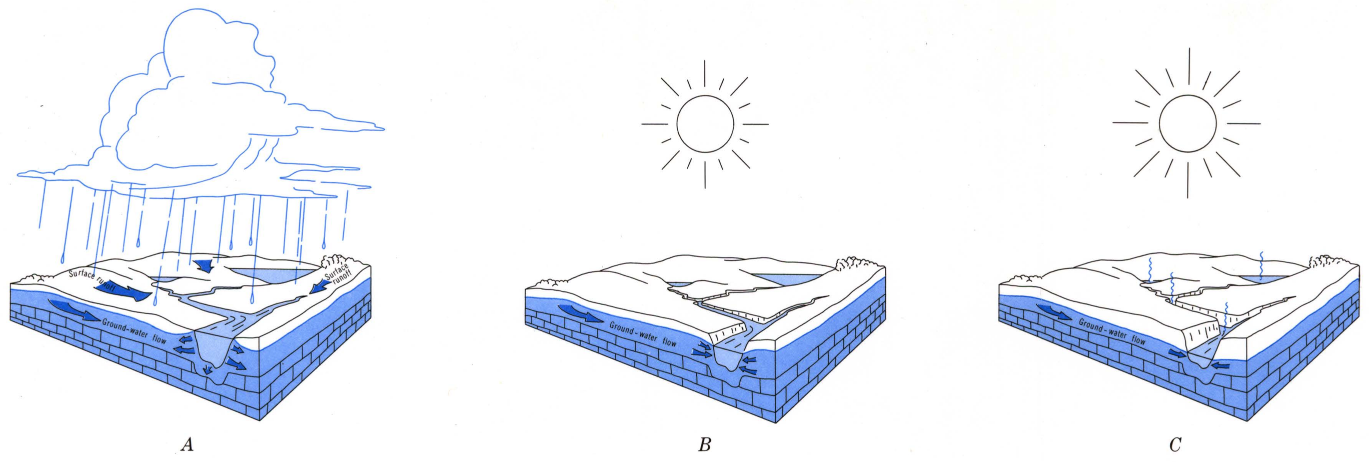
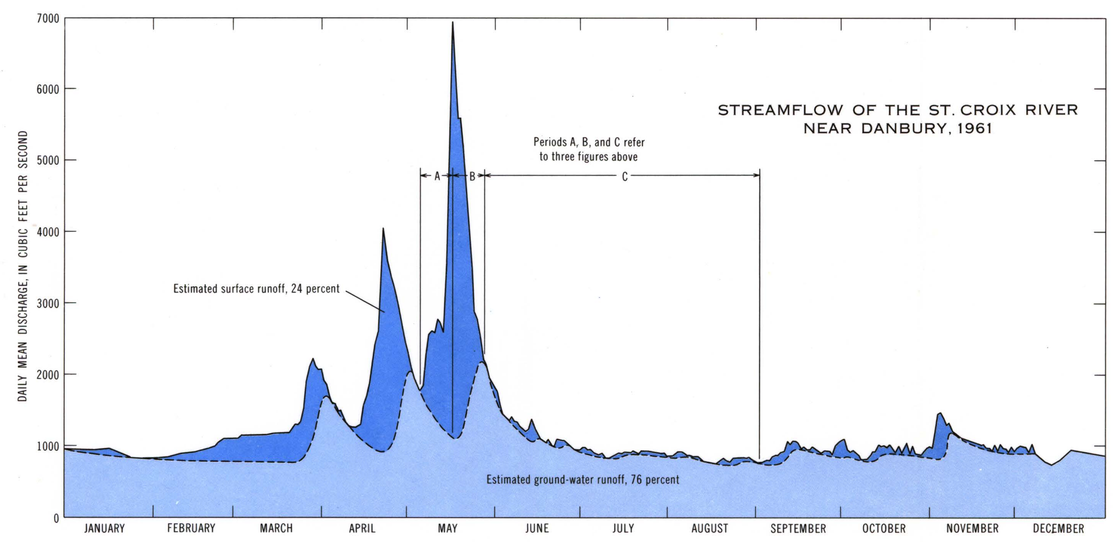
GROUND-WATER-SURFACE-WATER RELATIONSHIPS



GROUND-WATER RELATION TO STREAMFLOW

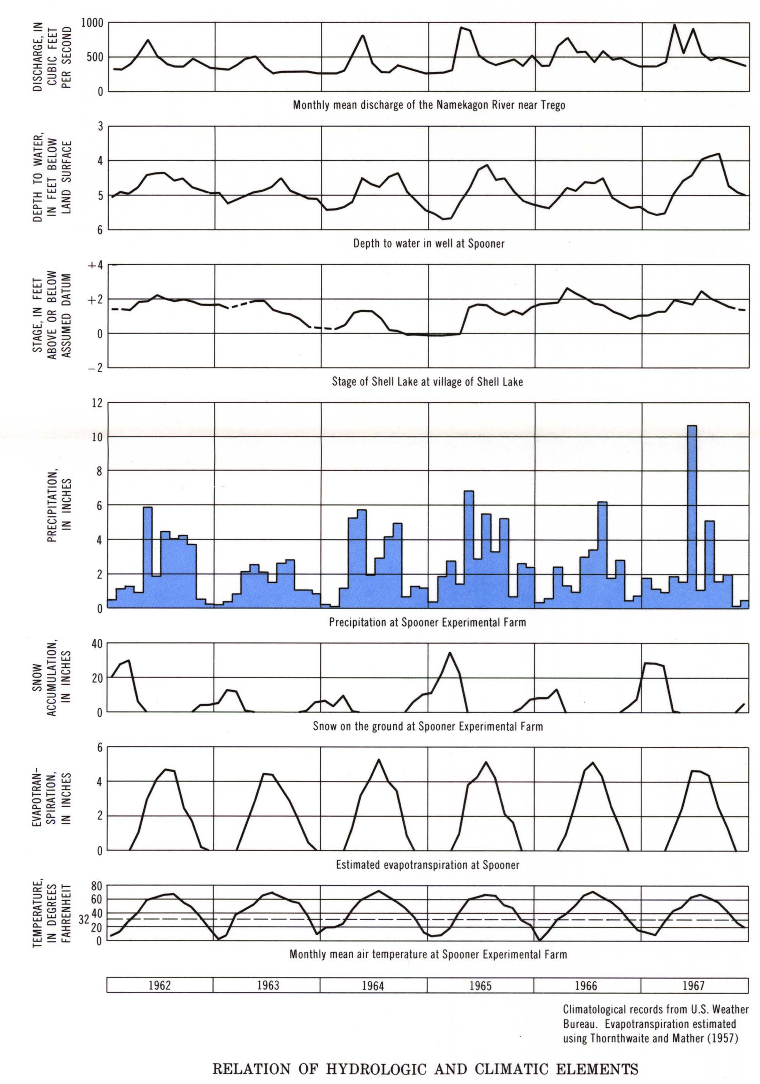
Streamflow is a combination of surface and ground-water runoff. During snowmelt and periods of prolonged, heavy rainfall, surface runoff moves rapidly to streams. Water is recharged to the ground-water reservoir during these periods. Ground water is discharged more slowly and maintains streamflow during dry periods. The three sketches show the general relationship between streamflow and ground water in response to heavy rainfall. During periods of prolonged rainfall and/or snowmelt, stream stage and the water table rise (A). Surface water moves into streambanks, raising the water table adjacent to the streams. As stream stage recedes, water stored in the streambanks returns to the streams, and the water table declines as ground water discharges to the streams (B). Stream stage and the water table continue to decline (C) until the next significant rainfall or snowmelt. Representative periods that approximate these conditions are shown on the hydrograph separation below.

The important features of the hydrograph are the relatively uniform contribution of ground water to low flow for 9 months of the year and the high surface runoff during short periods. Snowmelt in late March and heavy rainfall in April and May produced the major high flows of the year. Ground-water runoff also increased sharply during the periods of high flow but receded slowly after the flood crest passed. The mean discharge for 1961 was 1,272 cfs, very near the average discharge of 1,286 cfs for the period of record



GROUND-WATER CONTRIBUTION TO STREAMFLOW

Ground water and surface water are intimately and directly related in all phases of their movement within the basin. Both seasonal and long-term increases or decreases in precipitation cause corresponding increases or decreases in ground-water levels, streamflow, and lake stages. Similarly, natural or manmade changes in ground-water levels, streamflow, or lake stage cause corresponding changes in the others. The quality of ground water and surface water is similar, although surface-water quality is subject to greater variability.



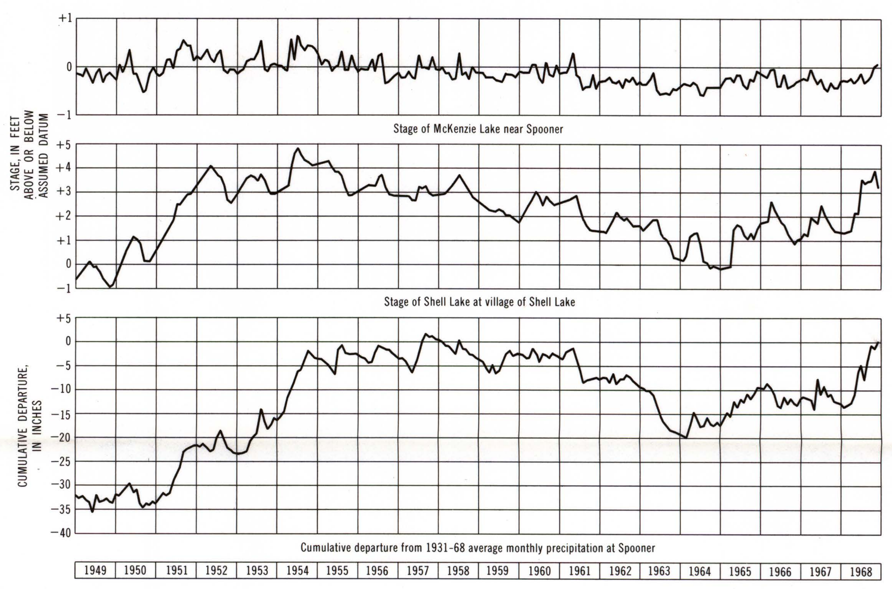
RELATION OF HYDROLOGIC AND CLIMATIC ELEMENTS

The direct relationships between streamflow, ground-water level, lake level, and climatological factors is shown by a comparison of records for 1962-67 in the Spooner area. These relationships apply to the basin in general. Rainfall and snowmelt increase streamflow and raise ground-water and lake levels, and periods of no recharge and periods of evapotranspiration produce declines. Runoff in the spring increases sharply when a thick snow cover melts rapidly.

Streamflow peaks generally are the result of heavy rainfall, spring snowmelt, or a combination of the two. Peak flows in spring are primarily from snowmelt but may be augmented by rainfall, as in 1962, 1964, and 1965. Heavy rainfall in summer also produces peak flows, except during periods of highest evapotranspiration and soil-moisture deficit (see Monthly Water Balance, sheet 1).

The water level in the well at Spooner and the level of Shell Lake are expressions of the water table and respond similarly to recharge and discharge. The water table generally declines from midsummer or early fall until early spring because of natural ground-water discharge and evapotranspiration; little recharge occurs while the ground is frozen.

The rise of water levels in the lake and well is slower than the corresponding increase in streamflow. This time lag results from the difference between the slow rate of recharge to the water table and the fast rate of surface runoff. Because the lake also receives some overland flow, it has the shortest time lag. The water level in the shallow well is controlled primarily by ground-water movement to the discharge area near the Yellow River.



INFLUENCE OF LONG-TERM PRECIPITATION TRENDS ON LAKE STAGES

Changes in lake stage correlate with the long-term cumulative departure of precipitation from normal. The amount of fluctuation, however, is less in a drainage lake such as McKenzie Lake than in a seepage lake such as Shell Lake. Drainage lakes have surface inlets and outlets, but seepage lakes have neither and are sustained almost entirely by ground-water inflow. In both lakes, stages decline rapidly in summer during hot and dry periods when evapotranspiration is high and precipitation is low. The stage of McKenzie Lake fluctuates less than a foot because the stage is controlled by the natural outlet. In contrast, the stage of Shell Lake fluctuates about 6 feet in accord with fluctuations of the water table.

Low ground-water runoff in this area, which drains to the Totagatic River, is due to thin ground moraine over impervious bedrock, many swamps, and much soil with low permeability. Therefore, recharge over much of the area is inhibited, evapotranspiration is high, available storage is small, and ground-water discharge is low.

This subbasin of the Namekagon River has low ground-water runoff because evapotranspiration is high and ground-water storage is low. The wide outwash-filled valley is flanked by thick end moraines and is very swampy.

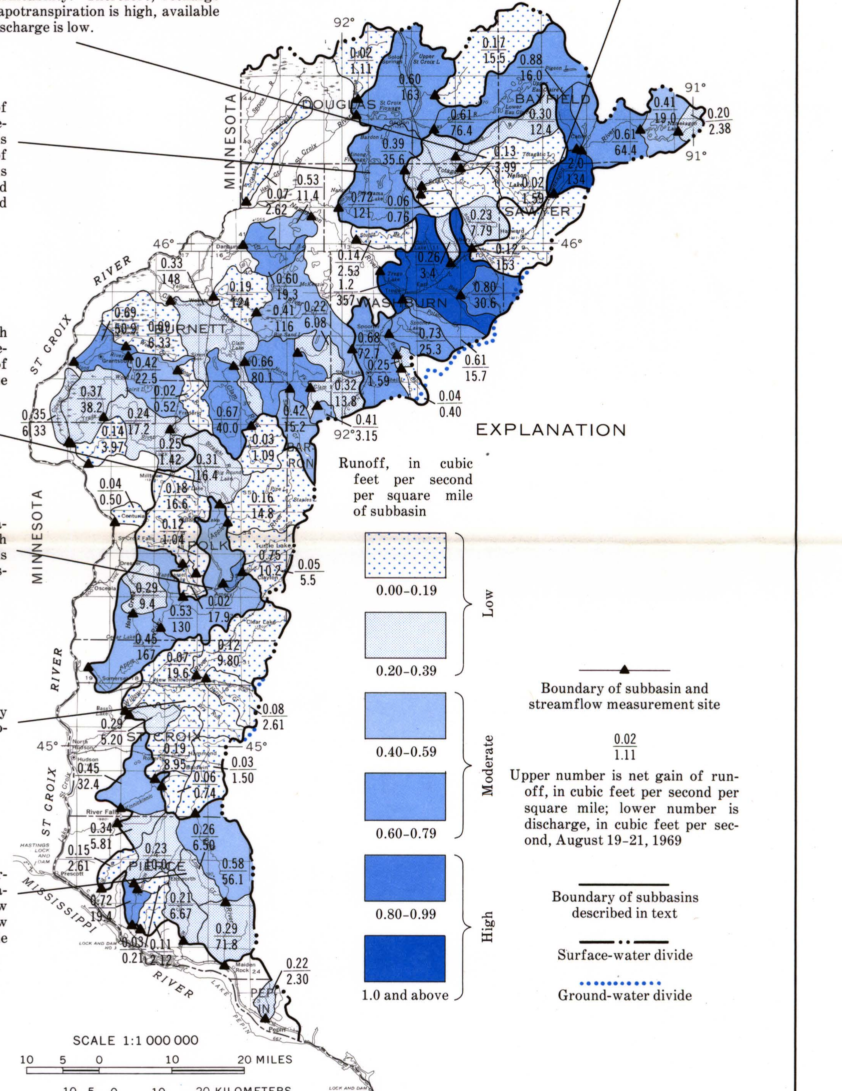
Ground-water runoff is moderate to high in this area because of relatively thick outwash and end moraine deposits and high soil permeability. Some increase in runoff in the southeastern part of the area is due to underflow from the Chippewa River basin (see position of ground-water divide). Low runoff in the Beaver Brook subbasins (0.04 and 0.25 cfs per sq mi) in the southern part of the area is caused by high evapotranspiration from reservoirs, a cranberry bog, and swamps.

This area of low runoff is characterized by thick pitted outwash and end moraine with many lakes and swamps, and soils with medium permeability rates. The low runoff may be due to high rates of evapotranspiration from lakes and swamps, low permeability of the drift, and ground-water underflow from the subbasins.

This area has generally moderate ground-water runoff. The relatively thick outwash and end moraine deposits are recharged through soils with moderately high permeabilities, and some underflow is received from upstream basins. Lakes are abundant and evapotranspiration may significantly reduce runoff.

Low ground-water runoff in this area is due to low permeability and the poor storage capacity of the moderately thick ground moraine and underlying Prairie duChien Group.

Ground-water runoff is low to moderate in this area, which is characterized by deeply dissected sedimentary rocks with little or no glacial drift. High surface runoff from steep land slopes and low permeability of thick silty soils reduce recharge in the areas of low ground-water runoff. Runoff is moderate where the water-table gradient is steep.



DISTRIBUTION OF LOW-FLOW RUNOFF, AUGUST 19-21, 1969

Discharges at 78 sites during a 3-day period of low flow (largely from ground water) show the range of low flow from subbasins within the St. Croix basin. Low flow is expressed in cfs (cubic feet per second) per square mile to eliminate the effect of differences in basin areas in comparing the contributions of the many subbasins.

Differences in low flow are due largely to differences in rock types, soils, rates of precipitation and evapotranspiration, surface relief, and the retention of water in lakes, marshes, and reservoirs. Ground-water runoff is high in areas of thick, permeable glacial deposits where recharge is high, surface runoff is low, and ground-water storage is large. Ground-water runoff is low in areas of thin ground moraine over crystalline bedrock. Runoff is moderate from the area of sedimentary rocks under thin drift, but low runoff and even losing stream reaches may occur in valleys filled with permeable outwash deposits. Low flow is reduced by high rates of evapotranspiration from swamps.

SURFACE WATER

Station no. 5-3335
St. Croix River near Danbury
Drainage area: 1,588 square miles
Period of record: 1914-present
Maximum instantaneous discharge: 10,200 cfs
Average discharge, 54 years: 1,286 cfs
Minimum instantaneous discharge: 393 cfs

Station no. 5-3360
St. Croix River near Grantsburg
Drainage area: 2,820 square miles
Period of record: 1923-present
Maximum instantaneous discharge: 26,300 cfs
Average discharge, 45 years: 2,300 cfs
Minimum instantaneous discharge: 510 cfs

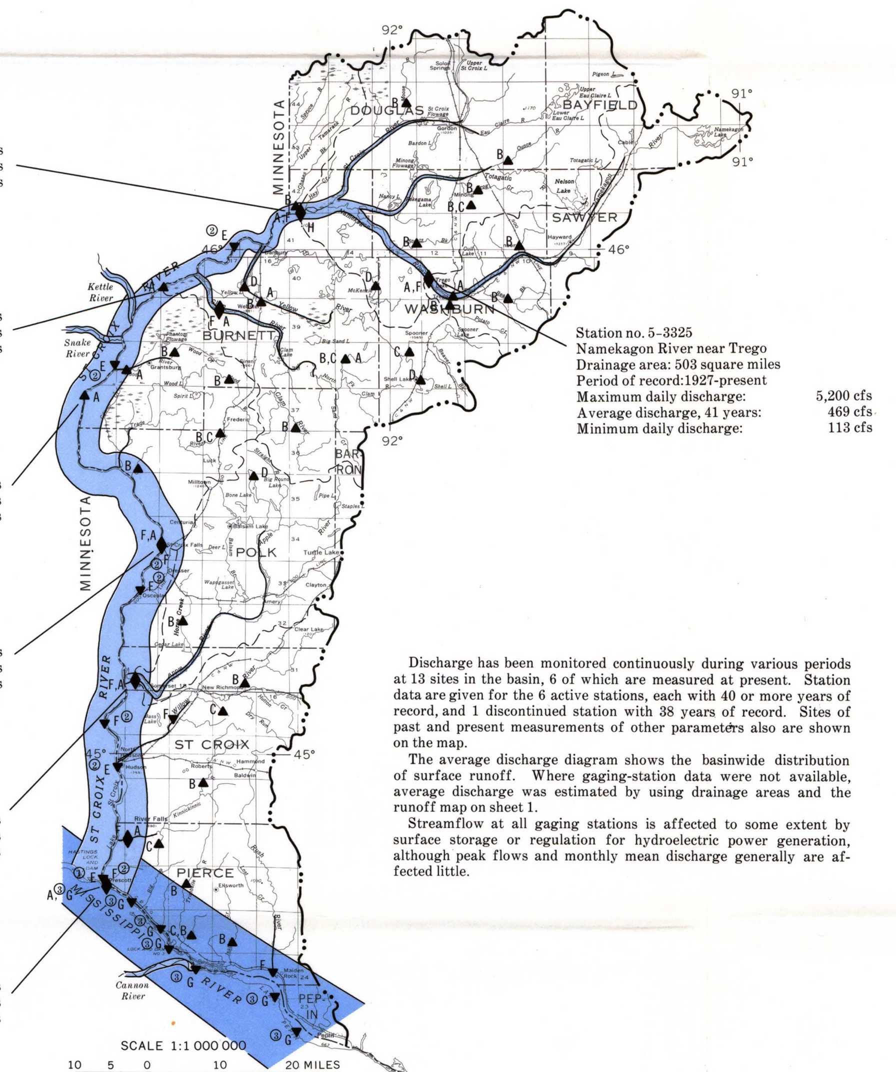
Station no. 5-3395
St. Croix River near Rush City, Minn.
Drainage area: 5,120 square miles
Period of record: 1923-1961
Maximum instantaneous discharge: 60,600 cfs
Average discharge, 38 years: 3,607 cfs
Minimum instantaneous discharge: 630 cfs

Station no. 5-3405
St. Croix River at St. Croix Falls
Drainage area: 5,930 square miles
Period of record: 1902-present
Maximum instantaneous discharge: 54,900 cfs
Average discharge, 66 years: 4,070 cfs
Minimum daily discharge: 75 cfs

Station no. 5-3415
Apple River near Somerset
Drainage area: 555 square miles
Period of record: 1901-present
Maximum daily discharge: 2,510 cfs
Average discharge, 67 years: 305 cfs
Minimum daily discharge: 7 cfs

Station no. 5-3445
Mississippi River at Prescott
Drainage area: 44,800 square miles
Period of record: 1928-present
Maximum instantaneous discharge: 228,000 cfs
Average discharge, 40 years: 15,330 cfs
Minimum daily discharge: 1,380 cfs

Station no. 5-3325
Namekagon River near Trego
Drainage area: 503 square miles
Period of record: 1927-present
Maximum daily discharge: 5,200 cfs
Average discharge, 41 years: 469 cfs
Minimum daily discharge: 113 cfs

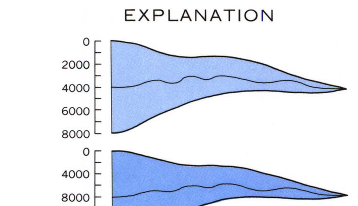


Discharge has been monitored continuously during various periods at 13 sites in the basin, 6 of which are measured at present. Station data are given for the 6 active stations, each with 40 or more years of record, and 1 discontinued station with 38 years of record. Sites of past and present measurements of other parameters also are shown on the map.

The average discharge diagram shows the basinwide distribution of surface runoff. Where gaging-station data were not available, average discharge was estimated by using drainage areas and the runoff map on sheet 1.

Streamflow at all gaging stations is affected to some extent by surface storage or regulation for hydroelectric power generation, although peak flows and monthly mean discharge generally are affected little.

EXPLANATION



Width of pattern indicates approximate average discharge of stream, in cfs (cubic feet per second). Discharge less than 50 cfs not shown

Measurement site symbol*	Parameter measured	Frequency of measurement
A▲	Stream discharge	Continuous
B▲	Low-flow stream discharge	Intermittent
C▲	Flood-flow stream discharge	Periodic
D▲	Lake stage	Periodic
E▼	Chemical quality	Monthly
F▼	Chemical quality	Intermittent
G▼	Chemical quality	Weekly
H▼	Sediment	Intermittent

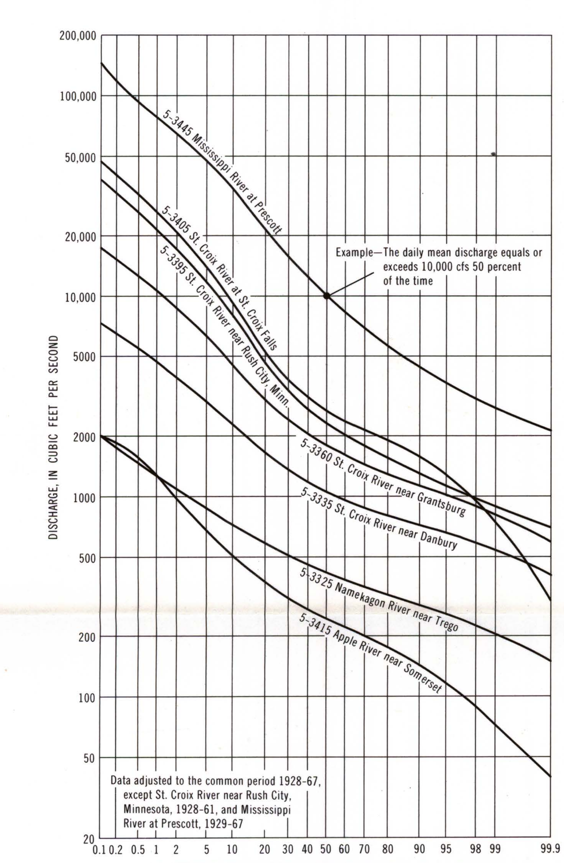
*Letter to left indicates present measurement; letter to right indicates discontinued measurement. Number by letter on map indicates operating agency:
① Wisconsin Department of Natural Resources
② Minnesota Pollution Control Agency
③ Minneapolis-St. Paul Sanitary District
All others, U.S. Geological Survey

Boundary of basin above active continuous record station

Surface-water divide

DATA NETWORK AND AVERAGE STREAMFLOW

Streams and lakes in the St. Croix River basin contain abundant water of good chemical quality. In some places man's use of the water has altered streamflow characteristics and quality slightly. About 750 billion gallons of surface water leave the basin as streamflow each year. Along its way this water passes through hydroelectric turbines and cooling towers, it receives wastes, and a very small amount is removed for irrigation and other uses. The water also passes through many stages of storage ranging from wetlands and small farm ponds to large reservoirs. At present surface water is not used for municipal supplies because the cost of treatment is high and because ground water is plentiful at most places where surface water is available.



DURATION OF DAILY MEAN DISCHARGE OF MAJOR RIVERS

The flow-duration curve shows the percentage of time specified discharges were equaled or exceeded during a given period. This curve reflects the hydrologic characteristics of a basin and shows the availability of a given streamflow.

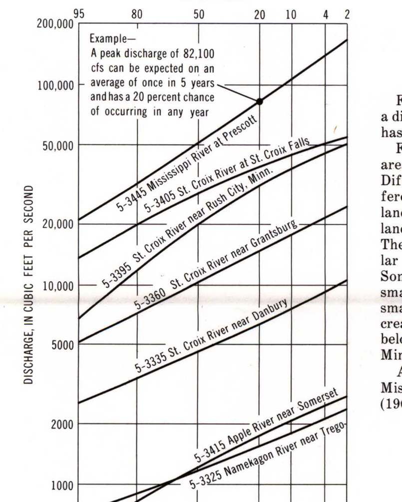
The lower part of a duration curve represents low flow at the gaging station and indicates some general characteristics of the basin. A flat slope indicates a nearly constant and uniform release of storage from ground-water reservoirs, surface reservoirs, or both. At the gaging stations in the St. Croix River basin the effect of ground-water runoff is masked by reservoir regulation. Low flows are higher than natural because water is released from reservoirs during dry periods. Pronounced steepening of the extremity of the curves of the St. Croix River at St. Croix Falls and the Apple River near Somerset reflect occasional flow detention during periods of very low streamflow.

The upper end of the flow-duration curve represents the high flow at the gaging station and indicates some general characteristics of the basin; a steep slope indicates short-term high flows from rainfall or rapid snowmelt. The upper ends of the curves shown are moderately steep but are flattened slightly, reflecting storage effects.

FLOODS

Damaging floods have been very infrequent in the basin. Damages are especially low along the St. Croix River in Wisconsin because use of flood plains is small. The most damaging flood of record on the St. Croix River was in April 1965 (Anderson and Burmeister, 1970). Total damages (all urban) were estimated at $5.5 million by the U.S. Corps of Engineers (1968). About half of the damage was in Stillwater, Minn. (northwest of Hudson), and much of the remainder was in Minnesota along Lake St. Croix. Backwater from the Mississippi River contributed significantly to flooding along the lake. The maximum recorded discharge at St. Croix Falls occurred May 8, 1950, at which time the stage of Lake St. Croix was 8 feet below its 1965 flood stage (U.S. Corps of Engineers, written commun., 1968). The flood of April 1969 was similar to the 1965 flood and was the second highest stage of record on Lake St. Croix, about 2 feet below the 1965 stage (Anderson and Schwob, 1970, p. 92).

Most floods in the basin occur either in spring or summer. Spring floods are the result of rapid snowmelt and, occasionally, concurrent rainfall. Summer floods are the result of widespread and heavy rainfall of many hours duration.



Curves based on log-Pearson type III frequency analysis of annual instantaneous peaks for the period 1923-68, except period is 1940-67 for station 5-3405 and annual maximum daily means for stations 5-3325 and 5-3415

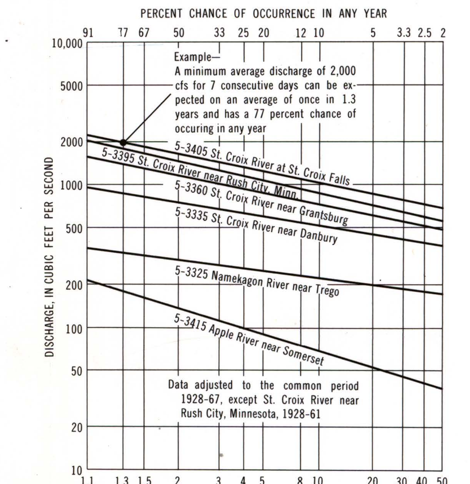
FLOODFLOW RECURRENCE OF MAJOR RIVERS

Flood-frequency curves show the probable recurrence interval of a discharge of given magnitude and the percent chance that discharge has of occuring in any given year.

Flood magnitude generally is related directly to size of drainage area and is a result of rapid runoff from precipitation or snowmelt. Different flood characteristics among basins are due mainly to differences in the amount and intensity of precipitation; channel slope; land slope; storage in lakes, marshes, and aquifers; soil infiltration; land-use practices; rock types; and the shape of the drainage basin. The size of the drainage areas and general flood magnitudes are similar for the Namekagon River near Trego and the Apple River near Somerset. Many reservoirs and lakes in the Apple River basin reduce small flood peaks by providing storage. Similarly, the reduction in small flood peaks on the St. Croix River near Rush City is due to increased storage, mainly in swamps, in the intervening drainage area below Grantsburg. This area includes the Kettle and Snake Rivers in Minnesota and Wood River in Wisconsin.

Additional data on flood frequency of the streams, except the Mississippi River, are available in reports by Ericson (1961) and Young (1963, 1965).

LOW FLOW



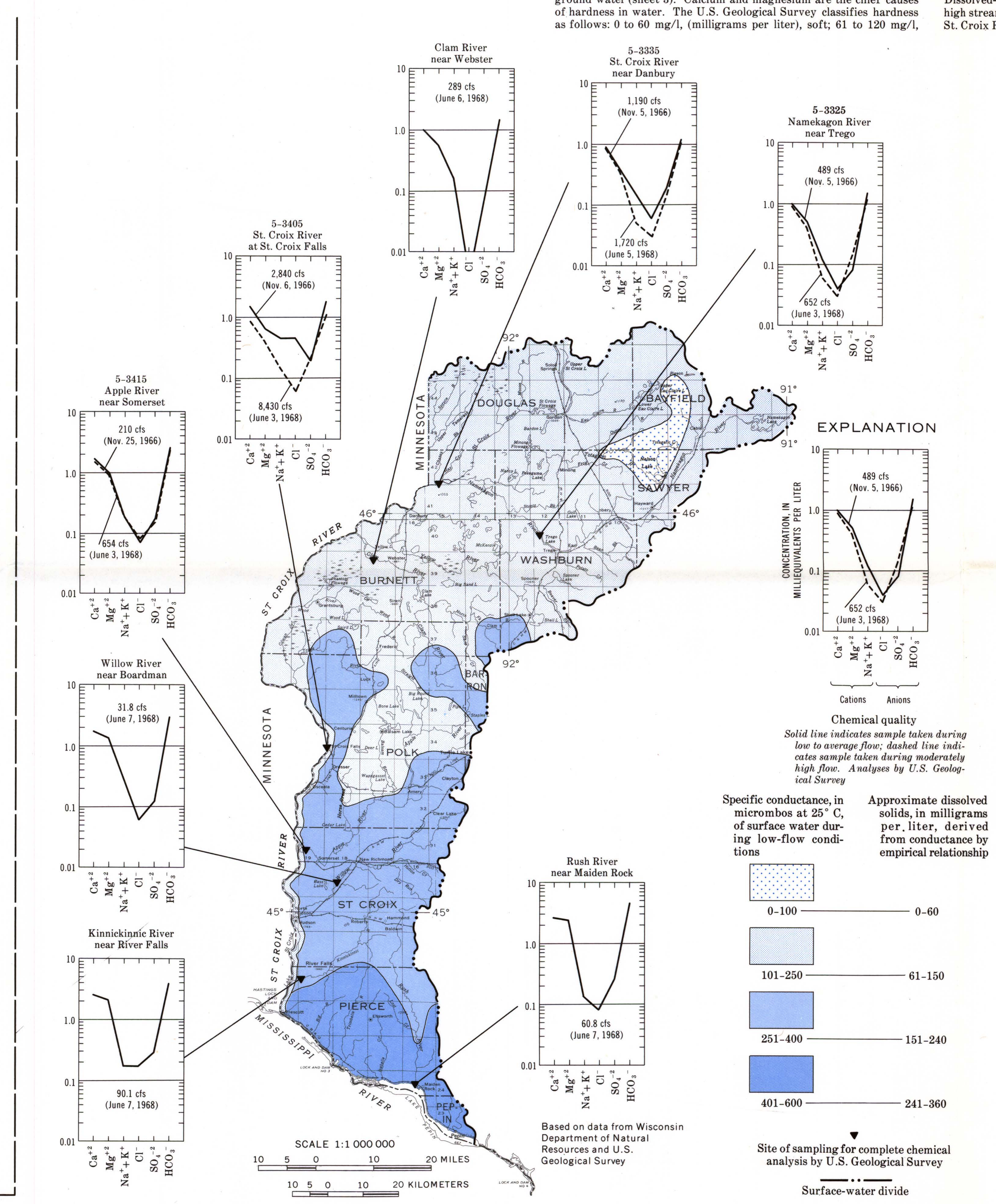
A knowledge of low flow of a stream is necessary to determine adequacy of streamflow for minimum supply needs, to maintain reservoir storage, to estimate ground-water discharge, to estimate a stream's capacity to accommodate and transport waste, and to plan allowable withdrawals from streams. The minimal stages of streams during low-flow periods influence stream life and recreation.

Low flow is expressed commonly as the lowest average discharge during 7 consecutive days in a year. This period generally excludes surface runoff from precipitation and averages the effects of abnormally low daily discharges caused by flow regulation. The curves give the probable recurrence interval or percent chance of occurrence of a 7-day minimum average discharge of given magnitude in any 1 year. Data for 10 additional periods of 1 to 274 days have been computed for these gaging stations, except for the Mississippi River at Prescott (Young, 1963, 1965).

Low-flow discharge depends primarily upon basin size but also depends upon characteristics presented in "Distribution of Low-Flow Runoff". Within a small basin these characteristics tend to be uniform, and their effects on low flow are easily identified. A large basin, however, integrates the effects of many small basins, and the resultant low flow is related most directly to basin size.

SURFACE-WATER QUALITY

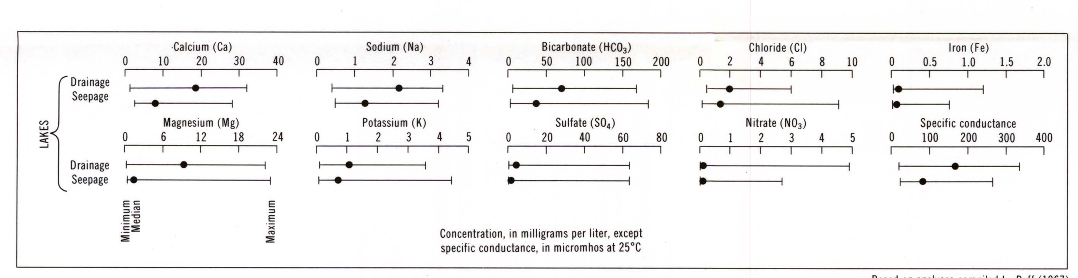
The chemical quality of water in streams and lakes in the St. Croix River basin is generally very good. The water is of the calcium magnesium bicarbonate type and its quality is directly related to that of ground water (sheet 3). Calcium and magnesium are the chief causes of hardness in water. The U.S. Geological Survey classifies hardness as follows: 0 to 60 mg/l, (milligrams per liter), soft; 61 to 120 mg/l, moderately hard; 121 to 180 mg/l, hard; and more than 180 mg/l as very hard. The water in the north is soft, but in the southwest it is very hard because of the dolomitic bedrock and calcareous glacial drift. Dissolved-solids content of streamflow in the basin is lowest during high streamflow in April, May, and June. Most stream reaches in the St. Croix River basin are relatively unpolluted.



SPECIFIC CONDUCTANCE AND CHEMICAL QUALITY OF RIVERS

Dissolved-solids content in streams during low flow, as indicated by specific conductance, is directly related to the dissolved-solids content in ground water because low flow is composed mainly of ground-water runoff and has only minor additions of waste water (except the Mississippi River). In general the specific conductance of water in streams is lowest in areas of outwash and is successively higher in areas of end moraine, ground moraine, sandstone, and dolomite. The distribution pattern shown on the map correlates well with glacial geology, except for the southern area of high conductance related to the Ordovician bedrock, and with the hardness of ground water (see sheet 3). Conductance in the St. Croix River does not increase appreciably downstream because the input of high conductance water from the lower basin is small.

Analyses of water from selected streams are shown on graphs around the map. Concentrations of ions are generally higher during lower-than-average flow, which is mainly from ground-water runoff, than during average-to-higher flow, which is largely from surface runoff. Concentrations of the dominant ions, calcium (Ca^{+2}), magnesium (Mg^{+2}), and bicarbonate (HCO_3^-), correlate generally with the mapped pattern of specific conductance. Concentrations of sodium (Na^+), potassium (K^+), chloride (Cl^-), and sulfate (SO_4^{-2}) are somewhat variable but are generally very low. The calcium-to-magnesium ratio decreases from north to south in relation to the increase in abundance of dolomite.



Based on analyses compiled by Poff (1967)

QUALITY OF LAKE WATER

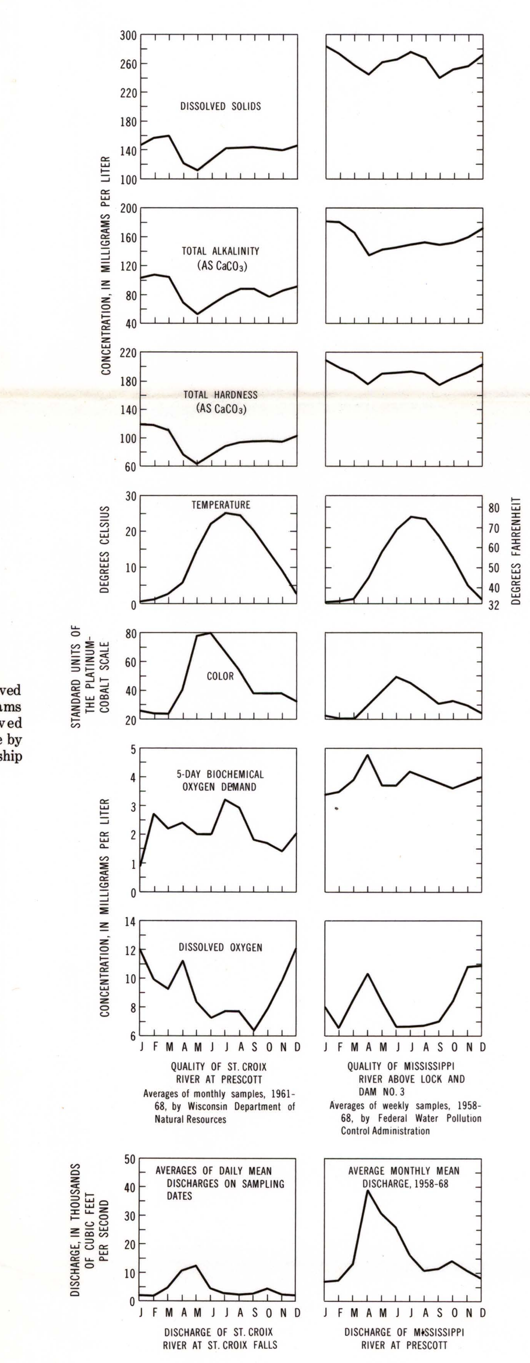
Lakes in the St. Croix basin have very low dissolved solids, as indicated by their specific conductance. Major chemical constituents are calcium, magnesium, and bicarbonate. Median concentrations of these constituents are higher in drainage lakes than in seepage lakes, but concentrations of most other constituents are similar or only slightly higher.

Lakes with hard water produce higher yields of fish than do lakes with soft water (Moyle, 1949, p. 324). Fish productivity generally is higher in drainage lakes than in seepage lakes (C. W. Threinen, oral commun., 1970).

POLLUTION

Wisconsin has set standards of surface-water quality, and its Department of Natural Resources is responsible for the detection and abatement of pollution. The Department's last inventory of sources of pollutants in the basin (Schraufnagel and others, 1965) showed that pollution occurred downstream from a few municipalities and industries; however, most of this pollution is concentrated in short reaches below points of waste disposal. A restudy of the basin by the Department is scheduled for 1971. A detailed study in 1964 by the FWPCA (U.S. Federal Water Pollution Control Administration, 1966) also showed very little pollution.

This FWPCA report shows that the Mississippi River is polluted severly, bacteriologically, before it reaches Prescott, but is in a stage of recovery throughout the reach included in the St. Croix basin. In most of the reach levels of dissolved oxygen, turbidity, and coliform density were considered unacceptable. Coliform density averaged about 75,000 mpn (most probable number) per 100 ml (milliliters) during June-October 1964 below the Hastings Lock and Dam, but it decreased steadily to an average of 250 mpn per 100 ml near the outlet of Lake Pepin. The report recommends a coliform density of not more than 1,000 mpn per 100 ml in water used for swimming and not more than 5,000 mpn per 100 ml in water used for other body contact activities. Specific recommendations were given for improvement of the quality of the Mississippi River by control of waste discharge and improvement of treatment facilities.



SEASONAL RELATIONSHIP OF SURFACE-WATER QUALITY TO DISCHARGE

Water quality of the St. Croix and Mississippi Rivers changes seasonally, primarily in relation to discharge. Dissolved solids are generally higher in the Mississippi River, although the quality shown represents a slight dilution caused by the addition of the St. Croix flow. On the days of sampling the St. Croix contributed, on the average, about 15-30 percent of the flow at Lock and Dam No. 3. The higher contributions are in March, May, and October and the lower are from June through September.

Dissolved solids, alkalinity, and hardness vary inversely with discharge because they have a relatively constant input from ground-water discharge and are diluted by overland runoff. These parameters are highest during winter low-flow conditions and are lowest during spring and fall high-flow conditions.

Water temperature follows the natural seasonal pattern of air temperature and has a wide range.

Color of the water is due mainly to organic matter from decomposed vegetal matter in swamps. This matter collects during winter and other low-flow periods because water movement is slow, and it is flushed out of the swamps by large increases in flow. The major rise in color concentrations on the St. Croix, therefore, occurs in spring after the runoff from snowmelt has moved the coloring matter into streams.

Biochemical oxygen demand (BOD) generally is low, less than 5 mg/l, and dissolved oxygen (DO) generally is above the minimum 5 mg/l required to support warm-water game fish (U.S. Federal Water Pollution Control Administration, 1968, p. 33). Wastes from the Minneapolis-St. Paul area cause higher BOD in the Mississippi River; at times BOD exceeds 10 mg/l, and DO is lowered to about 2 mg/l.

SEDIMENT CHARACTERISTICS

Sediment yields in the St. Croix River basin are among the lowest in Wisconsin. Average annual yields are estimated to range from about 10 to 40 tons per square mile (Hindall and Flint, 1970). Soil types (and parent glacial deposits), land cover, land use, and topography greatly influence sediment-yield characteristics. Natural and artificial stream controls also affect sediment yields.

The lowest sediment yields are in the northern part of the basin where sandy soils, heavy forest cover, low topographic relief, and many lakes and wetlands predominate. The highest yields are from the southern part of the basin where slopes are steep, land is cleared for agriculture, and silty soils and loess deposits provide conditions that lead to erosion and much sediment.

Base from U.S. Geological Survey
1:500 000, 1968

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D.C.—1973—W71239

WATER RESOURCES OF WISCONSIN—ST. CROIX RIVER BASIN

By
H. L. Young and S. M. Hindall

1973