Hydrology of the Little Plover River Basin Portage County, Wisconsin And the Effects of Water Resource Development

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1811

Prepared in cooperation with the Wisconsin Conservation Department and the University of Wisconsin Geological and Natural History Survey

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By E. P. WEEKS, D. W. ERICSON, *and* C. L. R. HOLT, JR.

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By E. P. WEEKS, D. W. ERICSON, and C. L. R. HOLT, JR.

ABSTRACT

The Little Plover River basin is in the sand-plain area of central Wisconsin. The basin and the surrounding sand-plain area provide a good fish and wildlife habitat and is a popular locale for sport fishing. Good yields may be obtained in the area from irrigated crops, and the irrigated acreage has been increasing rapidly in recent years. Sportsmen and conservationists are concerned about the effects of increased development of the water resources on the streams as trout habitat. In the past, many political and legal conflicts among water users have arisen from erroneous opinions as to the behavior of water. Many of these conflicts would be diminished or eliminated if the participants were cognizant of fundamental hydrologic principles.

This study was made to demonstrate the extent and nature of the interrelation of ground water and surface water and the fundamental hydrologic principles governing water movement. The study was also made to determine the hydrologic changes that might occur following development, to provide information that might be used as a basis for planning water development, and for drafting legislation that recognizes the relation between ground water and surface water.

Water has been developed in the Little Plover River basin for industry, for domestic and stock supplies, and for irrigation. Irrigated acreage is increasing in the area, and the use of water for irrigation may alter the hydrology of the basin somewhat. About 4,000–4,500 acres of land within the basin, or 50–60 percent of the basin area, is suitable for irrigated farming, but probably no more than 2,500 acres will be under irrigation in any one year, unless present crop-rotation practices are changed.

Most of the Little Plover River basin is underlain by from 40 to 100 feet of glacial outwash consisting of highly permeable sand and gravel. The glacial outwash is the main aquifer in the area and is capable of yielding large quantities of water to wells. An aquifer test in the area indicated that the coefficient of transmissibility of the glacial outwash is about 140,000 gallons per day per foot. The specific yield of the outwash is about 20 percent, as determined from water-level and streamflow data. Morainal deposits occur locally with the glacial outwash. These deposits transmit water readily and do not form barriers to ground water in the outwash. Relatively impermeable crystalline rocks underlie the glacial deposits, and a sandstone ridge of low permeability impedes the movement of ground water from the basin by underflow.

The glacial outwash and morainal deposits are recharged by infiltration of

9–10 inches of the 31 inches of precipitation that falls on the area in an average year. If it is not withdrawn by wells for consumptive use or by phreatophytes, water that infiltrates the sand and gravel discharges later into the Little Plover River. This ground-water discharge constitutes 90–95 percent of the total flow of the Little Plover River.

Annual evapotranspiration varies considerably, but generally ranges from 2 to 8 inches less than the potential evapotranspiration of 24 inches. Consumptive use of irrigation water averages about 4 inches per year. Most of the water pumped from wells otherwise would be discharged to the stream, and consumptive use of irrigation water will deplete streamflow by the amount of evapotranspiration.

Pumping wells have little effect on the water level in the highly permeable sand and gravel. Significant interference between wells would occur only if large capacity wells were within a few tens of feet of each other.

Ground water and surface water are closely interrelated in the sand-plain area and ground-water withdrawals near the Little Plover River may cause a measurable streamflow depletion. In a test, a well that was pumping about 1,120 gpm (gallons per minute) and that was 300 feet from the stream derived about 30 percent of its flow from the stream after 3 days of pumping.

For this study, the effects of increased ground-water development were evaluated from a hypothetical development schedule, for which it was assumed that 500 acres were irrigated the first year and that an additional 50 acres were irrigated in each succeeding year for 10 years. It also was assumed that the average annual consumptive-use requirement for irrigation water would be one-third of an acre-foot per acre. Calculations indicate that the maximum monthly rate of depletion due to the consumptive use of 4 inches of ground water per year on 500 acres would be about 0.4 cfs (cubic feet per second) the first year and 0.5 cfs after 10 years of pumping. Other computations indicate that the maximum monthly rate of depletion due to irrigating 500 acres the first year and 50 additional acres each year for 10 years would be about 0.8 cfs. Maximum depletion would occur during the summer months, concurrent with the irrigation withdrawals.

Because of the close interrelation between ground and surface water, surface-water withdrawals will cause an increased inflow of ground water to the stream and a decline in ground-water levels near the stream. These effects were demonstrated by pumping from the stream. After 29 hours of pumping, a depletion of 1,120 gpm at a site 7,000 feet downstream was about 200 gpm less than the diversion at the pump. Most of the 200 gpm was supplied from the streambanks, and ground-water levels near the stream declined as much as 0.3 foot. Computations indicated that ground-water inflow, following a streamflow diversion that lowered the stage 0.15 foot, would be 0.14 cfs after 5 days and 0.06 cfs after 30 days.

The demonstration of the quantitative relation between ground water and surface water, as given by this study, should provide a sound basis for planning water development to minimize conflicts of interest. The demonstrations also should provide a basis for drafting legislation that recognizes the interrelation of ground water and surface water.

Because the geology and the hydrology are relatively uniform throughout the sand plains, many of the methods and hydrologic values determined for this detailed study of the Little Plover River basin may be applied to other basins in the sand-plain area.

INTRODUCTION

Water use in many areas of Wisconsin has been increasing rapidly in the last few years, and diverse interests have developed among numerous water users. One important area where diverse interests occur is the sand plains of central Wisconsin. In this area, the development of ground water for irrigation has been increasing, and a conflict of interest has arisen between the irrigators and the sportsmen who are interested in maintaining the streams as trout habitat. Much of this conflict is due to misunderstandings by both groups as to the interrelation of ground water and surface water and as to the magnitude of the effects of ground-water withdrawals on streamflow. Because of conflicts of this type, the laws governing the development of water resources in Wisconsin are being examined with the view toward their possible revision. At present, the State water laws do not reflect the interrelations of surface water and ground waters.

PURPOSE AND SCOPE

The purposes of this study of the Little Plover River basin area are to demonstrate the natural relations between ground water and surface water within the sand-plain area; to determine the hydrologic changes that may occur as a result of man's development of the water resources; to obtain information that might be used by farmers, sportsmen, conservationists, industries, and others as a basis for planning the development of water resources of the sand plains; and to give information that will assist legislators in the drafting of laws that will recognize the relation between ground water and surface water.

Because of the detailed information required, only a relatively small area including the Little Plover River basin and the adjacent lands was studied during this investigation. However, geologic and hydrologic conditions within the Little Plover River basin are similar to those in other parts of the sand-plain area. Criteria used for evaluating the effects of water development in the basin during this investigation should be useful in evaluating changes in the hydrologic regimen brought about by development of water resources throughout the sand-plain area.

A large amount of data on geology, precipitation, streamflow, and ground-water levels in the area was obtained to meet the objectives of this study. The field studies began in July 1959, and field data obtained for the period October 1959 to February 1963 were analyzed for this report. It is planned to continue collection of hydrologic data until 1968 to provide information on long-term hydrologic trends in the basin. The study will be brought up to date at that time by another report.

A 16-mm color movie titled "The Little Plover Project, A Study in Sand Plains Hydrology," was produced as a byproduct of this study. The movie shows various field procedures used in the study and graphically illustrates some of the test techniques and results. Running time of the movie is about 33 minutes. Copies of the film may be purchased or borrowed from the University of Wisconsin, Bureau of Audio-Visual Instruction, Madison, Wis. Additional copies are on file at the U.S. Geological Survey, Washington, D.C.

LOCATION OF AREA

The Little Plover River basin includes an area of about 18 square miles in Portage County (fig. 1). The area of this report includes the entire Little Plover River basin and the adjacent area in Tps. 23 and 24 N., Rs. 8 and 9 E., and covers about 40 square miles.

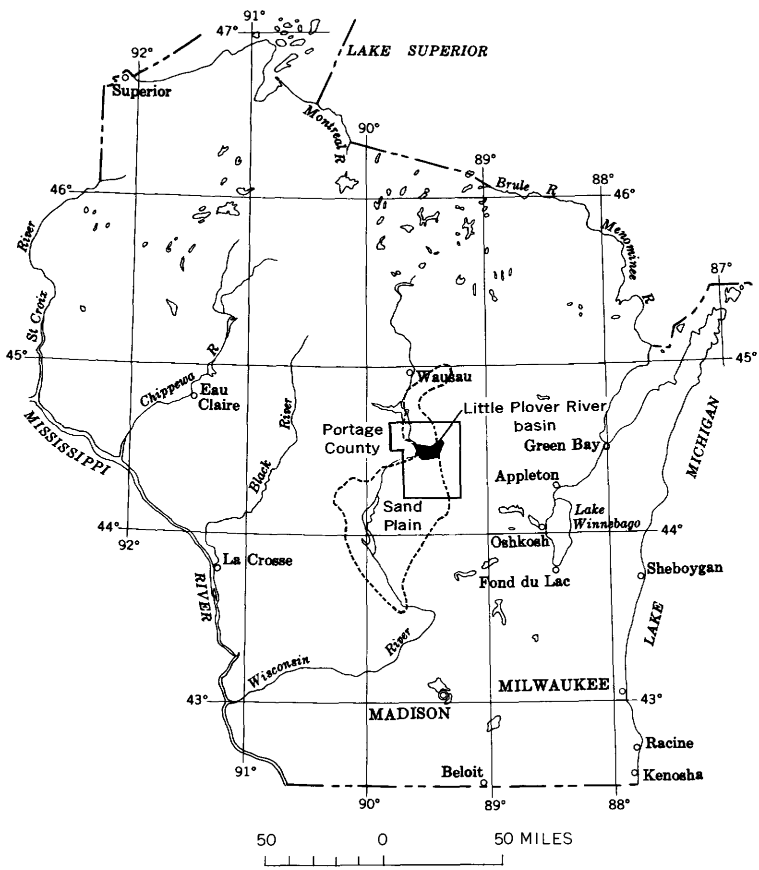

FIGURE 1.—Index map of Wisconsin.

Most of the Little Plover River basin lies in the sand plains of central Wisconsin. The location of the Sand Plain, an area of about 2,500 square miles, is also shown in figure 1.

A report on the geology and water resources of Portage County was made by Holt (1965). His report contained a general discussion of the hydrology and the surface and subsurface geology. That information served as a foundation for the Little Plover River basin study.

METHODS OF STUDY

Data on climate, hydrology, and geology (pl. 1) were collected at a large number of sites. Eight rain gages were installed to obtain data on total rainfall and rainfall distribution. About 40 holes, of which 14 reached basement, were drilled with a power auger to obtain subsurface geologic information. The auger holes were made into observation wells by installing well screens and pipes. Water-level altitudes and fluctuations were obtained from these wells and from about 20 privately owned wells. Four additional wells were drilled with hand augers and equipped with recording gages to obtain continuous records of water-level fluctuations. Three stream-gaging stations were established on the Little Plover River at 1-mile intervals. Each of these stations was equipped with a continuous recorder and a Parshall flume. The locations of precipitation gages, wells, and stream-gaging stations are shown on plate 2. Water-temperature gages were installed in the stream at gaging stations A and C, and an air-temperature gage was installed at gaging station C.

Additional equipment was installed for the aquifer tests and the stream-pumping test. The test instrumentation is discussed in the sections dealing with the individual tests.

WELL-NUMBERING SYSTEM

A three-segment system of letters and numbers is used to designate the location of wells, springs, and lakes (fig. 2). The first segment is the county designation derived from the county name (for example, Pt, Portage County). The second segment consists of the township, range, and section number based on the Federal system of land subdivision. In Portage County, all townships and ranges are north and east of the principal meridian. The letter E or W preceding a section number is used in oversized sections and indicates the east or west half of the section. The third segment is a serial number assigned in the order that the well was inventoried in the county. Serial numbers of springs are followed by the letter S. Only the serial number is shown on illustrations.

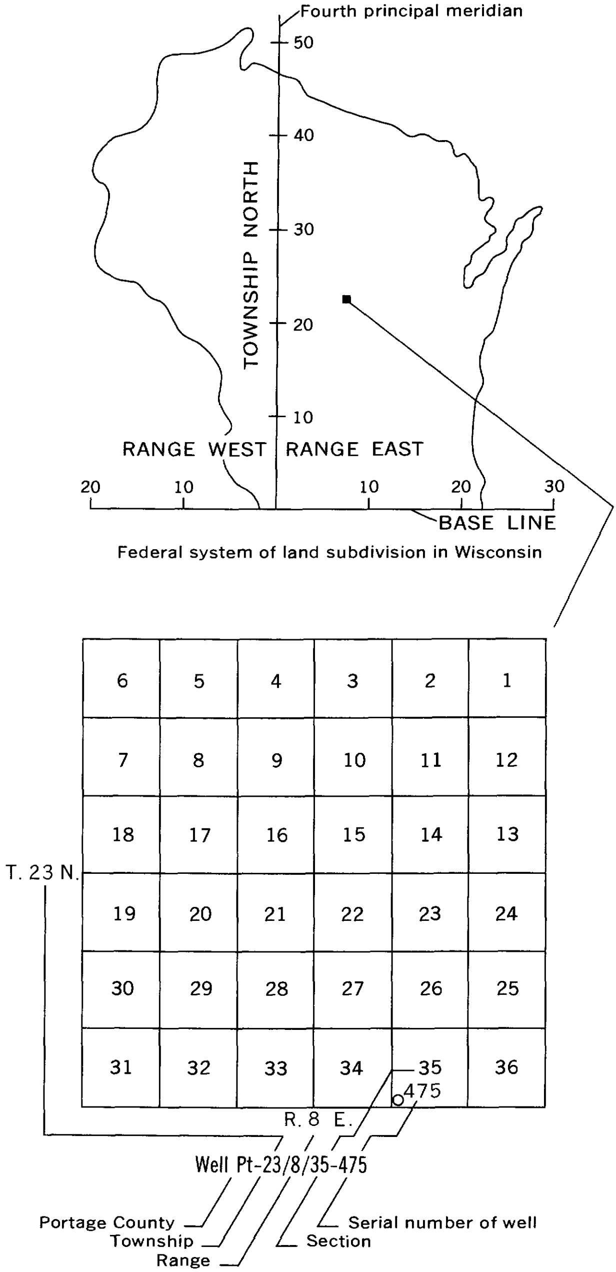

FIGURE 2.—Well-numbering system in Wisconsin.

ACKNOWLEDGMENTS

The study was planned and conducted by the U.S. Geological Survey in cooperation with the Wisconsin Conservation Department and the University of Wisconsin Geological and Natural History Survey, under the general supervision of C. L. R. Holt, Jr., district geologist of the Ground Water Branch, and K. B. Young, district engineer of the Surface Water Branch, for the U.S. Geological Survey in Wisconsin. D. B. Knowles was chief of the project from July 1959 to September 1961.

Acknowledgment is made to the potato growers and other residents in the area who provided information on their wells and gave access to their land and equipment for measurements and tests. Special acknowledgment is made to John and Alois Okray for the use of their irrigation equipment during the aquifer and stream-pumping tests. Well drillers were most helpful in providing local information. Personnel of the Wisconsin Conservation Department, Wisconsin State Board of Health, and the University of Wisconsin assisted in collecting data during the aquifer tests. Acknowledgment is made to G. F. Hanson, Wisconsin State Geologist; to Cyril Kabat of the Research and Planning Division; and to L. M. Christenson and R. J. White of the Fish Management Division, Wisconsin Conservation Department, for their review of the report.

USE OF WATER

Water in the Little Plover River basin is used for a variety of purposes. These different uses affect the hydrology of the area and the available water supply in different ways. Consequently, it is necessary to have a knowledge of present water use in the area and a concept of likely patterns of future development before the effects of development may be evaluated.

PRESENT DEVELOPMENT AND USE

Water in the vicinity of the Little Plover River basin has been developed for domestic, municipal, industrial, and agricultural use. Most of the water is from wells, although some of the industrial users have installed lateral collection galleries along the Plover River, which lies just north of the Little Plover River basin. Also, pits have been dug in areas where the water table is relatively shallow to provide water for irrigation.

DOMESTIC USE

Ground water has been developed for domestic use in rural areas. An inventory of domestic wells was not made, but there are probably between 200 and 300 wells in the area of this report. Assuming that the per capita consumption of water is about 100 gpd (gallons per day) and that each well serves four people, the total amount of water pumped for this purpose annually would be about 75–100 acre-feet, or less than 0.05 inch per year over the basin. Studies in other areas indicate that only about 10 percent of water used for domestic purposes is consumed; the remainder returns to the water table.

MUNICIPAL AND INDUSTRIAL USE

Considerable quantities of water are pumped by the city of Stevens Point from wells near the Plover River. Much of the water pumped from these wells is derived from induced infiltration from the stream. About 2,000 acre-feet of water is pumped annually from these wells, approximately 90 percent of which is returned downstream to the Wisconsin River. Because the Plover River lies between these wells and the Little Plover River basin, pumping the wells will not shift the ground-water divide between the Plover and Little Plover River basins. Consequently, the wells have no effect on the hydrology of the the Little Plover River basin.

Paper mills in Stevens Point and Whiting pump relatively large quantities of water from wells and lateral collection galleries near the Plover and Wisconsin Rivers. Most of the water pumped by the paper companies is derived from induced infiltration from these streams. Consequently, pumpage from the wells and collection galleries will change the location of the ground-water divide between the Little Plover River and the Wisconsin River only slightly, and the pumpage has little or no effect on the hydrology of the Little Plover River basin. Some ground water within the Little Plover River basin is pumped for washing gravel and potatoes. Little of the pumped water evaporates, and most of it returns to the ground-water reservoir relatively unimpaired in quality. A creamery at Arnott also pumps some water, but most of this water is returned to the water table.

IRRIGATION USE AND WATER REQUIREMENTS

Irrigated acreage in the Little Plover River basin has increased from 220 acres in 1953 to 300 acres in 1960 and to 510 acres in 1962. The amount of water used for irrigation within the limits of the basin has continuously increased, as more land was irrigated each year. The amount pumped has increased from 100 acre-feet from four wells and pits in 1953 to about 350 acre-feet from nine wells and pits in 1962. However, the amount of water applied per acre of irrigated land has changed from year to year depending on the distribution and amount of rainfall during the growing season.

The yields of many crops are increased by maintaining optimum soil-moisture conditions with irrigation water. The amount of irrigation water required may be determined from values for potential and estimated evapotranspiration (fig. 12). The potential evapotranspiration from different crops varies, depending on the length of their growing season, how much and how long plants shade the ground, plant height, and other factors. Tanner and Pelton (1960, p. 3391–3412) have given a more complete discussion of the factors governing potential evapotranspiration.

Tanner (written commun., 1957) has determined some approximate water requirements for certain crops by using heat budget and soil-moisture measurement techniques. These values are given in table 3. Potatoes, the main irrigated crop in the area, probably have a water requirement of about 16–20 inches for the growing season, and the land together with the crop has a water requirement of 20–24 inches annually. For this report, a value of 22 inches was used in computing annual evapotranspiration from irrigated land.

The supplemental water requirement for crops grown in the sand-plain area was computed from these values and the values for the computed evapotranspiration rates for the years 1960–62. These computations indicated that potatoes would have required about 6 inches of supplemental water in 1960 and about 2–3 inches of supplemental water in 1961 and 1962. The average requirement, as computed from long-term averages of precipitation and temperature, probably would be about 3.5–4.5 inches of supplemental water annually.

Potato plants have root systems that extract water from a relatively small soil volume. Because the plants can draw on only a small volume of soil-moisture storage, it usually is desirable to irrigate frequently and in excess of the water-use requirements of the crop. Consequently, many of the potato growers make from 3 to 6 applications of about 1.5–2 inches of water during the season. Excess water returns to the water table.

FISH AND WILDLIFE

The Little Plover River basin provides wildlife and fish habitat. The stream provides habitat for trout, and game animals are found in the vegetation growing near the stream.

Data on wildlife population are not available, but a trout-population inventory was made by the Wisconsin Conservation Department in October 1959 (R. J. White, 1960, written commun.). The inventory indicated there were more than 10,000 wild brook trout (*Salvelinus fontinalis*) in the stream at that time, about 10 percent of which were longer than 6 inches. The largest populations of trout were found where ground-water inflow was large (approximately between stream-measuring sites 1 and 4 and between sites 9 and 11, fig. 11). An inventory of trout nests throughout the stream revealed that brook trout selected these areas for spawning most frequently.

The Little Plover River is used to a moderate extent for sport fishing but quantitative data on the number of fishermen using the stream, and the number of days they fish it, are not available. The economic value of sport fishing to the nearby towns is not easily determined, but it is a factor to be considered in evaluating the use of a stream. Esthetic value is another factor to be considered. The enjoyment of fishing cannot be evaluated in economic terms, and it is not possible to compare the value of water for recreation and the value of water for other uses.

FUTURE DEVELOPMENT AND USE

Most of the future development and use of water resoures in the Little Plover River basin probably will be for irrigation and recreation. Future municipal and industrial use probably will be concentrated along the Wisconsin and Plover Rivers, and will not have a significant effect on the hydrology of the Little Plover River basin.

The development of water for irrigation in the sand-plain area has been increasing rapidly, and this trend probably will continue in the future. Although irrigated acreage in the Little Plover River basin has increased continuously since about 1950, the rate of increase has varied because the area is so small that the additional irrigation of one or two fields considerably altered the total irrigated acreage. Based on a comparison with trends in Portage County, the irrigated acreage in the Little Plover River basin may increase by an average of 30–50 acres per year.

The recent construction of potato-processing plants and increased storage facilities will aid in the expansion of the local potato industry.

The amount of land available for irrigation in the Little Plover River basin is less than the total basin area because some of the land is too stony or too irregular to irrigate. An estimate of suitable irrigation land, as determined by criteria of land slope and drainage, was made from field inspection and examination of aerial photographs. These estimates indicated that 4,000–4,500 acres of land within the basin are suitable for irrigation. The total land irrigated probably will be ⅓–½ of this figure if the practice of irrigating a field only once in 2 or 3 years is followed. As land becomes more valuable, the area of land under annual irrigation within the basin may increase, but probably will not exceed 4,000 acres.

FUTURE RECREATION NEEDS

Recreational use of water has increased rapidly since the end of World War II and is expected to increase in the years ahead. The increase in the number of fishermen has caused a more than proportionate increase in fishing pressure because the number of streams and lakes capable of supporting game fish does not increase and may decrease. This is especially true of waters containing trout. Streams in the sand-plain area are suitable habitat for trout because of the relatively large amount of ground-water inflow at a relatively constant temperature. This inflow may be reduced by ground-water pumpage for irrigation, which causes stream stages to decline and stream temperatures to rise; this decreases the suitably of some of the smaller streams in the area for trout (see p. 60 for details). Consequently, the conflict of interest between irrigators and groups interested in recreational activities could become more intense.

AREAL FACTORS CONTROLLING HYDROLOGY

The available water supply for various uses is dependent on the areal factors of climate, vegetation, topography, and geology, which control the movement of water through a cycle of precipitation, runoff, evaportranspiration, and precipitation. Climatic changes cause variations in the hydrologic cycle. Vegetation modifies the effects of climate on the hydrologic cycle, especially through evapotranspiration. The vegetation and drainage may be modified considerably by man. Topography and geology govern the storage of both ground water and surface water and govern their runoff relations.

CLIMATE

Although most climatic factors affect the hydrologic cycle to some degree, temperature and precipitation are the most important. Records of the daily high and low temperatures and the daily precipitation at Stevens Point since 1897 have been obtained. The importance of precipitation and temperature on the hydrology of the area was observed during the period of study (1960–62) and is discussed under the section on hydrology.

Climatic conditions show considerable long-term variation. Hydrologic factors were measured in the Little Plover River basin area for a relatively short time. A comparison of precipitation for 1960–62 to the long-term precipitation trends is useful in evaluating the significance of the hydrologic records. Figure 3 shows the annual precipitation at Stevens Point from 1893 to 1962 and the cumulative departure from the 1893–1949 average. The annual precipitation was 5.02 inches below normal in 1960, 2.58 inches above normal in 1961, and 3.06 inches below normal in 1962. Streamflow and ground-water storage will be greater in the wetter years and less in drier years than that occurring during this investigation.

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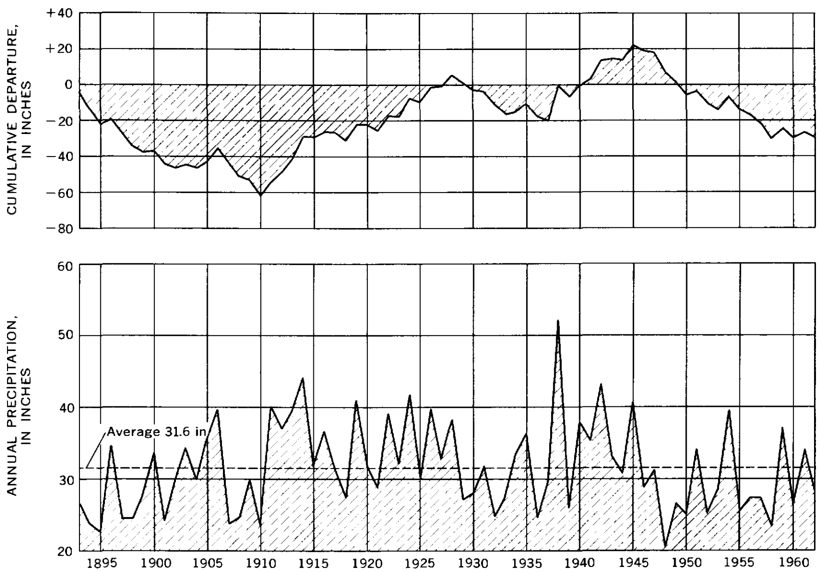

FIGURE 3.—Annual precipitation at Stevens Point, Wis., for the period 1893–1962, and cumulative departure from the 1893–1949 average. (From records of U.S. Weather Bur.)

Approximately 60 percent of the precipitation occurs during the growing season (May–September). The mean monthly precipitation is greatest during the months of April–September and least during the months of December, January, and February. The average monthly temperature and precipitation at Stevens Point is given in table 1.

TABLE 1.—*Average monthly temperature and precipitation at Stevens Point, Wis., 1893–1962*

[From records of U.S. Weather Bur.]

Month	Average temperature (° F)	Average precipitation (inches)
January	16.4	1.39
February	18.1	1.25
March	28.7	1.68
April	44.8	2.75
May	57.4	3.89
June	67.3	4.57
July	71.8	3.07
August	70.2	3.70
September	61.3	3.60
October	49.6	2.25
November	33.4	2.17
December	20.9	1.28

Temperatures in the area are warm in the summer and cold in the winter. The long-term average monthly temperature varies from 16.4°F in January to 71.8°F in July. Because of the cold temperatures during the winter, snow generally accumulates on the ground from December to March. Total snowfall during the winter months averages about 48 inches a year.

VEGETATION

The vegetation pattern reflects geologic and hydrologic conditions. In general, the low flat areas are covered by cultivated crops, by grasses, and by some stands of Norway pine and jack pine. The areas along the streambank are lined by phreatophytic plants tapping ground water. The areas of rolling hills are generally covered by deciduous forest.

Grasses and most crops are relatively shallow rooted. Consequently, transpiration from these plants, except where they are irrigated, is generally limited by available soil moisture during parts of the summer. Pines and deciduous trees have somewhat deeper root systems than grasses and draw moisture from a larger volume of soil. Nonetheless, transpiration by these plants is also curtailed somewhat by soil-moisture deficiencies. The phreatophytes and marsh grasses growing near the stream do not depend on soil moisture and maintain relatively high transpiration rates throughout the summer.

TOPOGRAPHY AND DRAINAGE

Topography controls the direction and, to a degree, the amount of surface runoff and influences the direction of ground-water movement. The topographic divides limit overland runoff toward the stream, and the slope of the land surface controls, to some extent, the part of the precipitation that infiltrates the soil. The number of tributaries in a surface-water drainage pattern has some influence on the amount of water that becomes direct runoff.

Most of the Little Plover River basin is relatively flat and has land-surface slopes of 10 feet per mile or less, but prominent hills occur in the eastern part of the area. Because of the low land-surface slope, the poorly developed surface-water drainage pattern, and the highly permeable soil, most of the precipitation infiltrates into the ground. Consequently, most of the surface runoff originates from a relatively small part of the basin. The general area is characterized by numerous topographically closed subbasins in which water gathers and infiltrates into the ground. Although the surface drainage pattern is poorly developed, most soil types are well drained.

Surface runoff occurs principally in sec. 18 T. 23 N., R. 8 E. Because the water table lies near the land surface in this area, little of the precipitation can infiltrate into the soil. Drainage ditches have been constructed in part of this area to drain the land for agricultural use.

GEOLOGY

The geology of the Little Plover River basin provides the main control on the movement of ground water and also influences considerably the movement of surface water. Therefore, it was necessary to determine the type, distribution, structure, and water-bearing characteristics of the rocks before the hydrology could be determined quantitatively.

The glacial-outwash deposits, the morainal deposits, and the peat and channel deposits compose the ground-water reservoir. The bedrock, consisting of crystalline rock of Precambrian age and sandstone of Cambrian age, is much less permeable than the glacial deposits and forms the base of the ground-water reservoir. Peat deposits and channel deposits occur along the stream channel and in the streambed. The distribution of these rock units at the land surface and the configuration of the bedrock surface are shown in the geologic map (pl. 1). The lithology and water-bearing properties of the rock units are discussed below. The crystalline rock and sandstone are briefly discussed, and the hydrologically more important unconsolidated deposits are treated in greater detail. A more complete discussion of the geology is given by Holt (1965).

CRYSTALLINE ROCKS OF PRECAMBRIAN AGE

Crystalline rocks of Precambrian age underlie the outwash, morainal deposits, and sandstone in the area of study, and they crop out west of the Wisconsin River near Whiting (pl. 1). These rocks consist of gneiss, schist, and coarse-grained granite (Holt, 1965.) The crystalline rocks are virtually impermeable and restrict the downward movement of water.

SANDSTONES OF CAMBRIAN AGE

Outcrops of fine-grained sandstone occur in secs. 2 and 14, T. 23 N., R. 8 E. These outcrops are the surface exposures of a buried ridge left as an erosional remnant of the sandstone of Cambrian age which once covered the area. The sandstone consists mainly of medium to coarse grains of quartz partly cemented by silica and iron oxide. The sandstone strata are much less permeable than the outwash materials, and the buried ridge forces much of the ground water to the surface and into the Little Plover River. Large springs and the large inflow of ground water to the stream in the W½ of sec. 14, T. 23 N., R. 8 E. are caused by the barrier action of the sandstone ridge.

The altitude of the bedrock surface that is composed of rocks of Precambrian and Cambrian age, as determined from wells and auger holes, is shown on plate 1.

GLACIAL OUTWASH DEPOSITS

LITHOLOGY

The glacial-outwash deposits of Quaternary age form the main aquifer in the Little Plover River basin. These deposits are relatively uniform in lithology, both laterally and vertically, and are composed of sand and gravel. The mean grain size and the grain-size distribution of the glacial outwash materials were determined by mechanical analysis of 91 samples from various depths in 10 test holes. The median grain size of most of the materials sampled is medium to very coarse sand. Medium sands are mostly better sorted than coarser material. Deposits of gravel occur near the moraines; some of the gravel has been exploited commercially.

Clay, which was probably formed by weathering of the underlying Precambrian crystalline rocks, occurs between the outwash deposits and the crystalline rocks.

HYDRAULIC PROPERTIES

The outwash deposits are the most important aquifer in the area and their hydraulic properties had to be determined before the availability of water and the effects of water development could be analyzed. These properties were determined from an aquifer test and by analyzing the recession of water levels in four observation wells following spring recharge.

An aquifer test at well Pt-279 indicated that locally the coefficient of transmissibility [1] is about 140,000 gpd per ft (gallons per day per foot) and that the coefficient of storage is about 0.15. For the test, well Pt-279 was pumped at an average rate of 1,060 gpm (gallons per minute) for 3 days, and water levels were observed in the pumped well and in 21 observation wells. The data were analyzed by using an equation derived by Hantush (1961a, p. 83–98, and 1961b, p. 171–195). Details of the test analysis are described elsewhere (Weeks, 1964b).

Because the thickness of the aquifer in the test area is about 80 feet, the coefficient of horizontal permeability is about 1,750 gpd. The vertical permeability of the outwash materials is less than the horizontal permeability owing to the bedded nature of the materials. The ratio of horizontal to vertical permeability is 15–20 to 1 (Weeks, 1964b), which is not unduly large for stream-deposited material. This nonuniformity does not affect the natural movement of ground

[1] See definitions of terms for hydraulic properties of aquifers on page 68.

water greatly, but it considerably affects the drawdowns of wells that partially penetrate the aquifer, and it may limit the rate at which ground water would move to or from a stream.

The average specific yield of the materials composing the ground-water reservoir is about 0.20, which is somewhat greater than the value obtained from the aquifer test (0.15, coefficient of storage). The specific-yield value was determined for a much longer period of time than the time of the aquifer test. Consequently, the specific-yield value of 0.20 should be more useful for analyzing long-term trends in ground-water storage. The specific yield was determined by a water-budget analysis of water-level and streamflow data, as described in the section on changes in ground-water storage.

The ratio of $\frac{T}{S}$ for the outwash deposits is between 100,000 and 180,000 sq ft per day (square feet per day), or 750,000 and 1,350,000 gpd per ft. The value was determined by analysis of water-level recessions observed in wells Pt-366, Pt-376, Pt-374, and Pt-361 following the spring recharge in the years 1960 and 1961. Assuming a specific yield of 0.2, the coefficient of transmissibility becomes 20,000–36,000 sq ft per day, or 150,000–280,000 gpd per ft. Details of the recession curve analyses are described elsewhere (Weeks, 1964a).

An attempt was made to determine the variation of transmissibility in the outwash deposits by a numerical analysis of the water-level altitudes in the observation-well network, as described by Stallman (1956, p. 456). The numerical analysis did not yield reasonable results, possibly because the computations were made for the differential equation defining confined flow in a horizontal aquifer. The numerical analysis might have been more successful if it had been based on the differential equation for ground-water flow in a sloping aquifer under water-table conditions. However, because of a lack of precise data on the altitude of the bedrock surface in the area where the observation-well spacing was suitable for numerical analysis, no computations were made using this equation.

MORAINAL DEPOSITS

The morainal deposits comprise the Arnott and Outer moraines. The Arnott moraine is composed of older deposits than the Outer moraine, as shown by the overlapping of the northern extension of the Arnott moraine by the Outer moraine. The moraines are similar in lithology, and are composed of sandy and stony unsorted till ranging in particle size from clay to boulders, although sand-size particles predominate (Holt, 1965).

The hydraulic properties of the morainal deposits were not determined. However, water levels measured near each side of the Arnott moraine fit the regional pattern of water levels in the outwash materials (pl. 4). This indicates that the moraine does not restrict the horizontal movement of water through the outwash deposits and that the morainal deposits must have a transmissibility of the same order of magnitude as the outwash deposits.

The vertical permeability of the morainal deposits is lower than that of the outwash deposits, and discontinuous perched or semiperched ground-water bodies occur locally in the moraine areas. The location of spring Pt–478S at a relatively high altitude and the unusually high water level in well Pt–389 are probably caused by perched or semiperched water in the Arnott moraine.

ALLUVIUM

Recent deposits of peat, silt, and alluvium have accumulated in the valley of the Little Plover River. These deposits are relatively permeable and thus may be considered as part of the ground-water reservoir. The permeability of these sediments is, however, considerably less than that of the outwash, and the main hydrologic significance of the alluvium is that it restricts the movement of water between the ground-water reservoir and the stream, especially when ground-water level or stream level is sharply changed by pumping. The vertical permeability of the alluvium underlying the stream ranged from 10 to 40 gpd per sq ft as computed from data obtained during the test on well Pt–410. (See p. 49.)

The permeability of the streambed materials differs considerably over relatively short distances; this difference indicates that the streambed materials are not homogeneous. Their permeability is relatively low in the reach near well Pt–410. The natural movement of water from the stream to the underground reservoir in this reach during much of the year may carry fine-grained sediments into the streambed materials. The permeability of the streambed materials between gaging stations A and B and near gaging station C may be somewhat greater than near well Pt–410. In these reaches, movement of water is from the ground-water reservoir to the stream during most of the year.

The vertical permeability of the streambed materials near well Pt–410 is less than the vertical permeability of the glacial outwash deposits by a factor of between 5 and 20, as determined by the aquifer test at the site of well Pt–279. In other reaches, the vertical permeability of the streambed materials may approach, but probably does not exceed, the vertical permeability of the glacial-outwash deposits. Thus, the vertical permeability of the streambed materials probably ranges from about 10 gpd per sq ft to about 200 gpd per sq ft.

HYDROLOGY

A detailed study of the hydrology of the area, as modified by area factors, was made to demonstrate the interrelations among precipitation; ground-water recharge, storage, and discharge; streamflow; and evapotranspiration. This information was needed to evaluate the effects of water use on the available water supply.

GROUND WATER

OCCURRENCE

Ground water is that water which occurs in the interstices of rocks within the zone of saturation below the water table. It is held in temporary storage within the rocks and moves from areas of recharge to areas of natural discharge such as streams and springs, or artificial discharge such as wells.

The ground-water reservoir is considered here to consist of the rocks below the water table that are sufficiently permeable to yield water to wells. In the Little Plover River area, the glacial-outwash deposits, the morainal deposits, and the peat and channel deposits below the water table compose the ground-water reservoir. Because the permeability of the deposits is generally uniform, except for the thin deposits of alluvium, the saturated thickness of the aquifer is the main factor governing the availability of water to wells. The aquifer is permeable and is generally more than 50 feet thick in the basin area. However, in areas where the saturated part is thin, it would be difficult to obtain adequate supplies of ground water for irrigation. The thickness of the saturated part of the deposits composing the ground-water reservoir is shown on plate 3.

MOVEMENT

The direction of ground-water movement may be determined from the slope of the water table (pl. 4). The water table was well defined except in areas covered by the moraines; there the altitude of the water surface was difficult to define because of the lack of wells and locally perched or semiperched water. The contours on the water table in the Outer moraine were obtained from the generalized piezometric map compiled by Holt (1965).

The area from which ground water moves toward the Little Plover River above gaging station A is shown by the location of the ground-water divides (pl. 4). In aquifers of fairly uniform characteristics, ground-water flow paths lie approximately at right angles to the contour of the water-table or piezometric surface. However, in areas where the transmissibility of the aquifer varies considerably, the direction of flow will not be at right angles to the contour of the water table, but will move at some acute angle to the contour in the direction of greater transmissibility. Consequently, the ground-water divide (pl. 4) near the buried sandstone ridge in secs. 2 and 14, T. 23 N., R. 8 E., was drawn somewhat arbitrarily at acute angles to the contour of the water table in order to account for the barrier effect of the ridge. In general, the ground-water divides upstream from the buried sandstone ridge (pl. 1) were determined by extending the flow paths perpendicular to the contours of the water table, although some adjustments in the direction of the flow paths constituting the divides were made for changes in transmissibility in the eastern part of the area.

Within the area enclosed by the ground-water divide (pl. 4), ground water moves continuously toward the Little Plover and Wisconsin Rivers. The location of the ground-water divide shifts somewhat with regional changes in the water level. Although the ground-water divide shifted as the water table fluctuated, the shift in the divide was minor. The area enclosed by the shifting divide varied by less than 5 percent of the 12 square mile area, and conforms mainly to the divide shown on plate 4. The enclosed area averages about 12 square miles.

The slope of the water table is proportional to the rate of ground-water movement and to the transmissibility of the aquifer. The slope varies a great deal in the Little Plover River basin, and in secs. 12 and 13, T. 23 N., R. 8 E., changes from about 5 feet per mile to about 30 feet per mile in a relatively short distance. This change in slope cannot be explained fully by known variations in the permeability or in the saturated thickness of the aquifer materials, or by any reasonable increase in the rate of ground-water movement. Possibly an undiscovered sandstone ridge parallel to the one in sec. 14, T. 23 N., R. 8 E., or less permeable morainal materials associated with the Arnott moraine, exists in this area and acts as a barrier to ground-water movement.

The rate of movement of ground water under natural conditions is relatively slow. In the Little Plover River basin area, the rate ranges from about 0.2 foot a day to about 3 feet per day as computed from an equation given by Butler (1957, p. 73). The rate of ground-water movement may be much greater near a pumping well, however, and may approach a rate of 1,000 feet per day.

WATER-LEVEL FLUCTUATIONS

Water levels in the Little Plover River basin rise rapidly in the spring because of recharge from snowmelt and spring rains. The water levels decline during the summer, when recharge does not occur because most of the precipitation evaporates, replaces soil moisture, or is transpired by plants. The water table may rise somewhat during the fall in response to recharge from rains, but the rise is generally much less than that occurring in the spring. The water table declines during the winter because the precipitation is stored as snow and frost and does not reach the water table until melting occurs. However, water levels may rise temporarily in response to recharge during some periods of thaw in the winter.

The pattern of water-level fluctuations in individual wells in response to a particular sequence of climatic events depends on the nature of the soil zone and underlying rock composing the unsaturated zone at the well site, the depth to the water table, and the proximity of the well to a point of discharge. The nature of the soil and underlying aquifer materials in the area of glacial outwash deposits is relatively uniform and is not an important factor governing differences in water-level fluctuation patterns. However, one observation well (Pt–389) in the morainal deposits apparently taps a perched or semiperched water-table zone, and water levels in this well show a different pattern of fluctuation than those in nearby wells.

The depth of the water table has considerable influence on the pattern of water-level fluctuations. Where the water table lies near the surface, such as near wells Pt–358 and Pt–379 (fig. 4), water levels begin to rise within a short time after the spring thaw begins, or a major rainstorm occurs, and they reach a peak within a few days.

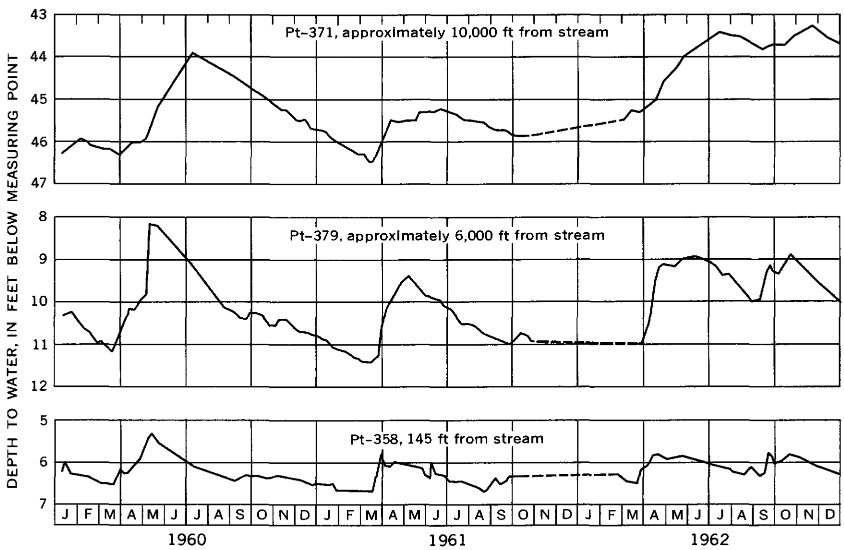

FIGURE 4.—Hydrographs of wells Pt–23/8/15–358, Pt–23/9/7E½–371, and Pt–23/8/24–379 showing the pattern of seasonal water-level fluctuations, the effects of depth to water, and the proximity of the stream on water levels.

Where the water table lies at considerable depth, such as near well Pt–371, water levels do not begin to rise until several days after the spring thaw begins or a major storm occurs, and they may not reach their peak until several weeks later.

Water levels in wells relatively near a stream, such as well Pt–379, may decline much more rapidly than in wells some distance from the stream, such as well Pt–371, because recharge to the ground-water reservoir in areas near the stream drains more quickly than recharge in the areas farther away. Water levels in wells within a few hundred feet of a stream, such as well Pt–358, may be controlled to a greater extent by changes in stream stage than by recharge conditions. The fluctuations in water levels in these wells generally show a direct comparison to the stream-stage fluctuations (fig. 5). Long-term trends in water-level fluctuations are similar to changes of cumulative departure from the long-term average of the annual precipitation (fig. 3).

CHANGES IN GROUND-WATER STORAGE

The level of the water table fluctuates in response to changes in storage within the ground-water reservoir in much the same manner as the water level in a surface reservoir varies with storage. When recharge exceeds discharge, ground-water storage is increased, and water levels rise. Conversely, when discharge exceeds recharge, ground-water storage decreases, and water levels decline. However, the water table does not rise or decline uniformly over the area with a change of storage, and changes in the water level of one well do not necessarily reflect changes throughout the ground-water reservoir. Periodic water-level measurements in a network of observation wells are, therefore, necessary to make quantitative estimates of changes in ground-water storage.

Storage changes were estimated by multiplying the change in the saturated volume of aquifer materials for selected periods by the

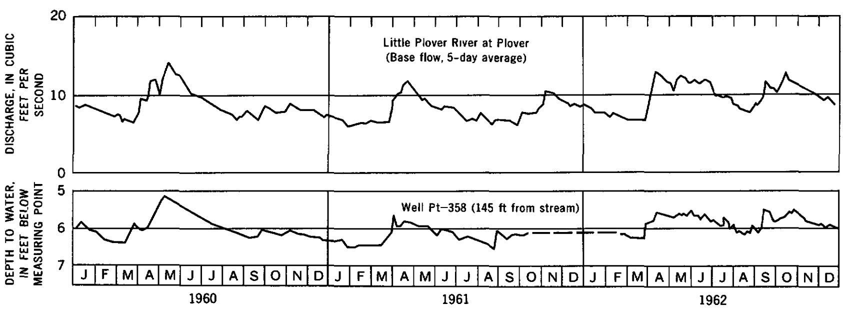

FIGURE 5.—Hydrographs comparing flow of Little Plover River, at Plover, to fluctuations of water level in well Pt–23/8/15–358.

specific yield of the aquifer. Changes in the saturated volume of the aquifer during selected periods were computed by multiplying the change in water level in each well by its area of influence.

To determine the area of influence of each well, the basin and its surrounding area were divided into polygons, each polygon including an observation well. The boundaries of the polygons for wells some distance from the stream were determined by the Theissen mean method (Theissen, 1911, p. 1082). The areas of influence for wells near the stream were arbitrarily assumed to lie within lines parallel to and one-eighth of a mile on each side of the stream. The polygon network for the observation wells is shown on plate 5.

The average specific yield of the aquifer materials in the basin is about 20.5 percent. This value represents the areally weighted average of the specific yield of the glacial-outwash deposits and the morainal deposits. It was computed by dividing the changes in saturated volume into the volume of stream discharge for a period during the winter of 1960–61 when little recharge occurred, and evapotranspiration losses from the ground-water reservoir were small.

Changes in ground-water storage above gaging station A were computed for selected intervals from January 1960 to February 1963, using the specific yield value of 20.5 percent. These changes were added algebraically to determine seasonal changes of storage (fig. 6).

The volume of sustained flow from the basin depends on the amount of ground-water storage. However, the streamflow (fig. 6) apparently is related more closely to the magnitude and time of recharge (fig. 6) than to the relative volume of ground-water storage (fig. 6). Water recharged to the ground-water reservoir near the stream is discharged fairly quickly; it thus maintains streamflow at a high level for a short time. Ground water stored at greater distances from the stream is discharged more slowly, and at a relatively uniform rate even when the amount of storage is relatively large.

ACCRETION

Accretion (Reed and Bedinger, 1961, p. 2424) is the water gained or lost to the aquifer in response to external forces. Gains by the ground-water reservoir are considered positive accretion, and losses are considered to be negative accretion. Infiltration of precipitation, or recharge, is the principal positive accretion to the aquifer in the Little Plover River basin. Negative accretion includes evapotranspiration of ground water, and the movement of water from the water table to the capillary fringe and to the frost zone. The accretion rates computed for this study also include the evapotranspiration occurring from applications of ground water for irrigation.

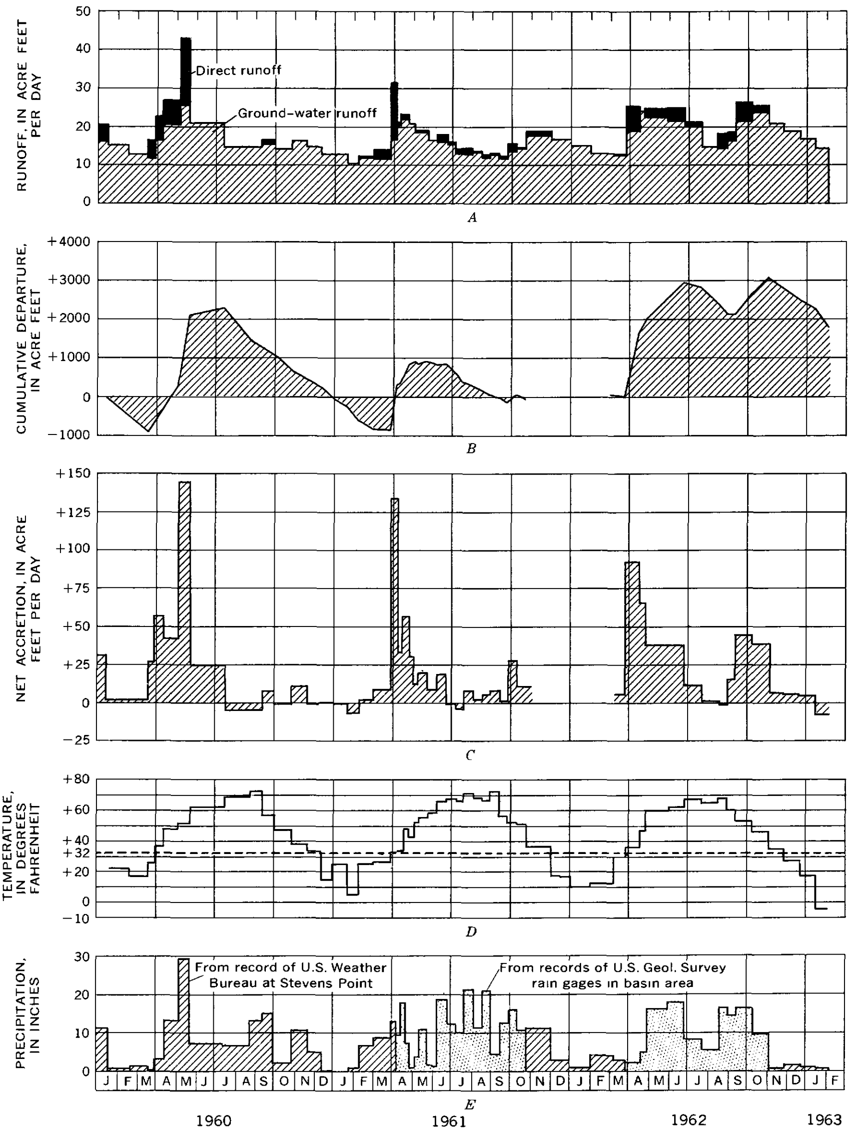

FIGURE 6.—*A*, Discharge of the Little Plover River at gaging station A; *B*, cumulative departure of ground-water storage within the Little Plover River basin from that of January 14, 1960; *C*, approximate net accretion to the ground-water reservoir within the Little Plover River basin; *D*, average temperature at Stevens Point; and *E*, precipitation; all for selected periods between January 1960 and February 1963. (Temperature and precipitation from records of U.S. Weather Bur.)

Most of the positive accretion is derived from snowmelt and rainfall in the spring and from rainfall in the autumn months. The net accretion to the ground-water reservoir was equivalent to about 9.5 inches of precipitation in 1960, 8.9 inches in 1961, and 15.2 inches in 1962. The values for the years 1960 and 1961 probably are near the average annual recharge for the area, because the precipitation during those years was near normal. These values also probably are representative for the entire sand-plain area, because of the similarity of the topography and the soil in the Little Plover River basin to that of the sand-plain area.

The approximate accretion rate was determined by adding computed changes in storage and the total base runoff (table 2, p. 33) for selected periods. For periods when the sum of changes in storage and base runoff is positive, the accretion rate represents the amount of recharge minus any losses to wells, phreatophytes, the capillary fringe, or the unsaturated zone. For periods when accretion is negative, losses to wells and phreatophytes and to the capillary fringe and unsaturated zone exceed recharge. Most of the recharge occurs in March, April, May, and June (fig. 6). Mean temperatures during this period range from above freezing to about 60°F and precipitation is relatively high (fig. 6). During these months, much of the water from snowmelt and from spring rains infiltrates to the water table, adding to the amount of water held in ground-water storage.

Recharge during July, August, and the early part of September generally is much more limited, because most of the precipitation during this period is lost to evapotranspiration before it can reach the water table. The average precipitation (fig. 6) is relatively high during this period, and the average temperature is at its maximum. During these months, negative accretion occurs because of evapotranspiration by phreatophytes and ground-water pumpage for irrigation. These losses are responsible for the loss from storage in excess of streamflow in July and August 1960 and in July 1961 (fig. 6). The net accretion rate is somewhat less than the recharge rate for periods when recharge occurs during the summer months because of the accretion loss to evapotranspiration and to ground-water pumpage.

During the autumn months when evapotranspiration rates are reduced, much of the precipitation can replace soil moisture and recharge the aquifer. Recharge during this period generally is much less than during the spring.

Recharge during the winter generally is limited, because much of the precipitation is stored as snow. However, some recharge may occur during periods of thaw.

Apparent negative accretion was computed for two periods of extremely cold weather (Jan. 19–Feb. 7, 1961, and Jan. 11–Feb. 2, 1963, fig. 6). Part of the apparent negative accretion may be accounted for by the effects on the measured streamflow by ice accumulation in the stream channel. The remainder of the negative accretion probably was caused by an increase in storage within the capillary zone and by the transfer of water vapor from the water table to the frost zone. These phenomena could be caused by the large temperature gradient between the water table and the land surface during periods of extremely cold weather. Schneider (1958, p. 1–15) reported observations indicating similar phenomena in Minnesota. The water removed from the ground-water reservoir by upward movement during periods of extreme cold is returned to the water table as soon as the frost melts, and has little or no net effect on ground-water storage.

UNDERFLOW

Ground water that leaves the basin underground is called underflow. There is little underflow from the basin of the Little Plover River above gaging station A, because of the sandstone barrier (pl. 1). An attempt was made to determine the amount of underflow from the basin by analyzing the data on changes in ground-water storage. Measurements and computations indicate that there is little loss in ground-water storage without a gain in streamflow, and that underflow from the basin is small.

DISCHARGE TO THE STREAM

Most of the recharge to the ground-water reservoir in the Little Plover River basin is eventually discharged to the stream. The amount of ground-water discharge to the stream varies from year to year, depending on the variation in precipitation and the amount of recharge to the aquifer, but it is much more uniform that the rate of recharge both on a seasonal and an annual basis. The slow release of ground water from storage prevents any drastic change in the rate of ground-water discharge to the stream. The ground-water discharge to the Little Plover River is discussed more thoroughly in the section on the interrelation of ground water and surface water.

SURFACE WATER

The topographic divide, which delineates the potential limit of surface runoff, includes an area of about 15 square miles for the part of the Little Plover River above gaging station A. However, as most of the streamflow is derived from ground-water runoff, rather than surface runoff, the drainage area of the stream is limited mainly by the ground-water divides, rather than the topographic divides. The ground-water divide to the stream above station A (pl. 4) includes an area of about 12 square miles, and this value was used to compute runoff from the basin.

STREAMFLOW CHARACTERISTICS

The flow characteristics of a stream are important in evaluating the stream as a source of water for development or as fish habitat. One means of showing the flow characteristics of a stream throughout its range of discharge is by flow-duration curves. Flow-duration curves are cumulative frequency curves that show the percent of time specified discharges were equalled or exceeded during a given period without regard to their sequence of occurrence. The shape of the curve reflects geologic and hydrologic characteristics of the basins. In basins where most of the streamflow is direct runoff there will be a large variation in the discharge so the flow duration curve will be steep. However, if a large amount of surface or underground storage stabilizes the streamflow, then the flow-duration curve will be relatively flat. The shape of the lower part of the curve is indicative of the perennial storage of the basin. All these characteristics are valuable in comparing one basin with another.

The flow-duration curves for gaging stations A and C are shown in figure 7. These curves are based on daily discharges for the 1960–62 water years. Although 3 years is too short a sampling period for

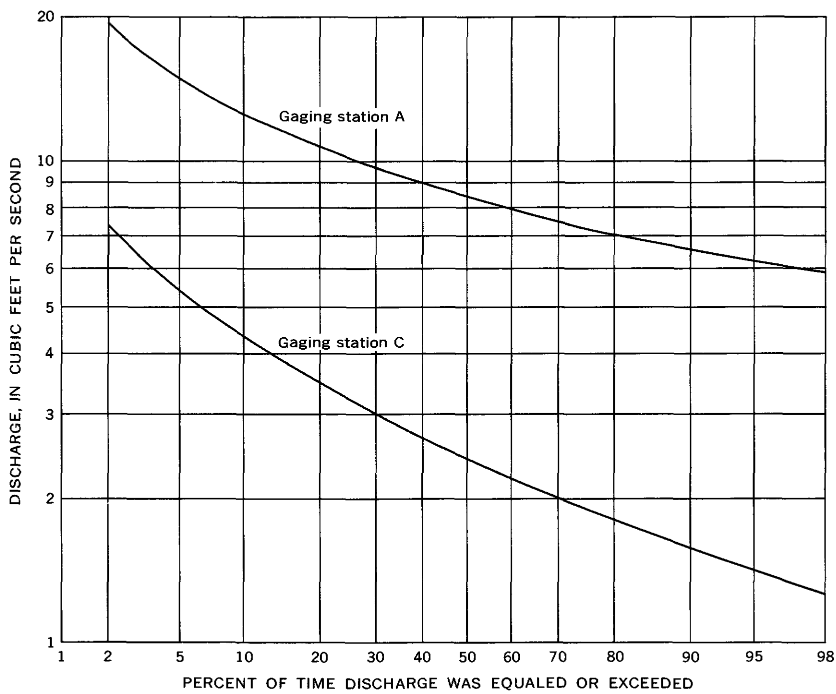

FIGURE 7.—Duration curves of daily flow of the Little Plover River at gaging stations A and C for water years 1960–62.

reliable duration curves, the 1960–62 period did approach average conditions, and the central part of these curves should not change drastically in the future. The curves indicate that the flow of the Little Plover River is quite stable, as would be expected from the large ground-water contribution to flow.

To compare the runoff during the 1960–62 water years with the long-term averages, the flow duration curve for gaging station A was compared to the flow duration curve for the Waupaca River near Waupaca gaging station in figure 8 (U.S. Dept. of Interior, 1961–62). The Waupaca basin, which lies just east of the Little Plover River basin, has a period of record at the gaging station extending from 1917 to 1962. The flow characteristics of the Waupaca River during 1917–62 and 1960–62 are similar. The average flow was 237 cfs (cubic feet per second) during 1917–62 and only 219 cfs during 1960–62. The curve for station A is similar to the Waupaca curves with some divergence at each extreme.

LOW FLOWS

There are generally two periods during the year when low flows occur on the Little Plover River. The first period is in late summer when evapotranspiration losses are high and there is little recharge to the ground-water reservoir. The second period is during the winter when most of the precipitation is stored as snow.

The minimum flow recorded at gaging station A during this study was 4.3 cfs on August 20, 1959. The minimum daily flows for each of

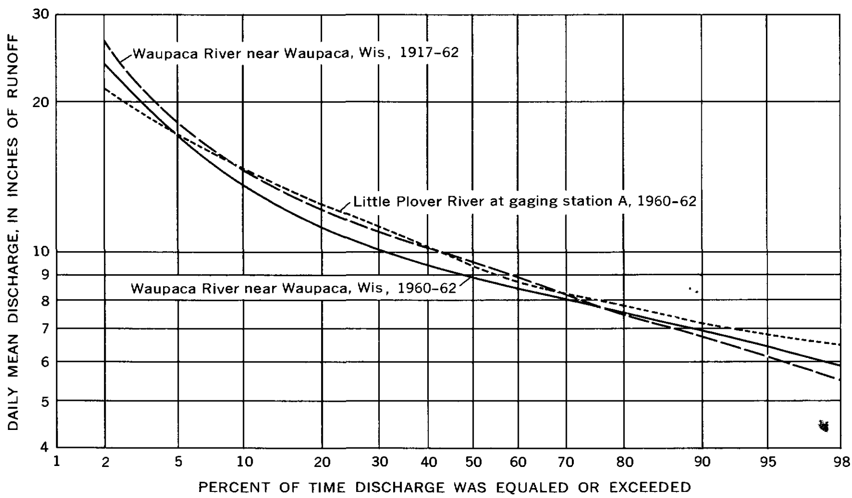

FIGURE 8.—Comparison of duration curves of daily flow for the Little Plover River at gaging station A with that of the Waupaca River near Waupaca.

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the water years 1960–62 at this station were 5.7, 4.6, and 6.2 cfs, respectively; and the minimum mean monthly flow was 5.6 cfs during July 1959. At gaging station C, a minimum flow of 0.8 cfs occurred on several days during July–September 1959. The minimum mean monthly flow at this station was 1 cfs for July 1959.

Recurrence intervals cannot be assigned to any of these low-flow discharges because of the short period of record. There was a severe drought in this area during 1958, and record low flows, particularly for 30- and 60-day periods, were recorded on several streams in central Wisconsin. From this it can be assumed that low flows on the Little Plover River during 1958 probably were lower than any observed during this study.

FLOODS

Flooding is seldom a problem in the Little Plover River basin because of the permeable soil, the flat topography, and the large part of the drainage basin that does not contribute to the surface runoff. The maximum instantaneous flow recorded during the study was 67 cfs at gaging station A on September 13, 1962. At this time, the peak flow at gaging station C was 66 cfs, which indicates that most of the drainage area that contributes surface runoff lies upstream from station C.

Peak flows of a much greater magnitude have occurred in the Little Plover River basin. One long-time resident of the area remembers two unusual floods. One occurred during the spring breakup, and the other occurred late in the summer. The year is unknown for either of these floods. A photograph of the summer flood taken downstream from gaging station B by the resident suggested that the flow might be several hundred cubic feet per second.

Many of the maximum annual peaks for streams in this area occur during the spring breakup which generally comes the latter part of March. The high infiltration capacity of the soil is reduced by deep layers of frost at this time of the year so surface runoff is increased.

DIURNAL FLUCTUATIONS IN STREAMFLOW

The streamflow fluctuates diurnally during the growing season because of evapotranspiration by phreatophytes growing near the stream. The maximum stage during the day generally occurs around 10:00 a.m. and the minimum stage at 6:00 p.m. These fluctations generally start in May, gradually increase to a maximum in July and August, and then decrease until they stop in October. The fluctuation is most conspicuous during periods when base flow conditions prevail.

At gaging station C the difference in discharge from peak to trough of the fluctuations ranges from 0.15 to 0.40 cfs during periods when the daily discharges range from 1.5 to 3.5 cfs. At gaging station A, this difference in discharge ranges from 0.2 to 0.5 cfs when the daily flows range from 6 to 11 cfs. Water-level records from well Pt–397, approximately 25 feet south of the stream at gaging station C, also show this diurnal fluctuation. The altitude of the water surface in the well is generally 1.0–1.3 feet higher than the water surface in the stream. This indicates that the fluctuations in the stream are the result of the diurnal fluctuation in the water table adjacent to the stream. The water table is near the surface in this area, and evapotranspiration by phreatophytes is large.

STREAM TEMPERATURES

The temperature of the stream depends on the net solar radiation to and evaporation from the open water surface, the heat added to or lost from the stream by conduction and convection with the air, and the temperature and rate of ground-water inflow. The net radiation and evaporation also depend on the area of open water and on the type and extent of vegetation along the stream.

Stream temperatures were measured continuously at gaging stations A and C. The results of these measurements and of the air temperature measurements made at gaging station C are shown in figure 9. Daily water-temperature variations at gaging station C are relatively large and the mean daily temperature is relatively high because of the large areas of open water exposed to radiation. The mean daily stream temperature and the temperature variations at gaging station A are considerably less than at gaging station C because the ground-water inflow just above gaging station A is large and because the reach between the gaging stations is relatively sheltered.

The temperature duration, or the percent of time that the daily mean and daily maximum temperatures exceeded a certain value, is of particular interest to fishery biologists. The stream-temperature duration at the two gaging stations on the Little Plover River is shown in figure 10.

INTERRELATION OF GROUND WATER AND SURFACE WATER

Under natural conditions, the interrelation of ground water and surface water is shown by the sustained flow of the stream in periods between rains, by the presence of springs along the streams, and by the close correlation of stream stage with water levels in nearby wells.

During this study, measurements were made to determine the pattern of ground-water inflow to the stream and the effects of stream stage on ground-water levels. The contribution of ground water to the Little Plover River also was determined.

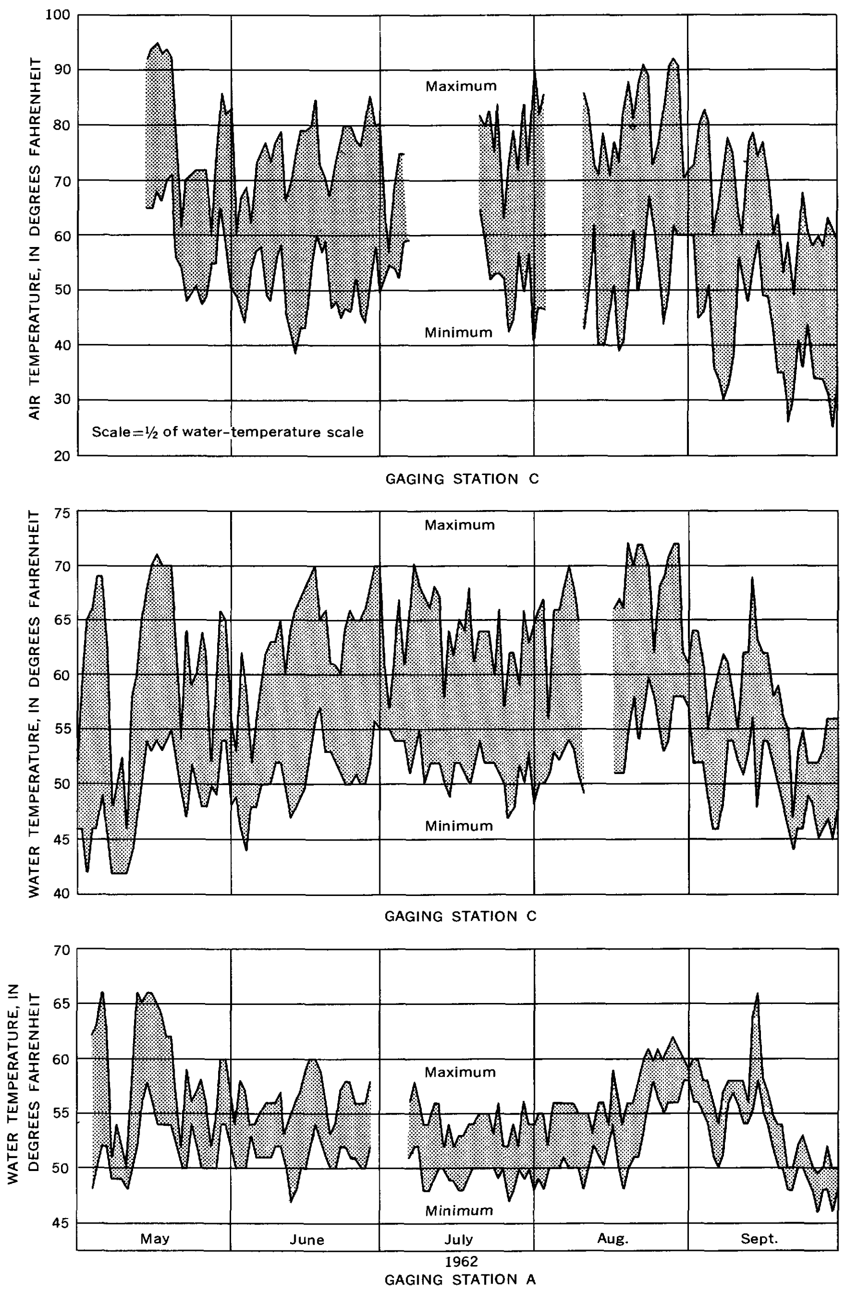


FIGURE 9.—Daily maximum and minimum water temperatures for the Little Plover River at gaging stations A and C, and daily maximum and minimum air temperatures at gaging station C.

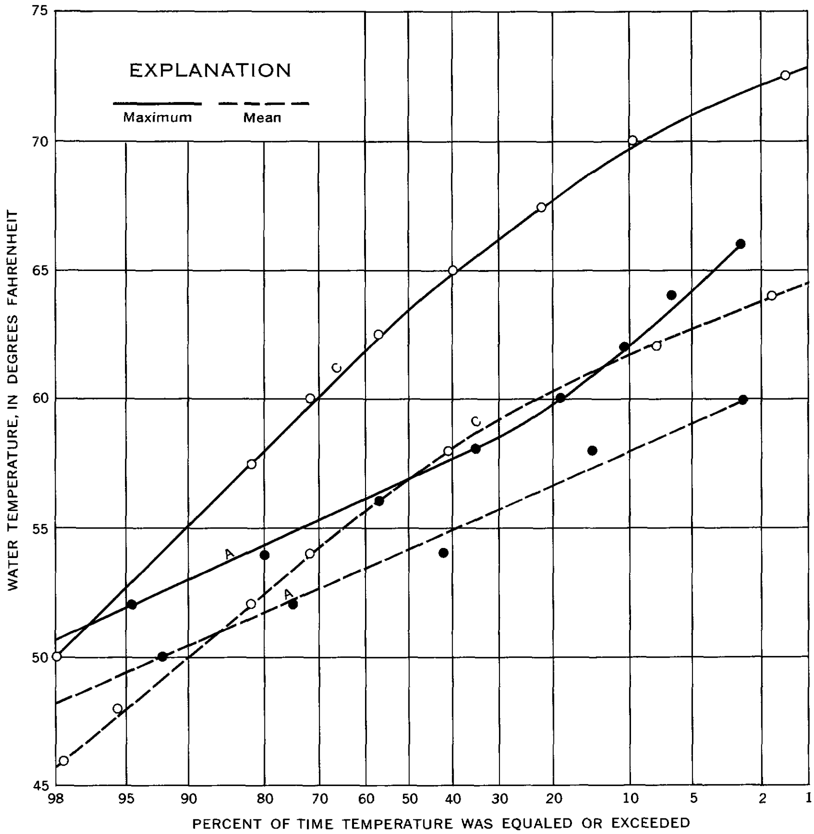


FIGURE 10.—Stream-temperature duration for the Little Plover River at gaging stations A and C for the months May through September 1960–62.

GROUND-WATER RUNOFF TO THE STREAM

Most of the flow of the Little Plover River is derived from water that infiltrates to the ground-water reservoir and then moves to the stream. However, some water is derived from surface runoff and from precipitation falling into the channel. The contribution of ground-water runoff to the total flow of the stream was determined by dividing the streamflow hydrograph into components of base runoff and direct runoff. Base runoff, as used in this study, includes ground-water inflow and a small amount of flow from bank storage. Direct runoff consists of precipitation falling into the channel, surface runoff, and most of the flow from bank storage. The base runoff during the 3 years of record constituted 91 percent of the total runoff at gaging station A and 82 percent of the total runoff at gaging station C.

Bank storage is the water absorbed into the banks of a stream channel when the stream stage is above the level of the water table and later released as the stream stage declines. There is a large amount of bank storage along the river because of the relatively small slope of the water table toward the stream along much of its length; the shallow entrenchment of the stream coupled with a flat flood plain, so that small rises in stream stage flood a relatively large area; and the high permeability of the deposits near the stream. Once the stream stage begins to decline, the return flow of water from bank storage to the stream is relatively slow because of the low permeability of the streambed materials.

Base runoff of the stream was determined from the recession characteristics of the stream during the summer and winter periods. Recession curves were developed for the two periods. It was assumed that as the stream was rising due to direct runoff, base runoff continued to recede until the stream crested. It was further assumed that after the crest had passed, base runoff increased rapidly and that from 2 to 4 days later all the flow would be composed of base runoff.

Considerable error may occur in separating base runoff from direct runoff for the month following the spring breakup. During this period, direct runoff is large and the ground-water inflow conditions vary considerably due to the large amount of recharge to the ground-water reservoir at this time. The results of the flow separations are listed in table 2. The higher percentage of direct runoff at gaging station C occurred because most of the area in the basin that contributes surface runoff is above this station.

SEEPAGE

Two series of seepage measurements made between gaging stations A and C provided information on the contribution of ground water to the stream. The first series of measurements was made on October 5, 1961, at eight stream-measuring sites between the gaging stations, and the second series followed about 1 year later on November 9, 1962, at nine sites. The sites for both series were generally at or very near the same locations. Base runoff conditions prevailed for both series; hence all the flow in the stream was from ground water. Additional data were available from the temporary network of sites used for the pumping test in the fall of 1961. Data obtained November 14, 1961, are complete for the reach downstream from site 9 (fig. 11). In figure 11, the discharge at gaging station C has been subtracted from each measurement to afford a better comparison between the periods.

TABLE 2.—*Monthly total runoff, direct runoff, and base runoff for the Little Plover River at gaging stations A and C, for water years 1960–62*

Year	Month	Gaging station A				Gaging station C			
		Runoff in acre-ft [1]			Base runoff as percent of total runoff	Runoff in acre-ft [1]			Base runoff as percent of total runoff
		Total runoff	Direct runoff	Base runoff		Total runoff	Direct runoff	Base runoff	
1959	October	664	90	574	86	108	22	86	79
	November	582	12	570	98	127	12	115	90
	December	570	111	459	81	140	45	95	68
1960	January	565	56	509	90	151	30	121	79
	February	411	0	411	100	108	-------	108	100
	March	462	78	384	83	134	22	112	83
	April	729	120	609	84	202	47	155	77
	May	1,090	322	768	70	387	150	237	61
	June	632	15	617	98	199	8	191	96
	July	514	9	505	98	173	2	171	99
	August	448	23	425	95	143	6	137	96
	September	456	27	429	94	148	12	136	92
	Annual total	7,123	863	6,240	88	2,020	356	1,664	82
1960	October	458	11	447	98	136	9	127	93
	November	482	15	467	97	159	11	148	93
	December	430	3	427	99	111	2	109	98
1961	January	376	0	376	100	83	-------	83	100
	February	341	11	330	97	85	8	77	90
	March	590	194	396	67	251	154	97	38
	April	674	31	643	96	212	26	186	88
	May	594	24	570	96	161	12	149	93
	June	523	37	486	93	147	22	125	85
	July	487	28	459	94	126	18	108	86
	August	430	30	400	93	125	25	100	0
	September	404	30	374	93	121	20	101	83
	Annual total	5,789	414	5,375	93	1,717	307	1,410	82
1961	October	502	41	461	92	151	27	124	82
	November	609	25	584	96	176	26	150	85
	December	545	5	540	99	143	5	138	97
1962	January	477	0	477	100	119	0	119	100
	February	392	9	392	100	98	0	98	100
	March	460	52	408	89	146	43	103	71
	April	800	103	697	87	334	116	218	65
	May	791	72	719	91	290	60	230	79
	June	752	61	691	92	273	46	227	83
	July	624	32	592	95	220	16	204	93
	August	509	29	480	94	201	19	182	90
	September	725	117	608	84	315	77	238	76
	Annual total	7,186	537	6,649	93	2,466	435	2,031	82

[1] An acre-foot is the quantity required to cover an acre to a depth of 1 ft and is equivalent to 43,560 cu ft.

The seepage data show that inflow to the Little Plover River varies considerably in different reaches of the channel. There was little or no inflow from ground water in the 8,000-foot reach between stream-measuring sites 4 and 10, but 2.5–3.5 cfs inflow in the 1,400 feet of channel between sites 3 and 4. Changes in the inflow rate along the stream are closely related to changes in the transmissibility of the aquifer and to the pattern of flow within the ground-water reservoir. The high rate of inflow between sites 3 and 4 occurs because the sandstone ridge in sec. 2 and 14, T. 23 N., R. 8 E., limits the movement of ground water to the west and forces it into the stream. Possibly the high rate of ground-water inflow just below gaging station C is due to an undiscovered buried sandstone ridge in that area. No apparent relation exists between the slope of the stream profile (fig. 11) and the reaches of high ground-water inflow.

Seepage conditions along the stream also vary with time, and some reaches may gain at one time and lose at another. Variations in seepage probably are caused by variations in the accretion rate to the ground-water reservoir.

Some of the areas of ground-water inflow are evident by visual inspection of the stream. In the reach between sites 3 and 4, many springs issue from the banks, some from as much as 2 feet above the water surface. During the winter, variations in ice conditions on the

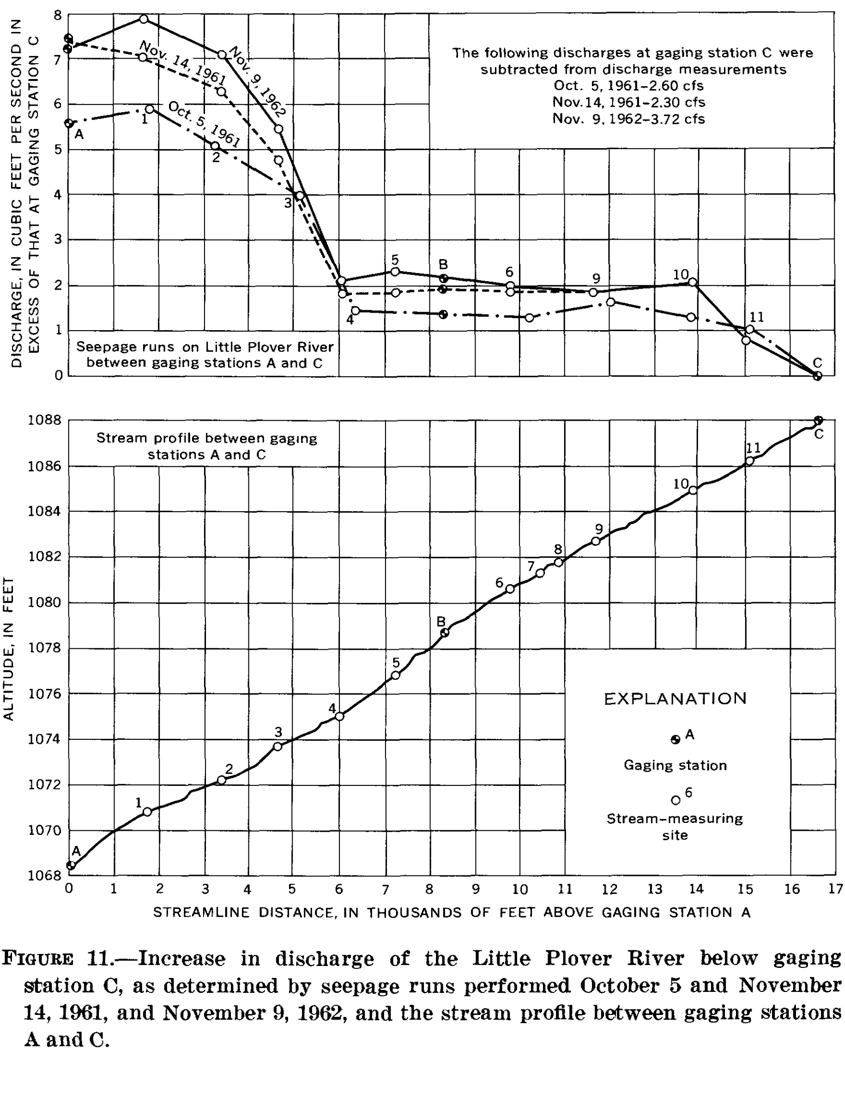


FIGURE 11.—Increase in discharge of the Little Plover River below gaging station C, as determined by seepage runs performed October 5 and November 14, 1961, and November 9, 1962, and the stream profile between gaging stations A and C.

stream reflect variations in inflow. Where the ground-water inflow to the stream is high, it freezes less readily in the winter time; hence, examination of the stream in winter may reveal influent and effluent reaches.

EVAPOTRANSPIRATION

Evapotranspiration is the combination of the natural processes of evaporation and transpiration whereby water returns from the land and the plants to the atmosphere. It is the discharge agent for all the precipitation in the basin which does not move out of the basin by streamflow or by underflow. Any development that increases evapotranspiration from the basin will reduce the amount of water available for runoff and eventually will reduce the flow of the stream. Evapotranspiration losses generally increase with irrigation because more water is made available to the plants and to the land surface. However, the evapotranspiration rate, even from irrigated land, is limited by the amount of energy available. The maximum evapotranspiration that could occur if there were no soil moisture deficiency is termed potential evapotranspiration. Water applied in excess of that needed to maintain the potential evapotranspiration would recharge the aquifer or run off overland. For this study, both the potential evapotranspiration and the estimated evapotranspiration were computed to determine the approximate irrigation water requirements.

Potential evapotranspiration is a function of vegetation and available energy, as determined by the net radiation input, air temperature, air humidity, and other factors such as heat used by photosynthesis and heating of the soil. Because data are not generally available on most of these factors, empirical methods have been developed (Thornthwaite, 1948, p. 55–94; and Blaney and Criddle, 1950) for estimating potential evapotranspiration from temperature data. The success of these methods relies on the correlation between air temperature and the energy available for evapotranspiration.

The potential evapotranspiration for the Little Plover River basin area was computed by the Thornthwaite method (Thornthwaite, 1948) for 3-day increments for the growing seasons for the years 1960–62. The results of the computations indicate that the potential evapotranspiration was about 24 inches in each of the 3 years. Variations in estimated and potential evapotranspiration in 1960 and 1961 are shown in figure 12.

Actual evapotranspiration is generally less than potential evapotranspiration because of unequal rainfall distribution and limited soil moisture. The effects of soil moisture on the evapotranspiration rate depend to some extent on the type of vegetation growing in the

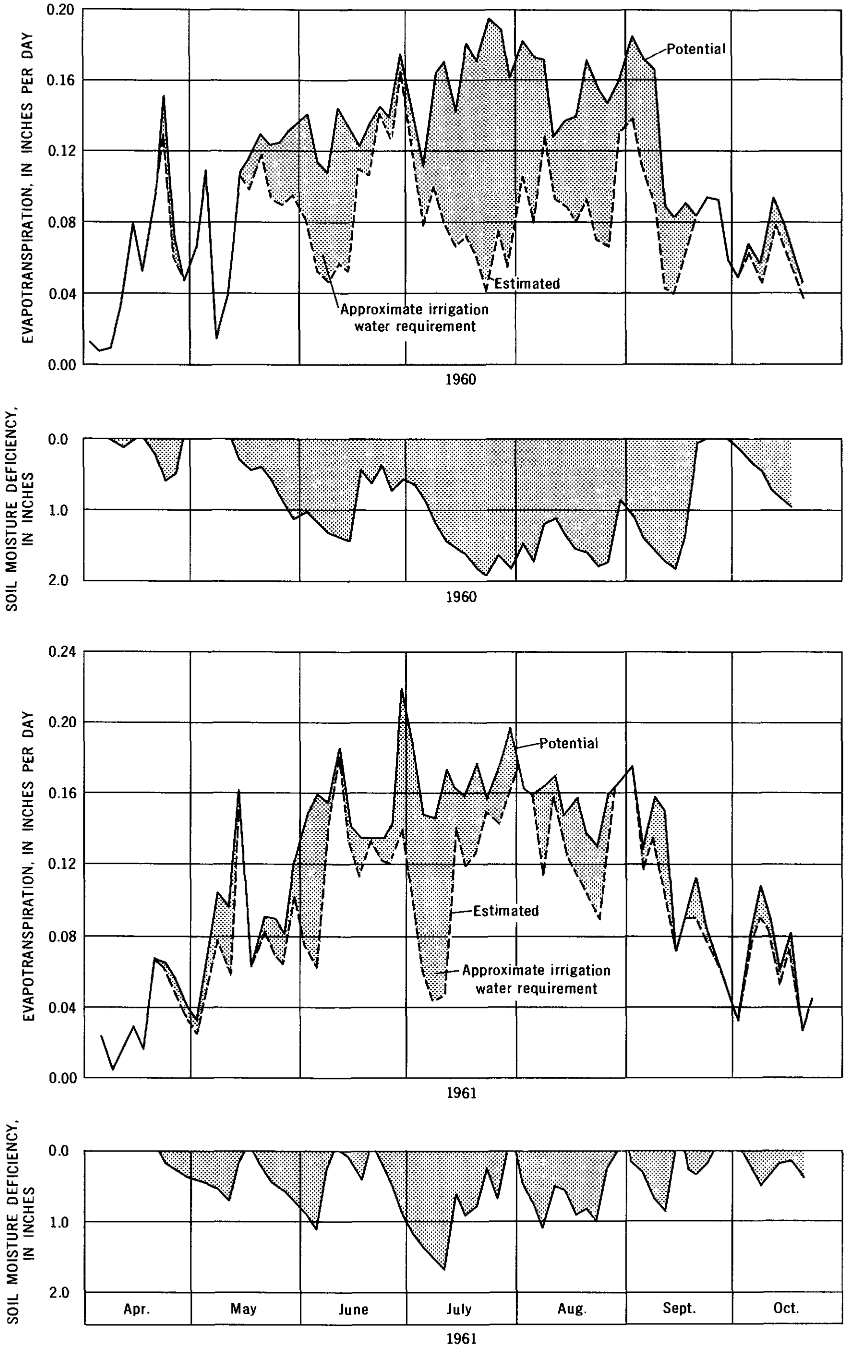


FIGURE 12.—Potential daily evapotranspiration as computed by the Thornthwaite method, and estimated daily evapotranspiration and soil-moisture deficiency, as computed by the method developed by Thornthwaite and Mather (1955), for the Little Plover River basin in the summers of 1960 and 1961.

area. Deep-rooted plants depend less on frequent rainfall because they draw on a greater volume of soil-moisture storage. Phreatophytes are not affected greatly by soil-moisture conditions, and actual evapotranspiration from areas covered by phreatophytes may nearly equal the potential evapotranspiration.

A method for computing the estimated evapotranspiration rate from temperature, precipitation, and soil-moisture capacity data has been developed by Thornthwaite and Mather (1955). Their method assumes that the estimated evapotranspiration rate is equal to the potential rate, computed by the Thornthwaite (1948) method, times the ratio of actual soil-moisture storage within the root zone to the soil-moisture content at field capacity.

Estimated evapotranspiration was computed by this method. For the computations, it was assumed that the soil in the area had a field moisture capacity of 0.8 inch, which is the same as that determined for soil of a similar nature at the University of Wisconsin Experimental Farm near Hancock, Wis., about 20 miles south of the area of this report (C. B. Tanner, oral commun., 1963). It also was assumed that the root zone deepened at the rate of 0.5 foot per month during the growing season, and deepened from 2 feet in April and May to 4 feet in September and October; these assumptions account for the small depth of influence of the sprouting crops on the evapotranspiration of soil moisture during the spring and early summer. The estimated evapotranspiration and the soil-moisture deficiencies computed by this method are shown in figure 12.

The estimated evapotranspiration computed by the method of Thornthwaite and Mather (1955) does not apply to irrigated areas or to areas covered by phreatophytes. The estimated evapotranspiration from irrigated areas was calculated by using an arbitrary value for the evapotranspiration rate of 22 inches a year, which is within the range of water-use requirements for crops (table 3). The amount of evapotranspiration from an area covered by phreatophytes was computed by multiplying the acreage covered by the phreatophytes

TABLE 3.—*Annual water requirements for land and certain crops in Wisconsin*

[From C. B. Tanner, written commun., 1957]

Crop	Annual water requirement for land and crops (inches)	Water requirement for crops during growing season (inches)
Alfalfa-brome	22–26	19–23
Corn	18–22	11–15
Grain	18–22	9–13
Forest	27–28	----------

by a value of 28 inches per year, which is the approximate potential evapotranspiration from forested land in Wisconsin (C. B. Tanner, written commun., 1957). The total annual evapotranspiration from the basin area for the years 1960–62 was then computed by adding values for the area covered by phreatophytes, the irrigated area, and the nonirrigated area (table 4).

TABLE 4.—*Evapotranspiration rates during the growing season in the Little Plover River basin, 1960–62*

Year	Evapotranspiration computed by Thornthwaite-Mather method	Evapotranspiration as determined from water budget
1960	15.9	16.0
1961	18.7	18.0
1962	20.1	18.8

The annual evapotranspiration also was computed from the water budget for the basin by subtracting annual runoff and changes in ground-water storage from the annual precipitation. The figures check closely with those derived from the computations made by using the method of Thornthwaite and Mather (1955), as shown in table 4. The close correlation between the evapotranspiration values occurred despite the fact that the Thornthwaite method is empirical and does not truly evaluate the energy flux available for evapotranspiration, which is given by the approximate heat-budget equation (Pelton, King, and Tanner, 1960, p. 387):

$$ET = Rn - S - A$$

where ET = Evapotranspiration or latent heat flux density,
Rn = Net radiation flux density,
S = Storage heat flux density,
A = Sensible heat flux density (to air).

The Thornthwaite (1948) method relies on the mutual correlation between Rn and A and between Rn and ET.

Pelton, King, and Tanner (1960, p. 387–390) found that the Thornthwaite (1948) method would give values that would be in error during the spring, when the soil is being heated, and during the autumn, when the soil is cooling, because of the effects of the storage heat flux term (S) on air temperatures during these periods. The error due to ignoring the heat-storage term probably was reduced in this study by the assumption of the steadily deepening root zone, which provides a correction factor somewhat similar to that used by Pierce (1958, p. 75).

Pelton, King, and Tanner (1960, p. 393) also found that 3- and 6-day values showed little correlation to measured values, although the Thornthwaite (1948) method gave fairly good monthly and seasonal values for potential evapotranspiration. From these results, it may be assumed that individual values of potential evapotranspiration determined for the Little Plover River basin are considerbly in error, although the average values probably are nearly correct.

The evapotranspiration rates computed by the method of Thornthwaite and Mather (1955) may be too high because it was assumed for the computations that no recharge or direct runoff occurred when soil moisture was deficient. This assumption is not met fully in nature because direct runoff occurs from the wetlands and the area near the channel even when soil moisture is deficient in most of the area. A small amount of recharge may occur even when soil moisture is deficient, but the error in the computed evapotranspiration due to this factor probably is quite small.

The evaporation of water from the snow, which generally covers the area 3–4 months during the winter, was not considered in the foregoing analyses. The evaporation from snow for the period from mid-November to mid-March in central Wisconsin was computed from net-radiation and energy-budget values to be equivalent to about 2 inches of water (C. B. Tanner, written commun., 1957). This amount of water loss exceeds that indicated by the water budget for the winter months for the Little Plover River basin, and is probably compensated for by frost accumulations on the snow and by the condensation of moisture from the air into the snow during humid periods when the air temperature is somewhat above freezing (Light, 1941). These figures indicate that additional research on the water budget during the winter is needed.

THE HYDROLOGIC BUDGET

The hydrologic budget for the Little Plover River basin, as based on long-term averages, indicates that about 31–32 inches of precipitation is contributed to the area annually, that about 20–22 inches is lost by evapotranspiration, and about 10–11 inches leaves the basin as runoff. Of the 10–11 inches of runoff, about 9–10 inches represents groundwater runoff.

The hydrologic budget for a given year may deviate considerably from the long-term average even during years of nearly average precipitation. The hydrologic budgets for the years 1960–62 are shown in table 5. No provision was made in the budgets for changes in storage within the unsaturated zone, which may be large, as indicated by the lag between the time heavy rain or snowmelt occurs and the time recharge ceases. Much of the indicated difference in evapotranspiration between the years 1961 and 1962 probably is caused by ignoring the changes in storage within the unsaturtaed zone.

More detailed data on changes in ground-water storage, runoff, and precipitation are shown in figure 6.

TABLE 5.—*The hydrologic budgets for the Little Plover River basin for the years 1960–62*

Items of hydrologic budget [1]	1960	1961	1962
Precipitation [2]	26. 7	33. 4	31. 4
Runoff at gaging station A	10. 4	9. 4	12. 0
Change in ground-water storage	. 3	1. 4	2. 3
Change in storage of water as snow	--------	1. 0	−1. 0
Evapotranspiration	16. 0	21. 6	18. 1

[1] Expressed in inches of water over the basin area.
[2] Precipitation data for the winter months, November–March, are for Stevens Point; precipitation data for April–October are from precipitation gages installed for this project.

EFFECTS OF WATER DEVELOPMENT

The hydrology of the area and consequently the amount and distribution of water available for development are altered by water use. The effects of water development on the hydrologic budget, water levels, and streamflow were evaluated to provide information for planning water development and to present information that will be useful in drafting laws that recognize the relation between ground water and surface water.

EFFECTS OF GROUND-WATER DEVELOPMENT ON THE HYDROLOGIC BUDGET OF THE BASIN

The ground water developed by pumping may be derived from one or more of four sources: water that leaves the basin as underflow, ground water that otherwise would be lost to evapotranspiration, storage within the ground-water reservoir, or water that otherwise would be discharged by streams. Underflow from the Little Plover River basin is limited by the sandstone barrier (pl. 3), and little or no discharge could be salvaged from this source. The discharge of ground water by evapotranspiration is generally limited to the area near the stream, where the water table lies near the surface. Even under relatively concentrated ground-water development, water levels would not be drawn below the root zone of plants in the area near the stream, and little ground water would be salvaged from evapotranspiration. Therefore, most of the water pumped would be derived from storage and from water that otherwise would be discharged as streamflow; the pumpage of water from storage would cause a decline in water levels in the area. Removal of water from storage within the ground-water reservoir would be temporary. Pumpage for irrigation is seasonal and recharge during the spring and fall generally will replace much of the ground water removed from storage. Most of the recharge intercepted by the wells otherwise would be discharged to the stream, and, after several years, ground-water pumpage for irrigation would therefore reduce the total volume of streamflow by about the amount that evapotranspiration is increased by irrigation.

An estimated additional 3.5–4.5 inches of water is lost to evapotranspiration annually from the irrigated fields. Consequently, the average annual runoff in the Little Plover River basin eventually will be diminished by about 0.3–0.4 acre-foot per year, or 0.0004–0.0005 cfs per acre of land irrigated within the basin. Thus, the irrigation of 500 acres of land within the basin would reduce the annual runoff at gaging station A by about 2.5 percent, although the seasonal streamflow depletion would be greatest near the end of the irrigation season and least just before irrigation begins.

ON BASIN BOUNDARIES

The area of ground-water runoff toward a stream may be changed by ground-water development within or adjacent to the area. When a well or well field is pumped, water levels are drawn down, ground-water flow paths are diverted toward the well, and the ground-water divides are shifted away from the well. Thus, a pumping well at a distance from a ground-water divide between streams would cause the divide to shift away from the well until recharge intercepted by the well balanced the well discharge.

Because of the possible shifts in the locations of ground-water divides, the concept of a basin limited by topographic and ground-water divides is inadequate when considering localized water development. A definition better suited to concepts of water development may be that the hydrologic basin is the area from which water may be derived by development at areas of concentrated withdrawal. Under this definition, the size of the basin and the nature of its boundaries depend on the type and degree of development within the basin. For surface-water development, the basin generally will be limited by the topographic and existing ground-water divides, because the ground-water divides generally are not affected by surface-water withdrawals. A basin in which ground water has been moderately developed will be limited by streams and by impermeable rocks bounding the aquifer. Under very heavy development, the water table declines below the stream and the effects of pumpage will reach beyond the streams.

If the development of ground water were concentrated within the Little Plover River basin, the cone of depression would expand northward and westward toward the Plover and Wisconsin Rivers, southward toward the drains tributary to Buena Vista Creek, and eastward toward the Waupaca River. The discharge of each of these streams, therefore, would be reduced, and water would be diverted from areas that had been drained by the other streams before the development along the Little Plover River basin began. Conversely, if the areas of one of the basins contiguous to the Little Plover River basin were to be heavily developed, the ground-water divide would be shifted toward the Little Plover River, and its flow would be reduced. However, development of ground water for irrigation appears to be fairly evenly distributed over the area, and the effects of development in the Little Plover River basin on the runoff from adjacent basins probably will equal the effects of development in the adjacent basins on the flow of the Little Plover River.

ON GROUND-WATER LEVELS

Water levels are lowered by ground-water pumpage, and in some areas the lower water levels may reduce the yield of wells. In the sand-plain area, however, regional water levels are not affected greatly by present pumpage from wells because of the relatively high transmissibility of the aquifer materials and the large volumes of recharge that occur every spring.

The effects of ground-water pumpage on water levels in an aquifer having properties similar to the glacial outwash materials in the area of this report were computed from an equation derived by Theis (1935, p. 541). The equation assumes that the aquifer is homogeneous, isotropic, and infinite in extent and that all the water pumped is removed from storage. From the computations, curves were derived showing drawdowns near wells being pumped at constant rates of 500 and 1,000 gpm and near a well being pumped intermittently at 1,000 gpm, 12 hours a day (fig. 13). These curves represent the drawdowns due only to pumping. Under actual conditions, the water levels may decline more or less than is shown by the graphs depending on natural fluctuations of the water table. As shown by the curves, no excessive interference between wells should be expected unless they are placed very close to each other.

The curves showing the drawdowns near a well being pumped cyclically were computed by a method similar to that used by Theis (1963, p. 319–323). The results show that at distances of 1,000 feet or greater, the drawdown due to a well that is pumped 12 hours a day will be approximately equal to that of a well pumped continuously at half the rate of the well pumped cyclically. The curves indicate that computations of well interference and streamflow depletion by cyclically pumped wells tapping the outwash deposits could be made by

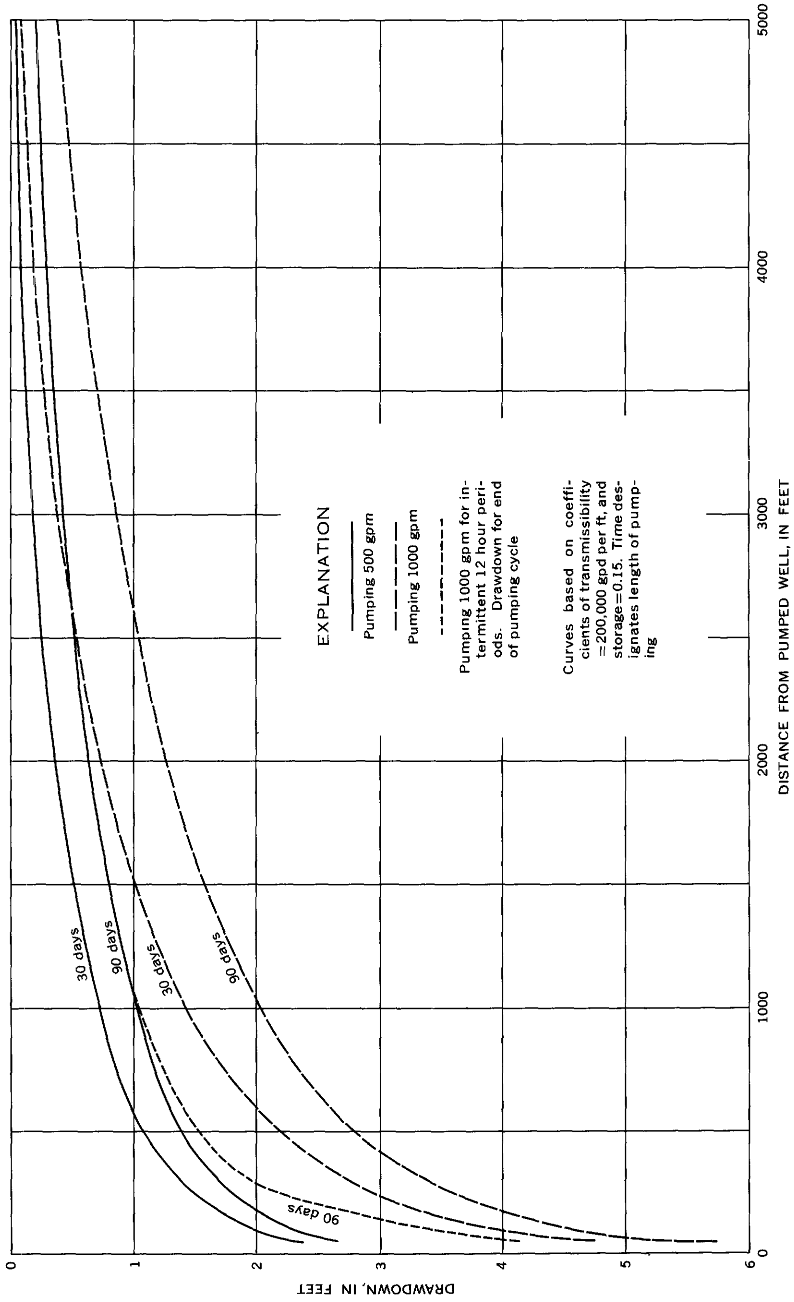


FIGURE 13.—Theoretical distance-drawdown curves for a pumped well in glacial outwash in the Little Plover River basin area. (Not adjusted for hydrologic boundaries.)

assuming that the wells are pumped continuously at an average rate, except for very closely spaced wells or wells very near the stream.

The computed curves represent drawdowns near wells in extensive aquifers and do not take into account the effects of less permeable rocks near the well, nor the effects of a stream flowing near the well. Rocks of low permeability impede ground-water flow and cause the actual drawdowns near the well to be somewhat greater than shown by the curves, because water would be removed from storage over a more limited area than is postulated by the equation. Drawdowns in wells near a stream would be less than those indicated by the curves, because some of the water would be derived from streamflow rather than from ground-water storage.

The effects of return flow from excess irrigation water also were ignored in computing the drawdowns. This return flow would cause the actual drawdowns to be less than indicated by the curves.

ON STREAMFLOW

Streamflow may be reduced by ground-water pumpage from the area adjacent to the stream. In areas where most of the ground-water pumpage occurs on a seasonal basis, as in the Little Plover River basin, baseflow of the stream also shows a seasonal variation, minimum baseflow being near the end of the peak withdrawal period for ground water.

The effects of an individual well on the streamflow were determined during a special test, estimates of the effects of pumpage from wells in existence in the basin in 1962 were made, and the magnitude of the effects of increased ground-water development for irrigation were computed from hypothetical ground-water development.

EFFECTS OF PUMPING AN INDIVIDUAL WELL

The effects of ground-water pumpage on streamflow are difficult to demonstrate under natural conditions because of the large number of variables affecting streamflow and because of the relatively large distances between the irrigation wells and the stream. Therefore, the effects of pumping a well near a stream were demonstrated by a special test. The test was performed by pumping well Pt–410, located about 300 feet from the Little Plover River, by measuring streamflow at five sites in the adjacent reach of stream, and by observing water levels in 28 nearby observation wells (fig. 14). The well was pumped at a rate of 1,120 gpm for 74 hours, and water-level and streamflow measurements were made continuously during this period and for 74 hours after the pumping ceased.

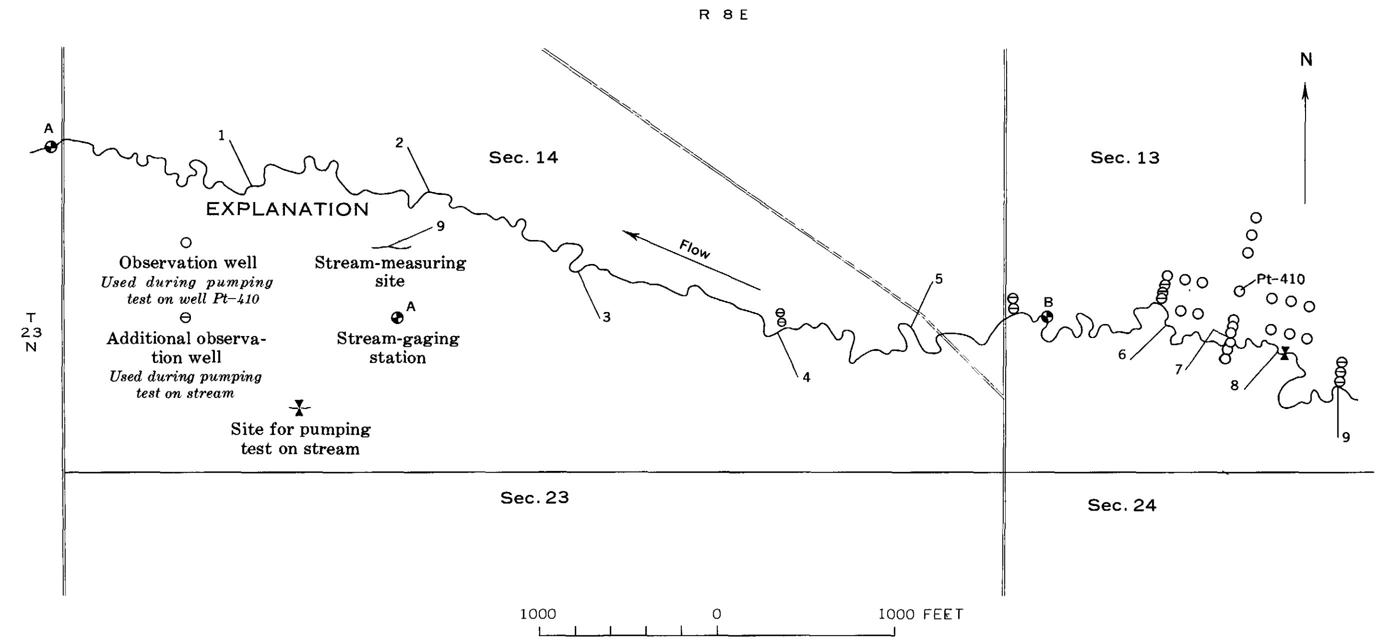


FIGURE 14.—Location of stream gages and observation wells used in the test on well Pt-410 and the test performed by pumping from the Little Plover River.

The test was made during the fall of 1961, when evapotranspiration losses were small and when baseflow conditions existed in the stream. Unfortunately, these baseflow conditions were disrupted by rain at three times during the test. A light rain occurred a few hours after the test started, which did not greatly affect streamflow. A heavier rain occurred after about 55 hours of pumping, causing an increase in streamflow that affected the results of the test considerably. After the pump had been off about 6 hours, a very heavy rain caused a sharp rise in the streamflow which masked the recovery of stream stage due to the cessation of pumpage.

The discharge hydrographs for each of the five streamflow-measuring sites observed during the test are shown in figure 15. The top line in this figure shows the natural streamflow entering the test area at site 9, just upstream from the area affected by the pumped well.

Prior to pumping, the streamflow was relatively constant and water levels were stable. About 15 minutes after the pump was started, the streamflow began to decrease and continued to decrease until the test was disrupted by runoff from rainfall 56 hours later (fig. 15). At that time, about 340 gpm, or 30 percent, of the well pumpage was being derived from the flow of the stream. The streamflow depletion probably continued to increase slowly throughout the remainder of the pumping period, although the effects of the depletion were masked by runoff from precipitation.

The results of the tests demonstrate the relation between ground water and surface water and the effects of ground-water pumpage on streamflow. However, this test shows the effects of pumpage at only one well site. An equation has been developed by Theis (1941) to estimate streamflow depletion caused by pumping wells at different locations. The equation is based on the assumption that the aquifer is under artesian conditions, is homogeneous and isotropic, and extends to infinity away from the stream. The equation also assumes that the stream completely penetrates the aquifer and is straight and infinite in extent.

Values for streamflow depletion caused by pumping well Pt–410 were computed from the equation and compared to the measured values to determine the validity of the equation in predicting streamflow depletion. For the computations, it was assumed that the aquifer had a coefficient of transmissibility of 200,000 gpd per ft and a coefficient of storage of 0.15. The comparison of these values (fig. 16) indicates that the depletion of flow between measuring sites 6 and 8 was a great deal less than the computed depletion, but the depletion between gaging station B and measuring site 6 (below sites 6–8) and between measuring sites 8 and 9 (above sites 6–8) agree fairly closely with the

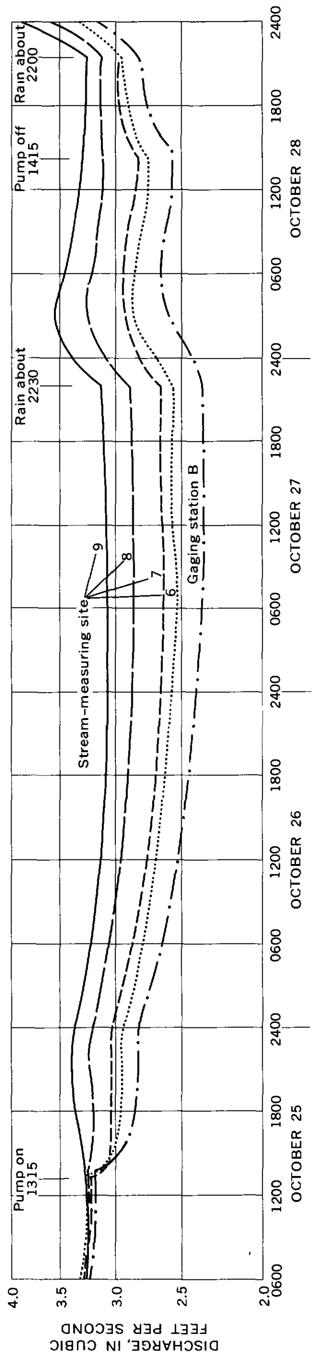


FIGURE 15.—Discharge hydrographs for the stream-measuring sites during the pumping test on well Pt-410, October 25–28, 1961.

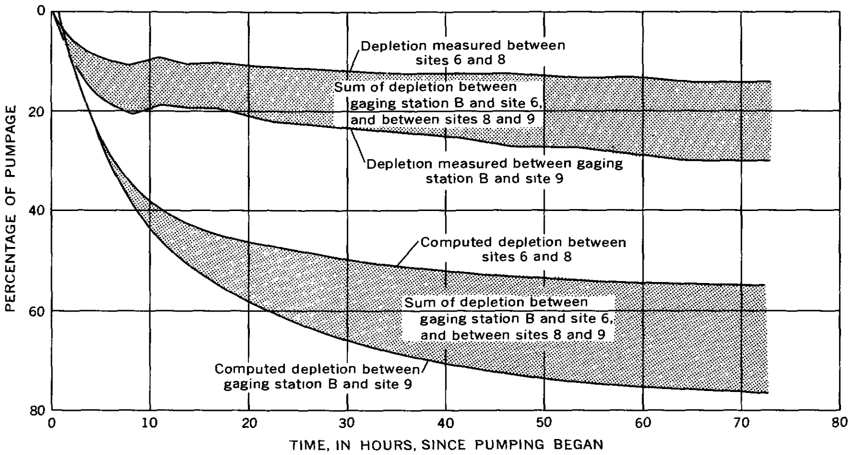


FIGURE 16.—Measured streamflow depletion during the test on well Pt–410 compared with values computed using an equation for streamflow depletion from a stream fully penetrating the aquifer.

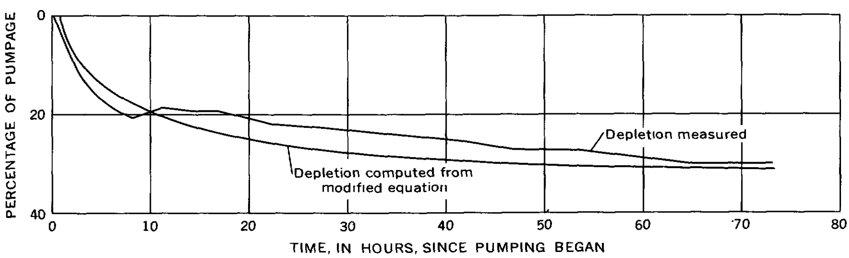


FIGURE 17.—Measured streamflow depletion between gaging station B and site 9 compared with values obtained from the equation as modified for a partially penetrating stream. (See pages 69–73.)

computed depletion (compare shaded areas, fig. 16). The reach of stream between measuring sites 6 and 8 lies near the well, and it is in this area that the differences in effect between the actual partially penetrating stream and the theoretical fully penetrating stream are greatest. Because the stream penetrates only a very small part of the aquifer, the water table was drawn below the bottom of the stream after the pump had been run for about 15 minutes. After this time, most of the water moving from the stream toward the well moved vertically downward through the less-permeable streambed materials.

The average permeabilities of the streambed materials for the reaches between measuring sites 6 and 7, 7 and 8, and 6 and 8 were computed by use of Darcy's Law (Ferris and others, 1962, p. 71).

This law states that the permeability of a material is equal to the discharge through the material divided by the area through which the flow is occurring and by the hydraulic gradient. For the computations of the permeability of the streambed materials in the designated reaches of the Little Plover River, the discharge, or downward flow, was considered to be equal to the streamflow depletion measured in each reach after well Pt–410 had been pumping for 48 hours. The streambed area for each reach was determined by multiplying the measured streamline length of the reach by an assumed average width of 10 feet. The hydraulic gradient was assumed to be equal to unity in each reach. The water table probably was pulled down below the streambed in each reach, as indicated by the constant rate of streamflow depletion in those reaches. Consequently, the actual hydraulic gradient across the section of streambed materials was somewhat greater than unity, depending on the thickness of the section and the depth of the stream. The gradient would approach unity as the section became thick or as the stream depth approached zero. Because of the low estimate of the hydraulic gradient, the permeabilities determined for the streambed materials are somewhat too high, although they probably are the right order of magnitude. The results of the computations are given in table 6.

TABLE 6.—*Streambed permeabilities along the Little Plover River, as determined by the test on well Pt–410*

Reach of stream between measuring sites (fig. 14)	Streamflow depletion (gpm)	Length of reach (feet)	Width of reach (feet)	Permeability of streambed materials (gpd per sq ft)
7, 8	115	405	10	40
6, 7	45	645	10	10
6, 8	160	1,050	10	21

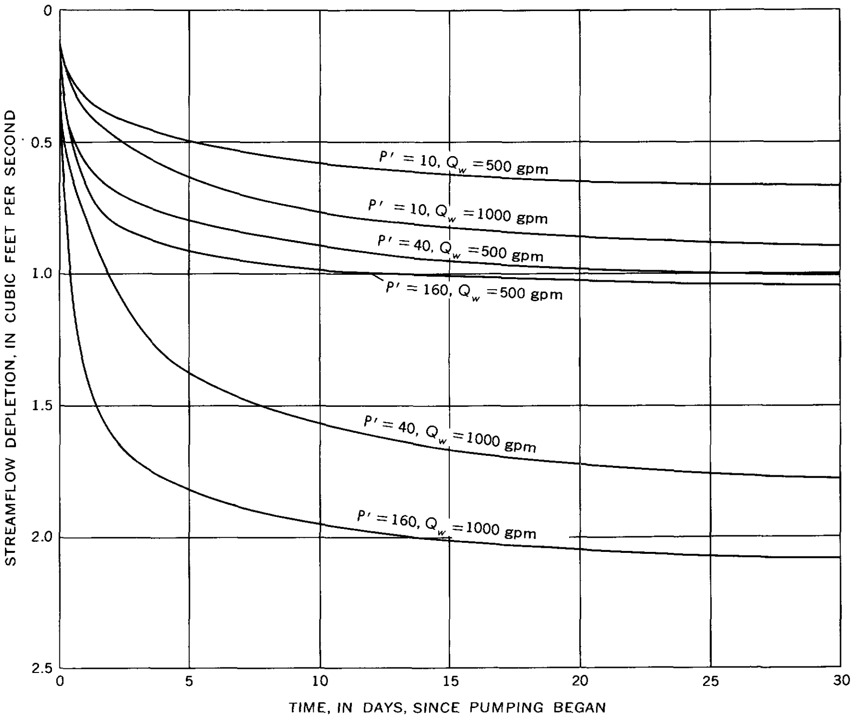
The vertical permeability of the streambed materials also was determined at two places near site 7 by an in-place infiltrometer that was installed by driving a section of thin-wall pipe into the sediments, filling the pipe with water and observing the rate at which the water level declined. The difference in piezometric head between the sediments at the streambed surface and the sediments at the base of the pipe were measured with piezometers, and the hydraulic gradient was determined by dividing the head difference by the thickness of sediments penetrated by the pipe. These tests gave values for the vertical permeability of 14 and 15 gpd per sq ft which agree closely with the values obtained by analysis of the pumping-test data.

The equation for streamflow depletion derived by Theis was modified to account for partial penetration and the low permeability of the streambed materials, as described on page 69. Values for streamflow depletion were computed from the modified equation and the results were again compared to the measured values to check the validity of the equation. The values for streamflow depletion computed from the modified equation showed good agreement with the measured values during the period of the test, as shown by figure 17. For the computations, it was assumed that the streambed below site 7 had a vertical permeability of 10 gpd per sq ft and that the streambed above site 7 had a vertical permeability of 40 gpd per sq ft.

The modified equation was used to compute the effects on streamflow due to ground-water pumpage by wells pumping at various rates near reaches of streams having different streambed permeabilities (fig. 18) and by wells at various distances from a stream (fig. 19). The curves were computed for a homogeneous and isotropic aquifer having a coefficient of transmissibility of 200,000 gpd per ft and a coefficient of storage of 0.15. Although the curves were drawn for hypothetical conditions, they show the magnitudes of the effects of ground-water pumpage on streamflow that could be anticipated under various conditions in the Little Plover River basin and other basins in the sand-plain area. The ratio of streamflow depletion to ground-water withdrawal after a given time of pumpage is greater for a well near the stream than for a well more distant (fig. 19) and for a well near a stream with a more permeable bed (fig. 18).

For wells near partially penetrating streams and discharging at different rates, the wells having smaller discharges will derive a greater part of their discharge from diverted streamflow although the total streamflow depletion will be smaller. This condition differs from that for a well near a fully penetrating stream, for which streamflow depletion is proportional to pumpage.

Any cyclic effect on streamflow caused by the cyclic or intermittent pumpage of ground water for irrigation would be of concern to conservationists interested in the stream as a trout habitat. The effects of a well on a stream that is 1,000 feet or more from the stream are considerably delayed as may be seen in figure 19. The cyclic pumping of a well at this distance from the stream probably would not cause a noticeable cyclic effect on streamflow (fig. 13) but would cause an effect similar to that of a well pumped continuously at the average discharge rate of the cyclically pumped well. Wells that are between 500 and 1,000 feet from the stream probably would have some cyclic effect on streamflow, although this effect probably would not be easily discernible. Cyclically pumped wells that are at distances of 500 feet or less from the stream probably would produce noticeable cyclic effects on streamflow.



On the basis of the equations, $P=\frac{2}{\pi}\int_0^{\frac{\pi}{2}} e^{-\frac{k}{2}\sec^2 u}\,du$ and $\left(\frac{Q_s a \tan 1^\circ}{Q_w/180}\right)^{1/2}\sec u$

$k=\frac{1.87a^2S}{Tt}$,

$T=200{,}000$ gpd per ft,

$S=0.15$,

$a=300$ ft, where $a=$ distance from well to stream,

$W=10$ ft, stream width,

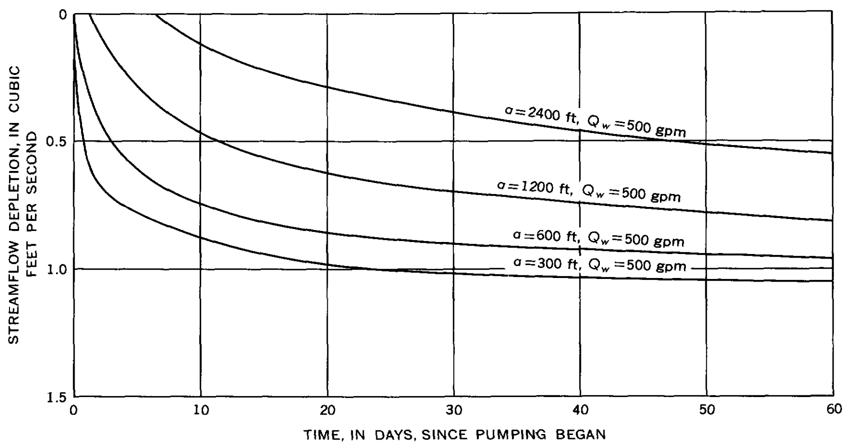
$\phi=1.3$, coefficient of sinuosity for stream,

$P'=$ Streambed permeability in gpd per sq ft, and

$I=1$ ft per ft, hydraulic gradient across bed limiting flow.

Other symbols defined on page 70.

FIGURE 18.—Time-depletion curves showing theoretical effects of ground-water pumpage on the flow of the Little Plover River by wells pumping at several rates and for reaches of stream having different streambed permeabilities.



On the basis of the equations $P=\frac{2}{\pi}\int_0^{\frac{\pi}{2}} e^{-\frac{k}{2}\sec^2 u}\,du$ and $\left(\frac{Q_s a \tan 1^\circ}{Q_w/180}\right)^{1/2} \sec u$

$k=\frac{1.87a^2S}{Tt}$,

$T=200{,}000$ gpd per ft,

$S=0.15$,

$a=$ Distance from well to stream,

$\phi=1.3$, coefficient of sinuosity for stream,

$P'=40$ gpd per sq ft, streambed permeability, and

$I=1$ ft per ft, hydraulic gradient across bed limiting flow.

Other symbols defined on page 70.

FIGURE 19.—Time-depletion curves showing theoretical effects of ground-water pumpage on the flow of the Little Plover River by wells located at various distances from the stream.

EFFECTS OF EXISTING PUMPAGE

Some ground water was pumped for irrigation in the Little Plover River basin throughout the period of study. This pumpage has affected the flow of the stream to some extent, but the effects are not directly discernible from the streamflow records. The effects of ground-water pumpage cannot be determined quantitatively from recession curves because the steeper declines are caused in part by evapotranspiration from phreatophytes near the stream. The farmers usually irrigate during 10- to 12-hour periods during the day, but the irrigation wells and pits are at considerable distances from the stream. Because of the distance, any cyclic effect of the pumpage on streamflow is greatly dampened and is completely masked by the diurnal effects of evapotranspiration by phreatophytes.

An estimate of the maximum effect of ground-water pumpage in 1962 on the streamflow was made from pumpage data by using the equation for streamflow depletion. For the computations, it was assumed that half the pumped water returned to the ground-water reservoir and that streamflow depletion was only half that which would have occurred if there had been no return flow from irrigation. It also was assumed that the maximum effect of each well occurred at the same time. The effects of pumping wells east of the Arnott moraine were ignored for the computations, because the wells are a considerable distance from the stream.

The results of the computations (table 7) provide an estimate for the existing irrigation for a typical year. The maximum depletion rate would be greater in a dry summer and less in a wet one. Although the results of the computations cannot be checked directly from the streamflow records, the values fall in the range of credibility when compared with the difference in summer and winter base-flow recessions and the negative accretion rate determined for the summer months (fig. 11).

TABLE 7.—*Estimated streamflow depletion due to pumpage for irrigation in 1962*

Well	Assumed discharge during pumping (gpm)	Average number of hours pumped per week	Average discharge as continuous rate (gpm)	Number of weeks pumped	Distance from stream (feet)	Maximum streamflow depletion (gpm)
Pt-279	800	72	340	6	1, 700	115
340	800	40	190	5½	1, 500	65
400	800	72	340	7	3, 700	65
4	800	60	290	5	2, 100	80
3	800	72	340	5½	6, 500	15
Total						340 gpm, or 0.75 cfs

EFFECTS OF PROJECTED FUTURE GROUND-WATER DEVELOPMENT

Ground-water development for irrigation is expected to continue to increase in the Little Plover River basin area, and streamflow depletion is expected to be greater in the future than at present. Although the rate and distribution of future ground-water development in the area is not known, the magnitude of future effects may be estimated from a hypothetical schedule of development. The values derived from these computations should be useful in anticipating future problems which may arise because of increased irrigation.

Estimates of the depletion of streamflow caused by increased ground-water pumpage were made from an equation derived by Glover (written commun. 1960). The equation assumes that the pumpage occurs as negative recharge behaving as a series of instantaneous withdrawals. This assumption implies that the wells intercept a uniform amount of water over the entire area. The use of this equation is described in detail by Hurley (1961), and he gives an example of its application to an alluvial aquifer bounded by relatively impermeable bedrock. It was also suggested in his report that the method be applied to areally extensive aquifers, but no examples were given.

The applicability of the equation to compute the influence of accretion on flow in the Little Plover River basin was checked by computing monthly streamflow for the 20-month period, January 1960 to October 1961, using the recharge rates determined from the water-level and streamflow data (fig. 11) and comparing the results with the measured monthly streamflow at gaging station A. To use the equation for this study, the basin was divided into three rectangular areas bounded by streams, ground-water divides, and impermeable boundaries, as shown in plate 6. The average ratio of T/S for the aquifer materials in area 2 (pl. 6) was determined to be about 1.3×10^5 sq ft per day from analysis of water-level recessions in two observation wells following recharge (Weeks, 1964a). A ratio of T/S of 1.0×10^5 sq ft per day for area 1 was computed from water-level recessions using an equation given by Brown (1963). A ratio of T/S of 1.0×10^5 sq ft per day was assumed for area 3.

The fact that the computed stream discharge reasonably agrees with the measured streamflow (fig. 20) indicates that the equation may be applied to an areally extensive aquifer such as that in the sand-plain

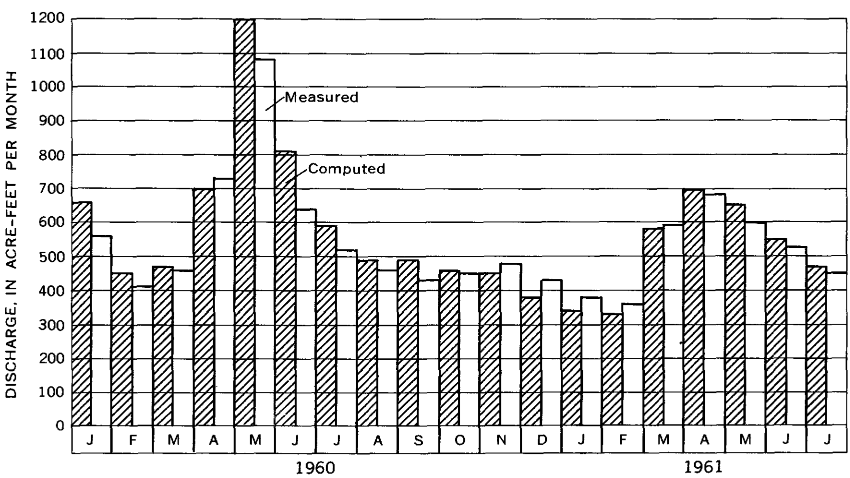


FIGURE 20.—Monthly streamflow of the Little Plover River, as computed from recharge data, compared with the measured flow at gaging station A.

area. The equation could be used both to estimate streamflow depletion due to ground-water pumpage and to compute streamflow rates.

It was assumed for the computations of streamflow depletion that the ground-water pumpage lost by evapotranspiration occurred at an annual rate of 160 acre-feet for 1 year and that the utilization increased at the rate of 16 acre-feet per year thereafter. These values were obtained by assuming that evapotranspiration is increased by 4 inches per year on the irrigated acreage, that 500 acres were under irrigation within the basin for the first year, and that the irrigated acreage increased by 50 acres per year. All the pumpage was assumed to occur during the months of July and August and to be divided equally between the 2 months. The pumpage for each month was assumed to have occurred on the 15th day of the month. The monthly streamflow depletion due to the evapotranspiration loss of 160 acre-feet of ground water each year for a period of 10 years was computed by this method. The monthly depletion rate due to the evapotranspiration loss of 160 acre-feet per year increasing at the rate of 16 acre-feet per year for 10 years was also computed. The results of the computations are shown by figure 21. The average annual depletion rate also is shown by this figure.

During exceptionally dry years, the streamflow depletion would be considerably more than the average rate, because of the increased consumptive use of irrigation water. For example, during an exceptionally dry summer, the consumptive use of irrigation water from 500 acres of land might be 160 acre-feet in June, 200-acre-feet in July, and 200-acre-feet in August. For these conditions, the increase in streamflow depletion in excess of that shown by figure 21 could be estimated by use of figure 22, which shows the monthly streamflow depletion following a month of pumpage as a percentage of the amount pumped. The depletion caused by pumpage in June would be obtained by multiplying the value of consumptive use of 160 acre-feet by the graph value from figure 22 of 0.17 to obtain the depletion in June, by 0.10 to obtain the depletion in July, by 0.07 to obtain the depletion in August, and so on. The effects of the greater-than-average pumpage in July would be computed by multiplying the increase in pumpage of 35 acre-feet by 0.17 to obtain the additional depletion occurring in July, by 0.10 to obtain the additional depletion in August, and so on. The same procedure would be used to compute the depletion resulting from the greater-than-average pumpage in August. The computed depletion rates resulting from the pumpage in June and the increased pumpage in July and August would be summed and added to the depletion rates shown in figure 21 to obtain the total streamflow depletion rate during and following a dry summer.

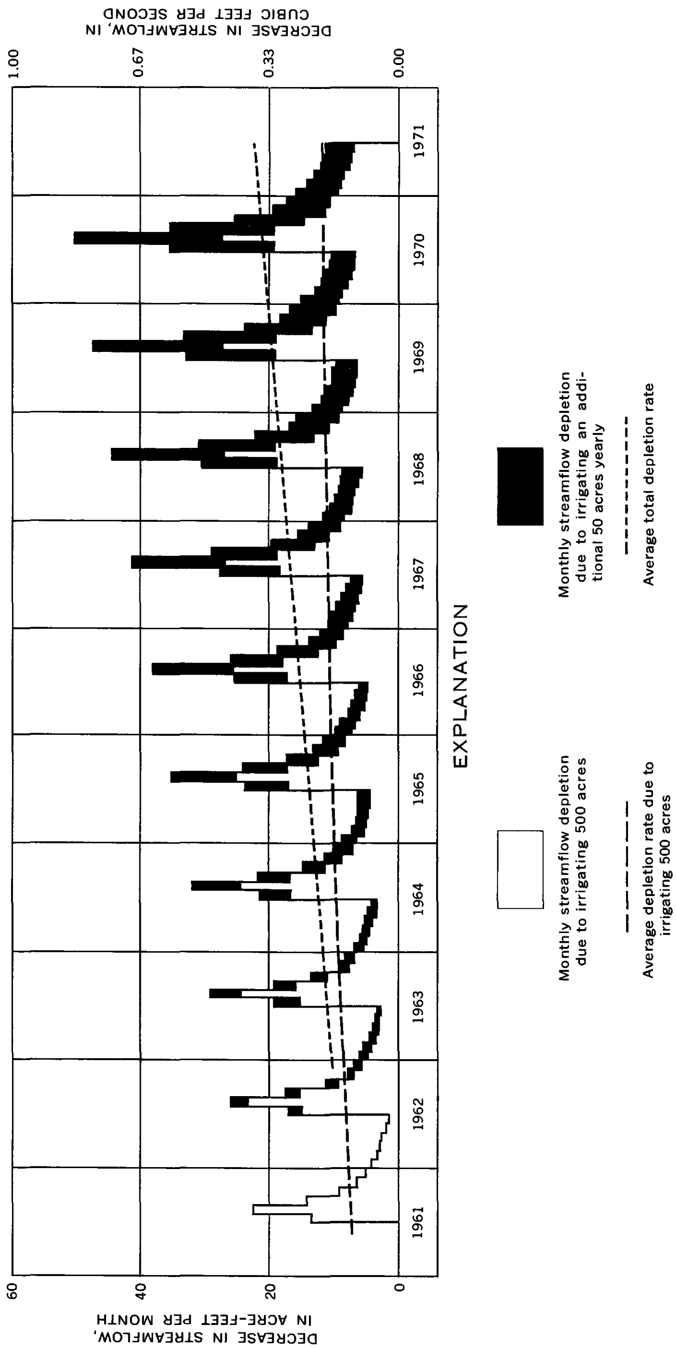


FIGURE 21.—Theoretical monthly streamflow depletion due to projected ground-water pumpage in the Little Plover River basin, as computed from the assumption that the basin area could be idealized as a system of rectangular segments.

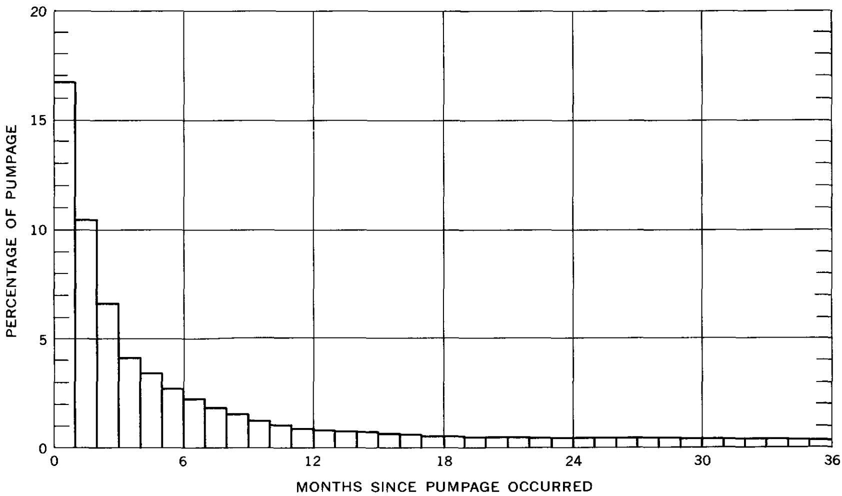


FIGURE 22.—Theoretical monthly rate of streamflow depletion due to uniformly distributed ground-water pumpage within the basin, expressed as a percentage of the monthly ground-water withdrawal. (All pumpage was assumed to have occurred on the 15th day of the first month.)

The streamflow depletion due to any other assumed sequence of monthly pumpage also could be computed from the values shown in figure 22 by using the procedure previously described.

ON STREAM TEMPERATURES

Stream temperatures depend to a certain extent on the quantity of ground-water inflow. Reduced ground-water inflow caused by pumpage might cause the mean summer temperature of the stream to rise and to have a greater diurnal variation. Because of the interest in the effects of ground-water inflow on stream temperatures, an attempt was made to determine an empirical relation between air temperature, streamflow, and stream temperature at gaging stations A and C. For the analysis, the data obtained at gaging station C were analyzed by a multiple regression technique, but no statistically relevant relation between stream temperature and ground-water inflow was found. Apparently data on some of the other factors governing stream temperatures, such as net radiation, wind speed, humidity, evaporation, and ground-water temperatures, are needed before the effects of ground-water inflow can be evaluated quantitively.

However, the order of magnitude of the effects of ground-water inflow on the stream temperatures at gaging stations A and C was obtained by dividing the difference in the mean water temperature between the two gaging stations by the gain in streamflow along that reach. These computations indicate that during the summer months the mean temperature of the stream at gaging station A (pl. 2) is reduced from that at gaging station C by about 1°F for each cfs of gain in the reach. Thus, if the ground-water seepage between the two stations were to be decreased by about 1 cfs, the mean temperature probably would increase by about 1°F.

The diurnal variation in temperature at the downstream station also would be increased by a decrease in pickup between the two stations. At present, daily variations in stream temperature are about 10°–15°F less and streamflow is about 5 cfs greater at gaging station A than at gaging stationC. Thus, if there is a linear relation between the difference in diurnal variation in stream temperature and the difference in streamflow the diurnal stream-temperature variation at gaging station A might be increased by 2°–3°F following a 1-cfs reduction in ground-water inflow between gaging stations A and C. Stream temperatures vary considerably in different reaches of the stream, depending on the rate of ground-water inflow, the width and depth of the stream, and the vegetation. Consequently, the relations described above would be true only for stream temperatures at the two gaging stations, and considerable variation in the relation could exist between the gages. Nonetheless, these figures indicate the probable range of increases in stream temperatures that might result from reductions in ground-water inflow.

EFFECTS OF SURFACE-WATER WITHDRAWALS

When water is removed from a stream, the rate of flow downstream is reduced, and the downstream stage is lowered. The lowered stream stage, however, causes the inflow of ground water to increase, or if the stream is losing water, the outflow to ground water will be decreased. Consequently, the rate of flow downstream is not reduced by the same amount as the withdrawal. Conversely, when withdrawal ceases, the rate of flow downstream does not recover completely until the water removed from ground-water storage is replaced. The rate at which the additional ground water moves to the stream during withdrawal is of interest both to those who withdraw water from the stream and to conservationists. This additional ground-water inflow will affect the supply rate, the water temperatures, and fish-habitat conditions downstream from the point of withdrawal.

The effects of pumpage from the stream on the downstream surface-water supply and on ground-water levels were demonstrated by a test on the Little Plover River. During the test, water was pumped from the stream at an average rate of 1,120 gpm for a period of 29 hours. Pumpage from the stream originally was scheduled to last for a longer period, but it was interrupted when the stream stage rose sharply because of precipitation in the basin. The water pumped was discharged 6,000 feet away from the stream into an area lying outside the basin. Water levels were measured in 11 observation wells near the stream, and streamflow was recorded at 9 sites. The location of wells and stream-measuring sites used during this test are shown in figure 14.

The stage downstream from the pumping site did not respond immediately to pumping from the stream, nor was the downstream flow reduced by as much as the stream was pumped (fig. 23). The hydrographs of the flow at each of the measuring sites show the effects both of surface-water storage within the stream channel and ground-water storage in the stream banks. The lag between the time pumping started and the time stream stages were lowered downstream represents the time required to reduce channel storage by an amount equal

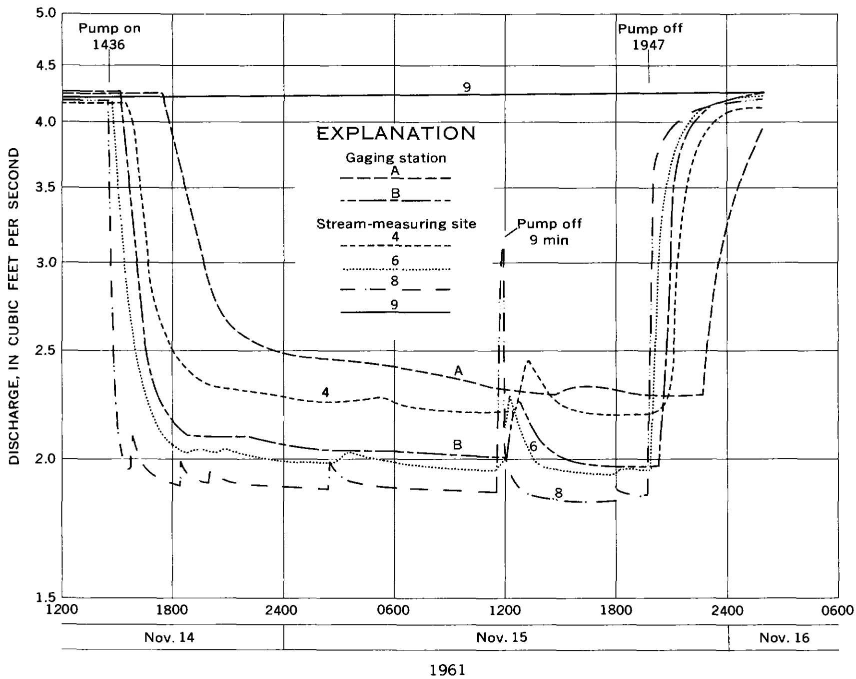


FIGURE 23.—Discharge hydrographs for sites 4, 6, 8, 9, and gaging stations A and B during test when 2.4 cfs were pumped from the Little Plover River, November 14–16, 1961. (All discharges are natural flows, except for discharge at gaging station A. The value of 5.45 cfs, equal to the difference in baseflow between gaging station A and site 9, has been subtracted from the measured flow at that station.)

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to the stage decline times the channel area between gages. Once the stream stage began to decline at a point downstream, it fell rapidly for a time, but then it stabilized somewhat and declined at a slower rate as water was removed from storage within the stream banks.

The measured value for the ground-water inflow to streamflow between the pump and gaging station A after 24 hours of pumping was compared with a value computed from an equation given by Rorabaugh (1963, p. 433). For the computations, it was assumed that the transmissibility of the aquifer was 200,000 gpd per ft, the coefficient of storage was 0.2, that the ground-water divides were located 5,000 feet from and parallel to the stream, and that the stream stage had been lowered 0.15 foot instantaneously as pumping began. The value of 8 cu ft per day per ft of stream channel determined from streamflow measurements for the 7,000-foot reach of the stream compared favorably with the value of 6.3 cu ft per day per ft computed by the equation, and indicated that the equation should yield results of sufficient accuracy to be useful in predicting additional ground-water inflow induced to the stream after longer periods of pumpage. Consequently, the theoretical ground-water contributions to the stream during the first 60 days of pumpage (fig. 24) were computed from the equation by using the previously assumed aquifer coefficients, spacing of ground-water divides, and stream-drawdown value.

POSSIBLE EFFECTS OF STREAMFLOW DEPLETION ON TROUT HABITAT

The depletion of streamflow that results from ground-water withdrawal could be detrimental to trout in the Little Plover River. Lower stream stages would cause a general reduction of living space, reduce the productive stream depth and hiding places, reduce the availability of food, and raise the summertime temperature of the stream. R. J. White, Wisconsin Conservation Department (oral commun., 1963) has observed that trout in Big Roche a Cri Creek, about 30 miles south of the project area, have a slower growth and a higher natural mortality during years when the stream stage is relatively low.

APPLICABILITY OF RESULTS TO OTHER PARTS OF THE SAND-PLAIN AREA

This study of the hydrology of the Little Plover River basin area is extremely detailed. It would not be feasible to study other basins in the sand-plain area as thoroughly. However, the geology and hydrology of the Little Plover River basin area are similar in many respects to much of the sand-plain area. Many of the values for the various hydrologic parameters determined during this study could be applied, with judgment, to other parts of the sand-plain area.

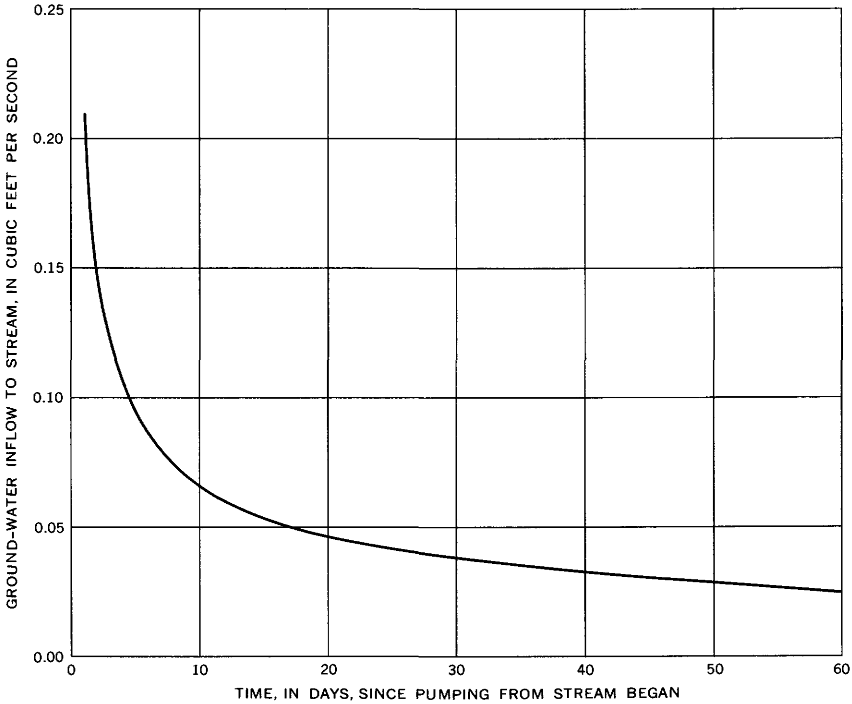

FIGURE 24.—Theoretical ground-water inflow to the Little Plover River induced by pumping from the stream. (Assumptions: Aquifer is homogeneous and isotropic, has a coefficient of transmissibility of 200,000 gpd per ft and a coefficient of storage of 0.2. It is also assumed that the ground-water divides lie 5,000 ft each side of and parallel to the stream. Discharge is to 7,000-ft reach of stream in which the stage has been instantaneously lowered 0.15 ft.)

The geology of the entire sand-plain area is relatively uniform; most of the area is underlain by glacial-outwash deposits, ranging in thickness up to 200 feet or more, which provide an aquifer of relatively uniform characteristics. The permeability of the outwash is probably fairly uniform, as indicated by its consistent lithology and by aquifer tests performed on outwash deposits in other parts of the sand-plain area (Holt, 1965). An approximate value for the transmissibility of the deposits may be estimated from an average value for the permeability of about 2,000 gpd per sq ft and the thickness of the saturated part of the deposits at the site being considered.

Moraine deposits similar to the Arnott moraine and Outer moraine occur within the outwash deposits in the eastern part of the sand-plain area. They appear to be hydraulically continuous with the outwash, and their presence probably does not greatly alter flow conditions within a basin.

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Sandstone ridges similar to the one cropping out in secs. 2 and 14, T. 23 N., R. 8 E., occur locally throughout the area. These ridges will affect the movement of ground water toward the streams, but will not alter greatly the hydrology of the basins in which they occur.

Sandstones of Cambrian age rather than crystalline rocks of Precambrian age form the floor of the ground-water reservoir in the southern part of the area, but this does not affect materially the hydrology of the basins.

Certain of the hydrologic characteristics of the drainage basins within the sand-plain area show considerable variation. The density of the surface-water drainage pattern, the area of the individual basin, and the part of the basin covered by wetlands vary considerably among the several basins. Because of the extensive artificial drainage channels that were constructed in the Buena Vista, Fourmile, Fourteenmile, and Tenmile Creek basins, to the south of the Little Plover River basin, these basins have a denser surface-water drainage pattern than the Little Plover River.

Many hydrologic factors are nearly constant throughout the area. The recharge rate to areas other than wetlands is nearly the same throughout the area, because of the generally flat topography and permeable soil. The seasonal patterns of recharge and of water-level fluctuations are also similar throughout the area.

Potential evapotranspiration is probably about the same throughout the sand-plain area, because the annual net radiation and the average annual air temperature are nearly constant. Actual evapotranspiration also should be about constant, although it might be slightly less in the southern part of the sand-plain area because of the lower average precipitation. Actual evapotranspiration would be somewhat higher in basins that have extensive wetland areas and phreatophytic vegetation.

Irrigation water requirements should be about the same throughout the area, because most of the soil is composed of sand and has a very low soil-moisture retention. Thus, the use of 3.5–4.5 inches for the average consumptive irrigation-water requirement in estimating streamflow depletion probably would be justified.

The effects of pumping for irrigation on the monthly rate of streamflow in the different basins in the sand-plain area would not be directly comparable to the Little Plover River basin. Analysis would have to be made of the geology and hydrology in each basin. The methods used to determine the depletion rate in the Little Plover River basin should be applicable to the other basins.

The effects of a pumping well that is very near a stream on the flow of that stream could be determined by the method described on pages 69–73 of this report, if the permeabilities of the streambed materials were known. Possibly the use of an in-place infiltrometer, as described in the section on the effects of a single well on streamflow, could be used to determine the permeabilities of streambeds throughout the area.

HYDROLOGIC PRINCIPLES AND WATER LAW

Wisconsin's water laws are broad and are capable of handling most types of reasonable water use. The few exceptions have resulted in recent reappraisals of the State's water laws (Kannenberg and others, 1955), and studies by a committee of the Legislative Council and by the State Natural Resources Committee of State Agencies (Scott, 1960) have been made.

Water law is generally complex, uncertain in some respects, and changing. The principal sources of Wisconsin's water laws are:

1. The Northwest Ordinance of 1787 (Wisconsin State Constitution, Article IX, Section 1) declares that the navigable rivers and lakes of Wisconsin "* * * shall be common highways and forever free, as well to the inhabitants of the state as to the citizens of the United States, without any tax, impost or duty therefor."
2. The common-law docrines of riparian rights and ground-water use.
3. Wisconsin statutes granting powers to State agencies and municipalities to regulate the use of water in certain specified instances.
4. The interpretations of State agencies deemed necessary to administer the power delegated by the statutes.
5. Ordinance of local municipalities.
6. Federal statutes and decisions.

Contrasting doctrines of water rights are applied in Wisconsin to surface water and ground water. In Wisconsin, the rights to water in watercourses follow a doctrine common to Eastern States which permits surface water to be used by riparian owners on riparian lands so long as the use is not unduly destructive to the rights of other riparian owners or of the general public.

The Wisconsin statutes generally assign the regulation of use of navigable surface waters to the Wisconsin Public Service Commission. Any manipulations of these public waters, such as using water from streams, building dams, straightening streams, filling in lakeshores, or diverting water to other watersheds, are regulated through permits.

The rights to ground water follow the common-law doctrine, whereby a landowner has an exclusive right to the water from wells on his own property. The exceptions are the public water-supply protection rules, enforced by the Wisconsin State Board of Health, that require authorization to construct or reconstruct a well or wells intended to pump more than 100,000 gpd. State authorization is not required for lesser amounts of pumping.

In the past, many conflicts of interest in water use have resulted from differing opinions, often not based on fundamental hydrologic principles, as to the behavior of water. Many of these opinions are based on the assumption that the effects of water development either are nonexistent or are greater in magnitude and extent than is actually true. For example, a claim by an owner of lakefront property that declining lake levels are due to pumping wells for irrigation may be false if facts show that the decline in lake levels was directly related to a deficiency in precipitation and that irrigation pumpage was in a different ground-water drainage area. Or a claim, by an owner of a well adjacent to a stream, that withdrawal of water from that well will not affect streamflow may be false if facts show that the aquifer supplying the well is hydrologically connected to the stream.

The extent of a conflict of interest involving alternate patterns or methods of water development may depend on the total depletion of the flow of a stream, on the maximum rate at which streamflow is depleted, or upon a combination of these two factors. For example, a water user depending on surface-water storage in reservoirs downstream from the development causing the conflict would be concerned with total annual reduction of inflow to the reservoirs by the development, but he would not be concerned that all streamflow depletion occurred in 1 or 2 months. Water users dependent on the downstream flow might not, however, be concerned if a certain upstream development reduced the annual flow of the stream by perhaps 5 percent, but they might be greatly concerned if this same development reduced the weekly or monthly flow of the stream by 20–30 percent for 1 or 2 months during the summer. Thus, in order to resolve conflicts of interest, the true interests of the affected parties, as well as the hydrologic factors involved, must be carefully determined.

This report has shown that the withdrawal of large quantities of water from a well tapping sand and gravel deposits within a few hundred feet of a stream will noticeably reduce streamflow during even a short period of pumping. Most of the streamflow depletion resulting from pumping such a well would occur during and shortly after the pumping period. A similar well half a mile or more from the stream and pumping for a relatively short period during the year might not produce a noticeable effect on streamflow. This is true because depletion caused by such pumpage would be distributed fairly uniformly throughout the year, and any changes in streamflow resulting from such depletion would be masked by changes in streamflow due to other factors. Despite the difference in seasonal rates of depletion by the two wells, the ultimate streamflow depletion by both wells would be nearly equal, if consumptive use of pumpage from each well was equal and if pumpage from neither well reduced evapotranspiration from ground water. Thus, conflicts of interest in which a major concern is to maintain streamflow at a certain rate during the peak withdrawal period could be minimized by requiring that wells be spaced a certain distance from the stream. However, if the conflict could be resolved only by keeping the total streamflow depletion below a certain amount, ground-water development leading to consumptive use would have to be limited within the entire basin. Furthermore, under these conditions, ground-water development in areas adjoining the basin would have to be limited to prevent a shift in ground-water divides which would reduce the area of ground-water runoff within the basin.

Increasing uses of water create many complex problems that require greater knowledge of water facts in order to develop possible solutions. Many solutions to water problems will involve legal questions. A knowledge of the interrelation of precipitation, surface water, and ground water can play an important role in clarifying water problems and may be expected to assist materially in the future in devising water laws that will be in accord with fundamental hydrologic principles.

SUGGESTED RESEARCH

Although a great deal of information was collected for this study, more research is needed to provide a better understanding of certain phases of the hydrology of the area.

The results of this study indicate that additional research is needed on the relation between stream temperature and base flow, the hydrologic budget during the winter, and movement of water in the unsaturated zone. The Little Plover River basin area is ideal for conducting additional hydrologic research because the detailed information already acquired provides a sound background from which to proceed.

The effects of base flow variations on stream temperature should be determined by a separate research study. This relation probably would have to be determined empirically because of the large number of variables involved. At the minimum, net radiation in the basin and ground-water temperatures would have to be determined, in addition to collection of data on water and air temperatures and streamflow. Data on relative humidity and on wind speeds also would be useful.

A study of the hydrologic budget for the winter months is needed. During this period, water is lost from the snow by evaporation and is gained by frost accumulation on the snow on cold clear nights. Water also is gained by the snow from condensation on warm humid days when the snow is melting rapidly (Light, 1941, p. 195). The quantitative aspects of snow evaporation, frost accumulation, and moisture condensation need to be studied in detail to provide a complete picture of the hydrologic budget.

Knowledge of the movement of water in the unsaturated zone is important to a complete understanding of the hydrologic system. Considerable quantities of ground water may move into the capillary fringe and, by vapor transfer, into the frost zone during periods of extreme cold, when a thermal gradient exists from the water table to the frost zone. The movement of water by vapor transfer along a thermal gradient could be studied in more detail by use of a neutron meter as described by Van Bavel, Underwood, and Swanson (1956). Data obtained with the neutron meter would give quantitative information on water in the frost zone and in the capillary fringe at various times.

A study of the movement of irrigation water into the unsaturated zone would aid greatly in evaluating the effects of irrigation on the hydrologic system and would provide a check on the consumptive-use requirements of the crops. This study also could be made by use of a neutron meter.

CONCLUSIONS

Ground water and surface water are closely interrelated in the Little Plover River basin area and neither may be considered as a separate or independent supply. The Little Plover area, as a representative basin within the sand plains, has geologic and hydrologic features that are characteristic of those features throughout the sand plains. Thus, all water within the sand plains, whether above or below the land surface, must be recognized as belonging to a unified water system.

The withdrawal of either ground water or surface water for consumptive use may cause both a decrease in streamflow and a lowering of ground-water levels. Because the water sources are so closely related, the withdrawal and consumptive use of any given amount of water within the Little Plover River basin area will cause an equal amount of streamflow depletion, if, as appears to be true in the Little Plover River basin, ground-water withdrawals do not reduce evapotranspiration from ground water.

Seasonal pumpage of water would reduce both the total supply of water and the seasonal rate at which it is available. Frequently, the seasonal effects of water development are more critical than the effects on the total supply. Consequently, both factors must be considered in evaluating the effects of development. This study has shown that the available surface-water supply downstream from the development area will be depleted at a rate less than the maximum pumpage rate, because some of the water pumped will be withdrawn from ground-water storage. This is true even when the water is withdrawn from the stream. The effects of ground-water storage would be greater and the maximum depletion rate less when the pumpage was from a nearby well than when the pumpage was from the stream. Furthermore, the maximum rate at which streamflow was diminished would decrease as the distance from the well to the stream increases. Thus, although the total depletion due to pumpage from the stream and from nearby wells would be nearly the same, the maximum rates at which depletion might occur would differ considerably under various patterns of development.

The principal consumptive use of water in the Little Plover River basin is for irrigation. During an average year, evapotranspiration losses from irrigated cropland in the area would be about 4 inches greater than from nonirrigated land planted to the same crop. The irrigation of an additional 500 acres within the basin could thus deplete the average annual streamflow of 6,500 acre-feet by about 2.5 percent at the downstream gaging station A, assuming that evapotranspiration losses from the land prior to irrigation were equal to evapotranspiration losses from the irrigated crop. Ultimate irrigated acreage within the basin may be as much as 2,500 acres; an annual depletion of about 13 percent of the normal streamflow would result.

If the irrigation development were from ground water, streamflow would be reduced below its normal flow throughout the year. However, the maximum rate of depletion would occur near the end of the irrigation season and would be concurrent with natural low flow during the summer months. Assuming consumptive use to be 4 inches per year, the irrigation of 500 acres for 10 years would cause a maximum monthly depletion of 0.5 cfs and 20 percent of the annual depletion would occur in that month.

Major streamflow depletion and the resulting decline of stream stage may have adverse effects on the resident trout. Lower stream stages would cause a general reduction of living space, reduce the protective stream depth and hiding places, and reduce the availability of food. If depletion is caused by reduced ground-water inflow to the stream, the summertime temperature of the stream water might increase.

With proper discretion, many of the principles and hydrologic values that are valid for the Little Plover River basin area may be applied to other areas of the sand plains. The methods used to determine streamflow depeltion should be applicable to other basins. The values of 2,000 gpd per sq ft for permeability and 0.15–0.2 for specific yield should be valid for other areas of outwash deposits in the sand plains. Application of these methods and values by water managers, farmers, and sportsmen should aid in the future development of water resources in the sand plains.

The quantitative proof that ground water and surface water are related in this area should aid in the management and the formulation of new legislation that recognizes all water as being part of an integrated hydrologic system. Whereas present laws do not acknowledge the interrelation of ground water and surface water, new laws might benefit from the knowledge that any consumptive use of water within a basin represents a loss of that water to any other potential user. Although the report deals only with the sand-plain area, where the interrelation is relatively easy to demonstrate, ground water and surface water are related in all areas of the State of Wisconsin.

DEFINITIONS OF TERMS FOR HYDRAULIC PROPERTIES OF AQUIFERS

To make estimates of the amount of water available for development within the ground-water reservoir, the water-bearing properties of the aquifer materials must be evaluated quantitatively. The water-bearing properties of the aquifer materials are expressed quantitatively as the coefficients of permeability, transmissibility, and storage. The specific yield, a parameter closely related to the coefficient of storage, is also useful in evaluating hydrologic changes.

Coefficient of permeability of an aquifer is a measure of the aquifer's capacity to transmit water. The U.S. Geological Survey generally expresses the coefficient of permeability as the rate of flow in gallons per day through a cross-sectional area of 1 sq ft under a hydraulic gradient of 1 ft per ft. Although these units are useful in expressing the concept of permeability, they are mathematically awkward. Thus, it is frequently more practical to express the coefficient of permeability in consistent units, such as feet per day.

Coefficient of transmissibility expresses the rate of flow of water in gallons per day, through a vertical strip of aquifer 1 ft wide extending the full height of the aquifer under a hydraulic gradient of 100 percent. The transmissibility is equal to the product of permeability and bed thickness and is expressed in units of gallons per day per foot or in square feet per day.

Coefficient of storage is the ability of a rock unit to release water under a change in head. The coefficient of storage represents the volume of water released from or taken into storage per unit surface area per unit change in piezometric head and is a dimensionless ratio. Under artesian conditions, the water released from storage when the head is reduced is derived from expansion of the water and compaction of the aquifer skeleton, and the coefficient of storage is very small, generally in the magnitude range of 10^{-6}–10^{-3}.

Specific yield is the volume of water involved in gravity drainage or refilling, divided by the volume of the drained materials. Under water-table conditions, most of the water released is derived not only from expansion of the water and contraction of the aquifer skeleton, but also by gravity drainage or refilling in the zone through which the water table moves. For most water-table aquifers, the coefficient of storage practically equals the specific yield.

MODIFICATION OF EQUATION FOR STREAMFLOW DEPLETION DUE TO PUMPING NEARBY WELLS

An equation to determine the depletion of flow from silted streams by nearby wells would be useful in many areas where water is used both from streams and wells. The equations currently in use (Theis, 1941, p. 734–738; Glover, 1954, p. 468–470) are not adequate to define the streamflow depletion in the case of a stream that has a silty bed because of the assumption that the stream completely penetrates, and is perfectly interconnected with, the aquifer. Consequently, the solution offered by Theis (1941, p. 735, eq. 1) was modified to account for the effects of limited permeability of streambed materials and the partial penetration of the stream on the streamflow depletion rate due to well pumpage.

The equation derived by Theis that is to be modified is as follows:

$$P=\frac{2}{\pi}\int_0^{\frac{\pi}{2}} e^{-\frac{k}{2}\sec^2 u}\,du \qquad (1)$$

where P=part of water pumped derived from streamflow,

$k=\frac{1.87a^2S}{Tt}$,

a=distance from well to stream along perpendicular, in feet,

S=storage coefficient or specific yield of aquifer,

T=transmissibility of aquifer, in gpd per ft,

t=time since pumping began, in days,

$u=\text{arc tan }\frac{x}{a}$,

x=distance along stream from perpendicular intersecting well.

This equation represents the flow across a line at distance a from the well when a constant head is maintained along the line representing the stream. Frequently, however, the permeability of the streambed materials is so low that the stream cannot supply water to the aquifer fast enough to maintain a constant head, and the water table is pulled below the bottom of the stream. Once this occurs, water moves from the stream to the well at a constant rate, and the remainder of the water that otherwise would be derived from streamflow is derived from storage within the aquifer.

The rate at which water is removed by a well from a reach of stream for which the water table lies below the streambed depends on the area of the streambed, on the permeability of the section of streambed materials limiting ground-water flow, and on the hydraulic gradient across that section. The area of the streambed for a given reach may be found from the base-line length, the degree of sinuosity, and the width of the stream. The permeability of the streambed section may be determined by an in-place permeameter, and the hydraulic gradient may be determined approximately by dividing the thickness of the limiting bed into the distance between stream level and the bottom of the bed.

The maximum rate at which a unit length of the stream would be depleted by ground-water pumpage may be expressed by the equation:

$$Q_s = \phi W P' I \tag{2}$$

where Q_s = rate of streamflow depletion,
ϕ = degree of sinuosity of the stream,
W = width of stream,
P' = vertical permeability of section of streambed materials limiting ground-water flow, and
I = hydraulic gradient across section.

Equation 2 is valid only for losing streams. For gaining streams, the maximum rate of depletion would be given by the equation:

$$Q_s = \phi W P' I + Q_i \tag{2a}$$

where Q_i = the rate of ground-water inflow per unit length of the stream.

The maximum rate of flow through the streambed materials may be related to the potential depletion rate due to pumping a nearby well by the following equations:

$$\left(\frac{Q_s a \tan 1^\circ}{Q_w/180}\right)^{\frac{1}{2}} \sec u \tag{3}$$

or

$$\left(\frac{Q_s a \tan 1^\circ + Q_i/\phi}{Q_w/180}\right)^{\frac{1}{2}} \sec u \tag{3a}$$

where Q_w = the discharge of the well. Equation 3 or 3a expresses the maximum rate at which a reach of the stream may be depleted by a well located a distance a from the stream and pumping at a rate of Q_w.

For aquifers of known hydraulic properties, the effects of a pumping well on the flow of a nearby semi-insulated stream may be determined approximately by preparing a graph of the function exp $-\frac{k}{2}\sec^2 u$ for the known or assumed values of a, S, T, and t. Values for the limiting equation (3 or 3a) for maximum rate of flow from the stream may be plotted on the same graph. The part of the well discharge derived from streamflow may be determined by graphically integrating the area enclosed by the limits $u=0$ (the axis of symmetry);

$$e^{-\frac{k}{2}\sec^2 u}; \text{ and } \frac{Q_s\, a \tan 1^\circ}{Q_w/180} \text{ or } \frac{Q_s\, a \tan 1^\circ + Q_i}{Q_w/180},$$

as appropriate (fig. 25). The length of the reach of stream for which the water table has been drawn down below the streambed may be determined from the value of u for the intersection of the line representing $\exp^{-\frac{k}{2}\sec^2 u}$ with that representing equation 3 or 3a.

Analysis of the data obtained from the test on well Pt–410 (fig. 15) indicates that values computed by the modified formula yield a fairly accurate estimate of streamflow depletion for periods of pumping of a few days or less. For longer periods of pumping, however, the modified equation would yield values which were too low, because the cone of depression for a well near a semi-insulated stream would expand at a faster rate than the cone for a well pumping near a completely penetrating stream. Because of this faster expansion of the cone, water would be diverted to the well from the more distant reaches of the partially clogged stream at a rate greater than that implied by the equation.

A second approximation of the rate of streamflow depletion due to a pumping well may be determined from estimates for depletion by wells located at greater distances from the stream. The rate of streamflow depletion should always be greater for wells near the stream than for wells more removed. Thus, in order to determine the lower limit of the rate of streamflow depletion for longer periods of pumping, the depletion rate due to a well located at a distance at which

$$\frac{Q_s a \tan 1^\circ}{Q_w/180}=1$$

may be computed and plotted on the same graph as that for depletion versus time for the well nearer the stream. Depletion due to wells successively closer to the stream may also be plotted on the graph.

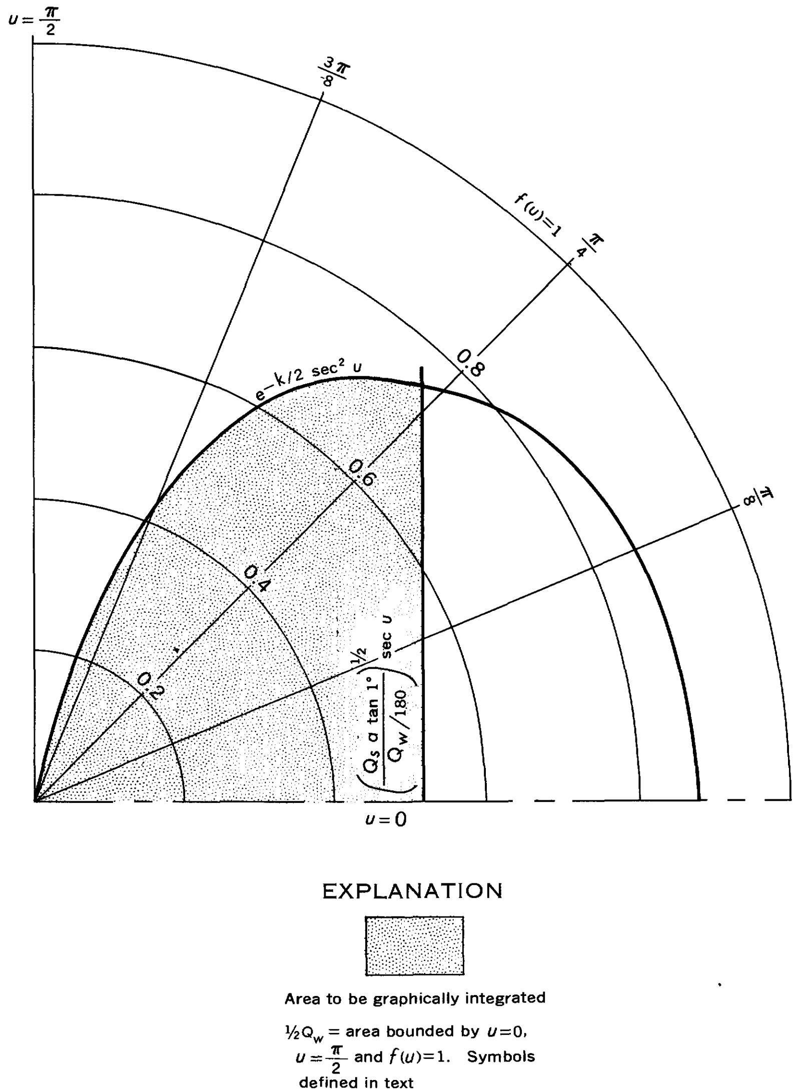

FIGURE 25.—Graph of the functions exp $\left(-\frac{k}{2}\sec^2 u\right)$ versus u, and $\left(\frac{Q_s a \tan 1°}{Q_w/180}\right)^{1/2}$ sec u versus u, showing the area to be integrated to determine the rate of streamflow depletion due to the pumping of a nearby well.

Once the values of depletion versus time for the more distant locations are plotted, a graph of streamflow depletion versus time for the well in question may be constructed by drawing a smooth curve below the computed points for the more distant wells. This should give a relatively good approximation of the streamflow depletion rate for longer periods of pumping.

Although the foregoing methods of analysis are not exact and lack mathematical elegance, they provide estimates of streamflow depletion due to the pumping of nearby wells which are much more accurate than those provided by equations which asume that the stream completely penetrates and has perfect hydraulic connection with the aquifer. Other investigators are attempting to determine an analytical solution to this problem. Until such a solution is found, however, the method given here should provide a usable approach to obtain approximate results.

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