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Influence of Streamflow Forecasts and Hydrometeorological Conditions on Stratton Dam Operations

by
H. Vernon Knapp

Prepared for the
Illinois Department of Natural Resources
Office of Water Resources

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Illinois State Water Survey
Watershed Science Section
Champaign, Illinois

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CONTENTS

INTRODUCTION

The Fox Chain of Lakes and the Fox River downstream of the lakes, located in McHenry and Lake Counties in northeastern Illinois, have long been popular for boating, fishing, and other recreational activities. Over the years there has been considerable residential development along most of the flat shorelines along the lakes and river, thus high floodwater levels have become an issue of great concern. During the warm seasons, high water levels also restrict recreational boating, which provides a valuable economic resource to the area.

Stratton Dam, located on the Fox River 7 miles downstream of the Chain of Lakes, partially controls the outflow of water from the lakes. The dam is owned by the State of Illinois and is operated by the Illinois Department of Natural Resources, Office of Water Resources (INDR-OWR). The primary function of Stratton Dam has been to maintain the recreational pools in the lakes, but in recent years flood control management has become an important secondary function of the dam.

In support of flood and high flow operations, a flow forecast model has been developed to provide the information needed to increase outflows and lower lake levels in the early stages of a high flow event. In general, three principal components are needed for such flow forecasting systems:

- a means of collecting input data, in particular rainfall and streamflow,
- a model for estimating quantitative forecasts of flow from this data, and
- a procedure for using these forecasts, either in a flood warning system or for reservoir operation.

This report focuses on the third component, i.e., developing a set of procedures to identify how the forecasts may be used in dam operation. Some issues concerning the use of input data also are addressed. The development of hydrologic and flow forecast modeling for this system is addressed in Knapp et al. (1991). The model developed in this study is hereafter referred to as the Fox River Forecast Model (FRF Model).

The objective of this study was to develop a scheme in which near real-time forecasts and other available hydrologic information can be used in dam operation to effectively reduce the probability and potential damage of flooding and other high flows in the Chain of Lakes area. Schemes for dam operations must necessarily be based on the probability of certain events occurring, or not occurring, because none of the available information provides perfect foresight for future conditions. Operational changes may not have the potential to produce substantial flood control benefits for all locations along the Chain of Lakes and Fox River. This study attempts to describe schemes that can produce practical improvements in water level control where possible, while avoiding known negative impacts on water levels at other times or locations.

Acknowledgments

This study was principally funded by a research contract from the Illinois Department of Natural Resources, Office of Water Resources (IDNR-OWR). Support was also provided by the Illinois State Water Survey, a Division of IDNR. William Rice, Steve Airman, and Arlan Juhl of IDNR-OWR provided valuable data and helpful review comments. William Rice served as project liaison.

The study was conducted under the general supervision of Nani G. Bhowmik and David T.-W. Soong of the Water Survey. Other Water Survey staff also contributed to this project. Christina Tsai, a graduate student at the University of Illinois, assisted in the analysis of the section on antecedent watershed conditions. Maitreyee Bera prepared the data sets and graphics related to quantitative precipitation forecasts. Eva C. Kingston and Agnes E. Dillon edited the report, Linda J. Hascall prepared the maps and reviewed the graphics, and Susan Gordon assisted in typing and formatting the final copy.

Any opinions, finding, and conclusion or recommendations expressed in this report are those of the author and do not necessarily reflect those of the Office of Water Resources or the State Water Survey.

BACKGROUND INFORMATION

Figure 1 shows a general map of the Fox River watershed upstream of Elgin. For purposes of describing runoff response, the five regions of the watershed are defined: (1) the northern portion of the watershed, located upstream of Lake Tichigan and primarily in Waukesha County, Wisconsin; (2) the southern Wisconsin portion, which is mostly the area between Lake Tichigan and the Illinois-Wisconsin border; (3) the Nippersink Creek watershed; (4) the vicinity of the Chain of Lakes and its local tributaries; and (5) the portion of the watershed located downstream of Stratton Dam.

Figure 2 provides a more detailed map of the Chain of Lakes vicinity. Of specific interest are the locations of the largest lakes within the Chain of Lakes, those being Pistakee, Grass, Fox, Nippersink, and Channel Lakes. Stage gages are located on the latter three of these lakes, as well as along the Fox River at Johnsburg and Stratton Dam (near McHenry).

Figures 1 and 2 both show the location of the continuous discharge gages in the Fox River watershed. Two gages, on the Fox River near New Munster (formerly at Wilmot) and on Nippersink Creek near Spring Grove, record streamflows from roughly 80 percent of the watershed upstream of the Chain of Lakes and Stratton Dam. These two gages are located directly upstream of the Chain of Lakes and provide an excellent measure of the inflow into the lakes; however, they do not provide the forecasting lead time needed for efficient operation of the dam during floods and high flows. Two gages in the northern portion of the watershed, at Mukwonago and Waukesha, potentially provide a longer lead time for forecasting, but they collectively record streamflows from only 16 percent of the watershed.

Because the stream gages in the watershed do not provide both lead time and an estimate of the total streamflow into the Chain of Lakes, a flow forecasting system involving computer modeling of the rainfall-runoff processes in the watershed is needed for use in dam operation. Most other applications of flow forecasting systems make predictions of flow conditions for short lead times, almost always less than 24 hours and typically 6 hours or less. These systems use real-time forecasting methods with data collection systems that immediately measure precipitation and streamflow conditions, and prepare a forecast within minutes or hours after a rain event. Many of these systems are needed to predict when evacuation of residents living along the river will be necessary.

Along the Fox River there is a much greater need for longer flow forecasts, for as much as one week in advance. The need for a longer flow forecast is related to the river's relatively slow runoff response to precipitation events, which is influenced by two factors: the significant amount of water storage in the watershed, associated with its numerous wetlands and lakes, and the gentle gradient of the Fox River.

Figure 3 shows an example of the runoff from the first four regions of the watershed resulting from a uniform 1-inch runoff event, as estimated by the FRF Model.

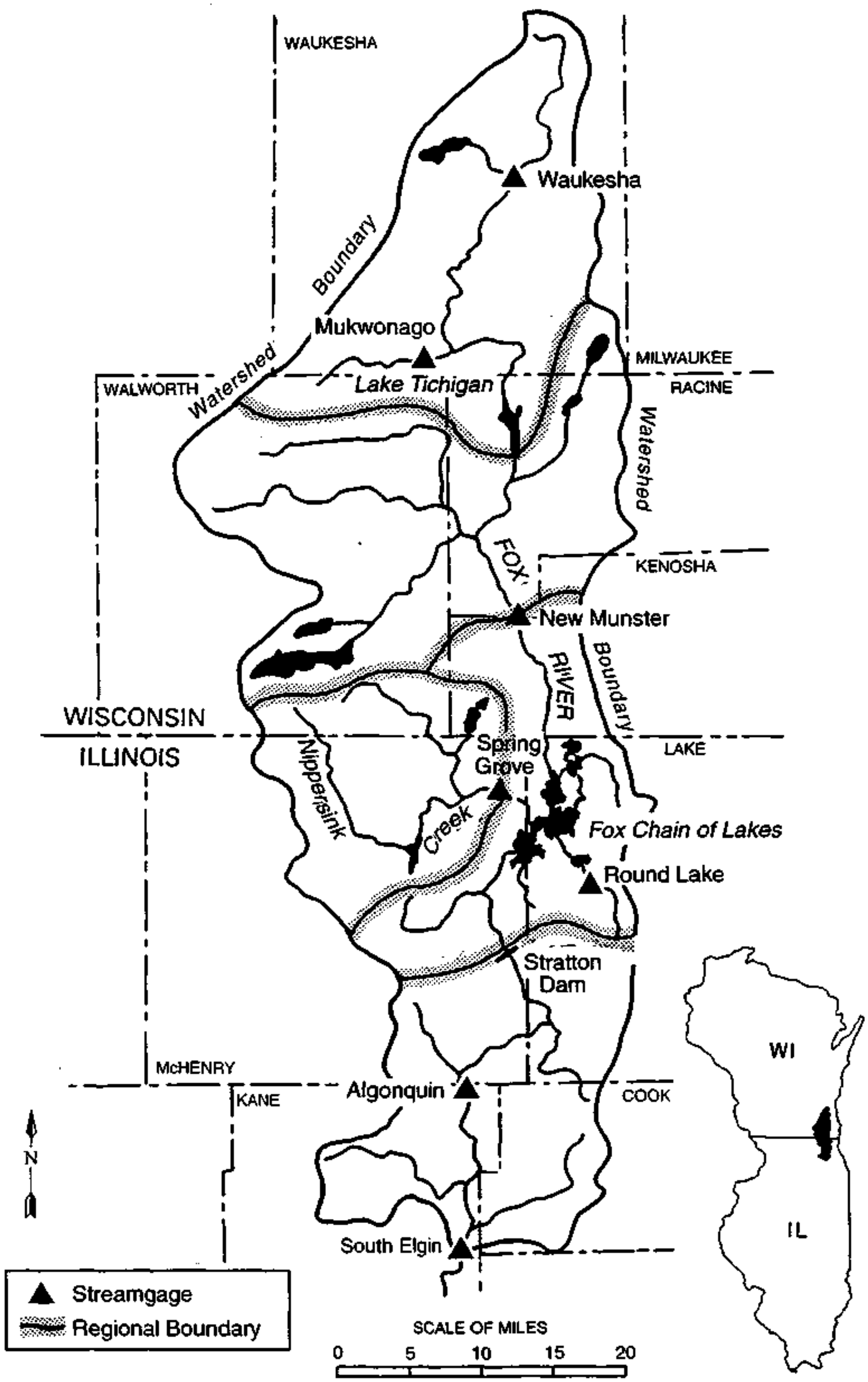


Figure 1. Map of the Fox River watershed.

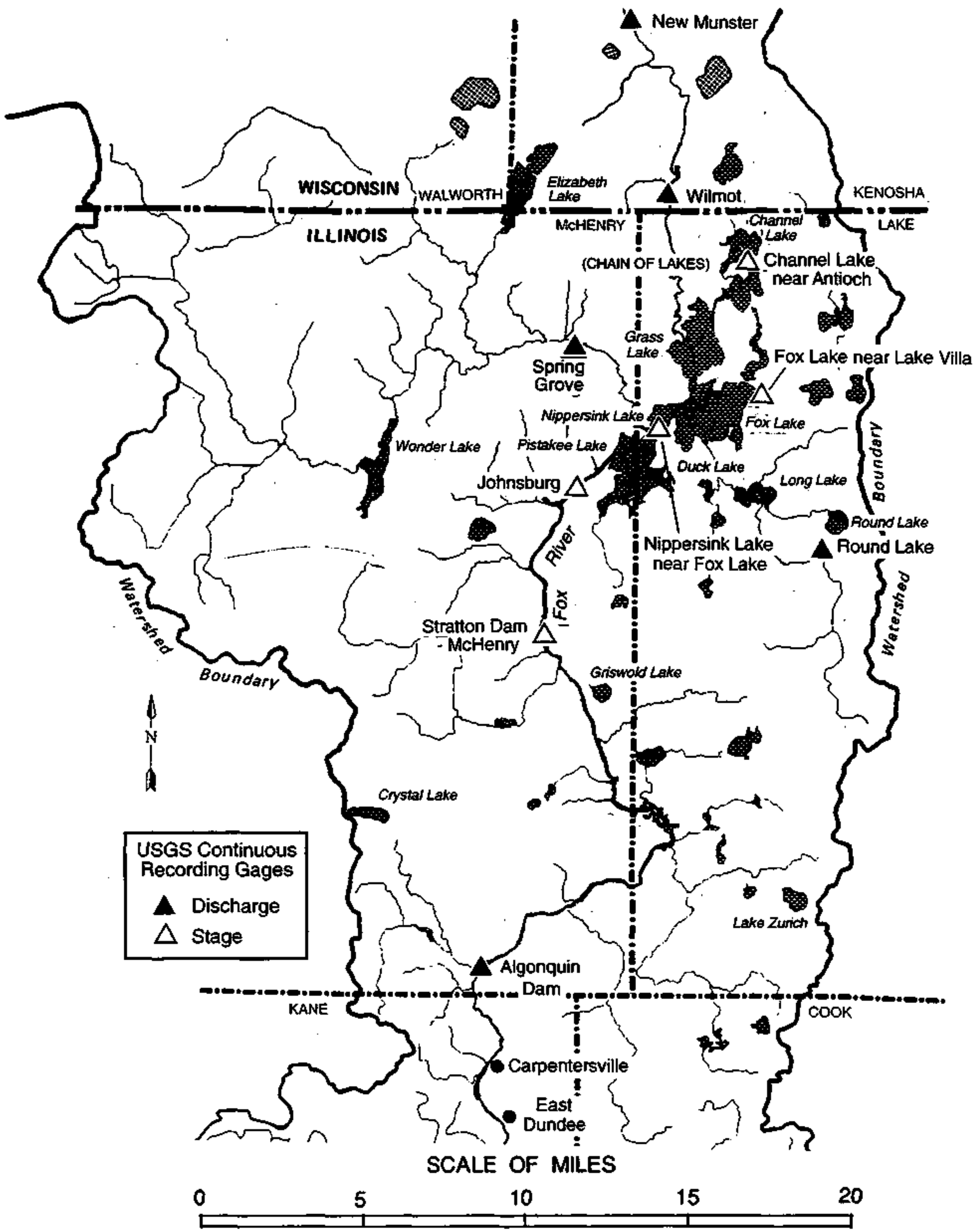


Figure 2. Location of the Chain of Lakes, Fox River, and streamgages.

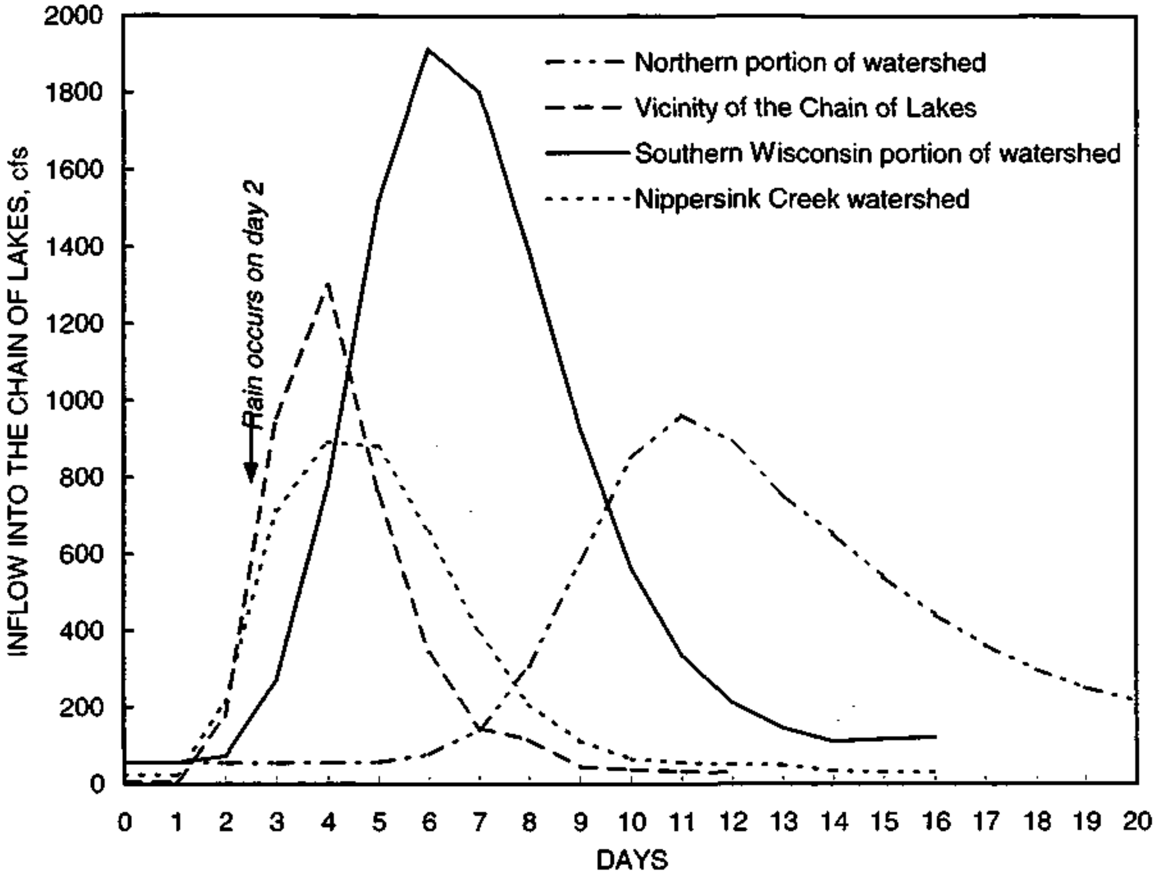


Figure 3. Streamflow from various regions of the Fox River watershed resulting from a uniform 1 inch runoff event (unit hydrograph).

Figure 3 illustrates that much of the volume of flow during flood events comes from Wisconsin and does not reach the Chain of Lakes for three to six days following a rainfall. A sizable portion of the streamflow originating from the northern part of the Fox River watershed may not reach the lakes until over a week after a rainfall event. The southern Wisconsin portion of the watershed represents approximately 40 percent of the watershed area and runoff volume upstream of Stratton Dam.

Given the runoff response of the Fox River watershed, it is possible to make changes in the dam operation within a day following a precipitation event and still take advantage of most of the flood reduction capability provided by the dam. By using precipitation data that has been measured within a 24-hour period, termed as near real-time forecasting, more common daily precipitation gages can be used to provide input into the model. These daily precipitation gages can provide a more complete coverage of total precipitation over the watershed without the need for installing a network of recording precipitation gages with telemetry.

STRATTON DAM AND CURRENT OPERATION GUIDELINES

Description of Stratton Dam and Outlet Facilities

Stratton Dam is located on the Fox River approximately 7 miles downstream of the Chain of Lakes (Figure 2). Flow from the lakes is primarily controlled from the dam; however, there are natural controls in the size of the channel between the lakes and the dam that limit the amount of outflow from the lakes under certain high flow conditions. Outflow from Stratton Dam occurs either over the spillway, which is 282 feet wide, or under five sluice gates, each of which is 13.75 feet wide. The crest elevation of the spillway is at 736.76 feet above mean sea level (ft-msl). The sluice gates can be opened to a maximum height of 9.0 feet above their sill elevation of 731.15 ft-msl. The relationship between gate settings and discharge from the dam is described in Fisk (1988).

During the summer season, the headwater pool level at the dam is normally kept approximately 3 inches above the spillway crest (an elevation of 737.0 ft-msl), allowing flow over the spillway. During the winter season, the target water level at the dam is 2 feet below the spillway crest (an elevation of 734.76 ft-msl), and all flow is through the sluice gates except during flooding conditions. During normal flow conditions, the lakes maintain a flat pool so that the pool elevations in the upper lakes (including Fox Lake, Nippersink Lake, Grass Lake, and Channel Lake, as shown in Figure 2) are only slightly higher than that at the dam.

When the sluice gates are fully open, the flow from the dam is primarily controlled by the headwater stage, or the height of water upstream of the dam. For example, to achieve an outflow of 3000 cubic feet per second (cfs), which approaches the maximum amount of flow that can be contained within the banks of the river downstream, it is necessary for the headwater stage to be at least as high as the spillway crest. If the hinged-crest gates were fully opened, the headwater stage could not be maintained at that level for any substantial period of time, unless a 1-foot gradient existed between the dam and the upper lakes so the stages in the upper lakes were approaching an elevation of 738.0 ft-msl, or roughly 0.5 foot below flood stage. This factor limits the ability of the dam to release water in advance of oncoming floods because the lake levels first must increase before a significant amount of release can be achieved.

The installation of an additional, hinged-crest gate at Stratton Dam was proposed by the U.S. Army Corps of Engineers (1984) to increase the outflow from the dam at lower headwater stages, thus potentially decreasing the flooding upstream associated with a particular outflow rate. The Corps of Engineers also recommended the development of a flow forecast model for Stratton Dam that would be used for operation of this new gate facility. The hinged-crest gate is expected to be 50 feet wide; when in use it will increase the cross-sectional area of flow through all gate structures by almost 75 percent. Other factors, such as the conveyance of the Fox River channel upstream of the dam and the tailwater stage below the dam, will impact the overall increase in discharge provided by the hinged-crest gate. Installation of a hinged-crest gate at the Algonquin Dam, located

17 miles downstream of the Stratton Dam, also was recommended to improve the overall conveyance through the Fox River/Chain of Lakes system. The performance of the proposed hinged-crest gates during flood conditions was evaluated by Knapp and Ortel (1992).

Current Operation Guidelines

The guidelines used to operate Stratton Dam are described in a report by the Illinois Division of Water Resources (1993), which is now the Office of Water Resources in the Illinois Department of Natural Resources. The following material is excerpted from that report.

Operations at Stratton Dam are divided into four operational categories, as defined by the amount of inflow into the Chain of Lakes system. These categories are listed in Table 1. Inflows are calculated as the summation of flows measured at the two streamgages on the Fox River near New Munster (formerly located at Wilmot) and Nippersink Creek near Spring Grove. These gages are located in Figure 2. The water level in the upper lakes, such as provided by the stage gages on Fox Lake or Channel Lake, also is used for determining flood flow operations.

In addition to the four categories listed in Table 1, there are separate operation guidelines for two transition periods: the winter drawdown and the transition from winter pool to summer pool. Also there are special flow-release considerations in mid-winter when ice jams occur on the river.

Normal and Low Flows

During normal flow operations, the outflow from Stratton Dam is approximately equal to the inflow, i.e., that flow needed to keep nearly constant lake levels at the summer recreational pool or the winter pool. Low flow operations follow the instream flow criterion developed by the Illinois State Water Plan Task Force (1983). In accordance with these standards, there is a gradual reduction in the minimum flow release from Stratton Dam as the inflows become less with an overall minimum release of 89 cfs. This overall minimum flow rate corresponds to a minimum gate opening of 0.1 foot.

Table 1. Operational Categories for Stratton Dam

Category	*Chain of Lakes inflows (cfs)*	*Frequency of occurrence (percent)*
Low Flow	less than 240	25
Normal Flow	240 to 960	55
Flood Warning	960 to 3000	18
Flood Flow	above 3000	2

Flood Warning

When the total inflow into the lakes exceeds 960 cfs, operation of the dam is considered to be in flood warning. Typically, true flood conditions will occur only during a small portion of that time. While inflows remain below 1800 cfs, operation of the gates remains the same as during normal flow, with inflows equal to outflow to maintain a nearly constant pool level. When inflows exceed 1800 cfs, dam operation initially may attempt to keep outflows at 1800 cfs so boat traffic on the river and in the Chain of Lakes can be maintained. When the dam outflow exceeds 1800 cfs, the river is subject to no-wake conditions, in which motor boats may not operate in a manner to create a wake, which could cause wave-induced damages along the shoreline.

If flood flow operation is not warranted, but inflows cause the lake levels to rise more than 0.5 foot above the summer pool, the outflow from the dam typically will be increased above the 1800 cfs level. The river and lakes will be closed to boating when the outflow reaches approximately 2250 cfs. The pool elevation in the upper lakes normally associated with mis discharge is approximately 738.0 ft-msl. Much of the operations above discharge levels of 1800 cfs are described in the section, Common Operation Practices not Explicitly Stated in the Guidelines.

Flood Flows

Flood damages on the Fox River begin about the time the outflows from the Stratton Dam exceed 3000 cfs. Thus, flood-flow operation is typically initiated when the inflows to the lakes exceed 3000 cfs. However, flooding conditions will not be reached in the upper Chain of Lakes until stages approach 738.5 ft-msl, or roughly 1.5 feet above the summer pool. Because of natural controls in river conveyance, outflows from the Chain of Lakes and Stratton Dam ordinarily will not exceed 3000 cfs until stages in the upper lakes approach 738.0 ft-msl. Flood flow operation guidelines are designed so the operation of the Stratton Dam gates will not directly induce flooding downstream, except when the flow forecast model indicates the approach of extremely high flows and an almost certain probability of downstream flooding.

Flow forecasts from the FRF Model currently are used for initiating flood flow operation as follows:

- If the peak flow forecast exceeds 3000 cfs, the Stratton Dam sluice gates are opened to 2.5 feet to increase flows to the maximum amount that does not create no-wake restrictions (1800 cfs). The gate opening may be increased as necessary to maintain this outflow rate.
- If the peak flow forecast exceeds 6000 cfs, the sluice gates are opened fully to allow the maximum possible outflow. This guideline also would apply to the proposed hinged-crest gate.
- For every 0.5 foot increment that the upper lakes exceed summer pool, the forecast flow needed to fully open the gates would decrease by 500 cfs. For

example, if the upper lakes are at an elevation of 737.5 ft-msl, or 0.5 foot above the summer pool, all gates would be opened fully when the peak flow forecast exceeds 5500 cfs.

Winter Drawdown

During the winter season, the water level at the dam is drawn down about 2 feet, which normally causes an 18-inch drawdown in the upper lakes to an elevation of about 735.5 ft-msl. The drawdown to the winter pool level begins on November 1 and continues to December 1 of each year. In previous years, the drawdown began as early as mid-October. There are no specific guidelines on the rate of the drawdown; but, under normal flow conditions, the outflow from the dam will be increased to 1000-1200 cfs, causing the lake to reach winter pool level in seven to ten days. When above average flows are experienced, the drawdown may be delayed until inflow levels recede or, if necessary, the outflow may be increased.

Transition to Summer Pool

May 1 is the target date for completing the process of raising the lake levels to summer pool (737.0 ft-msl). This coincides with the date for opening the locks at Stratton Dam to navigation. Historically, the transition to summer pool normally has occurred earlier in the year, sometimes as early as in March. The major concern during the spring is that the transition to summer pool should occur when there is a reduced flooding potential. The transition can begin earlier than May 1 when three criteria are met: (1) high flows caused by the spring snow melt and ground thaw must have passed, (2) the inflow must have dropped below the long-term annual mean flow rate of 685 cfs, and (3) there must be no precipitation indicated in the 48-hour quantitative precipitation forecast (QPF).

Ice Jams

During severe cold spells each winter, ice jams occur on the Fox River near East Dundee, 20 miles south of Stratton Dam. Unless the flow in the river is kept low during these periods, generally below 1100 cfs, these ice jams can cause river levels to rise above flood stage. If the inflow into the Chain of Lakes during these periods is greater than 1100 cfs, some flow will be retained in the lakes to prevent flood stages downstream, as long as such retention does not lead to flooding problems in the lakes.

Common Operation Practices not Explicitly Stated in the Guidelines

The operation guidelines do not state how or if the gate levels will be increased if the forecast is in the range of 3000-6000 cfs and water levels continue to rise. Following the operation guidelines, it is expected that, with these conditions, the gates would already be open to 2.5 feet, providing outflow rates of 1800 cfs.

Based on observed operations, increases in the outflow at Stratton Dam occur mostly in response to levels in the upper lakes, and to a lesser degree on recent precipitation events. During the summer recreational season, the outflow from the lakes typically has been increased above 1800 cfs as the upper lake levels become more than about 0.75 foot above the summer pool (at roughly 737.75 ft-msl). When the upper lake levels begin to exceed 738.0 ft-msl, outflows are increased to the range of 2800-3000 cfs.

When the outflows exceed much more than 3000 cfs, the river downstream of the dam no longer may be contained within its banks, and damages may be incurred. For this reason, outflows exceeding roughly 3000 cfs will not be released until flood levels are reached in the upper lakes, or when it appears imminent that the lake levels may surpass 738.5 ft-msl. This has occurred when the lake levels were as low as 738.3 ft-msl. Even as outflows are increased under these conditions, there may be relatively little flow over the spillway because water levels at Stratton Dam often will be a foot lower than levels in the upper lakes.

During winter pool conditions, the increase in outflows from the dam above 1800 cfs will be initiated at lower elevations, and typically will begin when the upper lake levels become approximately 736.6 ft-msl. Increasing outflows during these winter pool conditions frequently will require increasing the gate settings so free weir flow under the sluice gates is occurring. Outflows usually will reach 3000 cfs when the upper lakes start exceeding the summer pool level (at about 737.2 ft-msl).

When there is a major precipitation event, typically greater than 2 inches in the summer or 1 inch in the spring, gate openings may be increased to reduce the lake levels in anticipation of local and watershed flooding, which could result from the rainfalls. If the lake stage is already high when the precipitation occurs, this release may increase outflows above the bank full discharge level, if the potential for flooding appears to be high. Use of flow forecasts for gate operation possibly could eliminate the use of precipitation data for operations, if the forecasts are accurate enough to reliably estimate the runoff associated with that precipitation.

Range of Operation Guidelines Analyzed in this Report

Use of flow forecasting during low or normal flow operations generally is not needed because no advantage in dam operation is gained by knowing these flow conditions in advance. Therefore, this study focused on the use of forecasting on flood warning and flood flow conditions. Because flow forecasts are not 100 percent accurate, the probability of forecast error and its impact on operations must be evaluated. Other data available on a near real-time basis, such as lake levels and flows observed at streamgages, play a crucial role in verifying the general accuracy of the forecast during flood warning and can be used directly in operation decisions, as evaluated later in this report.

EVALUATION OF AVAILABLE PRECIPITATION DATA FOR USE IN FLOW FORECASTING AND OPERATIONS

Three basic categories of precipitation are available for use in flow forecasting using the FRF Model: (1) that measured at precipitation gages located in and near the watershed, (2) precipitation estimated from radar data, and (3) quantitative forecasts of expected precipitation during the next 24 to 48 hours. There are two basic concerns when analyzing the usefulness of precipitation data: accuracy in both the precipitation data and the resulting streamflow forecast, and the lead time of the forecast. The precipitation gaging network provides accurate rainfall at the point of measurement; but only a few gages have telemetry, and there may be considerable delay before this data is available. Also there is the concern about whether this location-specific data provides the best spatial estimate of watershed precipitation. Radar-based data can provide a spatial estimate of the precipitation in a timely manner, but it may lack the accuracy of gage measurements. Quantitative precipitation forecasts provide the greatest amount of lead time, but they introduce considerable uncertainty into the streamflow forecasting process.

Present Precipitation Gaging Network

Figure 4 presents the location of precipitation gages in and near the Fox River watershed that were active as of November 1998. Two of these gages, New Munster and Spring Grove, are located at U.S. Geological Survey streamgages and provide real-time data during the warm season of the year, when the probability of freezing is low. The Milwaukee and McHenry gages are recording gages that provide year-round, real-time data. The other gages shown in Figure 4 are measured daily.

The gages that provide near real-time data, as reported daily by the Midwestern Climate Center (MCC) in August 1997, are given in Figure 4. Over time there has been some variability in the number and location of gages that provide near real-time data. The Waukesha, Union Grove, Sullivan, Dousman, Whitewater, and Germantown gages only recently began providing near real-time data. The Oconomowoc gage previously provided this data, but the reporting of data was discontinued in the summer of 1997. As a result of ongoing changes such as these, the forecast model may need periodic adjustments to account for the available precipitation data.

The reliability of reporting from the precipitation gages also should be considered in the forecasts. The Milwaukee gage provides precipitation data with virtually 100 percent reliability. Daily data from the McHenry gage is not reported by the MCC with 100 percent reliability; however, these data are available directly to IDNR-OWR, which operates the gage. Most of the other stations reported by the MCC have data available for only 60-90 percent of all possible days. One of the least reliable gages in reporting data is that at Burlington. Unfortunately, the Burlington gage is one of the most important gaging sites in the watershed, in that it is the only gage near a large portion of the watershed in Wisconsin. Obtaining a reliable rainfall estimate from this central portion of

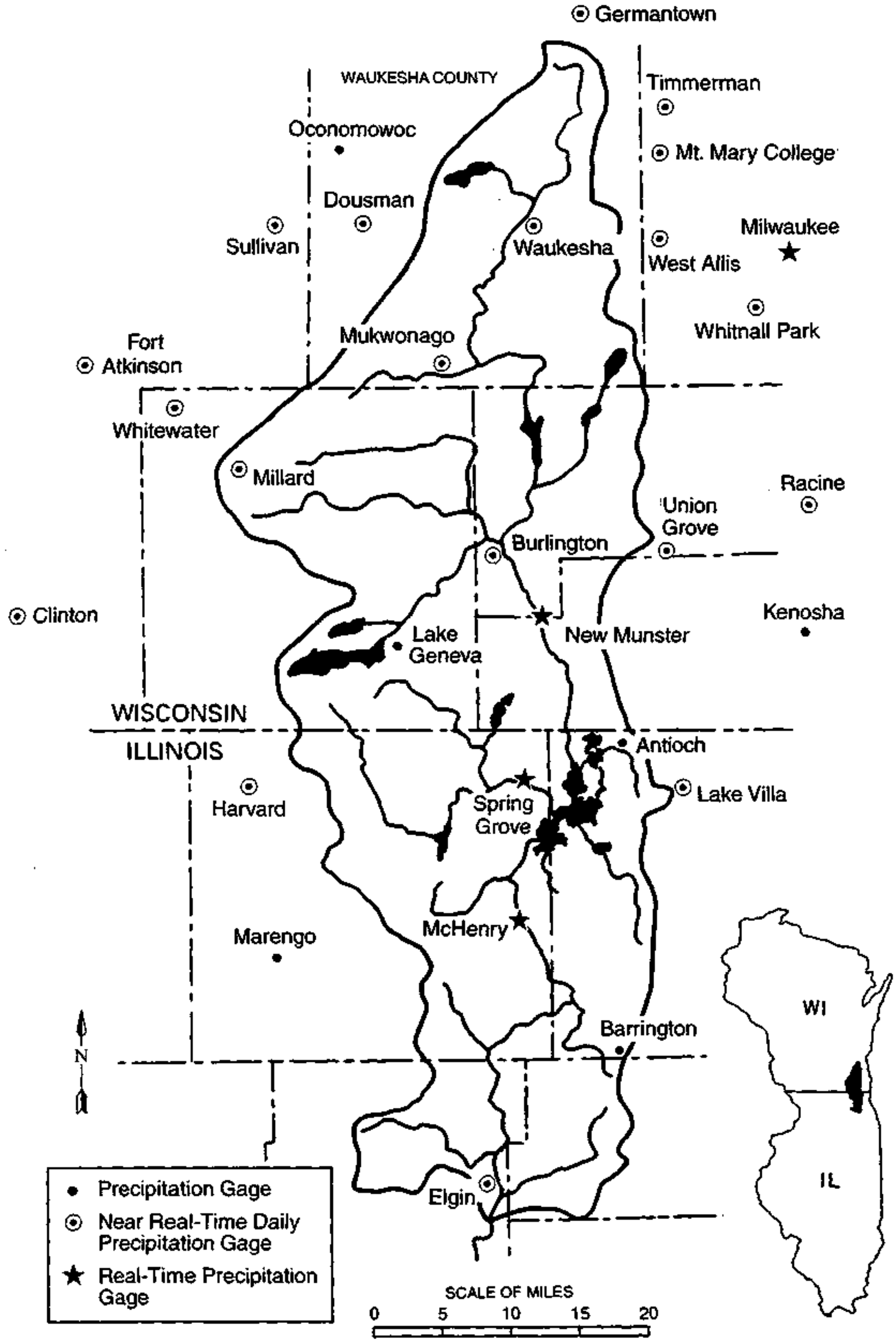


Figure 4. Active precipitation gages in and near the Fox River watershed as of November 1998.

the watershed, either from the Burlington gage or from a new gage, should be a priority for maintaining accurate forecasts.

For the eastern and southern portions of the Fox River watershed, the available gages provide precipitation data for roughly every 50-100 square miles and provide a good density of coverage for estimating watershed precipitation. In the northern and western portions of the watershed in Wisconsin, the gage density is reduced to about 200 square miles per gage. The impact of gage density on the estimation of watershed precipitation is discussed in the following section.

Estimating Watershed Precipitation from Measured Precipitation

The estimation of watershed precipitation usually produces one of the largest errors in the flow forecasting process. The best way to improve the spatial description of the precipitation that occurs over a watershed, and thus improve the flow forecast, is to increase the density of the precipitation gages. The placement of gages also can have a significant impact on how well the watershed precipitation is estimated.

Fontaine (1991) examined the influence of gage location on the estimation of the watershed's areal mean precipitation (AMP) for two extreme rainfall events. Fontaine indicated that a centrally located gage normally provided the best estimate of the AMP for a small watershed. However, as the size of the watershed increased, a set of gages located on the periphery of the watershed provided better estimates, and the relative accuracy of the centered gage arrangement was reduced. These results do not mean that the presence of a gage in the center of a larger watershed is necessarily undesirable; rather there is greater error when one gage within the watershed is given an inordinate weight in the estimate of the AMP.

Fontaine (1991) also compared the AMP using a standard rain gage density (192 square miles per gage) with that for a density of 96 square miles per gage and found that the more dense network had less than half the AMP error compared to the standard gage density. An additional finding was that there was a bias to underestimate the AMP with the less dense gage network.

Huff (1970) analyzed the general relationship between the gaging network and the error in the estimate of the AMP and found that the error varies based on the gage density, mean precipitation, storm duration, total area of the watershed, season, and storm type. Based on Huff's findings, the error increases with shorter storm duration, smaller drainage area, higher precipitation rates, and a less dense gaging network. According to Huff's formulae, when the gage density is increased from 192 to 96 square miles per gage, the error in the precipitation estimate will be reduced by 44 percent.

Neither of the above studies examined the impact of precipitation estimation error on the calculation of watershed runoff. However, numerous other literature and applied studies indicate that errors in estimating the watershed precipitation will be magnified when calculating watershed runoff.

Use of Radar-Based Estimates of Precipitation

Radar-based precipitation (RP) estimates offer the potential to estimate spatial differences in precipitation across the watershed without the need for a dense gaging network. The NEXRAD radar system provides more spatially detailed and frequent measurements than precipitation gages, and with reliable ground-truthing (i.e., the matching of radar estimates to measured precipitation amounts) the use of this information should be able to improve the estimate of watershed precipitation.

Review of Other Studies Comparing RP Estimates with Gaged Precipitation

Fortune et al. (1995) compared RP estimates with raingage measurements in the Chicago area using seven cool-season stratiform rain events. They found that the comparison was poor when either the radar or the gage reported small rainfall amounts (less than 0.1 inch). Fortune et al. found that the radar precipitation estimates tended to underestimate the measured precipitation, on average, by 20 percent. In about half of the samples, the measured precipitation was over twice that as the RP estimates. These tended to be events with smaller amounts of precipitation. Fortune et al. also found a definite change in the gage to the radar precipitation ratio at a distance beyond 50 km (31 miles) from the radar, with the amount of underestimation increasing linearly with distance from the radar. They identified the underestimation as being related to an incorrect adjustment in one of the adaptive parameters used to define the radar estimate from gage data. They concluded that the Z-R relationship (the ratio between precipitation and the radar reflectivity) used is one that is more appropriate for convective rainfall. They also concluded that the change in the gage-to-radar ratio with distance could be caused by the choice of the elevation angles used in the Precipitation Processing Subsystem (PPS) with the NEXRAD algorithm.

A similar study was conducted by Klazura and Kelly (1995), who examined the gage-to-radar precipitation ratios for 23 events in Oklahoma. The stratiform precipitation events examined by Klazura and Kelly exhibited significant underestimation by the RP estimates by an average of 70 percent. The degree of underestimation was smallest in the range of 50-100 km (31-62 miles) from the gage, and increased both nearer gage and farther from the gage. For warm-season, convective rainfall events, there generally was good comparison between the radar estimates and gage precipitation, with the radar estimates overestimating gage precipitation by approximately 10 percent. The amount of overestimation increased with distance from the radar.

Evaluation of RP Estimates for the Chain of Lakes Watershed

Radar-based precipitation estimates for the northeastern Illinois and southeastern Wisconsin area were obtained from the Weather Services International (WSI)

Corporation (Billerica, MA) by way of public access across the Internet, specifically through the Intellicast web page for Chicago (http://www.intellicast.com). Precipitation data were obtained for selected storms from August 1995-March 1998. Twenty-four-hour precipitation amounts were obtained to match the daily rainfall amounts available at most raingages. In the earlier part of the 1995-1997 period, the procurement of the RP estimates for major storm events was problematic. The major storm data frequently were not loaded to this site; and, in some cases when it was, the precipitation estimates were provided only for short periods during the storm. But over time, the regular availability of the RP data has improved significantly. In all, RP estimates for more than 50 precipitation events were gathered. Nineteen of the events had either measured precipitation amounts or RP estimates in excess of 0.5 inch, and these events were used in the following analysis.

Comparisons between the RP estimates and measured rainfall were made for each event at six gaging locations in or near the Chain of Lakes watershed: Mt. Mary College, Oconomowoc, Burlington, Harvard, Lake Villa, and McHenry (Stratton Lock and Dam). The time of measurement for the Oconomowoc, Lake Villa, and Mt. Mary College gages did not match that of the RP data (7 a.m.); therefore, in some cases the measured precipitation from the previous day was used for comparison. The results from these three stations are similar to those for the remaining three stations. Figure 5 compares the RP estimate and the measured precipitation at these six gages for all storms used in the analysis.

The average ratio between the RP estimate and the measured precipitation (the R/G ratio), for the selected 19 events and 6 gaging locations, was 1.78. The RP estimates overestimated the measured precipitation in 78 percent of the gage comparisons. Variations in the R/G ratio between gages also were examined; and, although there were differences in the average ratio for each gage, these did not appear to be related to distance from the radar or any other easily identified geographic pattern. The Mt. Mary College and Lake Villa gages had the smallest average R/G ratios, 1.52 and 1.58, respectively. The Harvard gage had the highest average R/G ratio, equal to 1.99.

Each R/G ratio was differentiated by season. The tendency for the RP estimates to overestimate precipitation was greatest during summer events (June through August), with an average R/G ratio of 2.14. The RP estimates underestimated precipitation during the winter season (November through February), with a ratio of 0.88. This winter ratio closely matches the findings of Fortune et al. (1995) for cool-season stratiform events. The R/G ratios for the spring and fall seasons were 1.53 and 1.94, respectively.

Table 2 compares the radar precipitation estimates with the observed precipitation for the eight largest storms for which complete data were obtained. For most events the RP greatly overestimates the measured precipitation. In most cases the RP estimates give a reasonable representation of geographic differences in the rainfall, even when the absolute magnitude of the RP estimates may be poor. The average R/G ratio for these eight large events, 1.82, is not much different than the ratio for all storms. The RP

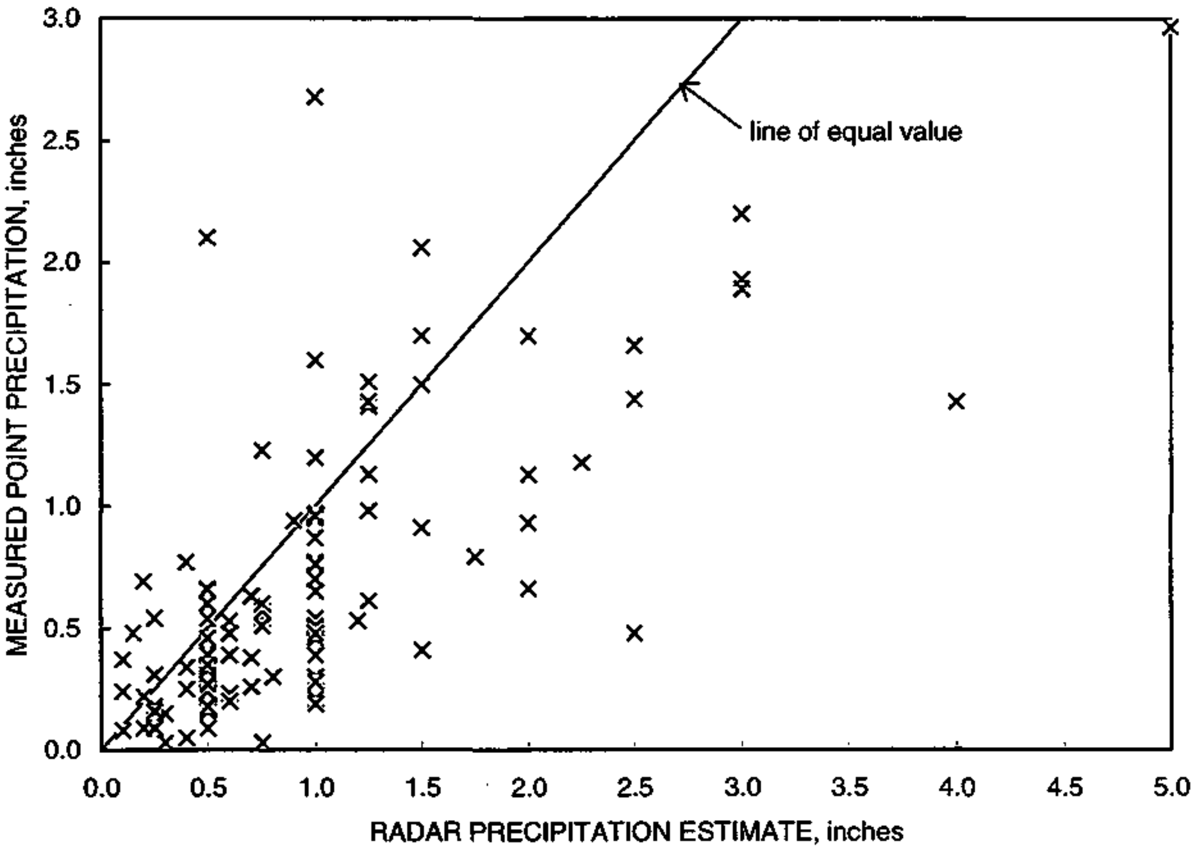


Figure 5. Comparison of radar-based precipitation estimates and measured precipitation for selected gages in the Chain of Lakes watershed.

estimates for two events, February 21, 1997, and May 1, 1997, compare favorably with the measured precipitation.

Examples of Error in the Flow Forecast Using RP Estimates

The FRF Model was used to produce flow forecasts for the May 10, 1996, event using three types of precipitation estimates: (1) the RP estimates, (2) measured precipitation, and (3) a combination of the two. Figures 6 and 7 show flow forecasts developed using these three types of precipitation data compared with the observed streamflow at two locations: the Fox River near New Munster and Nippersink Creek near Spring Grove. In general, the flow forecasts based on the measured rainfall compare favorably with the observed flows, although the forecasts for the Spring Grove gage are somewhat high. The RP estimates are considerably higher than the measured precipitation. Thus, the flow forecasts using the RP estimates significantly overestimate the eventual flow. Based on the present operation guidelines, the inflow forecast for the Chain of Lakes using the May 10 radar precipitation would be almost great enough to warrant the onset of flood flow operations. In other words, this would be close to

Table 2. Comparison of Radar-Based Precipitation Estimates (RPE) and Measured Precipitation (MP) for Eight Major 24-Hour Events

Location	*RPE (inches)*	*MP (inches)*	*R/G ratio*	*RPE (inches)*	*MP (inches)*	*R/G ratio*
	August 29, 1995			*May 10, 1996*		
Mt. Mary College	1.5	1.85	*0.81*	2.2	0.86	*2.56*
Oconomowoc	2.2	0.71	*3.10*	2.0	0.93	*2.15*
Burlington	2.0	0.84	*2.38*	2.0	1.70	*1.18*
Harvard	1.0	0.19	*5.26*	2.5	1.44	*1.74*
Lake Villa	1.0	0.66	*1.52*	3.0	1.93	*1.55*
McHenry	0.6	0.22	*2.73*	2.5	1.66	*1.51*
	July 18, 1996			*October 17, 1996*		
Mt. Mary College	2.5	0.48	*5.21*	0.8	0.51	*1.57*
Oconomowoc	2.0	0.66	*3.03*	2.0	1.13	*1.77*
Burlington	4.0	1.43	*2.80*	1.5	0.41	*3.66*
Harvard	3.0	1.89	*1.59*	1.5	0.91	*1.65*
Lake Villa	5.0	3.11	*1.61*	1.0	0.76	*1.32*
McHenry	3.0	2.20	*1.36*	1.0	0.51	*1.96*
	February 21, 1997			*May 1, 1997*		
Mt. Mary College	1.0	1.02	0.95	0.9	0.94	*0.96*
Oconomowoc	1.3	1.41	*0.92*	1.0	1.20	*0.83*
Burlington	1.3	1.13	7.75	1.0	0.97	*1.03*
Harvard	1.3	1.43	0.97	1.0	0.87	7.75
Lake Villa	1.5	1.70	*0.88*	1.2	1.51	*0.79*
McHenry	1.5	2.06	*0.73*	1.0	0.96	*1.04*
	September 17, 1997			*March 31, 1998*		
Mt. Mary College	1.4	0.73	7.92	1.0	1.10	0.97
Oconomowoc	1.0	0.65	*1.54*	2.0	2.36	*0.85*
Burlington	2.5	1.91	7.37	0.5	0.62	*0.81*
Harvard	1.8	1.81	*0.99*	0.3	0.70	*0.43*
Lake Villa	1.5	1.22	*1.23*	0.5	0.52	*0.96*
McHenry	1.5	1.37	7.09	0.5	0.74	*0.68*

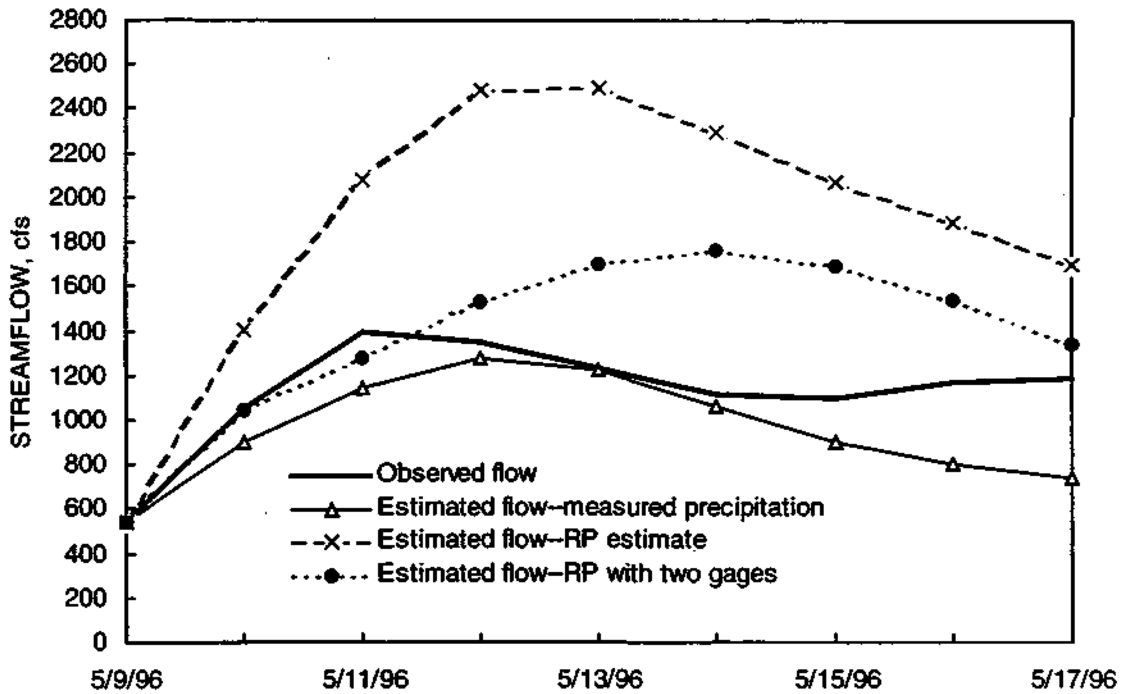


Figure 6. Comparison of observed streamflows and estimated flows using three types of precipitation data; Fox River near New Munster May 9-17, 1996.

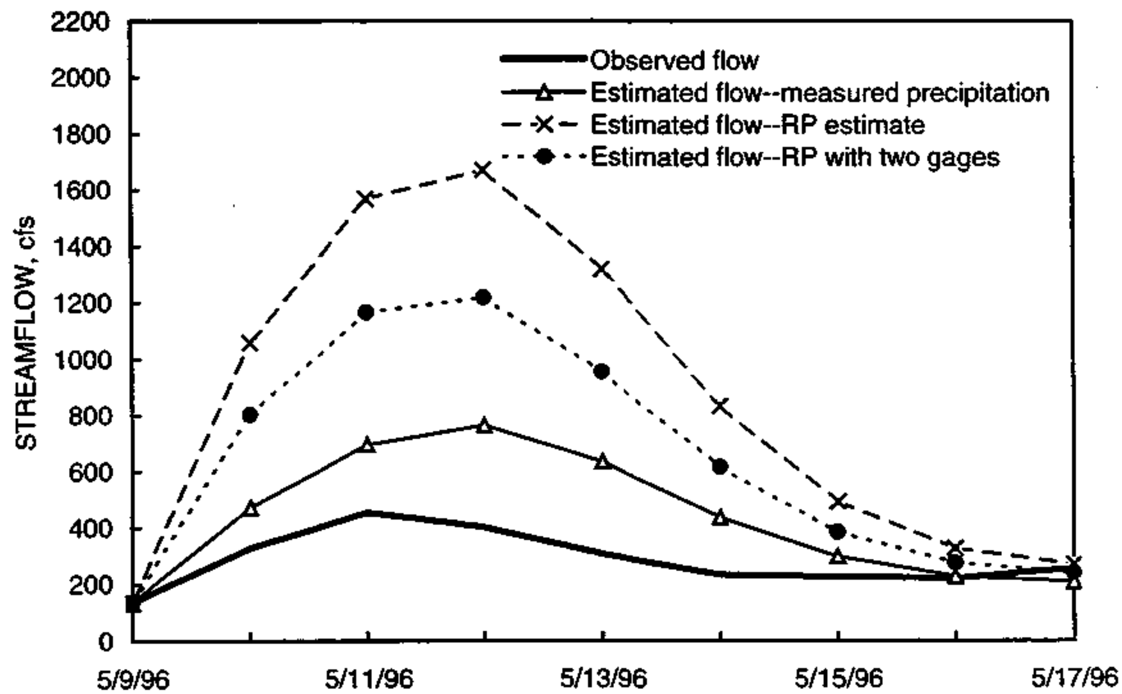


Figure 7. Comparison of observed streamflows and estimated flows using three types of precipitation data; Nippersink Creek near Spring Grove May 9-17, 1996.

creating a "false alarm" that flood conditions were impending. Subsequent rainfall events later that month did in fact bring the Chain of Lakes close to flood conditions, but that is not relevant to this comparison.

Combined Use of RP Estimates and Measured Precipitation for Flow Forecasting

The information from areal RP estimates and measured precipitation were combined by using measured precipitation values from the Milwaukee and McHenry precipitation gages to adjust the RP estimates. The measured data were used to determine the average R/G ratio for each precipitation as well as the north-to-south variation in the R/G ratio. For example, if the R/G ratio at Milwaukee were 1.3 and the ratio at McHenry were 1.6, the ratio along a line halfway between these two points would be estimated as 1.45. Areal precipitation amounts for all subwatershed units in the Chain of Lakes watershed then were estimated from the RP image using the computed R/G ratio for each location.

The accuracy of the flow forecast simulation using the adjusted RP estimates is much better than that using radar data only, but overall still not as good as that using measured precipitation data only (Figures 6 and 7). It was concluded that a more refined estimate of the R/G ratios would be necessary for combined use of the RP data with measured precipitation. In other words, more measured precipitation data is necessary to better define the areal watershed precipitation.

The use of only two gages to estimate the R/G ratios for the entire watershed was designed to most closely reproduce the present real-time forecasting capability of the watershed. Only the McHenry and Milwaukee gages have recording gages that can provide year-round, real-time precipitation data; these are also the two gages for which daily data are available virtually 100 percent of the time. As more measured precipitation data are used, the flow forecasts using the RP data more closely approach the observed flow values. However, the RP flow forecasts were not similar to either the observed flows or the forecasts produced using measured precipitation until five gages were used to define the geographic variation in the R/G ratios. Ordinarily, flow forecasts produced with measured precipitation used data from nine gages.

Conclusions

For the events analyzed, the RP does not provide enough accuracy in estimating watershed precipitation to be useful in flow forecasting for the Fox River. Examination of the RP image with the R/G ratios for nearby gages can be useful in estimating precipitation for missing gage values, and it can be used with measured precipitation to provide an improved estimate of the variation in watershed precipitation. However, RP estimates should not be accepted as a replacement for measured precipitation data. Strategically placed precipitation gages, providing a broad geographic coverage of the watershed, as yet still provide the best information for accurate estimates of watershed precipitation. It is anticipated that future improvements in RP estimates may change this evaluation, and their utility in flow forecasting should be re-examined as these improvements occur.

Use of Quantitative Precipitation Forecasts

The National Centers for Environmental Prediction (NCEP), a division of the National Weather Service, issues quantitative estimates of expected precipitation over time periods ranging from six hours to ten days into the future. The accuracy of these QPFs depends upon the forecasting period, with shorter forecasting periods having greater accuracy. The 24- and 48-hour QPFs are considered in this study for possible use in forecasting streamflows, and they can be obtained from several Internet web servers, including:

- the U.S. Army Corps of Engineers, Rock Island District (http://ncrbkp.ncr.usace.army.mil/docs/qpf.html),
- NCEP (http://www.ncep.noaa.gov/HPC/hpcwks.shtml), and
- the Purdue University Weather Processor (http://wxp.atms.purdue.edu).

Previous Studies

No studies were found that directly compare the relationships between QPFs with the subsequent measured amounts of precipitation. Reed et al. (1997) compared the accuracy of flow forecasts with and without the use of QPFs, as applied to the Arkansas River Basin Forecast Model. The time to peak of the hydrographs being analyzed ranged from 6 to 54 hours. A 24-hour QPF was used in the analysis. When the hydrograph's time to peak was short, use of the QPF provided little improvement in the error of the forecast. When the hydrograph's time to peak was longer, the root mean squared error (RMSE) of the stage forecasts was reduced by 25-30 percent. In general, the QPF improved the estimate of peak flow by approximately 20 percent over those forecasts that assume no additional precipitation will occur.

Reed et al. (1997) also estimated that, even though the model error is improved with use of the QPF, the number of false alarms produced by the model is increased. False alarms are situations in which a flood warning is issued based on the flow forecast, but the flow conditions do not develop into a flood event. To avoid false alarms, they suggest that a flood warning should not be issued for conditions more than 24 hours into the future if the forecasted flood is based only on the QPF. Otherwise, the number of flood events correctly forecasted by the model with and without use of the QPF was identical, but the QPF river forecasts provided more lead time.

Evaluation of QPF Values for the Chain of Lakes Watershed

The QPF data for 46 precipitation events from April 1992-December 1994 were initially analyzed to determine the relationship between the QPF estimates and the subsequent measured precipitation. The IDNR-OWR provided these data. These data were supplemented with QPF data from 30 larger storms from September 1995-May 1997, obtained from the Internet sites listed earlier.

The QPF generally gives little spatial resolution between the northern and southern portions of the Chain of Lakes watershed; and, when spatial differences can be discerned, they generally show less than a 0.25-inch variation in the QPF. Therefore, one value was always used as the average expected rainfall for the watershed. In general, measured precipitation is compared with the 24-hour QPF. In a few cases, when precipitation occurred on consecutive days, the comparison was made between the two-day measured amounts and the 48-hour QPF.

A total of 54 storms was evaluated, 25 of which were above 1 inch as either measured from any one raingage data or using the QPF. The maximum QPF value in this sample was interpolated as 2.25 inches. The maximum observed point rainfall in those storms was 4 inches, and the maximum average precipitation over the Fox River watershed was 2.3 inches.

Figure 8 compares the QPF for these 54 storm events with the average measured watershed rainfall and the maximum measured point rainfall. The average measured watershed precipitation was computed as the unweighted mean of all point rainfall estimates in and adjacent to the Fox River watershed. The values show that the QPF significantly overpredicts the watershed precipitation. For example, when the QPF is 2 inches, the average expected watershed precipitation is only 0.7 inches. The QPF underpredicts the watershed precipitation in only four cases, and in only one of these cases was the average measured watershed rainfall greater than 1 inch. The QPF corresponds much closer to the maximum point rainfall observed within the watershed, as shown in Figure 8b. Still, there is a considerable amount of scatter between the QPF and measured rainfall values, with an average difference of almost 60 percent.

Conclusions

The QPF does not provide very good estimates of the average expected watershed precipitation. However, it generally indicates the potential for heavy rainfall and the possible maximum point rainfall to be expected from a storm, which can be useful for qualitative evaluations of flood potential. The QPFs can provide information on the potential for rainfall for the 48 hours following the forecast, and this information can be used for limited changes in gate operations. But major operation decisions, such as that which would cause flood damages or bring the lakes to no-wake conditions, should not be based on the use of QPFs.

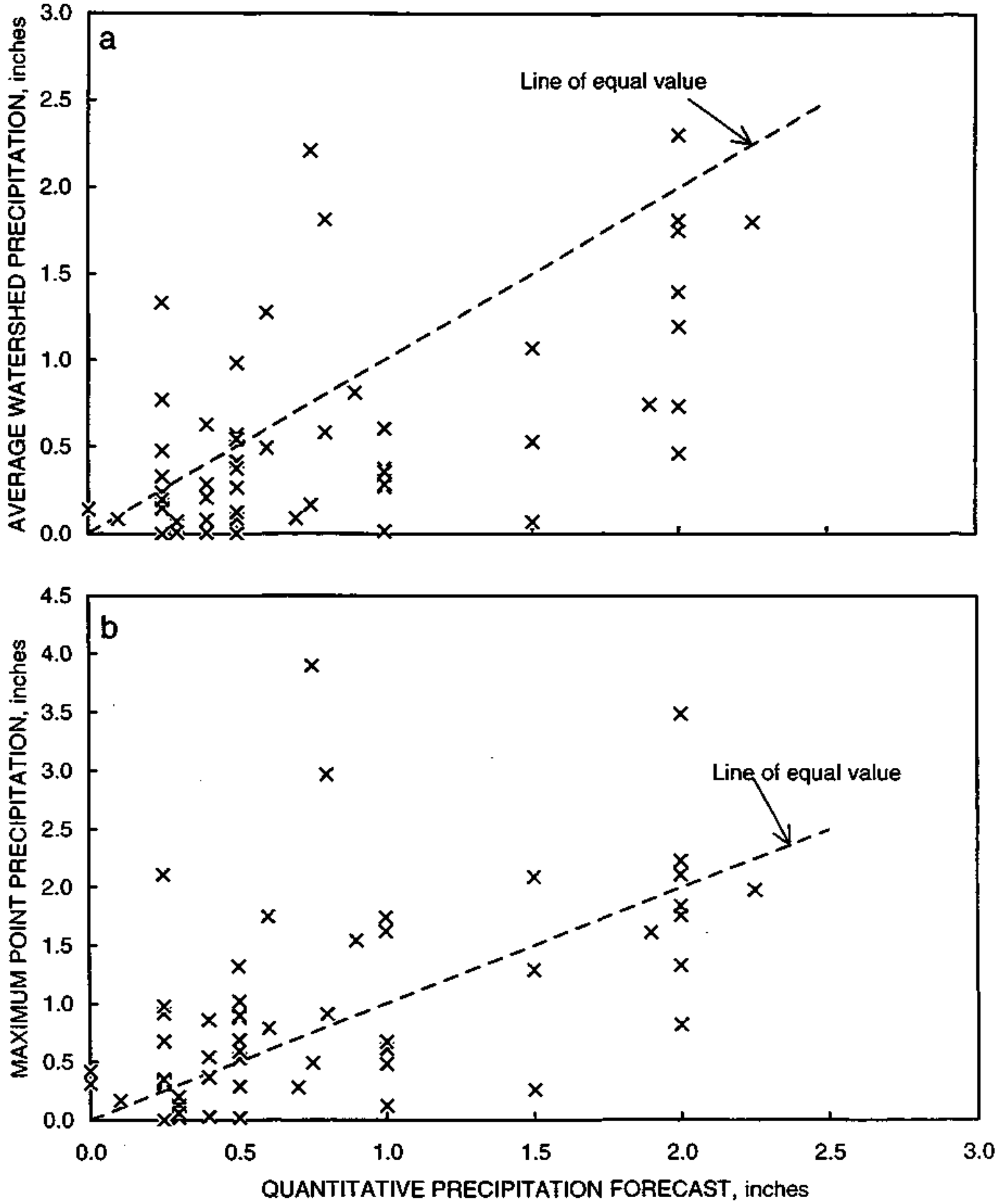


Figure 8. Comparison of QPF estimates for the Fox River watershed with (a) the average measured rainfall from all gages in the watershed, and (b) the maximum measured point rainfall.

Soil moisture, lake and stream levels, the occurrence of frozen soil, and snow accumulation all will influence the amount of runoff that will occur following a given precipitation event. These factors could produce favorable conditions for flooding, which may be identified prior to the rainfall or snowmelt event that eventually produces the flood runoff. The observed state of antecedent hydrologic conditions in the watershed may not necessarily predict that flooding events will occur, but it can provide information on the probability that such flooding may happen in the not-too-distant future, and thus may provide a mechanism to adjust lake levels prior to a potential flooding event.

The FRF Model is designed to produce an estimate of streamflows for up to ten days following the occurrence of rainfall. The flow forecast normally assumes that there is no additional rainfall following either that observed or the 48-hour QPF. Therefore, the flow forecast will be applicable only for the period prior to the next rain event. To be useful, a probability forecast based on antecedent conditions must look beyond the ten-day period forecasted by the model and examine the likelihood that additional rainfall events will occur. The following analysis examines the relationship between the antecedent conditions in the watershed and the flows and lake levels in the two-week period in the future. Five state variables, or parameters, describing the antecedent conditions are used. These parameters, and the sources of data for these parameters, are listed in Table 3. Data on these parameters are available on a near real-time basis and, if needed, could be used for dam operation decisions.

Correlation Analysis

The value of each parameter was computed for the end of each week over the 48-year period, 1948-1995, with the exception of the rainfall and streamflow, which were computed as weekly averages. This created a data series of 2496 values (52 weeks times 48 years) for each parameter. These values then were correlated to the average streamflows for the subsequent two weeks and the lake level at the end of that two-week period. For example, the soil moisture at the end of the first week, January 1-7, was correlated to the streamflows for the next two weeks, January 8-14 and January 15-21.

Table 3. Source of Data for Examining Antecedent Conditions

Parameter	*Source of data*
Average watershed rainfall (inches)	Observed from Midwestern Climate Center
Flow at New Munster gage (cfs)	Observed from U.S. Geological Survey
Average Snowpack (inches)	Observed from Midwest Climate Center
Fox Lake stage (feet)	Observed from U.S.Geological Survey
Average soil moisture over the entire watershed (inches)	Simulated by the Fox River Forecast model

Results of the correlations were segregated by week of the year, so all of the pairs of data for week 1 were pooled together.

The primary purpose of the correlation analysis was to identify a probabilistic relationship between the preceding, or antecedent, conditions and the chance that a flood or high flow event would occur in upcoming weeks. As expected, the data display a strong correlation between preceding streamflow conditions and future flow conditions, as shown by the correlations in Figure 9. In other words, if flows have been high, there is a greater probability they will continue to be high in the next two weeks or further into the future. This persistence of flow conditions, as indicated by the correlations given in Figure 9, is strongest during the fall when flows tend to be lower and less variable, and weakest during the early spring when flows are higher and more variable. Despite the high correlations shown in Figure 9, the persistence of flows by itself is not useful for forecasting oncoming high flow conditions because the river must first be experiencing high flows before future high flows can be predicted.

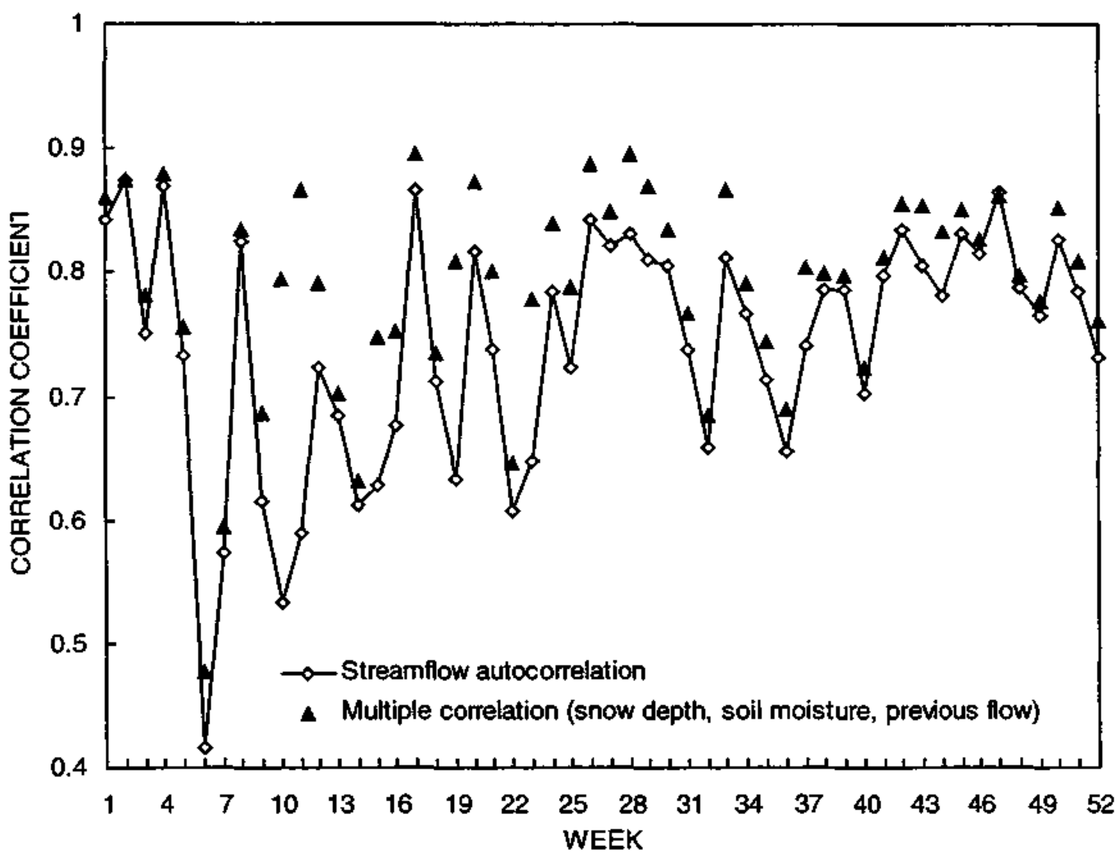


Figure 9. Correlation of future flow conditions to present flows and the multiple correlation to snow depth, soil moisture, and previous flows.

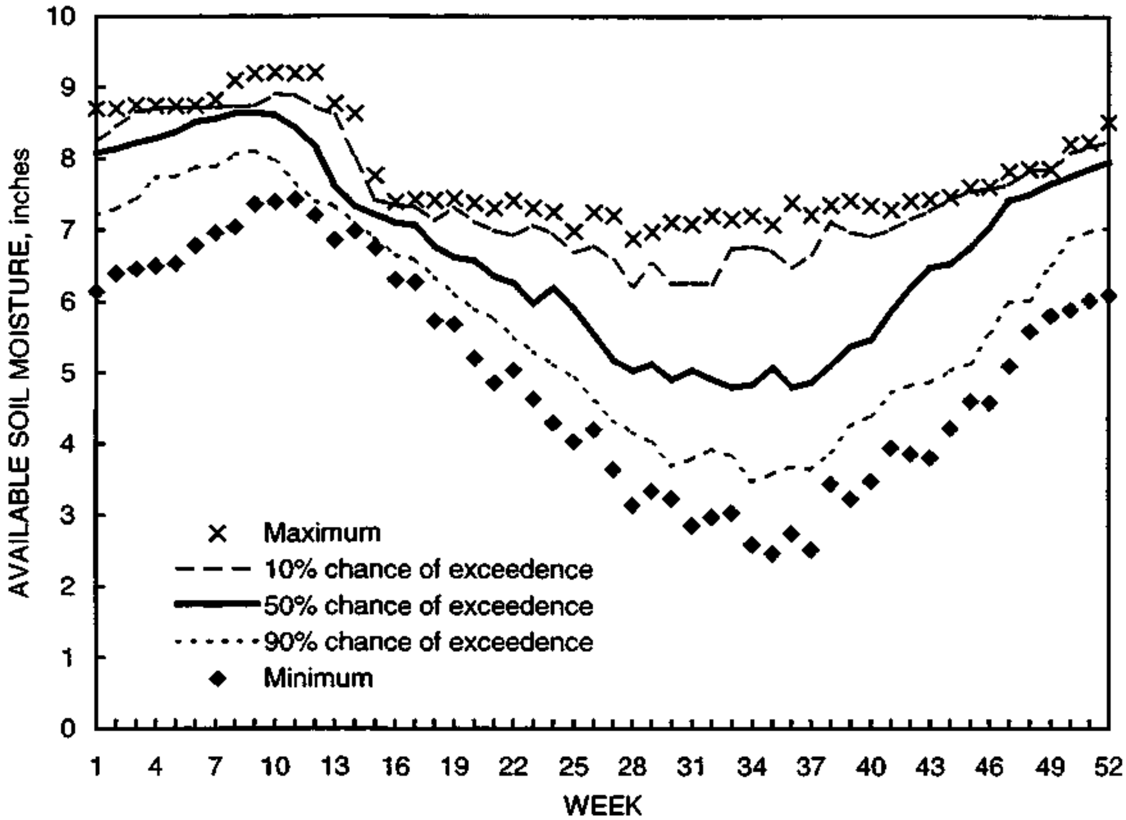


Figure 10. Probability distribution of available soil moisture in the Fox River watershed.

Of more concern in the analysis was the relationship between soil moisture and the snow depth on future flow conditions. Figure 10 shows the seasonal distribution of soil moisture for the 48 years that were analyzed. The 90, 50, and 10 percent lines in Figure 10 indicate the probability that the soil moisture during that week is exceeded. For example, during week 29, there is roughly a 90 percent probability that the average avalaible soil moisture over the watershed will exceed 4 inches. The maximum and minimum represent the extreme soil moisture amounts for each week of the year, as simulated using the FRF Model for 1948-1995. The soil moisture (in inches) is the available water in the upper two meters (79 inches) of the soil column. The available water at field capacity is roughly 7.4 inches. Moisture levels can surpass the field capacity in winter and early spring when the soil is frozen and accumulates water above the amount that ordinarily would remain after gravity drainage. Moisture levels in the late winter and early spring almost always are at or above field capacity. The season of greatest variation in soil moisture is summer, when the available water can range from less than 2.5 inches to field capacity.

Figure 11 shows the correlations between the antecedent soil moisture and the future flow conditions. Also shown in Figure 11 is the correlation to future flow

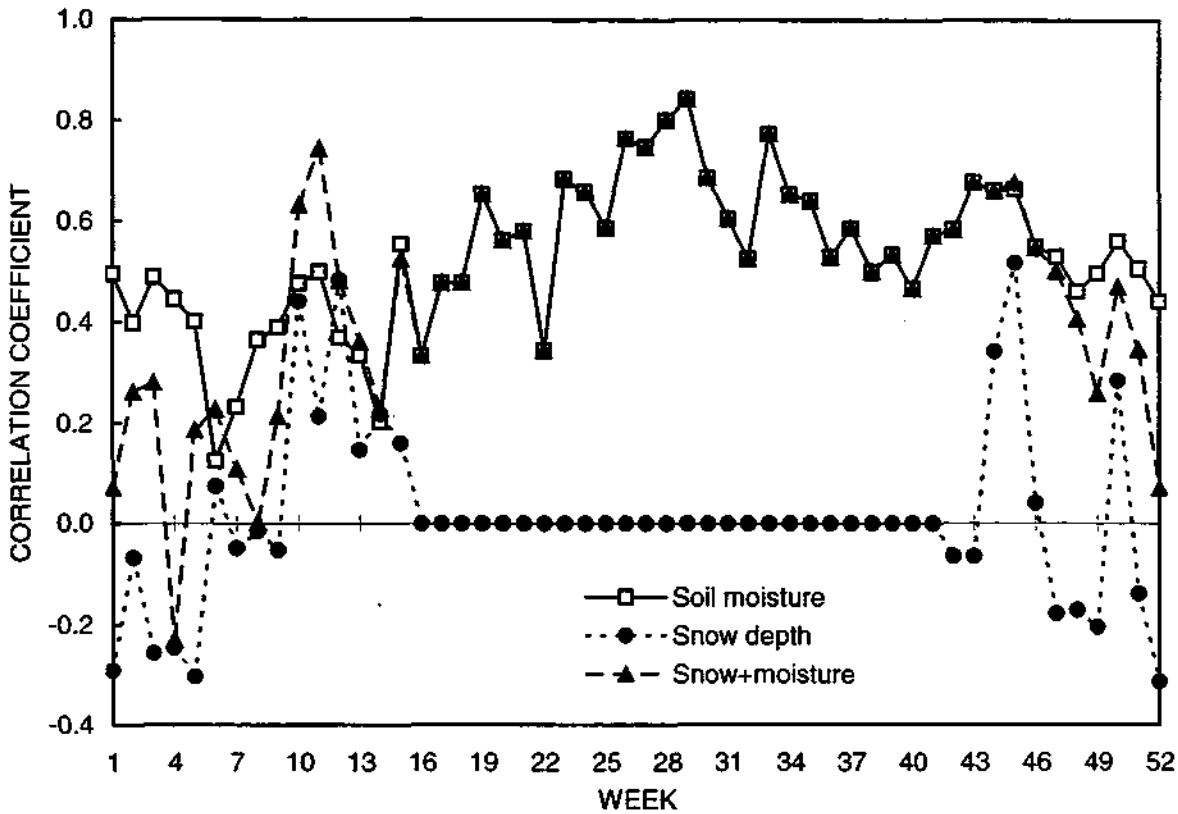


Figure 11. Correlation of future flow conditions to soil moisture, snow depth, and the total water stored in the snow pack and soil (snow + moisture).

conditions to snow depth and "snow + moisture," both of which will be described later. There is a moderately strong relationship between soil moisture conditions and future flow amounts, with correlation coefficients generally in the range of 0.5-0.7. The correlation is greatest during summer months, and weakest during the winter. An example of the relationship between soil moisture and future flow conditions during the summer, when the relationship is strongest, is shown in Figure 12 for week 29 (July 16-22). Figure 12 illustrates that soil moisture could be used as a reasonable indicator of future flow conditions. However, even when the soil is saturated, the average anticipated flow levels for the next two weeks is only about 1500 cfs. This anticipated flow level may provide enough concern that lake levels could be kept slightly lower than normal, but of not enough concern to initiate any high flow operations.

Figure 13 shows the probability distribution of snow depth for the 48 years analyzed. As described with Figure 10, the 10 and 50 percent lines indicate the probability that the snow depth for that particular week will exceed the plotted amount. The maximum observed snow depths for each week of the year also are given. Snow depth usually is greatest in January and early February, and is reduced by late February.

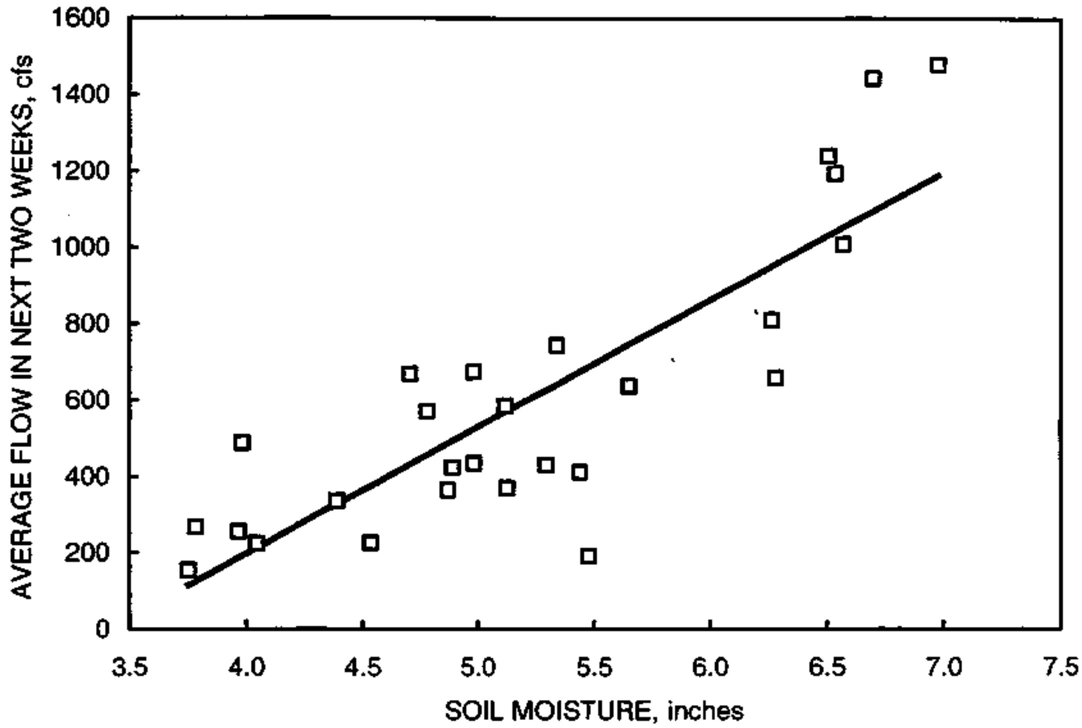


Figure 12. Relationship between soil moisture and future flow conditions, week 29.

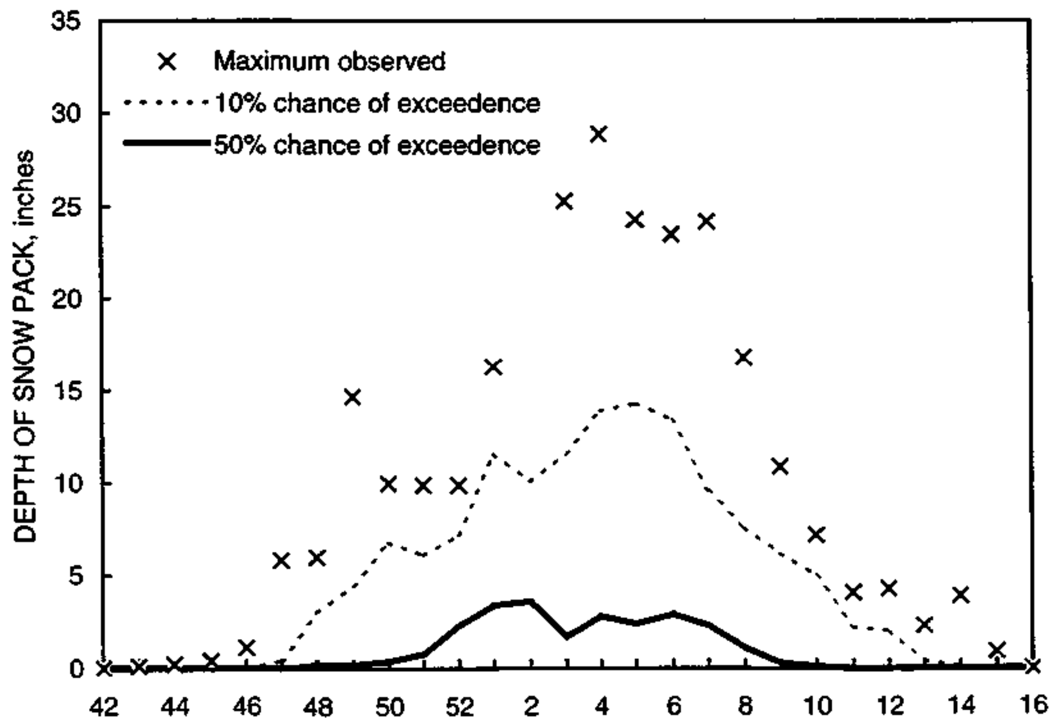


Figure 13. Probability distribution of the snow depth in the Fox River watershed.

The reduction in the snow pack can occur as the snow pack is compacted, as water melts and runoffs into the streams, or as water melts and refreezes as it drains into the soil.

Figure 11 shows the correlation of the snow depth to future flows. This correlation is highly variable from week to week, but it is strongest in March when the snow pack is expected to melt and run off. When the soil moisture and equivalent water in the snow pack are added together (to form the parameter "snow + moisture"), an even stronger correlation exists in the early spring. The correlation of "snow + moisture" to future flow amounts for mid-March is 0.75, as shown in Figure 11.

Figure 14 shows the probability and seasonal distribution of the weekly precipitation averaged over the Fox River watershed. The relationship between recent precipitation and flow conditions is fairly consistent throughout the year, with an average correlation coefficient of 0.44. This correlation is generally less than the correlation of streamflows to antecedent moisture and flow conditions. The correlation of precipitation to streamflow also deteriorates quickly when there is a lag between the two, enough that

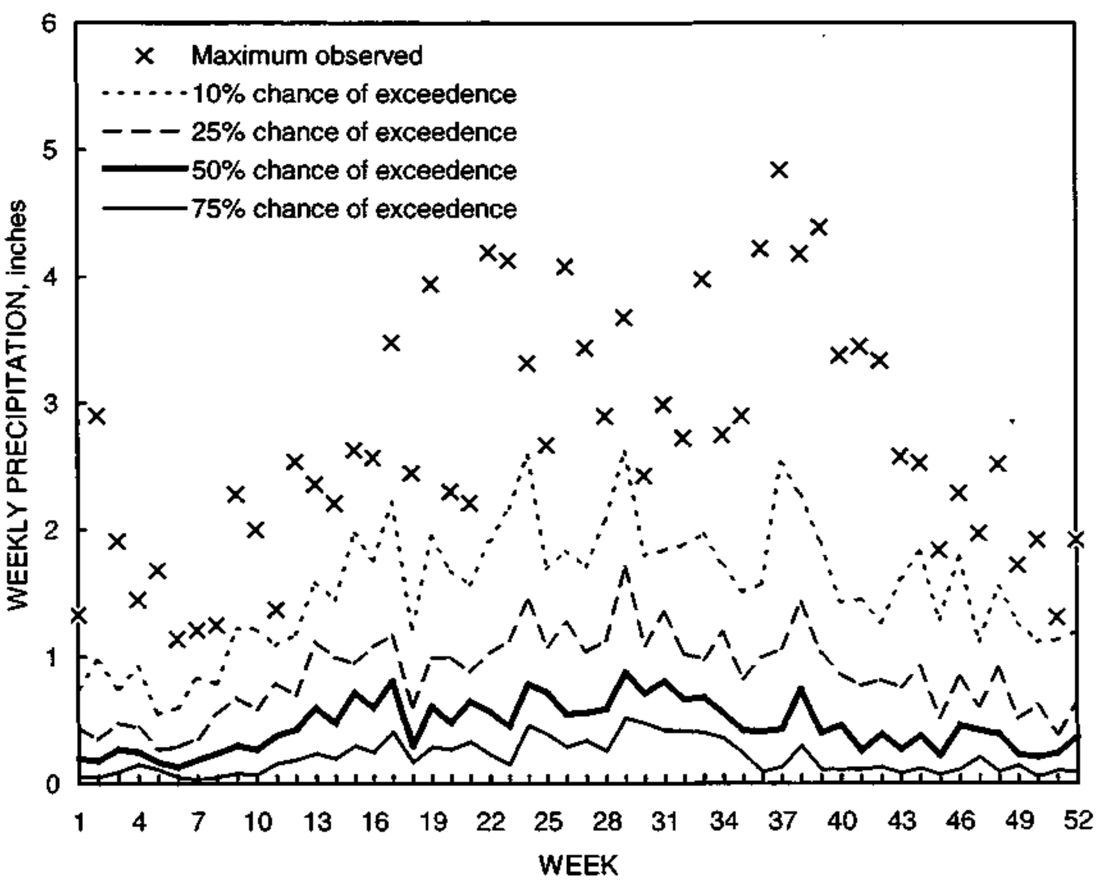


Figure 14. Probability distribution of the areal mean weekly precipitation in the Fox River watershed.

the precipitation alone is a relatively poor predictor of flow conditions beyond one week into the future. The relationship between antecedent conditions and the probability of future precipitation also was examined; however, that analysis indicated there was virtually no correlation between the two parameters, thus the results are not shown.

The relationship between antecedent conditions and future lake levels also is weak, primarily because lake levels tend to be highly controlled. For example, during summer flow conditions when lake levels are held constant, there essentially is no correlation between flows and lake levels except during high flow conditions.

Relationship of the Snow Pack to Spring Flooding

As shown earlier, there is a variable correlation between the thickness of the snow pack and streamflows in the following two-week period. But, when the maximum depth of the snow pack during the winter is compared to the magnitude of the subsequent spring flood, regardless of time lag, the relationship becomes much stronger. Figure 15 compares the maximum snow depth observed during the winter to the maximum daily discharge measured at the New Munster (Wilmot) gage in the late winter or early spring. The depth of the snow pack has exceeded 12 inches in 12 separate years. In 11 of those 12 years, subsequent flooding occurred in the Chain of Lakes. A comparison of flood

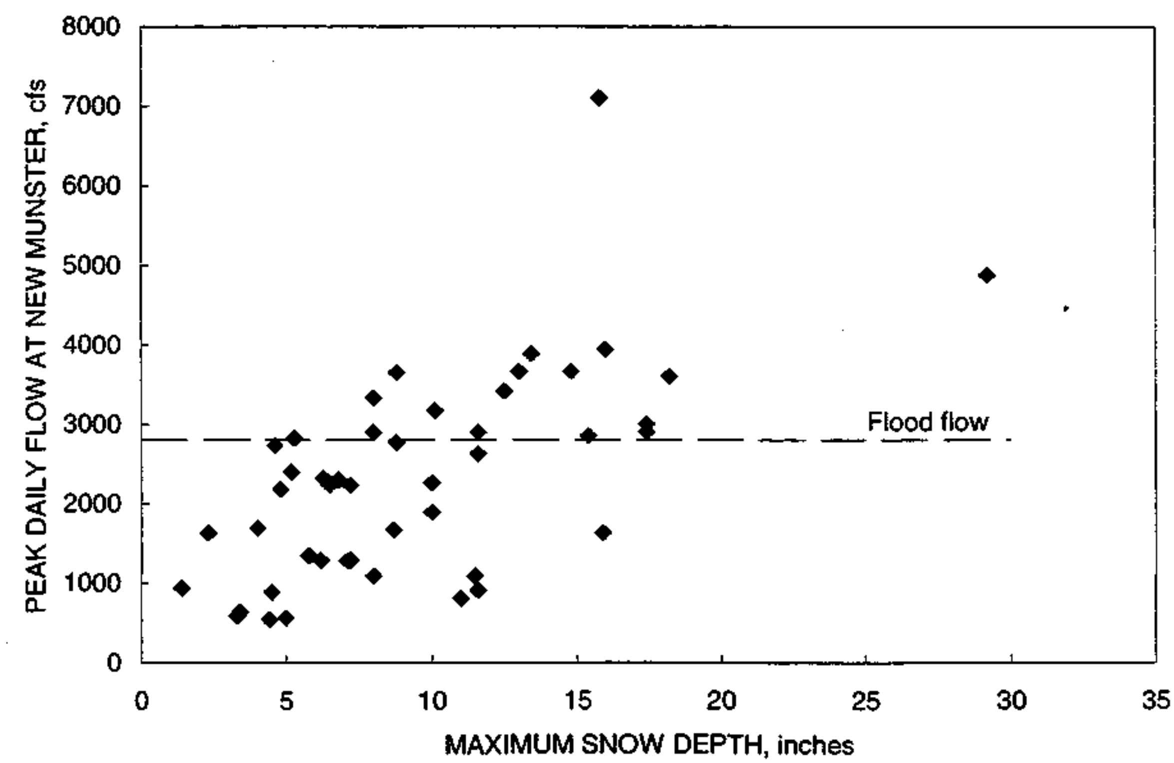


Figure 15. Comparison of maximum snow depths to the peak spring flow in the Fox River near New Munster.

Table 4. Thick Snow Packs and Their Associated Floods

Year	*Maximum snow depth, watershed average, inches*	*Maximum level of Fox Lake, ft-msl*	*Peak daily flow at New Munster, cfs*
1951	14.8	739.3	3660
1952	13.0	739.7	3660
1959	15.4	738.7	2850
1960	15.8	741.2	7100
1962	16.0	740.3	3940
1974	13.4	740.0	3880
1978	15.9	737.4	1630
1979	29.2	739.5	4880
1982	17.4	738.8	3000
1985	17.4	738.9	2900
1986	12.5	738.8	3410
1994	18.2	740.0	3600

magnitude and snow depth for those 12 events is given in Table 4. When the depth of snow is reduced through the course of the winter, there still is a high probability of flooding because most of the moisture remains either in the snow pack or frozen in the upper layers of the soil. In years with a deep snow pack, it is recommended that dam operation should maintain a discharge to keep the lake elevations at or below the winter pool level, if possible, including using the hinged-crest gates to increase discharge.

OPENING GATES IN ADVANCE OF FLOODING AND HIGH FLOWS

Three sources of data that may provide useful information for identifying oncoming flood conditions were examined. These are: the peak flows from the FRF Model, observed flow levels at the Spring Grove gage on Nippersink Creek, and increases in levels on the upper lakes. All three sources provide useful information on identifying whether the lakes will rise to flood levels.

Use of the Flow Forecasts To Identify Oncoming Floods and High Flows

Simulation of a 50-year Flow Record

Hows in the Fox River watershed were simulated for the 50-year period, 1948-1997, using the **FRF** Model and daily values of precipitation measured at nine precipitation gages. For most of the period, the following nine precipitation gages were used: Antioch, Burlington, Lake Geneva, Marengo, McHenry, Mt. Mary College, Oconomowoc, Union Grove, and Waukesha. The Harvard gage was used in place of the Marengo gage for 1990-1997. When needed, missing precipitation records were estimated using records from nearby gages, which also included the use of the Racine and Milwaukee gages. The simulated flow values are used as surrogate values for the flow forecasts that would have been available in the days preceding flooding and high flow events.

Over the 50-year period, there are 31 flooding events in which the peak stage in the upper lakes (represented by the gage on Fox Lake near Lake Villa) exceeded 738.5 ft-msl. These events are listed in Table 5. In 18 events, the peak stage exceeded 739.0 ft-msl, and there are nine major flood events in which the level in the upper lakes equaled or exceeded 740.0 ft-msl. The longest continuous duration of flooding was 39 days, occurring in 1993. There are 70 additional high flow events in which the peak stage in the upper lakes exceeded 738.0 ft-msl. Given the present operations at the dam, these events would ordinarily lead to closure of the lake to boating; and other events may lead to the imposition of no-wake conditions on the lakes and Fox River. Many of these high-flow events also pose the threat for potential flooding conditions.

An examination of Table 5 indicates that there are several flood events in which the flood stage of 738.5 ft-msl was exceeded in the upper lakes, but the bank flow discharge of 3470 cfs was not exceeded downstream on the Fox River at Algonquin. There is only one incident, in May 1996, when flooding occurred downstream but flood stages were not reached in the upper lakes.

Terminology of Flood Forecasting Successes and Failures

The flow forecast provides a good estimate of oncoming flood conditions, but it is not a perfect predictor of the magnitude of flooding or high flows. There always will be some degree of underestimation and overestimation of oncoming flow conditions. The

Table 5. Historical Flooding Events on the Chain of Lakes, 1948-1997, Listing Peak Stages on Fox Lake and Maximum Flows at Algonquin

Period of flooding	*Peak stage (ft-msl)*	*Maximum Algonquin flow (cfs)*	*Period of flooding*	*Peak stage (ft-msl)*	*Maximum Algonquin flow (cfs)*
Mar 19 - Apr 4, 1948	740.2	4560	Jan 31 - Feb 5, 1974	738.8	4290
May 13 - May 19, 1948	738.8	2800	Mar 5 - Mar 21, 1974	740.0	5290
Apr 1, 1950	738.6	2980	May 18 - May 29, 1974	739.4	4640
Apr 27 - Apr 29, 1950	738.7	3310	Mar 6-Mar 18,1976	739.5	4370
Feb 28-Mar 15, 1951	739.3	3900	Mar 19 - Apr 18, 1979	740.6	6610
Mar 15 - Apr 2, 1952	739.7	4400	Apr 28 - May 10, 1979	739.5	4710
Mar 28-Apr 6, 1959	738.7	3340	Mar 20- Apr 19, 1982	738.8	3970
Jan 14 - Jan 25, 1960	739.4	4090	Dec 6 - Dec 15, 1982	739.4	4300
Mar 31-Apr 26, 1960	741.2	6480	Apr 5 - Apr 21, 1983	739.7	5130
Mar 23 - Apr 16, 1962	740.3	4870	Mar 5 - Mar 15, 1985	738.9	4340
Apr 11 - Apr 15, 1965	738.7	3890	Mar 15 - Mar 23, 1986	738.8	3770
Jun 14 - Jun 17, 1967	738.8	3940	Sep 25 - Oct 15, 1986	740.7	6130
Feb 25-Mar 9, 1971	739.1	3760	Mar 17 - Mar 20, 1990	738.7	3420
Apr 20 - Apr 27, 1972	738.8	3190	Mar 28 - May 5, 1993	740.3	6090
Sep 18 - Oct 7, 1972	739.7	4690	Feb 23-Mar 1, 1994	740.0	3720
Apr 22 - May 15, 1973	740.4	5710			

primary goal in flood control operation is that these estimation errors do not cause flood damages above what would occur without the use of the flow forecast. Ideally the estimation errors should have as little impact on flood control operations as possible. On the Fox River and Chain of Lakes, there is no vital need for the forecasting system to provide evacuation warnings, and the overall reduction of flood levels is the primary operation objective.

Hood forecasting terminology normally defines three categories of success or failure of the forecasting system: "hits," "misses," and "false alarms." A hit is a flood that is properly forecasted as an oncoming flood event, a miss is a flood event that is not forecasted to reach flood levels, and a false alarm is an event that is forecasted to be a flood but does not reach flood levels. Getting a hit is obviously the desirable category, leading to an early response to oncoming flood conditions.

In the Stratton Dam operations, a false alarm is a potentially more harmful outcome than a miss. In a miss, the flood control operation at Stratton Dam is expected to proceed in exactly the same manner as it did without the use of the flow forecast system. Thus, although no advantage is gained by such a forecast, no additional damage is caused. In a false alarm, it is possible that the gates could be opened in advance of the expected flood waters, causing downstream flooding where flooding otherwise would not have occurred. A false alarm that occurs when the lakes are at the summer pool level is the most undesirable situation because relatively greater amounts of water may be discharged through the Stratton Dam gates, causing higher flows downstream. Knapp and Ortel (1992) simulated the impact of a potential summer false alarm, and they found that the peak water levels downstream at Algonquin exceeded the bank full elevation by less than 0.1 foot. The simulation indicated that, even though the Stratton Dam gates and the proposed hinged-crest gates were fully opened, the outflow from the gates did not exceed flood discharges during the two-day period in which the gates were opened. It is expected that false alarms occurring at the winter pool level will be comparatively less harmful, because the amount of flow that can be discharged by the Stratton Dam at low pool levels is not sufficient to cause downstream flooding.

Relationship between the Flow Forecast Peak and Expected Flood Levels

There is a strong relationship between the peak discharge of the forecasted inflows into the Chain of Lakes and the eventual degree of flooding on the lakes and the Fox River. Table 6 shows the relationship between the flow forecast peak and the maximum flood stage reached in the upper lakes. In all 12 historical cases when the forecast inflow peak exceeds 7000 cfs, the upper lakes exceed the flood stage of 738.5 ft-msl; and in 10 of the 12 cases, the eventual flood stage exceeds 739.0 ft-msl. As the magnitude of the inflow forecast decreases, the relative certainty of oncoming flood conditions also decreases. When the forecast peak is between 6000 and 7000 cfs, there is only a 70 percent chance that flood conditions also will arrive. Thus, over the historical record there were seven hits and three false alarms.

An examination of Table 6 indicates that, in every case when the flow forecast exceeds 5000 cfs, the level in the upper lakes can be expected to exceed 738.0 ft-msl. It is recommended that the gate openings at the dam be increased to release 3000 cfs when the flow forecast exceeds 5000 cfs, for the following reason. Given the current operation

Table 6. Probability of Flooding or High Water Levels in the Upper Lakes Based on the Flow Forecast

$$\frac{\text{Number of events above specified water level}}{\text{Total number of events within discharge range}} \times 100 = \text{Probability (\%)}$$

Peak discharge of forecast (cfs)	<u>*Maximum water level of flooding or high flows*</u> *>738.0ft-msl*	*>738.5 ft-msl*	*>739.0ft-msl*
>7000	12/12=100%	12/12=100%	10/12=83%
6001-7000	10/10=100%	7/10=70%	5/10=50%
5001-6000	16/16=100%	11/16=69%	4/16=25%
4501-5000	8/12=67%	1/12=8%	0/12=0%
4001-4500	12/16=75%	2/16=12%	0/15=0%
3501-4000	15/22=68%	0/22=0%	0/22=0%
3001-3500	13/30=43%	0/30=0%	0/30=0%

practices, the outflow from the Stratton Dam is always increased to approximately 3000 cfs when the upper lakes reach an elevation of 738.0 ft-msl. Thus, if the gates were opened to release 3000 cfs at the time of the flow forecast, the dam operation would not be causing flows any greater than otherwise would happen later. In addition, given this flow forecast, there is a 70 percent probability that flood conditions will develop; and by opening the gates early, there is a possibility that flooding either can be lessened or avoided entirely.

Table 6 also shows the probability that the lake stage will exceed 738.0 ft-msl based on the forecast. High-water levels above 738.0 ft-msl were experienced in all 38 cases when the flow forecast was above 5000 cfs. Thus, with reasonable certainty, it can be expected that lake closure and outflows approaching 3000 cfs will be needed to prevent the lake levels from exceeding this high-water level. Without increased gate openings, there is also a 70 percent chance that flood levels will be reached. By increasing outflows to 3000 cfs at the time of the forecast, the probability that flooding conditions will be experienced will be reduced.

Table 7 shows the relationship between the threshold value used to identify an oncoming flood event and the number of hits, misses, and false alarms created using that threshold value. Fewer than half of the historical flood events would have been correctly forecast before a false alarm was encountered. Use of a higher threshold flow value (7000 cfs) for gate operations will provide for a conservative use of the flow forecast model and assures that there are no false alarms. Table 8 (Criterion A) identifies the early gate openings that hypothetically could have occurred for historical flood events using the flow forecast model and a threshold value of 7000 cfs for gate operations.

Use of a more aggressive operation policy, using a lower threshold value, would increase the probability that gates were opened early for major flood events but would increase false alarms. The potential impact of false alarms should be examined more closely before taking the more aggressive operation approach. If simulations of false alarms suggest little negative impact on downstream flooding, consistent with the example given in Knapp and Ortel (1992), then using the lower threshold value would

Table 7. Flow Forecasting Success Based on the Threshold Level Used To Identify Flooding Conditions (Water Level in the Upper Lakes Exceeds 738.5 ft-msl)

Threshold flow (cfs)	*Hits*	*Misses*	*False alarms*
7000	12	19	0
6000	18	13	3
5000	29	2	6
4500	30	1	16
4000	31	0	31

Table 8. Early Gate Openings that Could Have Occurred for Historical Flood Events Using the Flow Forecast Model

Criterion A. Open gates when the peak flow forecast exceeds 7000 cfs

January 11, 1960	March 4, 1976	April 1, 1983
March 29, 1960	March 19, 1979	September 26, 1986
April 6, 1965	April 25, 1979	March 9, 1990
February 18, 1971	December 2, 1982	February 19, 1994

Criterion B. Open gates when the adjusted peak forecast value exceeds 7000 cfs

March 18, 1948	September 17, 1972	March 17, 1979*
February 26, 1951	April 20, 1973	September 24, 1986*
March 13, 1952	May 16, 1974	March 26, 1993
March 25, 1959		

Criterion C. Open gates when the daily flow at Spring Grove is greater than 1300 cfs and the adjusted peak forecast value is between 5000 and 7000 cfs

June 11, 1967	March 14, 1982
March 4, 1974	March 11, 1986

Criterion D. Open gates when the Fox Lake stage is at least 738.1 ft-msl, there is a one-day increase in the Fox Lake stage of at least 0.4 foot and the adjusted peak forecast value is 6000 to 7000 cfs

May 12, 1948	April 18, 1972
April 25, 1950	

Note: * = Flood events are detected two days earlier than that identified with Criterion A.

provide greater benefit in identifying floods and providing an early response for overall reduction of flooding levels.

A comparison was made to the flow forecasts used for gate operation in Knapp and Ortel (1992). In general, the forecasts produced by the newer version of the flow forecast model are roughly 20 percent lower in magnitude and more closely match the expected inflow quantities for the Chain of Lakes. However, the relative probability of having false alarms is increased with the newer version, and thus may require a more conservative operations policy to avoid the false alarms.

Use of the Flow Forecast in Combination with Initial Lake Stages

When the water level in the Chain of Lakes is higher than normal, an inflow event of relatively smaller magnitude may be able to cause flood stages. Figure 16 shows the relationship between the peak flow forecast value, the initial stage on Fox Lake at the time the flow forecast is originally developed, and whether the event caused the water level in the upper lakes to reach flood stage, and thus is identified as a "flood" or "non-flood" event. An examination of Figure 16 indicates that flood stages can be expected when the initial Fox Lake stage is 738.0 ft-msl and the flow forecast is greater than 5500 cfs. Similarly, flood stages can be expected when the initial lake stage is 737.5 ft-msl and the flow forecast is greater than 6250 cfs. At normal summer pool levels, a flow forecast of 6500 cfs is sufficient to reliably identify an approaching flood.

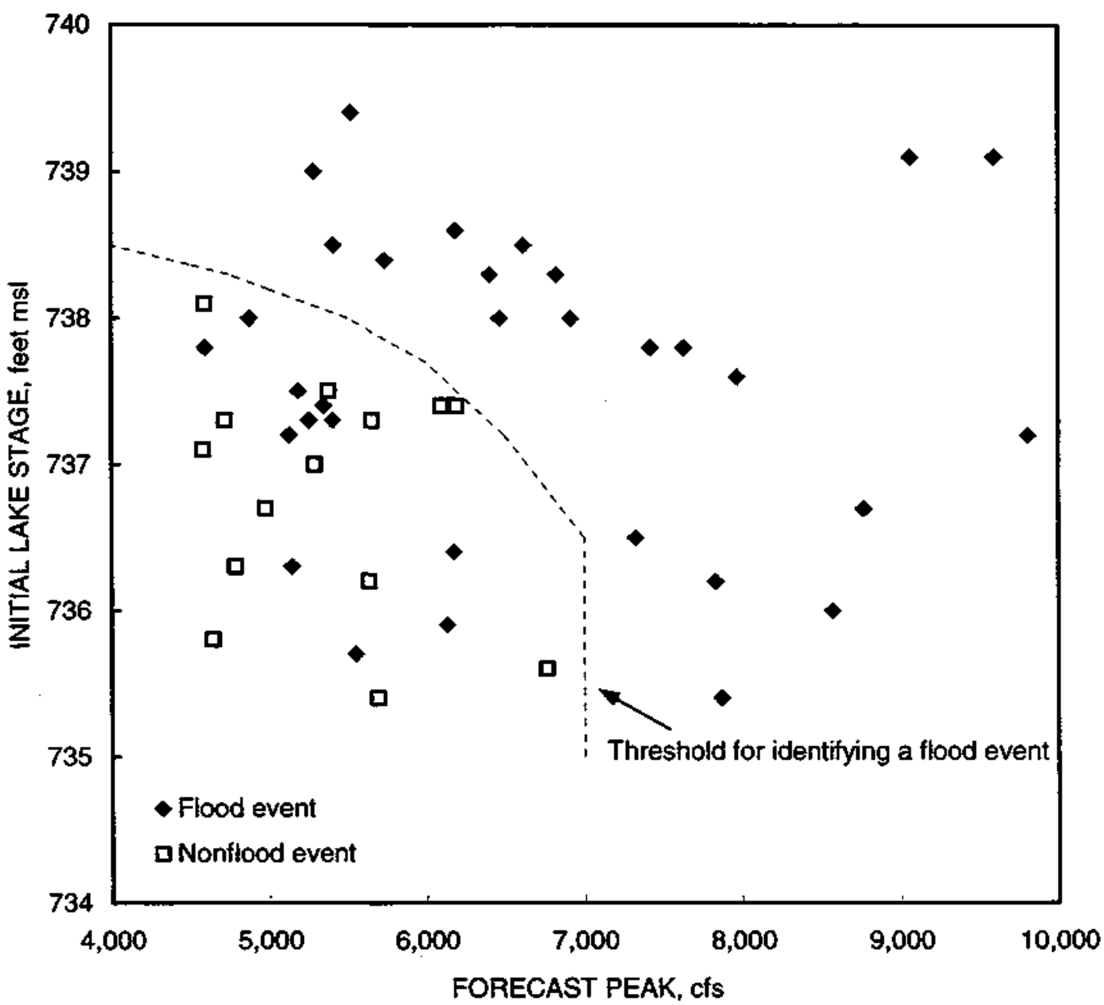


Figure 16. Relationship between flow forecast peak, initial stage of Fox Lake at the time of the forecast, and whether the event caused the water levels in Fox Lake to reach flood stage.

The recommended approach to using the lake stage information in the flood operation plan is to adjust the flow forecast amount based on the initial lake stage. Table 9 lists the recommended adjustments to the flow for selected values of the stage on Fox Lake at the time the flow forecast is developed. A dashed line in Figure 16 provides an estimate of the stage versus flow forecast needed to produce an adjusted forecast value equal to the operation threshold of 7000 cfs.

The adjusted forecast value can be used to identify a greater number of forecasting hits and to provide earlier identification of some flood events. Table 8 (Criterion B) lists the additional flood events that can be recognized using the initial stage and adjusted forecast value. Two of the flood events listed also were identified in Criterion A in Table 8, but for those events the adjusted forecast value provides the ability to begin flood operations two days earlier.

Use of Nippersink Creek Gage at Spring Grove To Identify Oncoming Floods

Nippersink Creek is the largest tributary to the Fox River, and the runoff from this creek provides a useful indication of the overall response of the watershed to a particular rainfall event. Though not specifically stated in the current operation guidelines, the rate of rise in the hydrograph for Nippersink Creek at Spring Grove occasionally is used to indicate the potential for flooding in the Chain of Lakes. The runoff response from the entire Fox River watershed is not always of similar magnitude as the runoff from the Nippersink Creek watershed because rainfall rates during heavy storms typically show considerable variability. However, it is uncommon for flooding to occur in the Chain of Lakes without a substantial contribution of flow from Nippersink Creek.

Table 10 relates the flow amounts observed at the Spring Grove gage to the probability of flooding conditions in the Chain of Lakes. The flow values used in this comparison are average daily flows. Instantaneous flow values on Spring Grove for operations should be used cautiously because the relationship between the instantaneous

Table 9. Recommended Adjustments to the Flow Forecast Value Based on the Initial Stage Level on Fox Lake

Fox Lake stage (ft-msl)	*Adjustment to forecast value (cfs)*
736.5	No adjustment
736.9	Add 250
737.2	Add 500
737.5	Add 750
737.7	Add 1000
738.0	Add 1500
738.2	Add 2000
738.4	Add 2500

Table 10. Probability of Hooding (stages above 738.5 ft-msl) in the Upper Lakes Based on Daily Flows at Spring Grove

$$\frac{\text{Number of flood events}}{\text{Total number of events within discharge range}} \times 100 = \text{Probability (\%)}$$

Discharge (cfs)	*Probability*	*One-day change in discharge (cfs)*	*Probability*
>2200	3/3=100%	>1100	3/3=100%
1301-2200	10/11=91%	751-1100	5/6=83%
1001-1300	6/13=46%	501-750	8/10=80%

peak flow and the volume of storm runoff is inconsistent. Both the daily flow and the one-day change in flow at the Spring Grove gage were examined as potential indicators of flooding conditions.

As shown in Table 10, the Chain of Lakes has experienced flooding conditions in 13 out of 14 cases when the daily flow at the Spring Grove gage has exceeded 1300 cfs. The one exception is the storm event of July 1, 1993 (for which the maximum daily flow at Spring Grove was 2040 cfs). This event experienced a peak stage in the upper lakes of 738.38 ft-msl. To avoid such a false alarm, it would not be appropriate to fully open the sluice gates and/or hinged-crest gates when the Spring Grove daily flow exceeds 1300 cfs. However, it would be useful at such times to open the sluice gates to provide an outflow of 3000 cfs because the probability of flooding would be great. Use of a higher threshold to fully open the sluice gates and hinged-crest gates, such as a 2200 cfs threshold, could avoid false alarms; but this method would not identify any additional flood events beyond that given by the 7000 cfs flow forecast threshold, used with Criteria A and B in Table 8. Use of the observed flows at the Spring Grove gage is generally not able to identify potential flood conditions until two days following the precipitation event, thus one day after the event is normally identified using the flow forecast.

The one-day change in flow at the Spring Grove gage is another potential indicator of oncoming floods. For example, the Chain of Lakes has experienced flood conditions in all three events when the one-day change in daily flow at Spring Grove has exceeded 1100 cfs, specifically the events of June 11, 1967, February 19, 1971, and February 20, 1994. Note that the latter two events also were identified in Criterion A in Table 8, but the use of Criterion A allows for an earlier detection of the floods. Thus, the change in flow at Spring Grove offers limited additional information for identifying approaching flood conditions.

Use of Spring Grove Gage Information in Combination with the Flow Forecast

As indicated previously, the use of the Spring Grove flow data by itself for forecasts is relatively ineffective because the threshold for identifying floods must be high in order to avoid false alarms. However, when a high flow value at Spring Grove coincides with a high inflow forecast value for the Chain of Lakes, the chance of having a false alarm is greatly reduced. Table 11 shows the probability of flooding from the historical record for various combinations of adjusted forecast values and Spring Grove flow conditions. When the adjusted forecast value is between 5000 and 7000 cfs and the daily average flow at Spring Grove is greater than 1300 cfs, there is a high probability (100 percent for all historical events) that flood stages will be observed for the Chain of Lakes. The probability of flooding drops off significantly when the daily flow at Spring Grove is less than 1300 cfs.

Table 8 (Criterion C) lists the four historical flood events that experienced daily flows at Spring Grove above 1300 cfs and have a simulated adjusted forecast value between 5000 and 7000 cfs. Note that the floods listed with Criterion C cover only the period of record of the gage, from 1966 through 1997. If the gage had been active over the entire 50-year period being analyzed, it is likely that additional floods from the period 1948-1966 also could have been identified using these criteria.

As indicated in Table 11, the occurrence of a large one-day change in flow at Spring Grove is also a successful indicator of potential flooding, when combined with an adjusted forecast of greater than 5000 cfs. However, both flood events identified by this method, June 11, 1967, and March 14, 1982, also have daily flow values greater than 1300 cfs, and thus are already listed in Table 8 (Criterion C).

Use of Water Level Increases in the Upper Lakes To Identify Oncoming Floods

The rise of lake levels provides additional information concerning oncoming flood events, although it may provide even less advance warning for a potential early flood response. Table 12 presents the probability that flooding will occur when the stages in

Table 11. Probability of Flooding (stages above 738.5 ft-msl) in the Upper Lakes Based on Flows at Spring Grove and the Flow Forecast Value

$$\frac{\text{Number of flood events}}{\text{Total number of events within discharge range}} \times 100 = \text{Probability (\%)}$$

Spring Grove flow (cfs)	*Peak discharge of forecast (cfs)*	*Probability*	*One-day change in Spring Grove flow (cfs)*	*Peak discharge of forecast (cfs)*	*Probability*
>1300	6000-7000	2/2=100%	>750	5000-7000	1/1=100%
1301-2200	5000-6000	2/2=100%	501-750	5000-7000	1/1=100%
1001-1300	6000-7000	1/3=33%			
1001-1300	5000-6000	1/3=33%			

Table 12. Probability of Flooding in the Upper Lakes with a One-Day Change in Lake Level ≥ 0.4 foot

$$\frac{\text{Number of flood events}}{\text{Total number of events within specified ranges}} \times 100 = \text{Probability (\%)}$$

Fox Lake level (ft-msl)	*Adjusted Flow Forecast Value, Q (cfs)*			
	Q<3000	*3000≤Q<5000*	*5000≤Q<6000*	*6000≤Q<7000*
≥738.1	1/1=100%	1/1=100%	0/0	4/4=100%
737.6-738.0	0/3=0%	3/7=43%	0/0	3/6=50%
≤737.5	0/8=0%	3/22=14%	1/8=12%	3/7=43%

the upper lakes increase by at least 0.4 foot during a 24-hour period. A large increase in lake stage does not necessarily indicate approaching flood conditions unless the increase occurs when the lake stages are already high. As indicated in Table 12, flooding conditions have developed in all historical events when a large, one-day increase in stage has brought the level in Fox Lake up to 738.1 ft-msl. Most of these historical events also have had an adjusted forecast value greater than 6000 cfs. There is generally less than a 50 percent chance that flood conditions will occur if the Fox Lake stage has not reached 738.1 ft-msl.

For purposes of initiating flood operations at Stratton Dam, it would be prudent to require three criteria: a Fox Lake stage of at least 738.1 ft-msl, an increase of at least 0.4 foot in the Fox Lake stage over the last 24 hours, and an adjusted forecast value of 6000-7000 cfs. These criteria could have been used to initiate flood operations in the three historical events in Table 8 (Criterion D). A fourth historical event, March 4, 1974, also satisfies these criteria, but the initiation of flood operations for this other event was previously identified in Table 8 (Criterion C).

CLOSING GATES FOLLOWING FLOODING AND HIGH FLOWS

After a flooding or high flow event, a decision needs to be made about when the Stratton Dam gates should be closed, which will reduce the rate of outflow from the Chain of Lakes. Flow levels on the Fox River must be reduced before the lakes can be reopened to boat traffic, and/or before the no-wake restrictions are lifted. Thus the decision to reduce flows is critical because, during the warm season, recreational boating on the Chain of Lakes and Fox River provides a valuable economic resource to the area. Reduction of flow should not occur, however, before the threat of additional flooding can be minimized. Thus the pertinent question is, "at what time or situation is the risk of additional flooding sufficiently reduced so reductions in outflow may be considered?"

Daily records of lake and river stages and river discharge for the 50-year period, 1948-1997, were examined to ascertain the consequences of reducing the outflow from Stratton Dam during the "falling limb" of historical flood events. The analysis used volumetric estimates of lake storage and outflow. Hypothetically, if the dam's outflow during an historical event had been reduced by a specified amount, that water would be stored in the lakes and cause a relative increase in lake level above the historical amount. For example, a reduction in the dam's outflow of 500 cfs for one day was estimated to cause a relative increase in the water level in the lakes of approximately 0.1 foot. If that reduction in outflow were maintained over a five-day period, there would be a relative increase in the lake levels of 0.5 foot, and so forth. A relative increase does not necessarily mean an actual increase in lake level. For most cases it means only that the lake level does not recede as quickly as it would if the gates had been maintained at a wider opening. In reality, the stage increase would not be completely uniform upstream of the Stratton Dam, and greater increases in stage would likely occur between the Stratton Dam and the outlet to the Chain of Lakes (near Johnsburg) than in the upper lakes.

Because the following analysis deals with reductions in lake outflow and not specifically with gate settings, it should apply to operations involving both the current outlet facilities of Stratton Dam and the additional proposed hinged-crest gates.

Impact of Gate Closure on the Probability of Future Flooding

The partial closing of the Stratton Dam gates immediately following a flood event can potentially cause extended flooding upstream on the lakes by either lengthening the time during which the lake level remains above flood stage, or failing to lower the lakes in advance of a subsequent storm event, thereby creating or exacerbating flooding in the future. However, the failure to reduce the gate openings after the danger of upstream flooding has passed could lengthen the period during which either downstream levels are above flood stage or the river is closed to boating.

For each flood event being analyzed, a judgment was made about whether the hypothetical gate closure would alter lake levels to the extent that further flooding might be caused. For each event, it was judged either that *yes,* gate closure will lead to extended flooding on the lakes, or *no,* gate closure will not lead to extended flooding. By analyzing the lake level recession following all flood events in the 50-year record, the probability of extended flooding could be estimated.

Two factors were found to influence the probability that gate closure could potentially lead to additional flooding: the current lake level and the magnitude of the proposed reduction in the outflow. The proposed reduction in outflow can be substituted with two related data: the magnitudes of the present outflow and the proposed lake outflow.

Table 13 lists the probability that the Chain of Lakes will experience prolonged or additional flood stage if the gates are closed to end the overbank flooding that is concurrently happening downstream of Stratton Dam. The probability of prolonged flooding is significant when *the* lake levels continue to be above flood stage (738.5 ft-msl). However, the probability of additional flooding becomes small, less than 15 percent, when lake levels are reduced below the level of flooding. In almost all cases examined, the lake levels continue to recede. This does not necessarily mean that subsequent flooding cannot occur, but chances are that lake levels will continue to recede to normal pool levels before an event large enough to cause flooding will occur again. Thus, the probability of reaching flood levels is not enhanced by decisions to release less water.

Tables 14, 15, 16, and 17 show the probability of prolonged high flows at various stages of closing the Stratton Dam gates following a flood or high flow event. In all cases, the probability of prolonged high water levels is increased when the outflow from the dam is high. Therefore, it makes sense to avoid a large reduction in the outflow at any one time.

Table 13. Probability of Extended Flooding (stages above 738.5 ft-msl) in the Upper Lakes If Outflow from Stratton Dam Is Reduced to 3000 cfs

Fox Lake level (ft-msl)	*Approximate level at Johnsburg (ft-msl)*	*Outflow (Q), in cfs, prior to flow reduction*		
		All flows	*Q<3500*	*Q≥ 3500*
738.8	738.3	82%	0%*	100%
738.7	738.2	74%	16%*	100%
738.6	738.1	35%	8%	62%
738.5	738.1	14%	15%	12%
738.4	738.0	4%	0%	25%*
≤738.3		<4%		

Note: * Denotes that the probability was developed from a small sample size

Table 14. Probability of Extended Flooding (stages above 738.5 ft-msl) in the Upper Lakes If Outflow from Stratton Dam Is Reduced to 2250 cfs

Fox Lake level (ft-msl)	*Approximate level at Johnsburg (ft-msl)*	*Outflow (Oh in cfs, prior to flow reduction*		
		All flows	*Q<3000*	*Q≥ 3000*
738.5	738.1	90%	75%*	94%
738.4	738.0	74%	54%	87%
738.3	737.9	68%	75%*	67%
738.2	737.8	36%	22%	50%
738.1	737.8	14%	6%	36%
738.0	737.7	14%	5%	40%
737.9	737.6	6%	0%	20%
≤737.8		<4%		

Note: * Denotes that the probability was developed from a small sample size

Table 15. Probability of Extended High Water Levels (stages above 738.0 ft-msl) in the Upper Lakes If Outflow from Stratton Dam Is Reduced to 2250 cfs

Fox Lake level (ft-msl)	*Approximate level at Johnsburg (ft-msl)*	*Outflow (Q), in cfs, prior to flow reduction*			
		All flows	*Q<2700*	*2700≤Q<3000*	*Q≥ 3000*
738.3	737.9	95%	---	75%*	100%
738.2	737.8	90%	70%	92%	100%
738.1	737.8	45%	10%	82%	82%
738.0	737.7	30%	10%	42%	73%
737.9	737.6	14%	5%	---	---
737.8	737.5	7%	<4%	---	---
737.7	737.4	7%	<4%	---	---
≤737.6		<4%			

Note: * Denotes that the probability was developed from a small sample size

In most cases, any potential prolonged period of high water levels is caused by moderate rainfall that is not sufficient to cause flooding, but increases the lake inflows enough to cause water levels to rise. An analysis of the historical records indicates that, when these events occur, the choice to reduce outflow levels lengthens the period of high water levels by an average of five days. Thus, if there is a 40 percent probability that gate closure will cause lengthened high water levels, the average result (or expected return) of choosing gate closure will be two additional days of high water levels.

Historically, the average rate of recession in lake levels following a flood or high flow event has been about 0.10 foot per day. But since 1982, the average rate of recession has been about 0.15 foot per day, as outflows have been kept higher to lower

Table 16. Probability of Extended High Water Levels (stages above 738.0 ft-msl) in the Upper Lakes If Outflow from Stratton Dam Is Reduced to 1800 cfs

Fox Lake level (ft-msl)	*Approximate level at Johnsburg (ft-msl)*	*Outflow (0), in cfs, prior to flow reduction*			
		All flows	*Q<2400*	*2400≤Q<2700*	*Q≥ 2700*
738.2	737.8	95%	50%*	100%	100%
738.1	737.8	91%	71%	100%	100%
738.0	737.7	73%	31%	85%	96%
737.9	737.6	**47%**	10%	64%	90%
737.8	737.5	34%	9%	59%	71%
737.7	737.4	22%	7%	22%	61%
737.6		17%	8%	33%	80%*
737.5		11%	<4%	28%*	72%*

Note: * Denotes that the probability was developed from a small sample size

Table 17. Probability of Extended High Water Levels (stages above 737.75 ft-msl) in the Upper Lakes If Outflow from Stratton Dam Is Reduced to 1800 cfs

Fox Lake level (ft-msl)	*Approximate level at Johnsburg (ft-msl)*	*Outflow (Q), in cfs, prior to flow reduction*			
		All flows	*Q<2200*	*2200≤Q<2400*	*Q≥ 2400*
738.1	737.8	98%	80%*	100%	100%
738.0	737.7	91%	67%	86%*	100%
737.9	737.6	77%	31%	71%	100%
737.8	737.5	52%	<4%	67%	89%
737.7	737.4	35%	<4%	36%	64%
737.6		21%	<4%	17%	59%
737.5		17%	<4%	23%	57%

Note: * Denotes that the probability was developed from a small sample size

the lake levels more quickly. Thus in most circumstances, it is expected that, by waiting a day or two to close the gates, there will be a significant drop in the lake level and a corresponding drop in the probability that gate closure will cause extended high water levels. However, there is always some probability of extended high water levels; and typically, when that probability is reduced to 10-15 percent, there is little additional advantage to waiting another day before closing the gates.

Proposed Sequence of Gate Closures Following a Flood or High Flow Event

It is believed that the information provided in Tables 13-17 may be most useful when applied in a step-by-step manner. For example, as flooding levels in the upper lakes recede below an elevation of 738.45 ft-msl, outflow from the dam can be reduced to approximately 3000 cfs, thus also causing an elimination of flood flows downstream of the dam. Outflows could remain at approximately 3000 cfs until the levels in the upper lakes fall below 738.0 ft-msl, at which point outflows could be reduced to 2250 cfs, or roughly the flow that allows the lakes and river to be reopened. Flows then could remain at the 2250 cfs level until the lakes fall to a level of 737.7 ft-msl, at which point the flows could be reduced to approximately 1800 cfs, or the flow needed to eliminate no-wake restrictions on the lake. Coincidentally, these gate closures closely mirror the gate openings that typically occur as lake stages rise.

The sequence of events presented in the foregoing example assumes that the lake levels continue to fall over time. Upon the reduction in outflows, the lake levels would likely stabilize before they would begin to recede again. Also it is possible at any time that, with additional rainfall, lake inflows would increase and the lake levels would start to rise. Under those conditions, the sequence of gate closures would be terminated, and the gates would be operated similarly to other inflow events.

This scenario also assumes that operation is occurring during the recreational boating season. It is believed that, during the winter season, there may be no need to reduce flows while the lakes are above the winter pool except that needed to eliminate downstream flooding. During the winter season, gate closures can mirror the common procedures used to open gates during high flows, and described earlier in the section on Common Operation Practices not Explicitly Stated in the Guidelines. An outflow of 3000 cfs may be maintained when the upper lake levels exceed 737.2 ft-msl. As the upper lake levels recede to an elevation of 736.6 ft-msl, the outflow from the gates may be gradually decreased to an outflow of 1800 cfs. These outflows can usually be maintained using free weir flow under the sluice gates. If necessary, the proposed hinged-crest gates could be used to maintain higher outflow from the dam at low pool elevations. As with other winter operations, these procedures will be modified during ice jams.

POTENTIAL CHANGES IN OPERATIONS

The potential operation changes given here are based on the historical flow records for the period 1948-1997, as evaluated in this report. They do not represent all possible flow conditions that could happen in the future. Flow forecasts of future flood events are expected to perform similarly to those simulated for past events; however, future experiences may appropriately lead to adjustments in the proposed guidelines. Significant changes in the precipitation and streamflow gage network used for flow forecasting may lead to increased forecasting accuracy and greater dependence of operations on its results. A re-evaluation of operations after the potential installation and initial performance of the proposed hinged-crest gates also would be appropriate.

The analyses in previous sections indicate that 27 of the 31 historical flood events during the period 1948-1997 could have been identified in advance of flooding using the criteria proposed below. The dates on which flood operations could have been initiated in these 27 flood events are provided in Table 8. These dates are provided as examples of circumstances similar to those when the following criteria could be used for future dam operations. As specified below, it is expected that the criteria could be used in the future to open both the sluice gates and the proposed hinged-crest gates. Four historical flood events would not have been identified in advance of flooding using these criteria. These floods occurred on the following dates: April 1, 1950, March 23, 1962, January 31, 1974, and March 5, 1985.

1. The adjusted flow forecast used in the remaining criteria is the peak flow forecast value produced by the FRF Model plus an additional flow adjustment based on the stage level on Fox Lake at the time the peak flow amount is initially forecasted, as detailed in Table 9. To maintain consistency with the findings in this report, the adjusted forecast value should not be updated during the remainder of the flood event unless there is additional runoff that creates a new peak in the inflow forecast.
2. If the adjusted flow forecast exceeds 7000 cfs, open sluice gates to the maximum setting and open the proposed hinged-crest gates.
3. If the adjusted flow forecast exceeds 5000 cfs, open sluice gates to provide an outflow of 3000 cfs. If necessary, such as at winter pool, open the proposed hinged-crest gates to increase the outflow up to, but not greater than, 3000 cfs.
4. If the adjusted flow forecast exceeds 5000 cfs and the discharge for the Nippersink Creek gage near Spring Grove gage exceeds 1300 cfs, set the sluice gates to the maximum setting and open the proposed hinged-crest gates.
5. If the adjusted flow forecast exceeds 6000 cfs, the Fox Lake stage is at least 738.1 ft-msl and the one-day increase in the Fox Lake stage is at least 0.4 foot, set the sluice gates to the maximum setting and open the proposed hinged-crest gates.
6. If there is a substantial snow pack on the watershed (>12 inches), maintain a discharge that keeps the lake elevations at or below the normal winter pool level, if possible, including using the proposed hinged-crest gates to increase discharge.

7. If none of the above conditions are met, continue to open the gates during flood events following current procedures.
8. As lake levels recede following a flooding event, it appears gate openings can be reduced shortly after the immediate flooding and high flow concerns have passed, without causing a significant increase in the probability of future flooding. However, if lake levels do not continue to recede after gate closure, measures to reopen the gates may be appropriate.

Figure 17 presents a decision-making flow chart that can be used for gate operations at Stratton Dam, applying the analytical results presented in this study as well as some current operation policies. Operation guidelines in the flow chart have been specified such that they can be used for both opening gates at the onset of flood operations and gate closings as the lakes are dewatered following a flood or high flow event. The flow chart does not provide any guidelines for gate operations under three conditions: lowering of lake levels in November for winter drawdown, the transition from winter pool to summer pool in the spring, and ice jams on the Fox River.

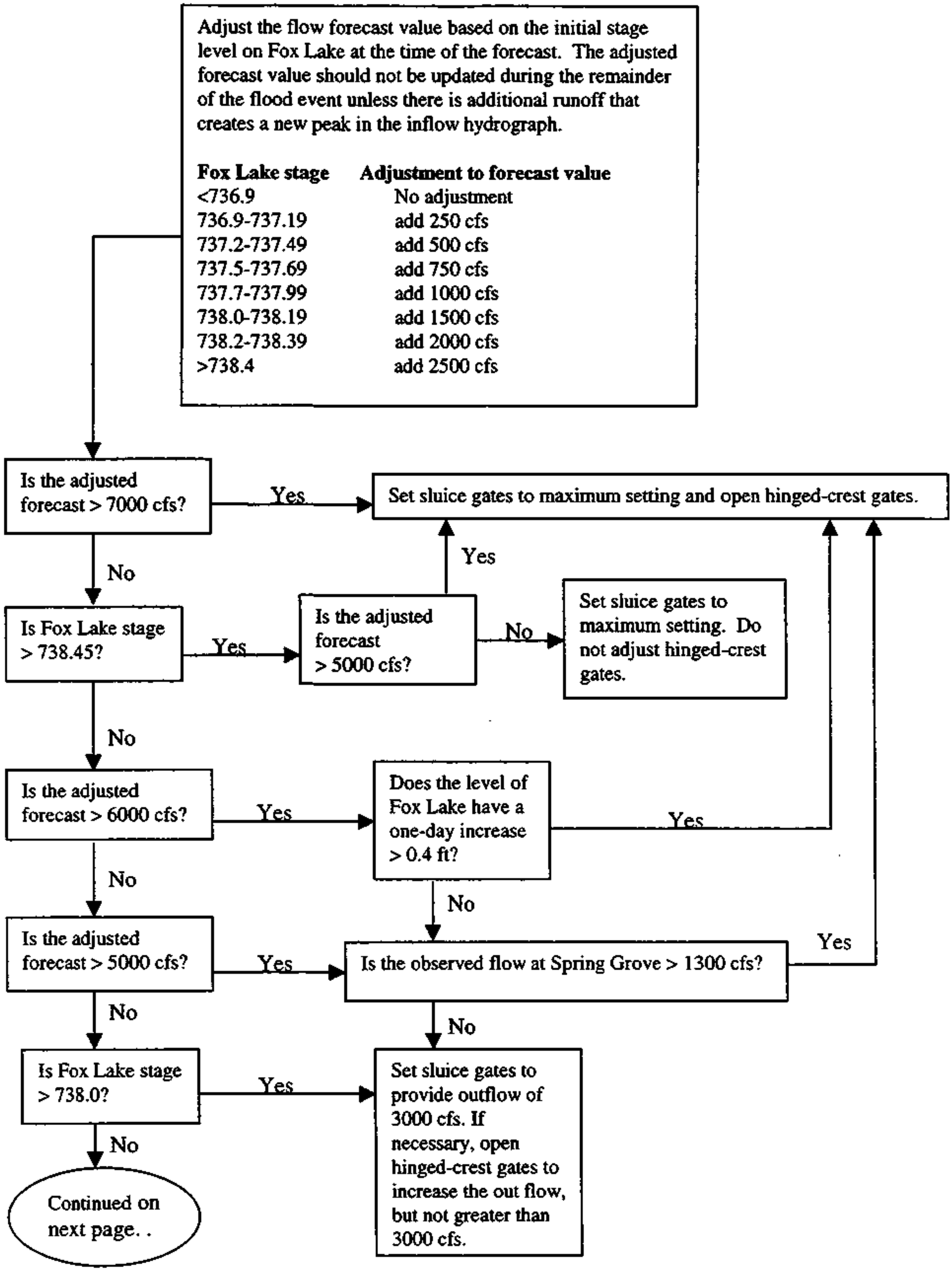
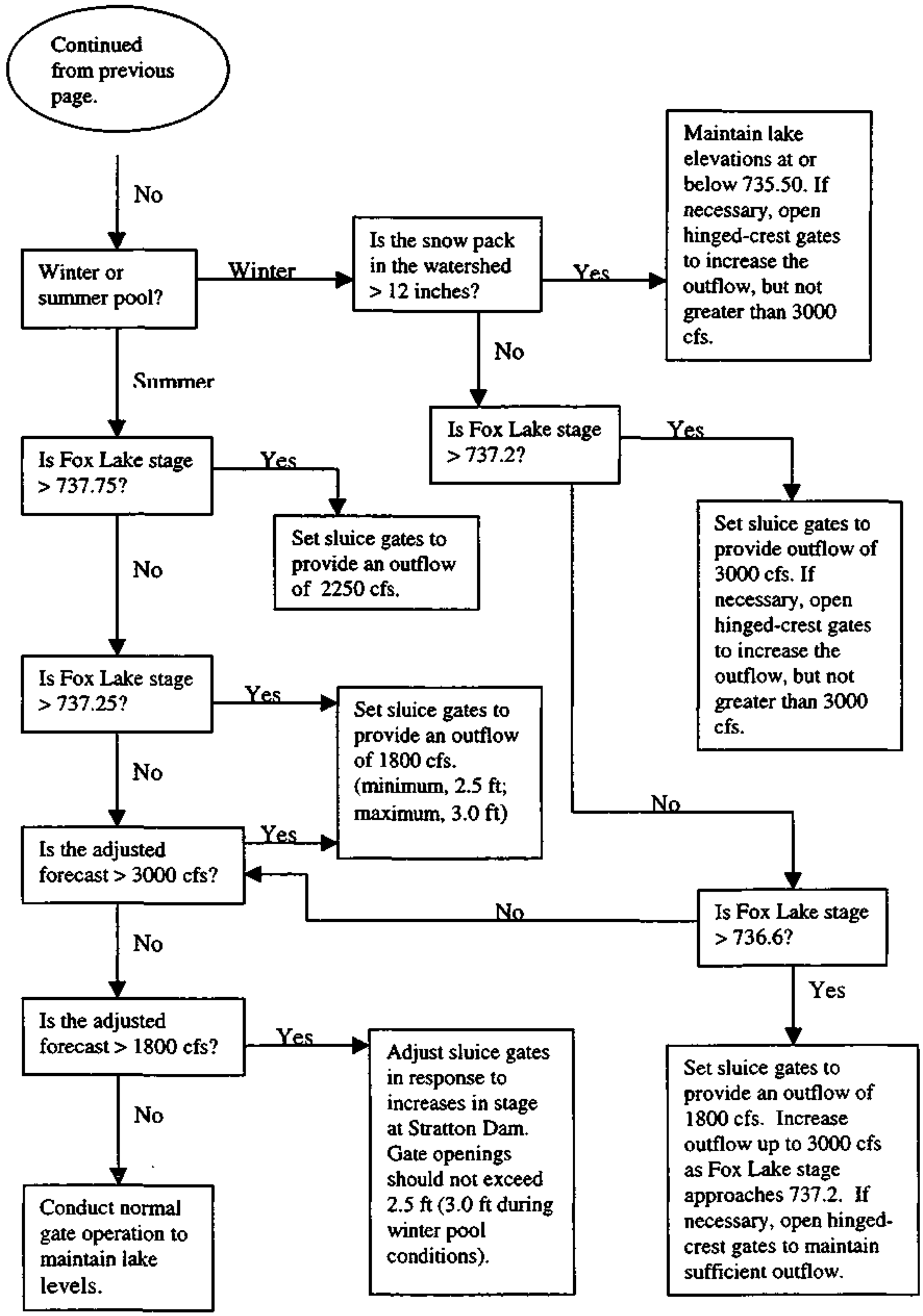


Figure 17. Flow chart for gate operation at Stratton Dam.


Continued from previous page.
No
Winter or summer pool?
Winter
Is the snow pack in the watershed > 12 inches?
Yes
Maintain lake elevations at or below 735.50. If necessary, open hinged-crest gates to increase the outflow, but not greater than 3000 cfs.
No
Summer
Is Fox Lake stage > 737.2?
Yes
Set sluice gates to provide outflow of 3000 cfs. If necessary, open hinged-crest gates to increase the outflow, but not greater than 3000 cfs.
Is Fox Lake stage > 737.75?
Yes
Set sluice gates to provide an outflow of 2250 cfs.
No
Is Fox Lake stage > 737.25?
Yes
Set sluice gates to provide an outflow of 1800 cfs. (minimum, 2.5 ft; maximum, 3.0 ft)
No
Is the adjusted forecast > 3000 cfs?
Yes
No
Is Fox Lake stage > 736.6?
No
Yes
Is the adjusted forecast > 1800 cfs?
Yes
Adjust sluice gates in response to increases in stage at Stratton Dam. Gate openings should not exceed 2.5 ft (3.0 ft during winter pool conditions).
Set sluice gates to provide an outflow of 1800 cfs. Increase outflow up to 3000 cfs as Fox Lake stage approaches 737.2. If necessary, open hinged-crest gates to maintain sufficient outflow.
No
Conduct normal gate operation to maintain lake levels.

CONCLUSIONS

The flow forecasts are not reliable enough to correctly anticipate all flood events. Most major floods will be correctly identified using the flow forecasts, but moderate floods may be missed. When a flow forecast misses, or underestimates an oncoming flood, the opportunity to lower lake levels prior to the flood is lost, and operations should continue using current guidelines. However, there are no direct negative impacts related to a missed forecast.

False alarms occur when a nonflooding event is overestimated. If dam operation treats these events as floods, there is a potential negative impact in causing overbank flooding downstream. To avoid false alarms, it is necessary to raise the threshold level of the forecast at which flood operations begin. The potential impacts of false alarms on flood damages are not fully understood. If there are no negative impacts under certain conditions, the threshold level for beginning flood operations could be lowered, providing more flood control benefit to a greater number of flood events.

Observed flows at the Spring Grove gage offer verification of many oncoming floods, and in some instances can be used to identify flood conditions of events missed by the flow forecast. Normally there is a one-day lag after the flow forecast is issued before the Spring Grove flows can be used to identify a flood.

Increasing stages in the upper lakes also can be used to identify and verify oncoming flood events. Using changes in stage is generally less useful than the flow forecast and observed flows at Spring Grove, in part because there is a greater lag before flood conditions can be identified.

The use of antecedent conditions for medium-range forecasting and possible water level control generally provided disappointing results, particularly relating to the use of soil moisture data. However, information on snow depth is useful in defining the amount of stored water in the basin and in estimating the general magnitude of spring flooding.

Flow forecasts in this report used all available precipitation data in the watershed. Operations based on a full set of precipitation data, therefore, will be expected to conform to the results of this report. Operations based on flow forecasts with incomplete precipitation have the potential to behave differently. Therefore, the reliable availability of precipitation within the current gage network is crucial for use in the model application. Installation of additional precipitation and streamflow gages will provide for greater conformity and improved analysis of flood potential.

Radar-based precipitation estimates by themselves do not provide sufficient accuracy in estimating watershed precipitation to be used in flow forecasting. Comparison of the radar precipitation image with measured precipitation gages can be useful in filling in gaps in the measured precipitation, but good coverage from gage measurements is still important in accurate estimation of watershed precipitation. Quantitative precipitation forecasts do not provide very good estimates of the average expected watershed precipitation, and they should not be used for major operation decisions. Strategically placed precipitation gages, providing a broad geographic coverage of the watershed, as yet still provide the best information for accurate estimates of watershed precipitation.

REFERENCES

Fisk, G.G. 1988. *Discharge Ratings for Control Structures at McHenry Dam on the Fox River, Illinois.* U.S. Geological Survey Water-Resources Investigations Report 87-4226. Urbana,IL.

Fontaine, T.A. 1991. Predicting Measurement Error of Areal Mean Precipitation During Extreme Events. *Water Resources Bulletin* **27**(3):509-519.

Fortune, M.A., K. Labas, and N.E. Westcott. 1995. *Accuracy of Point Rainfall Estimates from an 88-D Radar in the Cool Season: The Illinois Experience.* Preprints, 27th Conference on Radar Meteorology, Vail, CO, October 9-13, 1995, American Meteorological Society, Boston, MA.

Huff, F.A. 1970. Sampling Errors in Measurement of Mean Precipitation. *Journal of Applied Meteorology* **9**:35-44.

Illinois Division of Water Resources. 1993. *Operation of Stratton Dam.* Department of Transportation, Springfield, IL.

Illinois State Water Plan Task Force. 1983. *Instream Flow Protection: A Planning Standard for Illinois Streams.* Special Report No. 6 of the Illinois State Water Plan Task Force. Printed by the Division of Water Resources, Illinois Department of Transportation, and the Illinois Department of Conservation, Springfield, IL.

Klazura, G.E., and D.S. Kelly. 1995. *A Comparison of High Resolution Rainfall Accumulation Estimates from the WSR-88D Precipitation Algorithm with Rain Gage Data.* Preprints, 27th Conference on Radar Meteorology, Vail, CO, October 9-13, 1995, American Meteorological Society, Boston, MA.

Knapp, H.V., and T.W. Ortel. 1992. *Effect of Stratton Dam Operation on Flood Control Along the Fox River and Fox Chain of Lakes.* Illinois State Water Survey Contract Report 533.

Knapp, H. V., T.W. Ortel, and R.S. Larson. 1991. *Hydrologic Modeling of the Fox River Watershed.* Illinois State Water Survey Contract Report 518.

Reed, W.B., B.G. Olsen, and J.A. Schmidt. 1997. *An Evaluation of River Forecast Model Output for Simulations with and without Quantitative Precipitation Forecasts (QPF).* National Oceanic and Atmospheric Administration Technical Memorandum NWS SR-187. National Weather Service, Arkansas-Red Basin River Forecast Center, Tulsa, OK.

U.S. Army Corps of Engineers. 1984. *Interim Report, Fox River and Tributaries, Illinois: Feasibility Report with Final Environmental Impact Statement.* Chicago District.

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