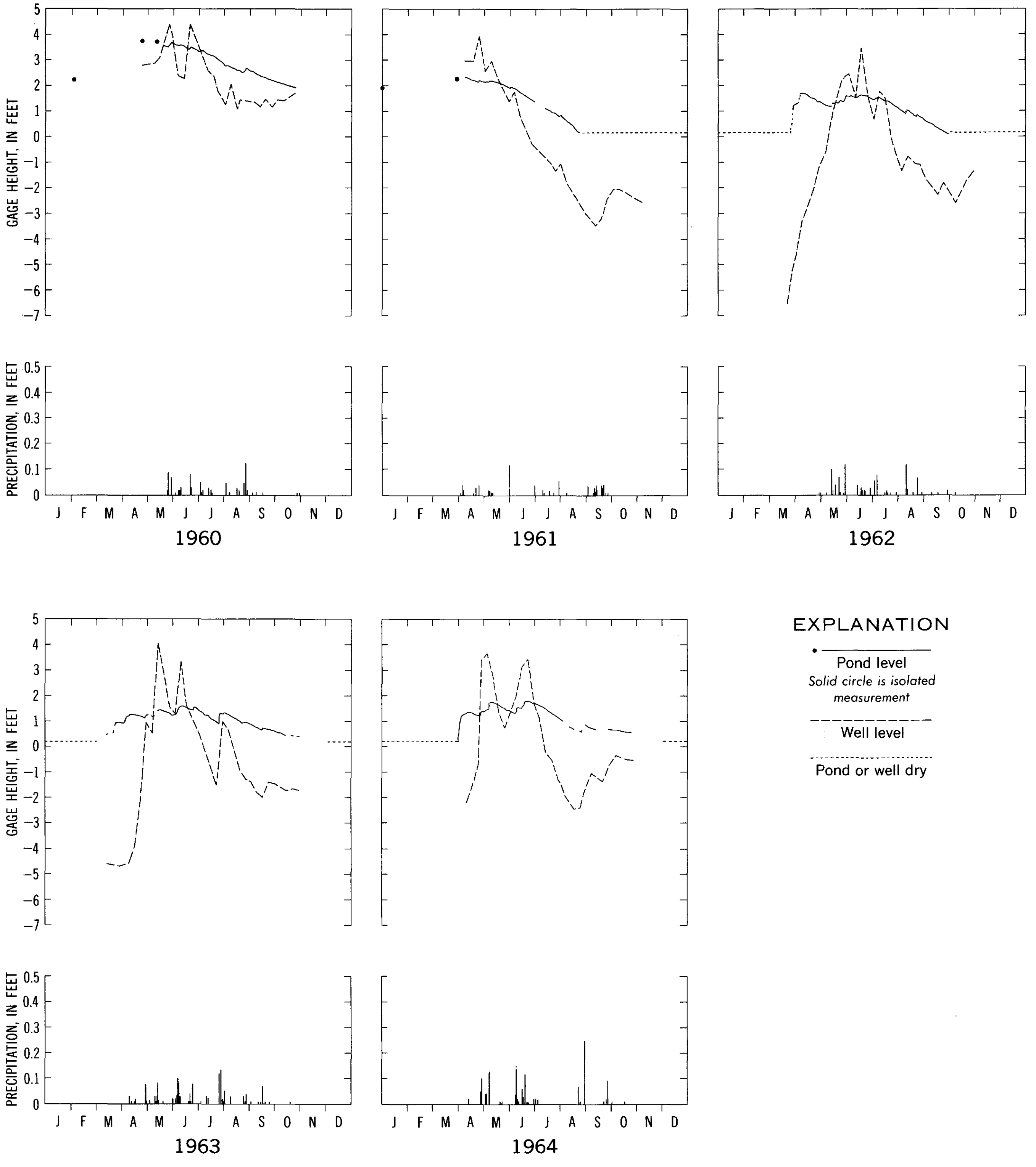
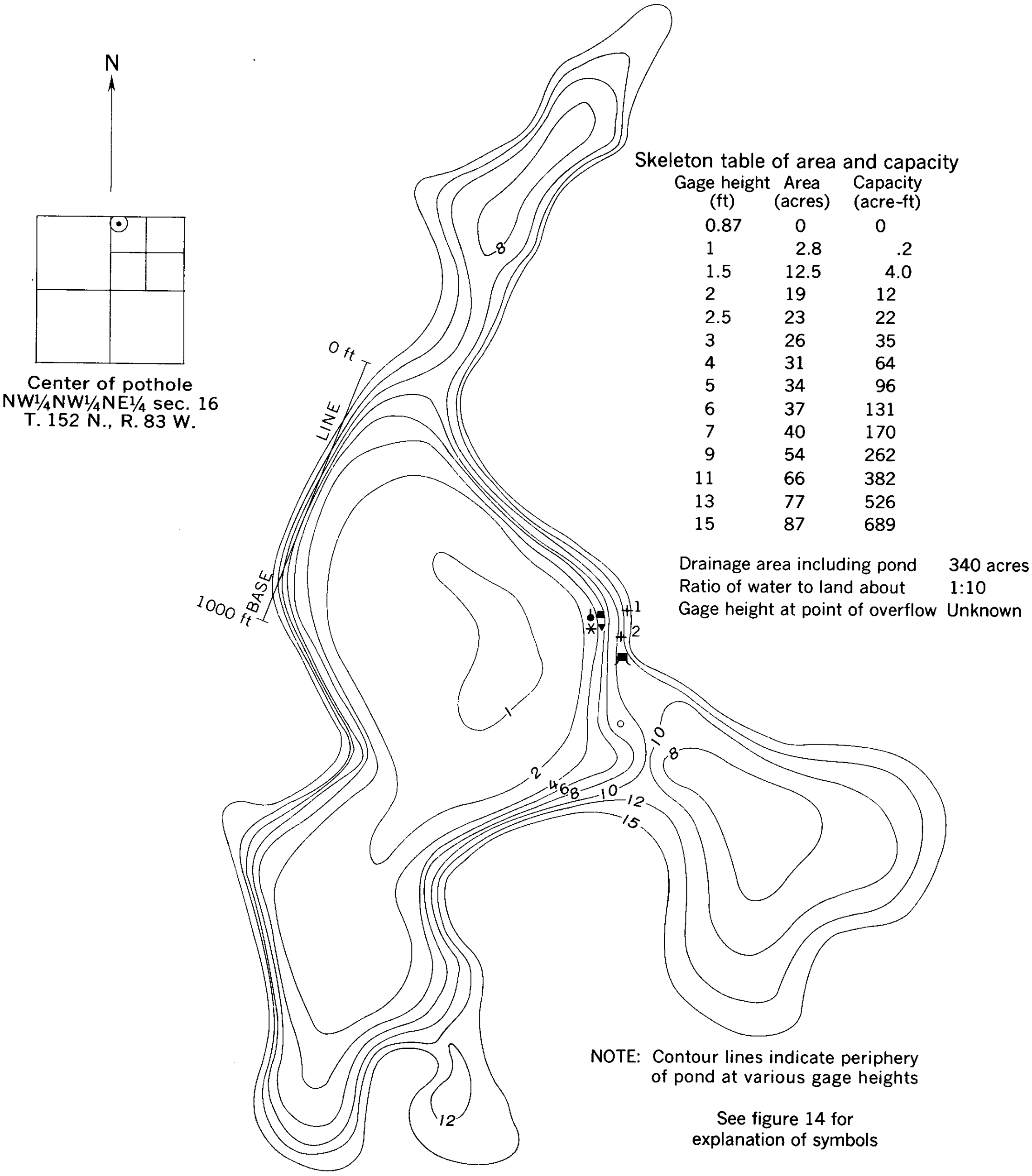


FIGURE 17.—Hydrographs for pothole 2, showing water levels in pond and observation well, and daily precipitation.



Skeleton table of area and capacity

Gage height (ft)	Area (acres)	Capacity (acre-ft)
0.87	0	0
1	2.8	.2
1.5	12.5	4.0
2	19	12
2.5	23	22
3	26	35
4	31	64
5	34	96
6	37	131
7	40	170
9	54	262
11	66	382
13	77	526
15	87	689

Drainage area including pond	340 acres
Ratio of water to land about	1:10
Gage height at point of overflow	Unknown

FIGURE 18.—Contour map for pothole 3 with skeleton table of area and capacity.

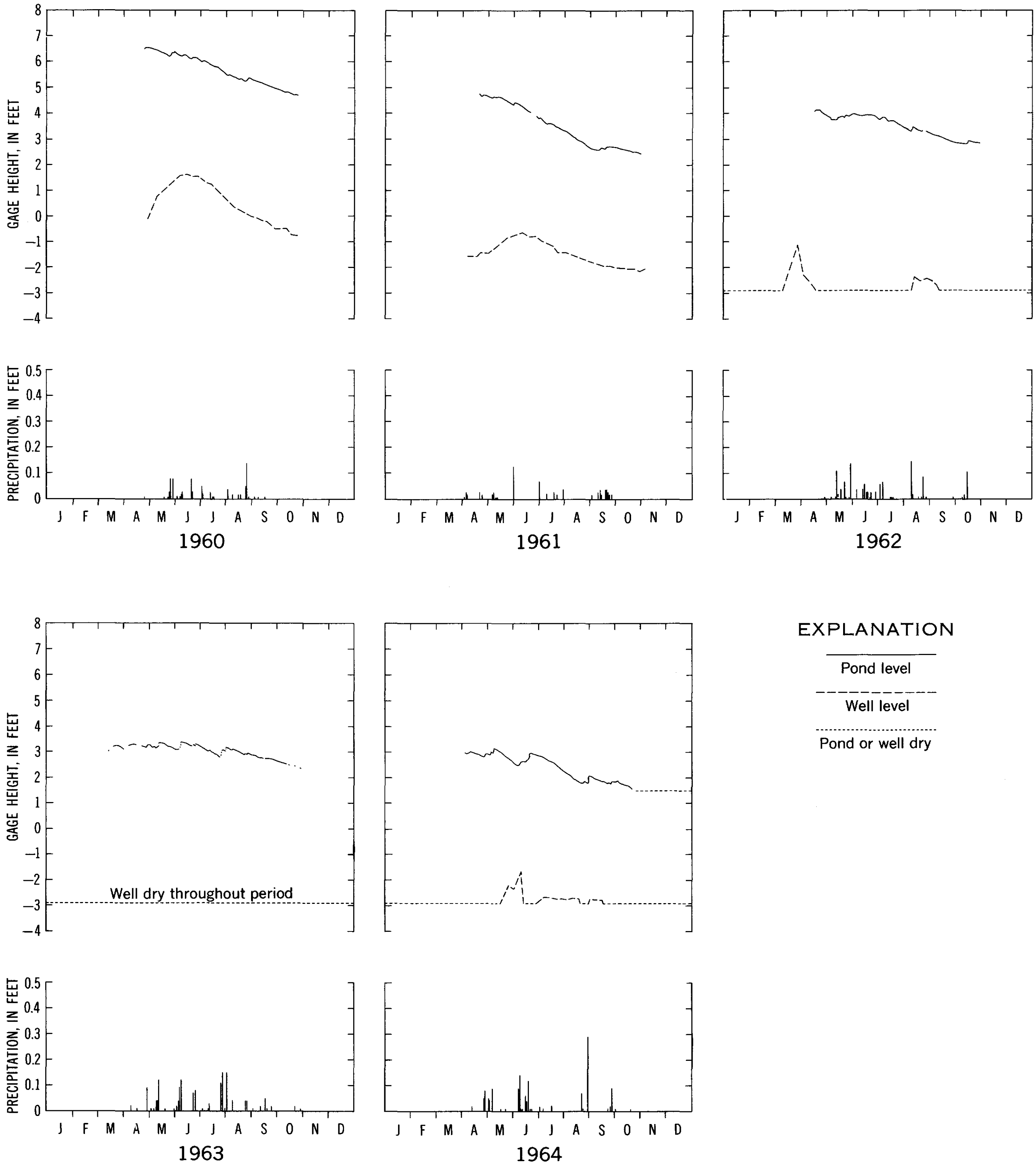
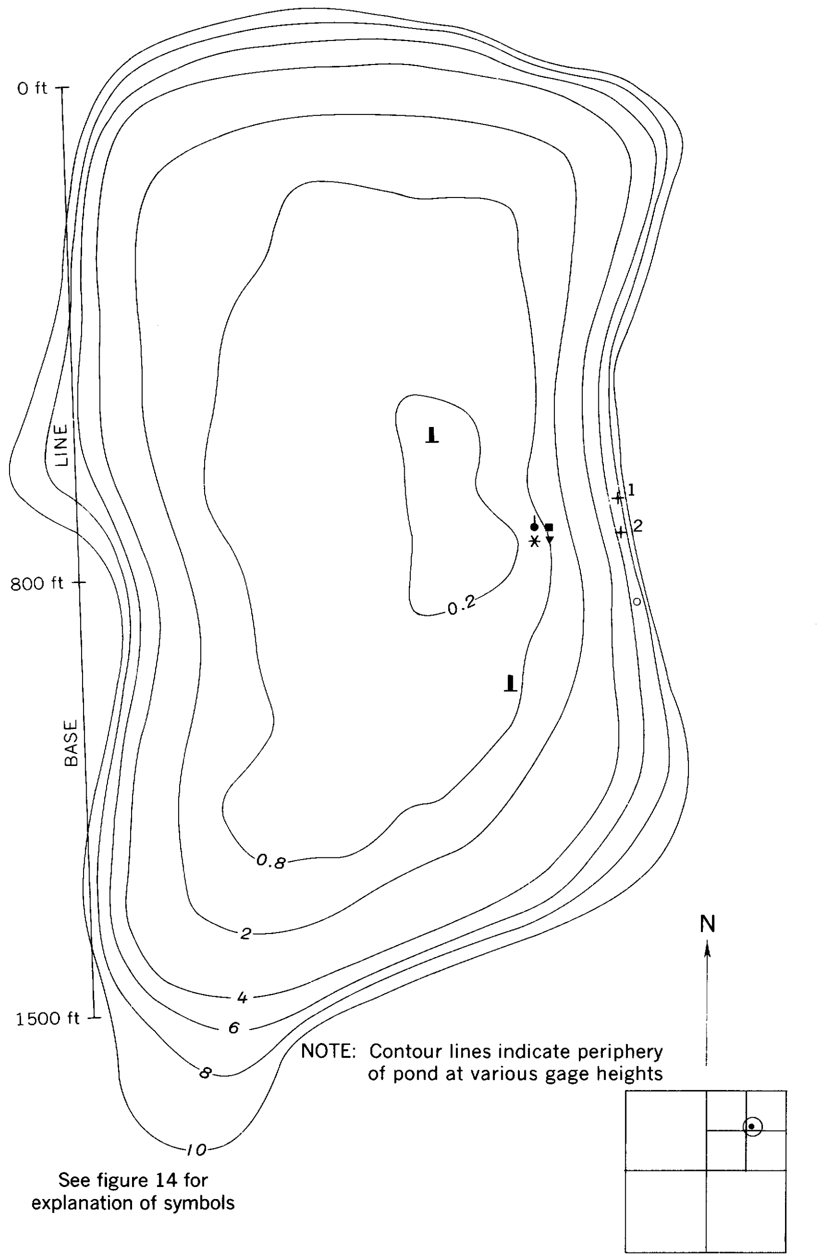


FIGURE 19.—Hydrographs for pothole 3, showing water levels in pond and observation well, and daily precipitation.



Skeleton table of area and capacity

Gage height (ft)	Area (acres)	Capacity (acre-ft)
0.13	0	0
.5	6.0	1.1
1	14	6.2
1.5	16	14
2	18	23
3	22	43
4	25	66
5	27	92
6	28	120
7	29	148
8	31	179
9	32	210
10	34	243

Drainage area including pond 74 acres
Ratio of water to land about 1:3
Gage height at point of overflow 16.0 ft

FIGURE 20.—Contour map for pothole 4 with skeleton table of area and capacity.

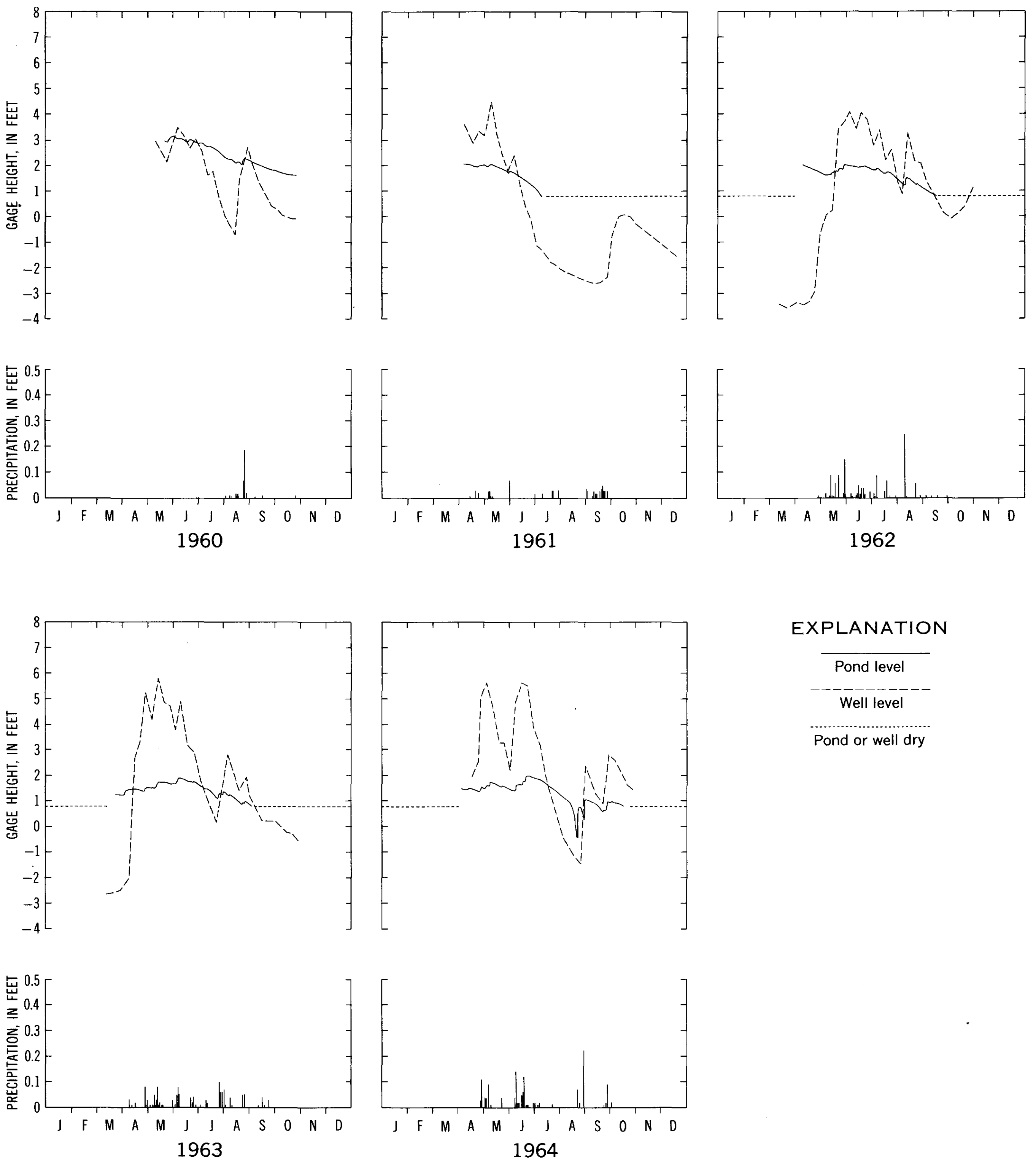
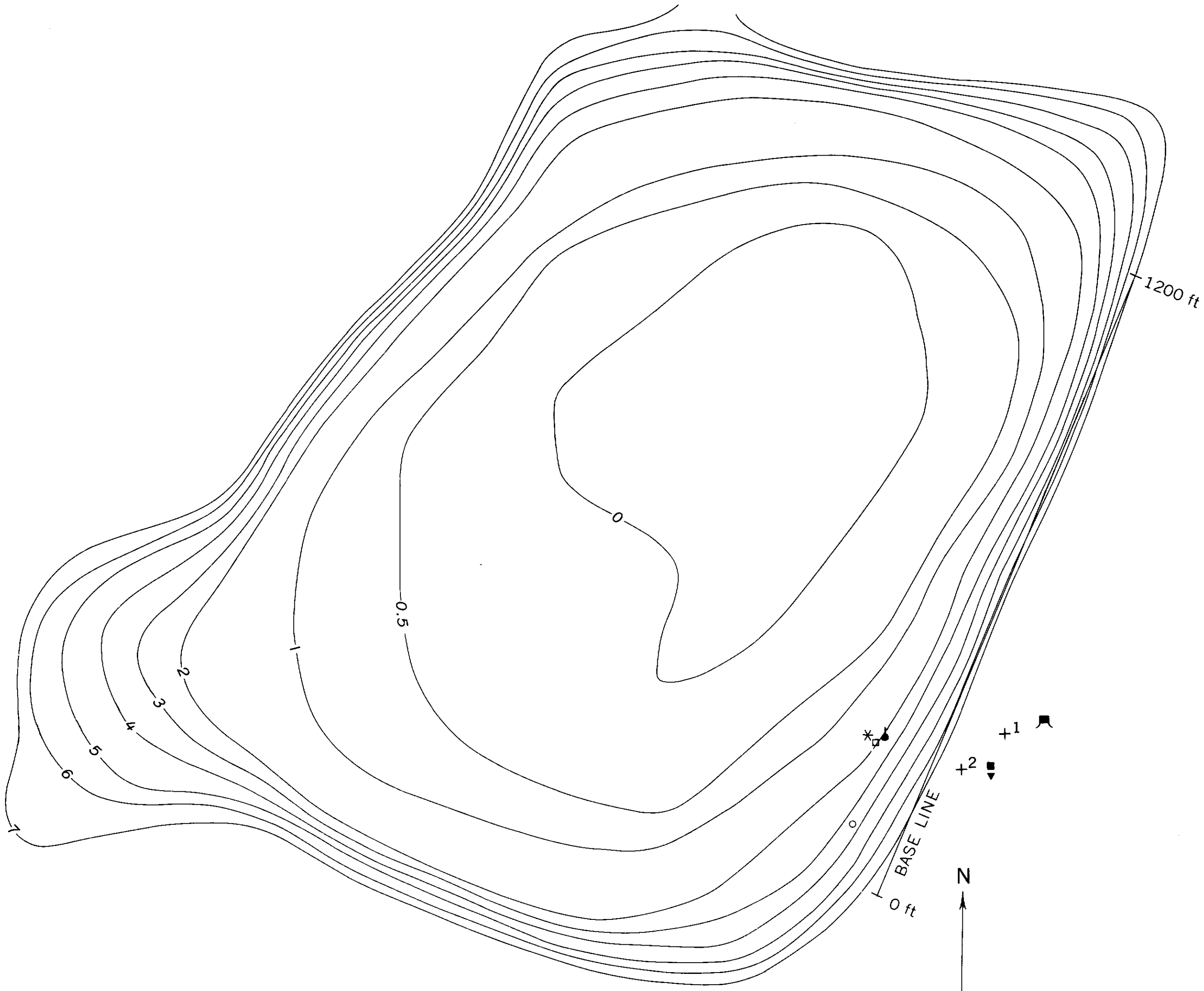


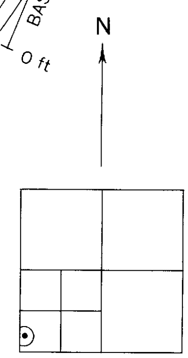
FIGURE 21.—Hydrographs for pothole 4, showing water levels in pond and observation well, and daily precipitation.



Skeleton table of area and capacity

Gage height (ft)	Area (acres)	Capacity (acre-ft)
−0.2	0	0
0	7.8	.8
.5	21	8.2
1	28	21
1.5	33	36
2	36	53
3	40	92
4	43	133
5	46	178
6	49	225

NOTE: Contour lines indicate periphery of pond at various gage heights



Center of pothole
SW¼SW¼SW¼ sec. 32
T. 142 N., R. 66 W.

See figure 14 for explanation of symbols

Drainage area including pond	243 acres
Ratio of water to land about	1:5
Gage height at point of overflow	6.0 ft

FIGURE 22.—Contour map for pothole C–1 with skeleton table of area and capacity.

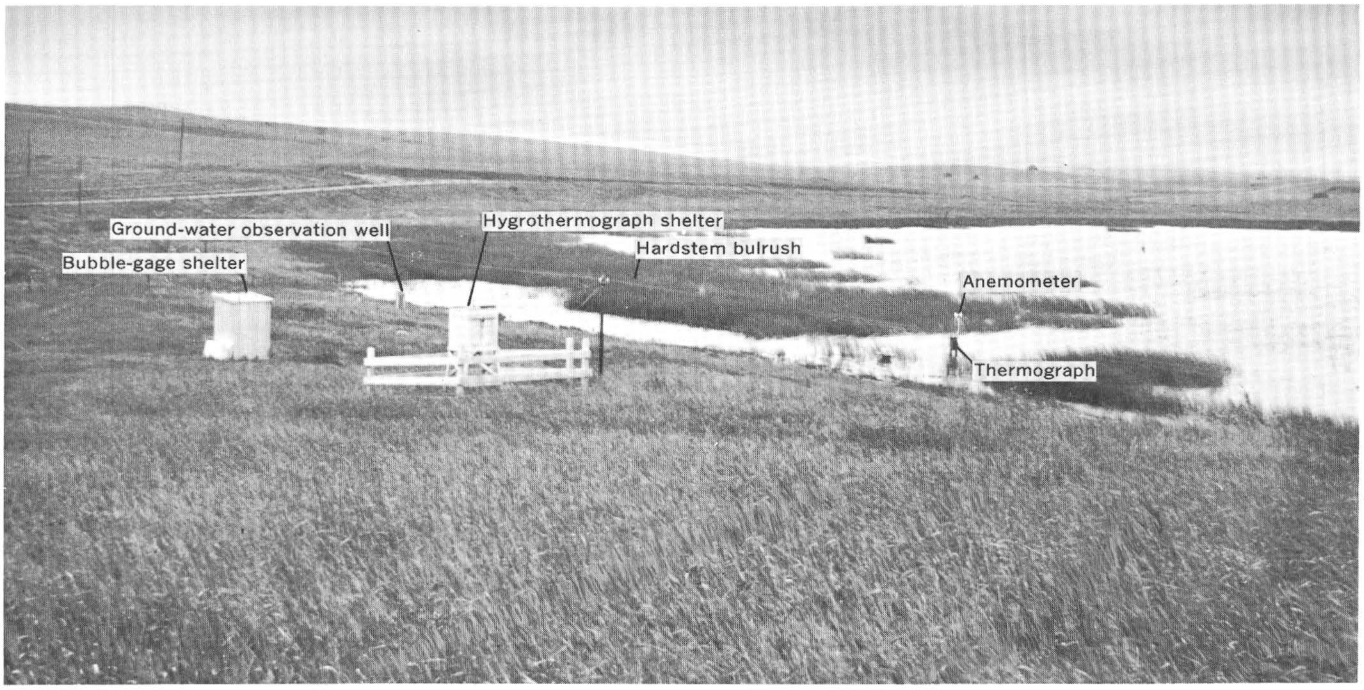


FIGURE 23.—Pothole C–1 near Buchanan. Photograph by Roger Pewé, September 14, 1965.

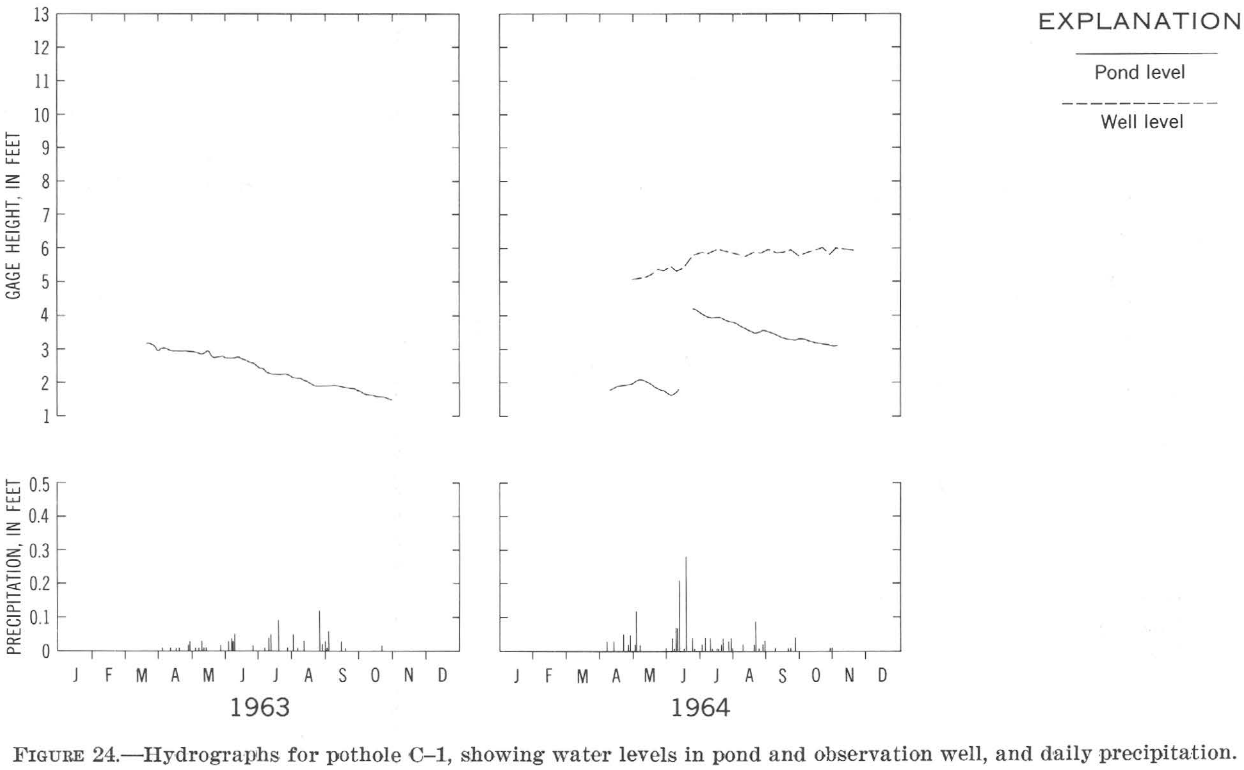
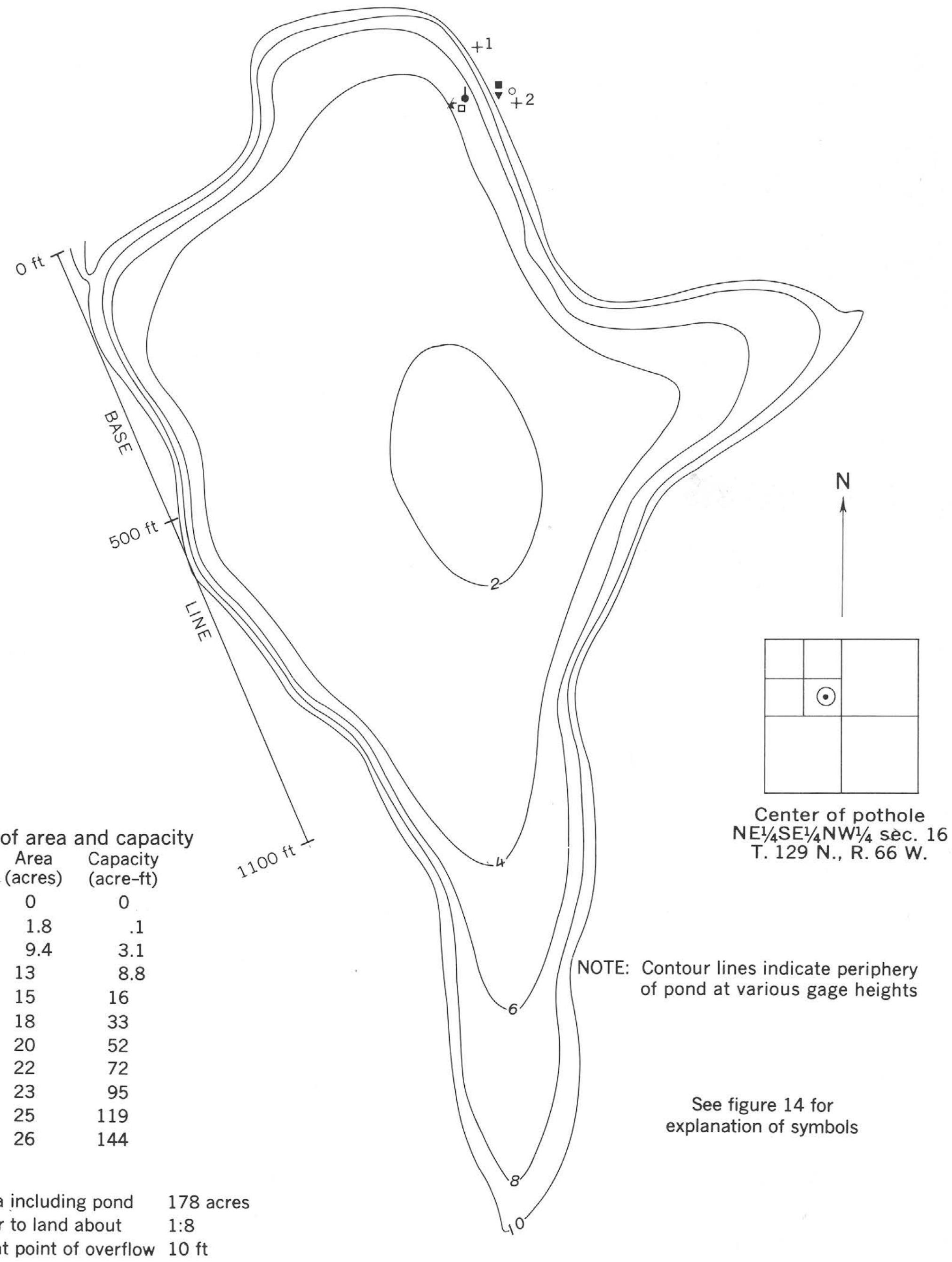


FIGURE 24.—Hydrographs for pothole C–1, showing water levels in pond and observation well, and daily precipitation.



Skeleton table of area and capacity

Gage height (ft)	Area (acres)	Capacity (acre-ft)
2.44	0	0
2.5	1.8	.1
3	9.4	3.1
3.5	13	8.8
4	15	16
5	18	33
6	20	52
7	22	72
8	23	95
9	25	119
10	26	144

Drainage area including pond 178 acres
Ratio of water to land about 1:8
Gage height at point of overflow 10 ft

FIGURE 25.—Contour map for pothole 5 with skeleton table of area and capacity.

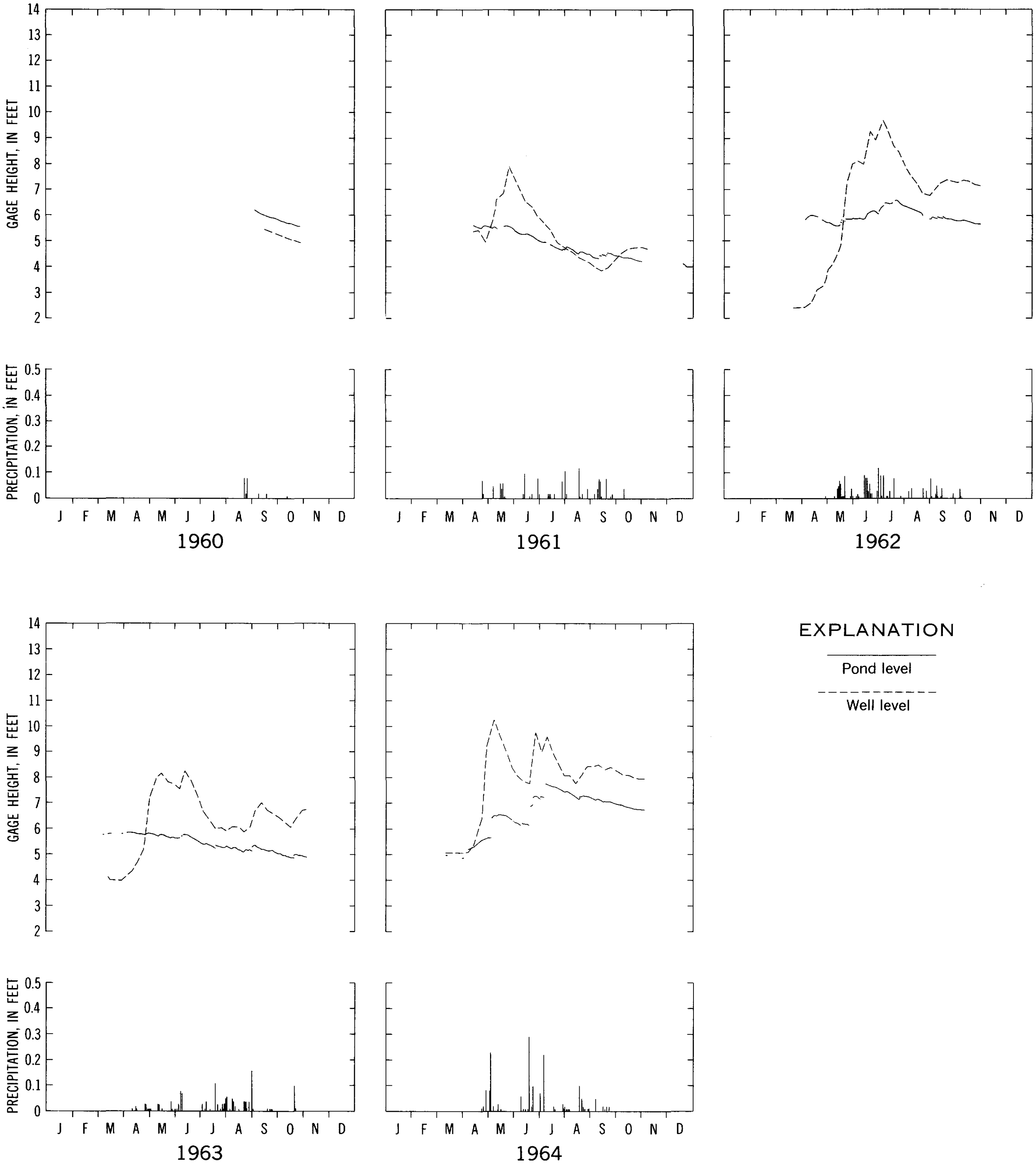
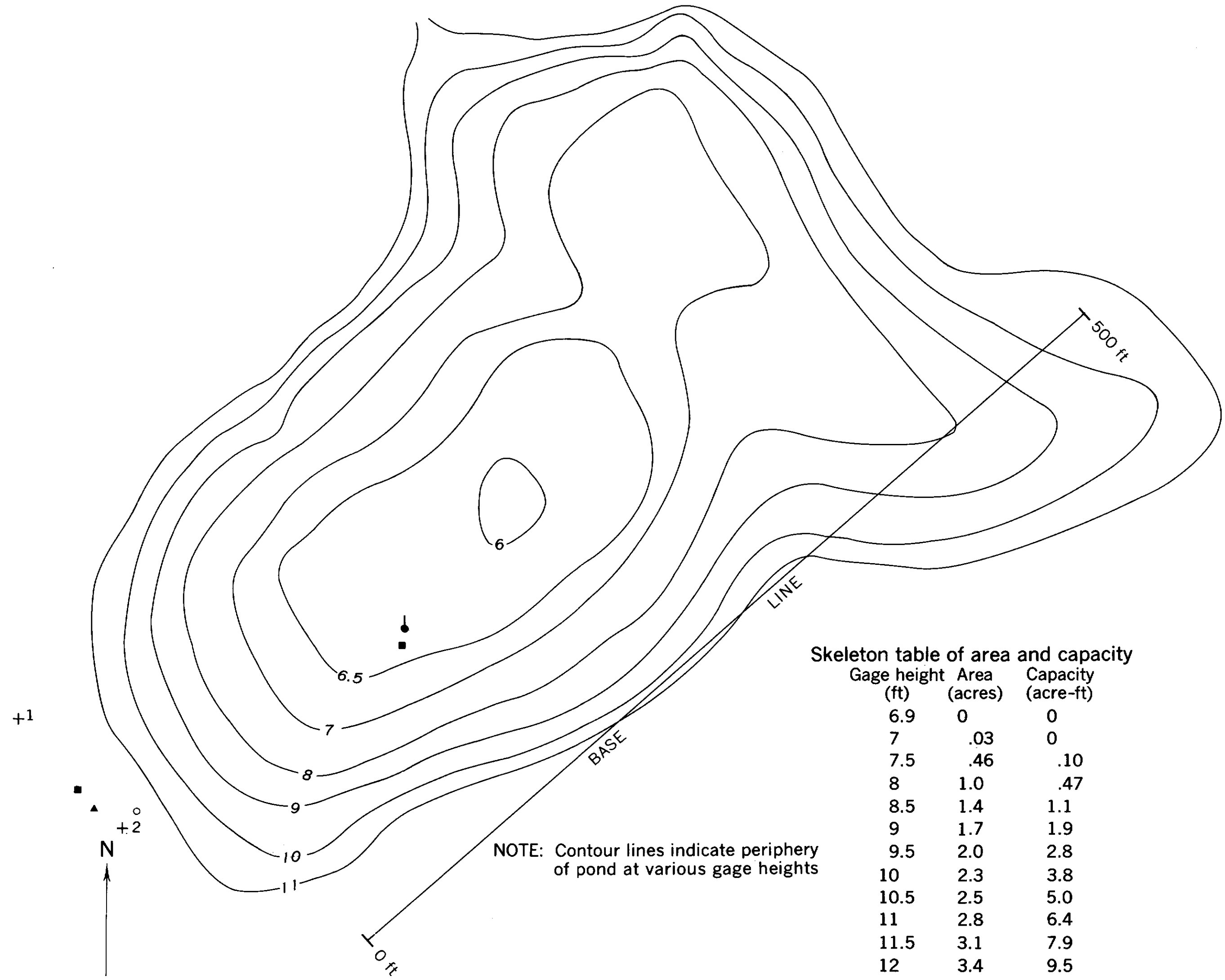


Figure 26.—Hydrographs for pothole 5, showing water levels in pond and observation well, and daily precipitation.

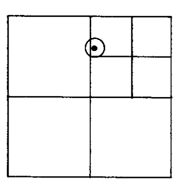


Skeleton table of area and capacity

Gage height (ft)	Area (acres)	Capacity (acre-ft)
6.9	0	0
7	.03	0
7.5	.46	.10
8	1.0	.47
8.5	1.4	1.1
9	1.7	1.9
9.5	2.0	2.8
10	2.3	3.8
10.5	2.5	5.0
11	2.8	6.4
11.5	3.1	7.9
12	3.4	9.5
12.5	3.7	11.2

See figure 14 for explanation of symbols

Drainage area including pond	Unknown
Ratio of water to land about	Unknown
Gage height at point of overflow	11.7 ft



Center of pothole
SW¼NW¼NE¼ sec. 16
T. 129 N., R. 66 W.

FIGURE 27.—Contour map for pothole 5A with skeleton table of area and capacity.

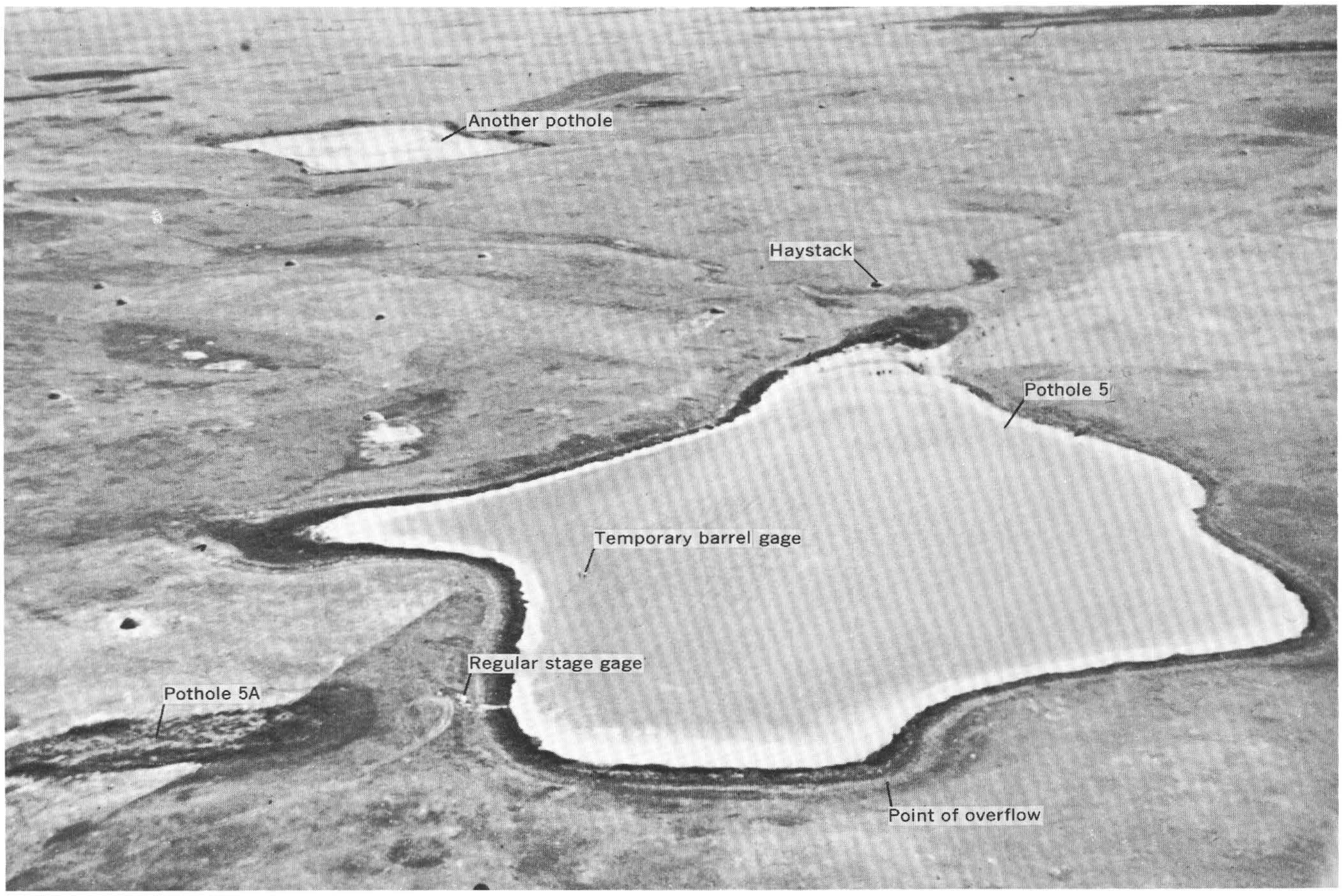


FIGURE 28.—Potholes 5 and 5A near Forbes. Photograph by W. P. Sebens, Executive Secretary, North Dakota State Soil Conservation Committee, September 16, 1961.

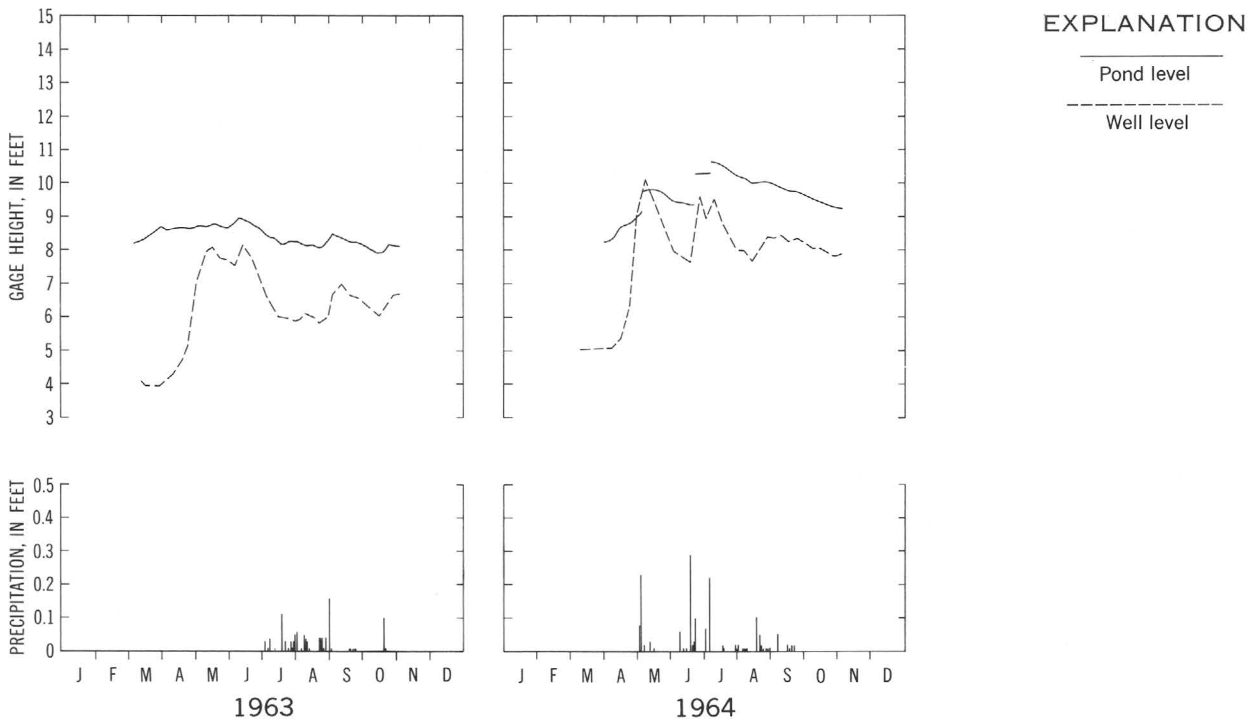
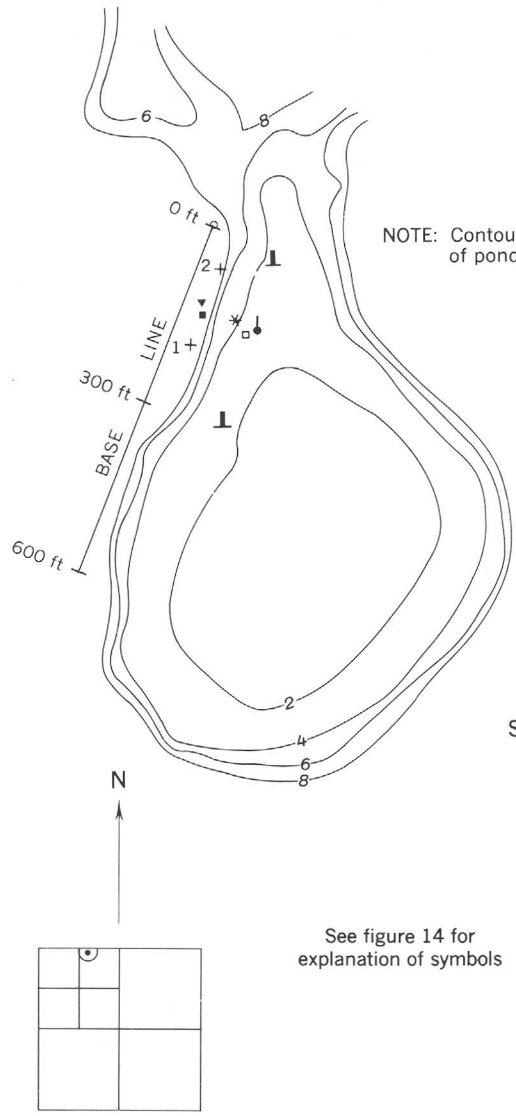


FIGURE 29.—Hydrographs for pothole 5A, showing water levels in pond and observation well, and daily production.



NOTE: Contour lines indicate periphery of pond at various gage heights

Center of pothole
NW¼NE¼NW¼ sec. 30
T. 129 N., R. 66 W.

See figure 14 for explanation of symbols

Skeleton table of area and capacity

Gage height (ft)	Area (acres)	Capacity (acre-ft)
1.7	0	0
2	3.7	.7
2.5	5.3	3.0
3	6.1	5.9
3.5	6.7	9.1
4	7.3	13
4.5	7.8	16
5	8.3	20
5.5	8.6	25
6	9.0	29
6.5	9.3	34
6.6	9.4	35

Drainage area including pond	36 acres
Ratio of water to land about	1:4
Gage height at point of overflow	6.6 ft

FIGURE 30.—Contour map for pothole 6 with skeleton table of area and capacity.

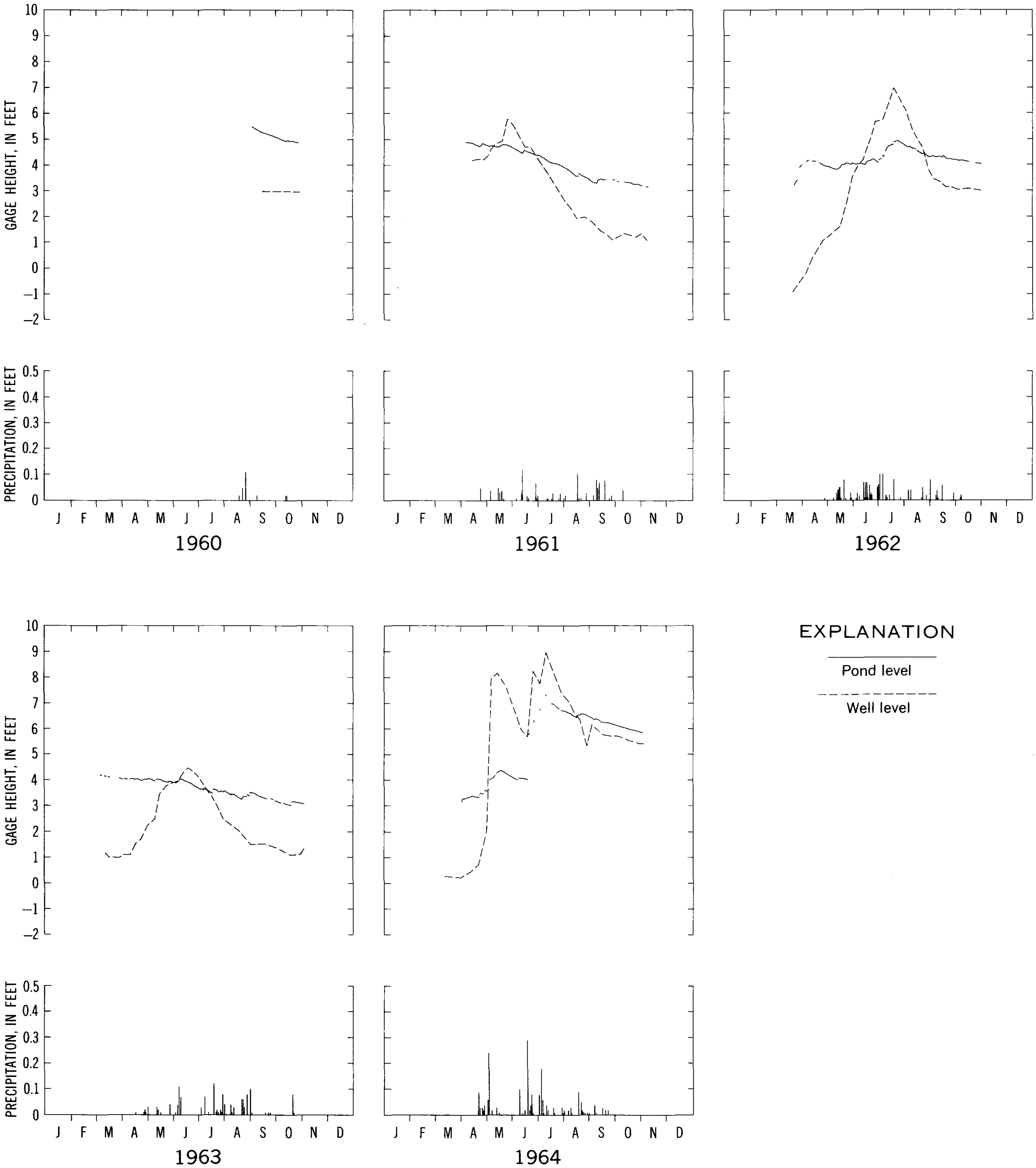
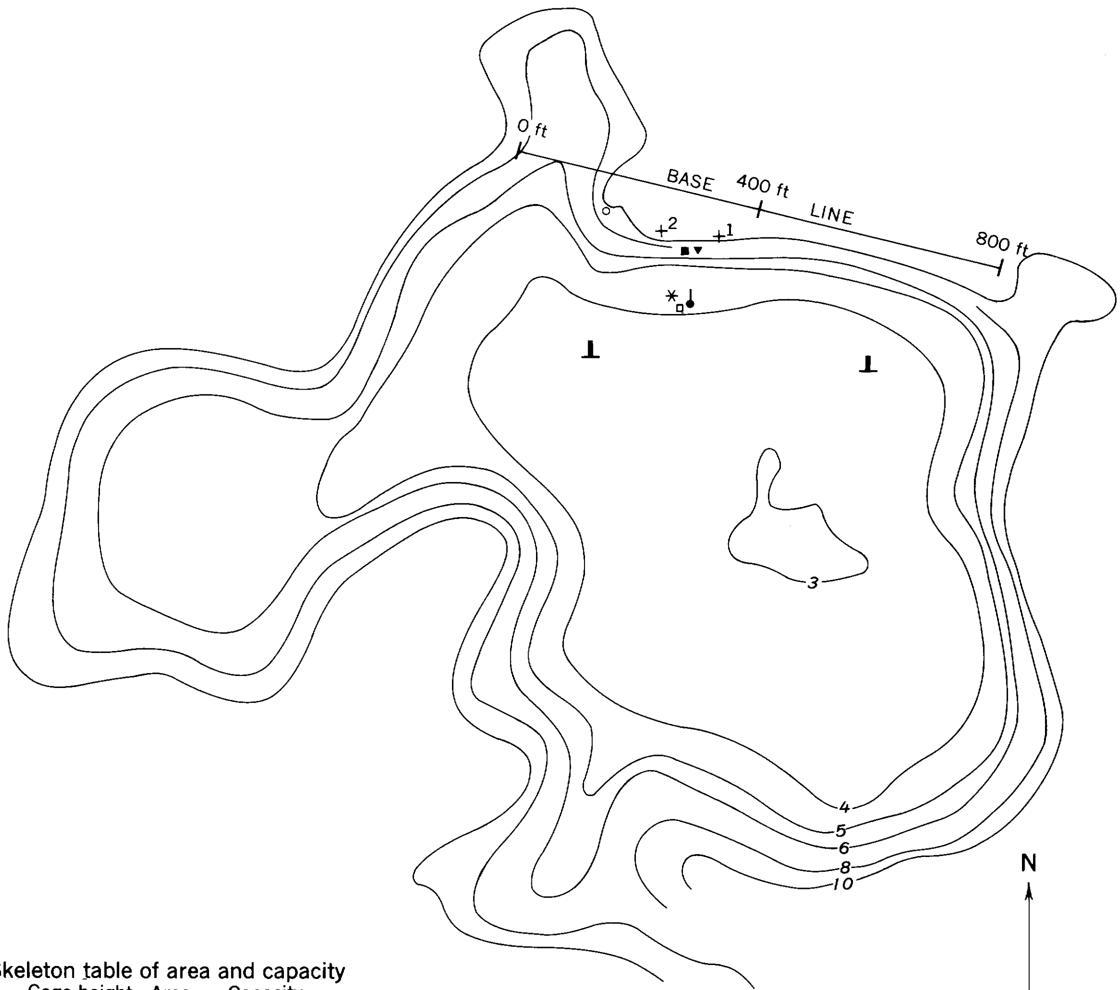


FIGURE 31.—Hydrographs for pothole 6, showing water levels in pond and observation well, and daily precipitation.

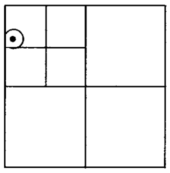


Skeleton table of area and capacity

Gage height (ft)	Area (acres)	Capacity (acre-ft)
2.97	0	0.
3	.5	.01
3.5	7.1	2.0
4	11	6.7
4.5	14	13
5	16	20
5.5	19	29
6	21	39
6.5	23	50
7	24	62
7.8	26	82

NOTE: Contour lines indicate periphery of pond at various gage heights

See figure 14 for explanation of symbols



Center of pothole
SW¼NW¼NW¼ sec. 27
T. 129 N., R. 66 W.

Drainage area including pond	88 acres
Ratio of water to land about	1:3
Gage height at point of overflow	7.8 ft

FIGURE 32.—Contour map for pothole 7 with skeleton table of area and capacity.

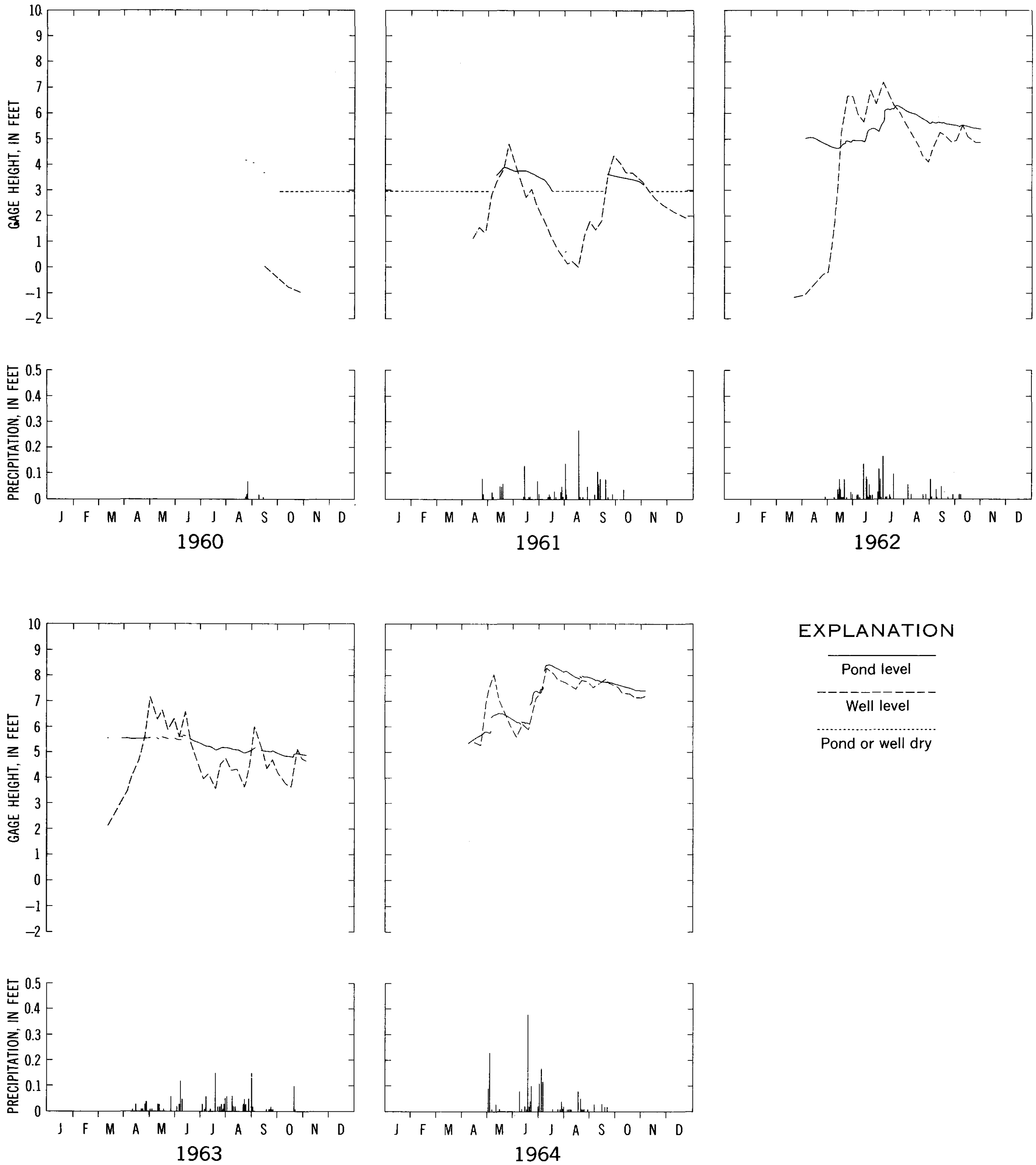
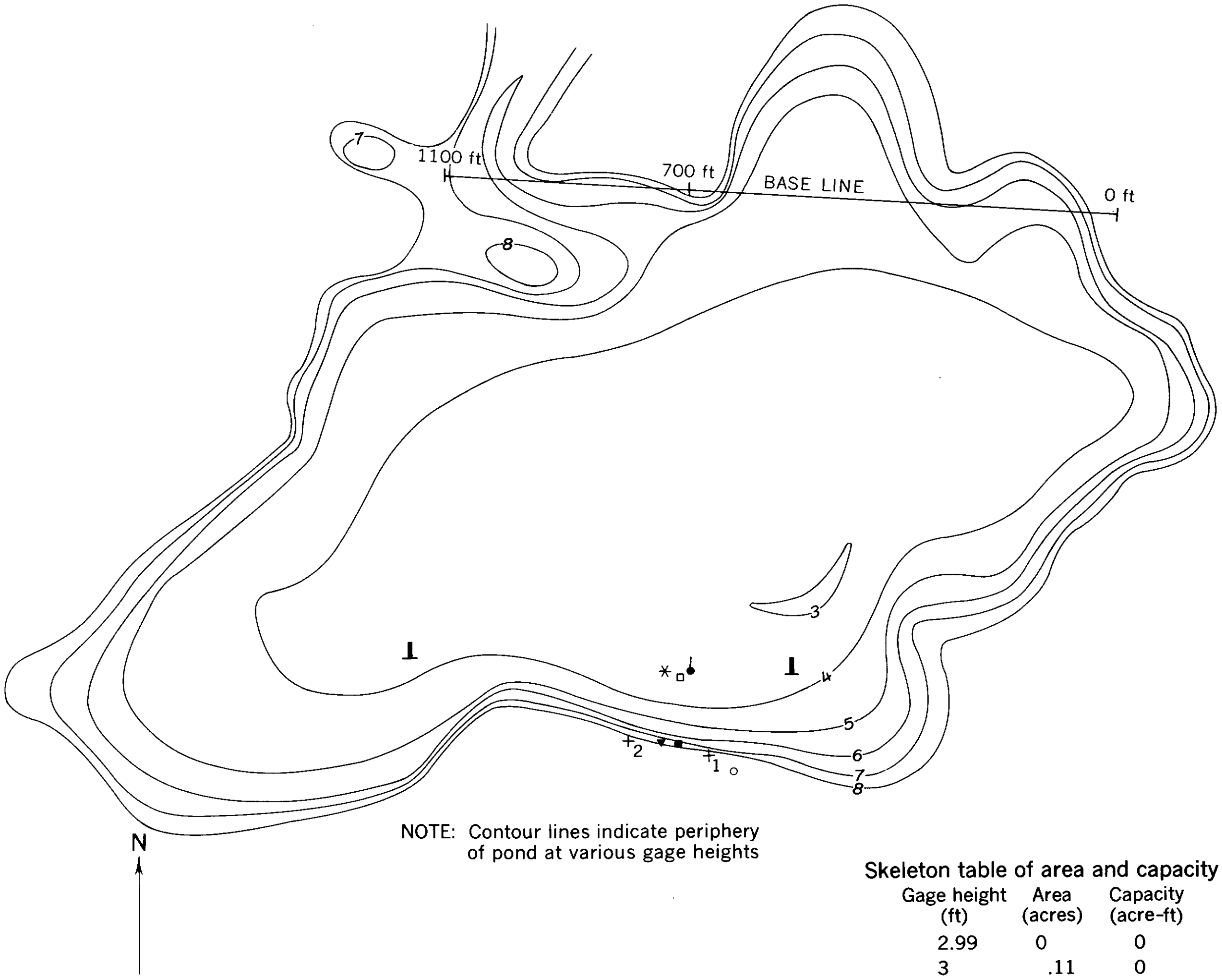
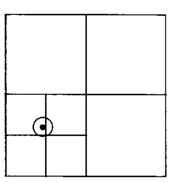


FIGURE 33.—Hydrographs for pothole 7, showing water levels in pond and observation well, and daily precipitation.



NOTE: Contour lines indicate periphery of pond at various gage heights



Center of pothole
SE¼NW¼SW¼ sec. 28
T. 129 N., R. 66 W.

See figure 14 for explanation of symbols

Skeleton table of area and capacity

Gage height (ft)	Area (acres)	Capacity (acre-ft)
2.99	0	0
3	.11	0
3.5	8.4	2.6
4	14	8.2
4.5	21	17
5	24	28
5.5	26	40
6	28	54
6.5	29	68
6.7	30	74

Drainage area including pond	81 acres
Ratio of water to land about	1:2
Gage height at point of overflow	6.7 ft

FIGURE 34.—Contour map for pothole 8 with skeleton table of area and capacity.

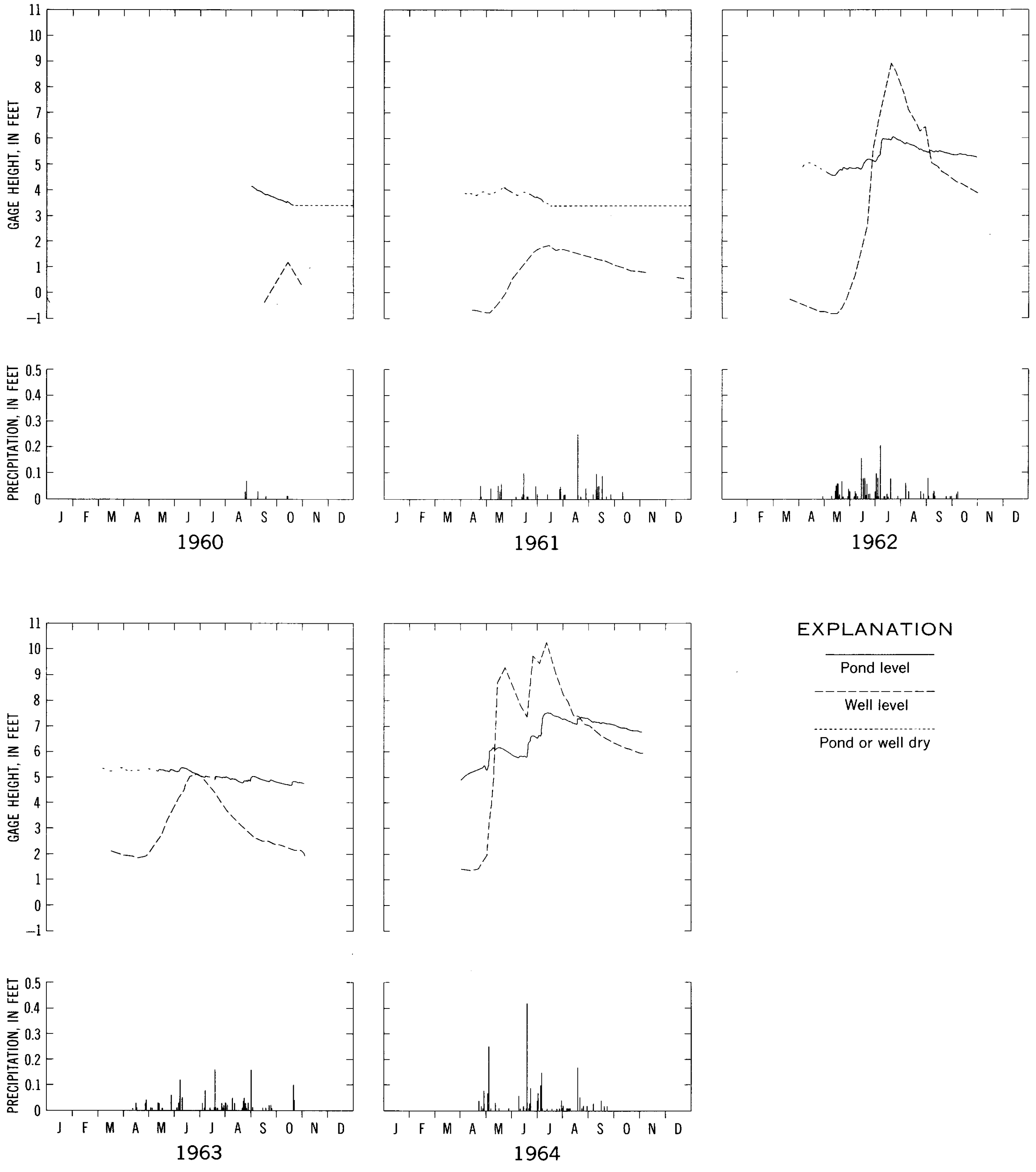


FIGURE 35.—Hydrographs for pothole 8, showing water levels in pond and observation well, and daily precipitation.

Cross sections of the water area were made at right angles to the base line using the base line as the starting point. The bottoms of the ponds were very spongy, and there were hummocks of roots where vegetation was dense. This soft, uneven condition precluded accurate determination of the bottom elevation of the pothole and the practicability of resurveys for the purpose of determining the rate of sediment accumulation during the relatively short study period. A plan to make the pothole surveys in the winter by drilling through the ice cover to locate bottom was considered but not used because of probable inaccuracies due to frost heave. Most likely, the entire pothole heaves if the bottom becomes frozen.

The contours were drawn on a map from the plane-table survey, and the area of each interval was determined by planimeter. The areas thus determined were plotted with gage height, in feet, as the ordinate and area, in acres, as the abscissa; and a smooth curve was drawn through the points. Values were picked from the curve for each 0.05 foot of gage height and corrected by adjusting the first and second differences between the planimetered figures. The areas corresponding to each 0.1 foot of gage height were tabulated to form the stage-area table; and the areas for the 0.05 points were accumulated, the decimal moved one place to the left, and the figures tabulated to form the capacity table. The capacity-table figures were rounded to two places to the right of the decimal, and both tables were again adjusted slightly between the planimetered points to make them as smooth as possible. A rough check of the volume thus computed was made by use of the prismoidal formula $V=\frac{h}{6}(A_1+4A_2+A_3)$, where V is volume, A is area, and h is height of increment (1 ft. in this study).

WATER-LEVEL FLUCTUATIONS

The hydrographs in figures 15, 17, 19, 21, 24, 26, 29, 31, 33, and 35 show the levels of the water surface in the ponds and in the ground-water observation wells, plotted to a common datum.

The sudden increases in water level in the ponds are from direct precipitation on the pond surface and from runoff from the drainage basin, whereas the gradual decreases in water level in the ponds are due to evapotranspiration and outflow seepage. The water level in the ground-water observation wells usually remained about 3 feet below the bottom of the ponds throughout the winter. About the first of May, the water level in the observation wells began to rise and continued rising for several weeks until it was 2 or 3 feet above the water level in the ponds. This rise in the ground-water level would usually start about the same time that the frost disappeared from the ground and about a month after the snowmelt runoff had entered the ponds. Precipitation during early May did not appear to be a major factor in the rise. The most likely explanation is that the rise is the result of thawing of the frost layer in the ground (Willis and others, 1964).

The water level in the observation wells did respond rapidly to precipitation later in the spring and during the summer, when a 1-inch rain was observed to cause as much as a 1-foot rise in the ground-water level. The amount of rise varied widely and was probably affected by such factors as intensity of rainfall, antecedent moisture conditions in the soil, storage capacity of the soil, evapotranspiration from plants, and evaporation from the soil surface. Unfortunately, none of the observation wells was equipped with a continuous recorder, which might have aided in defining some of these relationships. There seemed to be no ready interconnection between the ground-water wells and the ponds (Hans M. Jensen, U.S. Geol. Survey, Grand Forks, N. Dak., written commun.).

COMPUTATIONS

EVAPOTRANSPIRATION

Evapotranspiration was computed by means of the mass-transfer equation solved simultaneously with the water budget. The meteorological factors used in the mass-transfer equation can be readily obtained in the field by proper instrumentation. This method yields evapotranspiration and seepage—the two most important factors in the hydrologic cycle of a prairie pothole. The principle has been used with varying degrees of success on other projects: Langbein, Hains, and Culler (1951), Harbeck, Golden, and Harvey (1961), Marciano and Harbeck (1954), and Harbeck, Kohler, Koberg, and others (1958). The technique is described fully by Harbeck (1962) and Eisenlohr (1966b).

Water losses to the air can be computed by the mass-transfer formula for both vegetated and clear potholes, but the methods differ slightly. Eisenlohr (1966a, p. 443) stated, "The water loss to the air from a natural pond in which hydrophytes are growing consists of two parts, evaporation and transpiration. As both parts vary directly with the same meteorological factors, the total loss, evapotranspiration, can be computed by means of a mass-transfer equation in which the coefficient has been evaluated for that pond by means of a water budget."

Since evaporation and transpiration vary directly with the same meteorologic factors, no attempt has been made to separate these quantities in this study. The mass-transfer equation is expressed as

$$ET=Nu(e_0-e_a)$$

where

ET = evapotranspiration, in feet per day,
N = a coefficient of proportionality, hereafter called the mass-transfer coefficient,
u = wind speed, in miles per hour, at a fixed height above the water surface—4 meters in this study,
e_0 = saturation vapor pressure, in millibars, corresponding to the temperature of the water surface, and
e_a = vapor pressure of the air, in millibars.

In explaining the factors in this formula, we find that "The mass-transfer coefficient, N, represents a combination of many variables in the published mass-transfer equations. Among these are the manner of the variation of the wind with height, the size of the lake, the roughness of the water surface, atmospheric stability, barometric pressure, and density and kinematic viscosity of the air * * *" (Harbeck, 1962, p. 102). In the mass-transfer equation $ET=Nu\Delta e$, $(\Delta=e_0-e_a)$, we find that the factor $u\Delta e$ is dependent upon meteorological conditions that can be obtained in the field at any time, but the factors N and ET are more difficult to obtain. N is a coefficient of proportionality and can only be obtained by solving the equation when all of the other factors are known. ET can be obtained easily from a water budget for periods when there is no precipitation or runoff.

A water budget for the potholes studied can be written as follows in terms of unit area of water surface:

$$\Delta H=ET+S-P-R$$

where

ΔH = decrease in storage, as measured by the stage of pond,
ET = evapotranspiration,
S = net seepage outflow,
P = precipitation, and
R = runoff.

However, the water budget can be simplified if there is no precipitation or runoff. Then these items become zero and the equation can be written $\Delta H=ET+S$.

This means that the decrease in stage during periods when there is no precipitation or runoff is equal to the sum of the evapotranspiration loss and the net seepage outflow. The evapotranspiration loss and seepage outflow can be separated because they behave differently. Evapotranspiration varies greatly from day to day because it is dependent upon the wind speed and the drying power of the air, whereas the net seepage outflow is assumed to be constant from day to day because it is dependent mainly upon the soil conditions around and beneath the pothole. Fortunately, no significant variations in net seepage outflow have been observed, so the assumption that it is constant seems well founded.

When the values for ΔH are plotted as the ordinate and the values for $u\Delta e$ are plotted as the abscissa, the slope of the best-fitting line drawn through the points is the coefficient of proportionality, or the mass-transfer coefficient, N, and the Y-intercept is the seepage rate, S, in feet per day. Harbeck (Shjeflo and others, 1962, fig. 4) illustrated this principle. Each period used to define a value of N is called a rating period.

The diagonal line (fig. 40) shows the variation of ΔH with $u\Delta e$, and the Y-intercept shows the part of ΔH that does not vary with $u\Delta e$, which is seepage. If there were no seepage, the line would pass through the origin of the plot. A Y-intercept above the origin indicates net seepage outflow, and a Y-intercept below the origin indicates net seepage inflow.

The least-squares method was found to be the most effective way to determine the best-fit line and the Y-intercept.

These computations were performed easily on a desk calculator with a 10-row keyboard. The use of this machine led to the use of more figures in the computations than were truly significant, as shown in the illustrations showing examples of the computation.

With N known, we can solve the mass-transfer equation for ET at all times. Once N has been determined for a clear pothole, it usually will remain constant throughout the year or for several years, provided there are no large changes in water stage or wind direction. However, the N for a vegetated pothole is variable because it is based partly on transpiration, which is constantly changing as the plants alternately grow and dry up or freeze (Eisenlohr, 1966a).

In selecting a rating period for the determination of N, there are certain practical requirements that must be met in addition to the theoretical considerations. These requirements are:

1. No precipitation.
2. No runoff.
3. Wind at beginning and end of period must not be so strong as to interfere with obtaining an accurate stage reading.
4. All instruments must be working properly.
5. Period should be on a single weekly chart.
6. A minimum of 3 days was found to be desirable to obtain a good distribution of points and a reliable average.

A suitable rating period would be one such as that of June 18–20, as shown in figure 36.

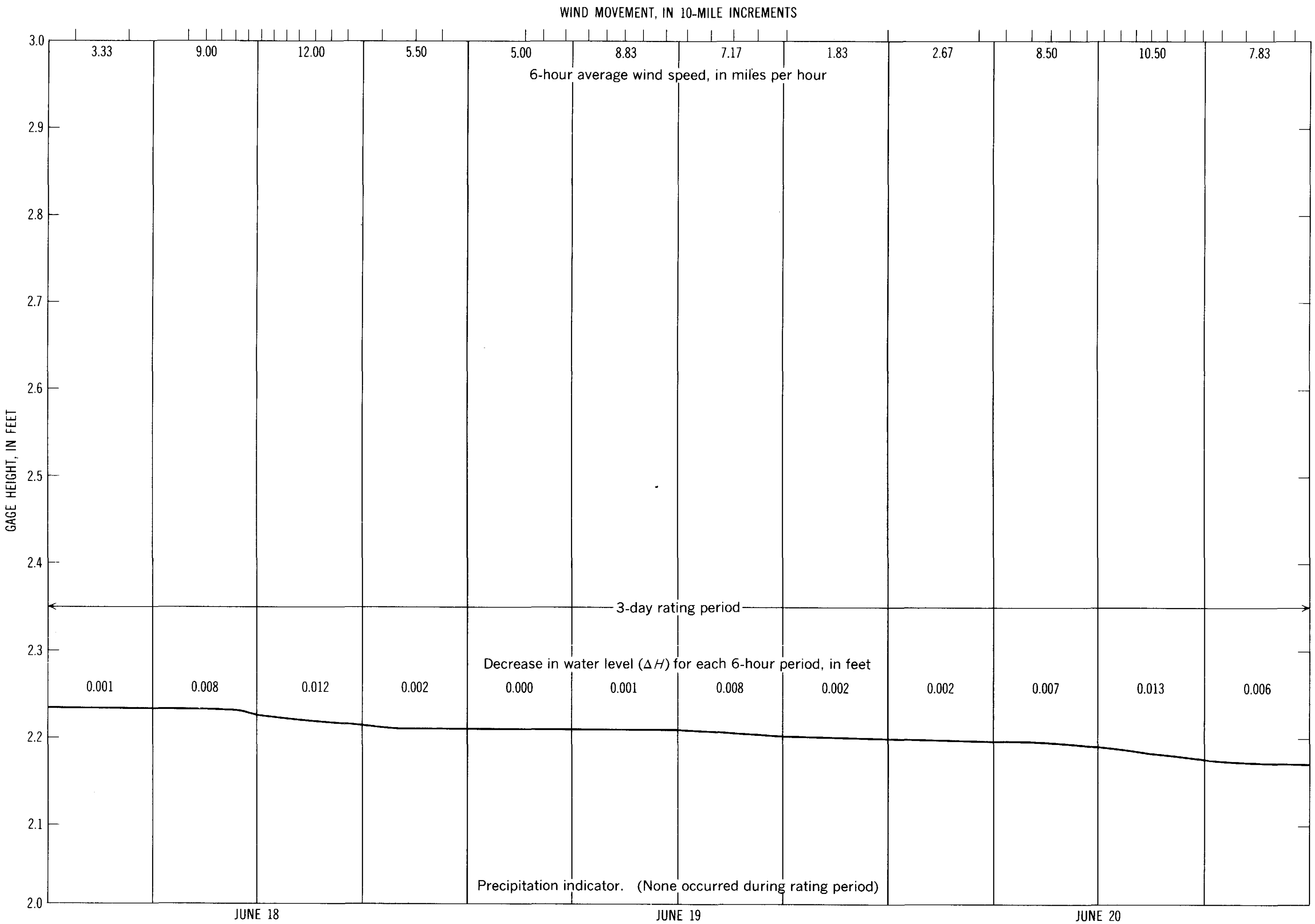


FIGURE 36.—Recorder chart for pothole 1 near Douglas, June 18–20, 1963, showing a 3-day rating period.

A great many more rating periods are needed to define the variable N for a vegetated pothole than are needed for a clear pothole, where the N is constant throughout the season. An N determination was needed about once every 10 days for a vegetated pothole, but for a clear pothole, one N determination each year, or even one N determination for the entire period of record, as was done in this study, was found to be ample. Since good rating periods occurred infrequently, it became necessary to divide the rating periods into 6-hour units for the vegetated potholes, as shown in table 2, to get enough points for a reliable determination. Sometimes all the acceptable single days scattered over a 10-day period were divided into 6-hour units and used to obtain values of N.

TABLE 2.—*Worksheet used in determining* $u\Delta e$, *pothole 1, Ward County, 1963*

[Rating period, D_{10}]

June date	Number of 6-hour units	Water temperature in degrees Fahrenheit, (T_o)	e_0	Air temperature in degrees Fahrenheit, (T_a)	Saturation vapor pressure (e_s)	Relative humidity (RH)	e_a	Δe	ΔH (6 hours)	u (average)	$u\Delta e$
17	0.96	69	23.2	75	29.6	45	12.8	10.4	-------	----------	--------
	1.00	67	22.6	62	19.0	73	13.9	8.7	-------	----------	--------
18	1.00	62	19.0	56	15.3	90	13.8	5.2	0.001	3.33	17.32
	1.00	65	21.1	66	21.8	75	16.4	4.7	.008	9.00	42.30
	1.00	74	28.7	74	28.7	56	16.1	12.6	.012	12.00	151.20
	1.00	69	24.2	67	22.6	70	15.8	8.4	.002	5.50	46.20
19	1.00	64	20.3	55	14.8	98	14.5	5.8	0	5.00	29.00
	1.00	63	19.6	55	14.8	88	13.0	6.6	.001	8.83	58.28
	1.00	68	23.4	63	19.6	66	12.9	10.5	.008	7.17	75.28
	1.00	65	21.1	57	15.9	80	12.7	8.4	.002	1.83	15.37
20	1.00	59	17.0	51	12.7	97	12.3	4.7	.002	2.67	12.55
	1.00	63	19.6	63	19.6	70	13.7	5.9	.007	8.50	50.15
	1.00	71	25.9	71	25.9	46	11.9	14.0	.013	10.50	147.00
	1.00	66	21.8	62	19.0	57	10.8	11.0	.006	7.83	86.13
21	1.00	59	17.0	54	14.2	76	10.8	6.2	-------	----------	--------
	1.00	59	17.0	57	15.9	74	11.8	5.2	-------	----------	--------
	1.00	67	22.6	72	26.8	60	16.1	6.5	-------	----------	--------
	1.00	66	21.8	71	25.9	67	17.4	4.4	-------	----------	--------
22	1.00	63	19.6	59	17.0	96	16.3	3.3	-------	----------	--------
	1.00	65	21.1	65	21.1	90	19.0	2.1	-------	----------	--------
	1.00	75	29.6	76	30.6	61	18.7	10.9	-------	----------	--------
	1.00	71	25.9	69	24.2	68	16.5	9.4	-------	----------	--------
23	1.00	64	20.3	56	15.3	78	11.9	8.4	-------	----------	--------
	1.00	65	21.1	56	15.3	70	10.7	10.4	-------	----------	--------
	1.00	68	23.4	61	18.3	72	13.2	10.2	.007	3.8	38.8
	1.00	63	19.6	58	16.5	90	14.8	4.8	.002	2.5	12.0
24	1.00	61	18.3	56	15.3	92	14.1	4.2	.001	3.8	16.0
	1.00	65	21.1	65	21.1	95	20.0	1.1	.002	6.2	6.8
	.15	74	4.3	78	32.7	72	3.5	.8	-------	----------	--------
Weekly total	--------	----------	610.2	----------	----------	----------	405.4	204.8	-------	----------	--------

For vegetated potholes, when a suitable rating period was found, ΔH was computed directly from the recorder chart for each 6-hour unit, as shown in figure 36, and recorded on the worksheet, as shown in table 2. The change in stage had to be in feet per day, so the change for each 6-hour unit had to be multiplied by 4 to obtain a daily rate. For clear potholes, a period several days long had to be divided by the number of days in the period to obtain the daily rate.

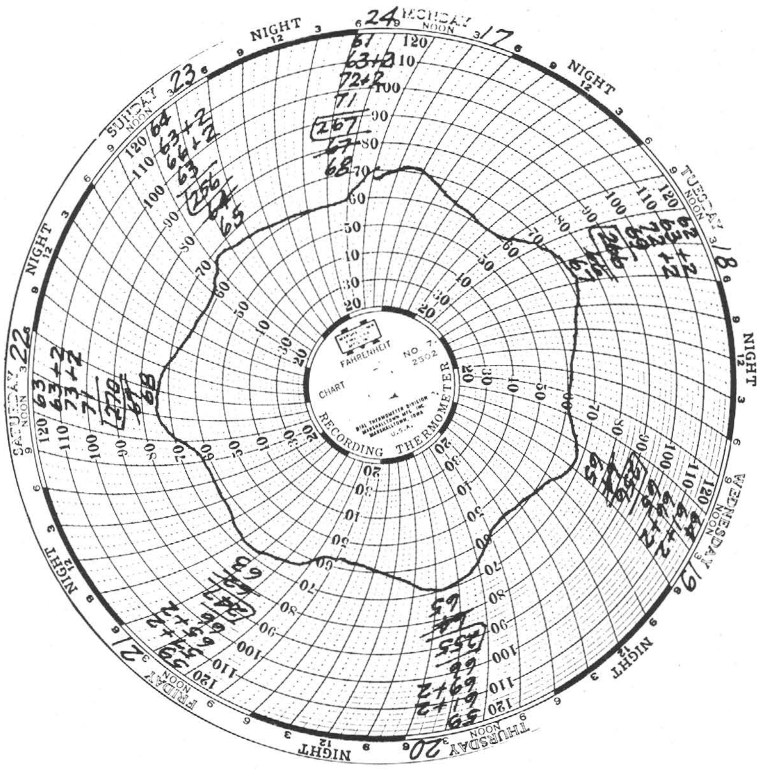
The average wind speed, u, in miles per hour, had to be determined for each period also. This was done by counting the pips on the recorder chart during each period, multiplying by 10, and dividing by the number of hours in the period, as shown in figure 36; this figure was then recorded on the worksheet as shown in table 2.

The remaining factor in the formula is the vapor pressure difference, $e_o - e_a$, or Δe. The saturation vapor pressure, e_0, corresponds to the temperature of the water surface, in millibars. The water temperature near the surface was recorded on a separate circular weekly chart, as shown in figure 37. The days were divided into 6-hour units, beginning at midnight, and the average temperature for each 6-hour unit was recorded on a worksheet as shown in table 2. The days were divided into 6-hour units because vapor pressure does not vary directly with temperature, and the use of daily averages might have given results that were grossly in error owing to the extremes in temperature during some days. Actually then, the 6-hour units served two purposes: (1) they provided more points and a better distribution of points when making an N determination by least squares, and (2) they gave a more nearly correct determination of the average vapor pressure for the rating periods. Rather than treat the rating periods, and days with a large range in either water temperature or air temperature, differently than the remaining days, the entire record was computed on the basis of 6-hour units. The saturation vapor pressure corresponding to the water-surface temperature was obtained from table 3, and recorded on the worksheet.

TABLE 3.—*Saturation vapor pressure, in millibars, over water*

Temperature °F	0°	1°	2°	3°	4°	5°	6°	7°	8°	9°
30°	------	------	6.1	6.4	6.6	6.9	7.2	7.5	7.8	8.1
40°	8.4	8.7	9.1	9.4	9.8	10.2	10.6	11.0	11.4	11.8
50°	12.3	12.7	13.2	13.7	14.2	14.8	15.3	15.9	16.5	17.0
60°	17.7	18.3	19.0	19.6	20.3	21.1	21.8	22.6	23.4	24.2
70°	25.0	25.9	26.8	27.7	28.7	29.6	30.6	31.7	32.7	33.8
80°	35.0	36.1	37.3	38.5	39.8	41.1	42.4	43.8	45.2	46.7
90°	48.2	49.7	51.3	52.9	54.5	56.2	58.0	59.8	61.6	63.5
100°	65.5	------	------	------	------	------	------	------	------	----

NOTE.—Based on table of e_0 in "Handbook of Chemistry and Physics" (Chemical Rubber Publishing Co., 1950) and converted to millibars and degrees Fahrenheit. Graphical curvilinear interpolation below 77°F; linear above.



FRONT

BACK

FIGURE 37.—Thermograph chart showing the diurnal fluctuation of water temperature.

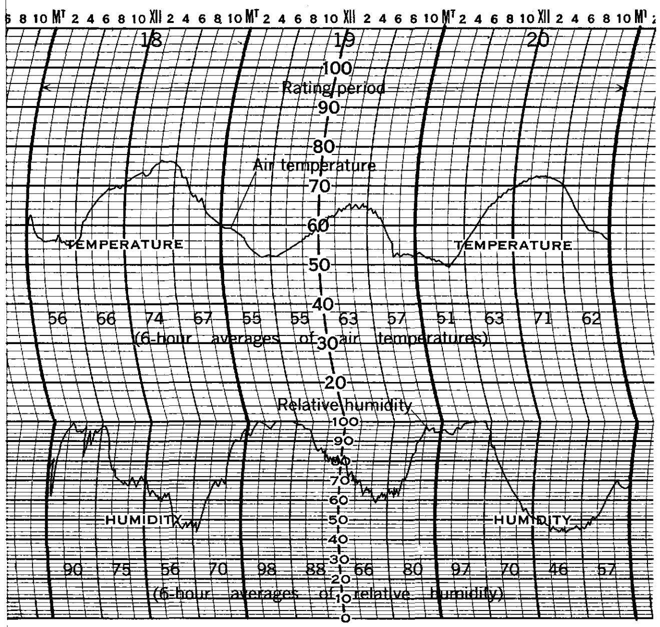


FIGURE 38.—Hygrothermograph chart showing air temperature and relative humidity.

The vapor pressure of the air, e_a, is given in millibars. The air temperature was recorded on the hygrothemograph chart, as was the relative humidity (fig. 38). The air-temperature and relative-humidity graphs were also divided into 6-hour units. The saturation vapor pressure corresponding to the average air temperature for the 6-hour unit was obtained from table 3 and recorded on the worksheet as shown in table 2. This value was multiplied by the average relative humidity for the corresponding 6-hour unit to obtain the average vapor pressure of the air. The difference between e_0 and e_a was the vapor pressure difference, Δe.

The computation procedure was the same for clear potholes except that the 6-hour values for e_0 and e_a were summed for the entire rating period and the average for the period determined. Therefore, for a clear pothole only one pair of values, $u\Delta e$ and ΔH, would be obtained per rating period, whereas for a vegetated pothole this same rating period would yield a pair of values for each 6-hour unit.

The values of $u\Delta e$ and ΔH for the 6-hour units in each rating period were plotted on graph paper, and the least-squares line and Y-intercept were then shown, as illustrated in figure 40, to aid in analyzing the data.

A large variation in the Y-intercepts, or seepage rates, was found. This is illustrated by the scattering of the points in figure 39. Data for some of the vegetated potholes indicate that the seepage rates were highest when the mass-transfer coefficients were the highest, such as during the peak of the growing season in July and August. As this correlation was poorly defined and could not always be found, the seepage rate was assumed to be constant from the first of June until the potholes froze in the fall.

An average seepage was computed for each vegetated pothole as the average of the individual Y-intercepts. A new value for N could then be computed as shown in the following table for pothole 1 in 1963.

Rating period	*Y-intercept (seepage in ft per day)*
A	---------
B	---------
C	0.0057
D_9	.0047
D_{10}	.0010
E	.0120
	4 | .0234
	.0058 (avg)

N *recomputed using the average seepage of 0.0058*

Rating period	$\overline{Y}$	Average seepage				$\overline{X}$		Adjusted *N*
A	0.0128	−0	=	0.0128	÷	63.75	=	0.000201
B	.0175	−0	=	.0175	÷	67.19	=	.000260
C	.0190	−.0058	=	.0132	÷	58.00	=	.000228
D_9	.0197	−.0058	=	.0139	÷	47.62	=	.000292
D_{10}	.0207	−.0058	=	.0149	÷	60.75	=	.000245
E	.0273	−.0058	=	.0215	÷	66.33	=	.000324

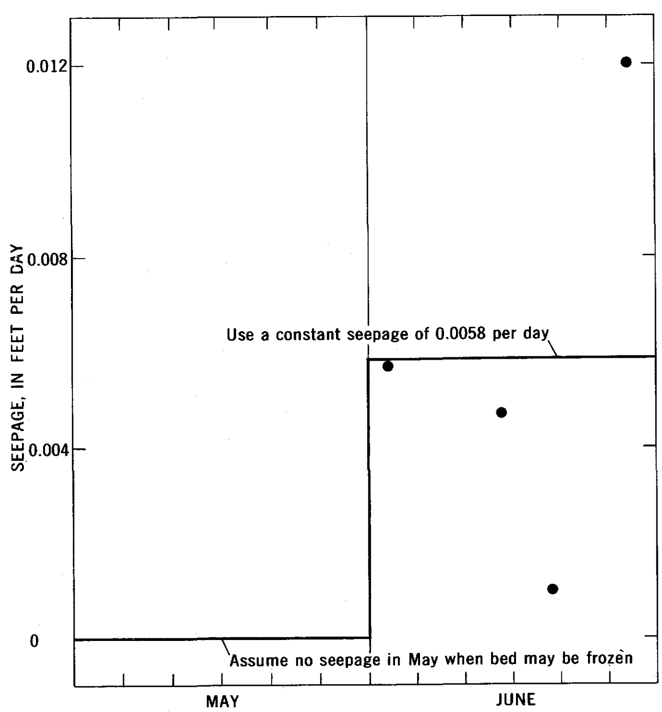


FIGURE 39.—Seepage outflow from pothole 1.

This computation was checked graphically by replacing the least-squares line with a line drawn from the average Y-intercept through the means of the plotted points, as shown in figure 40.

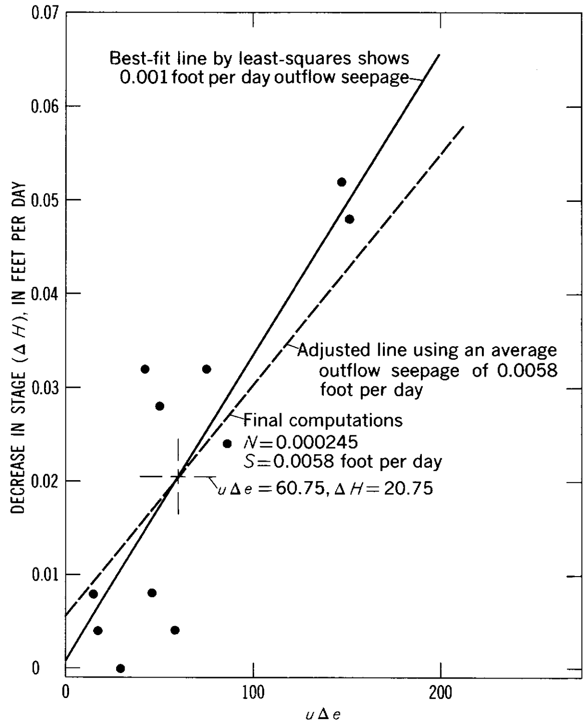


FIGURE 40.—Least-squares line showing intercept on Y-axis.

The mass-transfer coefficients for the vegetated potholes were plotted with respect to time. Figure 41*A* shows the data that result from the sample computations illustrated in figures 36–40. As this *N* curve is not complete for the season, a complete curve is illustrated in figure 41*B*. This curve usually showed an increase in evapotranspiration from the middle of May to the end of July and a decrease from late August until some time in October when it became constant. *N* values for the vegetated potholes were picked from this curve at the middle of each computation period.

For clear potholes, the *N* coefficient is constant as illustrated by the well-defined line in figure 42. This figure is comparable to figure 40, except that the *N* determination is for 2 years instead of 3 days.

As stated previously, after *N* is determined, the evapotranspiration, *ET*, can be computed for any period, regardless of the meteorologic conditions. Because the pothole instruments were serviced each week, the time lapse between these weekly inspections made a convenient computation period and was used in this study.

The computation procedure is illustrated in table 4, which is the computation sheet for pothole 1, near Douglas, for 1963. Footnotes to the table give a brief explanation of how the value in each column was obtained.

Most of the potholes lost water at about the same rate as long as the water depth was 0.5 foot or greater,

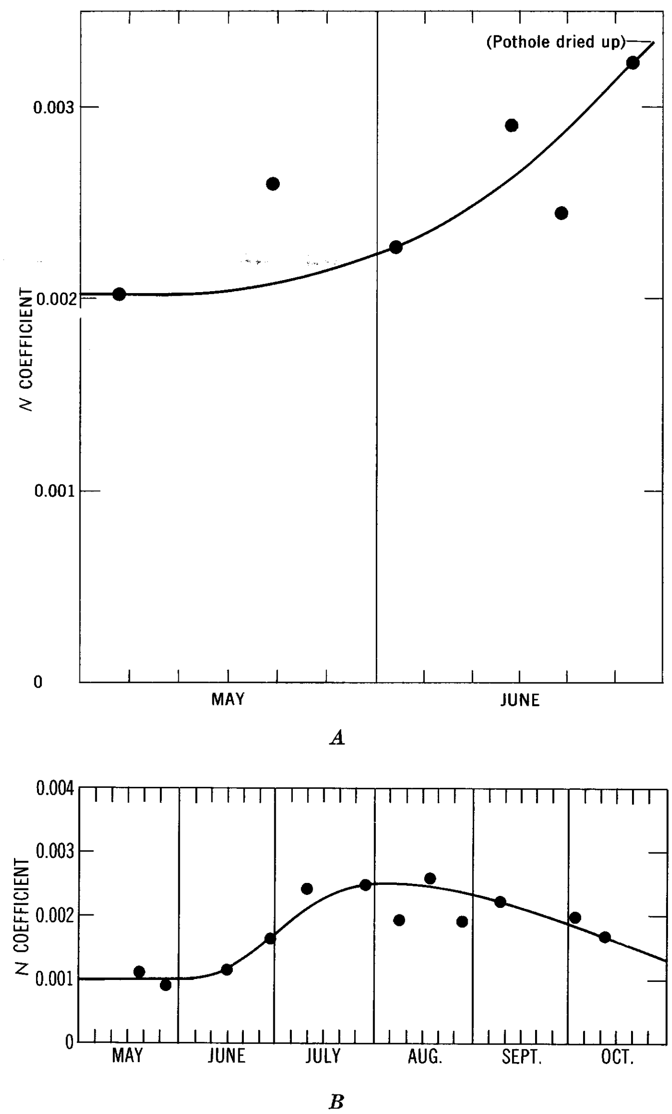


FIGURE 41.—*A*, Variation of the *N* coefficient with time for a vegetated pothole. *B*, Another example of how the *N* coefficient varies with time for a vegetated pothole.

but as soon as the water became less than 0.5 foot deep, the losses became very erratic. On hot days, the losses became extremely high, and on cool days relatively low. The rate of water loss was so variable that it was impossible to compute a mass-transfer coefficient or the amount of evapotranspiration during the shallow-water periods.

Several reasons why the potholes behaved this way as they began to dry up may be:

1. The shallow water would heat up faster and become warmer than the deeper water.
2. Submerged plants such as mosses, watermilfoil, and pondweed formed a mat on the water surface as the pond dried up. These areas absorbed the direct rays from the sun and became lukewarm—perhaps

TABLE 4.—*Evapotranspiration computation sheet for May and June 1963 for pothole 1 near Douglas*

Computation period: From Day	From Hour	To Day	To Hour	Length (days)	Wind: End of period reading (miles)	Wind: Increment (miles)	Wind: u (mph)	Sum of unit averages: e_0 (mb)	Sum of unit averages: e_a (mb)	Sum of unit averages: Difference Δe	Period average e	$u\Delta e$	N / 0.000	$Nu\Delta e$ (ft per day)	ET mass-transfer (ft)	GH end of period (ft)	ΔH (ft)	Precipitation and runoff (ft)	Ground-water level (ft)	Seepage outflow: Feet per day	Seepage outflow: Feet	ET water budget (ft)	Average water surface (acres)	Monthly ET: Feet	Monthly ET: Acre-feet
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
		Mar. 13	1250	------	------	------	------	------	------	------	------	------	------	------	------	1.83	------	------	------	------	------	------	------	------	------
Mar. 13	1250	21	1830	8.24	------	------	------	------	------	------	------	------	------	------	------	2.06	−0.23	------	Dry	------	------	------	------	------	------
21	1830	27	1210	5.74	------	------	------	------	------	------	------	------	------	------	------	2.14	−.08	------	Dry	------	------	------	------	------	------
27	1210	31	2400	4.49	------	------	------	------	------	------	------	------	------	------	------	2.07	.07	------	Dry	------	------	------	------	------	------
Apr. 1	0000	Apr. 8	1340	7.57	0000	------	------	------	------	------	------	------	------	------	------	2.30	−.23	------	Dry	------	------	------	------	------	------
8	1340	15	1315	6.98	1020	1020	6.09	322.9	181.5	141.4	5.07	30.88	------	------	------	2.28	.02	------	−1.25	------	------	------	------	------	------
15	1315	22	1215	6.96	2491	1471	8.80	395.6	144.7	150.9	5.41	47.61	------	------	------	2.24	.04	0.06	1.35	------	------	------	------	------	------
22	1215	29	1345	7.06	3799	1308	7.72	347.7	202.4	145.3	4.14	39.68	------	------	------	2.31	−.07	.14	3.40	------	------	------	------	------	------
29	1345	30	2400	1.43	------	391	11.39	61.6	28.4	33.2	5.81	66.18	------	------	------	2.30	.01	------	3.65	------	------	------	------	------	------
May 1	0000	May 6	1400	5.58	5409	1219	9.10	294.2	156.0	138.2	6.19	56.33	201	0.0113	0.063	2.22	.08	.01	4.63	0	0	0.09	------	------	------
6	1400	13	1300	6.96	6797	1388	8.31	360.8	251.1	109.7	3.94	32.74	203	.0066	.046	2.49	−.27	.36	6.50	0	0	.09	------	------	------
13	1300	20	1345	7.03	8347	1550	9.19	477.5	233.9	243.6	8.66	79.59	205	.0163	.115	2.42	.07	.06	5.56	0	0	.13	------	------	------
20	1345	27	1300	6.97	{9684 / 3322}	1337	7.99	442.4	218.2	224.2	8.04	61.24	212	.0136	.095	2.29	.13	------	4.60	0	0	.13	------	------	------
27	1300	31	2400	4.46	------	646	6.04	395.6	208.0	187.6	10.52	63.51	220	.0140	.062	2.25	.04	.04	4.49	0	0	.08	7.91	0.42	3.32
June 1	0000	June 3	1245	2.53	4326	358	5.90	234.0	164.4	69.6	6.86	40.47	227	.0092	.023	2.24	.01	.03	4.41	.0058	.015	.02	------	------	------
3	1245	10	1300	7.01	5646	1320	7.85	676.9	417.8	259.1	9.24	72.53	238	.0173	.121	2.40	−.16	.25	5.79	.0058	.041	.05	------	------	------
10	1300	17	1215	6.97	6588	942	5.63	590.8	337.6	253.2	9.08	51.12	261	.0133	.093	2.26	.14	------	4.25	.0058	.040	.10	------	------	------
17	1215	24	1255	7.03	7773	1185	7.02	610.2	405 4	204.8	7.28	51.11	292	.0149	.105	2.17	.09	.06	3.47	.0058	.041	.11	------	------	------
24	1255	30	2400	6.46	------	1127	7.27	651.0	429.2	221.8	8.58	62.38	323	.0201	.130	2.05	.12	.06	2.80	.0058	.037	.14	7.55	.47	3.62
July 1	0000	July 1	1240	.53	9019	119	9.36	43.1	30.9	12.2	5.75	53.82	------	------	------	2.03	.02	------	2.75	------	------	------	------	------	------
1	1240	8	1400	7.06	9840	821	4.85	------	------	------	------	------	------	------	------	1.85	.18	------	2.98	------	------	------	------	------	------
8	1400	15	1245	6.94	970	1130	6.78	778.1	470.1	308.0	11.08	75.12	------	------	------	1.73	.12	.05	1.30	------	------	------	------	------	------
15	1245	22	1615	7.15	1793	823	4.80	------	------	------	------	------	------	------	------	Dry	------	------	.52	------	------	------	------	------	------
22	1615	29	1830	7.09	2725	932	5.48	------	------	------	------	------	------	------	------	1.82	------	.21	.04	------	------	------	------	------	------
29	1830	31	2400	2.23	------	211	3.94	354.2	143.5	67.2	7.53	29.67	------	------	------	1.82	0	.03	0	------	------	------	------	------	------
Aug. 1	0000	Aug. 5	1415	4 59	3596	660	5.99	406.0	279.1	126.9	6.90	41.33	------	------	------	1.86	−.04	.14	−.08	------	------	------	------	------	------
5	1415	12	1230	6.93	4497	901	5.42	712.8	484.5	228.3	8.24	44.66	------	------	------	1.76	.10	.05	−.43	------	------	------	------	------	------
12	1230	19	1315	7.03	5434	937	5.55	------	------	------	------	------	------	------	------	1.38	.38	------	−.73	------	------	------	------	------	------
19	1315	26	1315	7.00	6295	861	5.12	------	------	------	------	------	------	------	------	Dry	------	.10	−.83	------	------	------	------	------	------
26	1315	31	2400	5.45	------	523	4.00	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------

COLUMN EXPLANATIONS

1. Beginning date—month and day.
2. Beginning hour of day to nearest 5 minutes—international time.
3. Ending date—month and day. This is also the beginning of the next period.
4. Ending hour of day to nearest 5 minutes—international time. The computation periods are from inspection to inspection of the pothole stage record on the A35 Stevens recorder chart. Since inspections were usually made on the same day of each week, the computation periods are approximately one week in length. A break was necessary at the end of each month causing a few periods to be quite short.
5. The difference between ending and beginning time, converted to days.
6. Anemometer dial readings made by the hydrographer at very nearly the same time as the inspection of the A35 recorder. Two sets of figures for the same date indicate a change of instrument.
7. The difference between the ending and beginning anemometer readings or total miles of wind movement passing over the pothole during the period. The wind pips (1 pip for every 10 miles of wind movement) on the A35 recorder chart are counted and checked against this difference. The pips also have to be counted to get values for the rating periods and for the short periods at the end and beginning of each month.
8. Column 7 divided by (col. 5×24 hr) to obtain the average wind speed during the period.
9. The sum of unit averages of the saturation vapor pressure, e_0, corresponding to the water surface temperature.
10. The sum of unit averages of the vapor pressure of the air, e_a.
11. Column 10 subtracted from column 9 gives the difference in the sums of the unit averages for the computation period.
12. Column 11 is divided by the number of 6-hour units in the computation period to obtain the average vapor pressure difference during the period. The vapor pressure difference is sometimes referred to as "the drying power of the air."
13. Column 8 multiplied by column 12. This figure gives the value of the meteorological factors that affect evapotranspiration during the period.
14. Obtain from N curve for a vegetated pothole or from least-squares determination for a clear pothole.
15. Column 14 multiplied by column 13. This is the average rate of evapotranspiration per day during the period.
16. Column 5 multiplied by column 15. This is the total evapotranspiration during the period.
17. Gage reading at time of the A35 recorder inspection and the reading from the chart for the end of the month, as shown in figure 36.
18. Decrease in stage during the period, derived from column 17.
19. Precipitation and runoff. Precipitation is computed by counting the jogs of the tipping-bucket rain gage for each day on recorder chart and converting inches to feet. Runoff is the difference between the total rise in gage height as shown on the recorder chart and the total precipitation on any particular day, with a small allowance for evapotranspiration and seepage when appropriate.
20. Ground-water level, in feet, measured at end of period at a nearby observation well using same datum as for pothole stage gage.
21. Average of Y-intercepts from the N-curve determination. No seepage was used during May because many times the hydrographer would note that he was walking on frozen ground in the pothole during May even though there may have been a foot or two of water and half a foot of muck on top of the frost layer. It was assumed there would be no seepage as long as the pothole bed was frozen. As the time of thawing was indeterminate, it was set arbitrarily at May 31.
22. Column 5 multiplied by column 21. This gives seepage outflow for the period.
23. Column 18 plus column 19 minus column 22. This is the water budget. If the pothole was receiving runoff unassociated with precipitation or was overflowing, the computations for the period were not made.
24. Add gage heights available in column 17 for any particular month and divide by number of readings to obtain a rough average gage height for the month. Enter area table and find area corresponding to the gage height for the month.
25. Sum of the evapotranspiration, ET, for each of the computation periods during the month using figures shown in columns 16 and 23. If there had been precipitation or runoff during the period, column 16 was used, but if there had been none, column 23 was used.
26. Column 24 multiplied by column 25 gives the quantity of water lost by evapotranspiration during the month from the pothole.

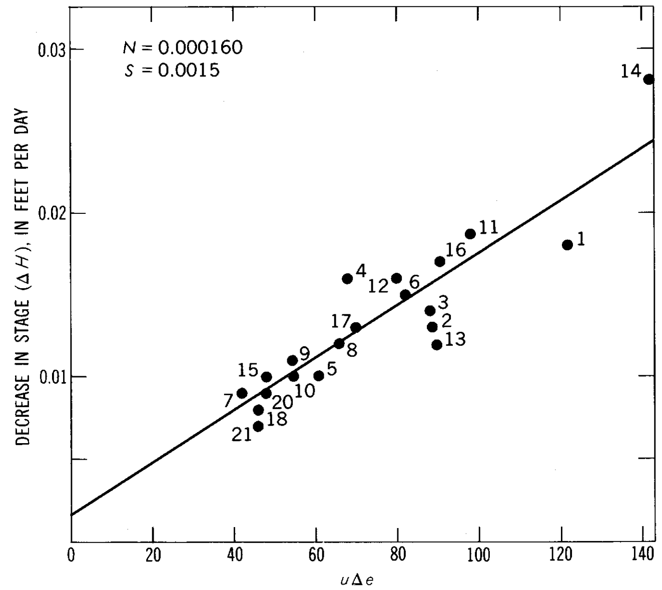


FIGURE 42.—*N* coefficient remaining constant for a clear pothole.

10°–15°F warmer than the surface of clear, deep water.

3. The root systems of some of the plants protruded above the water surface in the form of hummocks when the water in the pothole became low. This reduced the apparent water surface area and water volume even though the plants were still demanding water as before.

Some of the vegetated potholes in Ward County dried up during the summers of 1961 and 1962. Because the gage well was set about 3 feet into the pothole bed, the recorder continued to give a gage-height record showing a diurnal fluctuation (fig. 43) even though the water had receded from around the well. Therefore, because the record probably reflected water-table elevations at the root zone of the surrounding vegetation, the fluctuation may have been caused by the variation in evapotranspiration demand during the day.

SEEPAGE

In comparing the water losses from clear potholes with those from vegetated potholes, the computations showed that the evaporation was about 11 percent greater from a clear pothole than the evapotranspiration from a vegetated pothole. However, seepage losses were only about one-third as great from a clear pothole, so the total water loss was actually about 14 percent less from a clear pothole than from a vegetated pothole.

Why the seepage losses are less from a clear pothole is not known. Possibly the roots in a vegetated pothole cause the bottom to be more permeable, or perhaps the chemistry of the water may be a factor.

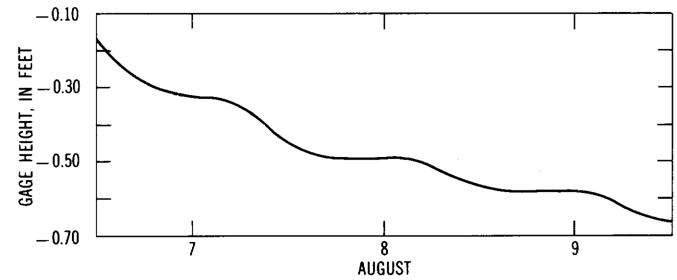


FIGURE 43.—Diurnal fluctuation of water level in gage well as pothole 2 dried up in 1962.

An average net seepage outflow, in feet per day, was determined for each pothole for June to October of each year when the data were adequate. The values were obtained by averaging the Y-intercepts from the least-squares calculations for all rating periods for each pothole, and they are given in the following table.

Year	Pothole				
	1	2	[1] 3	4	[1] C-1
1960	0.0089	0.0053	0.0035	0.0031	----------
1961	----------	.0105	.0035	----------	----------
1962	.0070	.0065	.0035	.0091	----------
1963	.0058	.0036	.0035	.0083	0.0015
1964	.0086	.0056	.0035	.0090	.0015
Average	.0076	.0063	.0035	.0074	.0015

Year	Pothole				
	[1] 5	5A	6	7	8
1960	----------	----------	----------	----------	----------
1961	0.0008	----------	0.0072	----------	----------
1962	.0008	----------	.0045	0.0041	0.0023
1963	.0008	0.0094	.0040	----------	.0032
1964	.0008	.0081	.0055	.0029	.0045
Average	.0008	.0088	.0053	.0035	.0033

[1] Clear pothole.

Even though the soil has a very low permeability, certain hydrologic relationships probably exist. Attempts were made to graphically correlate (Ezekial, 1950, p. 479–485) outflow seepage with the pothole water-surface level, ground-water level, their difference, and water temperature, but no correlation was found.

An attempt was also made to evaluate the seepage during the winter when other factors in the water budget are zero or very small, but it was unsuccessful except for a rough determination. Evapotranspiration should be negligible in winter, so that theoretically, if periods were selected when there was no precipitation or runoff, the decrease in stage should be equal to the seepage. However, the precipitation presented a problem. Small amounts of snow falling on the pond would immediately cause an increase in gage height. Blowing and drifting snow also caused changes at times other than when it was snowing, so that what was causing the changes in stage was doubtful.

The problem was further complicated because some of the water went into ice storage, and this ice was supported by the ground at the shoreline and, therefore, was not reflected in the gage height. Frost heave at the shoreline of the smaller potholes could also become a complicating factor when trying to detect minute changes in height.

RUNOFF

Most prairie potholes are good collectors of snow. Large drifts often accumulate in and near the potholes because of their depressed position, the rough terrain surrounding them, the roughness due to aquatic plants, and brush that often grows nearby. Large snow drifts also occur on the leeward side of hills, and these may produce appreciable runoff if the melting is rather sudden and the ground is still frozen.

Normally 75 percent of the annual precipitation occurs during the 6-month period May–October. The precipitation (particularly snow) during the remaining 6-month period is very important, however. Even though this is only 25 percent of the annual precipitation, it produced 30 percent of the water reaching the potholes during the period of this investigation, and in some years, at certain potholes, it exceeded 50 percent.

Some observers believe that spring snowmelt generally contributes more water to potholes than do summer rains, and this would be true if direct precipitation on the pothole pond surface were not considered. However, this study has indicated that direct precipitation on the pond surface is normally the largest single factor in maintaining the water level in a pothole; it supplied about one-half of the water received by the potholes during the study.

Of 30 station years of records for the period 1960–64, there were only 5 station years when the water received as a result of the snowmelt in the spring exceeded the direct rainfall and runoff during the following summer. Curiously, the winters of 1959–60 and 1961–62, which were below normal for precipitation, and the summers that followed, which were normal or above, contained 4 of the 5 records that showed snowmelt producing more than 50 percent of the water received for that year.

This occurs when winters are continuously cold so that the snow accumulates until spring and then melts and runs off quickly while the ground is still frozen. In 1960, February and March temperatures averaged 4.5°F below normal, and in 1962, these months averaged 3.3°F below normal; in neither year did the snow begin to melt until March 25—a week or two later than normal.

Records for pothole 3, near Max, were analyzed to determine the average annual rate of runoff from the land surface of the drainage basin into the pothole. Pothole 3 has a drainage area of 340.3 acres. About one-half of the basin is ordinarily noncontributing, as it was during this study, owing to a 3-foot depression near the east side. (See fig. 18.) Most of the basin is rolling grassland, and only a small portion near the north end is under cultivation. Pothole 3 is a clear one—free of emerged aquatic vegetation, except for a small ring of rushes at the shoreline. This study was conducted during the relatively dry period from 1960–64. The pothole dried up during the last month of data collection in October 1964, but it had not been dry for about 25 years previously. Because the records were continuous during the 5-year study period, except for the last month, and because there was no spilling into or from other potholes, pothole 3 was the only pothole being studied that was suitable for this type of analysis.

Runoff from the drainage basin into the pothole came from two sources: (1) snowmelt in the spring while the ground was still frozen, and (2) rainfall excess from intense summer storms. Measurements showed that the snow depths on pothole 3 did not differ greatly from the depths that the U.S. Weather Bureau reported to be on the ground in this area. Nearly equal distribution of snow on pond and land can be expected at a large clear pothole, but at a small vegetated pothole the snow depth might be several times greater than on the surrounding land, owing to the roughness of the pothole's surface. However, the writer concludes that this uneven distribution of snow on pond and land would be insignificant at pothole 3 if the small area of the pothole were considered in relation to the total drainage area, as the ratio of water to land is about 1:10.

The computations showed that the average runoff from the drainage basin into pothole 3 (excluding the pond) was about 1.2 inches per year during the period 1960–64. Of this amount, 1.0 inches was from snowmelt in the spring and 0.2 inch was from rainfall excess during the summer. The following table shows the seasonal variation of inflow that provided the basis for determining the average annual runoff into pothole 3 during the study period.

	Sources of inflow to pothole 3 (acre-ft)	
Year:	*Snowmelt*	*Rainfall*
1960	48. 25	1. 38
1961	6. 26	4. 34
1962	42. 47	3. 92
1963	10. 60	9. 34
1964	14. 51	9. 16
Average annual runoff, in inches	1. 0	. 2

The inflow was determined volumetrically from the rise in pond stage. The observed snowmelt volumes were reduced about 10 percent on an areal basis to exclude the snow estimated to have accumulated directly on the pond. The rainfall-excess volumes were determined from the difference between the amount of rainfall measured and the rise in pond stage immediately after each occurrence of precipitation.

On March 13, 1963, a snow survey was made of a small 2.53-acre closed basin near Buchanan to determine what percentage of the snowmelt in the basin entered the pothole. As the ground had been bare and frozen before a snow storm occurred on March 12, and as no additional precipitation occurred until after this snow had melted, it was assumed that any inflow into the pothole would be a result of the March 12 storm.

The average water equivalent of the snow cover on the basin at the time of the survey on March 13 was found to be 0.036 foot, and the volume of water 0.036 foot x 2.53 acres, or 0.091 acre-foot. The pond level increased during the melting period that followed so that by March 25 the pond was 0.5 foot higher and frozen solid. By using an average pond area of 0.15 acre, the volume of water added to the pond was computed as 0.07 acre-foot. Thus, the survey showed that of the 0.091 acre-foot of water on the basin, 0.07 acre-foot, or 78 percent, found its way into the pothole.

In general, on the basis of records for all potholes for all years during the study period (1960–64), a pothole receives its annual water supply from the following sources:

	Feet
Snowmelt—directly on pothole and as runoff from land surface in drainage basin	0.79
Rainfall—direct on pothole	1.21
Rainfall—runoff from land surface in drainage basin	.53
Average annual depth of water received in pothole	2.53

Even though the 0.79 foot of water per year from snowmelt was only 31 percent of the total depth received, it was probably the most vital part of the annual water supply. This water was available in the spring when the plants were beginning to grow and waterfowl were nesting, and this amount of water was sufficient to last until about July 1 even with no additional direct rainfall on the pond or runoff from the land surface in the drainage basin.

SUMMARY OF DATA

The basic data collected at each pothole for the months of May to October 1960–64, are listed in table 5. May to October are the ice-free months, and the use of these months conforms to U.S. Weather Bureau practice for determining evaporation, as shown by Kohler, Nordenson, and Baker (1959, pl. 4). Precipitation is the direct precipitation on the pothole, and runoff is that from the land surface only, with the pothole excluded. Evapotranspiration is the result of the mass-transfer computations. The term "evapotranspiration" has been used for both clear and vegetated potholes. This is considered appropriate since even the clear potholes support a limited amount of vegetation around the edges, and some transpiration probably occurs from this source. Seepage was computed by using the average of the Y-intercepts from the least-square computations. The seepage is net outflow seepage, although there are times when both inflow and outflow seepage may be taking place at the same time.

TABLE 5.—*Monthly water gains and losses, in feet, from prairie potholes, May to October 1960–64*

Month	Precipitation	Runoff	Evapotranspiration	Seepage outflow	Observed decrease in water level	Residual error
Pothole 1						
1960						
May	0.17	0.02	0.37	0	0.24	-----
June	.14	0	.30	.28	.46	-----
July	.10	0	.49	.28	.65	-----
Aug	.23	.03	.45	.28	.39	-----
Sept	.01	0	.26	.28	.49	-----
Oct	.01	0	.13	.28	.33	-----
Total	.66	.05	2.00	1.40	2.56	0.13
1961 [1]						
1962						
May	.39	.14	.27	0	−.21	-----
June	.34	.26	.36	.22	−.07	-----
July	.16	.12	.36	.22	.31	-----
Total	.89	.52	.99	.44	.03	−.01
1963						
May	.27	.21	.42	0	.05	-----
June	.26	.14	.47	.18	.20	-----
Total	.53	.35	.89	.18	.25	−.06
1964						
May	.21	.35	.41	0	.24	-----
June	.53	.66	.28	.27	−.71	-----
July	.05	0	.50	.27	.71	-----
Total	.79	1.01	1.19	.54	.24	−.31
Pothole 2						
1960						
Sept	0.03	0	0.31	0.17	0.42	-----
Oct	.02	0	.13	.17	.22	-----
Total	.05	0	.44	.34	.64	0.09
1961						
May	.18	.04	.37	0	.21	-----
June	.04	0	.37	.32	.65	-----
Total	.22	.04	.74	.32	.86	−.06
1962						
May	.38	.14	.28	0	−.28	-----
June	.28	0	.37	.20	.16	-----
July	.20	.02	.44	.20	.36	-----
Aug	.23	.06	.50	.20	.51	-----
Total	1.09	.22	1.59	.60	.75	.13
1963						
May	.20	.01	.38	0	−.02	-----
June	.40	.16	.47	.11	−.15	-----
July	.34	.19	.69	.11	.15	-----
Aug	.16	.02	.47	.11	.37	-----
Total	1.10	.38	2.01	.33	.35	.51
1964						
May	.23	.31	.33	0	−.05	-----
June	.47	.24	.23	.17	−.27	-----
July	.04	0	.49	.17	.60	-----
Total	.74	.55	1.05	.34	.28	−.18

See footnotes at end of table.

TABLE 5.—*Monthly water gains and losses, in feet, from prairie potholes, May to October 1960–64*—Continued

Month	Precipitation	Runoff	Evapotranspiration	Seepage outflow	Observed decrease in water level	Residual error
Pothole 3						
1960						
May	0.21	0.01	0.37	0	0.18	-----
June	.18	0	.50	.11	.34	-----
July	.11	0	.51	.11	.51	-----
Aug	.30	.03	.43	.11	.18	-----
Sept	.03	0	.35	.11	.39	-----
Oct	0	0	.15	.11	.25	-----
Total	.83	.04	2.31	.55	1.85	0.14
1961						
May	.21	.05	.42	0	.22	-----
June	.07	.01	.51	.11	.61	-----
July	.11	.02	.41	.11	.48	-----
Aug	0	0	.59	.11	.68	-----
Sept	.26	.07	.25	.11	-.04	-----
Oct	0	0	.15	.11	.25	-----
Total	.65	.15	2.33	.55	2.20	-.12
1962						
May	.40	.09	.24	0	-.09	-----
June	.27	0	.34	.11	.21	-----
July	.16	.01	.36	.11	.32	-----
Aug	.29	.03	.47	.11	.22	-----
Sept	.01	0	.28	.11	.36	-----
Oct	.14	0	.15	.11	.04	-----
Total	1.27	.13	1.84	.55	1.06	-.07
1963						
May	.24	.03	.32	0	.15	-----
June	.40	.13	.49	.11	-.08	-----
July	.32	.11	.49	.11	.17	-----
Aug	.27	.05	.37	.11	.13	-----
Sept	.11	.02	.31	.11	.23	-----
Oct	.03	0	.24	.11	.29	-----
Total	1.37	.34	2.22	.55	.89	.17
1964						
May	.20	.13	.51	0	.35	-----
June	.49	.16	.35	.11	-.27	-----
July	.05	0	.55	.11	.60	-----
Aug	.37	.08	.48	.11	.18	-----
Sept	.12	.02	.26	.11	.21	-----
Total	1.23	.39	2.15	.44	1.07	-.10
Pothole 4						
1960						
Sept	0.02	0	0.31	0.10	0.39	-----
Oct	.01	0	.15	.10	.22	-----
Total	.03	0	.46	.20	.61	0.02
1961 [1]						
1962						
May	.47	.07	.23	0	-.29	-----
June	.27	.03	.30	.28	.18	-----
July	.24	.01	.43	.28	.39	-----
Total	.98	.11	.96	.56	.28	.15
1963						
May	.30	.11	.21	0	-.16	-----
June	.30	.07	.31	.26	.04	-----
Total	.60	.18	.52	.26	-.12	.12
1964						
May	.22	.14	.32	0	.05	-----
June	.50	.24	.21	.28	-.42	-----
July	.06	0	.44	.28	.63	-----
Total	.78	.38	.97	.56	.26	.11
Pothole C-1						
1963						
May	0.09	0.01	0.31	0	0.20	-----
June	.17	.04	.47	.05	.28	-----
July	.20	.03	.46	.05	.33	-----
Aug	.23	.03	.49	.05	.21	-----
Sept	.14	.02	.29	.05	.17	-----
Oct	.02	0	.24	.05	.24	-----
Total	.85	.13	2.26	.25	1.43	0.10
1964						
May	.17	.11	.52	0	.24	-----
June	.78	2.18	.38	.05	-2.39	-----
July	.27	0	.43	.05	.25	-----
Aug	.19	.01	.42	.05	.26	-----
Sept	.05	.04	.29	.05	.22	-----
Oct	.02	0	.18	.05	.21	-----
Total	1.48	2.34	2.22	.25	-1.21	-.14
Pothole 5						
1961						
May	0.22	0.09	0.42	0	0.13	-----
June	.25	.02	.51	.02	.31	-----
July	.15	0	.44	.02	.43	-----
Aug	.32	.04	.55	.02	.23	-----
Sept	.33	.06	.30	.02	-.02	-----
Oct	.04	0	.20	.02	.19	-----
Total	1.31	.21	2.42	.10	1.27	-0.27
1962						
May	.40	.10	.28	0	-.14	-----
June	.44	.16	.38	.02	-.18	-----
July	.45	.31	.40	.02	-.31	-----
Aug	.14	0	.57	.02	.50	-----
Sept	.23	.04	.32	.02	.07	-----
Oct	.05	.02	.19	.02	.16	-----
Total	1.71	.63	2.14	.10	.10	-.20
1963						
May	.15	.03	.44	0	.18	-----
June	.20	.07	.48	.02	.20	-----
July	.36	.07	.55	.02	.17	-----
Aug	.36	.04	.51	.02	.15	-----
Sept	.21	.10	.35	.02	.07	-----
Oct	.11	.07	.28	.02	.14	-----
Total	1.39	.38	2.61	.10	.91	.03
1964						
May	.37	.67	.46	0	-.51	-----
June	.53	.77	.42	.02	-.90	-----
July	.38	.42	.49	.02	-.26	-----
Aug	.24	.04	.43	.02	.21	-----
Sept	.12	0	.27	.02	.23	-----
Oct	0	0	.23	.02	.26	-----
Total	1.64	1.90	2.30	.10	-.97	-.17
Pothole 5A						
1963						
Aug	0.36	0.31	0.53	0.29	0.09	-----
Sept	.22	.26	.25	.29	.01	-----
Oct	.11	.22	.14	.29	.03	-----
Total	.69	.79	.92	.87	.13	0.18
1964						
May [2]						
June [2]						
July [2]						
Aug	.24	.17	.48	.25	.28	-----
Sept	.12	.07	.23	.25	.28	-----
Oct	0	0	.12	.25	.38	-----
Total	.36	.24	.83	.75	.94	.04

See footnotes at end of table.

TABLE 5.—*Monthly water gains and losses, in feet, from prairie potholes, May to October 1960–64*—Continued

Month	Precipitation	Runoff	Evapotranspiration	Seepage outflow	Observed decrease in water level	Residual error
Pothole 6						
1961						
May	0.17	0.04	0.31	0	0.12	-----
June	.29	0	.39	.22	.25	-----
July	.10	0	.41	.22	.50	-----
Aug	.19	0	.47	.22	.48	-----
Sept	.34	.06	.18	.22	0	-----
Oct	.04	0	.04	.22	.21	-----
Total	1.13	.10	1.80	1.10	1.56	0.11
1962						
May	.32	0	.30	0	−.09	-----
June	.45	.01	.31	.14	−.09	-----
July	.40	.54	.42	.14	−.63	-----
Aug	.15	0	.49	.14	.47	-----
Sept	.24	.01	.28	.14	.10	-----
Oct	.03	0	.09	.14	.17	-----
Total	1.59	.56	1.89	.70	−.07	.51
1963						
May	.13	.03	.29	0	.12	-----
June	.23	0	.36	.12	.22	-----
July	.38	.02	.45	.12	.16	-----
Aug	.35	0	.44	.12	.17	-----
Sept	.14	.06	.28	.12	.16	-----
Oct	.09	.06	.14	.12	.11	-----
Total	1.32	.17	1.96	.60	.94	.13
1964						
May	.36	.60	.38	0	−.57	-----
June [3]	------	----	------	----	------	-----
July [3]	------	----	------	----	------	-----
Aug	.26	.03	.43	.17	.24	-----
Sept	.12	0	.22	.17	.29	-----
Oct	0	0	.11	.17	.29	-----
Total	.74	.63	1.14	.51	.25	.03
Pothole 7						
1961 [1]						
1962						
May	0.37	0.11	0.24	0	−0.23	-----
June	.51	.24	.40	.13	−.36	-----
July	.53	.62	.34	.13	−.80	-----
Aug	.12	.01	.60	.13	.50	-----
Sept	.24	.03	.27	.13	.09	-----
Oct	.04	.03	.07	.13	.13	-----
Total	1.81	1.04	1.92	.65	−.67	0.39
1963 [2]						
1964						
May	.36	.60	.40	0	−.51	-----
June	.68	.83	.44	.09	−1.11	-----
July	.49	.81	.53	.09	−.81	-----
Aug	.21	.02	.49	.09	.24	-----
Sept	.10	.01	.27	.09	.23	-----
Oct	0	0	.19	.09	.28	-----
Total	1.84	2.27	2.32	.45	−1.68	.34
Pothole 8						
1961 [1]						
1962						
May	0.39	0.06	0.26	0	−0.15	-----
June	.53	.10	.33	.07	−.23	-----
July	.55	.71	.38	.07	−.79	-----
Aug	.14	.01	.55	.07	.40	-----
Sept	.23	.02	.29	.07	.08	-----
Oct	.05	0	.10	.07	.12	-----
Total	1.89	.90	1.91	.35	−.57	0.04
Pothole 8—Continued						
1963						
May	0.15	0.03	0.31	0	0.07	-----
June	.21	.03	.36	.10	.19	-----
July	.41	.05	.41	.10	.08	-----
Aug	.30	.06	.44	.10	.14	-----
Sept	.24	.06	.22	.10	.01	-----
Oct	.13	.04	.12	.10	.05	-----
Total	1.44	.27	1.86	.50	.54	.11
1964						
May	.38	.67	.36	0	−.60	-----
June	.69	.41	.43	.14	−.66	-----
July	.44	.78	.42	.14	−.75	-----
Aug	.31	.10	.37	.14	.05	-----
Sept	.11	.01	.22	.14	.22	-----
Oct	0	0	.11	.14	.25	-----
Total	1.93	1.97	1.91	.70	−1.49	.20

See footnotes at end of table.

[1] Pothole dry.
[2] Faulty record.
[3] Streamflow into and from pothole.

The observed decrease in pond level during the month was determined from the stage gage. The residual error was determined by subtracting the observed decrease in the water level from the value computed according to the water-budget equation (p. B35).

The monthly evapotranspiration and seepage losses during the study period are shown graphically in figure 44 for each pothole. In general, this graph shows that the water losses were the greatest during July and August each year. Figure 45 shows the average monthly water loss and water gain for all potholes for the entire period of study. This graph shows that the potholes lost more water during the summer than they received. Consequently, many of them became dry during the summer and fall of each year unless there was an adequate supply in storage at the beginning of the season.

CONCLUSIONS

The purpose of this investigation was to obtain a better understanding of the hydrology of the prairie-pothole region with particular emphasis on evapotranspiration.

Direct summer precipitation on the pothole and spring runoff from snowmelt from the land surface were the major sources of water for the potholes. The average contributions to the annual water supply of a pothole with regard to the originating form as rain or snow are summarized as follows:

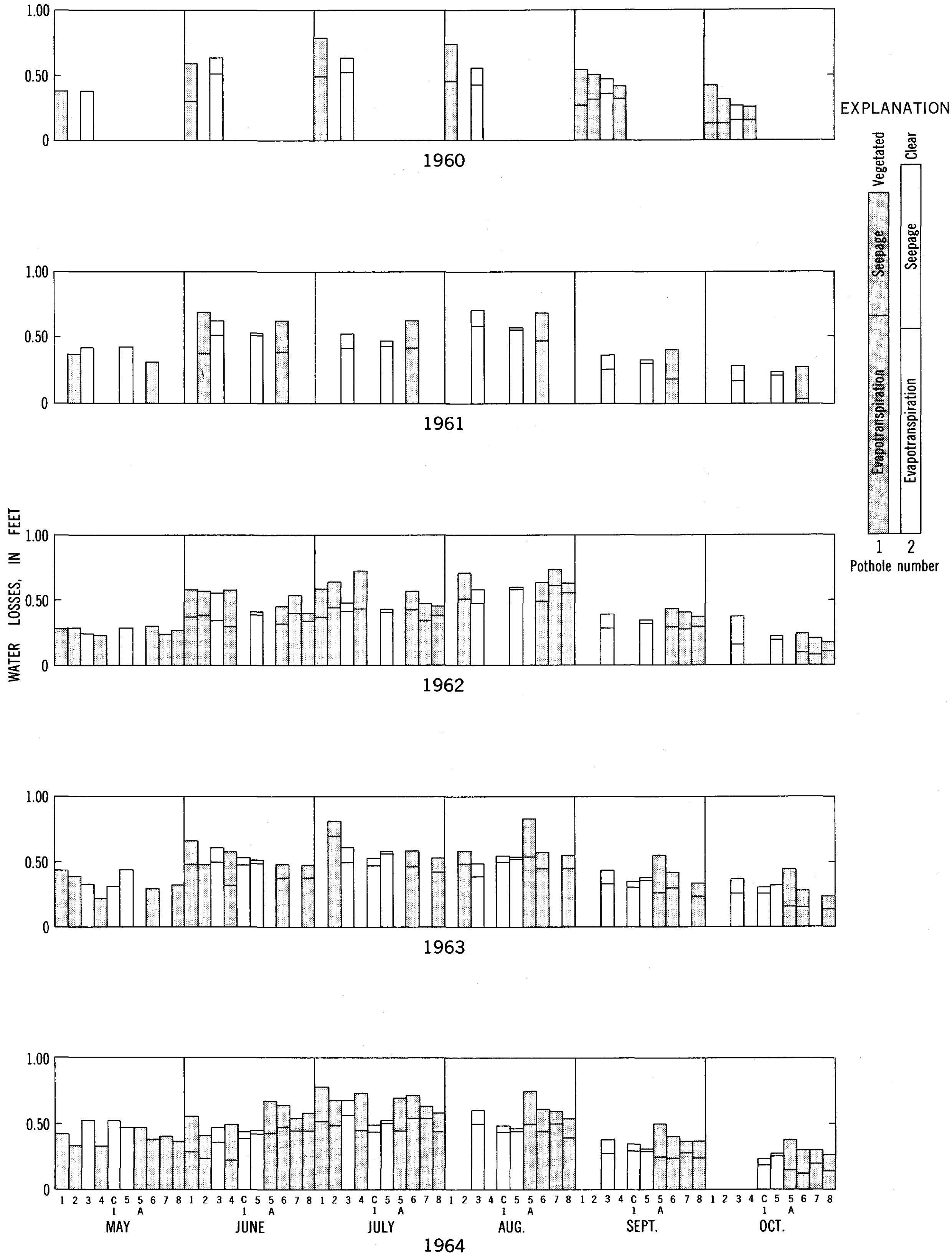


Figure 44.—Monthly evapotranspiration and seepage losses for each pothole, May to October 1960–64.

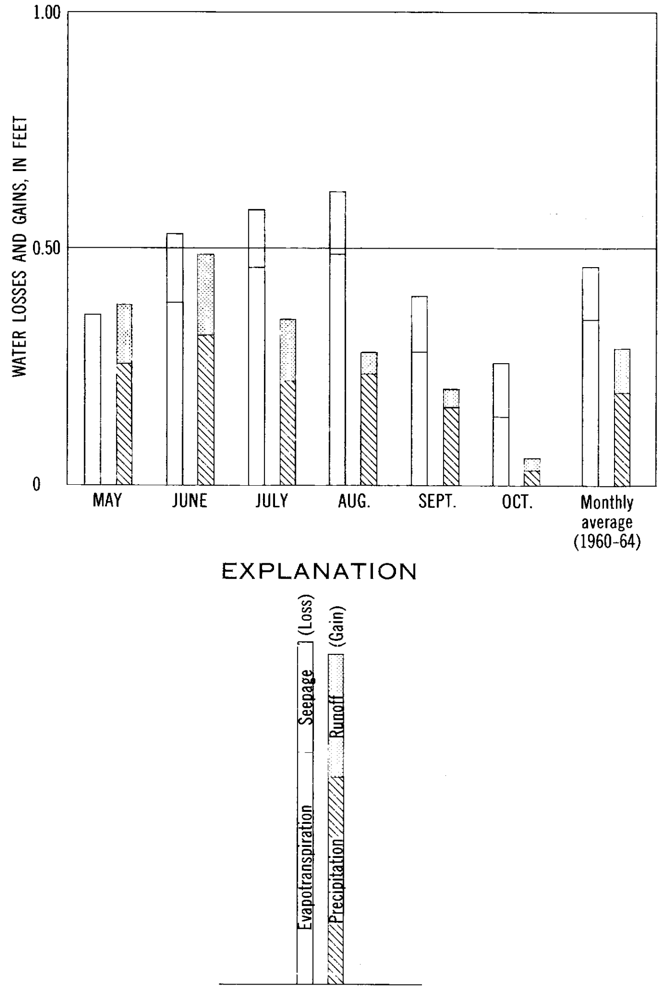


FIGURE 45.—Average monthly water losses and gains for all potholes, May to October 1960–64.

	Feet
Direct precipitation on pothole:	
Summer rainfall	1.21
Winter snowfall	[1].16
Runoff from land surface:	
Summer rainfall	.53
Winter snowfall	[1].63
Average annual rise in stage for all potholes	2.53

[1] The total of 0.79 foot was divided on basis of a study of pothole 3.

The average ratio of water-surface area to drainage-basin land area for most potholes in the study was about 1:10 when the potholes were at about normal stages. Most of the potholes dried up during the first 2 years of the study, when precipitation was below normal.

A study of pothole 3 showed an average runoff of about 1.2 inches per year from the drainage basin into the pothole. This amount of water, in addition to the direct precipitation on the pond, was insufficient to maintain the pothole, because the water level declined about 1 foot per year and the pothole finally dried up at the conclusion of the project, in the fall of 1964.

The major water loss was from evapotranspiration, and a lesser loss was from seepage into the ground. The average seasonal evapotranspiration losses were found to be about the same for both clear and vegetated potholes—roughly about 2.1 feet for the season May to October. Although transpiration increases with the growth of vegetation, evaporation from the water surface decreases, because the plants greatly reduce the wind velocity at the water surface. All the transpiration takes place during a relatively short period—about 3 months, June to August, while the plants are alive. However, the countereffect produced by greatly reduced wind velocity at the water surface takes place even if the plants are dead, and this effect continues in varying degrees throughout most of the year.

The average evapotranspiration loss for the 6-month period May to October 1960–64 was 1.98 feet for vegetated potholes and 2.24 feet for clear potholes (nearly free of emergent vegetation). This shows that the evapotranspiration loss from a vegetated pothole was 0.26 foot, or 12 percent, less than from a clear pothole. This may be significant, but, in this study, the significance is reduced because the seepage losses were found to be greater in the vegetated ponds, so that seepage more than offsets the gains due to reduction of evapotranspiration.

The computations showed the average net outflow-seepage losses to be 0.30 foot for the clear potholes and 0.90 foot for the vegetated potholes during the June to October period. It was assumed that no seepage took place during the winter months when the potholes were frozen to the bottom. On the basis of the thermistor records, it was assumed that the potholes did not freeze solid before December. Increasing the seepage for the losses during November, the average annual seepage rates would then be 0.36 foot for clear potholes and 1.08 feet for vegetated potholes, if the potholes froze to the bottom during the winter. The lowest seepage rate found was 0.0008 foot per day at pothole 5, in Dickey County, and the highest seepage rate found was 0.0105 foot per day at pothole 2, in Ward County.

The average evapotranspiration losses found in this study for the 6-month period May to October agree closely with lake evaporation rates given by Kohler, Nordenson, and Baker (1959, pls. 2, 4): 33 inches (2.75 ft.) per year, or 28 inches (2.31 ft.) for the period May to October.

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