

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES DIVISION

EFFECTS OF IRRIGATION ON STREAMFLOW IN THE CENTRAL SAND PLAIN OF WISCONSIN

By
E. P. Weeks and H. G. Stangland



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

Open-file report

MADISON, WISCONSIN
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ABSTRACT

Development of ground water for irrigation affects streamflow and water levels in the sand-plain area of central Wisconsin. Additional irrigation development may reduce opportunities for water-based recreation by degrading the streams as trout habitat and by lowering lake levels. This study was made to inventory present development of irrigation in the sand-plain area, assess potential future development, and estimate the effects of irrigation on streamflow and ground-water levels.

The suitability of land and the availability of ground water for irrigation are dependent, to a large extent, upon the geology of the area. Rocks making up the ground-water reservoir include outwash, morainal deposits, and glacial lake deposits. These deposits are underlain by crystalline rocks and by sandstone, which act as the floor of the ground-water reservoir.

Outwash, the main aquifer, supplies water to about 300 irrigation wells and maintains relatively stable flow in the streams draining the area. The saturated thickness of these deposits is more than 100 feet over much of the area and is as much as 180 feet in bedrock valleys. The saturated thickness of the outwash generally is great enough to provide sufficient water for large-scale irrigation in all but two areas--one near the town of Wisconsin Rapids and one near Dorro Couche Mound. Aquifer tests indicate that the permeability of the outwash is quite high, ranging from about 1,000 gpd per square foot to about 3,800 gpd per square foot. Specific capacities of irrigation wells in the area range from 14 to 157 gpm per foot of drawdown.

Water use in the sand-plain area is mainly for irrigation and water-based recreation. Irrigation development began in the area in the late 1940's, and by 1967 about 19,500 acre-feet of water were pumped to irrigate 34,000 acres of potatoes, snap beans, corn, cucumbers, and other crops. About 70 percent of the applied water was lost to evapotranspiration, and about 30 percent was returned to the ground-water reservoir. Irrigation development should continue in the sand plain; future development probably will include improved artificial drainage and land clearing.

The hydrology of the sand-plain area was studied from water budgets for seven basins and from water balances for eight types of vegetative cover or land use. During the study period about 16-20 inches of the 28- to 30-inch average annual precipitation were lost to evapotranspiration from different basins in the area. Evapotranspiration from different types of vegetative cover or land use ranged from about 14 inches per year for bare ground to about 25 inches per year from land covered by phreatophytes. Evapotranspiration is about 19 inches from forested land, about 16 inches from grassland and unirrigated row crops, about 19 inches from irrigated beans, and about 22 inches from irrigated potatoes.

Variations in evapotranspiration from the different types of vegetative cover result mainly from differences in soil moisture available to the plants. Available soil moisture ranges from about 1 inch for shallow-rooted grasses and row crops to about 3 inches for forest.

Most of the precipitation not used by plants or to replenish soil moisture seeps to the water table, and ground-water recharge in the area averages about 12-14 inches per year. However, computed recharge ranged from about 3 inches to about 22 inches during the 1948-67 period, depending upon the amount and seasonal distribution of precipitation. Of the average 12-14 inches of recharge, about 10-13 inches are discharged to the streams draining the area, and about 1-2 inches are used by phreatophytes or by irrigated crops.

Annual streamflow in the area averages about 11-12 inches per year, and because it is sustained mainly by ground water, its seasonal distribution is fairly uniform. However, streamflow varies seasonally, being highest in the spring, low in the summer, higher again in the fall, and lowest during winter. Different streams in the area show differing amounts of seasonal variation, depending upon the drainage pattern and the types of terrain drained by the stream. Streams in the headwater area east of the marshes and in the forested area downstream from the marshes show well sustained seasonal flows. Streams and drains in the marsh area, however, exhibit large seasonal variations in flow.

Both streams and ground-water levels are affected to some extent by irrigation development in the area. The most pronounced effects are in the headwater area of the streams, located between the Outer moraine and the marshes. Within the headwater area about one-fourth to one-third of the acreage has been developed for irrigation, mainly from grassland or unirrigated cropland. This change in land use has resulted in increased evapotranspiration of about 2-5 inches. The flow of streams draining the headwater area is depleted by this increased evapotranspiration by about 25-30 percent of the natural flow during an average summer. During severe drought, however, depletion of summer flow would be much greater, and could be as much as 70-90 percent of the natural flow of the headwater streams. Such depletion would result in decreased stream depth and increased stream temperatures, thus degrading the streams as trout habitat.

Water levels in the headwater area are drawn down both locally near pumping wells and regionally over the headwater area. Local drawdowns are insufficient to cause excessive well interference among irrigation wells as long as the wells are spaced one-eighth mile or more apart. Areally, water levels are drawn down by pumping for irrigation by about 0.5 foot during the summer, as compared to a 2- to 3-foot natural decline for the same period. Long-term declines in water levels are greatest in the major ground-water divide area, where they would be about 2-3 feet at the present level of development.

Development of land in the marsh area for irrigation has been limited, but about 1,600 acres have been brought under irrigation in areas where new drainage ditches have been dug and old ones cleaned. Evapotranspiration would be increased less by irrigation development in the marsh area than in the headwater area, and average annual streamflow depleted less. However, because the drainage works associated with irrigation would more rapidly dissipate ground-water recharge, summer low flows, particularly in dry years, would be severely diminished by extensive irrigation development in the marsh area.

Very little irrigation development has occurred in the forested area downstream from the marshes. Future development would result in conversion of forested land to irrigated crops, and the increase in evapotranspiration would be less than that resulting from conversion of grassland or cropland. Moreover, streams are widely spaced and streamflow well sustained during the summer in the downstream area. Consequently, streamflow depletion due to irrigation development would be less severe than in either the headwater area or the marsh area.

INTRODUCTION

Rapid development of ground water for irrigation in the sand plain of central Wisconsin is affecting streamflow and ground-water levels. More intensive ground-water development may impair opportunities for water-based recreation in the area.

In 1967 about 30 percent of the total acreage in the upper Big Roche a Cri, Fourteenmile, and Tenmile Creek basins was irrigated. This development, which began in the late 1940's, increased the area's economy. However, the possible effects of ground-water withdrawals on streamflow concerned persons seeking to maintain the streams as trout habitat. Information was needed concerning the magnitude of the hydrologic changes brought about by irrigation development so that the undesirable effects of irrigation could be minimized.

Reliable estimates of the effects of irrigation development will benefit the area. Lack of information might result in policies either unduly restrictive to irrigation development or in policies unduly liberal.

PURPOSE

The purposes of this study were to estimate the effects of irrigation development on streamflow and ground-water levels, to determine the magnitude and extent of irrigation in part of the sand-plain area, and to predict areas of future irrigation development. Additional purposes were to determine the hydrologic effects of draining wetlands and clearing trees, and to determine the hydrologic effects of alternative land uses, such as tree plantations.

LOCATION OF THE AREA

The study was conducted in a 650 square-mile area in the eastern part of the sand plain in central Wisconsin (fig. 1). The area includes all or parts of Townships 19, 20, 21, 22, and 23 north, Ranges 5, 6, 7, 8, and 9 east, in Portage, Waushara, Wood, and Adams Counties. Magnitude and extent of irrigation development and the areal factors that affect future development were studied throughout the area. Hydrology and the effects of irrigation on streamflow and water levels were studied in about 300 square miles above stream gages on the Little Plover River and Buena Vista, Big Roche a Cri, Fourmile, Tenmile, and Fourteenmile Creeks.

PREVIOUS INVESTIGATIONS

Effects of developing ground water for irrigation on streamflow in the Little Plover River basin, a basin within the study area, were determined by Weeks and others (1965). In that study, estimates were made of streamflow depletion due to pumpage during a series of years of assumed normal weather. Many study methods described in that report were used in this investigation.

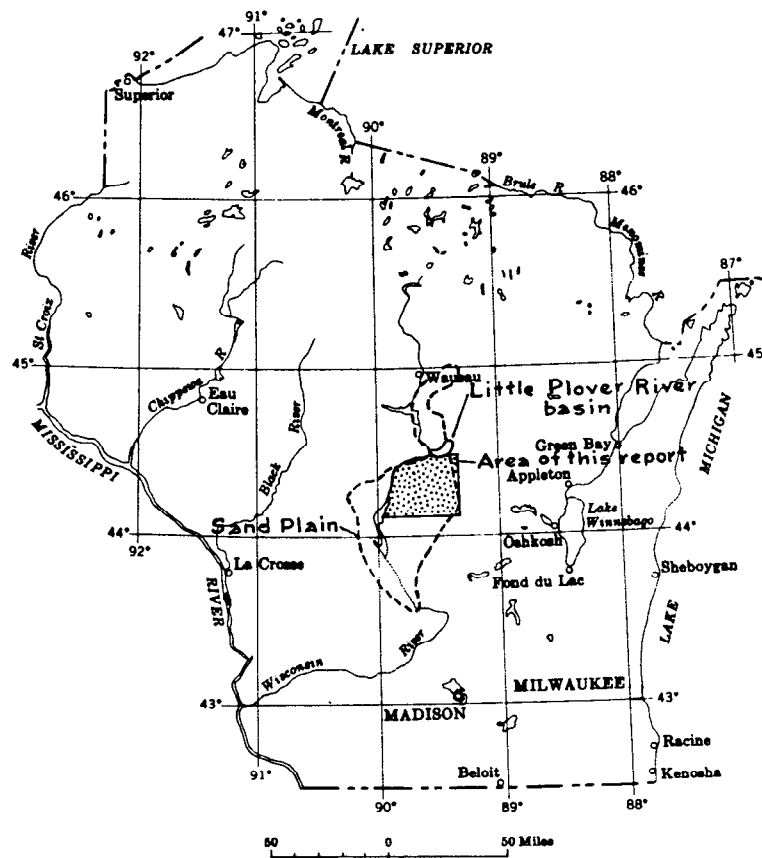


Figure 1.--Index map of Wisconsin showing area of report.

Several other studies have been made of the general geology and hydrology of the area. The general geology was mapped and described by Chamberlin (1877, 1883), Martin (1932), Thwaites (1940), and Bean (1949). Thwaites (1956) mapped the Pleistocene geology and described the glacial drainage and stratigraphy. Reports containing general information on ground water were prepared by Kirchoffer (1905), Weidman (1907), Weidman and Schultz (1915), Wisconsin Bureau of Sanitary Engineering (1935), Drescher (1956), and Holt and others (1964). Holt (1965) and Summers (1965) made relatively detailed studies of the geology and water resources of Portage and Waushara Counties, respectively. General information on the geology and ground-water resources of the central Wisconsin River basin, including the report area, is presented by Devaul and Green (1971).

In addition, considerable research on evapotranspiration has been conducted at the University of Wisconsin Experimental Farm at Hancock. Suomi and Tanner (1958) describe an energy-balance study for estimating evapotranspiration from irrigated alfalfa-brome grass, and Tanner and Pelton (1960a) present the meteorological and lysimeter data obtained for the study. Tanner and Pelton (1960b) and Pelton and others (1960) describe the use of the energy balance and lysimeter data to evaluate the Penman (1948, 1956) and Thornthwaite (1948) methods for determining potential evapotranspiration, respectively. Black (unpublished master's thesis, 1968) describes lysimeter data on evapotranspiration from bare ground in 1967, and Fuchs and Tanner (1967) and Tanner and Fuchs (1968) describe methods for computing evapotranspiration from bare soil using meteorological data.

Wilde and others (1953), also of the University of Wisconsin, investigated the relationship between vegetative cover, depth to water, and altitude of the water table in areas of shallow water table near the Dorro Couche Ranger Station and near Dead Horse Creek, both in the southwestern part of the report area. These data were used to infer conditions under which the vegetation was phreatophytic.

ACKNOWLEDGMENTS

The study was planned and conducted by the U. S. Geological Survey in cooperation with the Wisconsin Department of Natural Resources and the University Extension--the University of Wisconsin Geological and Natural History Survey.

Acknowledgment is made to irrigators and other residents who provided well information and gave access to their land and equipment for measurements and tests. Special acknowledgment is made to Ronald Busse and Raymond Berard, of the Paramount Farms, to Floyd Foster and Charles Slinger, to Ericson Produce Company, and to Clifford West for allowing their wells, equipment, and property to be used for aquifer tests. Well drillers also provided useful information.

Acknowledgment also is made of data and assistance provided by personnel of State agencies. Eugene Mosely and William Johnson, both of the Wisconsin Department of Natural Resources, provided water-level data obtained at check dams on drainage ditches and data for stream profiles of Big Roche and Cri Creek, respectively. Also, Dr. Champ Tanner, of the University of Wisconsin Soils Department, provided information on evapotranspiration in the area and weather data for the station at Hancock.

FACTORS AFFECTING HYDROLOGIC SYSTEM

Several factors influence the effects of irrigation development on streamflow and ground-water levels. Climatic factors influence precipitation, evapotranspiration, and runoff. Geology, topography, drainage, and soil type affect the suitability of land and the availability of water for irrigation, the rate and distribution of ground-water contribution to streams, and the changes in base flow resulting from ground-water pumpage. The effects of irrigation on streamflow are influenced by the difference between the amount of water used by the irrigated crops and the amount previously used by the replaced vegetative cover. The effects of irrigation development on water levels and streamflow depend upon the distribution and areal extent of irrigation and the amount of water pumped.

CLIMATE

Many climatic factors (including precipitation, temperature, solar radiation, humidity, and wind speed) determine evapotranspiration, runoff, and the irrigation water requirements of crops. Of these factors, only daily precipitation and maximum and minimum daily temperatures have been recorded for long time periods in the area, but they are adequate to define the major effects of climate on hydrology on a seasonal and annual basis.

Precipitation and temperature have been measured at Coddington since 1921, at the University of Wisconsin Experimental Farm at Hancock since 1902, and at Stevens Point and Wisconsin Rapids since 1893. Average annual precipitation for the period 1931-60 diminishes slightly from north to south and ranges from 31.40 inches at Stevens Point to 29.59 inches at Hancock.

Average monthly precipitation in the area ranges from about 1 inch in December to more than 4 inches in June, and about 60 percent of the annual precipitation occurs during the growing season (May-September). Most precipitation that contributes to recharge and runoff occurs in the spring.

Precipitation varies from year to year and affects runoff and water levels, especially when precipitation is above or below average for several years in succession. During the field study (1964-67), annual precipitation in the area ranged from about 8 inches above normal to about 6 inches below normal, and averaged about normal (fig. 2). During the period for which water-balance computations were made, 1948-67, average annual precipitation was about 1 inch less than that for the field study period of record (1964-67).

Temperature may be used to estimate evapotranspiration and to determine whether precipitation will be stored as snow. Mean monthly temperatures in the sand-plain area range from about -8°C (Celsius) (16°F) in January to about 22°C (72°F) in July; however, in marsh areas they average about 1 degree lower.

Because winter temperatures are low, snow generally accumulates from December to March. Annual snowfall averages about 45 inches.

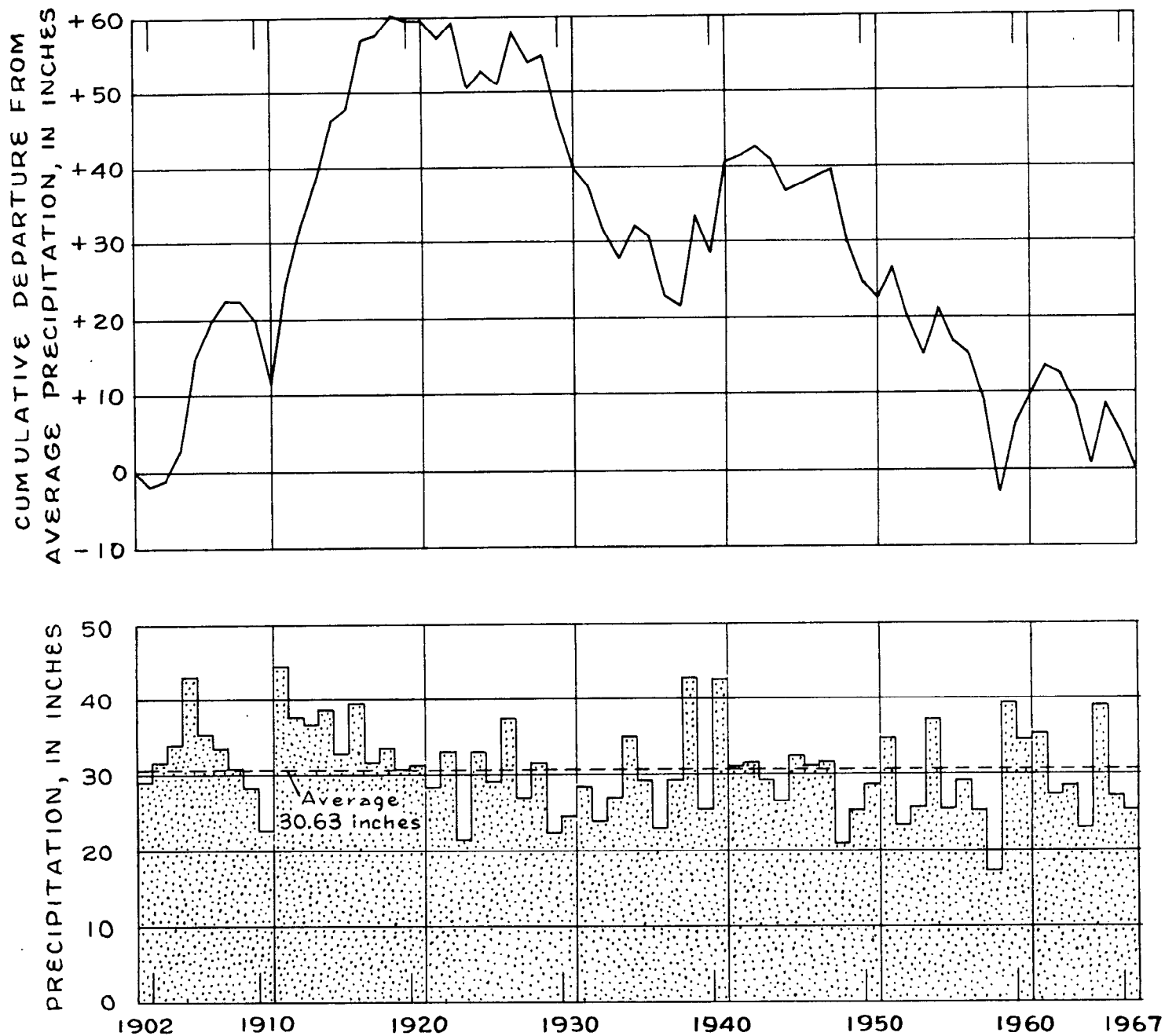


Figure 2.--Annual precipitation at Hancock, Wis., 1902-67, and cumulative departure from the 1902-67 average. (From records of U.S. Weather Bureau.)

GEOLOGY--PHYSICAL AND HYDRAULIC PROPERTIES OF ROCKS

Geologic conditions among other factors control the rate at which ground-water discharges to the streams and the degree to which withdrawals of ground water affect streamflow. Hydrogeologic conditions also control the availability of ground water for irrigation and influence factors that determine the suitability of land for irrigation (topography, drainage, and soils).

Consolidated rocks underlying the area include crystalline rocks of Precambrian age and, in much of the southern part of the area, sandstones of Cambrian age. The crystalline rocks are relatively impermeable and form the floor of the ground-water reservoir. The sandstone, although an important aquifer in much of the State, is much less permeable than most overlying unconsolidated deposits in the study area.

Unconsolidated sediments include pitted and unpitted outwash, till, and lake deposits, all of glacial origin; and peat, alluvium, and dune sand of more recent origin. Glacial deposits generally are thick and highly permeable and, thus, form the main aquifer in the area. The most recent deposits generally are thin, areally limited, or are above the water table and are not important aquifers.

Consolidated Rocks

Crystalline Rocks

Although the study area is underlain by crystalline rocks of Precambrian age, they crop out only along the Wisconsin River near Wisconsin Rapids and Nekoosa, and at Hamilton Mounds in northern Adams County (fig. 3). The outcrops along the Wisconsin River are gneiss. The outcrop at Hamilton Mounds consists of brecciated quartzite with kaolinite clay along the breccia planes. Clay, probably derived from weathered schist, was recovered from some test holes in Wood County. Weathered granite was described by University of Wisconsin personnel in some samples from irrigation wells in T. 22 and 23 N., R. 7 E., and weathered granite was recovered from a test hole in SW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 24, T. 21 N., R. 7 E.

Sandstone

Sandstone of Cambrian age occurs throughout most of the southern part of the report area. Its northern extent, as shown in figure 3, was determined by extensive test drilling in the area. The contact between sandstone and crystalline rock differs considerably from that shown by Weidman (1907) and by Bean (1949).

Sandstone crops out in several ridges and mounds that are erosional remnants of sandstone that once covered the area more deeply and uniformly. It also crops out in the bluff above the Wisconsin River at Nekoosa, in the bank of Petenwell Flowage a half-mile below the Adams-Wood County line, and in the bed of Fourteenmile Creek at the Deerlodge Lake dam. Some mounds and ridges have considerable relief and form prominent landmarks in the sand plain. Others have little relief; these mounds are difficult to locate and are easily mistaken for sand dunes. It is likely that a few additional, unmapped outcrops exist in the area.

The sandstone ranges in grain size from fine to coarse; sandstone samples recovered from test drilling in the area are predominantly medium grained. The sandstone is poorly to well cemented with silica and limonite and contains silt and clay.

The thickness of sandstone in the area ranges from less than 1 foot at the sandstone-crystalline rock contact to about 300 feet beneath outcrops. The greatest thicknesses of sandstone penetrated by wells were 118 feet at Hancock and 129 feet in sec. 11, T. 20 N., R. 7 E., in Adams County.

The sandstone is a source of water but is little used in the report area because of the greater amount available in the glacial deposits. One irrigation well drilled in the sandstone in the SW $\frac{1}{4}$ sec. 11, T. 20 N., R. 6 E., yields less than 700 gpm (gallons per minute). Some irrigation wells have been drilled in thicker sections of sandstone in Adams County south of the report area.

Bedrock Topography

The topography of the bedrock surface in the area partly controls the nature and thickness of the overlying unconsolidated deposits. It directly affects ground-water storage and movement and indirectly affects streamflow. Consequently, the bedrock surface was mapped (fig. 3) from outcrops, from sample logs of high-capacity wells, and from data obtained in test holes.

The map of the bedrock surface indicates the major preglacial drainage pattern and areas where the bedrock surface is generally high. This surface is irregular, particularly in areas underlain by sandstone. The bedrock contours are generalized from test-hole control points about 3 miles apart.

Two major preglacial stream valleys were detected in the sand plain area. A major valley, probably representing the course of the ancestral Wisconsin River, trends southwest across the area from a point about 2 miles east of Whiting to the northern part of Adams County. The course of this valley may extend southwest under the present Wisconsin River channel and through a bedrock low in sec. 4, T. 19 N., R. 4 E., west of the report area. An alternate interpretation is that the main channel trends south between the sandstone mound in sec. 26, T. 20 N., R. 5 E., and Dorro Couche Mound, in sec. 28, T. 20 N., R. 6 E.

The other preglacial valley was carved by a west-flowing tributary to the ancestral Wisconsin River. It has been defined from east of Plainfield to its intersection with the main channel in or near sec. 1, T. 20 N., R. 6 E.

These bedrock valleys are important to ground-water movement because they define the thickest parts of the unconsolidated deposits, and because they are filled with coarser, more permeable material than the remainder of the outwash plain.

Unconsolidated Deposits

Unconsolidated deposits in the area were deposited either by glaciers, glacial streams, or by recent stream and wind action. The glacial deposits consist of unsorted deposits (till, such as in moraines) and sorted and stratified deposits (outwash, kame, and glacial lake deposits). The recent deposits consist of peat, alluvium, and dune sand.

Morainal Deposits

Till was deposited as moraines during periods when the forward flow of ice was balanced with melting and wastage. Till consists of intermixed and poorly stratified material ranging from boulders to clay. Gravel and boulders in the till are granite, quartzite, felsite, gneiss, and sandstone. The large amount of quartz sand in the till originated from glacial erosion of sand and sandstone to the east and northeast.

Three moraines (fig. 4) occur in the area--the Arnott, Outer, and Second moraines. The Arnott moraine is the most westerly of the three and forms an irregular ridge rising from 50 to 80 feet above the surrounding outwash plain. The Arnott moraine is the oldest of the three moraines and is much more weathered and eroded. Near Stevens Point this moraine is overlapped by the Outer moraine. The Outer moraine is a terminal moraine formed from glacier-borne material dumped at the westernmost known limit of advance of the glacier during Cary age. The Second moraine is a recessional moraine formed from material dumped where the retreat of the Cary glaciation was temporarily halted. The Second moraine merges with the Outer moraine in the northern part of the area.

Both the Outer and Second moraines are irregular ridges rising 50-150 feet above the surrounding outwash and till. Till and kame deposits in the moraines may be as thick as 300 feet.

The saturated thickness of the deposits in moraine areas probably is about 100-200 feet. These deposits have not been tapped by high-yielding wells in the area, although several wells that tap moraine deposits yield water for domestic and stock uses.

The hydraulic properties of the morainal deposits were not determined from aquifer tests nor were data available on performance of high-capacity wells tapping the morainal deposits from which the hydraulic properties could be inferred. The deposits are more poorly sorted than outwash in the area, and they presumably would be less permeable. However, the slope of the potentiometric surface (fig. 9) is about the same in the areas of the Arnott and Outer moraines, as in the adjacent areas underlain by outwash. This indicates that the morainal deposits do not greatly impede ground-water flow, and that they are nearly as permeable as outwash materials. The morainal deposits may yield as much as 500 gpm to deep wells; however, the widespread presence of boulders would make drilling difficult.

Near the Second moraine the potentiometric surface is steeper than in most of the report area, as indicated by Holt (1965, pl 2) and Summers (1965, pl 1). Thus, the deposits of the Second moraine may be less permeable than those of the Outer and Arnott moraines.

Outwash

As the glacier melted and formed the Outer and Second moraines, large volumes of melt water flowed west and transported gravel, sand, and silt. Gravel and sand were deposited near the glacier front and in the preglacial valleys of the Wisconsin River and its tributaries. Bedrock valleys filled with sand and gravel and, as backwater from glacial Lake Wisconsin reduced stream velocity,

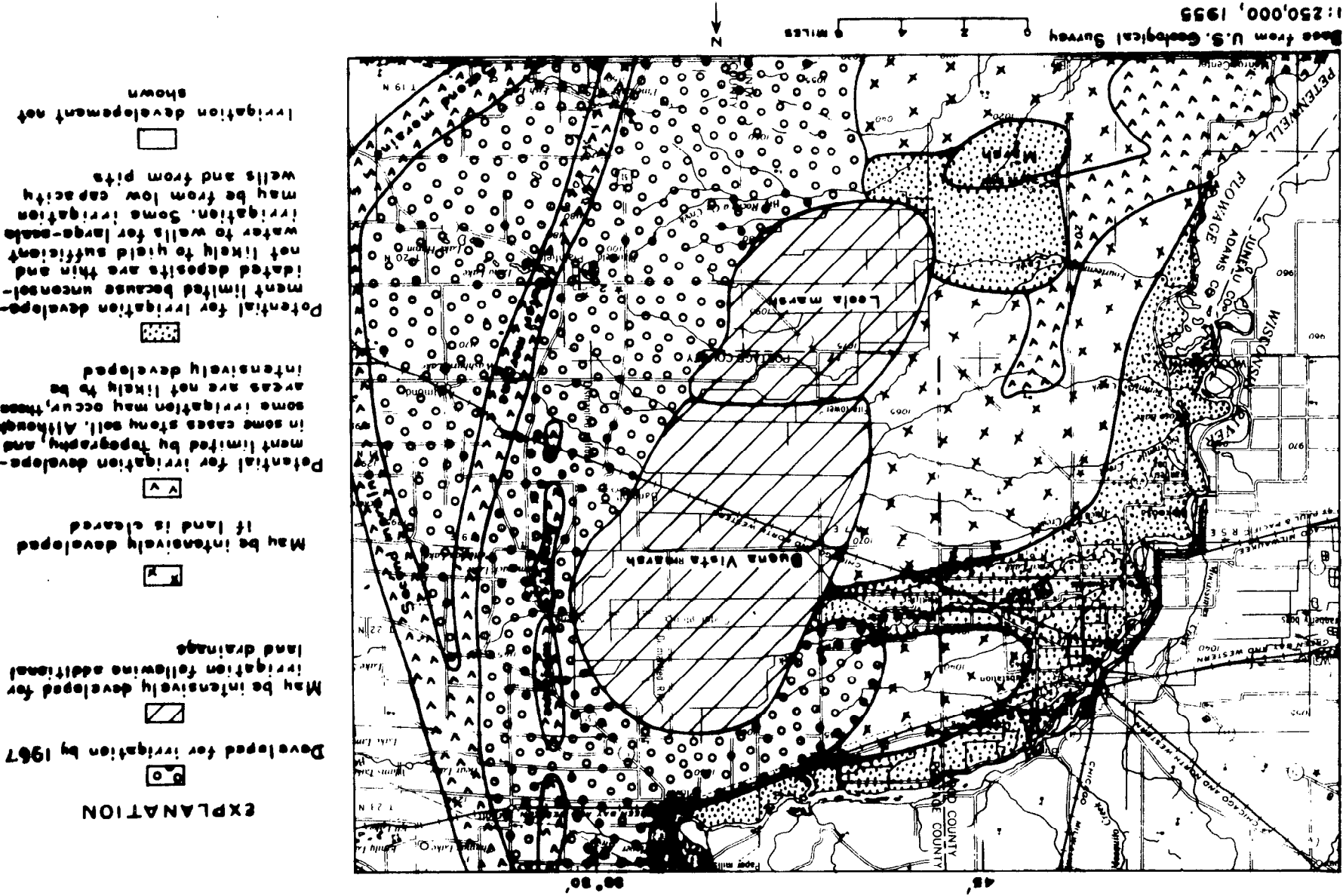


Figure 4.--Map showing location of moraines, drained marshes, and areas of present and potential development in part of the sand plain of central Wisconsin.

the melt waters spread out to form a broad flood plain of fine-grained sand and silt. The present surface of the outwash plain is smooth and slopes a few feet per mile to the west.

The size of sediments generally decreases from west and south of the Outer moraine. Fine-to-coarse grained gravel is along the moraine front. Medium-to-coarse grained sand predominates in the central part of the plain, and medium-to-fine grained sand is adjacent to glacial lake deposits in the southwest.

Outwash west of the Outer moraine generally is nearly free of silt, although beds of silty sand occur locally. Unusually silty sand near some sandstone mounds and ridges indicates that these beds may have been formed in lee areas on the outwash plain.

Pebbly red clay beds were near the base of test holes in NW $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 34, T. 21 N., R. 8 E., and NW $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 5, T. 20 N., R. 8 E. Possibly these deposits originated as ground moraine from a pre-Cary age glacier.

The total thickness of outwash west of the Outer moraine ranges from less than 1 foot at the contact with sandstone mounds to about 200 feet in bedrock valleys. A test hole near Plainfield in SW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 10, T. 20 N., R. 8 E., penetrated 195 feet of outwash.

The saturated part of the outwash beneath the water table governs the amount of water the outwash transmits to wells and streams. The saturated thickness of unconsolidated deposits west of the Outer moraine, mainly outwash but with some alluvium and intercalated glacial lake deposits, was mapped (fig. 5) by comparing the potentiometric map (fig. 9) with the bedrock topography map (fig. 3). The contours on the map (fig. 5) indicate that the saturated thickness is more than 100 feet over much of the area and is more than 180 feet in a bedrock channel near Plainfield. Saturated thickness of unconsolidated deposits is less than 40 feet only near Wisconsin Rapids, near Dorro Couche and Hamilton Mounds, and in local areas surrounding sandstone outcrops.

Outwash between the Outer and Second moraines probably was deposited from glacial melt waters when the glacier front was at the Second moraine. The Outer moraine, already in existence, partly dammed the melt waters and created a different depositional environment than west of the moraine. The outwash plain between moraines slopes generally west about 10 feet per mile, but it is pitted by numerous depressions as much as 50 feet deep, which formed when large blocks of ice, buried by outwash, melted. Gaps eroded in the Outer moraine during the deposition of the outwash, and some melt water flowed west. These melt waters deposited outwash west of the moraine, as indicated by the consistency of slope of the outwash plain across the Outer moraine (fig. 3, section B-B).

Pitted outwash consists mainly of medium-to-coarse sand and fine gravel, but it generally is more poorly sorted and contains more gravel than outwash west of the moraine. Cobbles and boulders, rare west of the Outer moraine, are common in the pitted outwash, especially in the northern part of the outcrop area and near the Second moraine. However, local gravel and cobble beds and a few beds of clay and silt have been noted in wells and test holes throughout the area.

Pitted outwash probably is as much as 300 feet deep; however, only one well penetrates 286 feet of these deposits. Two test holes drilled for the project penetrated 195 and 223 feet of pitted outwash.

The saturated thickness of the pitted outwash deposits probably ranges from 100 to 200 feet over most of the outcrop area. Data available on depth to bedrock were insufficient to map the saturated thickness in detail.

In the southwestern part of the area, where the outwash contains beds of lake clays, unconsolidated deposits are finer grained and less permeable than those in the rest of the area. Although no specific capacity data are available from high-capacity wells tapping outwash in the lake-clay area, data are available from a few wells in Adams County. Specific capacities of seven of these wells averaged 24 gpm per foot of drawdown and ranged from 10.5 to 68 gpm per foot of drawdown. These values are lower than the values for wells tapping outwash just west of the Outer moraine in the report area. The hydraulic properties of the outwash materials were determined by comparing specific capacities of wells, by aquifer tests, and by analysis of water-level recessions in wells.

The hydraulic properties of outwash were estimated by comparing specific capacities (ratio of the yield of a pumping well to its drawdown, expressed as gpm per foot) of wells in the area. These comparisons seem valid, although the specific capacity values are affected by well construction and well development as well as the water-bearing properties of the aquifer at the well site. Most irrigation wells are similarly constructed and developed, so these effects should be approximately the same for each well.

The mean values of specific capacities for wells tapping the pitted outwash are significantly lower, on a statistical basis, than for wells tapping outwash west of the moraine. The specific capacities reported by well drillers for 54 wells west of the Outer moraine average 50 gpm per foot of drawdown and ranged from 18 to 157 gpm per foot of drawdown. Reported specific capacities of 34 wells tapping pitted outwash east of the moraine averaged 36 gpm per foot of drawdown and ranged from 14 to 62 gpm per foot of drawdown. The lower values indicate that the saturated part of the pitted outwash probably is less permeable than the saturated outwash west of the Outer moraine.

Eight aquifer tests (fig. 3) were analyzed to determine the hydraulic properties of the outwash. The test results are summarized in table 1. Details of the test analyses, except for tests 5 and 7, are described elsewhere (Holt, 1965; Weeks, 1964b and 1969). Test 5 was analyzed by the method described by Weeks (1969), and test 7 was analyzed for transmissivity only using the Theis recovery formula (Ferris and others, 1962, p. 100-102). Transmissivity is a measure of the ability of the entire aquifer thickness to transmit water under a head gradient. It is defined as the rate of flow of water through a vertical strip of aquifer of unit width extending the full height of the aquifer under a hydraulic gradient of unity.

The transmissivity of the outwash, as determined from the aquifer tests, differed considerably throughout the sand plain because of differences in saturated thickness and in hydraulic conductivity. Hydraulic conductivity is a measure of the ability of aquifer materials to transmit water, and is expressed

Table 1.--Results of aquifer tests in the sand-plain area.

Location of test site	Number of ob- servation wells	Length of test hrs	Aquifer thick- ness ft	Trans- missivity		Hydraulic conductivity		Ratio of horizontal to vertical	Storage co- efficient	Refer- ence
				gpd/ft	sq ft/day	gpd/ft ²	ft/day			
SW $\frac{1}{4}$ sec. 15, T. 21 N., R. 9 E.	1	12	140 $\frac{1}{2}$ /	270,000	36,000	1,900	260	- - - - -	0.15	Holt, 1965.
NE $\frac{1}{4}$ sec. 9, T. 21 N., R. 9 E.	1	12	150 $\frac{1}{2}$ /	330,000	44,000	2,200	290	- - - - -	0.14	Do.
NW $\frac{1}{4}$ W $\frac{1}{2}$ sec. 18, T. 23 N., R. 9 E.	21	74	80	140,000	19,000	1,750	230	20	0.15	Weeks, 1964.
SE $\frac{1}{4}$ sec. 36, T. 23 N., R. 7 E.	6	48	70	170,000	23,000	2,400	320	7		Weeks, 1968.
NE $\frac{1}{4}$ sec. 2, T. 22 N., R. 8 E.	5	37	120 $\frac{1}{2}$ /	450,000	60,000	3,800	500	1	0.20	None.
SW $\frac{1}{4}$ sec. 22, T. 21 N., R. 8 E.	6	48	80	80,000	11,000	1,000	130	2	0.16	Weeks, 1968.
SW $\frac{1}{4}$ sec. 14, T. 20 N., R. 8 E.	5	48	140 $\frac{1}{2}$ /	180,000	24,000	1,300	170	- - - - -	- - - - -	None.
NE $\frac{1}{4}$ sec. 5, T. 19 N., R. 8 E.	6	80	120 $\frac{1}{2}$ /	164,000	22,000	1,400	180	4	0.18	Weeks, 1968.

 $\frac{1}{2}$ / Estimate.

as the rate of flow through a cross-section of unit area under a hydraulic gradient of unit change in head over unit length of flow path. The horizontal hydraulic conductivity is determined by dividing transmissivity by the aquifer's thickness. The hydraulic conductivity of the outwash at sites 3, 7, and 8 probably represents most of the sand plain west of the Outer moraine. The hydraulic conductivity at site 4 is relatively high, apparently because the aquifer at the site consists of coarse material. The hydraulic conductivity at site 4 may represent only a local area near the Wisconsin River between Wisconsin Rapids and Plover. The outwash is finer grained and, consequently, less permeable to the south.

The high hydraulic conductivity at site 5 may represent outwash in the major bedrock valleys in the area. The outwash at this site includes coarse gravel deposited in the ancestral Wisconsin River channel.

The hydraulic conductivity at site 6 may represent only local areas near sandstone mounds. This test was made in outwash that contains much silt at a site near sandstone mounds.

The hydraulic conductivity at sites 7 and 8 in pitted outwash in Portage County were as high as those in the sand plain; however, they may represent only local conditions near the test sites. Specific capacities of high-capacity wells in the pitted outwash indicate that this outwash is not as good an aquifer as outwash west of the Outer moraine.

The vertical hydraulic conductivity of the outwash generally is less than the horizontal hydraulic conductivity because of horizontal bedding of sediments. Ratios of horizontal to vertical hydraulic conductivity range from 1:1 to 7:1, as determined from tests 4, 5, 6, and 8. The hydraulic conductivity ratio of 20:1, previously determined for test 3 (Weeks, 1964b), is not typical for outwash in the central sand plain. Because the hydraulic conductivity of the outwash is low, this aquifer may be considered isotropic for most theoretical analyses of large scale pumping effects. However, the ratio should be considered for analysis of local effects observed during short-term aquifer tests (Weeks, 1969).

Storage coefficients determined from the aquifer tests are fairly uniform, ranging from 0.14 to 0.20. The storage coefficient is defined as the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in head and is a dimensionless ratio. The aquifer-test values are for short periods of pumping, and are somewhat lower than they would be after pumping for longer periods. In an unconfined aquifer the storage coefficient is virtually equal to the specific yield.

The specific yield of the material, which is defined as the ratio of the volume of water it will yield by gravity drainage or refilling to its own volume, was determined by three methods. Specific yield was determined by equating changes in volume of saturated thickness, as determined from changes in water level in observation wells, with the streamflow of Big Roche a Cri Creek near Hancock and Ditch 5 of Tenmile Creek near Bancroft measured during cold or dry winter periods. The specific yields of 0.19 and 0.17 for the upper Tenmile and upper Big Roche a Cri Creek basins, respectively, were slightly lower than the 0.20 value determined for the Little Plover River basin by the same method (Weeks and others, 1965, p. 22). Also, a specific yield of 0.27 was determined

by laboratory analysis of samples obtained from a test hole in the Little Plover River basin (Holt, 1965, p. 35). Finally, specific yields of 0.20-0.24 were determined from soil-moisture profiles obtained at three sites with a neutron logger using a method described by Meyer (1962, p. 174-176). A specific yield of 0.20, which is about midpoint in the range, is used for theoretical analyses of effects of ground-water development or for artificial drainage of the outwash aquifer.

Values for the ratio of transmissivity to storage, T/S , called the hydraulic diffusivity of an aquifer, were determined by analysis of the rate at which water levels in selected observation wells receded following the end of recharge to the aquifer. Methods of analysis are described by Rorabaugh (1960), Weeks (1964a), and Stallman and Papadopoulos (1966). Analyses of water-level recessions in three wells (T-51, T-52, and T-53, locations given in table 2) located between parallel artificial drains in the Buena Vista Marsh area and one well (T-46, table 2) about midway between the streams forming the headwaters of Ditches 5 and 6 of Tenmile Creek were analyzed using theoretical recession curves developed for an aquifer between infinite parallel drains (Jacob, 1943; Rorabaugh, 1960; Brown, 1963). Also, the water-level recession in a well (T-43, table 2) near the intersection of the headwaters stream for Ditch 5 with the ditch was analyzed using the theoretical recession curve developed for a wedge-shaped aquifer (Stallman and Papadopoulos, 1966).

Transmissivity values computed from the ratio of transmissivity to storage, assuming a storage coefficient of 0.2, ranged from 100,000 to 350,000 gpd per foot (table 2), about the same as that determined from aquifer tests. However, the value for well T-52 disagrees with those for wells T-51 and T-53 and cannot be explained readily. All three wells are in or near the bedrock channel formed by the ancestral Wisconsin River, and their recessions are expected to indicate high transmissivity. Possibly the assumptions made for the recession-curve analyses do not meet actual conditions as well as the assumptions for aquifer-test analyses. Nonetheless, the recession-curve analyses provide useful estimates of the hydraulic properties in areas where aquifer-test data are lacking.

Glacial Lake Deposits

Glacial lake deposits in the report area consist mainly of fine-to-medium grained, well-sorted sand, but they contain a few thin beds of dense gray clay. These deposits were laid down in glacial Lake Wisconsin, a large lake formed when the ancestral Wisconsin River was blocked by an advancing glacier front at the north end of the Baraboo bluffs (Thwaites, 1946). Because lake and outwash deposition occurred concurrently and both deposits consist of sand, the contact between the deposits is not distinct. Consequently, the contact is assumed, following Thwaites (1956), to lie at the highest known lakeshore altitude of 1,000 feet. This shoreline altitude approximates the highest altitude of lake clay beds found by test drilling during this study.

Glacial lake clays, which lie between outwash deposits, extend beyond their outcrop (fig. 3). Thin beds of clay have been penetrated by wells as far as 9 miles east of the outcrop area. These clays overlie coarse sand and fine gravel in bedrock valleys and underlie thick and extensive outwash (section B-B, fig. 3). Apparently outwash deposition continued after the lake drained or filled with sediment, burying the lake clays.

Table 2.--Results of Recession-Curve Analyses.

Observation well no.	Location	Aquifer shape Assumed	Average	Transmissivity		Reference for method used
			$\frac{T}{S}$ value sq ft per day	sq ft per day	Gallons per day per ft	
T-51	SW $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 20, T. 22 N., R. 8 E.	Infinite strip	84,000	18,000	130,000	Rorabaugh (1960) semilog plot solution
			93,000	19,000	140,000	Weeks (1964b) type- curve solution
T-52	NW $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 31, T. 22 N., R. 8 E.	do	250,000	50,000	370,000	Rorabaugh (1960) semilog plot solution
			195,000	39,000	290,000	Weeks (1964b) type- curve solution
T-53	SW $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 7, T. 21 N., R. 8 E.	do	70,000	14,000	100,000	Rorabaugh (1960) semilog plot solution
T-46	SE $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 22, T. 21 N., R. 8 E.	do	100,000	20,000	150,000	Weeks (1964b) type- curve solution
T-43	SE $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 16, T. 21 N., R. 8 E.	wedge	66,000	13,000	100,000	Stallman (1966) type-curve solution

The combined thickness of outwash and glacial lake deposits is as much as 150 feet in the area. The thickness of lake deposits is not known.

It is likely that the glacial lake deposits would yield considerably less water to wells than the outwash deposits. However, no high-capacity wells have been installed in the small area of outcrop.

Peat and Alluvium

The material mapped as peat consists of organic matter mixed with silt and sand and was deposited in swamps and marshes. The peat is too thin to be an aquifer, ranging from a few inches to a few feet thick, but it is sufficiently permeable to allow recharge to the underlying outwash.

Alluvium, consisting of sand and gravel derived mainly from reworked outwash, has been deposited along present stream channels. The thickness of the alluvium ranges from a few feet along streams in the outwash plain to as much as 60 feet along the Wisconsin River. The water-bearing properties of the alluvium are similar to those of outwash, and the two geologic units are considered as a single aquifer. The alluvium is in slowly drained flood plains of the streams, however, and except for cranberry bogs along the Wisconsin River, is not likely to be irrigated.

Dune Sand

Dunes, consisting of fine-to-medium, well-rounded, well-sorted sand, occur throughout the sand plain area. However, they have been mapped only in the southwestern part of the area where they form sufficiently irregular relief to limit irrigation development.

Although the dunes are permeable, they are mainly above the water table and are not an aquifer. These dunes are anchored by vegetation and form numerous ridges rising 50-60 feet above the lake or outwash plain.

TOPOGRAPHY

Topography reflects the glacial character of the report area and is an important control on present and potential land use. For example, end moraines rise 50-100 feet above the outwash plain and are well drained except for kettle lakes in the glacial drainage channels. However, they generally are too steep or rough to irrigate.

Pitted outwash deposits between the end moraines also are well drained except for kettle lakes and generally are flat enough to irrigate. A smooth to gently rolling outwash plain between the Outer moraine and the Wisconsin River is well drained and is suitable to irrigate.

Farther west, in the areas of the Buena Vista and Leola Marshes (fig. 4), the slope of the plain decreases to about 3-6 feet per mile. About 150 miles of artificial channels, dug in 1902-04 to a depth of 5-10 feet, drain the area. Since 1904 water plants have partly filled and choked the channels. Consequently, the drained marsh areas now flood during periods of heavy precipitation or snow melt. Drainage has improved recently because several of the old ditches were cleaned and deepened and new ones were dug.

A less extensively drained wetland area is near Dorro Couche and Hamilton Mounds. This area is flooded much of the year and needs extensive drainage before it can be cultivated.

West of the marshes (fig. 4), a 6- to 7-mile wide strip of the plain is well drained by streams tributary to the Wisconsin River. These streams cut deeply into the plain, allowing ground-water drainage at altitudes considerably below the plain. Except for sand dunes in the southwest, much of this area is flat and might be suitable for irrigation if cleared of trees.

SOILS

Soil types affect ground-water recharge by governing infiltration rates. Soil types, combined with geology and topography, determine the relative amounts of overland and ground-water runoff. Also, because the soil stores water for plants, the soil type influences the relative amounts of water lost to evapotranspiration and runoff.

Soils have been mapped in Adams County (Whitson and others, 1924), Portage County (Whitson, Geib, Dunnewald, and Hanson, 1918), Waushara County (Whitson and others, 1913), and Wood County (Whitson, Geib, Conrey, Post, and Boardman, 1918). A generalized soils map of central Wisconsin, including the entire report area, was prepared by Beatty (1964). These maps show a number of soil types based upon topography, drainage, composition, and texture.

Almost the entire sand-plain area is underlain by sandy soils. Deposits of sandy peat, less than 18 inches thick overlie sandy subsoils in much of the Buena Vista and Leola Marsh area, as indicated by the peat and alluvium mapped in figure 3. A relatively thick deposit of peat occurs near Owens Rock in the Leola Marsh. All of the soils allow rapid infiltration and, except for those saturated by a high water table, are low to moderately low in water-holding capacity (Beatty, 1964, soils map and table 22).

LAND USE AND VEGETATIVE COVER

Land use and vegetative cover affect evapotranspiration and the hydrology of the area. Moreover, the effects of irrigation development depend in part on the land use and vegetative cover existing before such development.

In moraine areas the stony soil and the irregular topography limit cultivation. These areas are covered by hardwood forests, mainly oak and hickory, numerous small fields of corn and hay, and large permanent pastures. The moraine areas provide habitat for wildlife and game animals, including deer, squirrels, and grouse.

The pitted outwash area and the sand plain west of the Outer moraine and east of the marshlands (fig. 4) are extensively cultivated and irrigated. Irrigated crops include potatoes, snap and wax beans, cucumbers, corn, peppers, and some small experimental plots of cabbages, tomatoes, peas, lima beans, and other crops. Unirrigated acreage is planted mainly with corn, hay, and pasture, but some acreage is planted with snap beans, soybeans, and other crops. Intensively cultivated areas are not good habitat for game and wildlife; however, the intermorainal area along streams and near lakes provides good habitat for deer, rabbits, and grouse.

The marsh areas, where frost hazard is relatively high, have been drained only locally for intensive cultivation. However, in the Leola Marsh new drainage ditches have been dredged and existing ditches deepened. Land has been cleared and planted with corn, potatoes, snap beans, cabbage, grains, and other crops. Previously this area was in blue grass and marsh pasture, which provided habitat for prairie chickens, rabbits, foxes, and other wildlife. The value of Leola Marsh as wildlife habitat has declined with intensified cultivation.

In the Buena Vista Marsh the development of intensive cultivation has been slower, although some drainage ditches along the northern edge of the marsh have been cleaned and potatoes planted nearby. Ditch 3 and a lateral tributary have been cleaned and deepened, with potatoes, onions, and corn planted in the drained area. Much of the Buena Vista Marsh is pasture, but small fields of corn, hay, and small grains are common. The area is used extensively for grazing beef cattle.

About 4,000 acres of land in the Buena Vista Marsh have been purchased by or for the Dane County Conservation League, the Society of Tympanuchus Cupido Pinnatus, and the Prairie Chicken Foundation for the preservation of prairie chicken habitat. Other wildlife, including rabbits, foxes, song birds, and hawks flourish in the area. The drainage ditches support brook trout.

The swamp area near Dorro Couche and Hamilton Mounds is mainly forested with birch, aspen, willow, and alder. This area is excellent habitat for deer.

West of the marsh areas, forests containing jack pine, oak (including scrub oak), hickory, and white pine are dominant. Numerous clearings in the forest are mainly in grass, although a few are planted with corn, hay, or grain. Wood for paper is the major harvest, and the Nekoosa-Edwards Paper Company owns about 33,000 acres of land in this area. Also, private land owners harvest and sell pulpwood to paper companies. The wooded area provides excellent habitat for deer, and the streams support brown and rainbow trout.

To determine the effect of changes in land use and vegetative cover on the water budgets, acreages under different types of vegetative cover (table 3) were determined for the basin areas where stream-discharge data were available. Vegetative cover for irrigated areas in these basins was determined from extensive field checks, from recent aerial photographs made by the Wisconsin Highway Department, and from land-cover maps prepared by the Crop Reporting Service, Wisconsin Department of Agriculture. Vegetative cover for nonirrigated acreages for the large basins was taken mainly from maps of approximate land cover.

WATER USE

Water in the sand plain area is used for irrigation, water-based recreation, and municipal, industrial, domestic, and stock supplies. Of these uses, irrigation has the greatest effect on the hydrology. Water-based recreation has little effect on hydrology, but it may be affected adversely by irrigation development. The amount of water used for municipal, industrial, domestic and stock purposes, except for that taken from the Wisconsin River, is relatively small and probably will not be affected adversely by irrigation development.

Table 3.--Vegetative cover in seven basins for which stream-discharge data are available.

Vegetation type	Big Roche a Cri Creek above <u>nr Hancock</u> gage	Ditch 5 of Tenmile Creek above <u>nr Bancroft</u> gage	Big Roche a Cri Creek above <u>nr Adams</u> gage	Tenmile Creek above <u>nr Nekoosa</u> gage	Fourmile Creek above <u>nr Kellner</u> gage	Fourteenmile Creek above <u>nr New Rome</u> gage	Buena Vista Creek above <u>nr Kellner</u> gage
Irrigated acreage:							
Potatoes- - - - -	500	950	500	1,950	440	620	2,360
Snap beans- - - - -	1,500	480	5,600	1,920	700	1,740	220
Cucumbers - - - - -	30	140	860	320	580	1,150	220
Corn- - - - -	170	200	70	170	190	60	30
Other - - - - -	20	- - - - -	50	- - - - -	- - - - -	- - - - -	230
Total- - - - -	2,220	1,770	7,080	4,360	1,910	3,570	3,060
Nonirrigated acreage:							
Cleared land:							
Pasture, hay, and grain- - - - -	2,200	1,200	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
Marshland pasture - - - - -	- - - - -	700	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
Corn- - - - -	500	500	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
Other - - - - -	200	200	- - - - -	- - - - -	- - - - -	- - - - -	- - - - -
Total- - - - -	2,900	2,600	21,430 ^{1/}	22,070 ^{1/}	20,810 ^{1/}	22,630 ^{1/}	19,960
Forested land:							
Evergreen - - - - -	280	400	4,100	6,030	870	1,540	950
Deciduous - - - - -	840	200	3,540	2,620	1,970	6,950	3,120
Swamp, undiffer- entiated- - - - -	710	280	3,740	4,900	3,350	7,850	1,330
Total- - - - -	1,830	880	11,380	13,550	6,190	16,340	5,400
Roads, bare yards, fallow fields, buildings, etc. -	300	250	810 ^{2/}	820 ^{2/}	590 ^{2/}	860 ^{2/}	580 ^{2/}
Total- - - - -	7,250	5,500	40,700	40,800	29,500	43,400	29,000

^{1/} Includes mainly pasture, hay, grain, and small acreages of corn and other crops.^{2/} Estimated as 2 percent of the basin area.

Irrigation

History of Irrigation

Ground-water pumping for large-scale irrigation in the sand plain began in the late 1940's. Development, mainly from large pits excavated a few feet below the water table, gradually increased until 1958. The reverse-rotary method was first used to drill irrigation wells in the area in 1958, and from then until 1966 irrigation development from wells was rapid (fig. 6), and most of the pits were replaced by wells. The development rate declined in 1966 and 1967, as indicated by decreased drilling activity. This decline was partly due to a shortage of bank credit and, possibly, to a shortage of parcels of land large enough to be irrigated economically.

The rate of ground-water pumpage for irrigation has increased more rapidly than the number of wells in use. Wells installed in recent years have larger yields, and the motor-driven and self-propelled sprinkler systems allow larger fields to be irrigated from a single well. Also, chemical fertilizers have ended the need for crop-rotation practices that kept some wells idle each year. For example, as recently as 1962 most irrigators in the Little Plover River basin area rotated irrigated crops once every 2 or 3 years, and many wells were not pumped every year. By 1967 most fields in this area were irrigated yearly.

Present Use

Irrigation development in the sand plain was determined by inventories of irrigation wells, irrigated acreage in 1967, and of ground-water pumpage for irrigation during the period 1965-67. Well information was obtained from reports submitted by well drillers to the Wisconsin Department of Natural Resources and the Geological and Natural History Survey, from previous studies (Holt, 1965; Summers, 1965; and Weeks and others, 1965), from well owners, and from field inspection. Irrigated acreage was mapped mainly by field inspection. Pumpage was inventoried from records submitted to the Department of Natural Resources for about 60 percent of the wells in the area. This inventory was adjusted for unreported pumpage by using the average amount of water applied per acre for each crop (table 4A). The amount of water pumped for irrigation in each basin, listed below, also was determined in this manner.

Pumpage and water application for 1965 and 1966 (table 4-B) were assumed to be proportional to the number of wells and crop acreages in those years compared to wells and acreages in 1967. This assumption appears reasonable on the basis of partial inventories of irrigated acreage in 1965 and 1966.

The amount of irrigation water needed depends upon the amount of precipitation during the growing season. The amount of irrigation water applied in 1965 and 1967 (table 4-B) was the amount needed during years of normal precipitation. The amount applied in 1966 was that needed in a dry year. For a year in which precipitation for the growing season approaches record lows, applications might reach 16 inches for potatoes, 8 inches for beans, and about 12 inches for corn and other crops. For years in which precipitation during the growing season is above normal, applications might be only about 6 inches for potatoes, about 3 inches for beans, and about 5 inches for corn and other crops. In a summer as wet as the wettest of record, irrigation would be almost zero.

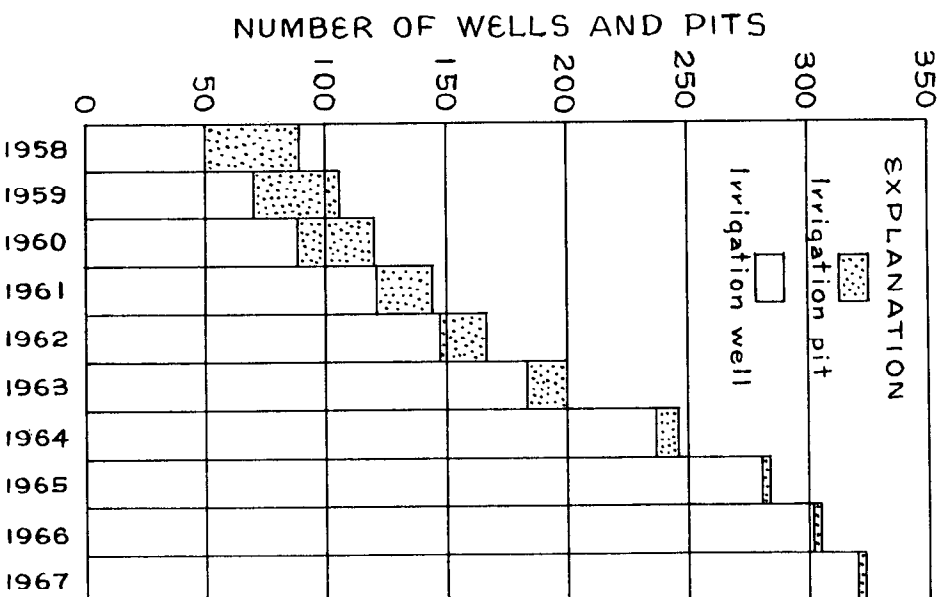


Figure 6.--Number of wells and pits in use for irrigation water supply, 1958-67.

Table 4A.--Amount of ground water pumped for irrigation in report area
for individual crops in 1967.

	Per acre application in inches	Acreage	Total water pumped acre ft
Potatoes- - -	9.7	10,300	8,400
Snap beans- -	4.8	15,500	6,200
Corn- - - - -	7.3	6,500	3,900
Cucumbers - -	7.2 ^{1/}	1,400	800
Other - - - -	7.2 ^{1/}	300	200
Total - - - - -	- - - - -	34,000	19,500

^{1/} Estimated.

Table 4B.--Ground-water pumpage for irrigation in the central sand plain
for the years 1965-67.

Year	Total pumpage acre ft	Per acre application inches			
		Potatoes	Snap beans	Corn	Cucumbers and others ^{1/}
1965 -	16,000	10	5	7.5	7.5
1966 -	22,000	12	6	9	9
1967 -	19,500	10	5	7.5	7.5

^{1/} Estimated.

Table 4-C.--Amount of ground water pumped for irrigation
in different subbasins in the report area for 1967.

	<u>Pumpage</u> <u>acre ft</u>
Basins for which water budgets were computed:	
Upper Big Roche a Cri Creek- - - - -	1,040
Big Roche a Cri Creek ^{1/} - - - - -	2,200
Fourteenmile Creek - - - - -	1,900
Ditch 5 of Tenmile Creek - - - - -	1,160
Tenmile Creek ^{2/} - - - - -	1,500
Fourmile Creek - - - - -	1,100
Buena Vista Creek- - - - -	2,300
Other basins:	
Wisconsin River (area near Plover) - - - - -	1,900
Fox River drainage - - - - -	5,800
Carter Creek - - - - -	600
Total- - - - -	19,500

1/ Excluding acreage in Upper Big Roche a Cri Creek basin.

2/ Excluding acreage in basin of Ditch 5 of Tenmile Creek.

Consumptive Use

Part of the irrigation water applied is not consumed by the plants and returns to the water table. Water applications may exceed plant needs, or rain on recently irrigated land may raise the soil moisture above field capacity.

Consumptive use of irrigation water, the amount used by the plants, is estimated to be about 70 percent of the reported pumpage. This value is obtained by dividing the estimated increase in evapotranspiration resulting from irrigation during the growing season by the reported irrigation pumpage for that year (table 4-B).

Present and Potential Development

Present irrigation development is concentrated in the area (fig. 4) between the Second and Outer moraines, west of the Outer moraine and east of the Buena Vista and Leola Marshes, and north between the Wisconsin River and Buena Vista Marsh. About one-fourth to one-third of these areas was irrigated in 1967. Irrigation development will continue in this area, although possibly at a slower rate than in the early 1960's (fig. 6). Most development will be from land now used for crops and pasture.

In addition to the areas described above, some irrigation development is occurring and is likely to continue in the Leola and Buena Vista Marshes, although these areas are subject to frost during the growing season (fig. 4). The extent and rate of the development probably will depend upon the severity of frost damage.

Development of land for irrigation in marshes requires improved drainage, which results in substantial hydrologic changes. New ditches were dug or cleaned during the period 1964-67 over an extensive area in the Leola Marsh and along the eastern and northern edges of Buena Vista Marsh. If irrigation development in the marsh areas becomes extensive, most drains will be deepened and many new drainage ditches will be dug.

Large-scale development also may occur between the marshes and the Wisconsin River where sufficient ground water is available (fig. 4). Much of this land is covered with trees and would require clearing before it could be cultivated. The area probably will not be as intensively developed as the plain east of the marshes because much of the land is owned by paper companies and is used for tree farms. However, large individual tracts are privately owned and development could be fairly rapid.

Water-Based Recreation

The sand-plain area supports much water-based recreation. The headwaters of streams and many of the drainage ditches support brook trout and are moderately fished. The lower reaches of the streams, mainly downstream from the marshes, support rainbow and brown trout but are less heavily fished. Many kettle lakes in the moraine areas are fished for largemouth bass, northern pike, and pan fish, as are Nepco Lake and Lake Wauzeka on Buena Vista Creek. The Wisconsin River and Petenwell Flowage provide fishing for walleye and other species of warm-water game fish. The drainage ditches, lakes, and ponds also provide duck-hunting areas.

Some lakes are bordered by numerous summer cottages and public parks. These lakes and shoreland areas are heavily used by picnickers, fishermen, boaters, and swimmers. The demand for lakeshore cottage or home sites exceeds the supply. An impoundment, called Lake Sherwood, was completed in the spring of 1968 on Fourteenmile Creek a short distance below Deer Lodge Lake to provide lakeshore lots.

The value of streams and lakes for recreation decreases when stream and lake stages decline, and recreational users may be adversely affected by irrigation development.

Municipal, Industrial, Domestic, and Stock Uses

Municipal supplies from ground water have been developed only for Plainfield and Hancock. In 1967, pumpage for the two villages, with a combined population of about 1,000 people, was about 32 million gallons.

Industrial use of ground water in the sand plain is small and includes a canning factory near Plover, a few creameries, a few gravel pits, and washing operations at potato-packing sheds. Water use in 1967 by the canning factory was 64 million gallons, or about 200 acre-feet. The other industrial users pumped a few million gallons of water in 1967. Most of the ground water pumped for industrial use returns to the ground-water reservoir and has little effect on ground-water supplies.

Water for municipal and industrial purposes along the north and west margins of the sand plain is obtained from the Wisconsin River or from collection galleries in river alluvium and do not depend upon runoff or storage within the sand plain. However, the Nekoosa-Edwards Paper Company collects runoff from Buena Vista and Fourmile Creeks at Nepco Lake for paper manufacture, power generation, and to supplement the water supply for Port Edwards.

Water used for domestic and stock supplies has little effect on the hydrology in the area. The amount of water used for domestic and stock purposes is insignificant compared to the amount used for irrigation. Moreover, little of this water evaporates, and most returns to the water table.

HYDROLOGIC SYSTEM

A knowledge of the hydrologic system, including the quantitative interaction of precipitation, evapotranspiration, soil-moisture storage, ground-water and surface-water storage, recharge, and runoff, is needed to determine the effects of present and anticipated withdrawals of ground water on streamflow and water levels. The water-budget and the water-balance methods were used to evaluate the hydrologic system in the sand plain.

METHODS OF ANALYZING THE SYSTEM

Water-Budget Method

The water budget is a quantitative account of water entering the basin, of changes in water storage within the basin, and of water leaving the basin. The water budget, as determined for this study, may be expressed in the equation:

$$ET + \Delta SMS = P - RO - \Delta GWS - \Delta SWS - \Delta SS$$

where: ET=evapotranspiration,
 ΔSMS =change in soil-moisture storage,
 P=precipitation,
 RO=runoff,
 ΔGWS =change in ground-water storage,
 ΔSWS =change in surface-water storage,
 and ΔSS =change in storage of water as snow.

Water budgets for eight basins were prepared (tables 5 and 6) for water years 1965-67 by analyzing monthly and annual precipitation measured in nearby rain gages, runoff measured at the stream gages, and changes in ground-water storage estimated from changes in water levels in observation wells. Changes in storage of water as snow were estimated from precipitation records for the monthly budgets (table 5) and were zero for the annual budgets (table 6).

Evapotranspiration plus the increase in soil-moisture storage was determined by use of the water-budget equation. Components of the budget also were used to estimate recharge, as the algebraic sum of runoff and change in ground-water storage (tables 5 and 6); and evapotranspiration from ground water, as ground-water storage decline minus runoff during dry summer periods (table 10). The estimate of precipitation used in the water budget for each basin was obtained from weighted averages of measured precipitation in the gages nearest each basin.

The water budgets were used to evaluate evapotranspiration and recharge on an areal basis. A number of land uses and types of cover occur within each basin, and the budgets represent only their composite effects. The budgets could not be used to determine differences in evapotranspiration and recharge from land under different uses or covered by different types of vegetation. Moreover, water budgets could be prepared only for the relatively limited time for which streamflow records are available.

Table 5.--Comparison of monthly water-budget and water balance values, in inches, of recharge and of evapotranspiration, plus algebraic increase for the basin of Big Rock and Cri Creek near Hancock for water years 1965-67.

Date at end of period	Water budget values					Water balance values		
	Precipitation	Stream-flow	Change in ground-water storage	Net recharge	Evapotranspiration plus increases in soil moisture ^{1/}	Estimated water as snow	Net recharge	Evapotranspiration plus increases in soil moisture
1964								
October 31- - - -	0.27	0.73	-0.69	0.04	0.24		-0.09	0.89
November 30 - - -	1.37	0.65	-0.62	0.03	1.34		0.06	0.74
December 31 - - -	0.66	0.56	-0.59	-0.03	0.69			0.01
1965								
January 31- - - -	0.56	0.52	-0.54	-0.02	-0.02	0.56		0.01
February 27 - - -	1.26	0.39	-0.39	0.00	0.00	1.82	8.95 ^{2/}	0.02
April 3 - - - - -	3.42	1.17	1.36	2.53	0.89	1.82		0.03
May 1 - - - - -	4.09	1.71	3.09	4.80	1.13			1.02
May 31- - - - -	3.16	1.12	-0.30	0.82	2.34		0.30	2.86
June 30 - - - - -	2.58	0.93	-0.63	0.30	2.28		-0.21	3.40
July 31 - - - - -	3.57	0.91	-0.61	0.30	3.27		-0.29	3.99
August 31 - - - -	3.93	0.69	-1.05	-0.36	4.29		0.14	3.11
October 2 - - - -	9.26	1.48	4.84	6.32	2.94		6.36	2.69
Water-year total	34.13	10.86	3.87	14.73	19.43		15.22	18.77
1966								
October 31- - - -	1.44	1.19	-0.74	0.45	0.99		0.17	1.54
November 30 - - -	2.57	1.23	0.30	1.53	1.04		1.96	0.34
December 26 - - -	2.51	1.22	1.52	2.74	-0.23			0.07
1966								
February 5- - - -	1.04	1.43	-1.49	-0.06	-0.06	1.04		0.00
February 26 - - -	2.81	1.07	1.03	2.10	0.00	1.75	9.71 ^{2/}	0.05
March 26- - - - -	3.96	1.54	2.76	4.30	0.52	0.89		0.51
April 30- - - - -	1.27	1.88	-0.62	1.26	0.90			1.03
May 31- - - - -	1.27	1.33	-0.93	0.40	0.87		-0.15	2.01
June 30 - - - - -	1.54	1.00	-1.36	-0.36	1.90		-0.53	2.34
July 31 - - - - -	3.44	0.80	-0.90	-0.10	3.54		-0.62	4.30
August 26 - - - -	3.81	0.73	-0.51	0.22	3.59		0.53	3.62
September 30- - -	2.94	0.87	-1.17	-0.30	3.24		0.20	2.28
Water-year total	28.60	14.29	-2.11	12.18	16.42		11.27	18.09
1967								
October 31- - - -	0.65	0.81	-0.76	0.05	0.60		-0.09	0.89
November 30 - - -	0.73	0.75	-0.64	0.11	0.62		0.02	0.30
December 31 - - -	2.92	0.72	-0.52	0.20	0.89	1.83		0.05
1967								
January 31- - - -	1.97	0.72	-0.26	0.46	0.00	3.34		0.00
February 28 - - -	1.05	0.62	-0.65	-0.03	-0.03	4.39	6.87 ^{2/}	0.00
March 25- - - - -	0.41	0.56	-0.02	0.54	0.30	3.96		0.28
April 30- - - - -	2.73	2.00	4.09	6.09	0.60	0.00		1.26
June 3- - - - -	1.34	1.10	-0.89	0.21	1.13		0.36	1.69
July 2- - - - -	8.40	1.19	1.81	3.00	5.40		3.21	4.06
July 31 - - - - -	0.58	0.91	-1.66	-0.75	1.33		-1.28	3.35
August 31 - - - -	2.20	0.68	-1.69	-1.01	3.21		-0.61	2.21
September 30- - -	2.52	0.70	-0.37	0.33	2.19		0.58	1.85
Water-year total	25.50	10.76	-1.56	9.20	16.30		9.06	15.94

1/ Estimated during months with changes in water as snow.

2/ Totals given only, as no provision was made for computing water as snow.

Table 6.--Annual water budgets and water balances, in inches, for water years 1965-67 for basins of selected streams in the report area.

Basin	Water year	Water budget					Water balance	
		Precipitation	Runoff	Change in ground water storage	Recharge	Evapotranspiration plus increases in soil moisture	Recharge	Evapotranspiration plus increases in soil moisture
Ditch 5 of Tenmile Creek near Bancroft- - - - -	1965	33.4	10.8	+4.6	15.4	18.0	15.3	18.9
	1966	25.3	14.2	-3.8	10.4	14.9	11.2	16.7
	1967	25.7	10.3	+0.8	11.1	14.6	7.2	16.0
Average- - - -		28.1	11.8	+0.5	12.3	15.8	11.2	17.2
Big Roche a Cri Creek near Hancock - - - - -	1965	34.1	10.9	+3.9	14.7	19.4	15.2	19.0
	1966	28.6	14.3	-2.1	12.2	16.4	11.3	17.2
	1967	25.5	10.8	-1.6	9.2	16.3	9.1	16.2
Average- - - -		29.4	12.2	-0.2	12.0	17.3	11.8	17.5
Tenmile Creek near Nekoosa - - - - -	1965	36.0	10.8	+3.1	13.9	22.1	14.9	18.8
	1966	25.2	16.9	-4.0	12.9	12.3	11.6	16.5
	1967	27.4	10.1	+1.6	11.7	15.7	9.6	16.1
Average- - - -		29.5	12.6	+0.2	12.8	16.7	12.0	17.1
Big Roche a Cri Creek near Adams - - - - -	1965	34.1	11.7	+3.1	14.8	18.3	15.5	18.7
	1966	28.6	14.2	-2.0	12.2	14.0	12.5	16.2
	1967	25.5	10.8	-1.6	9.2	16.7	8.9	14.9
Average- - - -		29.4	12.2	-0.2	12.1	16.3	12.3	16.6
Buena Vista Creek near Kellner - - - - -	1965	32.2	13.2	+5.0	18.2	14.0	14.8	18.7
	1966	27.9	16.6	-3.1	13.5	14.4	10.7	15.3
	1967	29.4	11.7	0.0	11.7	17.7	11.0	14.4
Average- - - -		29.8	13.8	+0.6	14.5	15.3	12.2	16.1
Fourteenmile Creek near New Rome- - - - -	1965	34.1	8.0	+2.4	10.4	23.7	15.5	19.0
	1966	28.6	13.3	-3.0	10.3	18.3	10.6	17.7
	1967	25.5	7.5	+0.4	7.9	17.6	7.2	16.0
Average- - - -		29.4	9.6	-0.1	9.5	19.9	11.1	17.6
Fourmile Creek near Kellner - - - - -	1965	32.6	10.8	+3.0	13.8	18.8	14.7	19.0
	1966	26.6	16.6	-1.1	15.5	11.1	10.0	15.8
	1967	27.9	10.1	+2.7	12.8	15.1	10.5	14.9
Average- - - -		29.0	12.6	+1.5	14.0	15.0	11.7	16.6
Little Plover River at Plover ^{1/} - - - - -	1963	27.7	10.6	-2.9	7.7	20.0	- - - -	- - - - -
	1964	30.6	7.8	-2.2	5.6	25.0	- - - -	- - - - -
	1965	39.5	11.3	+3.5	14.8	24.7	- - - -	- - - - -
	1966	24.6	12.9	-1.2	11.7	12.9	- - - -	- - - - -
	1967	30.2	12.6	-0.8	11.8	18.4	- - - -	- - - - -
Average (63-67)		30.9	11.0	-0.7	10.3	20.1	- - - -	- - - - -
Average (65-67)		31.4	12.3	+0.5	12.8	18.6	- - - -	- - - - -

^{1/} Water budgets for the Little Plover River are for calendar years rather than water years.

Estimates of evapotranspiration and recharge for different land uses and types of vegetation over a relatively long period were needed to evaluate effects of changes in land use, including irrigation development. Consequently, a second method was used to analyze the hydrologic system.

Water-Balance Method

The water balance, as defined by Thornthwaite and Mather (1955), is an estimate of evapotranspiration, soil-moisture storage, and recharge. It is determined from measurements of precipitation, from estimates of potential evapotranspiration based on climatic data, and from estimates of the amount of soil moisture available for evapotranspiration by different types of vegetation. The water balance differs from the water budget by accounting for water movement into, storage within, and discharge from the soil zone supporting a given type of vegetation rather than from an entire stream basin.

For the water-balance computations, a running balance, for successive intervals, of the difference between the estimated potential evapotranspiration, computed for this study by the Thornthwaite (1948) method, and precipitation is maintained. This difference is used to compute changes in soil-moisture storage. During periods when precipitation exceeds potential evapotranspiration, evapotranspiration is assumed to occur at the potential rate, soil-moisture storage is assumed to increase to a maximum value (termed the field-moisture capacity), and any computed increase in soil moisture above field-moisture capacity is assumed to recharge the ground-water reservoir. During periods when potential evapotranspiration exceeds precipitation, soil moisture is depleted, recharge is zero, and evapotranspiration is estimated as a function of potential evapotranspiration and available soil moisture.

For this study, it was assumed that evapotranspiration occurs at the potential rate until a certain fraction of the available moisture is depleted. Below that level, evapotranspiration occurs at a decreasing rate as a function of the remaining amount of soil-moisture storage. The method used for the computations coincides with that used by Palmer (1965), and is described in detail by Weeks (unpublished data).

The water-balance method also was used to estimate evapotranspiration of ground water by phreatophytic plants and by irrigated crops. For these estimates evapotranspiration from ground water was assumed to equal the difference between total evapotranspiration and precipitation.

Computed values of evapotranspiration and recharge were used to estimate effects of changes in land use and the effects of irrigation development on streamflow. Evapotranspiration and recharge for land under the different types of vegetation or land use listed in table 3 were computed using weather records at Hancock for the period 1948-67 and weather records at Coddington during 1960-67. These computations were made by assuming that the amount of available soil moisture for each type of vegetative cover was different during at least part of the year.

Water balances for the different types of vegetative cover and land use also were used to compute evapotranspiration, recharge, and soil-moisture storage for eight basins (tables 5, 6, and 7). The basin values were determined

Table 7.--Average annual evapotranspiration (ET) and recharge, in inches, for the period 1948-67, as computed
for four basins in the area by the water-balance method.

Year	Ditch 5 of Tenmile Creek		Big Roche a Cri Creek		Tenmile Creek		Fourteenmile Creek near New Rome	
	ET	Recharge	ET	Recharge	ET	Recharge	ET	Recharge
1948- -	13.3	7.5	14.0	6.8	14.6	6.2	- - -	- - - -
194 - -	17.6	8.0	18.3	7.4	19.0	6.7	- - -	- - - -
1950- -	16.4	11.9	16.9	11.4	17.4	10.9	- - -	- - - -
1951- -	15.8	18.9	16.3	18.4	16.9	17.8	- - -	- - - -
1952- -	15.1	8.7	15.6	8.2	16.3	7.5	- - -	- - - -
1953- -	14.1	11.9	14.8	11.2	15.3	10.7	- - -	- - - -
1954- -	17.3	19.8	17.9	19.2	18.5	18.6	- - -	- - - -
1955- -	16.8	8.8	17.4	8.2	18.1	7.6	- - -	- - - -
1956- -	17.3	11.7	17.8	11.2	18.2	10.8	- - -	- - - -
1957- -	16.1	9.5	16.7	8.9	17.3	8.3	- - -	- - - -
1958- -	14.5	3.4	15.1	2.9	15.6	2.5	- - -	- - - -
1959- -	17.1	22.3	17.7	21.7	18.4	20.9	- - -	- - - -
1960- -	15.5	15.0	17.2	17.0	17.7	16.5	18.2	16.0
1961- -	16.5	13.6	17.4	17.3	18.0	16.7	18.4	16.3
1962- -	18.8	11.2	19.3	8.4	19.8	8.0	20.1	7.7
1963- -	17.1	11.2	18.5	9.7	19.2	9.0	19.6	8.6
1964- -	17.3	6.1	18.0	5.0	18.5	4.5	18.9	4.1
1965- -	18.2	19.7	18.5	19.7	19.0	19.3	19.3	19.0
1966- ^{1/}	15.4	8.6	16.5	8.2	16.6	8.3	17.4	7.6
1967 ^{1/}	12.9	8.7	13.4	8.2	13.7	8.0	14.3	7.2
Average for period of record	16.3	12.0	17.0	11.6	17.6	11.1	18.8	10.6

^{1/} For first nine months only.

by multiplying monthly values determined for each vegetation or land-use category by its acreage (table 3) in the basin. Monthly values for recharge (table 5) were used to compute streamflow for a period before records were obtained.

The water-balance technique is based on rather arbitrary assumptions regarding the relationship between potential evapotranspiration and mean air temperature, and between vegetation type and available soil moisture. Consequently, values for total evapotranspiration, evapotranspiration from ground water, and recharge determined by the water-balance method were compared to the water-budget values (tables 5, 6, and 10). The relatively good agreement of the values determined by the two methods indicates that the water-balance technique is valid for the sand plain area. As an additional check, computed differences in evapotranspiration between forest and grassland have been compared with those obtained from vegetation manipulation studies on small watersheds in other areas.

AREA OF HYDROLOGIC STUDY

The area of hydrologic study was smaller than that for the rest of the study because water-budget analyses and analyses of the effects of irrigation on streamflow could be made only for the basins of gaged streams. However, the hydrologic study area includes terrain typical of the sand plain, and the results of the hydrologic studies may be extrapolated, with judgment, over most of the sand plain.

The basins of three streams, the Little Plover River at Plover, Ditch 5 of Tenmile Creek near Bancroft, and Big Roche a Cri Creek near Hancock, are relatively small, ranging from 8.5 to 12 square miles. Ground water in these basins has been relatively intensively developed for irrigation. The basins are the best suited of those gaged for analysis of the effects of irrigation on streamflow, and they were studied more intensively than the others.

Five basins, including those of Buena Vista Creek and Fourmile Creek near Kellner, Tenmile Creek near Nekoosa, Fourteenmile Creek near New Rome, and Big Roche a Cri Creek near Adams, have areas of 45-68 square miles. They include diverse terrains including areas intensively developed for irrigation; areas, mainly in grassland, that have been drained by closely spaced ditches; and areas of naturally well drained, forested land. Because the terrain and land use differ and because the irrigated acreage is a small part of the total acreage, hydrologic data available for these basins are not adequate to analyze the effects of irrigation. However, water budgets for these basins provide data for evaluating the effects of land drainage and of forest cover on hydrology. These basin areas may be more intensively developed for irrigation in the future, and mathematical models were formulated for different areas within the basin of Tenmile Creek near Nekoosa to predict effects of hypothetical development.

The Little Plover River near Arnott has an estimated drainage area of about 4 square miles. However, the actual ground-water drainage area could not be determined with sufficient accuracy to provide useful water-budget values, and no attempt was made to obtain a water budget for that basin.

Ground-water Drainage Area

The basin areas were considered to be those contributing ground water to the streams rather than the topographic basins because most streamflow in the area is from ground water. However, areas of topographic basins also were determined for comparison with the ground-water drainage areas.

The areas contributing ground water to the streams above the gaging stations were determined from a potentiometric map (fig. 7). The map shows the water table in October 1965 and was prepared from altitudes of water levels in wells, pits, ponds, and streams. A major ground-water divide approximately follows the Outer moraine and separates areas contributing ground water to the Wisconsin River from those contributing ground water to the Wolf River. Ground-water divides between the tributaries to the Wisconsin River were determined by extending flow paths perpendicular to the water-table contours from the gaging station sites to the major ground-water divide (fig. 7). The ground-water drainage areas for each basin listed in table 8 were determined by planimeter.

The ground-water subbasin areas (fig. 7) generally should be accurate within about 10 percent. The location of the major ground-water divide in the northeastern part of the report area is imprecise because few measurable wells were available, and the ground-water drainage areas for Fourmile and Buena Vista Creek subbasins may be in error by as much as 20 percent.

Changes in ground-water levels will shift the positions of ground-water divides. Such shifts were small in the Little Plover River basin (Weeks and others, 1965, p. 19) and probably are small for the basins of Ditch 5 of Tenmile Creek and of Big Roche a Cri Creek near Hancock. These three basins have similar geology, topography, and drainage. Divides may shift more in the areas of closely spaced drains, especially where check dams (fig. 12) along the ditches alter stream stages. Insufficient water-level data were obtained in the interdrain areas to define such shifts, but if significant, the shifts could account for some of the problems involved in evaluating changes in ground-water storage in the basins of Fourmile, Tenmile, and Fourteenmile Creeks. This also may account for the anomalously low runoff and high evapotranspiration rates computed from the water budget for Fourteenmile Creek basin.

Topographic Drainage Area

Topographic (surface water) drainage areas were determined to compare with the ground-water drainage areas (table 8). For the purpose of this study the topographic divide east of the streams draining the sand plain was assumed to be the crest of the Outer moraine. The subbasin divides were approximately located from recognizable topographic divides, from the traces of channels formed by occasional overland runoff, and from the ground-water drainage divide. Topographic drainage areas were determined from preliminary U.S. Geological Survey topographic quadrangle sheets and from aerial photographs by planimeter.

The topographic drainage areas agree within about 20 percent with ground-water drainage areas (table 8). Computed runoff and evapotranspiration from topographic drainage areas were less reliable than those computed from the ground-water drainage areas.

Table 8.--Ground-water drainage areas, topographic basin areas, and drainage densities for eight gaged streams in the report area.

Station name	Drainage area		Length of channel miles	Drainage density, based on ground-water drainage area
	Surface water sq mi	Ground water sq mi		
Little Plover River, at Plover- - - - -	15	12	6.1	0.51
Buena Vista Creek, near Kellner - - - - -	44	44	25	0.57
Fourmile Creek, near Kellner - - - - -	51	46	41	0.84
Tennile Creek (Ditch 5), near Bancroft- - - - -	8.8	8.5	6.1	0.72
Tennile Creek, near Nekoosa - - - - -	64	64	55	0.86
Fourteenmile Creek, near New Rome- - - - -	77	68	73	1.07
Big Roche a Cri Creek, near Hancock - - - - -	9.5	11.4	6.1	0.54
Big Roche a Cri Creek, near Adams - - - - -	54	64	53	0.83

PRECIPITATION

Precipitation, including condensation, is the only source of water entering the study area. The seasonal distribution of precipitation, the magnitude and intensity of individual storms, and the amount of water released from snowmelt control the amount of water available for recharge to the ground-water reservoir and the amount of soil moisture available for evapotranspiration. The amount and distribution of rainfall during the growing season influences the amount of ground water pumped for irrigation.

Precipitation data were available from four stations maintained by the U.S. Weather Bureau and from four rain gages maintained by project personnel during the April through October period of the years 1965-67. The rain gages were inadequate to delineate the areal distribution of precipitation during individual storms. However, the local variations in precipitation appear to average out over the season and year, and the rain-gage measurements describe adequately the areal distribution of seasonal and annual precipitation.

EVAPOTRANSPIRATION

Evapotranspiration is the process by which water returns to the atmosphere through direct evaporation or by transpiration of vegetation. Evapotranspiration varies seasonally and, if water were always readily available, would range from about one-half inch per month during the winter to 5 or 6 inches per month in summer. However, the low moisture-storage capacity of the sand-plain soils limits available water, and actual evapotranspiration during the summer is less than potential evapotranspiration. Evapotranspiration varies with the amount and distribution of precipitation, the nature of the vegetative cover, and land-use practices.

Differences with Type of Vegetative Cover

Irrigation increases evapotranspiration and decreases runoff. To determine the magnitude of evapotranspiration increases, estimates were needed of the amount of evapotranspiration that occurred before and after irrigation. These estimates were made by using the water-balance technique for evapotranspiration resulting from several types of land use and vegetative cover, including five types of nonirrigated vegetation or land use, native phreatophytic vegetation, and three irrigated crops.

The amount of evapotranspiration from plants that are not irrigated and do not tap ground water varies with the depth of the root zone and the length of the plants' growing season. These factors were assumed to differ significantly among coniferous forest; deciduous forest; grasslands; row crops; and bare ground. Consequently, separate water-balance computations were made for evapotranspiration from each of these categories.

From computations based on weather records at Hancock, average annual evapotranspiration during the 1948-67 period for evergreen forest was 19.4 inches; deciduous forest, 19.0 inches; grasslands, 16.0 inches; unirrigated row crops, 15.6 inches; and bare ground, 14.1 inches. Computed annual evapotranspiration from the different categories varies somewhat from year to year, depending mainly on the amount and frequency of precipitation. Annual evapotranspiration

for the different vegetation types ranged from about 25 percent below to about 15 percent above the 19-year average during the period.

Sufficient data were not available to compute differences in evapotranspiration of divergent types of vegetation within specific categories. For example, the grasslands include alfalfa, clover, prairie grasses, rye grass, blue grass, small grains, and other types of grasses. Differences in evapotranspiration rates within this category are large. Also, the forest category includes forests and tree plantations in which the maturity and density of the trees differ greatly, resulting in different rates of evapotranspiration. Thus, the evapotranspiration values are averages for each category and should be used to estimate the effects of irrigation development only for large areas.

Estimates of evapotranspiration by phreatophytes were needed to assess the hydrologic effects of land drainage and clearing in the marsh area and to estimate evapotranspiration from ground water. Areas covered by phreatophytes were assumed to be only the wooded areas near the streams or the marshes. Evapotranspiration from areas covered by phreatophytes was assumed to occur at the potential rate throughout the year. Average annual evapotranspiration for the 1948-66 period was computed to be 24.8 inches and ranged from 22.7 to 27.4 inches, depending upon variations in mean air temperature.

Separate evapotranspiration estimates were made for beans, potatoes, and corn, the principal irrigated crops in the area. Computations of evapotranspiration from irrigated cropland were made by multiplying potential evapotranspiration by monthly water-use factors for each crop. These factors, shown in table 9, were based mainly on the ratio of the acreage of the crop irrigated in a given month to the total crop acreage. However, some provision was made for incomplete ground cover during the early stages of growth.

Based on these computations evapotranspiration from irrigated beans was about 19 inches per year; for potatoes, assuming that acreages of early and late maturing varieties were about equal, about 21.5 inches; and for irrigated corn, about 21 inches. Evapotranspiration from irrigated bean fields is about 3 inches greater than from grassland and is about equal to that from nonphreatophytic forested land. Evapotranspiration from other irrigated crops is about 5 inches greater than from grassland and about 2 inches greater than from forests.

Computed annual evapotranspiration from irrigated crops varies less than evapotranspiration from unirrigated land because soil water is replenished regularly during the peak use period. Annual evapotranspiration for beans ranged from about 17 to 21 inches, and for potatoes from about 19 to 23 inches.

Differences between Basin Areas

Estimates of average annual evapotranspiration from four basins (table 7) were determined from the water-balance estimates for each type of vegetation of land use. Average annual evapotranspiration for the period 1948-66 ranged from 16.3 inches for the basin of Ditch 5 of Termile Creek to 18.8 inches (1960-66) for the basin of Fourteenmile Creek.

Table 9.--Monthly weighting factors used for computing evapotranspiration from land planted to selected irrigated crops, determined from approximate planting schedules and from tables of water-use requirements versus crop maturity described by Hargreaves.

Crop or cover type	Month			
	June	July	August	September
Potatoes and cucumbers- - -	0.8	1.0	0.8	0.3
Beans - - - - -	0.35	0.65	0.65	0.25
Corn- - - - -	0.8	1.0	0.8	0.0
Phreatophytic trees - - - -	1.0	1.0	1.0	1.0

Estimates of evapotranspiration plus changes in soil-moisture storage were made by the water-budget method (table 6) for seven basins. Estimates of monthly values for one basin (Big Roche a Cri Creek) are shown in table 5. Although soil-moisture storage is significant for the monthly and annual values, the average change in soil-moisture storage over the 3-year period is small. Average values of evapotranspiration plus increase in soil-moisture storage (table 6) ranged from 15.0 inches for the basin of Fourmile Creek to 19.9 inches for Fourteenmile Creek. Average water-balance evapotranspiration values for the same period (table 6) ranged from 16.1 to 17.6 inches.

SOIL MOISTURE

Soil moisture, water within the soil above the water table, is the water used by nonphreatophytic plants. In general the moisture available within the root zone for plant use is limited by the field capacity of the soil (the amount of water held in the soil against gravity by capillary forces) minus water held so tightly that it cannot be extracted by plants.

The amount of soil moisture available for different types of vegetation controls their water use. Available soil moisture was estimated for several types of vegetation by periodic soil-moisture measurements with a neutron logger during the 1967 water year. Measurements were made in groves of oak, pine, and birch and aspen trees; a patch of grassland, a marsh pasture, a cornfield, and a patch of bare ground.

An estimate of field capacity was made from measurements obtained beneath bare ground during periods when there was little evapotranspiration or ground-water recharge. These measurements indicated that the top 5 feet of soil contained about 9 inches of water, or about 1.8 inches of water per foot.

Soil-moisture storage beneath bare ground, oak trees, and pine trees is compared in figure 8. Following snowmelt, soil-moisture storage increased to more than field capacity at each site, and there was substantial ground-water recharge. During the spring soil-moisture storage declined as water percolated to the water table and was depleted by evapotranspiration. Soil-moisture storage increased to more than field capacity during heavy rains in June, and again there was substantial ground-water recharge. Soil-moisture depletion was substantial during July and August because rainfall was low and evapotranspiration was high.

Maximum soil-moisture depletion was in August, about 0.6 and 3.0 inches, respectively, under bare ground and under areas with oak or pine trees. These values were used to represent available soil moisture to the two cover types for the water-balance computations.

Moisture changes measured during 1967 in the top 2.5 feet of soil beneath grassland, unirrigated corn, and bare ground (fig. 9) are similar to the changes in soil-moisture storage beneath oak and pine trees. However, maximum depletions beneath corn and grassland were about 1 and 1-1/2 inches greater, respectively, than the depletion measured beneath bare ground, but were somewhat less than depletion beneath trees. The available soil moisture was estimated from these measurements to be 1.5 and 2 inches for corn and grassland, respectively.

The available soil moisture of 3.0 and 0.6 inches for trees and for bare ground in August 1967 was used directly for the water-balance computations of evapotranspiration and recharge. However, 2.0 and 1.5 inches of available soil moisture for grassland and corn provided estimates of higher evapotranspiration and lower recharge than estimates from the water-budget analyses. An estimated field capacity of 1 inch for both grassland and corn was used in the water-balance computations. These computations agreed with evapotranspiration and recharge from the water budgets.

Other soil-moisture measurements were used to check soil-moisture storage beneath phreatophytes and irrigated crops. Measurements in a grove of birch and aspen trees, where the water table ranged from about 2 to 3 feet below land surface, indicated that summer depletion was small. Apparently the trees used ground water rather than soil moisture, a finding that justifies the assumption that phreatophytes do not deplete soil moisture.

Periodic soil-moisture measurements to determine deep percolation of irrigation water were made throughout the irrigation season at one site in a potato field, and occasional measurements were made at about 20 sites in fields of potatoes, corn, alfalfa, and beans. No deep wetting front, which would clearly indicate such percolation, was determined from any of the moisture logs. However, moisture a few feet below the surface was substantially greater in many irrigated fields than in the nonirrigated fields. Therefore, the measurements indicate deep percolation of irrigation water in some of the fields. The measurements also indicated that moisture storage in irrigated fields generally was near or above field capacity during the irrigation season.

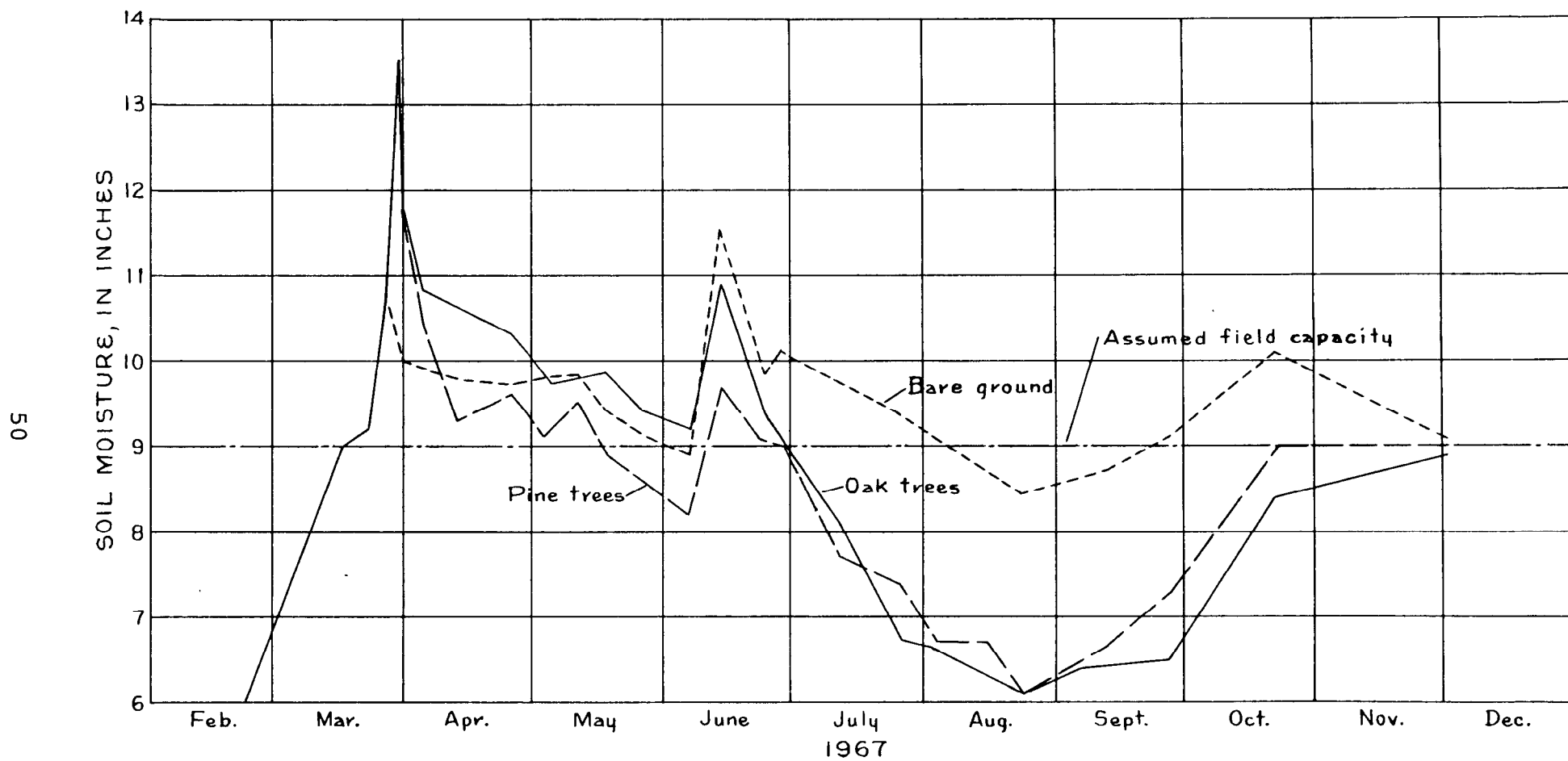


Figure 8.--Soil-moisture storage in the top 5 feet of soil beneath groves of oak trees, groves of pine trees, and bare ground.

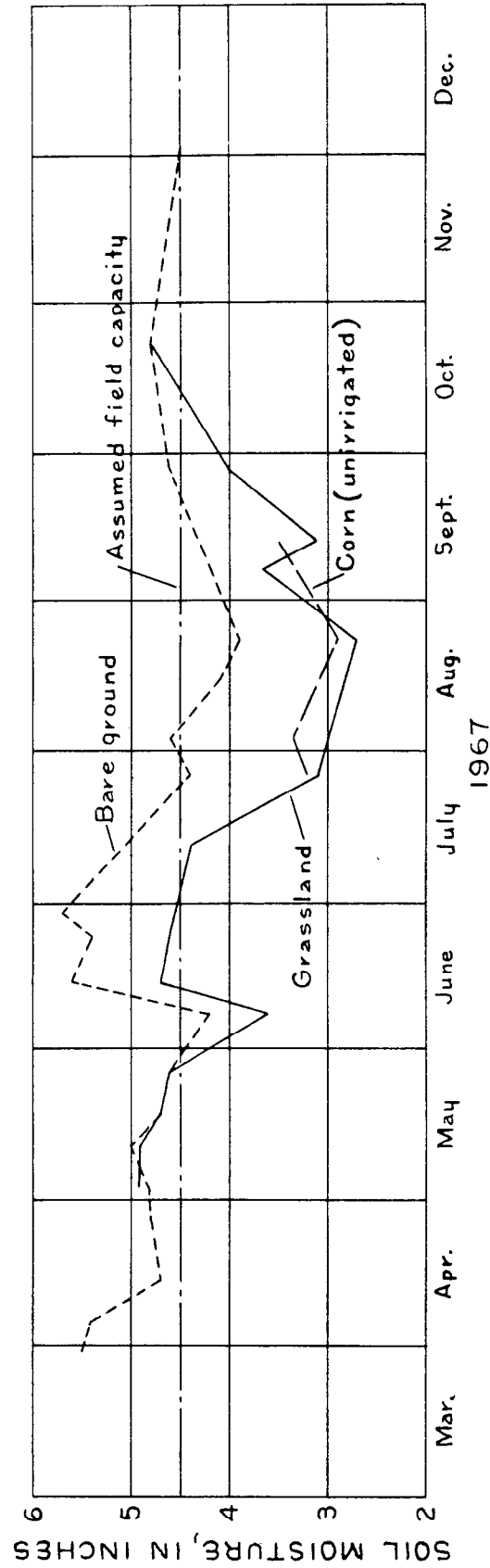


Figure 9.--Soil-moisture storage in the top 2.5 feet beneath grassland, unirrigated corn, and spaded bare ground.

GROUND WATER

The ground-water reservoir receives recharge from precipitation, stores it, and then releases it to surface-water bodies, phreatophytes, and wells. The operation of the ground-water reservoir was determined for this study by estimating changes in ground-water storage in several basins at approximately monthly intervals. The results were used to compute ground-water recharge and evapotranspiration from ground water.

Changes in Storage

The amount of water stored in the ground-water reservoir varies seasonally and yearly. Ground-water storage increases when recharge exceeds discharge, generally during the spring and fall; it decreases when discharge exceeds recharge, generally during summer and winter.

Changes in ground-water storage were computed by multiplying approximately monthly changes in water levels in each observation well in or near the basin by a weighting factor, summing, and multiplying by the specific yield. Weighting factors were determined by the Thiessen (1911) mean method, by multiple regression of water levels in each well against streamflow for dry winter periods, or by a combination of the two methods.

Monthly changes in ground-water storage for the basin of Big Roche a Cri Creek near Hancock during water years 1965-67 are shown in table 5. Water-level storage increased about 3-4 inches during each spring in response to recharge from snowmelt and spring rains and then generally declined throughout the rest of the year. In September 1965, however, ground-water storage increased by about 5 inches in response to near record rainfall. Greatest declines in ground-water storage occurred during the summer, when ground water was discharged to streams and irrigation wells. The maximum rate of storage decline was about 1.7 inches each month during July and August 1967.

Annual changes in ground-water storage, determined for seven basins during water years 1965-67, are shown in table 6. Ground-water storage increased by 2.4 to 5.0 inches in water year 1965 because of heavy rains near the end of the water year. Storage declined substantially throughout 1966 and was about the same at the end of the 1967 water year as at the beginning.

Recharge

Recharge is from precipitation in excess of that needed to replenish soil moisture depleted by evapotranspiration; thus it varies inversely with changes in evapotranspiration. The amount, distribution, and timing of recharge also control the areal and seasonal distribution of streamflow. Because of this relationship, streamflow for the period before streamflow records were collected was computed using recharge values determined by the water-balance method.

The recharge estimates determined by the water-budget and water-balance methods were for net recharge, defined here as recharge minus ground-water loss to evapotranspiration. Consequently, the recharge values can be negative in some months and are about 1-3 inches less per year than total recharge.

Monthly net recharge values were determined by water-budget analysis for the seven basins during water years 1965-67 and for one basin during calendar years 1963-67. Monthly recharge also was determined for five basins by the water-balance method from weather records at Hancock for the period 1948-67. Recharge was computed for three of these basins and for two others for the period 1960-67 from weather records obtained at Coddington.

Monthly recharge values determined by both methods for the basin of Big Roche a Cri Creek near Hancock during water years 1965-67 are shown in table 5. Recharge was substantial each spring and declined to negative values each summer. Substantial recharge occurred in the fall of 1965, but recharge was small during the falls of 1966 and 1967. Winter recharge, as determined from the water budgets, was small. Monthly values of recharge computed by the two methods are in reasonably good agreement. Some differences resulted as temporary soil-moisture storage moved downward in the unsaturated zone. Also, different precipitation totals were used for the two methods.

Annual values for recharge determined by the two methods during water years 1965-67 are listed for seven basins in table 6. Annual recharge in 1965 ranged from about 10 to 18 inches and averaged about 15 inches. Recharge for the other basins was about 7-15 inches in 1966 and 1967. Average recharge determined by the water-budget method for the different basins for the 3-year period ranged from 9.5 to 14.5 inches. Recharge determined from the water budgets for the basins of Fourteenmile, Fourmile, and Buena Vista Creeks may be erroneous because these basin areas may be inaccurately determined. Water-budget recharge values for the other five basins range from 10.3 to 12.8 inches. Average recharge determined for seven basins for the same period by the water-balance method ranged from 11.1 to 12.3 inches.

Annual recharge values computed by the water-balance technique for the basins of Ditch 5 of Tenmile Creek near Bancroft, Big Roche a Cri Creek near Hancock, and Tenmile Creek near Nekoosa for the period 1948-67, and for Fourteenmile Creek near New Rome for the period 1960-67, as shown in table 7. Computed values for the other basins are within the range of those shown. Computed average annual recharge of the period of record ranged from 12.0 inches for Ditch 5 of Tenmile Creek to 10.6 inches for Fourteenmile Creek, indicating that recharge among the various basins is nearly equal. However, the annual values of recharge determined by the water-balance technique showed a very wide range, from about 3 inches in 1958, the driest year of record, to about 22 inches in 1959.

Discharge

Ground-water discharge from the sand-plain area is to streams and to evapotranspiration. Ground-water discharge maintains relatively stable flow, stage, and water temperature in streams, making them good trout habitat. Phreatophytes and irrigated crops discharge ground water by evapotranspiration. Analyses were made of ground-water discharge both to streams and by evapotranspiration to project the effects of irrigation development on streamflow.

To Streams

Ground water was assumed to constitute all of the flow of the streams. This assumption is not entirely met because some streamflow originates from precipitation in the channel and from overland flow in wetlands. Nonetheless, the aquifers probably contribute more than 90 percent of the total streamflow, as determined by hydrograph separation, and little error is introduced from the estimate that streamflow is entirely ground water. Based on this assumption, the seasonal and areal distribution of ground-water runoff may be considered the same as that for streamflow.

To Evapotranspiration

Ground-water discharge by evapotranspiration in the sand-plain area is due mainly to ground water used by irrigated crops and to losses by phreatophytes. Minor losses result from evaporation of ground water pumped for other purposes. Estimates of ground water used by phreatophytes and by irrigation pumpage were made by the water-budget and the water-balance methods.

Estimates of ground-water discharge from the combined evapotranspiration of phreatophytes and irrigated crops were made for five basins (table 10) for June-July 1967. The estimates were made by subtracting streamflow during these periods from the computed changes in ground-water storage. It was assumed that recharge was negligible. This assumption probably is true because the selected periods were quite dry, and little or no recharge occurred from precipitation. However, some soil moisture may have percolated to the water table during the selected periods, particularly where the water table is deep. Such soil-moisture drainage would cause the computed evapotranspiration of ground water to be somewhat low.

Estimates of evapotranspiration from ground water for the same periods also were made by the water-balance technique. Estimated evapotranspiration of ground water by phreatophytes was computed as the difference between potential evapotranspiration and precipitation for each month of each period, multiplied by the acreage covered by phreatophytes (listed as swamp in table 3) in each basin. Evapotranspiration of ground water by irrigated crops was estimated as potential evapotranspiration less evapotranspiration and soil-moisture change for unirrigated row crops, times the irrigated crop acreages in 1967 and the crop factor.

Summary: Monthly evapotranspiration of ground water computed by the two methods is shown in table 10. Ground-water evapotranspiration computed from the water balance for June and July, 1966, and in July and August, 1967, compare favorably with those computed from the water budgets for those periods. However, during both periods, computed water-balance losses were greater for the first month and less for the second month than the water-budget values. Possibly this disagreement arose because the observation wells were at the edges of the fields, and their water levels did not show losses in ground-water storage due to pumping wells near the centers of the fields until the irrigation season had been in progress for some time.

Table 10.--Comparison of values, in acre-feet, of evapotranspiration from ground water determined as the decline in ground-water storage minus streamflow in June-July 1966 and July-August 1967 with those determined by the water-balance method for the same period.

Basin	Method of analysis	1966			1967		
		June	July	Total	July	August	Total
Big Roche a Cri Creek,	Budget	260	70	330	550	730	1,280
near Hancock - - - - -	Balance	590	440	1,030	740	370	1,110
Ditch 5 of Tenmile Creek	Budget	360	670	1,030	470	270	740
	Balance	430	470	900	840	230	1,070
Big Roche a Cri Creek,	Budget	1,300	1,400	2,700	3,000	2,600	5,600
near Adams - - - - -	Balance	2,300	1,600	3,900	2,800	1,400	4,200
Tenmile Creek near	Budget	2,600	2,700	5,300	3,500	1,900	5,400
Nekoosa- - - - -	Balance	2,200	2,100	4,300	3,400	1,700	5,100
Buena Vista Creek,	Budget	2,500	1,600	4,100	1,000	2,000	3,000
near Kellner - - - - -	Balance	1,100	800	1,900	1,400	800	2,200

Evapotranspiration from ground water determined by the water-balance method was also compared with seasonal changes in the flows of Fourteenmile Creek near New Rome and Tenmile Creek near Nekoosa. Monthly flows of these streams correlate well; however, the relation deviates during the summer because evapotranspiration of ground water differs in the two basins. An estimate of the different rates of evapotranspiration of ground water from the basins was made by preparing a double-mass curve (Searcy and Hardison, 1960) of the cumulative flow of Tenmile Creek from October 1964 to September 1967 and Fourteenmile Creek for the same period (fig. 10). This curve is approximately straight for the months October through May. A relative decrease in the flow of Fourteenmile Creek from June through August results in a lesser slope for those months. In the autumn the line resumes its previous slope.

If the displacement represents differences in ground-water evapotranspiration within the two basins, ground-water evapotranspiration in Fourteenmile Creek basin exceeded that in the Tenmile Creek basin by about 1,000 acre-feet in 1965, 1,600 acre-feet in 1966, and 1,800 acre-feet in 1967. Differences in ground-water evapotranspiration computed by the water-balance method for the same years were 800, 1,200, and 1,100 acre-feet.

To Underflow

The term "underflow" is often used to describe ground-water movement past an imaginary line, such as a county line or a topographic basin boundary that does not coincide with the ground-water divide. Underflow should be small in much of the sand-plain area because the basin boundaries are ground-water divides. However, underflow may occur in the southwestern part of the report area, which is underlain by glacial lake clays (fig. 3). The volume of such underflow, if any, is not known and was assumed negligible. However, significant underflow could account for the anomalously low runoff rates determined for the water budget of Fourteenmile Creek.

STREAMFLOW

Streamflow was measured and analyzed to determine its distribution in time and space, and its relationship to geologic conditions, topography, drainage, land use, and to vegetative cover. Streamflow data were used with other hydrologic data to develop and test a mathematical model to compute streamflow for a 16-year period (including a 13-year period before streamflow records were obtained). The effects of irrigation development and other land-use changes on streamflow during that period were computed.

Continuous streamflow measurements were obtained for water years 1965-67 at seven sites on five streams draining the area. Streamflow records were available for water years 1959-67 from two stations on the Little Plover River. Flows measured at approximately monthly intervals for one gaging site are listed in table 5, and annual streamflows for all eight sites are listed in table 6. Daily mean discharges for each station have been published by the U.S. Department of the Interior (1966, 1967, and 1968).

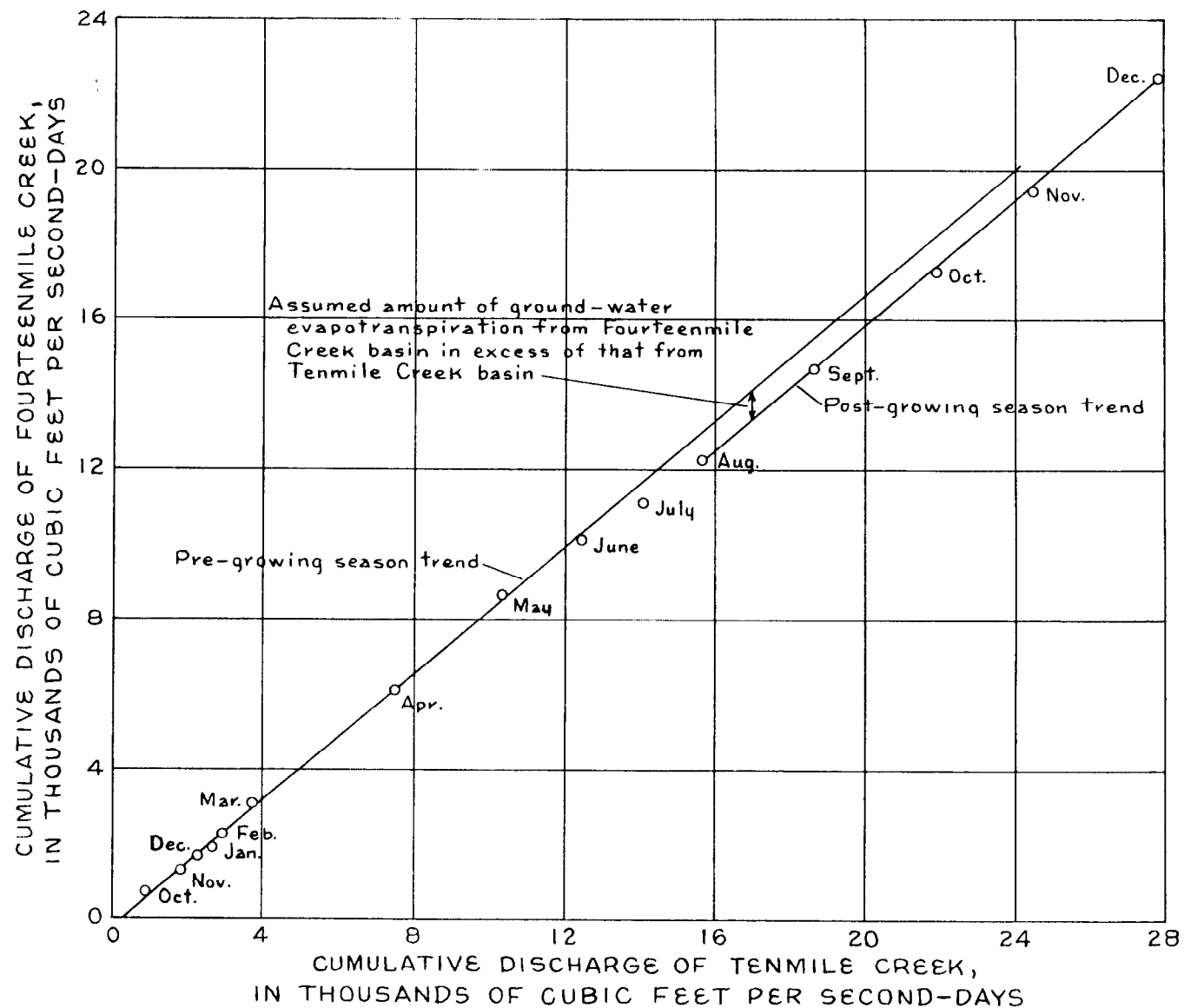


Figure 10.--Double-mass plot of cumulative monthly discharge of Fourteenmile Creek near New Rome versus cumulative monthly discharge of Tenmile Creek near Nekoosa for water year 1965, showing the effects of greater evapotranspiration of ground water in Fourteenmile Creek basin.

Components of Streamflow

Generally, streamflow consists of overland flow and ground-water runoff. Streamflow in the report area is mainly ground-water runoff. Overland flow may occur occasionally during snowmelt on frozen ground, but is not common because of the flat terrain, numerous closed depressions that store surface water, and the highly permeable soil. Streamflow in the area increases rapidly following the beginning of rain or snowmelt, and hydrographs of stream discharge are similar to those for streams in areas where overland flow contributes a significant part of streamflow.

A hydrograph separation was made using a method described by Linsley, Kohler, and Paulhus (1949, p. 400-01, fig. 15-7C). Their method indicates that about 10 percent of the flow in similar basins was from overland flow. Even this low value is too high for the sand-plain area. Much of the overland flow determined by the hydrograph separation probably is ground-water runoff from marshy areas near the stream. Thus, the ground-water runoff determined by the separation technique represents minimum values. The actual ground-water contribution probably is near 100 percent of the discharge, and it was assumed for the water-budget computations that all discharge was from ground water.

Average Runoff

The average runoff for water years 1965-67 from all the basins was fairly uniform, ranging from 9.6 inches in Fourteenmile Creek basin to 13.8 inches in Buena Vista Creek basin. Runoff from the other six basins (excluding that of the Little Plover River near Arnott) ranged from 11.8 to 12.6 inches (table 6). These differences result from differences in precipitation, in evapotranspiration rates, and, possibly, to errors in determining the basin areas, particularly for Buena Vista and Fourteenmile Creeks.

Seasonal Variability

Flow in the different streams varies seasonally. Streamflow generally is greatest in the spring, following snowmelt and spring rains. During this period water levels and ground-water runoff are high. Although precipitation generally is greatest in the summer, most of it replenishes soil moisture, and little ground-water recharge occurs. Consequently, streamflow during the summer is mainly from ground-water storage, and both streamflow and water levels decline. Streamflow is usually very low by August. During the fall evapotranspiration declines and some recharge may occur, causing increased streamflow and rising water levels. During the winter precipitation is stored as snow, and ground-water recharge is small. Streamflow during the winter is mainly from ground-water discharge and generally declines to its annual low in February or March.

Areal Variability of Streamflow

Streamflow differs among the streams, depending upon the transmissivity and the storage coefficient for the aquifer, the drain spacing, the shape of the basin, and the drainage pattern. Drain spacing differed the most in the study area and probably accounted for most of the differences in flow among the gaged streams.

Variability between Basins

Differences in variability of streamflow at the gaged sites are indicated by flow-duration curves (fig. 11), which show the percentage of time that a given mean daily discharge per square mile of basin area was equaled or exceeded. Flow-duration curves for Big Roche a Cri Creek near Hancock and near Adams, Buena Vista Creek near Kellner, and the Little Plover River at Plover show relatively little variability and indicate that time-discharge relationships for these streams are similar. None of these streams is close to adjacent streams, and all have few or no artificial drains. The flow-duration curve for Ditch 5 of Tenmile Creek near Bancroft is somewhat steeper than the others and indicates a greater variability of flow. The stream is close to the headwater streams of both Ditch 6 of Tenmile Creek and Ditch 4 of Fourmile Creek. Consequently the basin for Ditch 5 is quite narrow, and its drainage density is relatively high.

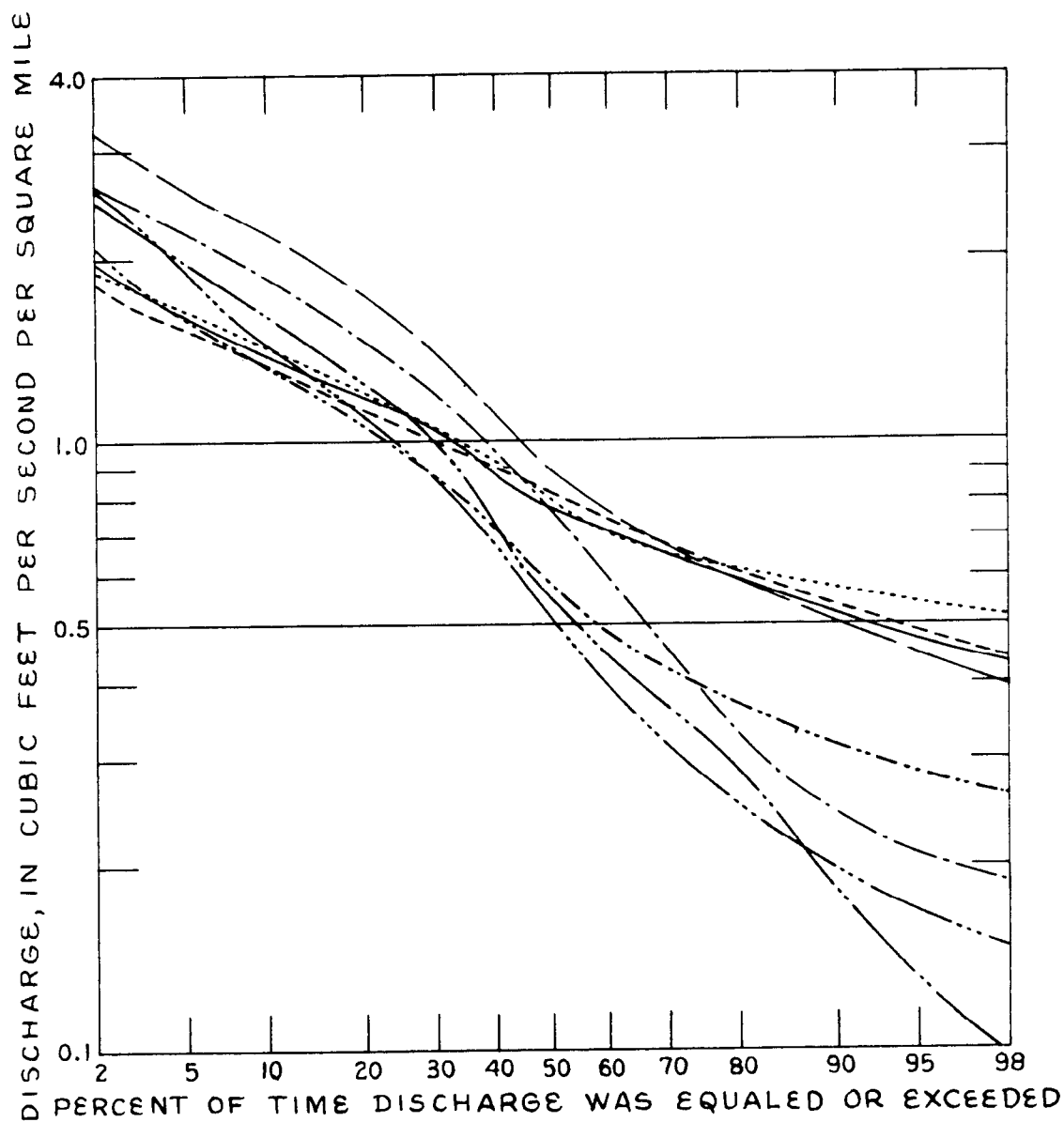
An approximate measure of the proximity of adjacent streams and drains is given by the drainage density, the ratio of miles of channel to drainage area. This ratio, shown on table 8, correlates fairly well with streamflow variability. However, the correlation is poor if much of the channel length is concentrated in a small part of the basin, leaving drainage density in the rest of the basin relatively low. This condition exists in the basin of Big Roche a Cri Creek near Adams, where a tributary network draining about 15 percent of the ground water drainage area contains 35 percent of the total length of the channels in the basin.

Variability within Basins

Drainage and land cover differ throughout the large basin areas. However, the terrain within the basin areas may be divided into three categories, within each of which the drainage characteristics and land cover are relatively uniform. These are designated headwater area, the drained marsh area, and the downstream forested area. The headwater area is characterized by relatively good drainage, little woodland, and large-scale development of ground water for irrigation. The drained marsh area is characterized by relatively closely spaced drains, shallow water table, and extensive grassland. The area downstream from the marshes is characterized by large drain spacing, a deep water table, and extensive woodland.

To evaluate ground-water runoff characteristics from the three types of terrain, five seepage runs were made along reaches of the streams. Streamflow was measured at about 50 sites (fig. 12) on October 6-8, 1964; August 24-26, 1965; and June 1-2, August 11-12, and October 10-12, 1966. These measurements, except those on August 11-12, 1966, were made 6-12 days after rain. Rain occurred 1 and 3 days before the August 1966 measurements.

The measurements (fig. 12) indicate that ground-water runoff per mile of channel during periods of base flow is moderately large in the headwater areas above the Leola and Buena Vista Marshes, is much smaller within the marsh areas, and is largest in the deeply incised streams downstream from the marshes.



EXPLANATION

Buena Vista Creek near Kellner

Tenmile Creek near Nekoosa

Fourteenmile Creek near New Rome

Fourmile Creek near Kellner

Ditch 5 of Tenmile Creek near Bancroft

Big Roche a Cri Creek near Hancock

Big Roche a Cri Creek near Adams

Little Plover River at Plover

Figure 11.--Flow-duration curves for streams of eight gaging stations for water years 1965-67 showing differences in variability of flow among the different streams.

Streamflow pickup in the headwater area is fairly large because drainage density is low and the permeability and local aquifer thickness decrease downstream. The permeability of the outwash decreases from east to west as the deposits become finer grained away from the moraine. The thickness of the outwash is locally reduced by numerous sandstone outcrops. Reduction in permeability and thickness of the outwash downstream lowers the capacity of the aquifer to transmit water into the streams.

Much ground water is pumped for irrigation or lost to evapotranspiration by phreatophytes in the headwater area, and is not available to sustain streamflow. These uses account for some of the differences between rates of gain in flow in the headwater areas and in the areas below marshes.

Streamflow pickup within the marsh area is low. Ditches within Buena Vista and Leola Marshes are closely spaced, and they generally have either small gains or losses in flow. This is partly because they are so close together and partly because the thickness and permeability of the aquifer increase, allowing ground water to move toward the deeply incised stream reaches downstream. Also, phreatophytes deplete ground-water storage within marsh areas during the summer.

The greatest flow gains, such as in Ditch 3, are in ditches that penetrate to greatest depths below the average ground-water surface (fig. 12). Ditch 3, which is lower than Ditch 8 (fig. 12), gained from 0.7 to 6.7 cfs between measuring sites 4 and 6. The change in flow in Ditch 8, determined from measurements made at the same time as those in Ditch 3, ranged from a gain of 0.2 cfs to a loss of 2.4 cfs between measuring sites 3 and 7.

Check dams, installed in 1934-36, have temporary and local effects on flow in ditches within the marsh area. Few of these dams are now in use, and they probably are not an important control on the areal pattern of flow in the drained marsh area.

Downstream from the drained marsh area there are substantial gains in flow. This is partly because the streams are widely spaced and partly because the aquifer is thinner and less permeable, forcing ground water into the streams. Also, steep stream profiles in this area probably affect the gains in flow. As the streams deepen below the marsh area, they may provide drains for ground water in the marsh area.

Low evapotranspiration rates and the small amount of irrigation development also contribute to large gains in streamflow below the marsh. Evapotranspiration occurs only in the narrow valley floors because the streams are deeply incised and the water table throughout most of the area is far below the land surface. Thus, losses to ground-water evapotranspiration are less than in either the headwater area or in the marsh area.

Extended Streamflow Records

Long-term streamflow records were needed to evaluate the effects of irrigation development on streamflow. Because most of the streams had only 3 years of record, monthly streamflow for the period 1952-67 was computed using the water-balance recharge values and mathematical models of the stream-aquifer system for each basin. The stream-aquifer models were formulated by dividing each basin

into three or more rectangular areas, each approximately bounded by streams and ground-water divides. An example of such a division is shown for the Little Plover River basin at Plover by Weeks and others (1965, pl 6). Monthly recharge within each rectangular area is assumed to be discharged to the stream at a rate given by an equation presented by R. E. Glover (1960, written communication). Total discharge to the stream is computed by summing discharge from recharge in each previous month as described by Hurley (1961) until such contributions are small.

Streamflow was computed for five basins within the study area: Big Roche a Cri Creek near Hancock, Ditch 5 of Tenmile Creek near Bancroft, Tenmile Creek near Nekoosa, Buena Vista Creek near Kellner, and Big Roche a Cri Creek near Adams. Only the first three stations are used in this report because the records for Buena Vista Creek near Kellner and Big Roche a Cri Creek near Adams closely resemble the record for Big Roche a Cri Creek near Hancock.

Results of the computations for Big Roche a Cri Creek near Hancock and for Ditch 5 of Tenmile Creek near Bancroft are compared with measured flows in figures 13 and 14. Computed values for these streams are given for the period 1952-67 in tables 11 and 12. These values were computed assuming that the acreage irrigated in 1967 was unirrigated grassland throughout the period. Thus, they represent streamflow that would have occurred without irrigation.

Monthly ground-water contributions to streamflow were computed separately for the marsh area and the forested area downstream from the marsh in the basin of Tenmile Creek near Nekoosa. The computations for the period 1948-67 were based on water-balance values for the entire basin area computed from weather records at the Hancock weather station. The streamflow contributions for the 1960-67 period, however, were computed from separate recharge estimates for the marsh and forested areas.

Computed ground-water contributions to streamflow from the marsh area agree reasonably well with values determined from the seepage runs (fig. 12). The computed values are useful data for estimating effects of irrigation development on streamflow in the marsh area.

Ground-water contributions computed for the downstream forested area consistently were about half as large as the contributions determined from the seepage runs. Failure of the stream-aquifer model to provide accurate estimates of ground-water contributions from the downstream area also caused computed streamflow for Tenmile Creek near Nekoosa to differ considerably from the measured flow.

Although the magnitude of the computed downstream flow contribution is inaccurate, it appears to be proportional to the actual flow. Hence, percentage changes in streamflow computed using the stream-aquifer model assumed for the downstream area should be reasonably accurate.

Some difference between computed and measured streamflow exist because the actual timing of recharge within a given month may differ from that assumed for the computations. Also, recharge, transmissivity, and specific yield differ within each rectangular area, and the assumed rectangular boundaries only approximately fit the actual boundaries of the basin. Such variables may be accounted

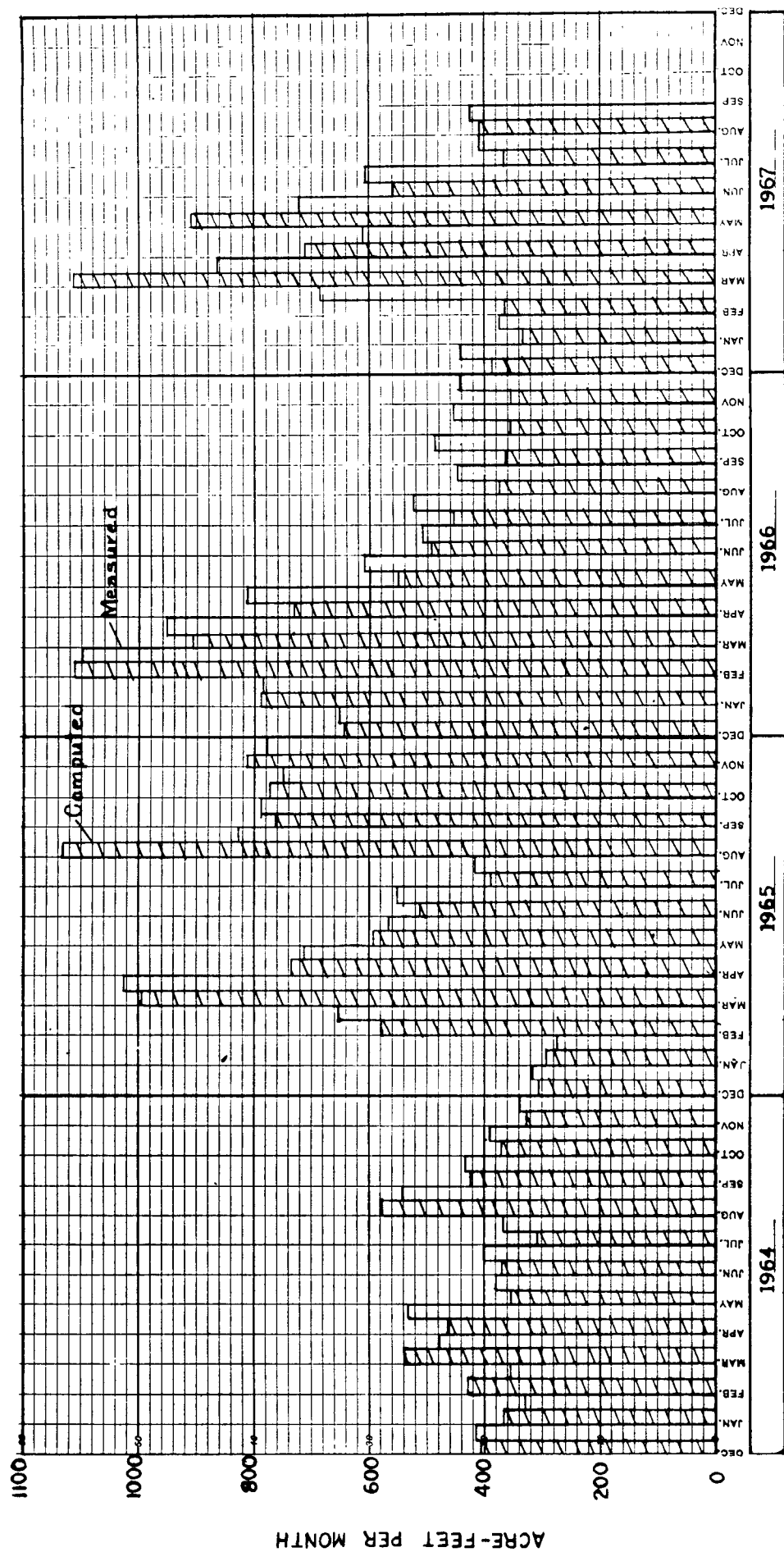


Figure 13.---Comparison of measured monthly streamflow to computed monthly streamflow from water-balance recharge for Big Roche a Cri Creek near Hancock.

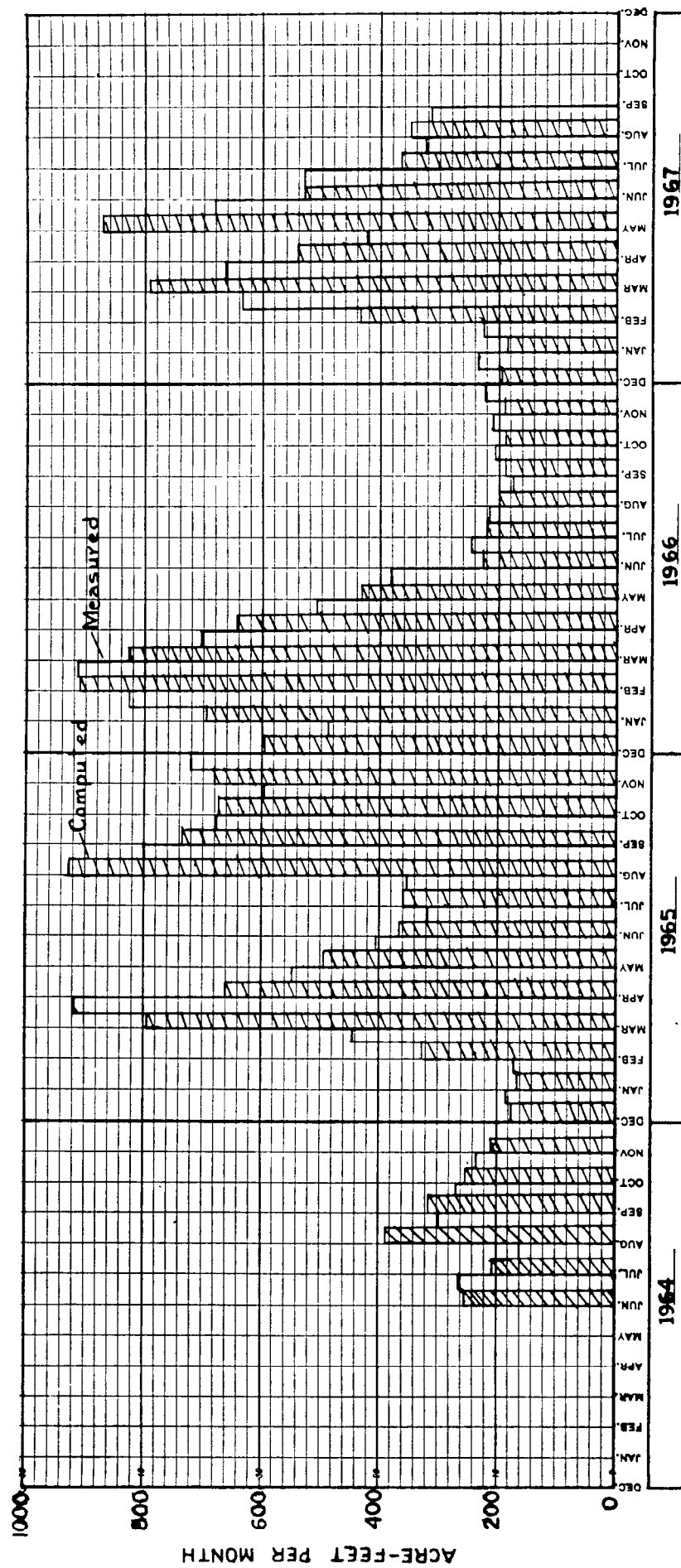


Figure 14.--Comparison of measured monthly streamflow to computed monthly streamflow from water-balance recharge for Ditch 5 of Tenmile Creek near Bancroft.

Table 11.--Monthly streamflow in acre-feet for Big Roche a Cri Creek near Hancock
for the period 1952-67, as computed from monthly recharge values
obtained assuming that all irrigated acreage mapped in 1967 had
remained in grassland during the entire period.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
65 1952	443.	374.	544.	835.	708.	546.	419.	419.	327.	294.	361.	425.
1953	331.	292.	653.	1210.	830.	589.	471.	460.	366.	309.	318.	455.
1954	348.	307.	519.	895.	749.	705.	726.	519.	1023.	1092.	817.	703.
1955	559.	476.	571.	755.	594.	621.	489.	372.	327.	534.	577.	529.
1956	426.	374.	513.	748.	860.	607.	482.	536.	475.	389.	674.	578.
1957	455.	394.	474.	624.	705.	591.	442.	358.	423.	350.	626.	562.
1958	436.	376.	424.	526.	377.	304.	308.	241.	327.	268.	269.	262.
1959	241.	228.	448.	781.	882.	553.	527.	649.	717.	1171.	982.	959.
1960	691.	562.	652.	851.	1217.	843.	612.	784.	969.	882.	805.	667.
1961	552.	483.	705.	1072.	777.	651.	511.	782.	876.	799.	1023.	852.
1962	663.	564.	691.	933.	738.	696.	566.	560.	541.	638.	506.	455.
1963	411.	381.	537.	784.	666.	561.	838.	607.	522.	438.	524.	480.
1964	411.	373.	435.	547.	468.	358.	373.	310.	588.	415.	370.	390.
1965	335.	306.	642.	1158.	761.	574.	485.	458.	1182.	759.	841.	931.
1966	668.	551.	793.	1214.	780.	588.	488.	535.	481.	408.	379.	403.
1967	356.	331.	516.	802.	582.	867.	559.	449.	482.	405.	364.	335.

Table 12.---Monthly streamflow in acre-feet for Tenmile Creek near Bancroft for the period 1952-67, as computed from monthly recharge values obtained assuming that all irrigated acreage mapped in 1967 had remained in grassland during the entire period.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	375.	299.	412.	648.	583.	460.	348.	331.	254.	207.	242.	294.
1953	227.	185.	449.	912.	711.	512.	400.	378.	294.	232.	216.	317.
1954	245.	199.	350.	659.	603.	579.	603.	446.	802.	903.	711.	594.
1955	463.	373.	423.	566.	469.	476.	382.	287.	231.	371.	415.	384.
1956	300.	246.	341.	531.	651.	496.	377.	399.	358.	282.	483.	437.
1957	336.	273.	321.	441.	522.	462.	346.	269.	301.	243.	440.	419.
1958	321.	261.	282.	426.	312.	238.	225.	175.	224.	182.	167.	158.
1959	138.	124.	289.	571.	698.	488.	453.	545.	606.	950.	861.	833.
1960	625.	490.	530.	679.	979.	745.	549.	651.	800.	748.	676.	554.
1961	442.	364.	512.	807.	637.	524.	406.	600.	690.	640.	799.	692.
1962	532.	429.	504.	693.	580.	541.	432.	413.	390.	457.	359.	299.
1963	255.	223.	334.	538.	491.	416.	633.	489.	396.	319.	367.	337.
1964	276.	235.	274.	364.	322.	246.	250.	205.	408.	306.	252.	259.
1965	216.	187.	437.	868.	650.	490.	402.	366.	904.	665.	692.	764.
1966	575.	455.	615.	954.	685.	512.	408.	420.	371.	302.	259.	264.
1967	225.	198.	331.	569.	449.	579.	496.	376.	378.	307.	258.	223.

for more adequately by use of an electric analog or a digital finite-difference model to simulate the stream-aquifer system. However, because the needed information concerning effects of irrigation on streamflow is general in scope, and because the values for recharge and irrigation withdrawals are approximate, the increased accuracy of such models were not considered necessary.

Should irrigation development of ground water in the sand-plain area be limited by law, such models would provide administrative information. Many of the data needed for the models are available from this study.

Stream Temperatures

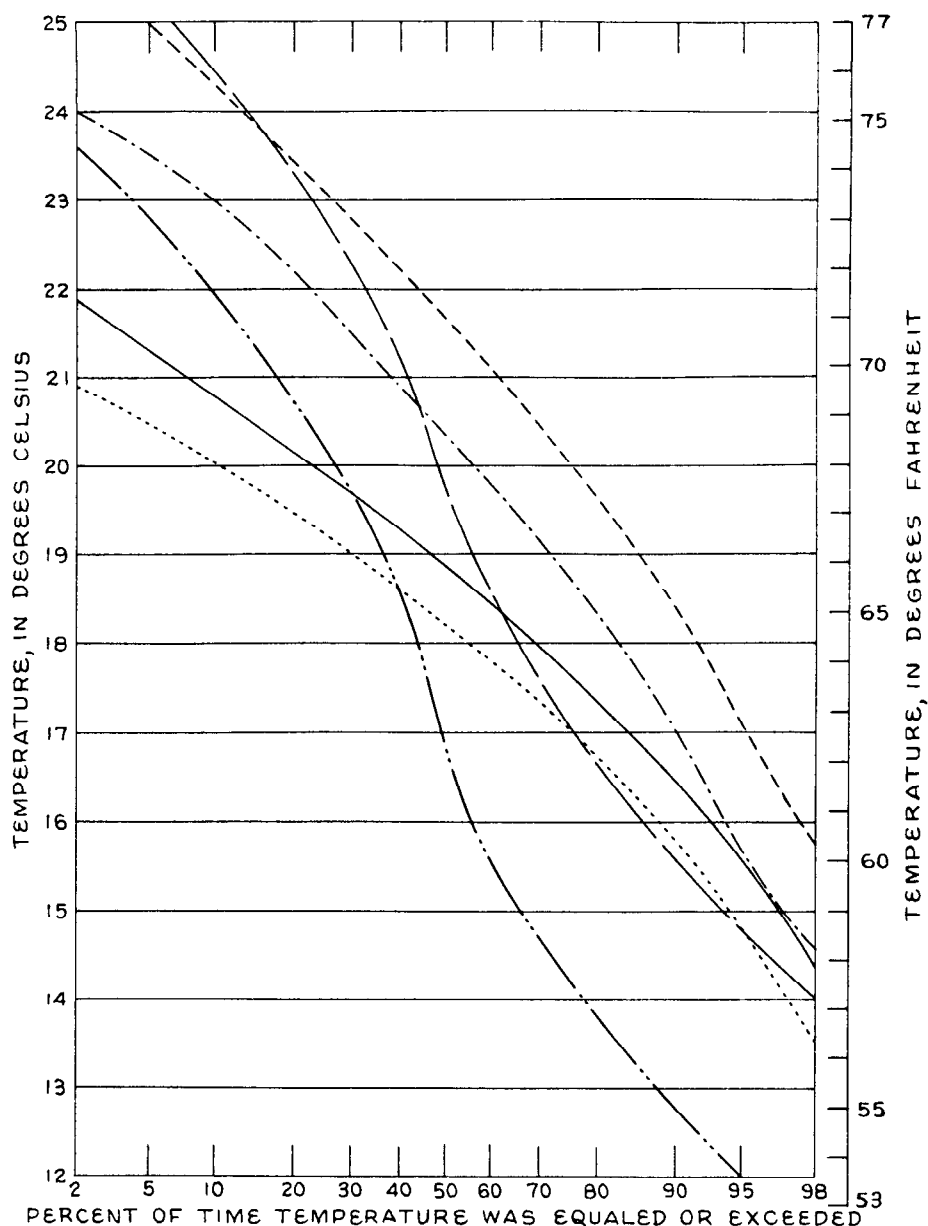
Water temperature is a major factor governing the suitability of the stream as trout habitat. Generally trout have greatest growth rates in water temperatures of about 7-18°C (45-65°F) (White and Brynildson, 1967, p. 40). Brook trout, common in the area, die if temperatures rise above 26°C (78°F) for more than a few hours (Brasch and others, 1962).

Stream temperature records were obtained during the study period for six sites in the headwater area and three in the downstream forested area. Stream temperatures were measured from 1960 to 1967 at the gage site on the Little Plover River near Arnott and from 1964 to 1967 at the gage site on Buena Vista and Fourmile Creeks near Kellner, on Ditch 5 of Tenmile Creek near Bancroft, and on Tenmile Creek near Nekoosa. Maximum and minimum daily temperatures determined for the Little Plover River near Arnott, for Buena Vista Creek near Kellner, and for Ditch 5 of Tenmile Creek near Bancroft are listed by the U.S. Department of the Interior (1963-68). Stream temperatures also were measured by the Wisconsin Department of Natural Resources at four sites on Big Roche a Cri Creek, including sites 2 miles above, 1 mile below, and 3 miles below the gage site near Hancock.

Maximum stream temperatures differ within the headwater area, depending upon the rate of ground-water inflow and the extent of shading by bank vegetation. Variations in the frequency of occurrence of maximum temperatures during July 1965-67 at four sites on headwater streams and computed temperatures at two sites assuming streamflow depletion are shown in figure 15. Maximum temperatures were greatest at the Little Plover River near Arnott and at Big Roche a Cri Creek measurement site 11 (fig. 12). Maximum temperatures were somewhat lower at the gaging sites on Ditch 5 of Tenmile Creek near Bancroft and Big Roche a Cri Creek near Hancock.

Stream temperatures in the downstream areas also are fairly uniform because of the large volume of ground-water inflow (fig. 12) and because the streams are densely shaded. Maximum water temperatures in the downstream area were about the same as those at the gage sites on Ditch 5 of Tenmile Creek and on Big Roche a Cri Creek near Hancock (fig. 15).

Maximum stream temperatures in the marsh areas probably are greater than in the headwater area or in the downstream area because the rate of ground-water inflow frequently is low and many streams are unshaded. Some streams or ditches in the marsh area do not support trout, probably because maximum water temperatures are intolerable.



EXPLANATION

Little Plover River near Arnott
Measured

Little Plover River near Arnott
*Computed assuming a 35 percent
reduction in streamflow at the
site*

Ditch 5 of Tenmile Creek near Bancroft

Big Roche a Cri Creek at Nelsons
bridge, site 11
Measured

Big Roche a Cri Creek at Nelsons
bridge, site 11
*Computed assuming a 25 percent
reduction in streamflow at the
near Hancock gage site*

Big Roche a Cri Creek near Hancock

Figure 15.--Curves showing frequency of occurrence of maximum daily stream temperatures during July 1965-67.

EFFECTS OF IRRIGATION AND LAND-USE CHANGES ON HYDROLOGY

The development of land for irrigation causes seasonal and long-term changes in ground-water levels, and in streamflow, stream stage, and stream temperatures. Detailed analyses of the effects of irrigation development were made for the basins or parts of basins typical of the headwater area, the drained marsh area, and the downstream forested area.

EFFECTS OF PRESENT DEVELOPMENT IN THE HEADWATER AREA

About one-third of the land in the headwater area--that area lying approximately between the Outer moraine and the drained marshes (fig. 4)--is developed for irrigation, and irrigation development is likely to continue. This area contains prime brook trout streams and borders some kettle lakes that provide lakeshore home or cabin sites and opportunities for fishing, swimming, and boating. Consequently, a potential conflict of interest exists between irrigators and those interested in recreational development in the area.

Evapotranspiration, Soil-Moisture Storage, and Net Recharge

The most immediate effects of irrigation development on the hydrology of the headwater area are on evapotranspiration, soil-moisture storage, and net recharge (recharge minus evapotranspiration from ground water and ground-water pumpage). Irrigation effects are seasonal. Evapotranspiration is lower and soil-moisture storage and net recharge are higher from newly planted bare fields than from grassland or forest in the spring. In summer evapotranspiration and soil-moisture storage are higher from irrigated acreage than from unirrigated acreage, but net recharge is lower. In the fall evapotranspiration is about the same from irrigated and unirrigated acreage. However, net recharge is higher beneath irrigated acreage during the fall because soil moisture is near field capacity at the end of the irrigation season but may be depleted beneath unirrigated acreage. Therefore, rain on irrigated fields in the fall may increase net recharge, but rain on unirrigated fields might only replenish soil moisture.

Of the above factors, net recharge most directly affects streamflow. The decrease in net recharge resulting when irrigated crops replace grassland or evergreen forest was determined for the months April-December for the period 1948-67. This decrease was computed as the difference between evapotranspiration from the irrigated crop and the algebraic sum of evapotranspiration and soil-moisture changes for the assumed prior cover type. Changes in streamflow were estimated by using the decrease in the net recharge, computed as the decrease in recharge times the fraction of the basin area converted to irrigation, in the stream-aquifer model (see section on Extended Streamflow Records) for each basin analyzed.

Streams

Streams in the headwater area will be considerably affected by irrigation development. Seasonal low flows and drought flows are reduced, resulting in lower stream stages and higher stream temperatures. These effects in turn cause a deterioration in the stream as trout habitat.

Seasonal Flow

Changes in streamflow have the same seasonal pattern as changes in net recharge. Effects of irrigation development on streamflow are greatest in the summer, decrease in the fall and winter, and are small in the spring.

Changes in streamflow resulting from conversion of grassland or forest to irrigated crops were determined from the stream-aquifer models, based on differences in monthly recharge computed by the water-balance technique. Computations were made for two types of vegetative cover in the basins of Big Roche a Cri Creek near Hancock and of Ditch 5 of Tenmile Creek near Bancroft. These computations include the effects on streamflow that would have occurred had the irrigated acreage mapped in 1967 been planted with the same crops and irrigated throughout the period 1948-67, and for the same areas in grassland and in forest. The results of these computations for the period 1952-67 are presented in tables 13 and 14. Changes in streamflow are shown in acre-feet per month and as a percentage of the streamflow computed to occur without irrigation.

If the acreage irrigated in 1967 had been converted entirely from grassland, the flow of Big Roche a Cri Creek near Hancock in July and August would have been depleted by an average of 110-130 acre-feet per month, or by 25-30 percent of the natural flow. The depletion rate would have diminished rapidly during the fall and winter. By spring irrigation-affected streamflow would have been only slightly less than the unaffected flow. The flow of Ditch 5 of Tenmile Creek would also have been depleted by 110-130 acre-feet per month during July and August, averaging about 30-40 percent of the natural flow. Although the percentage of irrigated acreage in each basin was about equal, computed streamflow depletion is relatively greater in Ditch 5 because a higher percentage of the irrigated acreage is in potatoes and a lower percentage is in beans. Also, a given amount of pumpage in the irrigation season depletes summer streamflow to a greater extent in the basin of Ditch 5 than in the basin of Big Roche a Cri Creek near Hancock because the drain spacing is smaller.

Summer streamflow would be depleted less by conversion of cleared forest to irrigated cropland than by conversion of grassland. Computed July and August streamflow for Big Roche a Cri Creek for the period 1952-67 (table 13) was reduced by about 70 acre-feet per month, 15-20 percent of the natural flow, after conversion to irrigated cropland from forest. For the same conditions, the flow of Ditch 5 (table 14) was reduced by about 80 acre-feet per month during July and August.

Seasonal variations in streamflow were more pronounced after converting to irrigated cropland from forest. For example, although summer flows decreased, spring flows increased following conversion.

Drought Flow

Streamflow is affected more severely by irrigation development during dry periods than in years of normal or near-normal precipitation. Streamflow depletion in acre-feet will be greater than average during dry periods after converting to irrigation because of the greater usage of irrigation

Table 13. --Change in flow of Big Roche a Cri Creek near Hancock that would have resulted in the 1952-67 period if the irrigated acreage mapped in 1967 had prevailed throughout the 1948-67 period.

Minus sign indicates decrease in flow.

A. In acre-feet per month, assuming that irrigated land had formerly been grassland.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	-34.	-31.	-28.	-26.	-9.	-47.	-94.	-109.	-96.	-68.	-54.	-45.
1953	-39.	-35.	-32.	-29.	-27.	-71.	-128.	-161.	-137.	-95.	-75.	-62.
1954	-53.	-46.	-42.	-38.	-26.	-78.	-151.	-135.	-83.	-69.	-58.	-51.
1955	-45.	-41.	-38.	-36.	-21.	-61.	-107.	-186.	-139.	-99.	-79.	-66.
1956	-57.	-51.	-46.	-42.	-39.	-94.	-102.	-74.	-77.	-60.	-52.	-46.
1957	-42.	-39.	-37.	-35.	-17.	-71.	-117.	-152.	-104.	-79.	-65.	-56.
1958	-49.	-45.	-41.	-38.	-36.	-89.	-108.	-165.	-112.	-85.	-70.	-60.
1959	-53.	-47.	-43.	-40.	-22.	-86.	-158.	-179.	-129.	-97.	-79.	-67.
1960	-59.	-53.	-48.	-44.	-39.	-47.	-156.	-131.	-107.	-82.	-68.	-59.
1961	-53.	-48.	-45.	-42.	-30.	-65.	-129.	-151.	-95.	-77.	-65.	-57.
1962	-51.	-46.	-43.	-40.	-36.	-67.	-78.	-93.	-74.	-59.	-51.	-46.
1963	-42.	-39.	-36.	-34.	-28.	-68.	-138.	-128.	-84.	-68.	-58.	-50.
1964	-45.	-41.	-38.	-36.	-34.	-95.	-118.	-145.	-92.	-73.	-62.	-53.
1965	-47.	-43.	-40.	-37.	-21.	-44.	-87.	-85.	-57.	-49.	-43.	-39.
1966	-36.	-34.	-32.	-30.	-29.	-99.	-128.	-109.	-87.	-67.	-56.	-48.
1967	-43.	-39.	-36.	-34.	-32.	-30.	-143.	-149.	-112.	-83.	-67.	-57.

Table 13-B.--As a percentage of the unaffected flow, based on values in table 16-A.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	-8.	-8.	-5.	-3.	-1.	-9.	-22.	-26.	-29.	-23.	-15.	-11.
1953	-12.	-12.	-5.	-2.	-3.	-12.	-27.	-35.	-37.	-31.	-23.	-14.
1954	-15.	-15.	-8.	-4.	-3.	-11.	-21.	-26.	-8.	-6.	-7.	-7.
1955	-8.	-9.	-7.	-5.	-4.	-10.	-22.	-50.	-42.	-19.	-14.	-13.
1956	-13.	-14.	-9.	-6.	-5.	-16.	-21.	-14.	-16.	-15.	-8.	-8.
1957	-9.	-10.	-8.	-6.	-2.	-12.	-27.	-43.	-25.	-23.	-10.	-10.
1958	-11.	-12.	-10.	-7.	-10.	-29.	-35.	-68.	-34.	-32.	-26.	-23.
1959	-22.	-21.	-10.	-5.	-2.	-16.	-30.	-27.	-18.	-8.	-8.	-7.
1960	-8.	-9.	-7.	-5.	-3.	-6.	-25.	-17.	-11.	-9.	-9.	-9.
1961	-10.	-10.	-6.	-4.	-4.	-10.	-25.	-19.	-11.	-10.	-6.	-7.
1962	-8.	-8.	-6.	-4.	-5.	-10.	-14.	-17.	-14.	-9.	-10.	-10.
1963	-10.	-10.	-7.	-4.	-4.	-12.	-17.	-21.	-16.	-16.	-11.	-10.
1964	-11.	-11.	-9.	-7.	-7.	-26.	-32.	-47.	-16.	-18.	-17.	-14.
1965	-14.	-14.	-6.	-3.	-3.	-8.	-18.	-19.	-5.	-6.	-5.	-4.
1966	-5.	-6.	-4.	-2.	-4.	-17.	-26.	-20.	-18.	-16.	-15.	-12.
1967	-12.	-12.	-7.	-4.	-5.	-3.	-25.	-33.	-23.	-20.	-18.	-17.

Table 13-C.--In acre-feet per month, assuming that the irrigated land
had formerly been in forest.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952												
1953	9.	6.	4.	3.	65.	7.	-53.	-55.	-53.	-32.	7.	43.
1954	19.	11.	8.	5.	4.	-42.	-98.	-112.	-82.	-55.	-34.	37.
1955	9.	2.	-1.	11.	35.	-1.	-81.	-83.	34.	5.	-0.	-2.
1956	-3.	-4.	-4.	6.	31.	1.	-54.	-144.	-99.	17.	-3.	-8.
1957	-9.	-9.	-9.	-8.	-8.	-58.	-71.	-3.	-21.	-17.	42.	15.
1958	7.	3.	0.	7.	2.	-37.	-88.	-126.	-60.	-46.	17.	-3.
1959	-7.	-8.	-9.	4.	-2.	-62.	-73.	-133.	-70.	-53.	-39.	-27.
1960	-25.	-22.	-20.	44.	47.	-38.	-87.	-25.	-0.	-9.	-11.	-11.
1961	-11.	-11.	-11.	7.	1.	7.	-114.	-9.	8.	11.	1.	-2.
1962	-4.	-5.	-6.	-6.	9.	-41.	-91.	3.	44.	22.	11.	6.
1963	3.	1.	-1.	4.	2.	15.	-19.	-14.	9.	26.	12.	7.
1964	4.	3.	2.	14.	13.	-8.	-14.	-39.	-16.	-12.	36.	35.
1965	19.	13.	9.	9.	6.	-58.	-61.	-99.	19.	-3.	-5.	14.
1966	4.	2.	0.	-0.	26.	-33.	-57.	-59.	17.	-0.	-3.	-3.
1967	-3.	-3.	-3.	-3.	-3.	-79.	-137.	-61.	-39.	-32.	-26.	-6.
	-11.	-11.	-10.	33.	14.	50.	-86.	-105.	-30.	55.	17.	8.

Table 13-D.--As a percentage of the unaffected flow, based on values in table 16-C.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	2.	2.	1.	0.	4.	1.	-13.	-13.	-16.	-11.	2.	10.
1953	6.	4.	1.	0.	0.	-7.	-21.	-24.	-22.	-18.	-11.	8.
1954	3.	1.	-0.	1.	5.	-0.	-11.	-16.	3.	0.	-0.	-0.
1955	-1.	-1.	-1.	1.	5.	0.	-11.	-39.	-30.	3.	-1.	-2.
1956	-2.	-2.	-2.	-1.	-1.	-10.	-15.	-1.	-4.	-4.	6.	3.
1957	2.	1.	0.	1.	0.	-6.	-20.	-35.	-14.	-13.	3.	-1.
1958	-2.	-2.	-2.	1.	-1.	-20.	-24.	-55.	-22.	-20.	-14.	-10.
1959	-10.	-10.	-5.	6.	5.	-7.	-17.	-4.	-0.	-1.	-1.	-1.
1960	-2.	-2.	-2.	1.	0.	1.	-19.	-1.	1.	1.	0.	-0.
1961	-1.	-1.	-1.	-1.	1.	-6.	-18.	0.	5.	3.	1.	1.
1962	0.	0.	-0.	0.	0.	2.	-3.	-2.	2.	4.	2.	2.
1963	1.	1.	0.	2.	2.	-2.	-2.	-6.	-3.	-3.	7.	7.
1964	5.	3.	2.	2.	1.	-16.	-16.	-32.	3.	-1.	-1.	4.
1965	1.	1.	0.	-0.	3.	-6.	-12.	-13.	1.	-0.	-0.	-0.
1966	-1.	-1.	-0.	-0.	-0.	-13.	-28.	-11.	-8.	-8.	-7.	-1.
1967	-3.	-3.	-2.	4.	2.	6.	-15.	-23.	-6.	14.	5.	2.

Table 14.--Change in flow of Ditch 5 of Tenmile Creek near Bancroft that would have resulted in the 1952-67 period if the irrigated acreage mapped in 1967 prevailed throughout the 1948-67 period.

A. In acre-feet per month, assuming that irrigated land had formerly been grassland.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	-30.	-25.	-21.	-18.	-4.	-40.	-89.	-107.	-94.	-69.	-54.	-43.
1953	-35.	-29.	-25.	-21.	-19.	-64.	-124.	-160.	-139.	-102.	-78.	-62.
1954	-50.	-42.	-35.	-30.	-18.	-70.	-146.	-139.	-93.	-72.	-58.	-47.
1955	-39.	-33.	-29.	-25.	-13.	-51.	-99.	-173.	-140.	-103.	-80.	-64.
1956	-52.	-43.	-37.	-32.	-28.	-86.	-99.	-74.	-70.	-55.	-44.	-37.
1957	-32.	-28.	-24.	-22.	-8.	-60.	-110.	-146.	-108.	-82.	-65.	-52.
1958	-44.	-37.	-32.	-28.	-25.	-81.	-105.	-157.	-117.	-88.	-70.	-57.
1959	-47.	-40.	-34.	-30.	-14.	-78.	-153.	-179.	-137.	-103.	-81.	-66.
1960	-54.	-46.	-39.	-34.	-28.	-35.	-140.	-130.	-106.	-81.	-64.	-53.
1961	-45.	-38.	-33.	-29.	-19.	-54.	-118.	-145.	-100.	-77.	-62.	-51.
1962	-43.	-37.	-32.	-28.	-24.	-57.	-70.	-84.	-69.	-54.	-44.	-37.
1963	-32.	-28.	-25.	-23.	-17.	-58.	-131.	-129.	-91.	-71.	-57.	-47.
1964	-40.	-34.	-30.	-26.	-24.	-89.	-118.	-143.	-101.	-78.	-62.	-51.
1965	-43.	-37.	-32.	-28.	-15.	-34.	-78.	-81.	-57.	-46.	-38.	-32.
1966	-28.	-25.	-22.	-20.	-19.	-94.	-131.	-116.	-93.	-72.	-57.	-47.
1967	-40.	-34.	-30.	-26.	-24.	-21.	-129.	-147.	-116.	-87.	-69.	-56.

Table 14-B.--As a percentage of the unaffected flow, based on preceding values.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	-8.	-8.	-5.	-3.	-1.	-9.	-25.	-32.	-37.	-33.	-22.	-15.
1953	-16.	-16.	-6.	-2.	-3.	-13.	-31.	-42.	-47.	-44.	-36.	-20.
1954	-21.	-21.	-10.	-4.	-3.	-12.	-24.	-31.	-12.	-8.	-8.	-8.
1955	-9.	-9.	-7.	-4.	-3.	-11.	-26.	-60.	-61.	-28.	-19.	-17.
1956	-17.	-18.	-11.	-6.	-4.	-17.	-26.	-19.	-20.	-19.	-9.	-8.
1957	-9.	-10.	-8.	-5.	-1.	-13.	-32.	-54.	-36.	-34.	-15.	-13.
1958	-14.	-14.	-11.	-6.	-8.	-34.	-47.	-90.	-52.	-48.	-42.	-36.
1959	-34.	-32.	-12.	-5.	-2.	-16.	-34.	-33.	-23.	-11.	-9.	-8.
1960	-9.	-9.	-7.	-5.	-3.	-5.	-25.	-20.	-13.	-11.	-10.	-10.
1961	-10.	-10.	-6.	-4.	-3.	-10.	-29.	-24.	-14.	-12.	-8.	-7.
1962	-8.	-9.	-6.	-4.	-4.	-10.	-16.	-20.	-18.	-12.	-12.	-12.
1963	-13.	-13.	-7.	-4.	-3.	-14.	-21.	-26.	-23.	-22.	-16.	-14.
1964	-14.	-15.	-11.	-7.	-7.	-36.	-47.	-70.	-25.	-25.	-25.	-20.
1965	-20.	-20.	-7.	-3.	-2.	-7.	-19.	-22.	-6.	-7.	-5.	-4.
1966	-5.	-6.	-4.	-2.	-3.	-18.	-32.	-28.	-25.	-24.	-22.	-18.
1967	-18.	-17.	-9.	-5.	-5.	-4.	-26.	-39.	-31.	-28.	-27.	-25.

Table 14-C.--In acre-feet per month, assuming that the irrigated land
had formerly been in forest.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	10.	7.	5.	4.	50.	6.	-54.	-63.	-59.	-42.	-9.	25.
1953	14.	8.	5.	3.	2.	-47.	-105.	-124.	-98.	-71.	-49.	11.
1954	1.	-3.	-4.	6.	26.	-2.	-80.	-91.	1.	-5.	-7.	-7.
1955	-6.	-6.	-5.	3.	23.	1.	-54.	-139.	-110.	-17.	-15.	-15.
1956	-14.	-12.	-11.	-9.	-8.	-62.	-79.	-25.	-28.	-23.	24.	13.
1957	6.	3.	1.	7.	3.	-38.	-92.	-131.	-80.	-60.	-6.	-11.
1958	-12.	-11.	-10.	1.	-2.	-65.	-81.	-135.	-89.	-66.	-49.	-35.
1959	-29.	-25.	-21.	30.	41.	-39.	-92.	-44.	-15.	-15.	-14.	-13.
1960	-11.	-10.	-9.	5.	3.	7.	-107.	-33.	-7.	1.	-3.	-4.
1961	-5.	-5.	-5.	-5.	7.	-43.	-95.	-25.	20.	13.	6.	3.
1962	1.	-1.	-2.	2.	1.	11.	-18.	-17.	2.	17.	10.	6.
1963	3.	2.	1.	10.	10.	-11.	-18.	-41.	-25.	-19.	20.	25.
1964	15.	10.	7.	7.	4.	-64.	-75.	-109.	-19.	-18.	-17.	-0.
1965	-3.	-4.	-4.	-4.	16.	-39.	-67.	-70.	-10.	-12.	-11.	-10.
1966	-9.	-8.	-7.	-6.	-6.	-87.	-150.	-91.	-61.	-48.	-38.	-19.
1967	-18.	-16.	-14.	20.	13.	39.	-81.	-111.	-53.	23.	9.	2.

Table 14-D.--As a percentage of the unaffected flow, based on preceding values.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	3.	2.	1.	1.	9.	1.	-16.	-19.	-23.	-20.	-4.	9.
1953	6.	4.	1.	0.	0.	-9.	-26.	-33.	-33.	-31.	-23.	3.
1954	1.	-1.	-1.	1.	4.	-0.	-13.	-20.	0.	-1.	-1.	-1.
1955	-1.	-2.	-1.	1.	5.	0.	-14.	-48.	-48.	-4.	-4.	-4.
1956	-5.	-5.	-3.	-2.	-1.	-12.	-21.	-6.	-8.	-8.	5.	3.
1957	2.	1.	0.	2.	1.	-8.	-27.	-49.	-27.	-25.	-1.	-3.
1958	-4.	-4.	-3.	0.	-1.	-27.	-36.	-78.	-40.	-36.	-29.	-22.
1959	-21.	-20.	-7.	5.	6.	-8.	-20.	-8.	-3.	-2.	-2.	-2.
1960	-2.	-2.	-2.	1.	0.	1.	-19.	-5.	-1.	0.	-0.	-1.
1961	-1.	-1.	-1.	-1.	1.	-8.	-24.	-4.	3.	2.	1.	0.
1962	0.	-0.	-0.	0.	0.	2.	-4.	-4.	0.	4.	3.	2.
1963	1.	1.	0.	2.	2.	-3.	-3.	-8.	-6.	-6.	5.	8.
1964	6.	4.	2.	2.	1.	-26.	-30.	-53.	-5.	-6.	-7.	-0.
1965	-1.	-2.	-1.	-0.	2.	-8.	-17.	-19.	-1.	-2.	-2.	-1.
1966	-2.	-2.	-1.	-1.	-1.	-17.	-37.	-22.	-17.	-16.	-15.	-7.
1967	-8.	-8.	-4.	4.	3.	7.	-16.	-29.	-14.	7.	3.	1.

water under these conditions. Because natural streamflow is reduced in dry periods, the flow reduction represents a greater percentage of flow than in periods of normal flow.

The effect of irrigation on streamflow during an extreme drought is indicated for 1958 in tables 13 and 14. That year was the driest of record (1902-67) at Hancock, and followed 3 years of low rainfall. Streamflow at that time probably was the lowest in the area during this century. Had the irrigated acreage mapped in 1967 prevailed in 1958, maximum streamflow depletion would have been about 60 percent of the flow of Big Roche a Cri Creek near Hancock and about 90 percent of the natural flow in Ditch 5 of Tenmile Creek. Under these conditions flow in Ditch 5 would be almost zero, and trout probably would die.

Stream Depth

Excessive declines in stream stage may reduce the quality of the stream as trout habitat. If the stream maintains a relatively constant stage, food for the trout grows over most of the streambed, and the living space for the fish remains fairly constant. However, if the stream stage declines drastically, both food supply and living space are reduced. Figure 4

Lower stream stages in the headwater area resulting from irrigation development would moderately reduce aquatic living space. However, during an extended drought the additional declines resulting from irrigation pumpage would seriously reduce the already low stage and temporarily destroy the habitat for trout and other aquatic life.

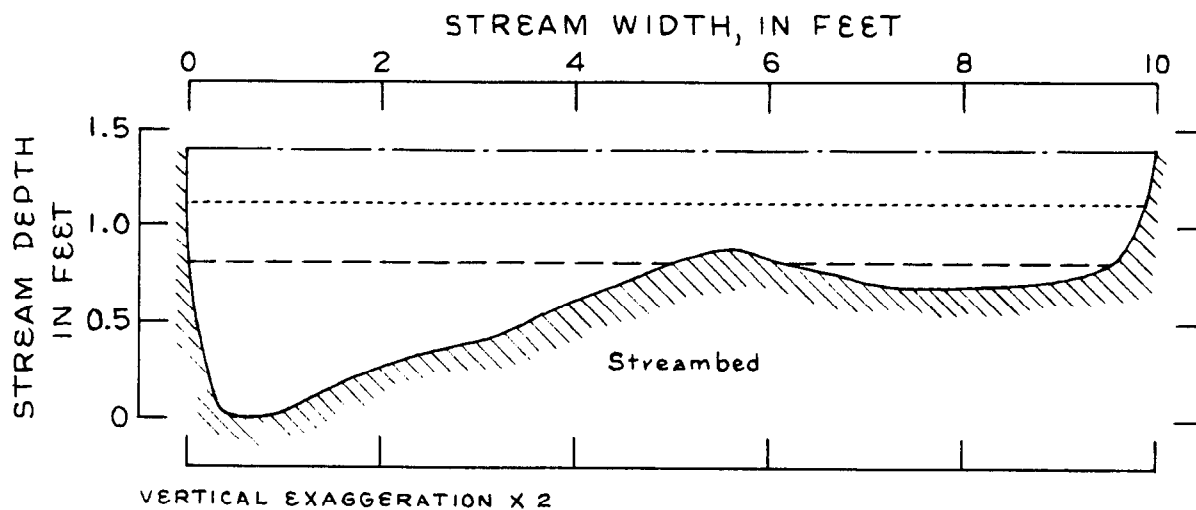
Estimates of stream stage, both with and without the effects of irrigation, during August in the drought year of 1958 were made for site 11 (fig. 12) on Big Roche a Cri Creek. The estimates, shown diagrammatically in figure 16, indicate that part of the streambed would have been above water in 1958 had the basin been irrigated as in 1967. Under these conditions the food supply and the living space for trout would be reduced substantially. The cross section of the stream at this site is typical, and the results of the analysis would apply to much of the stream.

Estimates of flow at the site were made from computed streamflow records for Big Roche a Cri Creek near Hancock (table 11) by assuming that the ratio of flow at the site to that near Hancock was the same as that determined from seepage measurements in 1966. Stream stage was estimated from the flow estimates by use of the Manning equation for steady flow in open channels (Ven Te Chow, 1959, p. 128-129).

Stream Temperature

The maintenance of relatively steady stream temperatures in the sand-plain area depends upon the large inflow of ground water at nearly constant temperature. Reduction of ground-water inflow could result in higher maximum water temperatures and a deterioration of the stream as trout habitat.

The effects of reduced ground-water contributions to streamflow on maximum stream temperature during the summer were estimated for four sites in the headwater area by regression analysis. The analysis for the Little Plover River near Arnott was made by regression of daily maximum water



EXPLANATION

— Stream stage during low flow, August 1966

Estimated stream stage, August 1958,
assuming that no irrigation occurred
in basin

- . - . - . -
Estimated stream stage, August 1958,
assuming that irrigated acreage in
basin was equal to that in 1967

Figure 16.--Cross section of Big Roche a Cri Creek at measurement site 11, showing the effects of flow depletion on stream stage, August 1958, a drought year.

temperature during July 1964-67 against concurrent mean daily streamflow at the site and maximum daily air temperatures at Stevens Point. Data from site 11 on Big Roche a Cri Creek (fig. 12) were analyzed by regression of daily maximum water temperatures during July 1964-67 against concurrent mean daily flow near Hancock and maximum daily air temperatures at Hancock. Analyses for Ditch 5 of Tenmile Creek near Bancroft and for Big Roche a Cri Creek near Hancock were made by regression of daily maximum water temperatures during July 1965-67 against concurrent mean daily streamflow at the respective stations and maximum daily air temperatures at Hancock.

The analysis for the Little Plover River near Arnott indicated that stream temperatures were highly dependent on flow at the site. Therefore, estimates were made from the regression equations of the effects that additional streamflow depletion would have had on frequency of daily maximum stream temperatures during July 1965-67. The regression equation obtained was:

$$WT=51+.3AT-2.4Q$$

where: WT=maximum daily water temperature, in degrees Fahrenheit,
AT=maximum daily air temperature, in degrees Fahrenheit,
and Q= mean daily flow, in cfs.

The equation is known to be valid only for the range of values of WT, AT, and Q used in the regression analysis (July 1964-67). Average flow at the site during July for the 4 years was 2.9 cfs. Assuming that this flow was depleted by an average of 1 cfs, equal to 35 percent of the measured flow, maximum daily stream temperatures would be increased by 2.4°F or 1.3°C (Celsius).

Maximum daily stream temperatures at measurement site 11 on Big Roche a Cri Creek correlated with mean daily streamflow near Hancock and maximum air temperature at Hancock by the equation:

$$WT=62.1+.27AT-2.4Q$$

Again, this equation is known to be valid only for the range of values used in the regression analysis (July 1964-67). A reduction in flow of 2.2 cfs, equal to 25 percent of the average flow of Big Roche a Cri Creek near Hancock for July 1965-67 would increase the maximum daily stream temperature at the site by about 5°F or 2.8°C. The results of such a temperature rise on the frequency of occurrence of maximum daily temperatures are shown in figure 16a.

The negative correlation of maximum stream temperature with flow of Ditch 5 of Tenmile Creek near Bancroft is definite, but the regression equation indicates that variations in streamflow had only minor effects on temperature. No attempt was made to predict the effects of streamflow reduction on temperature at this site.

The correlation of maximum water temperature with streamflow for Big Roche a Cri Creek near Hancock was questionable, although the analysis indicates that water temperature increases as flow declines. The effects of flow depletion on stream temperature were not estimated at this site because the correlation is poor.

Changes in Ground-Water Basin Area

Ground-water withdrawals may induce inflow from adjacent basins. Induced inflow could be a substantial source of water, particularly if wells are concentrated near only one side of the divide. In the sand plain, ground-water development for irrigation is distributed throughout the headwater area, and induced ground-water inflow in the different basins would not significantly shift the divides.

Ground-Water Levels

Pumping ground water results in water-level declines and, where ground water is intensively developed, declines may locally reduce well yields. Moreover, seasonal and long-term regional declines of water levels may lower the stages of kettle lakes. Because of these possible adverse effects, estimates were made of the magnitude of water-level declines due to ground-water development for irrigation in the headwater area.

Local Drawdowns Near Pumped Wells

Excessive drawdowns are not likely from irrigation pumpage in the sand-plain area. Irrigation wells in the area generally are located at the center or at a center edge of fields, and each well is used to irrigate 80-160 acres. Wells usually are spaced at least one-quarter mile apart, and interference between wells is negligible.

Estimates of the water-level decline near a pumped well may be obtained from an equation derived by Theis (1935, p. 520). For the equation, it is assumed that the aquifer is homogeneous, isotropic, and infinite in extent, that all the water pumped is removed from storage, that release of water from storage is instantaneous, and that the pumped well completely penetrates the aquifer. Not all of these assumptions are met in the sand-plain area because the aquifer is somewhat anisotropic, water is not released instantaneously from storage in the water-table aquifer, and most wells only penetrate part of the aquifer. However, the equation closely describes actual water-level declines due to well pumpage if the time since pumping began is longer than a few days and the distance from the pumped well is more than a few hundred feet. If adjustments are made in the equation for partial penetration and for anisotropy (Weeks, 1969), computed drawdowns near the pumped well agree closely with measured drawdowns after a few days of pumping, as determined from several aquifer tests.

The theoretical effects of pumping a well continuously at 1,000 gpm (gallons per minute) for 30 and 90 days (fig. 17), indicate that drawdowns would be less than 5 feet at a distance of 500 feet from the pumped well after 90 days of continuous pumpage. The computations were made using assumed hydraulic properties typical of those for outwash in the area. Under actual irrigation conditions wells are pumped intermittently throughout the growing season, and drawdowns would be less than those shown in figure 17 for the assumed 90-day pumping period. Moreover, it was assumed for the computations that none of the pumped water returned to the ground-water reservoir. Other computations indicate that as much as 30 percent of the applied water returns to the ground-water reservoir, indicating that the drawdowns in figure 17 are greater than actually would occur.

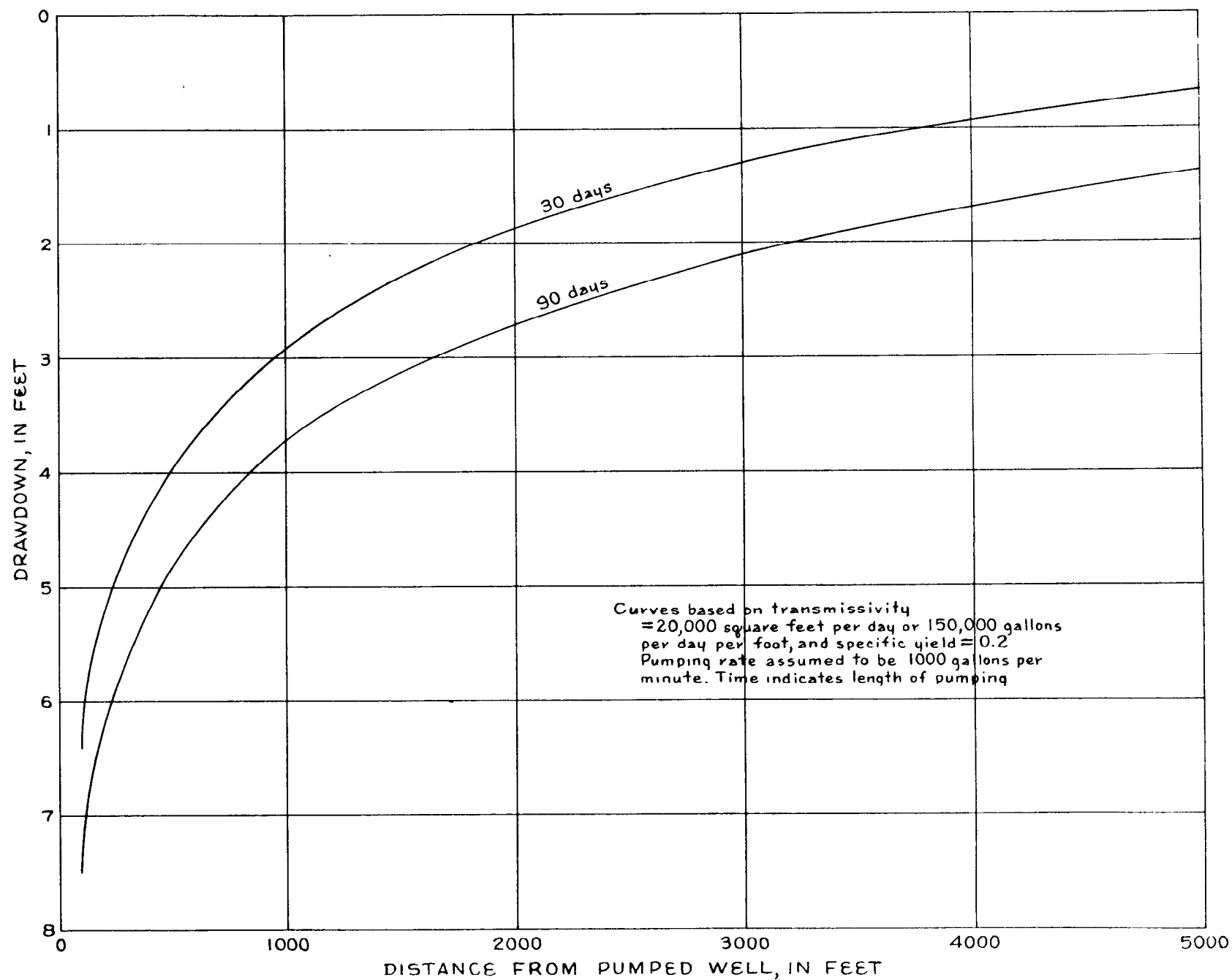


Figure 17.--Theoretical distance-drawdown curves for a pumped well in glacial outwash in the sand plain.

Regional Declines

In addition to local drawdown effects, regional water levels throughout the headwater area decline a small amount in the summer due to irrigation pumpage. The regional decline became apparent in the summer of 1966.

To determine the magnitude of the regional water-level decline, a composite recession curve was prepared from water levels for well Ws-20/8/14-7 for selected summer periods from 1952-64. The water-level hydrograph for 1966 (fig. 18) departed about 0.5 foot below that of the composite curve, indicating a lowering by regional irrigation pumpage. Water levels in several other observation wells also declined about 0.5-1.0 foot because of irrigation pumpage. Similar water-level declines also occurred in 1967.

The greatest long-term effects of pumpage on water levels occur along the major ground-water divide near the Outer moraine. This area contains a few kettle lakes that have declined in stage since the beginning of irrigation. However, the long-term effects of ground-water pumpage on lake stage were masked by climatic fluctuations and could not be determined from the water-level measurements. Therefore, water-level declines at the ground-water divide caused by ground-water pumpage were estimated using a method similar to one described by Bedinger and Reed (1964) and an equation described by Brown (1963). For the estimates, water levels were computed at the boundary of one of the rectangular areas used to simulate the stream-aquifer system for Big Roche a Cri Creek. Two sets of computations were made, one assuming that the irrigated acreage in 1967 had been irrigated throughout the 1948-67 period, and the other that the irrigated acreage mapped in 1967 had remained in grass throughout the period. Both sets of computations were made using water-balance recharge values for the Big Roche A Cri Creek basin.

The computed water levels are compared (fig. 19) with water levels measured in a long-term observation well near the major ground-water divide. The computations indicate that, with irrigation, water levels would average about 2 and 2-1/2 feet less in May and August, respectively, than those computed assuming no irrigation. The maximum difference for the period of computations would have been about 3 feet in August 1958. The seasonal declines in water level were computed to average about 0.5 foot. This decline agrees closely with those determined from the water-level measurements in observation wells in the major ground-water divide area.

The long-term effects of irrigation on water levels in the major ground-water divide area would be significant if the present acreage continues to be irrigated. However, these effects would be less than water-level fluctuations caused by variations in precipitation. For example, the maximum water-level decline due to irrigation was about 3 feet, compared to a natural decline of 7 feet resulting from the 1955-58 drought. The effects of continued irrigation development on water levels might increase declines to about 5 feet if the irrigated acreage of each crop in the area were doubled.

Declines in ground-water levels are most noticeable in lakes that are shallow near shore. A decline of several feet in stage will expose 20-30 feet of lake bottom and shrink the lake's area.

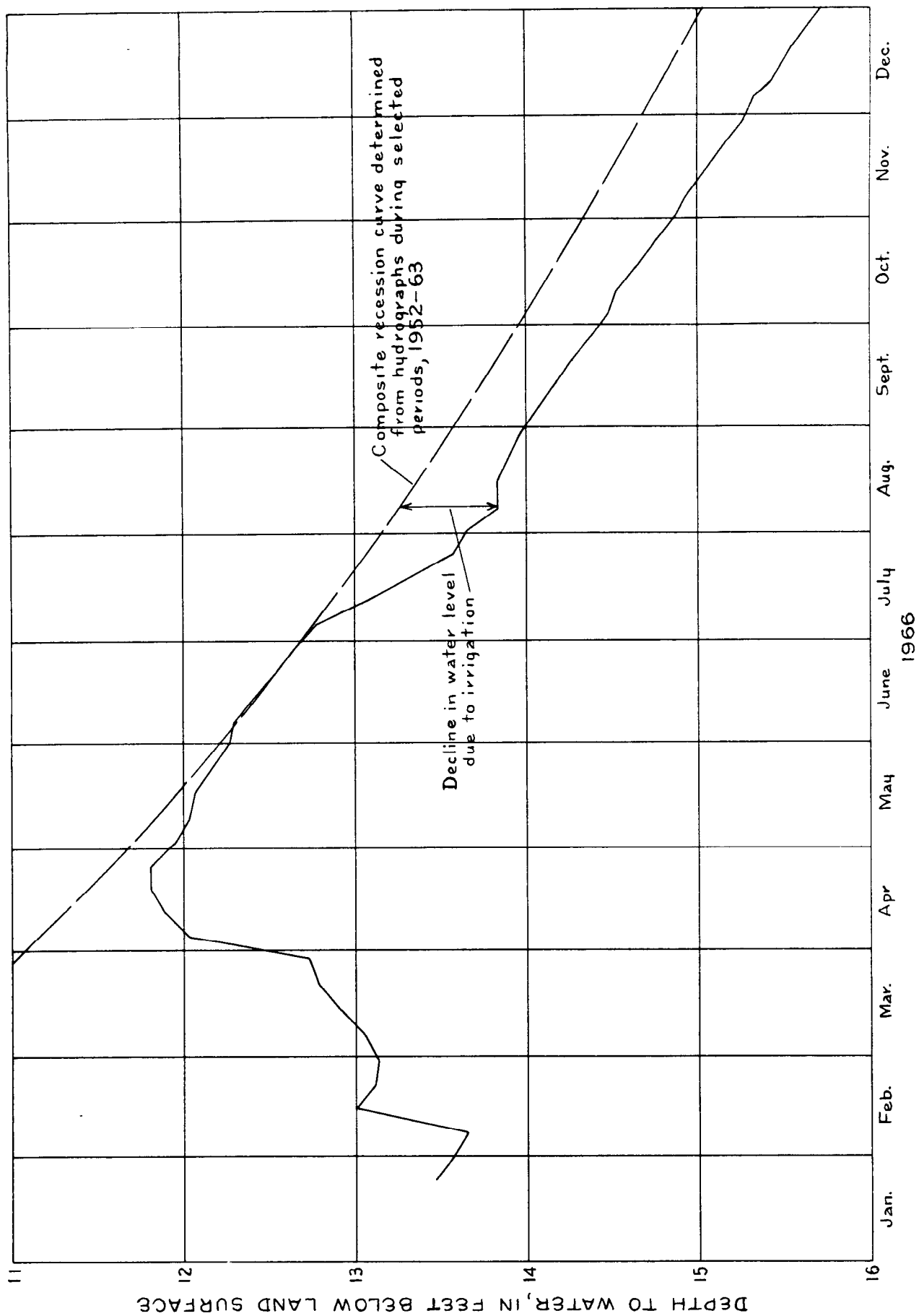


Figure 18.--Composite recession curve of well Ws-20/8/14-7 showing the general water-level trend before widespread pumpage for irrigation and hydrograph of the same well in 1966 showing effects of widespread pumpage for irrigation.

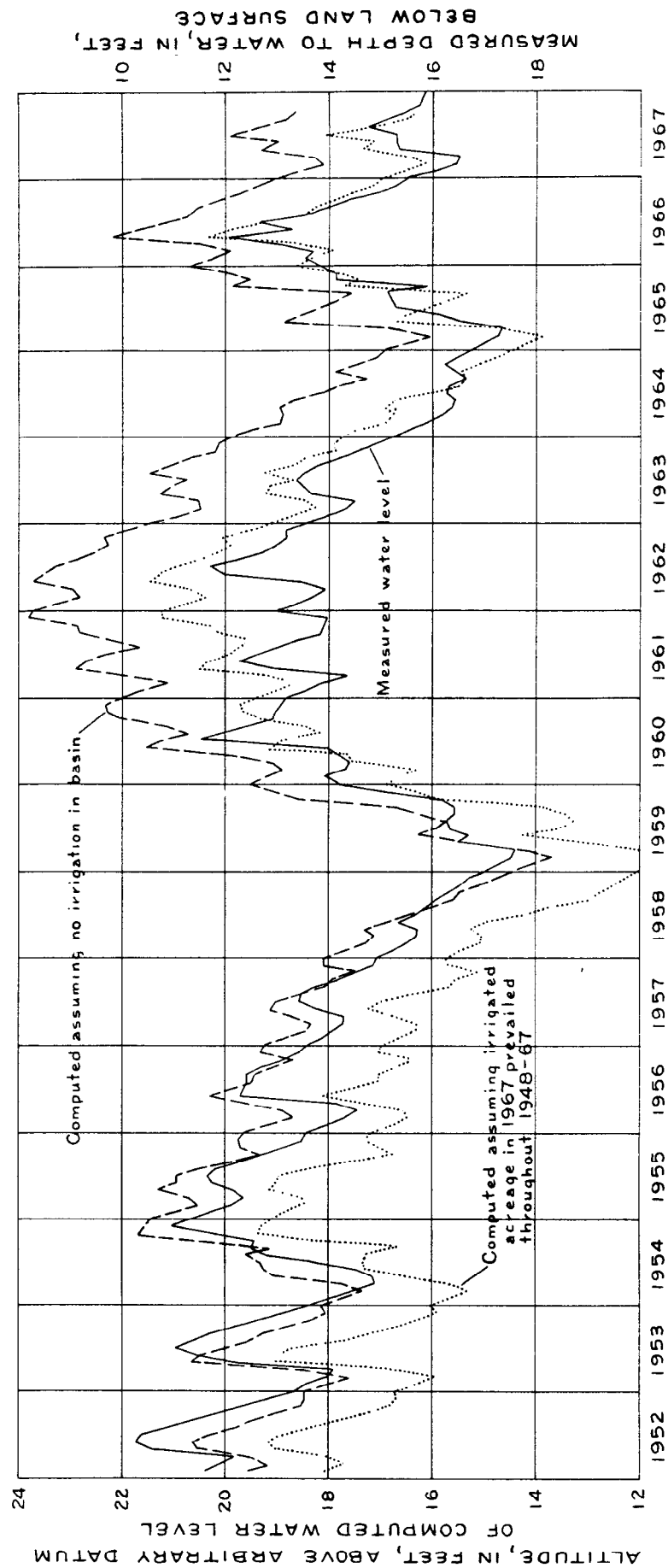


Figure 19.--Hydrograph of well Ws-20/8/14-7 compared with computed water levels for a site near the major ground-water divide in the basin of Big Roche a Cri Creek.

EFFECTS OF POSSIBLE FUTURE DEVELOPMENT IN THE HEADWATER AREA

Irrigation Expansion

Development of land for irrigation is expanding in the headwater area, and irrigated acreage likely will increase substantially in the near future. To estimate the effects of the potential development on streamflow, computations were made of the effects that would have occurred during the 1948-67 period if 10 percent of the evergreen forest and grassland were converted to irrigated potatoes and beans. The results of these computations are listed in tables 15 and 16 for Big Roche a Cri Creek and for Ditch 5 of Tenmile Creek both for depletion in acre-feet and as a percentage of natural flow.

The tabulated values may be used to estimate the effects of any assumed level of development and type of land-use change by summing the effects of 10-percent increments. For example, if 50 percent of the acreage of the basin of Big Roche a Cri Creek near Hancock were irrigated, including, say 30 percent in beans, of which 20 percent was converted grassland, and 10 percent converted from forest, and 20 percent in potatoes, including 10 percent each converted from grassland and forest, the streamflow depletion in August 1965, when streamflow depletion was about average for the period 1952-67, would have been about 130 acre-feet, or approximately 30 percent of the natural flow of the stream at that time. In August 1958, at the peak of the 1955-58 drought, however, depletion due to such development would have been about 240 acre-feet, or about as much as the entire flow of the stream.

Other computations indicate that the effects of irrigation development in the basin of Big Roche a Cri Creek near Hancock are about the same as those for the basins of Big Roche a Cri Creek near Adams and for Buena Vista Creek near Kellner. Also, the values listed for Big Roche a Cri Creek should be applicable to determine the effects of development in the Little Plover River basin. Monthly flows of the two streams are similar, indicating that their basins are hydrologically similar. Values listed for Ditch 5 of Tenmile Creek probably could be used to estimate effects of development in Ditch 6. Although the flow of Ditch 6 was not gaged during the project, the geologic conditions and drainage patterns of the basins indicate that the streams are similar.

The estimates for effects of irrigation of beans and potatoes on streamflow could be used to estimate the effects of irrigating other crops with growing seasons of similar length. For example, the values listed for effects of irrigating potatoes could be used to estimate the effects of irrigating cucumbers or field corn and the values listed for beans could be used to estimate the effects of irrigating sweet corn or other crops with a short growing season.

Forestation

Tree plantations are an alternate use of land should irrigation development decline or stop. These plantations would alter hydrologic conditions in the area.

Table 15.--Depletion of Big Roche a Cri Creek near Hancock that would have resulted during the period 1952-67 from the conversion, in 1948, of 10 percent of the basin area:

A. From grassland to irrigated beans, in acre-feet per month;

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	-9.	-8.	-7.	-7.	-6.	-13.	-25.	-29.	-26.	-18.	-14.	-12.
1953	-10.	-9.	-8.	-8.	-7.	-17.	-32.	-43.	-32.	-23.	-18.	-15.
1954	-13.	-11.	-10.	-9.	-9.	-16.	-27.	-30.	-17.	-15.	-13.	-11.
1955	-10.	-9.	-9.	-8.	-8.	-15.	-28.	-50.	-37.	-26.	-21.	-17.
1956	-15.	-13.	-12.	-11.	-10.	-22.	-25.	-18.	-19.	-15.	-13.	-12.
1957	-10.	-10.	-9.	-9.	-8.	-19.	-30.	-41.	-28.	-21.	-17.	-15.
1958	-13.	-12.	-11.	-10.	-9.	-21.	-27.	-43.	-29.	-22.	-18.	-15.
1959	-14.	-12.	-11.	-10.	-10.	-22.	-41.	-37.	-29.	-22.	-18.	-16.
1960	-14.	-13.	-12.	-11.	-10.	-12.	-40.	-34.	-28.	-21.	-18.	-15.
1961	-14.	-12.	-11.	-11.	-10.	-17.	-33.	-40.	-25.	-20.	-17.	-15.
1962	-13.	-12.	-11.	-10.	-10.	-17.	-20.	-25.	-19.	-16.	-13.	-12.
1963	-11.	-10.	-9.	-9.	-8.	-18.	-16.	-24.	-16.	-13.	-11.	-10.
1964	-9.	-9.	-8.	-8.	-7.	-21.	-28.	-37.	-23.	-18.	-15.	-13.
1965	-11.	-10.	-9.	-9.	-8.	-17.	-25.	-25.	-16.	-14.	-12.	-11.
1966	-10.	-9.	-8.	-8.	-7.	-23.	-31.	-27.	-28.	-20.	-16.	-14.
1967	-12.	-11.	-10.	-9.	-9.	-8.	-37.	-40.	-30.	-22.	-18.	-15.

Table 15-B.--From grassland to irrigated beans, as a percentage of the natural flow;

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	-2.	-2.	-1.	-1.	-1.	-2.	-6.	-7.	-8.	-6.	-4.	-3.
1953	-3.	-3.	-1.	-1.	-1.	-3.	-7.	-9.	-9.	-7.	-6.	-3.
1954	-4.	-4.	-2.	-1.	-1.	-2.	-4.	-6.	-2.	-1.	-2.	-2.
1955	-2.	-2.	-2.	-1.	-1.	-2.	-6.	-13.	-11.	-5.	-4.	-3.
1956	-3.	-3.	-2.	-1.	-1.	-4.	-5.	-3.	-4.	-4.	-2.	-2.
1957	-2.	-2.	-2.	-1.	-1.	-3.	-7.	-11.	-7.	-6.	-3.	-3.
1958	-3.	-3.	-3.	-2.	-2.	-7.	-9.	-18.	-9.	-8.	-7.	-6.
1959	-6.	-5.	-2.	-1.	-1.	-4.	-8.	-6.	-4.	-2.	-2.	-2.
1960	-2.	-2.	-2.	-1.	-1.	-1.	-6.	-4.	-3.	-2.	-2.	-2.
1961	-2.	-3.	-2.	-1.	-1.	-3.	-7.	-5.	-3.	-3.	-2.	-2.
1962	-2.	-2.	-2.	-1.	-1.	-2.	-4.	-4.	-4.	-2.	-3.	-3.
1963	-3.	-3.	-2.	-1.	-1.	-3.	-2.	-4.	-3.	-3.	-2.	-2.
1964	-2.	-2.	-2.	-1.	-2.	-6.	-8.	-12.	-4.	-4.	-4.	-3.
1965	-3.	-3.	-1.	-1.	-1.	-3.	-5.	-5.	-1.	-2.	-1.	-1.
1966	-1.	-2.	-1.	-1.	-1.	-4.	-6.	-5.	-6.	-5.	-4.	-3.
1967	-3.	-3.	-2.	-1.	-1.	-1.	-7.	-9.	-6.	-5.	-5.	-5.

Table 15-C.--From grassland to irrigated potatoes, in acre-feet per month;

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	-15.	-13.	-12.	-11.	-11.	-27.	-44.	-46.	-39.	-28.	-23.	-19.
1953	-17.	-15.	-14.	-13.	-12.	-34.	-56.	-65.	-48.	-35.	-28.	-24.
1954	-21.	-18.	-17.	-15.	-14.	-39.	-67.	-57.	-37.	-30.	-25.	-22.
1955	-20.	-18.	-17.	-15.	-15.	-31.	-49.	-75.	-55.	-40.	-32.	-27.
1956	-24.	-21.	-19.	-18.	-17.	-45.	-46.	-33.	-32.	-26.	-22.	-20.
1957	-18.	-17.	-16.	-15.	-14.	-38.	-54.	-64.	-44.	-34.	-28.	-24.
1958	-21.	-19.	-18.	-17.	-16.	-42.	-49.	-66.	-45.	-35.	-29.	-25.
1959	-22.	-20.	-18.	-17.	-16.	-45.	-72.	-61.	-47.	-36.	-30.	-26.
1960	-23.	-21.	-19.	-18.	-17.	-22.	-67.	-54.	-43.	-34.	-28.	-25.
1961	-22.	-20.	-19.	-17.	-16.	-33.	-57.	-62.	-40.	-33.	-28.	-24.
1962	-22.	-20.	-18.	-17.	-16.	-22.	-30.	-35.	-28.	-23.	-20.	-18.
1963	-17.	-15.	-15.	-14.	-13.	-34.	-61.	-54.	-36.	-29.	-25.	-21.
1964	-19.	-17.	-16.	-15.	-14.	-45.	-52.	-59.	-39.	-31.	-26.	-23.
1965	-20.	-18.	-17.	-16.	-15.	-36.	-46.	-42.	-29.	-24.	-21.	-19.
1966	-17.	-16.	-15.	-14.	-13.	-49.	-58.	-47.	-37.	-29.	-25.	-21.
1967	-19.	-18.	-16.	-15.	-14.	-17.	-63.	-62.	-46.	-35.	-28.	-24.

Table 15-D.--From grassland to irrigated potatoes, as a percentage of the natural flow;

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	-3.	-4.	-2.	-1.	-2.	-5.	-10.	-11.	-12.	-10.	-6.	-5.
1953	-5.	-5.	-2.	-1.	-1.	-6.	-12.	-14.	-13.	-11.	-9.	-5.
1954	-6.	-6.	-3.	-2.	-2.	-6.	-9.	-11.	-4.	-3.	-3.	-3.
1955	-4.	-4.	-3.	-2.	-2.	-5.	-10.	-20.	-17.	-8.	-6.	-5.
1956	-6.	-6.	-4.	-2.	-2.	-7.	-9.	-6.	-7.	-7.	-3.	-3.
1957	-4.	-4.	-3.	-2.	-2.	-6.	-12.	-18.	-10.	-10.	-5.	-4.
1958	-5.	-5.	-4.	-3.	-4.	-14.	-16.	-27.	-14.	-13.	-11.	-10.
1959	-9.	-9.	-4.	-2.	-2.	-8.	-14.	-9.	-7.	-3.	-3.	-3.
1960	-3.	-4.	-3.	-2.	-1.	-3.	-11.	-7.	-4.	-4.	-4.	-4.
1961	-4.	-4.	-3.	-2.	-2.	-5.	-11.	-8.	-5.	-4.	-3.	-3.
1962	-3.	-3.	-3.	-2.	-2.	-3.	-5.	-6.	-5.	-4.	-4.	-4.
1963	-4.	-4.	-3.	-2.	-2.	-6.	-7.	-9.	-7.	-7.	-5.	-4.
1964	-5.	-5.	-4.	-3.	-3.	-13.	-14.	-19.	-7.	-7.	-7.	-6.
1965	-6.	-6.	-3.	-1.	-2.	-6.	-10.	-9.	-2.	-3.	-3.	-2.
1966	-3.	-3.	-2.	-1.	-2.	-8.	-12.	-9.	-8.	-7.	-7.	-5.
1967	-5.	-5.	-3.	-2.	-2.	-2.	-11.	-14.	-10.	-9.	-8.	-7.

Table 15-E.--From evergreen forest to irrigated beans, in acre-feet per month;

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	3.	2.	2.	1.	20.	5.	-11.	-13.	-13.	-8.	4.	14.
1953	7.	4.	3.	2.	2.	-8.	-23.	-29.	-21.	-14.	-8.	13.
1954	4.	2.	1.	5.	12.	2.	-19.	-21.	13.	4.	2.	1.
1955	0.	0.	-0.	3.	10.	2.	-12.	-38.	-26.	8.	1.	-0.
1956	-1.	-1.	-1.	-1.	-1.	-12.	-16.	2.	-4.	-3.	15.	6.
1957	4.	2.	1.	4.	2.	-7.	-21.	-33.	-14.	-11.	8.	1.
1958	-0.	-1.	-1.	3.	1.	-13.	-16.	-34.	-17.	-13.	-9.	-6.
1959	-6.	-5.	-4.	15.	15.	-5.	-19.	-3.	3.	0.	-1.	-1.
1960	-1.	-1.	-2.	4.	2.	3.	-28.	1.	5.	6.	2.	1.
1961	1.	0.	-0.	-0.	4.	-8.	-21.	5.	16.	9.	5.	4.
1962	3.	2.	1.	3.	2.	6.	-3.	-2.	4.	9.	5.	3.
1963	3.	2.	2.	5.	2.	-0.	-2.	-9.	-3.	-2.	12.	12.
1964	7.	5.	4.	4.	3.	-11.	-14.	-25.	9.	2.	1.	6.
1965	3.	2.	1.	1.	4.	-5.	-12.	-14.	8.	2.	1.	1.
1966	1.	0.	0.	0.	0.	-17.	-34.	-13.	-8.	-6.	-5.	1.
1967	-1.	-1.	-1.	11.	6.	16.	-19.	-26.	-5.	19.	8.	5.

Table 15-F.--From evergreen forest to irrigated beans, as a percentage of the natural flow;

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	1.	1.	0.	0.	3.	1.	-3.	-3.	-4.	-3.	1.	3.
1953	2.	2.	0.	0.	0.	-1.	-5.	-6.	-6.	-4.	-3.	3.
1954	1.	1.	0.	1.	2.	0.	-3.	-4.	1.	0.	0.	0.
1955	0.	0.	-0.	0.	2.	0.	-3.	-10.	-8.	1.	0.	-0.
1956	-0.	-0.	-0.	-0.	-0.	-2.	-3.	0.	-1.	-1.	2.	1.
1957	1.	1.	0.	1.	0.	-1.	-5.	-9.	-3.	-3.	1.	0.
1958	-0.	-0.	-0.	1.	0.	-4.	-5.	-14.	-5.	-5.	-3.	-2.
1959	-2.	-2.	-1.	2.	2.	-1.	-4.	-0.	0.	0.	-0.	-0.
1960	-0.	-0.	-0.	0.	0.	0.	-5.	0.	1.	1.	0.	0.
1961	0.	0.	-0.	-0.	1.	-1.	-4.	1.	2.	1.	1.	0.
1962	0.	0.	0.	0.	0.	1.	-1.	-0.	1.	1.	1.	1.
1963	1.	1.	0.	1.	1.	-0.	-0.	-2.	-1.	-1.	2.	2.
1964	2.	1.	1.	1.	1.	-3.	-4.	-8.	2.	0.	0.	2.
1965	1.	1.	0.	0.	1.	-1.	-3.	-3.	1.	0.	0.	0.
1966	0.	0.	0.	0.	0.	-3.	-7.	-2.	-2.	-2.	-1.	0.
1967	-0.	-0.	-0.	1.	1.	2.	-3.	-6.	-1.	5.	2.	1.

Table 15-G.--From evergreen forest to irrigated potatoes, in acre-feet per month;

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	1.	0.	-0.	-1.	18.	-5.	-27.	-26.	-23.	-15.	-2.	9.
1953	3.	1.	-0.	-1.	-1.	-24.	-45.	-47.	-34.	-24.	-16.	6.
1954	-2.	-3.	-4.	0.	8.	-6.	-39.	-37.	2.	-5.	-5.	-5.
1955	-5.	-5.	-5.	-1.	6.	-5.	-27.	-58.	-40.	-3.	-7.	-8.
1956	-7.	-7.	-6.	-6.	-6.	-31.	-34.	-9.	-13.	-11.	8.	0.
1957	-2.	-3.	-3.	-1.	-3.	-21.	-42.	-53.	-28.	-22.	-1.	-7.
1958	-7.	-7.	-7.	-3.	-4.	-33.	-35.	-56.	-32.	-24.	-19.	-14.
1959	-13.	-11.	-10.	9.	10.	-27.	-44.	-19.	-9.	-10.	-10.	-9.
1960	-8.	-8.	-7.	-2.	-3.	-2.	-52.	-13.	-6.	-3.	-5.	-6.
1961	-6.	-6.	-6.	-6.	-1.	-24.	-43.	-9.	5.	-0.	-2.	-3.
1962	-4.	-4.	-4.	-2.	-3.	1.	-12.	-9.	-1.	4.	0.	-1.
1963	-2.	-2.	-2.	2.	1.	-8.	-10.	-18.	-10.	-8.	7.	7.
1964	3.	1.	0.	0.	-0.	-42.	-31.	-43.	-3.	-8.	-7.	-1.
1965	-3.	-3.	-3.	-3.	5.	-22.	-30.	-28.	-2.	-6.	-6.	-5.
1966	-5.	-5.	-4.	-4.	-4.	-42.	-63.	-32.	-22.	-18.	-15.	-8.
1967	-8.	-8.	-7.	6.	0.	11.	-43.	-46.	-1.	9.	-1.	-3.

Table 15-H.--From evergreen forest to irrigated potatoes, as a percentage of the natural flow.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	0.	0.	-0.	-0.	3.	-1.	-7.	-6.	-7.	-5.	-1.	2.
1953	1.	0.	-0.	-0.	-0.	-4.	-10.	-10.	-9.	-8.	-5.	1.
1954	-0.	-1.	-1.	0.	1.	-1.	-5.	-7.	0.	-0.	-1.	-1.
1955	-1.	-1.	-1.	-0.	1.	-1.	-6.	-16.	-12.	-0.	-1.	-1.
1956	-2.	-2.	-1.	-1.	-1.	-5.	-7.	-2.	-3.	-3.	1.	0.
1957	-0.	-1.	-1.	-0.	-0.	-4.	-9.	-15.	-7.	-6.	-0.	-1.
1958	-2.	-2.	-2.	-0.	-1.	-11.	-12.	-23.	-10.	-9.	-7.	-5.
1959	-5.	-5.	-2.	1.	1.	-5.	-8.	-3.	-1.	-1.	-1.	-1.
1960	-1.	-1.	-1.	-0.	-0.	-0.	-9.	-2.	-1.	-0.	-1.	-1.
1961	-1.	-1.	-1.	-1.	-0.	-4.	-8.	-1.	1.	-0.	-0.	-0.
1962	-1.	-1.	-0.	-0.	-0.	0.	-2.	-2.	-0.	1.	0.	-0.
1963	-0.	-1.	-0.	0.	0.	-1.	-1.	-3.	-2.	-2.	1.	2.
1964	1.	0.	0.	0.	-0.	-9.	-8.	-14.	-0.	-2.	-2.	-0.
1965	-1.	-1.	-1.	-0.	1.	-4.	-6.	-6.	-0.	-1.	-1.	-1.
1966	-1.	-1.	-1.	-0.	-1.	-7.	-13.	-6.	-5.	-4.	-4.	-2.
1967	-2.	-2.	-1.	1.	0.	1.	-8.	-10.	-4.	2.	-0.	-1.

Table 16.--Depletion of Ditch 5 of Tenmile Creek near Bancroft that would have resulted during the period 1952-67 from the conversion, in 1948, of 10 percent of the basin area:

A. From grassland to irrigated beans, in acre-feet per month;

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	-7.	-5.	-5.	-4.	-3.	-9.	-18.	-23.	-21.	-16.	-12.	-9.
1953	-8.	-6.	-5.	-5.	-4.	-11.	-24.	-34.	-27.	-20.	-16.	-12.
1954	-10.	-8.	-7.	-6.	-5.	-10.	-19.	-23.	-14.	-11.	-9.	-8.
1955	-6.	-5.	-5.	-4.	-4.	-9.	-20.	-38.	-32.	-23.	-18.	-14.
1956	-11.	-9.	-8.	-7.	-6.	-15.	-18.	-14.	-14.	-11.	-9.	-7.
1957	-5.	-5.	-5.	-4.	-4.	-12.	-22.	-32.	-24.	-18.	-14.	-11.
1958	-9.	-8.	-7.	-6.	-5.	-14.	-20.	-33.	-25.	-18.	-15.	-12.
1959	-10.	-8.	-7.	-6.	-5.	-15.	-30.	-30.	-25.	-14.	-15.	-12.
1960	-10.	-8.	-7.	-6.	-6.	-7.	-28.	-27.	-23.	-17.	-14.	-11.
1961	-9.	-8.	-7.	-6.	-5.	-10.	-24.	-31.	-21.	-16.	-13.	-11.
1962	-9.	-8.	-7.	-6.	-5.	-11.	-14.	-18.	-15.	-11.	-9.	-8.
1963	-7.	-6.	-5.	-5.	-4.	-11.	-11.	-17.	-12.	-9.	-8.	-7.
1964	-6.	-5.	-5.	-4.	-4.	-14.	-21.	-24.	-20.	-15.	-12.	-10.
1965	-8.	-7.	-6.	-5.	-5.	-11.	-18.	-14.	-13.	-11.	-9.	-7.
1966	-6.	-6.	-5.	-4.	-4.	-16.	-24.	-22.	-23.	-17.	-14.	-11.
1967	-9.	-8.	-7.	-6.	-5.	-5.	-26.	-32.	-26.	-14.	-15.	-12.

Table 16-B.--From grassland to irrigated beans, as a percentage of the natural flow;

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	-2.	-2.	-1.	-1.	-1.	-2.	-5.	-7.	-8.	-7.	-5.	-3.
1953	-3.	-3.	-1.	-1.	-1.	-2.	-6.	-9.	-9.	-9.	-7.	-4.
1954	-4.	-4.	-2.	-1.	-1.	-2.	-3.	-5.	-7.	-1.	-1.	-1.
1955	-1.	-1.	-1.	-1.	-1.	-2.	-5.	-13.	-14.	-6.	-4.	-4.
1956	-4.	-4.	-2.	-1.	-1.	-3.	-5.	-3.	-4.	-4.	-2.	-2.
1957	-2.	-2.	-1.	-1.	-1.	-3.	-6.	-12.	-8.	-7.	-3.	-3.
1958	-3.	-3.	-2.	-1.	-2.	-6.	-9.	-19.	-11.	-10.	-9.	-7.
1959	-7.	-7.	-2.	-1.	-1.	-3.	-7.	-6.	-4.	-2.	-2.	-1.
1960	-2.	-2.	-1.	-1.	-1.	-1.	-5.	-4.	-3.	-2.	-2.	-2.
1961	-2.	-2.	-1.	-1.	-1.	-2.	-6.	-5.	-3.	-3.	-2.	-2.
1962	-2.	-2.	-1.	-1.	-1.	-2.	-3.	-4.	-4.	-2.	-3.	-3.
1963	-3.	-3.	-2.	-1.	-1.	-3.	-2.	-4.	-3.	-3.	-2.	-2.
1964	-2.	-2.	-2.	-1.	-1.	-6.	-8.	-14.	-7.	-5.	-5.	-4.
1965	-4.	-4.	-1.	-1.	-1.	-2.	-5.	-5.	-1.	-2.	-1.	-1.
1966	-1.	-1.	-1.	-0.	-1.	-3.	-6.	-5.	-6.	-6.	-5.	-4.
1967	-4.	-4.	-2.	-1.	-1.	-1.	-5.	-8.	-7.	-6.	-6.	-5.

Table 16-C.--From grassland to irrigated potatoes, in acre-feet per month;

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	-10.	-9.	-7.	-6.	-6.	-18.	-32.	-37.	-33.	-24.	-19.	-15.
1953	-12.	-10.	-9.	-7.	-6.	-23.	-42.	-53.	-42.	-31.	-24.	-19.
1954	-16.	-13.	-11.	-9.	-8.	-26.	-50.	-47.	-32.	-25.	-20.	-16.
1955	-13.	-11.	-10.	-9.	-8.	-20.	-35.	-58.	-47.	-34.	-27.	-21.
1956	-18.	-15.	-12.	-11.	-9.	-31.	-34.	-26.	-24.	-19.	-15.	-13.
1957	-11.	-9.	-8.	-7.	-7.	-25.	-40.	-50.	-37.	-28.	-22.	-18.
1958	-15.	-13.	-11.	-10.	-8.	-28.	-36.	-51.	-38.	-29.	-23.	-19.
1959	-16.	-13.	-11.	-10.	-9.	-30.	-54.	-50.	-40.	-30.	-24.	-20.
1960	-16.	-14.	-12.	-11.	-9.	-13.	-47.	-43.	-35.	-27.	-21.	-18.
1961	-15.	-13.	-11.	-10.	-9.	-21.	-41.	-49.	-34.	-26.	-21.	-17.
1962	-15.	-13.	-11.	-10.	-9.	-13.	-19.	-25.	-20.	-16.	-13.	-11.
1963	-10.	-9.	-8.	-7.	-7.	-22.	-45.	-44.	-31.	-24.	-19.	-16.
1964	-13.	-12.	-10.	-9.	-8.	-31.	-40.	-47.	-33.	-26.	-21.	-17.
1965	-14.	-12.	-11.	-9.	-8.	-24.	-34.	-33.	-24.	-19.	-15.	-13.
1966	-11.	-10.	-9.	-8.	-7.	-34.	-45.	-39.	-31.	-24.	-19.	-16.
1967	-14.	-12.	-10.	-9.	-8.	-10.	-45.	-50.	-39.	-29.	-23.	-19.

Table 16-D.--From grassland to irrigated potatoes, as a percentage of the natural flow;

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	-3.	-3.	-2.	-1.	-1.	-4.	-9.	-11.	-13.	-12.	-8.	-5.
1953	-5.	-6.	-2.	-1.	-1.	-4.	-11.	-14.	-14.	-13.	-11.	-6.
1954	-6.	-7.	-3.	-1.	-1.	-5.	-8.	-11.	-4.	-3.	-3.	-3.
1955	-3.	-3.	-2.	-2.	-2.	-4.	-9.	-20.	-20.	-9.	-6.	-6.
1956	-6.	-6.	-4.	-2.	-1.	-6.	-9.	-6.	-7.	-7.	-3.	-3.
1957	-3.	-3.	-3.	-2.	-1.	-5.	-12.	-19.	-12.	-12.	-5.	-4.
1958	-5.	-5.	-4.	-2.	-3.	-12.	-16.	-29.	-17.	-16.	-14.	-12.
1959	-11.	-11.	-4.	-2.	-1.	-6.	-12.	-9.	-7.	-3.	-3.	-2.
1960	-3.	-3.	-2.	-2.	-1.	-2.	-9.	-7.	-4.	-4.	-3.	-3.
1961	-3.	-3.	-2.	-1.	-1.	-4.	-10.	-8.	-5.	-4.	-3.	-3.
1962	-3.	-3.	-2.	-1.	-1.	-2.	-4.	-6.	-5.	-3.	-4.	-4.
1963	-4.	-4.	-2.	-1.	-1.	-5.	-7.	-9.	-8.	-8.	-5.	-5.
1964	-5.	-5.	-4.	-2.	-2.	-13.	-16.	-23.	-6.	-8.	-8.	-7.
1965	-7.	-7.	-2.	-1.	-1.	-5.	-9.	-9.	-3.	-3.	-2.	-2.
1966	-2.	-2.	-1.	-1.	-1.	-7.	-11.	-9.	-8.	-8.	-8.	-6.
1967	-6.	-6.	-3.	-2.	-2.	-2.	-9.	-13.	-10.	-10.	-9.	-9.

Table 16-E.--From evergreen forest to irrigated beans, in acre-feet per month;

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	5.	4.	3.	2.	16.	8.	-4.	-8.	-10.	-6.	2.	11.
1953	7.	5.	4.	3.	2.	-3.	-14.	-20.	-17.	-12.	-7.	9.
1954	5.	3.	2.	5.	10.	5.	-9.	-13.	10.	6.	4.	3.
1955	2.	2.	1.	4.	9.	5.	-5.	-24.	-21.	4.	3.	1.
1956	1.	0.	0.	0.	0.	-6.	-10.	3.	-1.	-1.	12.	8.
1957	5.	4.	3.	4.	3.	-2.	-11.	-22.	-12.	-8.	6.	3.
1958	2.	1.	1.	3.	2.	-5.	-9.	-22.	-14.	-10.	-7.	-4.
1959	-3.	-3.	-2.	12.	15.	3.	-8.	1.	6.	4.	3.	2.
1960	1.	1.	1.	5.	4.	5.	-14.	2.	7.	8.	5.	4.
1961	3.	2.	2.	1.	5.	-2.	-11.	5.	15.	11.	8.	6.
1962	4.	3.	3.	4.	3.	6.	0.	-0.	4.	8.	6.	4.
1963	3.	3.	2.	5.	5.	2.	-0.	-6.	-3.	-2.	9.	10.
1964	7.	5.	4.	4.	3.	-5.	-8.	-17.	6.	3.	2.	6.
1965	4.	3.	2.	2.	7.	-0.	-6.	-9.	6.	4.	2.	2.
1966	1.	1.	1.	1.	1.	-8.	-20.	-10.	-5.	-4.	-3.	1.
1967	0.	0.	-0.	10.	7.	15.	-7.	-16.	-3.	16.	10.	7.

Table 16-F.--From evergreen forest to irrigated beans, as a percentage of the natural flow;

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	1.	1.	1.	0.	3.	2.	-1.	-2.	-4.	-3.	1.	4.
1953	3.	3.	1.	0.	0.	-1.	-3.	-5.	-6.	-5.	-3.	3.
1954	2.	2.	1.	1.	2.	1.	-1.	-3.	1.	1.	1.	0.
1955	0.	0.	0.	1.	2.	1.	-1.	-8.	-9.	1.	1.	0.
1956	0.	0.	0.	0.	0.	-1.	-3.	1.	-0.	-0.	3.	2.
1957	2.	1.	1.	1.	1.	-0.	-3.	-8.	-4.	-3.	1.	1.
1958	1.	0.	0.	1.	1.	-2.	-4.	-13.	-6.	-5.	-4.	-3.
1959	-2.	-2.	-1.	2.	2.	1.	-2.	0.	1.	0.	0.	0.
1960	0.	0.	0.	1.	0.	1.	-3.	0.	1.	1.	1.	1.
1961	1.	1.	0.	0.	1.	-0.	-3.	1.	2.	2.	1.	1.
1962	1.	1.	1.	1.	1.	1.	0.	-0.	1.	2.	2.	1.
1963	1.	1.	1.	1.	1.	0.	-0.	-1.	-1.	-1.	3.	3.
1964	3.	2.	1.	1.	1.	-2.	-3.	-8.	1.	1.	1.	2.
1965	2.	1.	0.	0.	1.	-0.	-2.	-2.	1.	1.	0.	0.
1966	0.	0.	0.	0.	0.	-2.	-5.	-2.	-1.	-1.	-1.	0.
1967	0.	0.	-0.	2.	2.	3.	-1.	-4.	-1.	5.	4.	3.

Table 16-G.--From evergreen forest to irrigated potatoes, in acre-feet per month;

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	3.	3.	2.	1.	15.	3.	-13.	-16.	-16.	-11.	-1.	9.
1953	5.	3.	2.	2.	1.	-11.	-27.	-33.	-26.	-19.	-13.	5.
1954	2.	0.	-0.	3.	9.	1.	-20.	-24.	3.	0.	-1.	-1.
1955	-1.	-1.	-1.	2.	8.	1.	-13.	-37.	-30.	-3.	-3.	-3.
1956	-3.	-3.	-2.	-2.	-2.	-15.	-20.	-5.	-6.	-5.	9.	5.
1957	3.	2.	1.	3.	2.	-9.	-23.	-35.	-21.	-15.	0.	-2.
1958	-2.	-2.	-2.	1.	0.	-16.	-20.	-36.	-23.	-17.	-13.	-9.
1959	-7.	-6.	-5.	10.	13.	-8.	-22.	-10.	-2.	-2.	-2.	-2.
1960	-2.	-2.	-2.	2.	2.	3.	-28.	-7.	0.	2.	1.	0.
1961	-0.	-1.	-1.	-1.	3.	-10.	-24.	-4.	8.	6.	3.	2.
1962	1.	1.	0.	1.	1.	4.	-4.	-4.	1.	6.	4.	2.
1963	2.	1.	1.	3.	4.	-2.	-4.	-11.	-6.	-5.	7.	8.
1964	5.	4.	3.	2.	2.	-15.	-19.	-28.	-3.	-3.	-3.	1.
1965	0.	-0.	-0.	-1.	5.	-9.	-17.	-18.	-1.	-2.	-2.	-2.
1966	-2.	-1.	-1.	-1.	-1.	-21.	-39.	-23.	-15.	-12.	-9.	-4.
1967	-4.	-3.	-3.	7.	5.	13.	-20.	-29.	-13.	9.	5.	2.

Table 16-H.--From evergreen forest to irrigated potatoes, as a percentage of the natural flow.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1952	1.	1.	0.	0.	3.	1.	-4.	-5.	-6.	-5.	-1.	3.
1953	2.	2.	0.	0.	0.	-2.	-7.	-9.	-9.	-8.	-6.	2.
1954	1.	0.	-0.	0.	1.	0.	-3.	-5.	0.	0.	-0.	-0.
1955	-0.	-0.	-0.	0.	2.	0.	-3.	-13.	-13.	-1.	-1.	-1.
1956	-1.	-1.	-1.	-0.	-0.	-3.	-5.	-1.	-2.	-2.	2.	1.
1957	1.	1.	0.	1.	0.	-2.	-7.	-13.	-7.	-6.	0.	-0.
1958	-1.	-1.	-1.	0.	0.	-7.	-9.	-21.	-10.	-9.	-8.	-6.
1959	-5.	-5.	-2.	2.	2.	-2.	-5.	-2.	-0.	-0.	-0.	-0.
1960	-0.	-0.	-0.	0.	0.	0.	-5.	-1.	0.	0.	0.	0.
1961	-0.	-0.	-0.	-0.	0.	-2.	-6.	-1.	1.	1.	0.	0.
1962	0.	0.	0.	0.	0.	1.	-1.	-1.	0.	1.	1.	1.
1963	1.	0.	0.	1.	1.	-0.	-1.	-2.	-2.	-1.	2.	2.
1964	2.	2.	1.	1.	1.	-6.	-8.	-14.	-1.	-1.	-1.	1.
1965	0.	-0.	-0.	-0.	1.	-2.	-4.	-5.	-0.	-0.	-0.	-0.
1966	-0.	-0.	-0.	-0.	-0.	-4.	-9.	-5.	-4.	-4.	-4.	-1.
1967	-2.	-2.	-1.	1.	1.	2.	-4.	-8.	-3.	3.	2.	1.

Estimates of the effects on streamflow resulting from converting 10 percent of the grassland in the basin of Big Roche a Cri Creek near Hancock to forest or tree plantations were made from differences in computed water-balance recharge for the two types of cover, using the stream-aquifer model for the basin. The computations indicate that converting 10 percent of the land in the basin to forest before 1948 would have reduced August and September streamflow in Big Roche a Cri Creek near Hancock by about 20 acre-feet or about 4 percent of the unaffected flow for the 1952-67 period. Computed streamflow reduction due to reforestation was not necessarily greater during drought, however, and the percentage reduction in August 1958 was only slightly greater than that for the entire period. Nonetheless, streamflow reduction might be significant if the entire basin area were reforested.

EFFECTS OF PRESENT AND POTENTIAL DEVELOPMENT IN THE MARSH AREA

Irrigation has been less intensive in the marsh area than in the headwater area because drainage is poor and the frost hazard is high. However, about 10 miles of new drainage ditches were dredged during 1964-67. About 1,200 acres were irrigated in the Leola Marsh in 1967, and about 400 acres were irrigated in Buena Vista Marsh. These areas have been irrigated from wells and pits, and a few fields were irrigated occasionally by pumping surface water from the ditches. Local areas adjacent to drain ditches are subirrigated by raising the stages of water in the ditches to bring the water table near the root zone of the crops.

The seasonal effects of irrigation on streamflow in the marsh area are more severe than those in the headwater area because less of the pumped water is from ground-water storage. Wells in the marsh area are generally placed near ditches, and a substantial part of the pumpage is diverted from streamflow soon after pumping begins, and little is from ground-water storage. Irrigation with surface water in excess of crop needs results in an increase in ground-water storage at the expense of streamflow. Depletion downstream from points of surface-water withdrawal are less than the diversion because additional ground-water inflow is induced by the lower stream stage (Weeks and others, 1965, p. 58-60). These effects are small and would not outweigh the impact of irrigation from pumped surface water on streamflow.

Effects of subirrigation on summer streamflow are more severe than the effects of irrigation from wells. In addition to evapotranspiration, ground-water storage is increased substantially at the expense of surface flow to build up water levels beneath the fields. Although this stored water returns to the stream after the irrigation season, it is not available to the stream during summer low flows.

The annual increase in evapotranspiration resulting from irrigation in the marsh area would be less than in the headwater area because more of the vegetation in the marsh area is phreatophytic. Replacing phreatophytes with irrigated crops would result in less evapotranspiration and more runoff because the growing season for the crops is shorter than for phreatophytes.

Evapotranspiration from irrigated crops would be only a little larger from the replaced native vegetation in areas of deep peat soils in the marsh. Soil-moisture storage in the peat is relatively large and provides sustained evapotranspiration without irrigation.

The hydrologic condition of plant growth in the marsh area is altered by expanded and improved drainage. In the drained area the water table and its capillary fringe is drawn down below the root zone of grasses and crops more rapidly after heavy rains or snowmelt, and the plants depend upon limited soil moisture rather than ground water for a longer part of the growing season. Under these conditions, pastures and grassland may deteriorate to the detriment of beef and dairy farmers and to prairie chicken habitat. Thus, both economic and ecologic diversity in the area would diminish.

Although improved drainage would increase annual runoff and reduce evapotranspiration, runoff from a given rainstorm would be more rapid. The effects of more rapid drainage would be greater flows during periods of high runoff and decreased low flows.

Some of the effects of irrigation development in the marsh area of Tenmile Creek basin were computed using the aquifer-stream model. Estimates of changes in the ground-water contribution to streamflow were made assuming that 10 percent of the grassland within the marsh was converted to irrigated beans and potatoes. For these computations it was assumed that evapotranspiration from grassland within the marsh area was equal to that in the headwater area. The increase in evapotranspiration resulting in conversion of the evergreens to irrigated crops also was computed. These computations indicate that streamflow depletion within the marsh area would increase about 70 acre-feet and about 100 acre-feet per month in July and August, respectively, during the 1952-67 period by converting to beans and to potatoes.

Computations were also made of the increase in streamflow from the marsh area due to clearing phreatophytic trees and irrigating potatoes. For these computations evapotranspiration from phreatophytes was assumed to occur at the computed potential rate. The decrease in evapotranspiration due to conversion to irrigated potatoes was computed as the difference between potential evapotranspiration and evapotranspiration from row crops for the nonirrigation season, and as the difference between potential evapotranspiration and that computed for irrigated potatoes for the irrigation season. The computations indicate that streamflow might increase, on the average, by about 30-50 acre-feet per month in May and June and by about 10-20 acre-feet per month in July and August during the 1952-67 period.

A net increase of streamflow would result if phreatophytes were converted to irrigated crops, but grassland is more likely to be converted than swampland, and summer streamflow losses probably would increase with irrigation development.

To estimate the effects of dredging new ditches in the marsh area, computations were made of the monthly ground-water contributions to streamflow from the area. It was assumed that a new ditch was dredged midway between Ditches 5 and 10 (fig. 12) of Tenmile Creek. These computations were made by

dividing the interdrain area in the model of the stream-aquifer system into two equal areas and assuming that monthly recharge rate was the same in both areas. Although the average flows for July and August for the 1952-67 period would be about the same with the added drain, the net gain in streamflow would be larger during wet summers and smaller during dry summers. For example, during the six Augusts of the 1952-67 period in which average losses in flow within the marsh area were computed to have occurred, the losses would have been increased about 10 acre-feet per month, or from about 150 to 160 acre-feet. Although these additional losses are small, they would further deplete streamflow.

No attempt was made to estimate the additional seasonal effects of irrigation from surface water or of subirrigation on streamflow. Also, no estimates were made of the decrease in evapotranspiration resulting from improved drainage or from conversion of grassland to unirrigated row crops. The effects of such irrigation and of decreased evapotranspiration would tend to cancel, and their combined effects probably would be small compared to those resulting from ground-water pumpage for irrigation.

The effects on streamflow due to irrigation in the marsh areas of Fourmile and Fourteenmile Creeks would be similar to those for the marsh area of Tenmile Creek basin.

POTENTIAL DEVELOPMENT IN THE FORESTED DOWNSTREAM AREA

The forested area downstream from the marshes had little irrigation development in 1967, but it may be developed in the future. Extensive development would require the clearing of forests because most fields are too small to be irrigated economically. Because most of the irrigated land would be converted from forest and because drain spacing in the area is fairly large, seasonal effects of irrigation on streamflow would be less pronounced than those in either the headwater areas or in the marsh areas. Streamflow is large and fairly steady in the downstream reaches, and streamflow depletion due to irrigation development would be less detrimental to aquatic life than development in the headwater area.

To estimate the effects of possible irrigation in the forested part of Tenmile Creek basin, computations were made using the rectangular aquifer-stream model. The results of these computations indicate that the average August streamflow would decrease about 7 percent after converting 10 percent of the forest acreage to potatoes. During the drought year of 1958, the streamflow depletion would be about 30 percent of the computed flow. Converting an equal acreage of forested land to irrigated beans would result in changes in August flow ranging from a decline of about 20 percent of the natural flow to a slight gain in flow. Average depletion of August streamflow would be about 3 percent of the flow contribution from the area.

Values for streamflow depletion in acre-feet per month are not given, because the streamflow contribution computed from the aquifer-stream model was only about one-half that measured for the seepage runs (fig. 12). The ratio of computed to actual streamflow was nearly constant, however, and the percentage values should be nearly correct.

Irrigation development in the forested downstream area of Fourteenmile Creek basin would be limited by the availability of ground water because the saturated thickness of unconsolidated deposits is thin (fig. 5). However, outwash and glacial lake deposits provide water to irrigation wells in a large area north of the stream. Development of land for irrigation in the north probably would have effects similar to those computed for the downstream area of Tenmile Creek basin.

CONCLUSIONS

Extensive development of ground water for irrigation in the sand-plain area has affected streamflow and water levels. The magnitude of these effects has been controlled by the geology, drainage, and topography of the area, by the land use before irrigation development, by the distribution of pumpage, and by the acreages and crops irrigated. Three areas in the sand plain differ significantly in drainage, topography, land use, and extent of development. They are the headwater area, the marsh area, and the forested area downstream from the marshes.

The headwater area (including the area immediately to the east of the ground-water divide between the Wisconsin and Wolf Rivers) is the most intensively developed of the three areas. Within the headwater area, about 34,000 acres, including 10,300 acres of potatoes; 15,500 acres of beans; 6,500 acres of corn; 1,400 acres of cucumbers; and about 300 acres of other crops; were irrigated in 1967. Irrigated acreage in the headwater area in 1967 amounted to about 30 percent of the total irrigable acreage. Pumpage for irrigation in the area ranged from about 16,000 to about 22,000 acre-feet during the 1965-67 seasons. Other estimates indicated that about 70 percent of the applied water is lost to evapotranspiration, and about 30 percent returned to the water table.

Irrigation development in the headwater area has increased evapotranspiration at the expense of runoff, and to a small extent, ground-water storage. Conversion of grassland to irrigated beans has increased evapotranspiration by about 3 inches a year, and conversion to irrigated potatoes has increased evapotranspiration by about 5 to 6 inches a year. Conversion of forested land to irrigated beans has resulted in little change in evapotranspiration, but conversion to irrigated potatoes has increased evapotranspiration by about 3 inches per year.

If the acreage irrigated in 1967 had been converted entirely from grassland, the flow of Big Roche a Cri Creek near Hancock in July and August would have been depleted by an average of 110-130 acre-feet per month, or by 25-30 percent of the natural flow. Moreover, streamflow would have been reduced by about 70 acre-feet per month, or 15-20 percent of the natural flow, after conversion to irrigated cropland from forest.

Ground-water levels have also been affected by pumpage for irrigation in the headwater area. These effects are too small to cause excessive well interference, but may have caused the declines in stage observed in some kettle lakes. The summer decline in water levels due to seasonal irrigation pumpage was about 0.5 foot in 1966 and 1967. This decline was in addition to an approximate 2- to 3-foot seasonal decline occurring naturally as ground water drained to the streams. The long-term decline in water levels in the vicinity of the major ground-water divide (the most affected area) would have ranged from 2 to 3 feet, had the acreage irrigated in 1967 been irrigated throughout the 1948-67 period. These values compare with natural fluctuations of about 7 feet near the divide during the 1952-67 period.

Irrigation development will continue in the headwater area, although probably at a slower rate than in the early 1960's. Such development will

further deplete streamflow. For example, irrigating 50 percent of the acreage in the headwater area would seriously deplete summer streamflow during drought, and some headwater streams might dry up if the drought were severe. Water levels in the major divide area might be reduced by about 4-5 additional feet under these conditions.

Some tree plantations are in the headwater area, and more may be planted in the future. Conversion of grassland to forest increases evapotranspiration at the expense of runoff, because the deeply rooted trees tap a larger amount of soil-moisture storage. Converting 10 percent of the headwater area from grassland to forest would decrease late summer streamflow by about 5 percent due to reduction of summer and fall recharge. However, planting nonphreatophytic trees would not necessarily reduce drought flow because little or no summer or fall recharge would occur under either forest or grassland.

The drained marshland west of the headwater area has some irrigation development. By 1967, such development included irrigation of about 1,600 acres of potatoes, beans, and corn. Summer flows in the streams and drains were reduced because improved drainage depleted ground-water recharge more rapidly than before and because evapotranspiration during late summer increased. These effects are reduced to some extent by decreases in evapotranspiration resulting from clearing phreatophytes. The reduced evapotranspiration partly compensates for the effects of irrigation on annual streamflow but has little effect on the depletion by irrigation pumpage on late summer low flows.

Very little irrigation development has occurred in the forested area downstream from the marshes. Should the area be developed, land would have to be cleared. Annual evapotranspiration would be about 0-3 inches greater from the irrigated acreage than from the forested land, less than the 3- to 6-inch increase in evapotranspiration resulting from converting grassland to irrigated cropland. Also, the seasonal effects of irrigation would be somewhat less in the forested area than in the headwater area or the drained marsh area. Converting 10 percent of the forested land in the downstream area of Tenmile Creek to irrigated potatoes would deplete average August flow by about 7 percent. In drought years, such as 1958, as much as 30 percent of the flow from the area would be depleted. Converting forested land in the same area to irrigated beans would have less effect on summer streamflows. The August flow contribution after converting to irrigated beans would range from a slight increase in wet years to an approximate 20 percent decline during very dry years.

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