PILOT STUDY OF FLUCTUATING LAKE LEVELS ON THE UPPER ST. CROIX LAKE, SOUTHWESTERN DOUGLAS COUNTY, WISCONSIN

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A report for the Upper St. Croix Lake and St. Croix Flowage Associations,
Solon Springs and Gordon, Wisconsin

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PROJECT SUMMARY

A two-year study of precipitation and fluctuating lake level on the Upper St. Croix Lake was initiated in 1999 to better understand controls on periodic flooding which causes shoreline erosion, property damage and land use planning problems for residents along the lakeshore. The goal of the field trial was to establish a protocol for monitoring precipitation (snow and rainfall), lake level, and stream discharge within the Upper St. Croix Lake sub-basin in order to establish a framework for conducting a long-term study of the inflow, outflow and storage components of the hydrologic budget.

A comparison of precipitation data from this study and historical records indicates that 1999 was an exceptionally wet year, exceeding average annual precipitation totals by 12.82 inches. Although snowfall accumulations during the winter of 1999 were below average, precipitation during the spring and summer were significantly above average. For example, the total rainfall for June and July exceeded all precipitation totals for the 95 years on record. The wet summer resulted in significant increases in lake level (greater than 4 feet), which peaked during a one hundred year flood event in late July. In contrast, precipitation during 2000 was slightly below average. Precipitation totals fell short of historical averages by 4.85 inches. Lake levels rose a modest 1.5 feet during the summer months of 2000.

Based on 1999 and 2000 precipitation and lake level hydrographs, a simple hydrogeologic model is proposed to explain stage fluctuations on the Upper St. Croix Lake. During relatively dry spring and summer seasons, the high infiltration rate and storage capacity of the glacial outwash "sandy" substrate that mantles the watershed absorbs a significant fraction of precipitation relative to runoff during moderate to long duration, low magnitude precipitation events. Slow groundwater flow delays the response of lake level to precipitation events by days and water level increases are modest and gradual as a result. In contrast, during relatively wet spring and summer seasons, soil moisture content gradually increases, reducing the capacity of the subsurface to absorb and temporarily store water. When intense rainstorms occur during periods of high soil saturation, surface runoff necessarily becomes the preferred avenue for water movement down slope. High water invading low-lying shoreline areas is enhanced simply because the soil zone storage is used up and the lake has a finite capacity to accept incoming discharge and move it through the system. The short lag times between precipitation events and lake level peaks are enhanced by the efficiency of high gradient tributaries that feed into the low gradient Upper St. Croix Lake system. During the exceptionally high magnitude and short duration rainfall events, overland flow completely overwhelms the capacity of the lake to accept incoming overland flow and flooding results.

Volumetric estimates indicate that the Upper St. Croix Lake has a capacity to hold up to 4.67×10^5 cubic feet (1.32×10^4 cubic meters) of water without significant flooding. The magnitude of precipitation events that occurred during June and July 1999 greatly exceeded the storage capacity of the lake, as well as the ability of the lake/stream system to move incoming water out of the system. The magnitude of the July 26th precipitation and other rainfall events during June and July can be appreciated by comparing the volume of water that fell on the watershed relative with the capacity of the Upper St. Croix Lake to store it. Volumetric calculations indicate that the five major precipitation events that occurred between June 1st and July 31st delivered water volumes to the basin that exceeded lake storage capacity by 280 to 1000 times!

The bottom line for residents of the Upper St. Croix Lake sub-basin is the recognition of the fact that if you occupy floodplain areas of the watershed sub-basin, you can expect to be impacted by rising lake levels. This is because of the natural physiography of the sub-basin (high gradient tributary streams feeding an exceptionally low gradient trunk stream), and the fact that the small drainage area of the sub-basin amplifies the effects of precipitation events when the infiltration capacity of the soil zone is overwhelmed by the intensity of precipitation in the watershed.

Several aspects of the Upper St. Croix Lake hydrogeology require further study in order to provide a quantitative model for flooding in the sub-basin. Daily (24-hour) monitoring does not provide the short-term data (resolution) necessary to understand how the magnitude and duration of precipitation events, surface runoff and lake level vary dynamically in "real time". It is recommended that instrumentation be acquired that would allow the monitoring of these parameters on hourly (or shorter) time intervals. In addition, a continuation of this field study should include: 1) documentation of seasonal soil moisture variations, 2) field and laboratory analysis of soil zone hydraulic conductivities, and 3) the initiation of seasonal field trials to document variations in depth to water table, map water table configuration, groundwater flow direction, and flow velocity. This information is necessary to more fully understand the role groundwater plays as a component of the Upper St. Croix Lake watershed hydrologic equation.

ACKNOWLEDGEMENTS

This project was funded by a grant from the State of Wisconsin's Department of Natural Resources Lake Management Planning Project Program. The Upper St Croix and St. Croix Flowage Lake Association membership provided valuable insights regarding the fluctuating lake levels from a historical perspective as well as logistical support in establishing precipitation and lake monitoring stations in the watershed.

Special thanks are extended to Jim and Pat Heim, Lou Koch, Steve and Lana Parker, and Peter and Polly Edmunds of the Upper St. Croix Lake Association, as well as George and Pat Graven and Tom and Linda Chandler of the St. Croix Flowage Association for their long-term commitment to this study and the quality of their precipitation and lake level measurements. Paul Hlina of the Douglas County Forestry Department provided invaluable assistance helping design and implement outreach activities to the Solon Springs community and local school districts. John Glindinning of the WDNR Forestry Office in Gordon, WI provided valuable snow accummulation and precipitation records for the winter months of 1999 and 2000, for which I am very grateful.

I wish to acknowledge the flexability and patience of the WDNR granting agency in extending the duration of this study in light of my medical problems during the fall 1999 and spring 2000. Dr. Christofer Keminitz and Jeanine Zaengle edited this report. Finally, UWS undergraduate researchers (Nicole Manners and Jon Hansen) provided a commitment to this project and the desire to ask the question "why?", that maintained the progress of this project from its initiation, throughout my illness and during the completion of this pilot study report.

Dr. Jack Zaengle
January 2001

INTRODUCTION

Pilot Project Study Area

This report summarizes the results of a two-year hydrogeologic investigation of the Upper St. Croix and Eau Claire Rivers watershed, which is located in the headwaters region of the St. Croix River National Scenic Waterway of Wisconsin and Minnesota. The watershed, which occupies portions of Douglas and Bayfield counties, can be divided into five principle sub-basins (Figure 1). The Upper St. Croix Lake, Ox Creek and Eau Claire River sub-basins represent the headwater regions of the Upper St. Croix and Eau Claire Rivers watershed as a whole. These sub-basins discharge into the St. Croix River that connects the headwater regions to the St. Croix Flowage (a.k.a. the Gordon Flowage), where surface waters exit the system into the St. Croix River National Scenic Waterway.

Of specific interest in this investigation is the Upper St. Croix Lake sub-basin which experiences "unusual" variations in water level that can result in flooding, shoreline erosion and land use planning problems. Residents of the sub-basin indicate that flooding problems are especially severe when rising lake levels accompany snowmelt during the spring thaw and short duration, high intensity precipitation events during the summer season. Inhabitants of the Gordon Flowage sub-basin on the other hand indicate that water levels in this part of the watershed system are commonly very low, reducing property values and the use of the flowage as a recreational resource.

The Fluctuating Lake Level Problem: A Historical Dispute

Fluctuating lake levels in the watershed have been a matter of public discourse and dispute for over sixty years. The controversy over water levels on the Upper St. Croix Lake dates back to the building of the St. Croix Dam (a.k.a. the Gordon Dam), which is located 6.25 miles west of Gordon (Figure 2). The dam was constructed in 1937 as part of a WPA project during the 1930's Great Depression. Residents of Solon Springs maintain that the St. Croix Dam is responsible for periodic flooding by creating backwater conditions on the Upper St. Croix Lake.

Newspaper articles from September 1945, shed light on the nature of the fluctuating lake-level dispute. In an article from the Superior Telegram (09/06/45), Upper St. Croix Lake property owners maintained that late summer rainfalls initiated flood events that inundated shoreline properties, resulting in significant damage to lakeshore properties (Figure 3). Their recommendation was to remove the dam to insure adequate surface runoff and the maintenance of normal water levels on the lake during storms.

Gordon Flowage residents on the other hand report in Superior Telegram articles (09/11/45 and 09/14/45; Figure 4), that water levels on the flowage were significantly below normal, leaving flowage shoreline properties high and dry. Flowage residents maintained the dam was necessary to ensure water levels sufficient for recreation activities and the maintenance of property values. Gordon Flowage residents argued that the dam had little or no effect on the Upper St. Croix Lake levels. They suggested that periodic flooding of Upper St. Croix Lake cottages was simply a consequence of building on swampy, lowland areas that would be prone to flooding whether the Gordon Dam was there or not.

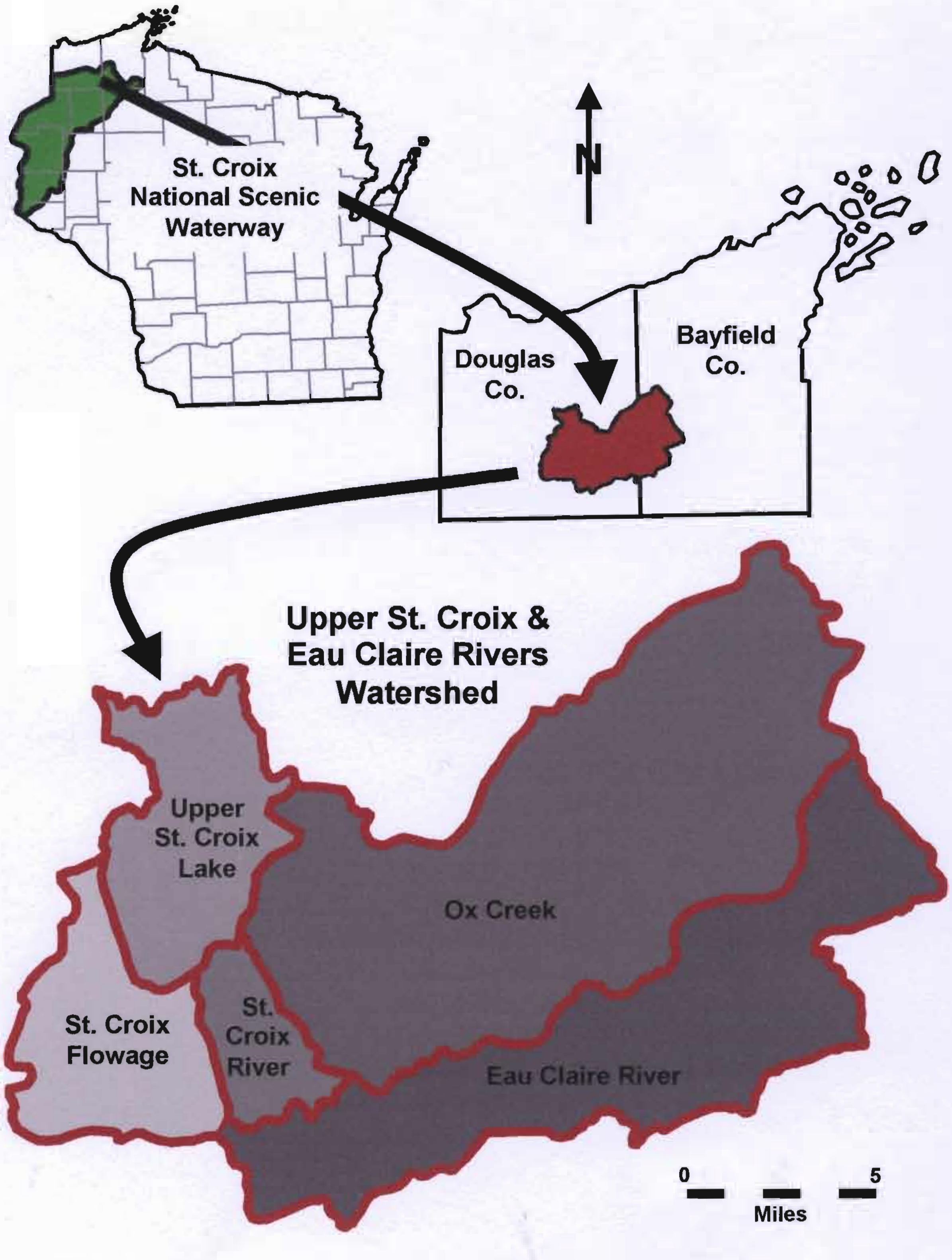


Figure 1 Study area location map illustrating the St. Croix and Eau Claire Rivers watershed of Douglas and Bayfield Counties, Wisconsin. The focus of this investigation is the Upper St. Croix Lake sub-basin that experiences "unusual" variations in water levels that result in flooding, shoreline erosion and land use planning problems.

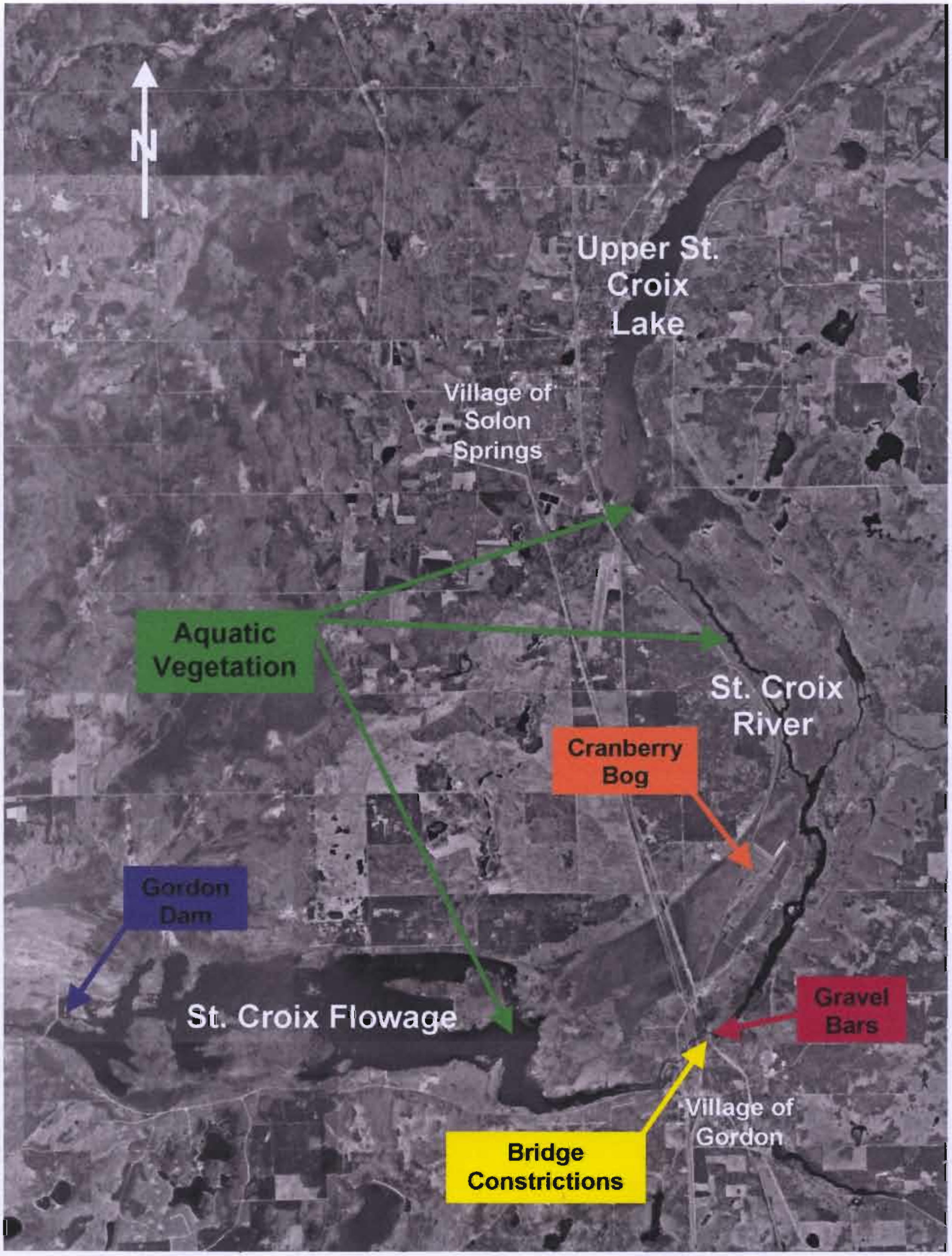
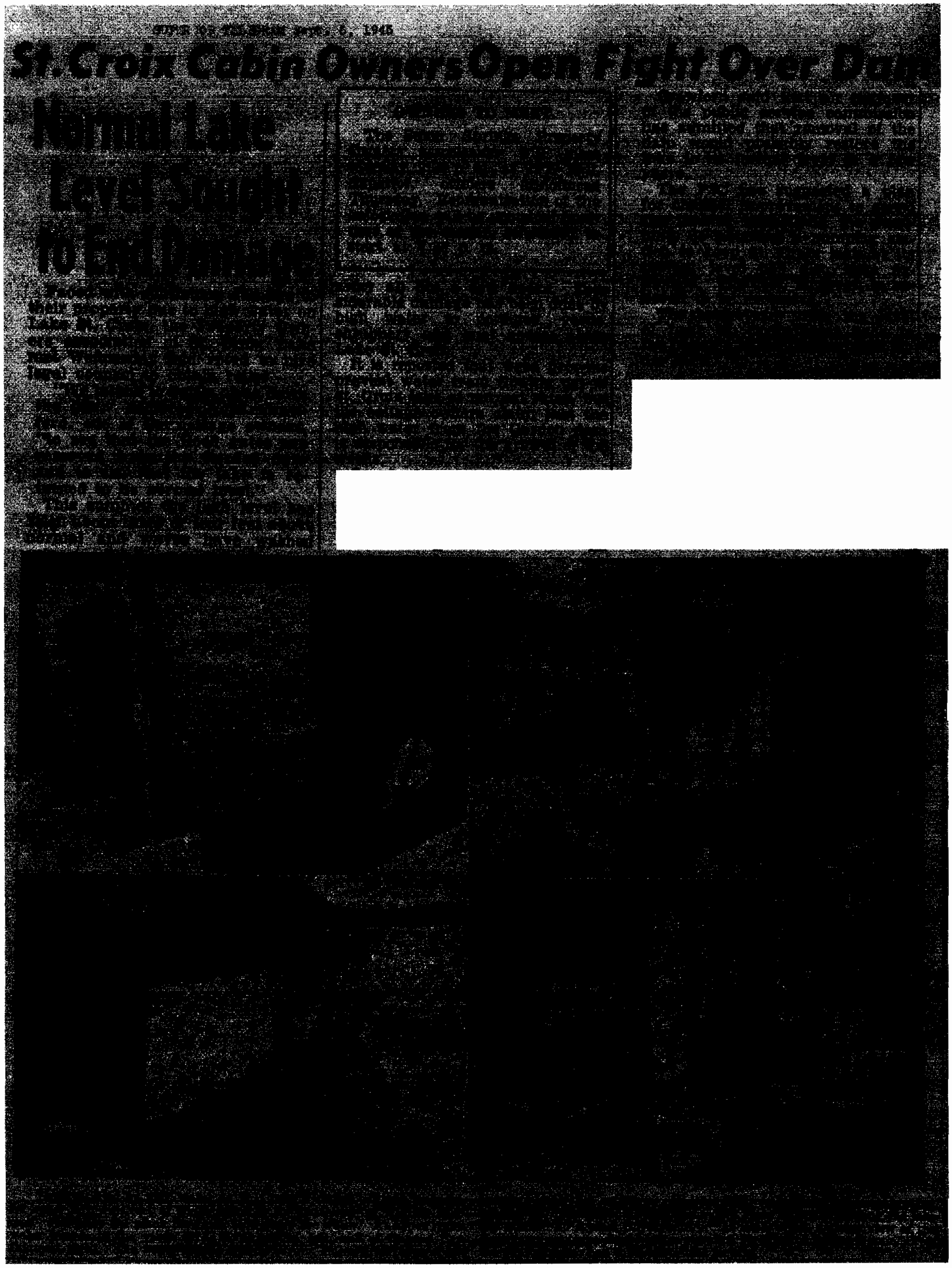


Figure 2 Air photo mosaic illustrating the position of the Upper St. Croix Lake and St. Croix Flowage (a.k.a. Gordon Flowage), as well as perceived causes of high water levels and flooding on the Upper St. Croix Lake.

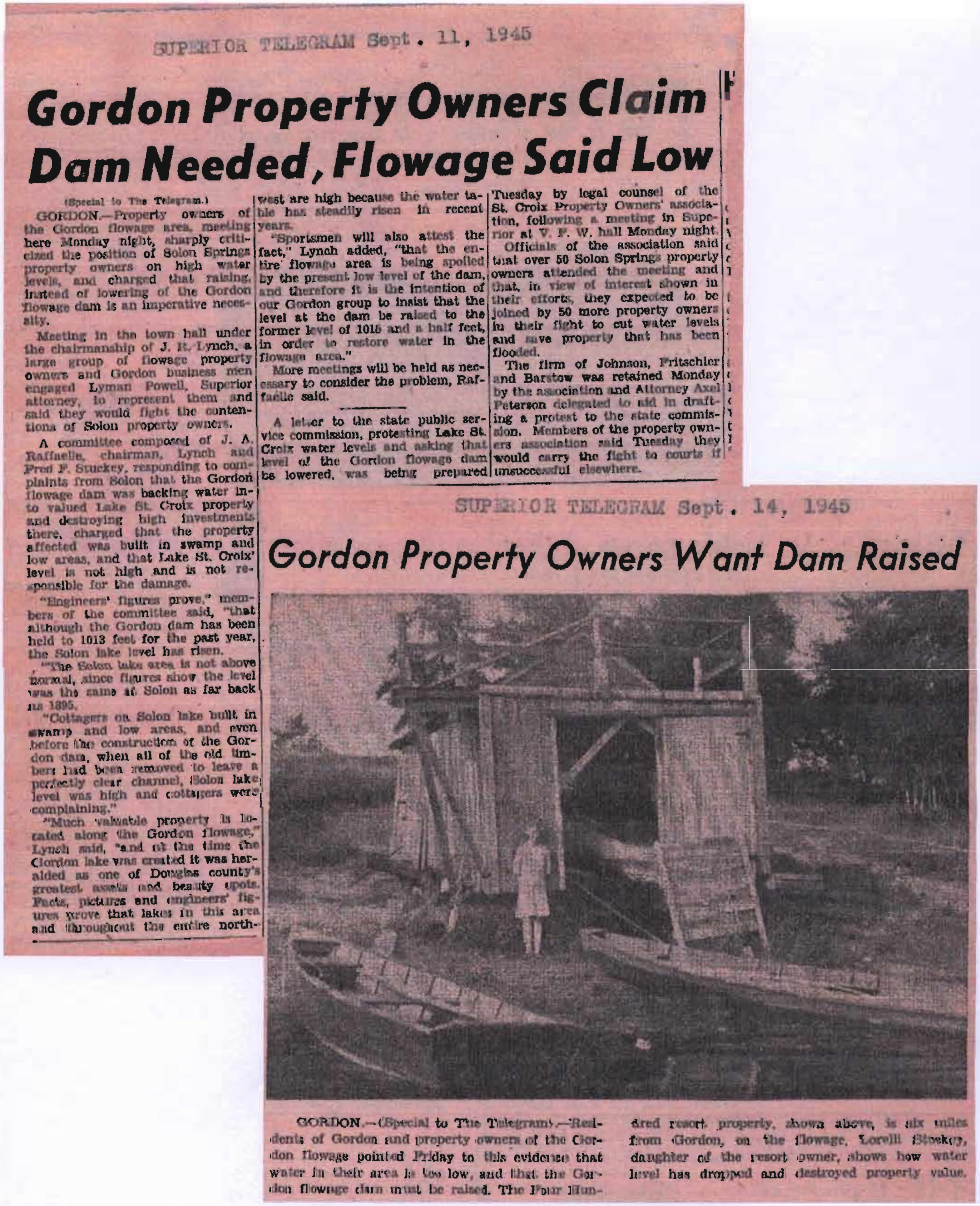


SUPERIOR TELEGRAM Sept. 6, 1945

St. Croix Cabin Owners Open Fight Over Dam

Normal Lake Level Sought to End Damage

Figure 3 Superior Telegram newspaper article highlighting the nature of the fluctuating lake level dispute from the perspective of residents of the Upper St. Croix Lake (September 6th , 1945).



SUPERIOR TELEGRAM Sept. 11, 1945

Gordon Property Owners Claim Dam Needed, Flowage Said Low

(Special to The Telegram.)

GORDON.—Property owners of the Gordon flowage area, meeting here Monday night, sharply criticized the position of Solon Springs property owners on high water levels, and charged that raising, instead of lowering of the Gordon flowage dam is an imperative necessity.

Meeting in the town hall under the chairmanship of J. R. Lynch, a large group of flowage property owners and Gordon business men engaged Lyman Powell, Superior attorney, to represent them and said they would fight the contentions of Solon property owners.

A committee composed of J. A. Raffaelle, chairman, Lynch and Fred F. Stuckey, responding to complaints from Solon that the Gordon flowage dam was backing water into valued Lake St. Croix property and destroying high investments there, charged that the property affected was built in swamp and low areas, and that Lake St. Croix' level is not high and is not responsible for the damage.

"Engineers' figures prove," members of the committee said, "that although the Gordon dam has been held to 1013 feet for the past year, the Solon lake level has risen.

"The Solon lake area is not above normal, since figures show the level was the same at Solon as far back as 1895.

"Cottagers on Solon lake built in swamp and low areas, and even before the construction of the Gordon dam, when all of the old timbers had been removed to leave a perfectly clear channel, Solon lake level was high and cottagers were complaining."

"Much valuable property is located along the Gordon flowage," Lynch said, "and at the time the Gordon lake was created it was heralded as one of Douglas county's greatest assets and beauty spots. Facts, pictures and engineers' figures prove that lakes in this area and throughout the entire northwest are high because the water table has steadily risen in recent years.

"Sportsmen will also attest the fact," Lynch added, "that the entire flowage area is being spoiled by the present low level of the dam, and therefore it is the intention of our Gordon group to insist that the level at the dam be raised to the former level of 1016 and a half feet, in order to restore water in the flowage area."

More meetings will be held as necessary to consider the problem, Raffaelle said.

A letter to the state public service commission, protesting Lake St. Croix water levels and asking that level of the Gordon flowage dam be lowered, was being prepared Tuesday by legal counsel of the St. Croix Property Owners' association, following a meeting in Superior at V. F. W. hall Monday night.

Officials of the association said that over 50 Solon Springs property owners attended the meeting and that, in view of interest shown in their efforts, they expected to be joined by 50 more property owners in their fight to cut water levels and save property that has been flooded.

The firm of Johnson, Fritschler and Barstow was retained Monday by the association and Attorney Axel Peterson delegated to aid in drafting a protest to the state commission. Members of the property owners association said Tuesday they would carry the fight to courts if unsuccessful elsewhere.

SUPERIOR TELEGRAM Sept. 14, 1945

Gordon Property Owners Want Dam Raised

GORDON.—(Special to The Telegram).—Residents of Gordon and property owners of the Gordon flowage pointed Friday to this evidence that water in their area is too low, and that the Gordon flowage dam must be raised. The Four Hundred resort property, shown above, is six miles from Gordon, on the flowage. Lorelli Stuckey, daughter of the resort owner, shows how water level has dropped and destroyed property value.

Figure 4 Superior Telegram newspaper articles highlighting the nature of the fluctuating lake level dispute from the perspective of residents of the Gordon Flowage (September 11th and 14th, 1945).

Property owners on both the Upper St. Croix Lake and the Gordon Flowage petitioned the Wisconsin Public Service Commission to mitigate the lake level dispute. During the course of this effort, three other potential causes of the lake level problem were brought to light. These included: the "weed", "gravel bar", and "multiple constriction" theories.

The "weed" theory holds that aquatic vegetation in the St. Croix Flowage restricts water flow causing a backwater effect on Upper St. Croix Lake (Figure 2). The "gravel bar" theory suggests that the major cause of high-water on Upper Lake St. Croix is a constriction produced by a 1700 sq. ft. gravel bar located at the Old Highway 53 bridge north of Gordon. The gravel bar is a sedimentary deposit formed at the mouth of the Eau Claire River where it intersects the lower gradient St. Croix River (Figure 2). The "multiple obstruction" theory maintains that high-water levels are a consequence of the combined effects of five major obstructions that existed along the approximately 14-mile section of the St. Croix River between Solon Springs and Gordon (Figure 2). In a downstream direction these included: the Cut-A-Way Dam, the SOO Line Railroad Bridge, the C&NW Railroad Bridge, and the Old Highway 53 Bridge.

Ultimately, the fluctuating water level problem and the question of whether or not to remove or modify the dam was not resolved, although strategies to help reduce the problem without removing the dam were suggested by engineering consultants participating in the dispute. These included channel dredging, weed eradication, and the construction of a flood pumping station to move water through the system more efficiently during high water periods. Currently, there is still no consensus as to the likely cause or causes of lake level fluctuations.

The WDNR developed hydraulic models in an attempt to quantify the contribution of potential backwater affects on the Upper St. Croix Lake. Although backwater affects are difficult to calculate, WDNR calculations suggest that:

1) The Gordon Dam has no effect on lake level at Solon Springs until the dam level exceeds an elevation of 1015 feet above sea level. Currently, water levels are maintained at an elevation of 1014 ft., with adjustments to 1013 ft. made just before and after winter freeze-up (although this compromise has not eliminated the problem or the concern of lake residents).

2) Aquatic vegetation and gravel bar removal would have a maximum benefit of lowering lake level by 0.22 and .10 ft. during a ten-year flood event respectively.

3) The contribution of transportation related obstructions along the St. Croix River during normal and ten-year flood stage flow range from approximately 0.5 to 1.55 ft. respectively.

Assuming that WDNR calculations are reasonable estimates, an individual might conclude that backwater affects are significant contributors to high water levels in the Upper St. Croix sub-basin. However, given the reality that: 1) the removal of the Gordon Dam and highway/railroad infrastructure is extremely unlikely; and 2) the fact that weed eradication and gravel bar removal would provide negligible and only short-term benefits at considerable cost, Upper St Croix Lake and Gordon Flowage residents have initiated programs to better understand relationships between development stress in the watershed and the natural workings of the lake system.

Pilot Project Objectives

One of the "missing links" in the fluctuating water level dispute is that basic scientific data regarding the hydrogeology of the Upper St. Croix and Eau Clair River watershed are fragmentary or nonexistent. The principle goal of this field trial was to establish a protocol for monitoring precipitation (snow and rainfall), lake level, and stream discharge (runoff) within the Upper St. Croix Lake sub-basin. This data combined with the analysis of existing historical precipitation and hydrogeologic data would establish a framework for understanding controls on fluctuating lake levels, with hopes of developing a conceptual model that would provide a context for initiating a long-term study of the hydrologic budget (the inflow, outflow and storage components of the hydrologic cycle) in the study area (Figure 5).

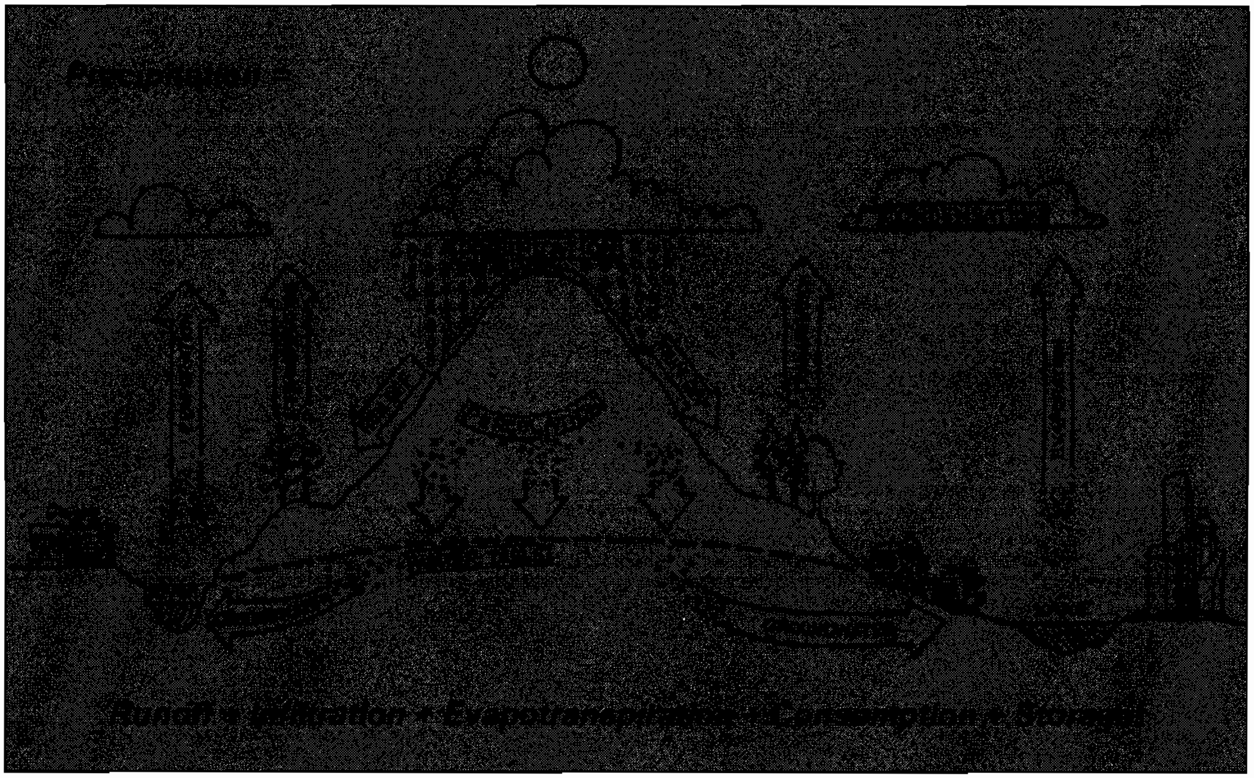


Figure 5 The hydrologic budget for a watershed can be represented by a simple equation. Precipitation as rain or snowfall (the inflow component), equals the algebraic sum of water output (surface runoff, groundwater flow, evapotranspiration, and the consumptive use by humans), plus short-term water stored in the system (typically as surface ponds, vegetation moisture and soil moisture).

A second goal of the pilot project focused on the initiation of educational outreach programs for the Solon Springs community emphasizing the basic principles of surface and groundwater hydrology pertinent to the Upper St. Croix Lake and Gordon Flowage. This effort focused on Lake Association, community and school group forums explaining how the various components of the hydrologic cycle operate on a drainage basin scale. Discussion topics emphasized the dynamic interactions between precipitation, surface runoff and infiltration, natural and anthropomorphic controls on river flooding, as well as field procedures used to monitor watershed hydrology.

Watershed Monitoring and Available Historical Data

In order to quantify annual precipitation in the study area, a monitoring network consisting of 57 area residents was established. Each resident was supplied with a rain gauge to monitor daily (24-hour) precipitation in tenths of an inch and/or in centimeters. Precipitation data was recorded on standardized monthly forms and were transmitted to UW-Superior via electronic mail or the U.S. Postal Service. UW-Superior student research assistants compiled this data into spreadsheets utilizing Microsoft Excel. During the winter months, a monitoring program was initiated to estimate total snow accumulation and snow moisture content. Snow monitoring data was supplemented by snow accumulation measurements made by the WDNR forestry station in Gordon and by area residents as well.

Historical records of monthly precipitation in the watershed from 1931 through 1998 were obtained from National Oceanic and Atmospheric Administration (NOAA) records. Additional precipitation records compiled by the Mid-continent Climate Center at the University of Illinois provided minimum, maximum and average daily/monthly precipitation data for the years 1906 to the present. The historical data sources were used to evaluate normal, wet and dry year averages as well as calculate precipitation recurrence intervals for the watershed.

Monitoring Upper St. Croix Lake level was initiated in early spring once lake ice had completely melted. Lake level monitoring continued until winter freeze-up in the late fall. Daily fluctuations in lake level were monitored at three stations on the Upper St. Croix Lake (Figure 6). Precipitation and lake level hydrographs were constructed to analyze interrelationships between precipitation events and lake-stage fluctuation. Hydrographs can provide a means of making a qualitative assessment of relative relationships between soil infiltration, surface runoff and lake level fluctuation. If data for hydrograph construction are collected for a large number of years, they can be useful in constructing a picture of the "normal" behavior of the watershed system to storm events of differing magnitude and duration.

Stream discharge monitoring stations were established on each of the seven tributaries that flow into the Upper St. Croix Lake from the west and northeast, as well as along the St. Croix River at the site of the Cut-a-way Dam (Figure 6). Stream surveys were performed to characterize the cross-sectional profile, wetted perimeter, and channel roughness characteristics. Flow velocity measurements were made using a rod-suspended flow meter with direct digital readout of flow velocity in feet or meters per second.

Subsurface lithologic and hydrologic information was gathered from water well driller's logs obtained from the Wisconsin Department of Natural Resources (WDNR). These data were useful in making a general assessment of subsurface lithologic and hydrologic characteristics. It is important to emphasize that interpretations made using this data are necessarily vague and are used to characterize only general subsurface relations. This is because the water wells are located imprecisely (only to the nearest quarter of a quarter section), driller's logs do not provide wellhead elevations that are necessary for subsurface mapping, and the fact that lithologic descriptions provided by different drilling contractors are quite variable (lack standardization).

Water table elevation and water production data from domestic well records provided a general impression of producing aquifers, but could not be used to accurately map water table elevation or flow directions because of the data limitations highlighted above and temporal differences in well drilling date. Water well data was supplemented by monthly water table fluctuation records obtained from the USGS (DS-0327) monitoring well, which is located near the southern end of the Upper St. Croix Lake sub-basin to the west of the St. Croix River (Figure 6). Although water table measurements are made only once a month, this data was useful in gaining insight as to the saturation state of the subsurface over time.

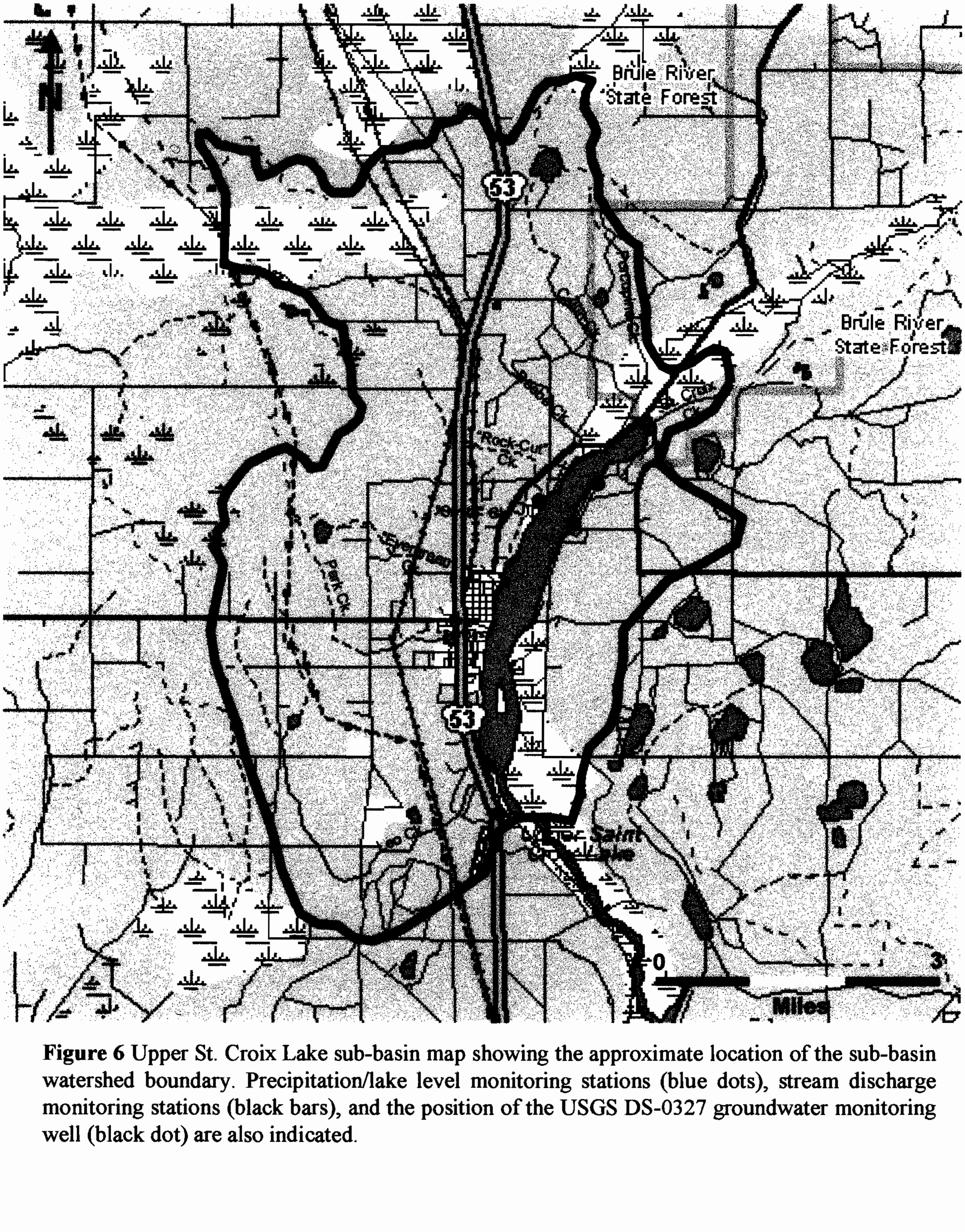


Figure 6 Upper St. Croix Lake sub-basin map showing the approximate location of the sub-basin watershed boundary. Precipitation/lake level monitoring stations (blue dots), stream discharge monitoring stations (black bars), and the position of the USGS DS-0327 groundwater monitoring well (black dot) are also indicated.

OVERVIEW OF THE UPPER ST. CROIX AND EAU CLAIRE RIVERS WATERSHED

The following sections describe the climatic, geomorphic, geologic and subsurface hydrologic characteristics of the Upper St. Croix and Eau Claire Rivers watershed. Specific attention is paid to the Upper St. Croix Lake sub-basin that is the focus of this investigation.

Watershed Climate

The Upper St. Croix and Eau Claire Rivers watershed is located in a temperate, continental climate zone that is characterized by marked seasonal changes. Average monthly air temperatures range from 10° to 15°F (-12.2 to -9.4°C), in January to 68° to 72°F (20 to 22.2°C) in July. The ground is generally frozen from late November through late March or early April. Maximum frost depth (typically occurring in early March) averages 34 in. (86.4 cm; Wisconsin Statistical Reporting Service, 1970). Watershed precipitation typically falls as snow from mid-November to April, with annual accumulations for the years 1961-1991 averaging 54.30 in. (137.9 cm; Figure 7).

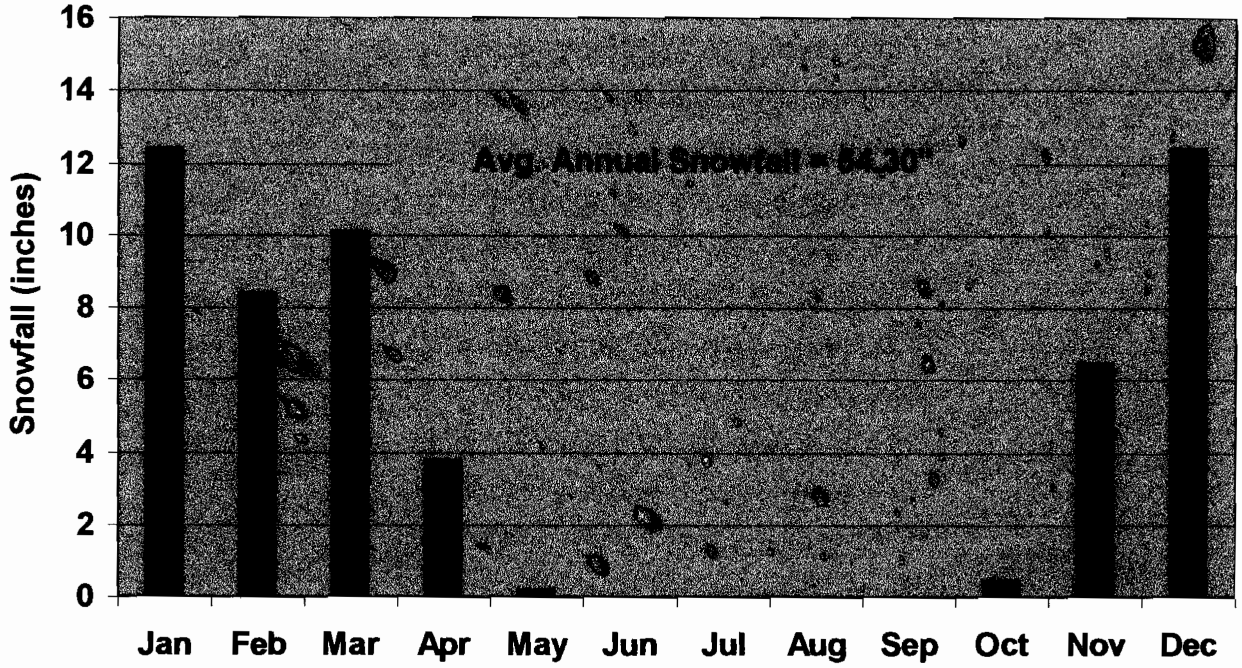


Figure 7 Histogram showing average total monthly snowfall (inches) on the Upper St. Croix Lake watershed for the years 1961 through 1991. Historical averages are based on data from the Midwestern Climate Center.

Total annual precipitation for the years 1961-1991 averaged 30.96 in. (78.5 cm; Figure 8). Periods of drought are infrequent. February is typically the driest month (less than .78 in.; 2 cm), while rainfall accumulations typically peak during the months of June, July and August. Rainfall accumulation during the summer months average 3.82 in. (9.7 cm), 4.29 in. (10.9 cm) and 4.32 in. (11.0 cm) respectively.

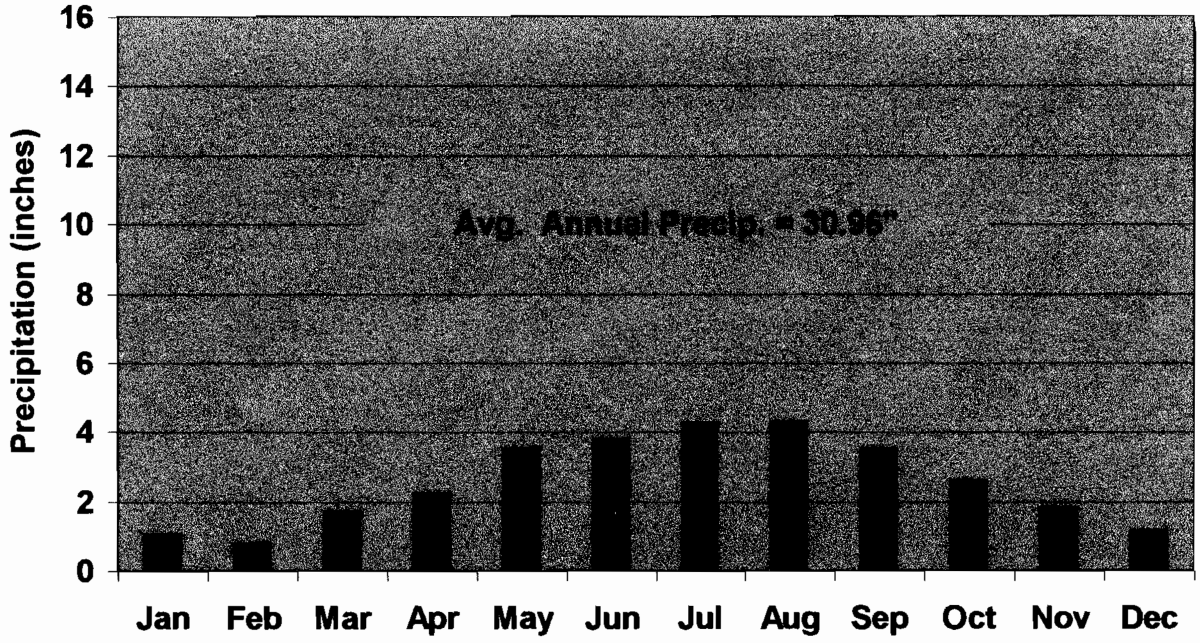


Figure 8 Histogram showing average total monthly precipitation (inches) on the Upper St. Croix Lake watershed for the years 1961 through 1991. Historical averages are based on data from the Midwestern Climate Center.

Estimates of evapotranspiration in the Upper St. Croix and Eau Claire Rivers watershed (Young and Hindall, 1973), suggest that approximately 60% of the total annual precipitation is returned to the atmosphere. This leaves approximately 40% of the average annual precipitation (12.36 in.; 31.4 cm), contributing to either runoff to surface reservoirs or for infiltration into the groundwater system.

Watershed Geomorphology, Topography and Drainage Characteristics

Ox Creek and Eau Claire Sub-Basins

The eastern portion of the Upper St. Croix and Eau Claire Rivers watershed includes the Ox Creek and Eau Claire River sub-basins that encompass an area of approximately 61,632 acres (96.3 square miles; Maislchke, Ryan, Sorge and Larson, 1974). The sub-basins have a subdued, low relief topography consisting of relatively flat undulating surfaces (pitted outwash plains) and gently rolling hilly areas consisting of glacial end moraines and drumlins; Figure 9. Pitted outwash plains consist of many closed depressions and irregular surfaces that interrupt surface flow and promote infiltration of precipitation into the groundwater system. Surface drainage is poorly developed except for the Upper Ox Creek, Mud Creek, Lower Ox Creek, the Eau Claire River and an unnamed creek.

Upper St. Croix Lake Sub-Basin

The Upper St. Croix Lake is a natural drainage lake located at the headwaters of the St. Croix River (Figure 9). The sub-basin includes an area of approximately 23,585 acres (36.9 square miles). The Lake has a surface area of 855 acres (1.76 square miles) and a maximum depth of 22 feet. Volumetric estimates indicate that the lake has a capacity to hold up to 4.67 x 10^5 cubic feet (1.32 x 10^4 cubic meters) of water without significant flooding.

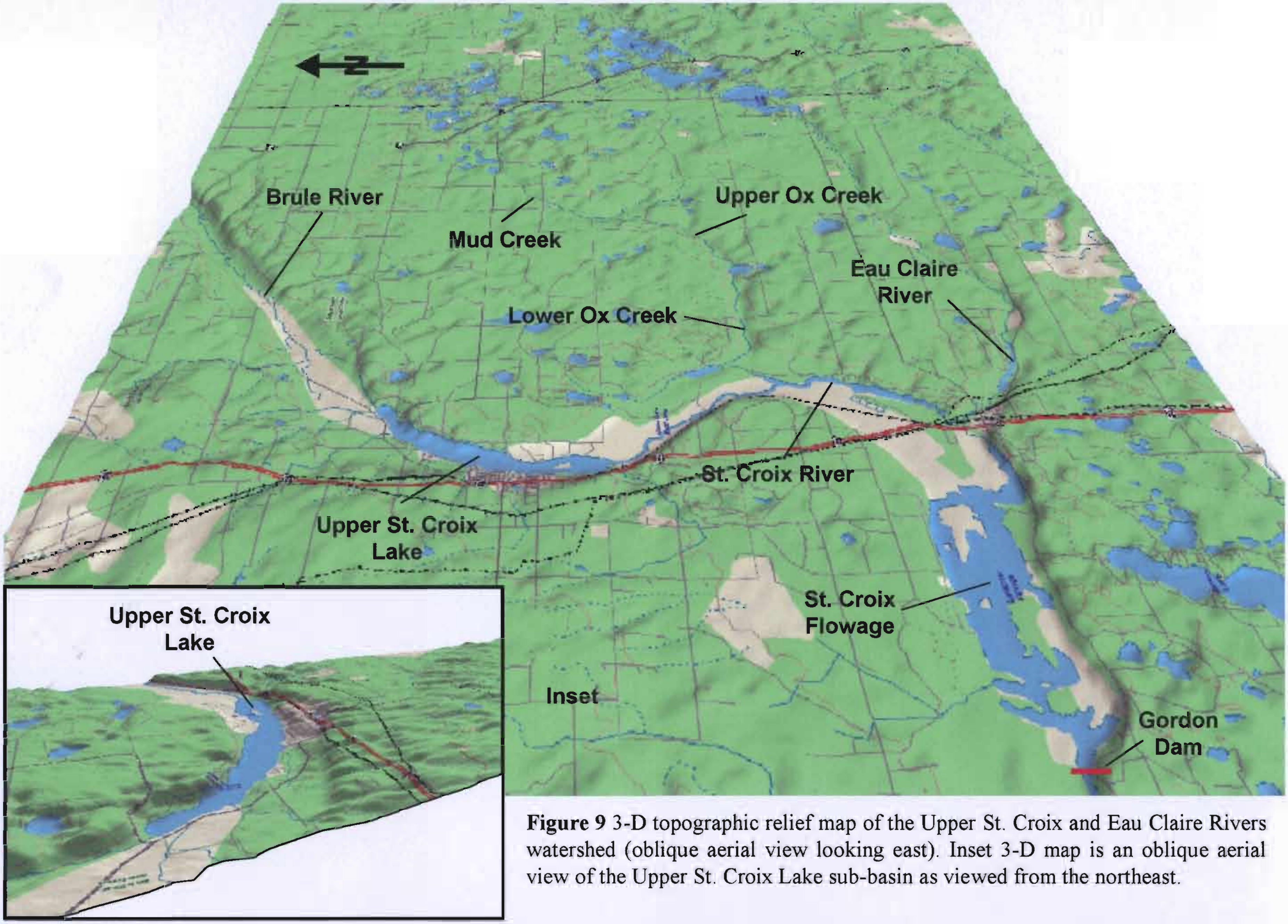


Figure 9 3-D topographic relief map of the Upper St. Croix and Eau Claire Rivers watershed (oblique aerial view looking east). Inset 3-D map is an oblique aerial view of the Upper St. Croix Lake sub-basin as viewed from the northeast.

The Upper St. Croix Lake sub-basin has relatively high local relief in excess of 200 feet. The well developed dissected valley topography and high gradient tributaries contrasts markedly with the undulating, low relief areas of adjacent sub-basins to the east (Figure 9). The sub-basin is of glacial origin, having formed as a major spillway for glacial outwash approximately 11,000 years ago during the retreat of the Pleistocene ice sheets.

Seven perennial streams and one intermittent tributary stream flow into the lake from the northeast and west (Figure 6). These moderate to high gradient (23-100 ft./mi.) tributaries include: St. Croix Creek, Porcupine-Catlin Creeks, Beebe Creek, Rock-Cut-Smith Creeks, Evergreen Creek, Park Creek, and Leo Creek. The St. Croix River, which connects the Upper St. Croix Lake and St. Croix Flowage to the southwest, is a low velocity stream with an average gradient of only 0.2 ft./mi (Figure 10).

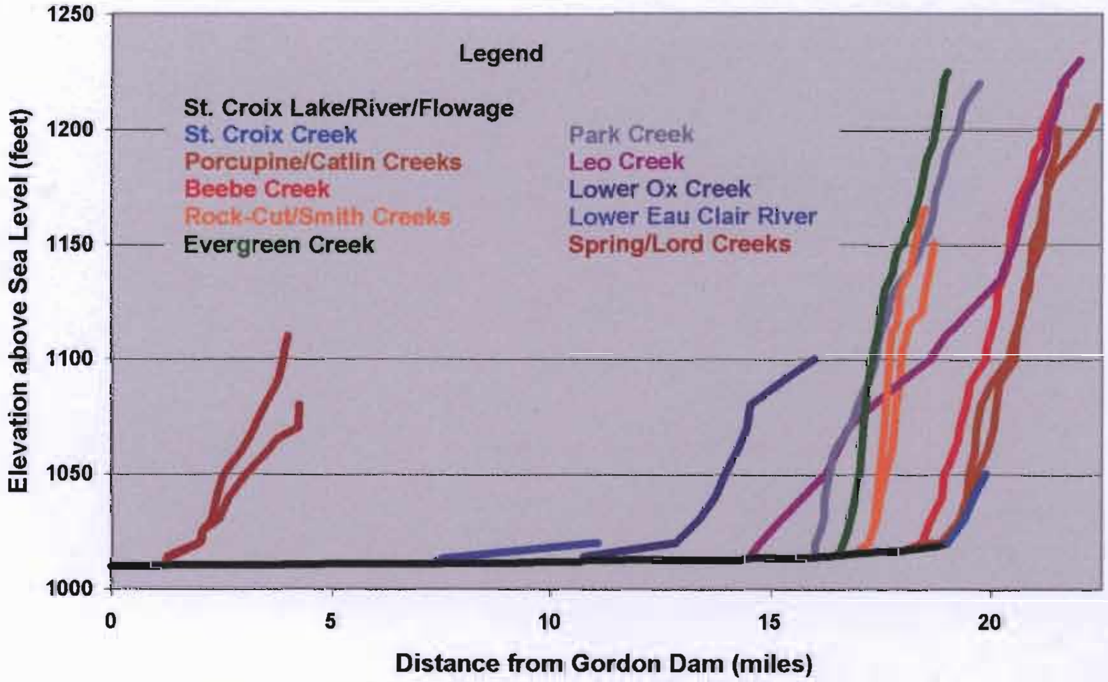


Figure 10 Upper St. Croix Lake/River/Flowage and tributary stream drainage profiles. The tributaries feeding into the Upper St Croix Lake, River and Flowage have high average gradients that range from 23 to 100 feet per mile. The Upper St. Croix Lake, River and Flowage from their headwaters to the Gordon Dam have an extremely low average gradient of 0.2 ft per mile.

Perennial tributary streams in the Upper St. Croix Lake sub-basin maintain at least a small continuous flow throughout most of the year. Stream discharge for tributary streams feeding into the Upper St. Croix Lake have normal flow discharges on the order of .2 to approximately 3.7 cubic feet per second (cfs; Table 1). Measurements made during 1999 when streams were at bank-full stage indicate instantaneous discharges can greatly exceed 50 cfs in response to high intensity summer storm events. Discharge from the lake to the St. Croix River is on the order of 134 cfs, although discharge values as low as 34 cfs were measured during low lake level in late April 1999, prior to the growth of aquatic vegetation.

Table 1– Upper St. Croix and Eau Claire Rivers Watershed Sub-Basins, Drainage Areas, Stream Length, Stream Type, Discharge and Substrate Type. Supplemental data from Sather and Johannes (1973).

SUB-BASIN NAME Stream Name	Drainage Area (mi^2)	Length (miles)	Stream Type*	Discharge (cfs)**	Substrate Type
OX CREEK	62.50	——	——	——	——
Ox Creek Outlet	62.50		P		Sand/Gravel
Upper Ox Creek	22.80	05.50	P	03.50(N.A.)	Silt/Sand
Mud Creek	——		P	01.40(N.A.)	Silt/Sand
Lower Ox Creek	39.70	03.50	P	15.50(N.A.)	Sand/Gravel
EAU CLAIRE RIVER	33.80	——	——	——	——
Eau Claire River	33.80	13.40	P	58.00(N.A.)	Sand/Gravel
Unnamed Creek1	——			N.A.(N.A.)	N.A.
UPPER ST. CROIX LAKE	36.90	——	——	——	——
Upper St. Croix Lake	10.60	00.75	L	34.00(134.00)	Silt/Sand
St. Croix Creek	00.80	00.80	P	03.00	Silt
Porcupine Creek	04.10	03.90	P	02.50(38.52)	Sand/Gravel
Cathine Ck.	——	04.00	P	02.50(N.A.)	Sand/Gravel
Beebee Creek	05.20	01.90	P	03.10(25.94)	Gravel
Rock-Cut Creek		0.210	P	01.27(51.29)	Sand
Spring Creek	——	01.76	I	04.75(48.69)	Sand
Evergreen Creek					
Park Creek	01.70	01.40	P	01.50(30.06)	Gravel
Lee Creek	07.20	04.50	P	03.70(N.A)	Sand
ST. CROIX RIVER	14.30	——	——	——	——
St. Croix River	14.30	07.90	P	34.00(134.00)	Sand
ST. CROIX FLOWAGE	28.30	——	——	——	——
St. Croix Flowage	17.00		F	N.A.(N.A.)	Sand
Spring Creek	11.30	02.50	P	02.50(N.A.)	Sand
Lord Cr.	——	02.00	P	01.00(N.A.)	Silt/Sand
Carlson Cr.	——	02.00	P	N.A.(N.A.)	Silt/Sand
Unnamed Cr.	——	N.A.	I	N.A.(N.A.)	Silt/Sand

*Stream Type: (P = Perennial; I = Intermittent; L = Lake)
**Discharge: Minimum (Maximum)

St. Croix River and St. Croix Flowage Lake Sub-Basins

The St. Croix River sub-basin connects the Upper St. Croix Lake sub-basin to the St. Croix Flowage. The sub-basin includes approximately 9123 acres or approximately 14.3 sq. mi (Maislchke, Ryan, Sorge and Larson, 1974). The very low gradient (.2 ft./mi.) river flows in a southerly direction for approximately 7.9 miles before entering the St. Croix Flowage just west of Gordon. The St. Croix Flowage sub-basin is approximately 18,085 acres (28.3 sq. mi.) in area (Maislchke, Ryan, Sorge and Larson, 1974). The flowage surface area accounts for 13.9% of the total sub-basin area or 2,508 acres (3.92 sq. mi.). The flowage is very shallow, with over 95% of its area less than 10 feet deep. One tributary stream (Spring Creek) feeds into the flowage near its western end.

Surface Geology and Hydrogeology

Bedrock underlying the Upper St. Croix and Eau Claire River watershed consists of basaltic lava flows, sandstone, conglomerate, shale and metamorphic rocks of Precambrian age. Glacial drift forms an almost continuous layer (in excess of 200 feet) over underlying bedrock. Glacial drift consists largely of stratified sand and gravel and pitted outwash that was deposited by melt-waters from stagnant and/or retreating Pleistocene glacial ice (Figure 11).

Sandy loams, loamy sands and subordinate organic-rich soils in low-lying wetland areas characterize surface soils throughout the watershed. The permeability of sandy soils is very high, with infiltration rates averaging between 5 to 10 inches per hour(Young and Hindall, 1973). Organic-rich soils in wetland and low-lying river floodplain areas of the watershed have much lower infiltration rates, ranging from 0.8 to 2.5 inches per hour (Young and Hindall, 1973).

Driller's logs from water wells in the Upper St. Croix Lake sub-basin indicate that unconsolidated glacial sediments consist of two layers of sand and gravel separated by an intermediate layer of "hardpan". The upper sand/gravel unit is an unconfined aquifer that produces water from depths of less than 15 to over 50 feet below the surface. Pump tests from driller's logs indicate that this is a porous and permeable unit, producing water at rates of 8 to over 50 gallons per minute (gpm). Groundwater flow in this unit likely flows from topographic highs toward depressions in the landscape where the water discharges into streams, lakes or wetlands.

Little can be deduced from driller's logs concerning the hydrologic properties of the underlying units. The "hardpan" layer is described as a clay-dominated unit containing gravel and boulders (possibly unstratified glacial till). It is likely that this unit has very low permeability and acts as an aquitard (resists fluid flow), or an aquiclude (does not transmit water). The lower sand/gravel unit is potentially a confined aquifer given the laterally extensive distribution of the overlying "hardpan" unit. Lake Association members report that wells producing water from the lower sand/gravel unit flow naturally at the surface, which supports this speculation. Driller's log well records indicate this unit likely has moderate to high permeability (pump tests from producing wells in this unit generally exceed 20 gpm).

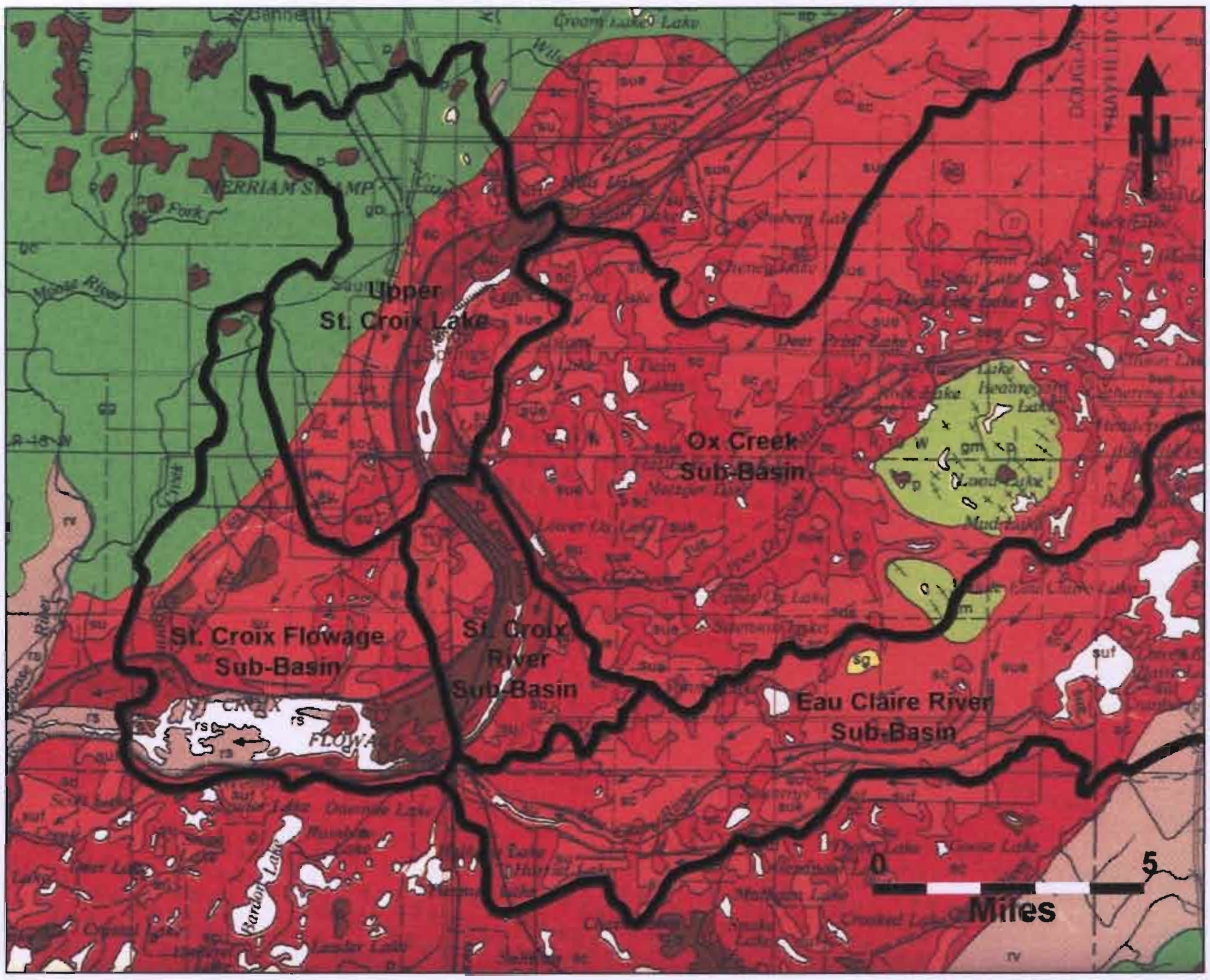


Figure 11 Map illustrating the surface geology of the Upper St. Croix Lake and associated sub-basins to the east and south. Map colors represent the following: 1) red-orange: pitted glacial outwash; 2) dark green: glacial outwash; 4) dark brown: peat bogs and organic-rich river sediments; 5) light brown: river alluvium.

Watershed Controls on Fluctuating Lake Level and Flooding

Before examining the data collected during this study, it is instructive to consider hydrogeologic factors that likely control lake level fluctuations and flooding in the Upper St. Croix Lake sub-basin. In many watersheds, there are a number of factors acting in tandem that determine whether or not high water and flooding will occur in response to a precipitation event. The quantity of precipitation involved and the rate at which it enters the lake are the major factors of importance in the Upper St Croix Lake sub-basin.

When precipitation falls in watersheds like the Upper St. Croix Lake sub-basin, two competing variables control the route and time it takes water to discharge into the lake. These variables are surface runoff versus soil infiltration. Factors impacting the relative importance of runoff versus infiltration include surface soil types and subsurface geology; the slope of the land surface (topography); vegetation interception; drainage basin size, and seasonal meteorological variations including: the magnitude and intensity and duration of precipitation events.

Surface Soil Characteristics

The rate of surface runoff is influenced by the extent of infiltration into the subsurface, which in turn is controlled by the soil type and how much soil is exposed for infiltration to occur. Soils, like rocks, vary in terms of their porosity (water storage capacity), and permeability (ability to transmit water). A dry, very porous and permeable soil allows a great deal of water to be absorbed quickly over relatively short periods of time. If a soil is less permeable, or the soil is covered by an artificial structure, the proportion of water that runs off over the surface increases. Once a porous and permeable soil becomes saturated with water however, any additional water entering the system via precipitation is necessarily forced to become part of the surface runoff component of the hydrologic budget. This is because in an initially dry soil, the surface effects between the soil particles and infiltrating water exert a tension that draws the moisture downward into the soil through capillary passages. As the capillary forces diminish with increased soil moisture content, the infiltration capacity drops off significantly.

Topography

Topography also influences the extent or rate of surface runoff. The steeper the terrain, the more readily water runs off over the surface, and the less it tends to percolate into the soil zone. Water that infiltrates into the subsurface tends to flow down gradient (much like surface water), and eventually discharges into the lake by simple percolation or through springs. However, the subsurface flow of water moves much more slowly than surface runoff via stream flow. The important point is that groundwater discharge to the lake increases the likelihood that stream discharge out of the lake will be adequate to carry the water away without rising water levels or causing a flood event.

Vegetation Interception

Vegetation may reduce the hazard of flooding in the watershed in a variety of ways. During a precipitation event, some rainfall is intercepted by vegetation before it reaches the ground. Intercepted rainfall may later fall to the ground or simply evaporate back into the atmosphere. Plants can act as a physical barrier to surface runoff, decreasing its velocity and slowing the rate at which water reaches the lake. Also, plant roots in the soil zone loosen it, which tends to maintain or enhance the soil's permeability and infiltration capacity, thus reducing the proportion of surface runoff. Plants also absorb water, using some of it to grow and releasing some slowly by transpiration from foliage into the atmosphere.

Drainage Basin Size

Drainage basin size can have a significant effect on the response of a lake or stream system to flooding. Hypothetical hydrographs (Figure 12), show accumulated rainfall associated with a thunderstorm event and discharge for drainage basins of varying size. The effects of rising water level vary dramatically depending on the size of the watershed. Small basins experience higher peak discharges soon after the initiation of the precipitation event, whereas larger basins experience significantly lower peak discharges and a delayed response to the initiation of a rainstorm. These differences in response are largely a function of the fact that in larger drainage basins it takes more time for surface water to travel to the point of discharge. In addition, larger drainage basins offer a greater opportunity for precipitation to be intercepted by vegetation and/or infiltrate into the soil zone.

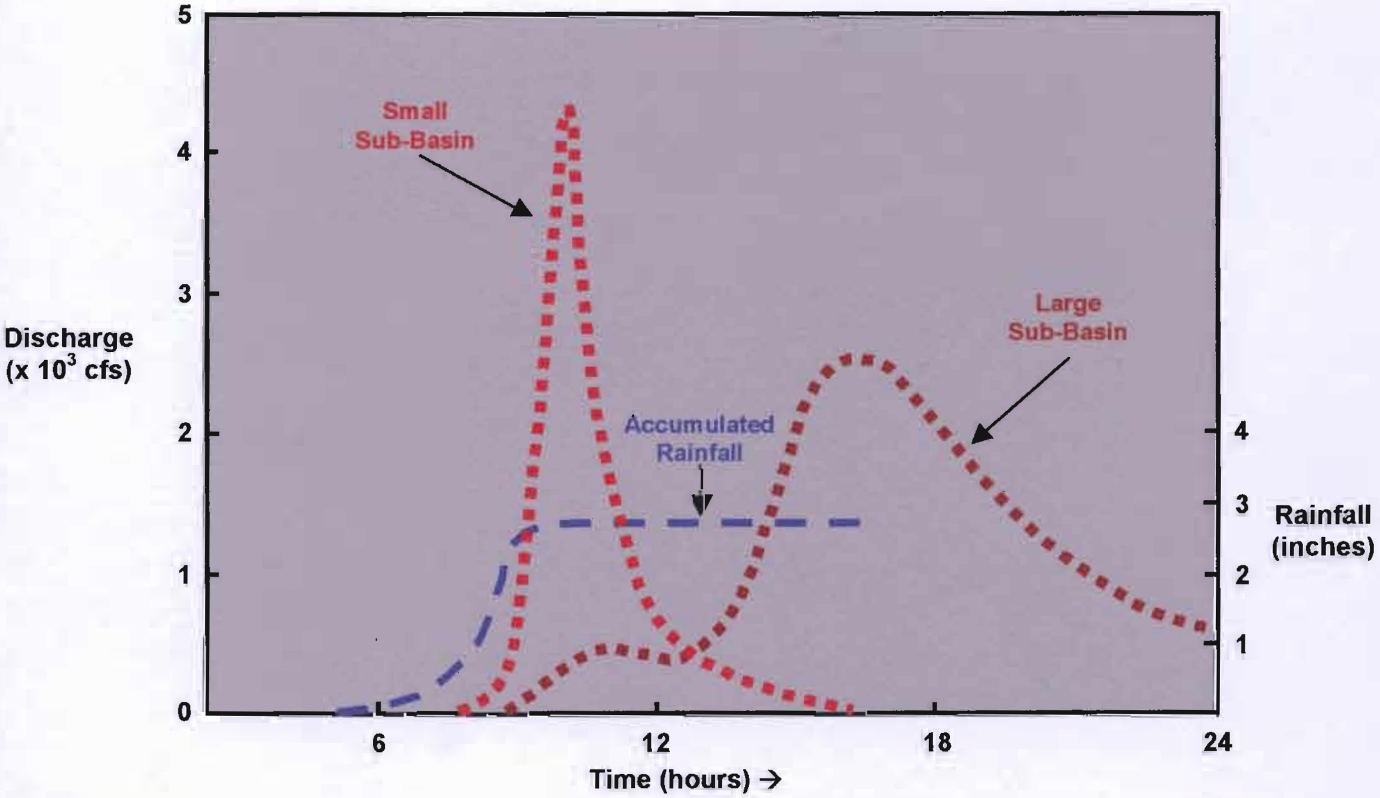


Figure 12 Flood hydrographs for two watershed sub-basins of different size. In a small watershed sub-basin, peak water levels quickly respond to a storm event. A large watershed sub-basin responds more sluggishly to a rainfall event of the same magnitude and duration.

Precipitation Event Magnitude and Duration

The intensity and duration of a storm can significantly affect infiltration/runoff relationships. During a low intensity, long duration precipitation event, sufficient time exists for water to infiltrate into the soil zone, minimizing surface runoff. On the other hand, during high magnitude, relatively short duration events, the volume of precipitation delivered to the watershed can overwhelm the ability of the soil zone to absorb it so that surface runoff becomes a more important avenue for water movement to the lake. During exceptionally large, short duration precipitation events, the amount of tributary stream discharge can overwhelm the capacity of the lake to hold the total volume of water and the ability of outflow streams to reduce lake levels. During these times, severe flooding can result.

The intensity and duration of a precipitation event can impact the likelihood and severity of lake flooding in other ways. For example, the amount of plant interception during a rainstorm is greatest at the beginning of a precipitation event and declines exponentially through time. If a rain is short–lived and light, a large percentage of the precipitation can be intercepted. Many have experienced this phenomenon at the start of a summer thunderstorm when no raindrops hit the ground, although drops can be heard striking tree foliage overhead. As a storm progresses however, once the storage capacity of the leaf surfaces is surpassed, water will run down the tree trunk and/or fall from the tree canopy to the ground. If the rain is heavy and persists for a long time, only a small percent of precipitation is ultimately intercepted.

Meteorological Fluctuations

All other factors being equal, the hazard of flooding within the Upper St. Croix Lake watershed may simply vary seasonally as a result of meteorological fluctuations. Just as soil already saturated from previous storms cannot readily absorb water during the summer months, solidly frozen ground occurring in this region during the winter months also prevents infiltration. A midwinter or early spring rainstorm (when the ground remains frozen), can potentially produce flooding with a quantity of rainfall (and/or snow melt), that would otherwise be absorbed by the soil during the summer. In addition, the extent and vigor of vegetation varies seasonally, as does atmospheric humidity and therefore evapotranspiration component of the hydrologic budget.

1999 AND 2000 PRECIPITATION DATA: A HISTORICAL COMPARISON

Historical Precipitation Records

Table 2 summarizes Upper Lake St. Croix Lake precipitation data for the years 1961-2000. Extreme values recorded in Table 2 are based on historical records from 1906 to 2000. Average total annual precipitation in the watershed is approximately 30.96 in. (78.7 cm). Annual precipitation on the watershed ranged from 13.17 in. (33.5 cm) below average in 1910 to 15.91 in. (40.4 cm) above average in 1951. Typically, about 65% of the annual precipitation falls during the growing season. Snowfall accounts for about 15% of the total annual precipitation.

Table 2 – Average Monthly Precipitation Data: Upper St Croix Lake Sub-basin.

	Total Precipitation (inches)							Snow (inches)		
Month	**Mean**	**High -**	**Yr.**	**Low -**	**Yr.**	**1-Day Maximum**		**Mean**	**High -**	**Yr.**
January	1.04	3.82	50	0.04	81	1.73	23/1982	12.4	37.9	69
February	0.78	3.15	22	0.07	69	1.60	22/1913	8.4	23.0	71
March	1.73	4.20	17	0.10	10	1.92	15/1945	10.1	30.3	52
April	2.24	5.62	60	0.34	43	2.91	24/1960	3.8	22.9	50
May	3.53	9.35	62	0.56	48	3.12	15/1962	0.2	11.0	54
June	3.82	9.92	67	1.20	10	3.85	15/1981	0.0	0.0	00
July	4.29	14.95	99	0.47	36	5.60	26/1999	0.0	0.0	00
August	4.32	9.80	41	0.40	30	8.95	31/1941	0.0	0.0	00
September	3.55	7.81	90	0.55	19	5.10	05/1990	0.0	0.0	00
October	2.64	7.73	71	0.25	53	3.95	02/1950	0.5	14.0	51
November	1.86	6.06	75	0.00	16	2.94	03/1991	6.5	53.5	91
December	1.16	3.24	68	0.02	43	1.50	05/1909	12.4	38.0	68
Annual	**30.96**	**46.87**	**51**	**17.79**	**10**	**8.95**	**08/31/41**	**54.3**	**120.2**	**50**
1999 Total	**43.78**							**33.5**		
2000 Total	**26.10**							**66.3**		

* Monthly averages (in inches) are based on 1961-2000 precipitation records.
** Extreme values (in inches) are based on records for the years 1906-2000.

1999 Precipitation Data vs. Historical Precipitation Records

A comparison of 1999 data with historical averages indicates that 1999 was an exceptionally wet year, exceeding historical averages by 12.82 in (32.6 cm). Although the winter months of 1999 received considerably less snow than average (Figure 13), precipitation deficits were made up during an unusually wet summer, (Figure 14). Note in Table 2, that total precipitation during the month of July and July 26th, 1999 exceeded rainfall accumulations for the entire 95 years of record.

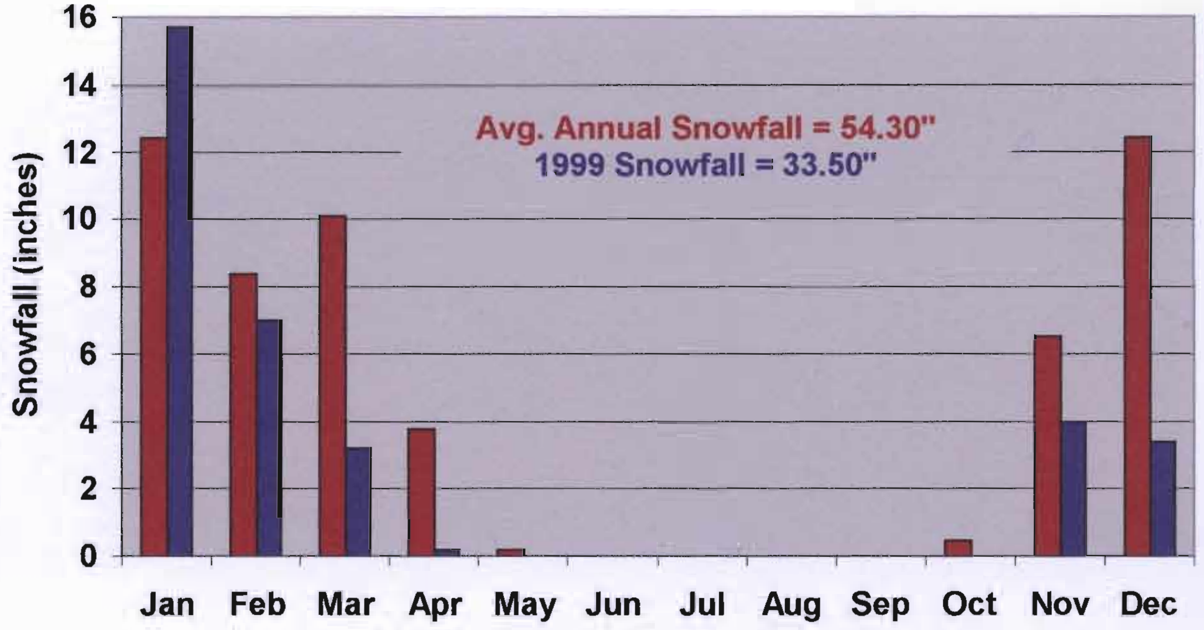


Figure 13 Histogram showing average total monthly snowfall in the Upper St. Croix Lake watershed for the years 1961 through 1991 (red bars) versus 1999 data (blue bars). Historical averages based on data from the Midwestern Climate Center.

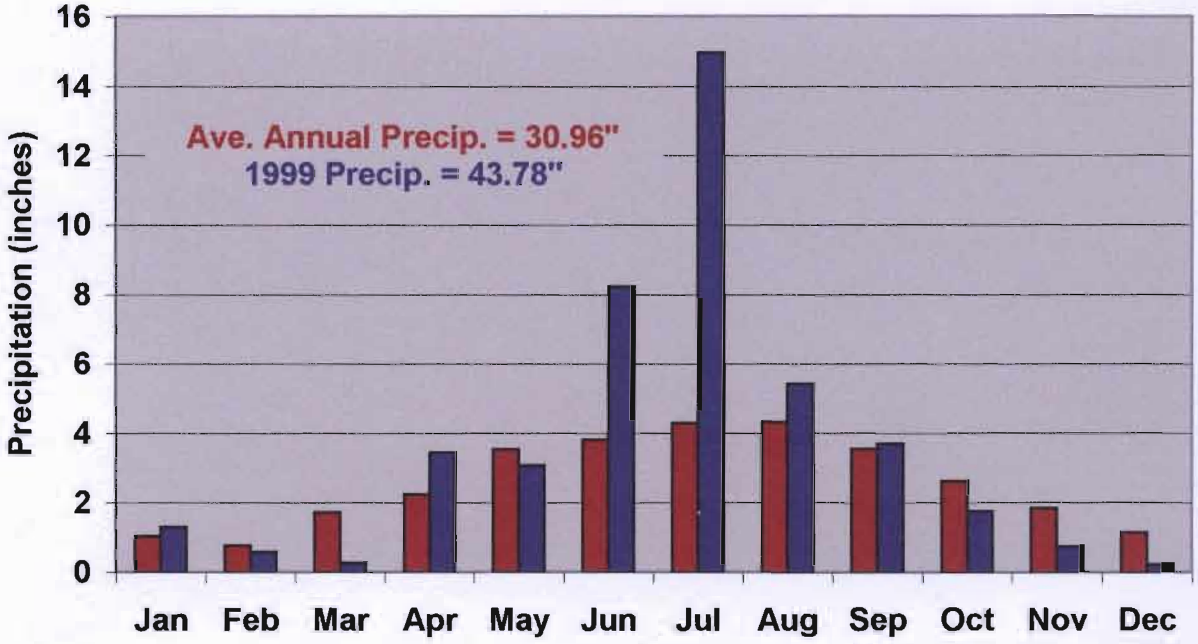


Figure 14 Histogram showing average total monthly precipitation in the Upper St. Croix Lake watershed for the years 1961 through 1991 (red bars) versus 1999 data (blue bars). Historical averages based on data from the Midwestern Climate Center.

2000 Precipitation Data vs. Historical Precipitation Records

A comparison of 2000 data with historical averages indicates that 2000 was a relatively dry year. Although above average amounts of total snowfall (12.00 in.; 30.5 cm) fell, the total accumulated precipitation (4.80 in.;12.2 cm) was below average (Figures 15 and 16).

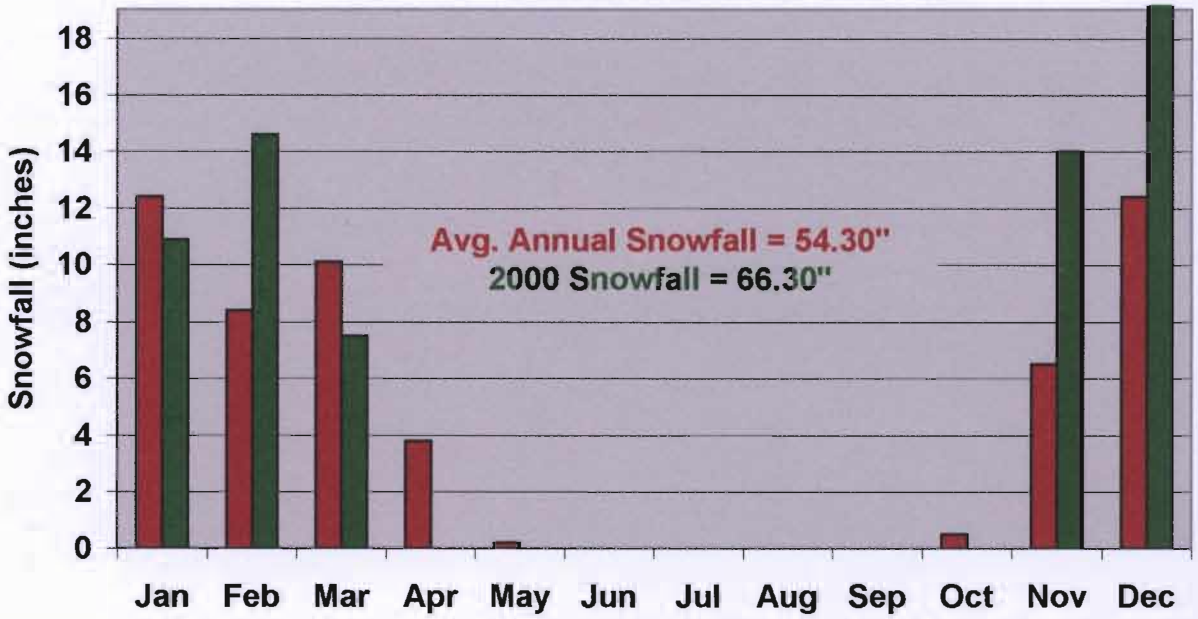


Figure 15 Histogram showing average total monthly precipitation in the Upper St. Croix Lake watershed for the years 1961 through 1991 (red bars) versus 2000 data (green bars). Historical averages based on data from the Midwestern Climate Center.

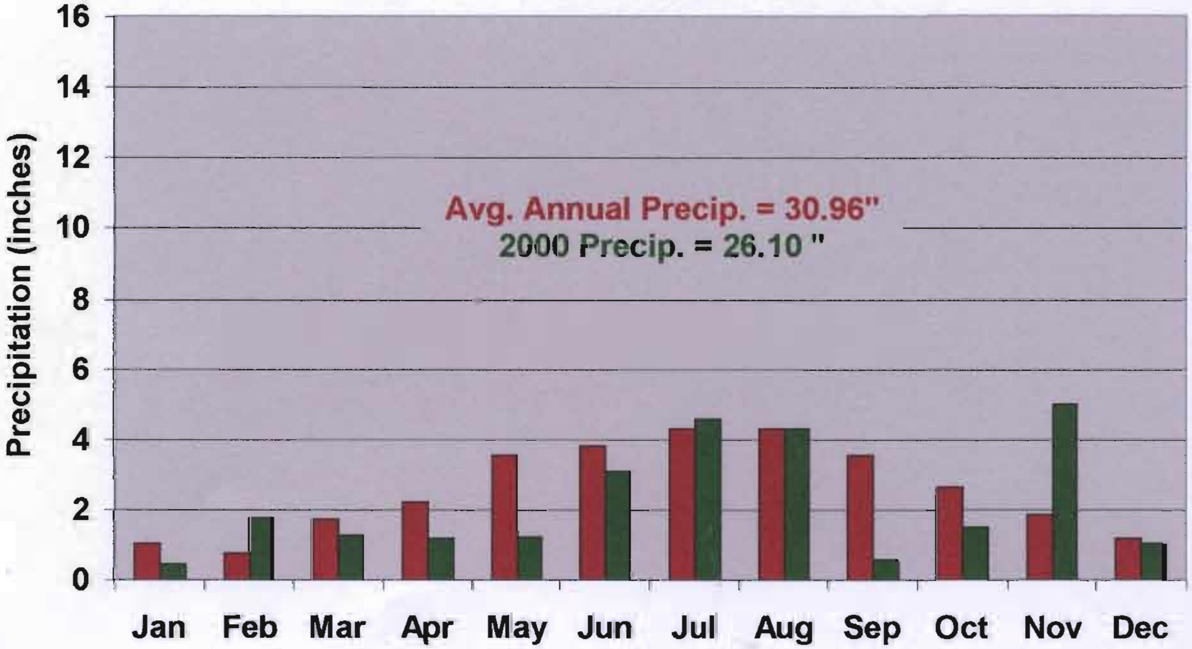


Figure 16 Histogram showing average total monthly precipitation in the Upper St. Croix Lake watershed for the years 1961 through 1991 (red bars) versus 2000 data (green bars). Historical averages based on data from the Midwestern Climate Center.

Precipitation Recurrence Intervals

Another way of analyzing the precipitation data gathered for 1999 and 2000 is in terms of precipitation event recurrence interval. The recurrence interval of a precipitation event is the number of years or frequency one might expect rainfall accumulations of a given magnitude to occur (on average). The availability of historical precipitation records from 1931 through 1998 makes it possible to construct a graph showing precipitation as a function of recurrence interval for the Upper St. Croix Lake sub-basin. It is calculated using the equation:

RI = (# of Years on Record +1)/(Rank Order of Rainfall Event)

A hypothetical precipitation frequency curve (Figure 17), illustrates how recurrence intervals can be used to describe precipitation events of differing severity. For example, imagine that the total precipitation for a given year is equal to 46 in. The graph shows that a yearly total precipitation value of this magnitude is likely to occur once every ten years or so. A yearly total precipitation of 50 in. occurs once every 50 years, on average, and so on.

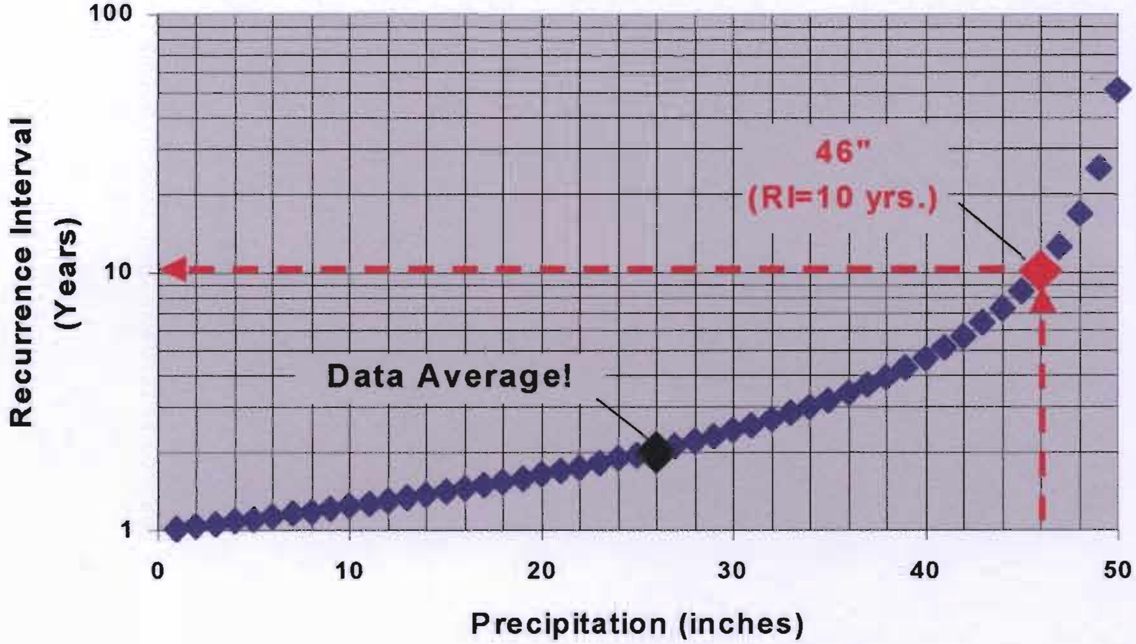


Figure 17 A hypothetical precipitation frequency curve illustrating how the recurrence interval of a rainstorm event can be determined graphically. The hypothetical curve is based on fifty data points.

Alternately, some hydrologists prefer to refer to the probability that a precipitation event of a given magnitude will occur in any given year. The probability of a precipitation event occurring is the inverse of recurrence interval. It is calculated using the equation:

Probability = Rank Order of Event/(# of Years on Record +1)

For the hypothetical example presented above, the total amount of precipitation that fell (46.0 in.), is called a "ten-year" event. This means that a year with this much precipitation occurs about once every ten years, or has a 10% (1 in 10) probability of occurring in any given year.

The precipitation frequency curve shown in Figure 18 indicates that the total amount of precipitation that fell in the Upper St Croix Lake sub-basin during 1999 (43.78 in.) has a recurrence interval of 20 years. Precipitation recurrence intervals for 2000 precipitation totals (26.10 in.) are only on the order 1.1 years. This data means that on average, a yearly total precipitation of 43.78 and 26.10 inches is likely to fall in the watershed every 20 and 1.1 years respectively.

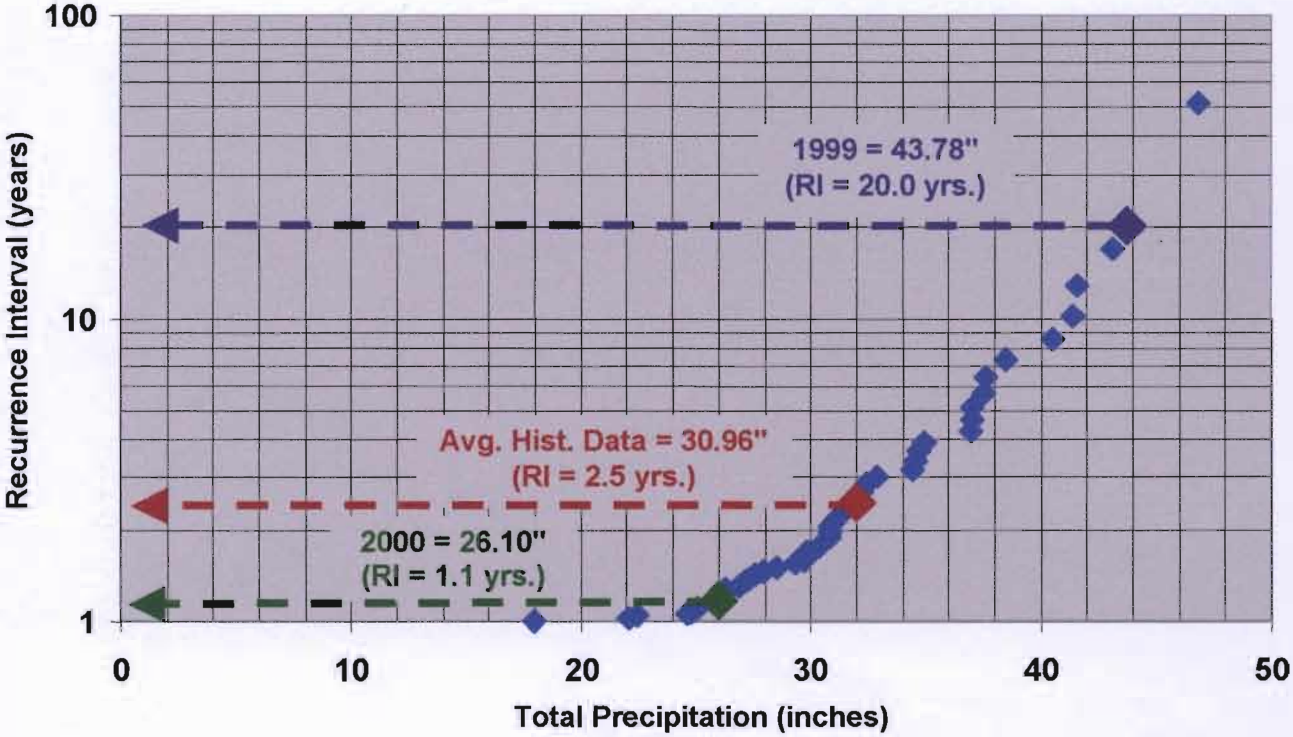


Figure 18 Precipitation frequency curve for the Upper St. Croix Lake sub-basin. Recurrence intervals are based on a 67-year record extending from 1931-1998.

Recurrence interval plots for the late spring, summer and early fall 1999 are shown in Figure 19. Note that the recurrence interval for total monthly precipitation during June and July 1999 are 10 and 100 years respectively. It is important to emphasize that precipitation amounts of this magnitude could occur at any time in the future. It could be next year, the year after next or 20, 50 or 100 years down the road. A recurrence interval calculation is a statement of the likelihood ("probability") that a precipitation event of a certain magnitude will occur over some interval of time. It is not a timetable used to predict a precipitation events reoccurrence. As long as this is kept in mind, the important point to emphasize is that summer 1999 rainfall accumulations were exceptionally large and greatly in excess of "average" values.

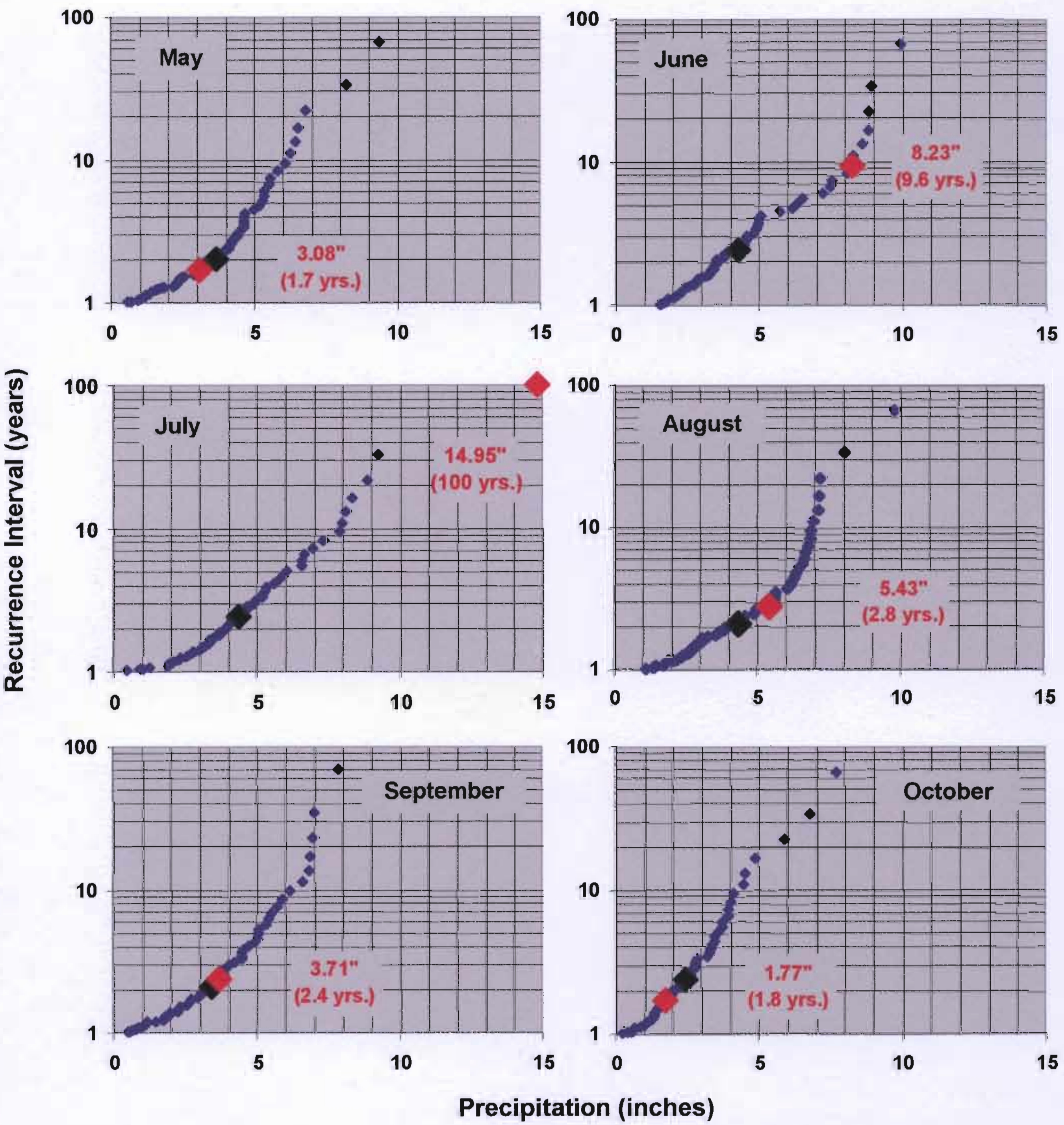


Figure 19 Precipitation frequency curves for May through October 1999. Red diamonds and red text indicate the precipitation total and the recurrence interval for the month of interest. Black diamonds represent the recurrence interval for the historical average. Recurrence intervals are based on a 67-year historical record extending from 1931-1998.

1999 AND 2000 PRECIPITATION AND LAKE LEVEL HYDROGRAPHS

A hydrograph is a simple graphical device that shows variations in some hydrologic variable as a function of time (Fetter, 1994). In this study, hydrographs are used to characterize variations in precipitation and variations in lake level for the months of April through October 1999 and 2000 (Figures 20 and 21).

Hydrographs provide a means of making a qualitative assessment of relative relationships between soil infiltration, surface runoff and lake level fluctuation. If data for hydrograph construction are collected for a large number of years, they can be useful in constructing a picture of the "normal" behavior of the watershed system to storm events of differing magnitude and duration during wet and dry seasons.

1999 Precipitation and Lake Level Hydrographs

The precipitation hydrograph for the months of April and May (Figure 20) indicates that rainstorms were low magnitude (<2 cm), long duration (2-5 day) events. Lake level during this period reached a maximum low of 29.5 cm (11.6 in.) below datum in early May, followed by a gradual rise of 8.5 cm (3.3 in) in response to spring rains during mid-May. By the end of May and early June, lake level again dropped to a level 28 cm (11 in.) below datum. The steady decline in lake level during middle to late April, and 2 to 10 day lag times between May rainfall events and peak lake levels suggests that soil infiltration generally exceeded surface runoff during this period. This interpretation is consistent with the exceptionally mild winter experienced during January, February and March, which likely contributed to low soil moisture content during the early spring of 1999.

The exceptionally wet months of June and July were characterized by an overall increase in lake level equaling 117 cm (48 inches) Precipitation during this period was characterized by a mix of low and high magnitude (1-14 cm), short duration (1-2 day) storms. Note in Figure 20, that the lag time between peaks in precipitation for the five high magnitude storms and peak lake level decreases from 2-3 days during early June to less than 1 day by late July. These observations suggest that increasing saturation and decreasing infiltration capacity of the soil zone likely contributed to a significant increase in the runoff component of the hydrologic equation by late July. This conclusion is supported be observations that water table levels increased 66 cm (26.0 in.) from the beginning of June to August (Figure 20). Unfortunately, apparent saturation of the soil zone coincided with a July 26th storm that delivered approximately 14.2 cm (5.6 in.) of rainfall to the watershed over a period of less than 6-8 hours. The intensity of this event delivered so much water over such a short period of time, that it overwhelmed the ability of the soil zone to absorb it so that surface runoff became the primary avenue for water movement to the lake. Extensive flooding was the result in Solon Springs and surrounding communities.

The precipitation hydrograph for the months of August through October indicate an overall decrease in storm frequency and magnitude compared to the summer months. Rainstorms during this period were low to moderate magnitude (<4 cm), long duration (>2 day) events. Lake level declined from a maximum value of 76.5 cm (30.1 in.) above datum to a minimum of -7.5 cm (-3.0 in.) below datum during this period. The overall net decline in lake stage, coupled with observations that the lag time between rainfall events and peak lake levels increased from late

July to the end of October suggests that soil infiltration gradually reestablished its dominance as an avenue for water movement in the watershed sub-basin.

2000 Precipitation and Lake Level Hydrograph

The majority of storms that occurred between late April and the end of October 2000 were low magnitude (<2 cm), moderate to long duration (2-5 day) events, except for two moderate to high magnitude (>2-4 cm), short duration (1 day) storms that occurred at the end of July and mid-August (Figure 21). Although lake level fluctuation displays an overall trend similar to that seen during 1999, (a gradual decline following spring melt, a steady increase in lake level during the summer rainy season, and then a gradual decline during autumn, prior to the onset of winter freeze-up), marked differences in lake level fluctuation and lag time are observed.

Lake level decreased 6 cm below datum shortly after spring melt and then maintained relatively constant levels through the middle of June. Lake level increased 40 cm (15.8 in) from mid-June to mid-August. The magnitude of lake level rise during this period is dwarfed by that which occurred in 1999 simply because of differences in the frequency and magnitude of summer storms. It is interesting to note that lag times between storm events and lake level peaks are on the order of 2-10 days and that the rate of increase in response to a rainfall event is relatively slow. This suggests that soil infiltration capacity remained high throughout the season and that increases in lake level reflect a greater contribution of groundwater flow to the lake. This conclusion is supported by observations of water table fluctuation that indicate a modest increase of slightly more than 14 cm from June to the beginning of August 2000.

HYDROGEOLOGIC MODEL

Addressing the question why the Upper St. Croix Lake experiences dramatic changes in lake level during spring melt and during high intensity summer rainstorms requires an appreciation of the geomorphology and hydrogeology of the watershed sub-basin. The following points are important to emphasize.

1. The total sub-basin area (36.9 mi^2) greatly exceeds the 1.76 mi^2 area of the Upper St. Croix Lake. In addition the lake is relatively shallow, maintaining maximum depths of only 22 feet.

2. Volumetric estimates indicate that the Upper St. Croix Lake has a capacity to hold up to 4.67×10^5 cubic feet (1.32×10^4 cubic meters) of water without significant flooding. The magnitude of precipitation events that occurred during June and July 1999 greatly exceeded the storage capacity of the lake, as well as the ability of the lake/stream system to move incoming water out of the system. The magnitude of the July 26th precipitation and other rainfall events during June and July can be appreciated by comparing the volume of water that fell on the watershed relative with the capacity of the Upper St. Croix Lake to store it. Volumetric calculations indicate that the five major precipitation events that occurred between June 1st and July 31st delivered water volumes to the basin that exceeded lake storage capacity by 280 to 1000 times.

3. The Upper St. Croix Lake is unlike other sub-basins of the Upper St. Croix and Eau Claire watershed (where low relief and poorly developed drainage dominates). The Upper St. Croix Lake watershed has a well-developed drainage of eight high gradient (23-100 ft/mi) tributary streams. Upper St. Croix Lake tributary streams feed into a trunk lake/stream system with a gradient of less than .2 ft/mi from its headwaters to the Gordon Dam, a distance of approximately 19 miles. The important point is that tributary streams bordering the watershed provide very efficient conduits for moving water to a significantly less efficient Upper St. Croix Lake/St. Croix River system.

4. Surface soils and glacial deposits that underlie the sub-basins have extremely high infiltration capacities of 5 to 10 inches per hour, that are easily capable of absorbing low magnitude, long duration rainfall events. However, if the soil zone becomes saturated sometime during the spring melt or during the summer months, the runoff component of water movement by necessity takes on an increasing importance in the systems hydrologic budget. There is simply nowhere else for the water to go.

A simple hydrogeologic model can be used to explain unusual stage fluctuations on the Upper St. Croix Lake. The high infiltration rate and storage capacity of the glacial outwash "sandy" substrate that mantles the watershed absorbs a significant fraction of precipitation relative to runoff during moderate to long duration, low magnitude precipitation events. Groundwater recharge to the lake delays lake stage response time to precipitation events by days. Water levels in the lake rise gradually as a result.

However, as the spring and summer progress, soil moisture content can increase, reducing the capacity of the subsurface to absorb and store water. When rainstorms occur during periods of high soil saturation, surface runoff necessarily becomes the preferred avenue for water movement down gradient. It is during these times when high magnitude, short duration storm events deliver large volumes of water to the lake by overland flow. The lag time between precipitation and lake level peaks is relatively short during these times because of the efficiency of the high gradient tributaries that feed into the low gradient lake system. The potential for high water invading low-lying shoreline areas is enhanced simply because the lake has a finite capacity to accept incoming discharge and move it through the system. If precipitation events are exceptionally large (like the July 26th, 1999 rainstorm), overland flow completely overwhelms the capacity of lake to accept total discharge and a major flood results.

CONSEQUENCES OF WATERSHED URBANIZATION

Upper St. Croix Lake Floodplain Development

The Village of Solon Springs and shoreline areas of the Upper St. Croix Lake are experiencing increasing development stress. A shoreline inventory survey (Hlina, 1997), of the Upper St. Croix Lake indicates that 67% of the shoreline is developed (256 residences), 27% is wooded to within 5 meters of the shoreline, and 6% is bordered by wetlands. The survey also indicates that forty-five landowner lots are floodplain properties susceptible to high water flood events. An additional seventy-one residences may experience partial flooding of low-lying acreage during high water.

General relationships between increased watershed development and its effects on runoff are illustrated in Figure 22. Peak lag time between a precipitation event and peak stream discharge typically decreases with increased urbanization. In addition, it is important to note that peak lake levels (stage) also are likely to increase.

Development stress impacts the sub-basin by reducing soil infiltration capacity when building materials such as impermeable asphalt and concrete are used to cover the ground when residential housing and roadways are constructed. When building materials, rather than native vegetation covers an increasing area of the watershed, surface runoff will be more concentrated and rapid, increasing the potential risk of lake flooding. In addition, floodplain development occupies space that otherwise would be available to accommodate excess water during a flood episode (Figure 23). Filling in a floodplain for construction, landscaping or other purposes decreases a floodplain's storage capacity and aggravates high water and potential flooding problems.

These problems are amplified when road construction methods constrict runoff flow in such a way so that it has a shorter, more direct route to the lake. For example, in residential areas bordering the Lucius Woods and the western shores of the Upper St. Croix Lake, many east-west roadbeds are constructed with a concave upward cross-sectional profile, rather than a convex profile. This construction style was likely chosen to minimize lawn erosion and flooding during spring melt. However, this allows precipitation runoff to take a direct route to the lake and virtually eliminates any possibility of infiltration, much to the detriment of lakeshore floodplain residences.

Flood Prevention Strategies

There is not one easy solution to the fluctuating lake level and flooding problems encountered by inhabitants of the Upper St. Croix Lake. Landowners of the lakeshore must simply recognize that "Mother Nature" (the physiography and hydrology of the lake watershed), dictates that high water and flood events will occur in the basin from time to time. It is important to emphasize that the likely contribution of various historical "culprits" (i.e., the dam, the weeds etc.), have little or no effect on the overall "flood" hydrology of the system. This is especially apparent in light of the precipitation events and flooding that occurred in the watershed during the summer of 1999.

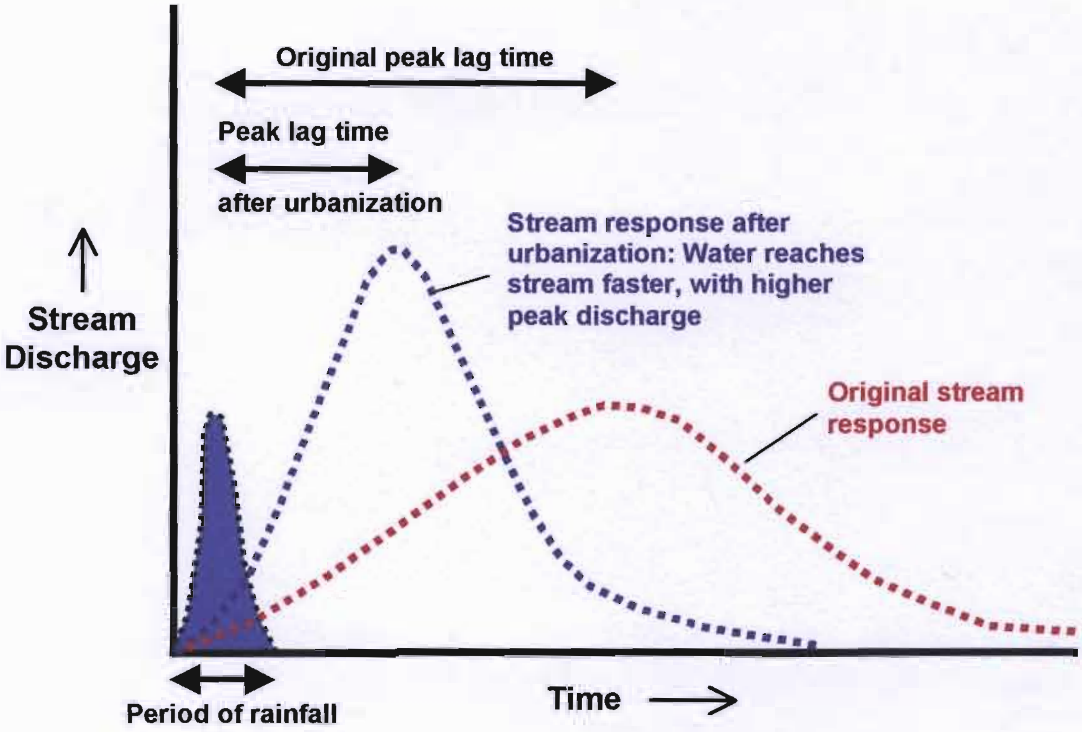


Figure 22 Precipitation and stream hydrographs reflecting changes in stream and/or lake level in response to precipitation events before and after urbanization of a watershed. Peak stream discharge and/or lake levels increase, while the lag time between precipitation peaks and stream/lake level peaks decrease.

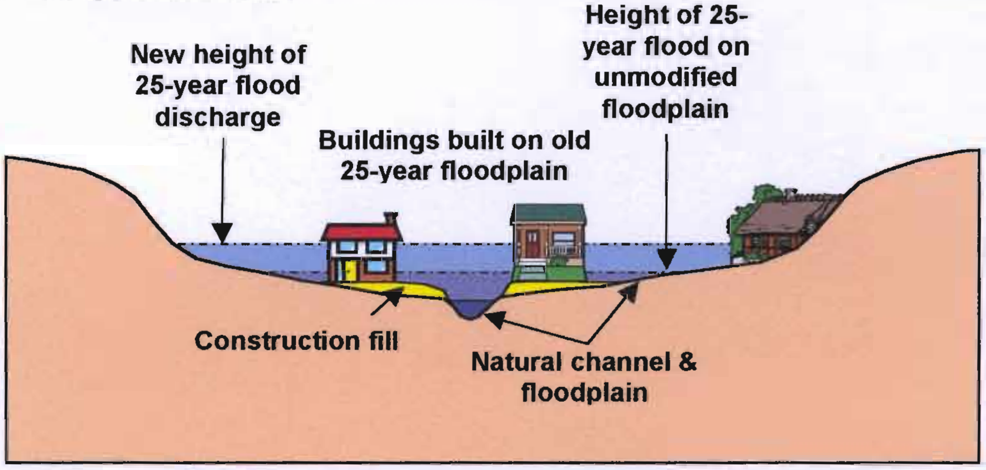


Figure 23 Schematic illustration of how floodplain development increases lake levels for precipitation events of a given magnitude.

Short of avoiding floodplain habitation altogether, waterproofing residential infrastructure, or elevating buildings on stilts, little can be done to safeguard property owners from flood hazards except to practice wise floodplain management practices. The first step would be to identify as accurately as possible lakeshore properties that are most at risk. Second, practice restrictive zoning policies that avoid watershed and lakeshore development that would contribute to flooding.

The construction of dams, floodwalls, and artificial levees, coupled with channel dredging are time-honored methods used to mitigate flood hazards in many communities prone to flood hazards. However these methods are very costly and commonly offer only short-term benefits (i.e., dams and channels silt up, levees break etc.). A possible alternative for the Upper St. Croix Lake watershed would be to consider the use of retention ponds that trap some of the surface runoff during a flood, keeping it from flowing immediately into the lake (Figure 24). Temporary storage would reduce overland flow, increase soil infiltration and the volume of water lost to the atmosphere via evaporation.

Retention ponds could be costly, elaborate structures or simply unused fields and forested lands dammed by dikes of piled up soil adjacent to watershed tributaries. An added advantage of retention ponds is that that they do not alter the character of stream dynamics in ways that might ultimately result in amplified flood events, rather than reducing flooding over time.

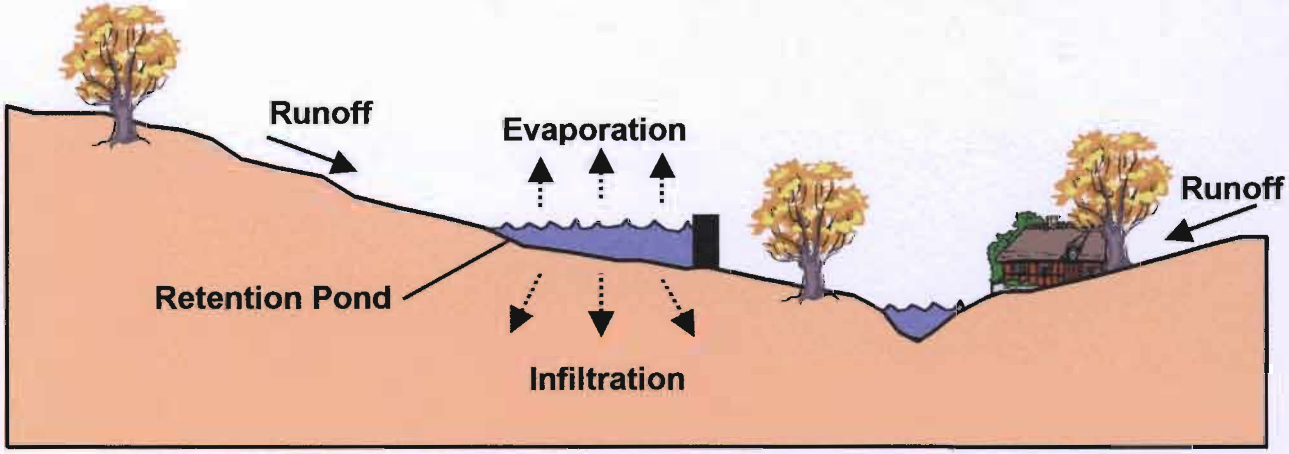


Figure 24 Retention ponds trap some surface runoff during high intensity storms, preventing water from reaching base level too quickly. Ponded water allows for slow infiltration and/or evaporation instead.

CONCLUSION: UNANSWERED QUESTIONS AND PROJECT CONTINUATION

The goal of this field trial was to establish a protocol for monitoring precipitation, lake level, and stream discharge within the Upper St. Croix Lake sub-basin. This data combined with the analysis of existing historical precipitation records and a survey of watershed geomorphic, geologic and hydrologic characteristics has allowed a formulation of a conceptual model for understanding the hydrogeology of the sub-basin. However, several important components of the sub-basins hydrologic budget require further study and quantification in order to test the model.

1) Monitoring precipitation and lake level on a daily (24-hour) basis provides useful hydrologic information. However, 24-hour measurements do not provide the short duration data necessary to understand how the magnitude and duration of precipitation events, surface runoff and lake level vary dynamically in "real time". The acquisition of automatic "tipping bucket" rain gauges and lake/stream level meters would allow the monitoring of these parameters on an hourly (or shorter) time interval.

2) An important aspect of the basins hydrologic equation that has not been quantified is how soil saturation and infiltration capacity varies over time. Soil moisture meters could be utilized to collect this data. In addition, the collection of field and laboratory hydrologic data documenting soil zone hydraulic conductivity and how soil infiltration rate varies as a function of soil saturation are necessary to better understand infiltration versus runoff characteristics in the sub-basin.

3) The initiation of seasonal field trials to document depth to water table, map water table configuration, and establish groundwater flow directions and velocity are necessary to understand the relative importance of the groundwater component of the hydrologic budget in the sub-basin.

UWS Students enrolled in the Physical Environmental Science program have the background in laboratory and field hydrology techniques necessary to address the questions highlighted above. Some of the instrumentation discussed above has been or is being acquired by the UWS Department of Biology and Earth Science. However, it is likely that additional funding would need to be acquired to insure adequate field supplies and support, should this project continue in the future.

The acquisition of the data summarized above would certainly improve our understanding of how the Upper St. Croix Lake sub-basin functions as a dynamic hydrologic system. The results of a continued research effort over the coming years in the sub-basin would not only benefit Solon Springs residents, but would provide hydrogeologic data that is pertinent to land use planning and environmental investigations in similar watersheds of southern Douglas County.

GLOSSARY

Aquiclude	A low-permeability unit that forms either the upper and/or lower boundary of a groundwater flow system.
Aquifer	A porous rock or sediment formation that is saturated and sufficiently permeable to transmit economic quantities of water to wells or springs.
Aquifer, confined	An aquifer that is overlain by a confining bed that has significantly lower hydraulic conductivities than the aquifer.
Aquifer, unconfined	An aquifer in which there are no confining beds between the zone of saturation and the surface. There will be a water table in an unconfined aquifer. Water-table aquifer is a synonym.
Aquitard	Low permeability formations that can store water, but can only transmit it slowly from one aquifer to another.
Capillary forces	Forces acting on soil moisture in the unsaturated zone, which are attributed to molecular attraction between soil particles and water.
Condensation	The process that occurs when an air mass is saturated and water droplets form on nuclei or on surfaces.
Confining layer	A geologic formation of low hydraulic conductivity that is positioned above or below an aquifer.
Current meter	A device that is lowered into a stream to record the rate (velocity) at which the current is moving.
Datum	A surface used as a reference when surveying changes in elevation.
Discharge	The volume of water flowing in a stream or through an aquifer past a specific point over a given period of time.
Drainage basin	The land area from which surface runoff drains into a stream system.
Drainage divide	*See* topographic divide.
Drumlin	A streamlined assymetrical hill composed of glacial till.
Evaporation	The process by which water passes from the liquid to the vapor state.
Evapotranspiration	The sum of evaporation and transpiration.
Geomorphology	The study of the physical and chemical processes that shape the landscape.

Glacial outwash	Well-sorted sand, or sand and gravel, deposited by melt water from a glacier.
Glacial pitted-outwash	Glacial outwash deposited on stagnant glacial ice that produces a low relief pitted surface topography with many closed depressions.
Glacial till	A glacial deposit composed of unsorted sand, silt, clay and boulders deposited directly from melting glacial ice.
Groundwater	The water contained in the interconnected pores below the water table in an unconfined aquifer or located in a confined aquifer.
Hydraulic conductivity	A coefficient describing the rate at which water can move through a permeable medium.
Hydrogeology	The study of the interrelationships of geologic materials and processes with ground and surface water.
Hydrograph	A graph that shows some property of ground water or surface water as a function of time.
Hydrologic cycle	The circulation of water from the oceans through the atmosphere to the land and ultimately back to the ocean.
Hydrologic equation	Expression of the law of mass conservation that describes the inflow, outflow and storage components of the hydrologic cycle. It may be stated as inflow equals outflow, plus or minus changes in storage.
Infiltration	The flow of water downward from the land surface into the upper soil layers.
Infiltration capacity	The maximum rate that infiltration can occur under specific conditions of soil moisture. For a given soil, the infiltration capacity is a function of the saturation (water content) of that soil.
Interception	The process by which precipitation is captured on the surfaces of vegetation before it reaches the ground (land surface).
Moraine	An undulating layer of glacial till deposited as an ice sheet retreats.
Overland flow	The flow of water over a land surface because of direct precipitation. Overland flow generally occurs when the precipitation rate exceeds the infiltration capacity of the soil zone.
Permeameter	A laboratory instrument used to measure the permeability and hydraulic conductivity of a soil or rock sample.

Pleistocene	An epoch of geologic time that began about 1.6 million years ago and ending about 10,000 years ago. Best known as a period of extensive continental glaciation.
Pore space	The volume between mineral grains in a porous medium.
Porosity	The ratio of void spaces in a rock or sediment to the total volume of a rock or sediment.
Rock, igneous	A rock formed by the cooling of molten rock material called magma in the subsurface or lava when magma is extruded onto the Earth's surface.
Rock, metamorphic	A rock formed by the application of heat and pressure to preexisting rocks.
Rock, sedimentary	A rock formed from the lithification of sediment.
Runoff	The total amount of water flowing in a stream, or running off the surface as overland flow.
Saturated zone	The zone in which voids in a rock, sediment or soil are filled with water at a pressure that is greater than atmospheric pressure. The water table is the top of the saturated zone in an unconfined aquifer.
Sediment	Mineral grains deposited by a geologic agent like water, wind, ice or gravity.
Soil moisture	The water contained in the unsaturated zone.
Stage	The level of water in a lake or a stream.
Sublimation	The conversion of a solid directly to a gas without passing through the liquid phase.
Surface water	Water found in ponds, lakes, streams and rivers.
Topographic divide	The elevation high between adjacent surface water runoff areas.
Transpiration	The release of water to the atmosphere by plants.
Unsaturated zone	The zone between the land surface and the water table where pore pressures are less than atmospheric.
Water budget	An evaluation of all the inflow sources and outflow processes of water applied to an aquifer or a drainage basin.
Water table	The water surface in an unconfined aquifer or confining bed where the pore water pressure is atmospheric.

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