Assessing Risk in Operational Decisions Using Great Lakes Probabilistic Water Level Forecasts

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ABSTRACT / A method adapted from the National Weather Service's Extended Streamflow Prediction technique is applied retrospectively to three Great Lakes case studies to show how risk assessment using probabilistic monthly water level forecasts could have contributed to the decision-making process. The first case study examines the 1985 International Joint Commission (IJC) decision to store water in Lake Superior to reduce high levels on the downstream lakes. Probabilistic forecasts are generated for Lake Superior and Lakes Michigan–Huron and used with riparian inundation value functions to assess the relative impacts of the IJC's decision on riparian interests for both lakes. The second case study evaluates the risk of flooding at Milwaukee, Wisconsin, and the need to implement flood-control projects if Lake Michigan levels were to continue to rise above the October 1986 record. The third case study quantifies the risks of impaired municipal water works operation during the 1964–1965 period of extreme low water levels on Lakes Huron, St. Clair, Erie, and Ontario. Further refinements and other potential applications of the probabilistic forecast technique are discussed.

The adverse consequences of extreme Great Lakes water level fluctuations on public and private interests are well documented (Levels Reference Study Board 1993). During low water level periods, such as those experienced in the 1920s, 1930s, and 1960s, commercial navigation suffers from loss of adequate navigation depths and reduced cargo capacity, hydropower generation is reduced, water intakes are exposed, and recreational use of the lakes is impaired. During high water level periods, such as those experienced in the 1950s, 1970s, and most recently in 1985 and 1986, shoreline property is damaged due to flooding and increased erosion, metropolitan sewer outfalls are submerged inhibiting discharge, and recreational use of beaches and marinas is impaired. Commercial navigation, which generally benefits from increased cargo capacity during high water periods, also experiences losses due to reduced speeds required to prevent shoreline damage from boat wakes in the connecting channels. In May 1993, commercial navigation was temporarily suspended on the St. Lawrence Seaway due to high velocities caused by record flows (released as a result of high levels) from Lake Ontario (International St. Lawrence Board of Control 1993).

During periods of extreme water levels, governments (local, state, and federal) and commercial and private interests are faced with making decisions regarding what actions, if any, they should take to avoid or mitigate damages and losses. They must weigh the risks (costs) of taking action versus no action. They must also decide when to take action. Because many measures take time to implement (i.e., construction of shore protection) or to become effective (i.e., deviations from lake regulation plans), decisions must be made well in advance of reaching critical water levels. Decisions also must be made with little certainty of future water levels. Recent analyses of state-of-the-art Great Lakes water supply and water level forecasts have shown that these forecasts are only marginally better than climatology for a one-month outlook and that their skill declines to the same or worse than climatology for a six-month outlook (Croley and Lee 1993, Lee 1992). Furthermore, the forecast skill cannot be significantly increased without improvements in long-range (30 days or more into the future) weather forecasting. In addition, the water level forecasts currently available to the public provide a deterministic, most probable forecast and/or a range of expected levels (US Army Corps of Engineers 1994, Canadian Hydrographic Service 1994). Probabilities of exceedance or nonexceedance are not explicitly given. The deterministic nature of these products leads users to rely too heavily on the midpoint of the forecasted range of levels; possibly resulting in flawed decision making.

KEY WORDS: Great Lakes; Water levels; Forecasting; Risk; Decision making

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Lake level statistics derived from the historical record using traditional frequency analysis (techniques developed for riverine systems) are not appropriate for assessing near-term risk either. These statistics do not reflect initial lake level and basin conditions and the strong autocorrelation in lake levels. The autocorrelation is present due to the large moisture storage capacity of the lake basins, the heat storage capacity of the lakes, and the restricted lake outlets. Potter (1990) and Buchberger (1991) demonstrated that the traditional frequency analysis approach overestimates risk when lake levels are low and underestimates risk when lake levels are high. Additionally, recorded lake levels reflect anthropogenic changes (lake regulation, channel dredging, watershed modifications) to the system made over time; a large portion of the historic record does not reflect the present hydraulic conditions of the system.

How then, can people affected by fluctuating Great Lakes water levels make decisions that depend on knowledge of future water levels? In addition, how do they measure the risks associated with their decision? As suggested by Croley and Lee (1993), the answer lies in the use of probabilistic forecasts. A probabilistic forecast gives the decision maker a range of outcomes with their associated probability of occurrence. This type of forecast was first applied to water resources by Day (1985) for streamflow forecasting. He presented the Extended Streamflow Prediction (ESP) procedure as an objective means for long-range hydrologic forecasting and the assessment of forecast uncertainty. This technique is now being adopted by the National Weather Service as part of their modernization program (National Oceanic and Atmospheric Administration 1993).

The ESP technique is adapted here to the circumstances of large-lake hydrology and is applied to illustrate the use of Great Lakes probabilistic water level forecasts in the assessment of risk for operational decision making. Three retrospective case studies are examined. The first case examines the risk of exceeding Lake Superior's upper regulation limit and Lakes Michigan–Huron's previous record level due to a 1985 International Joint Commission (IJC) decision to store water in Lake Superior to reduce high levels on the lower lakes (International Lake Superior Board of Control 1985). The probabilistic forecasts are used with riparian inundation value functions to assess the relative impacts of the decision on riparian interests of both lakes. The second case evaluates the risk of flooding at Milwaukee, Wisconsin, and the need to implement flood-control projects if lake levels were to continue to rise above the October 1986 record. The third case study looks at the risk involved to intake capacities of municipal water works on Lakes Huron, St. Clair, Erie, and Ontario during the low-water years of 1964 and 1965. Refinements of the forecast technique are suggested and other applications described. Recommendations are made to incorporate probabilistic forecasts in operational decision making in anticipation of future extreme Great Lakes water levels.

The Physical Setting

The Great Lakes are one of the Earth's most distinctive features and natural resources. The lakes contain 22,700 km^3 of water, which has been estimated to be 95% of the United States surface freshwater and 20% of the Earth's surface freshwater. The total land and water area of the basin is 781,000 km^2, with the surface area of the lakes comprising about 247,000 km^2, or one third of the total area. Eight US states (New York, Pennsylvania, Ohio, Michigan, Indiana, Illinois, Wisconsin, and Minnesota) and one Canadian province (Ontario) border the lakes' shoreline. The shoreline, including that of islands, is 18,400 km in length. The basin is home to about 37,000,000 American and Canadian citizens.

The five Great Lakes and Lake St. Clair comprise a natural series of storage reservoirs linked by connecting channels (rivers) and straits. Lake Superior is the most upstream lake and contains 53% of the total water of the system. Two diversions, the Long Lac and Ogoki, transport water from the Hudson Bay watershed to Lake Superior. Lake Superior has been regulated since 1921 by control structures located in the St. Marys River between the twin cities of Sault St. Marie, Michigan and Ontario.

The St. Marys River flows to Lake Huron, the level of which is 7 m below that of Lake Superior's. Lake Huron and Lake Michigan are connected by the deep Straits of Mackinac and act as one lake hydraulically (i.e., their average water levels are the same). The two lakes are often referred to as Lakes Michigan–Huron. The Chicago Diversion links Lakes Michigan–Huron with the Mississippi River Basin. Water from Lakes Michigan–Huron flows to Lake Erie via the St. Clair River–Lake St. Clair–Detroit River system. Lake Erie is only 2.4 m below the level of Lake Huron and exerts a backwater effect on Lakes Michigan–Huron.

Lake Erie, the smallest and shallowest of the five Great Lakes, empties into Lake Ontario via the Niagara River and Welland Canal, a man-made channel. No backwater effect occurs between Lake Erie and Lake Ontario due to the large change in elevation of the lakes, the majority of which occurs at Niagara Falls. The St. Lawrence River connects Lake Ontario to the Gulf of St. Lawrence and the Atlantic Ocean. Lake Ontario has

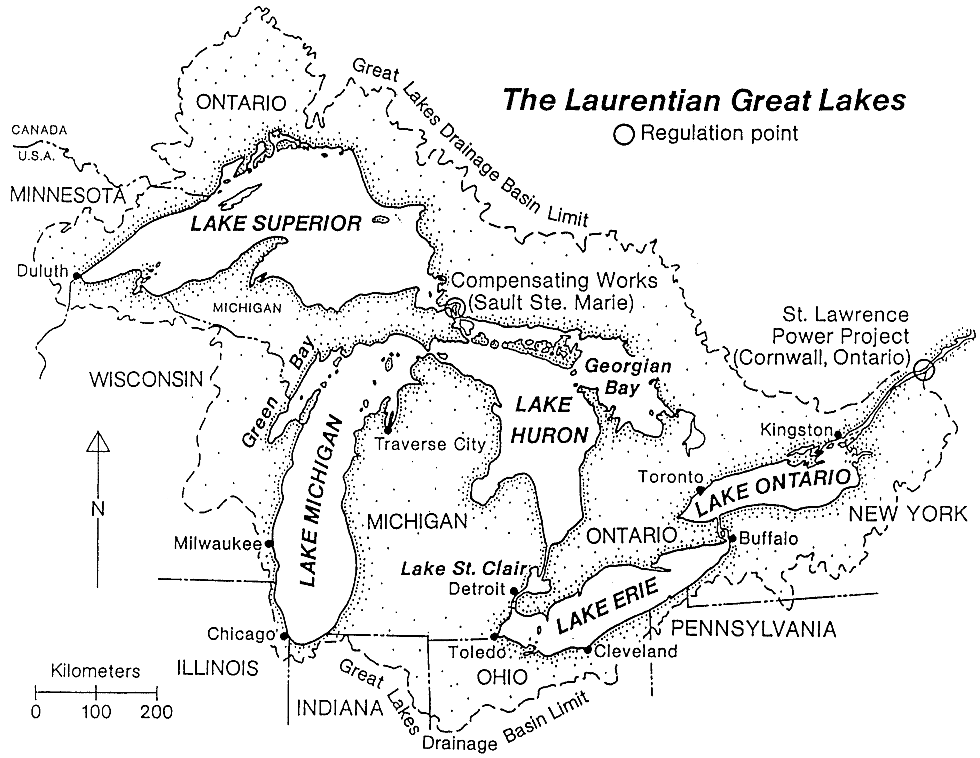

Figure 1. The Laurentian Great Lakes and their drainage basin.

been regulated since 1961 by structures located in the St. Lawrence River between Cornwall, Ontario and Massena, New York. Figure 1 illustrates the basin geography.

Because of questions arising between Canada and the United States over the shared waters of the Great Lakes, the Boundary Waters Treaty of 1909 was signed between Great Britain and the United States. The treaty established the IJC and gave it quasijudicial authority over matters concerning the quantity and quality of boundary waters along the length of the United States–Canadian border. The IJC's Boards of Control have the primary responsibilities for matters related to lake levels and connecting channel flows.

Adaptation of ESP Forecast Approach to Great Lakes Probabilistic Water Level Forecasts

The ESP procedure (Day 1985) uses conceptual hydrologic models to produce alternative future scenarios of stream flows using periods of historical meteorological data and current watershed conditions as initial conditions. Frequency analysis is then performed on the streamflow scenarios to derive a probabilistic forecast. Similarly, for each of the following case studies, alternative Great Lakes water level scenarios were produced by routing scenarios of historical water supplies through a hydrologic response model of the Great Lakes, using recorded lake levels and outflows for initial conditions. Because the historical water supplies exhibit monthly and annual autocorrelation (Buchberger 1994), the scenarios use temporally continuous sequences of historical supplies for multimonth forecasts. Because the supplies also exhibit cross-correlation from lake to lake (Buchberger 1994), temporally concurrent water supply sequences are used for multilake forecasts.

Ninety years (1900 to 1989) of historical monthly water supplies are available for use in producing the alternative water level scenarios. These supplies have been computed for each of the Great Lakes and Lake St. Clair by the US Army Corps of Engineers and Environment Canada. Quinn (1981) has shown that this period spans two distinct climate regimes. The first, a relatively dry regime, existed from the mid-1880s through 1939. The second, a relatively wet regime, was identified for 1940 through 1979 (the last year of data available to Quinn for analysis). For the purposes of this paper, the wet regime is considered to extend through 1986, based on the observations of record-setting high lake levels and supplies that have occurred since 1979. Herche and Hartmann (1990) and Keillor (1990) have shown the importance of conditioning water level probabilities on climate regime, in addition to initial lake levels and length of planning horizon. Therefore,

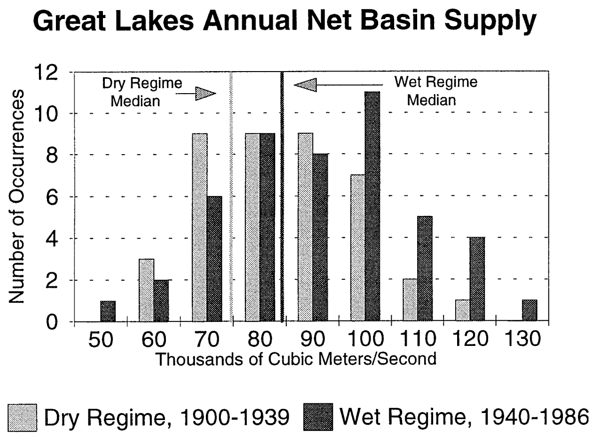

Figure 2. Distribution of Great Lakes annual net basin supplies for a dry regime (1900–1939) and a wet regime (1940–1986).

for the following case studies, the alternative water supply scenarios were chosen from the 1900–1939 period if the decision makers were more risk averse to falling water levels, and from the 1940–1986 period if they were more risk averse to rising water levels. The differences in the two regimes are illustrated by their distributions of annual water supplies shown in Figure 2.

The alternative water supply scenarios were routed through a hydrologic response model obtained from Environment Canada. This model embodies the Lake Superior and Lake Ontario regulation plans [as modified by Lee and others (1994) to incorporate rules of operation for extreme conditions] and middle lakes stage–discharge relationships. The hydraulic conditions of the system (lake outlet conditions, diversion rates, and ice and weed retardation) used in the routing are summarized in Table 1. Initial conditions of lake levels and outflows were taken from values published by the National Ocean Service and the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, respectively or forecast summary sheets from the US Army Corps of Engineers.

For each month of an extended (multimonth) outlook, the water levels resulting from the routed alternative water supply scenarios were ranked and probabilities assigned using the empirical distribution (Linsley and others 1982):

$$p_i(x) = \frac{m_i}{n_i + 1} \qquad (1)$$

where p_i is the probability of water level x being equaled or exceeded in a given month i, and n_i is the number of historical water supply scenarios available for that month. The variable m_i is the rank assigned to the water levels, sorted in descending order. The highest water level has $m_i = 1$; the lowest, $m_i = n_i$. The probability of nonexceedance is calculated by subtracting p_i from unity. For ease in interpreting the results, probabilities of exceedance are used for the case studies concerned with high water levels, and probabilities of nonexceedance are used in the case study concerned with low water levels. The empirical distribution for each month of the outlook was then interpolated to determine water levels associated with even intervals of exceedance (or nonexceedance) probabilities, and the results plotted to produce a probabilistic forecast. This probabilistic forecast technique is illustrated by the following case studies.

Table 1. Hydraulic conditions of the Great Lakes system[a]

Item	Conditions
Diversion rates	A constant Chicago diversion of 91 m^3/sec out of Lake Michigan A constant Long Lac and Ogoki diversion of 153 m^3/sec into Lake Superior, the average of recorded monthly flows 1944–1989 Monthly mean values of the Welland Canal diversion from Lake Erie into Lake Ontario based on the recorded monthly flows March 1973 to December 1989
Outlet conditions	Lake Superior outflows determined in accordance with Plan 1977-A (as modified by Lee and others 1994) Lake Ontario outflows determined in accordance with Plan 1958-D (as modified by Lee and others 1994) Lake Huron and Lake St. Clair channel conditions since the completion of the 8-m navigation channel dredging in 1962 Niagara River channel conditions representative of the period 1974–1986
Ice and weed retardation	St. Clair and Detroit River monthly median retardation values based on computed retardation from 1962 to 1989 Niagara River monthly average values of weed retardation computed for 1974 through 1989 and median ice retardation values as computed from 1974 through 1989

[a]Diversion rates, channel outlet conditions, and flow retardation rates used in routing the alternative water supply scenarios through the Great Lakes hydrologic response model.

Assessment of Risk in Great Lakes Operational Decision Making: Three Case Studies

Case Study 1: Lake Regulation

As described previously, Lake Superior is one of the two regulated Great Lakes, the other being Lake Ontario. The regulation of Lake Superior is conducted under the auspices of the IJC and its International Lake Superior Board of Control. The criteria, or guidelines, for the regulation of the lake are set forth in orders and supplementary orders of approval issued by the IJC. A regulation plan that strives to satisfy these criteria has been developed for the operational regulation of the lake. The main objective of Lake Superior's regulation plan is to specify an outflow from Lake Superior for the coming month that balances the levels of Lake Superior and Lakes Michigan–Huron relative to their long-term monthly mean levels. The plan strives to maintain Lake Superior levels between 182.39 m and 183.49 m [the reader should note that all water levels given here are referenced to the International Great Lakes Datum of 1955 (IGLD 55)]. In actual practice, when extreme water supplies and lake levels are experienced, the regulatory works are operated under the direction of the IJC to best meet the needs of the various interests. Such were the circumstances for the following case study, compiled from reports by the Crises Conditions Task Group (1993) and the International Lake Superior Board of Control (1985).

In December 1984, Lakes Michigan–Huron, St. Clair, and Erie water levels ranged between 40 and 50 cm above their long-term average and were approaching the record levels of 1973–1974 (Lakes Michigan–Huron experienced its record monthly mean level of 177.10 m in July 1974, as recorded at Harbor Beach, Michigan). Lake Superior was 14 cm above its long-term average. In early 1985, heavy precipitation over the middle lakes' basins caused their water levels to begin to rise rapidly. In response to public concerns of flooding, the IJC took steps in April of that year to mitigate the high water conditions. The IJC instructed the Lake Superior Board of Control to reduce outflows by 850 m^3/sec (about one third of those prescribed by the regulation plan), while not exceeding the upper regulation limit of 183.49 m. The reduction in flows increased Lake Superior storage and reduced levels of the downstream lakes. The IJC's instructions included limiting the flow through the Compensating Works, a gated control structure at the head of the St. Marys Rapids, as well as a reduction in the water available for power production. The reduction of flows was initiated in the beginning of May with Lake Superior at an elevation of 183.14 m and Lakes Michigan–Huron at an elevation of 177.00 m. In addition, at the request of the IJC to Ontario Hydro, water normally diverted into Lake Superior via the Ogoki Diversion Project, on average about 113 m^3/sec, was stored in Lake Nipigon from July to August 21 and then redirected to its natural drainage course (the Hudson Bay watershed) for the remainder of the year. The

Table 2. Effects of deviations from Lake Superior's regulation plan on lake levels[a]

	Change in lake level (m)			
Month	Lake Superior	Lakes Michigan–Huron	Lake St. Clair	Lake Erie
April	0	0	0	0
May	+0.02	−0.02	−0.01	0
June	+0.05	−0.04	−0.02	0
July	+0.08	−0.05	−0.03	−0.01
August	+0.11	−0.07	−0.04	−0.02
September	+0.11	−0.07	−0.04	−0.03
October	+0.07	−0.04	−0.03	−0.03
November	+0.05	−0.03	−0.03	−0.03
December	+0.04	−0.02	−0.02	−0.03

[a]Changes in lake levels for April–December 1985 due to the IJC's decision to store water on Lake Superior (International Lake Superior Board of Control 1985).

maximum effect of these actions occurred in September. Lake Superior levels were raised by about 11 cm, Lakes Michigan–Huron levels decreased 7 cm, and Lakes St. Clair and Erie levels were lowered by about 4 and 3 cm, respectively. The effects for the months of April–December for each lake are summarized in Table 2.

The reduction of Lake Superior outflows was discontinued in early September as Lake Superior's level approached 183.49 m due to heavy precipitation on its basin in August. At that time, the precipitation was estimated to be 35% above average. Lake Superior outflows were increased above those specified by the regulation plan to avoid exceeding 183.49 m and to eliminate the excess storage. Release of outflows through the Compensating Works was somewhat hindered due to construction of the Fishery Remedial Works in the St. Marys Rapids below the control structure. This project, initiated by the Ontario Ministry of Natural Resources, was designed to elevate the water surface profile along the shore of Whitefish Island to enhance fish habitat. A concrete dike was constructed parallel to the island, and a culvert to divert flow from the Sault Ste. Marie Canal to the Whitefish Channel was put in place. The construction, which began in July, was completed in December. During this period, combinations of limited gate openings and free flow through navigation locks (the American Sabin and Davis navigation locks and the Canadian lock) were used to obtain the desired Lake Superior outflows (in addition to the usual release of water through the American and Canadian hydropower facilities) while limiting water in the area of construction. The American locks sustained some minor damage during this time.

Despite the increased flows, monthly Lake Superior levels of 183.53 m and 183.52 m were reached in

October and November, respectively. By December, the monthly mean elevation had fallen to 183.43 m. Deviations from the regulation plan were discontinued at the end of March 1986, at which time 3 cm (over-lake depth) of excess storage remained on Lake Superior, and flows were again specified according to the regulation plan. The excess storage was eliminated between January and April of 1988 (N. Noorbakhsh, US Army Corps of Engineers, Detroit, Michigan, personal communication, 1995). Although the Lake Superior regulatory action did accomplish a small, temporary reduction in Lakes Michigan–Huron and Lake Erie levels, the levels of these two lakes continued to rise, setting record high levels in 1986.

What was the risk of exceeding Lake Superior's upper regulation limit if no action had been taken? What was the risk of exceeding Lake Superior's upper regulation limit with the proposed actions? What was the risk of exceeding Lakes Michigan–Huron's previous record water levels in either circumstance? As noted earlier, Potter (1990) and Buchberger (1991) showed that the traditional frequency analysis approach underestimates risk when lake levels are high. Knowledge of these risks would have aided the IJC in assessing whether the risk in exceeding Lake Superior's upper regulation limit was greater or less than the risk of exceeding Lakes Michigan–Huron's previous record levels. Additionally, this information could have been applied in considering postponement of construction of the Fishery Remedial Works.

The adapted ESP method described previously was applied to estimate these risks. Because the decision makers would have been risk averse to higher water levels, alternative water supplies for May through December were selected from the recorded data for the wet regime from 1940 through 1984. Data for the years 1985 and 1986 were not used, as this data would not have been available in 1985. These alternative scenarios were then routed to obtain scenarios of lake levels using the hydrologic response model and recorded initial conditions of lake levels and outflows for May 1985. To replicate the IJC's proposed regulatory actions, outflows projected by the regulation plan were reduced by 850 m^3/sec for May through October. The resulting probabilistic outlooks of lake levels for Lake Superior in the case of no reduction in outflows (no action), and the proposed reductions (action), are shown in Figures 3A and B, respectively. Similarly, Figures 3C and D show the results for Lakes Michigan–Huron. The monthly mean lake levels recorded at Pt. Iroquois, Michigan, on Lake Superior and Harbor Beach, Michigan, on Lake Huron are also shown for reference in Figures 3B and D, respectively. It should be noted that the Lake Superior regulation plan used for this case study is Plan 1977-A. In 1985, Plan 1977 was in use. Plan 1977-A incorporates some refinements and an extended historical reference (1900–1986 vs 1900–1976). In our experience, the plans produce very similar results, and the use of Plan 1977-A is satisfactory for illustrating the use of probabilistic outlooks and assessment of risk.

Table 3 summarizes the risks of exceeding 183.49 m on Lake Superior and 177.10 m on Lakes Michigan–Huron for May through December 1985. From this table, it can be seen that the proposed actions reduced the probability of Lakes Michigan–Huron exceeding 177.10 m, especially for June through October. The monthly exceedance probabilities were reduced for these months from a range of 12%–59% (no reduction in Lake Superior outflows) to 2%–34% (with reduction in Lake Superior outflows). The greatest reduction of risk occurred for July and August, with the probability of exceeding 177.10 m decreasing from 59% to 34%, and 52% to 18%, respectively.

Consistent with the reduction in Lake Superior outflows, the risk of Lake Superior exceeding its upper regulation limit of 183.49 m increased significantly for July through December. For these months, the probability of exceeding 183.49 m increased from a range of 2%–6% to 9%–40%. The greatest increase in risk of exceeding the upper regulation limit occurred for August, September, and October. With the reduction in outflows, the risk of Lake Superior exceeding its upper regulation limit became greater than the risk of Lakes Michigan–Huron exceeding its previous record level for August through December. The significant increase in risk of high Lake Superior levels (and the corresponding potential for high outflows) could have been weighed in the decision to begin construction of the Fishery Remedial Works.

It should be noted that these results are biased by the limited number of water-supply sequences available to obtain water level scenarios (1940–1984). For example, the highest annual precipitation on the Great Lakes basin was recorded in 1985, and the highest monthly precipitation was recorded in September 1986, but these years were excluded from our sample for the reasons given earlier. If they had been included, the probabilities of exceeding the two lakes' levels of concern would be higher. Better estimates of the risk could be obtained with a longer historical record or many stochastically generated water supply sequences.

With the risks of the action quantified, the decision to take action becomes a policy decision. Should one group's risk be increased to decrease the risk of another group? Can these risks be related to potential gains or losses by users of the lakes? In the recently completed IJC Levels Reference Study, an optimization approach was employed to assess the impacts to various interests

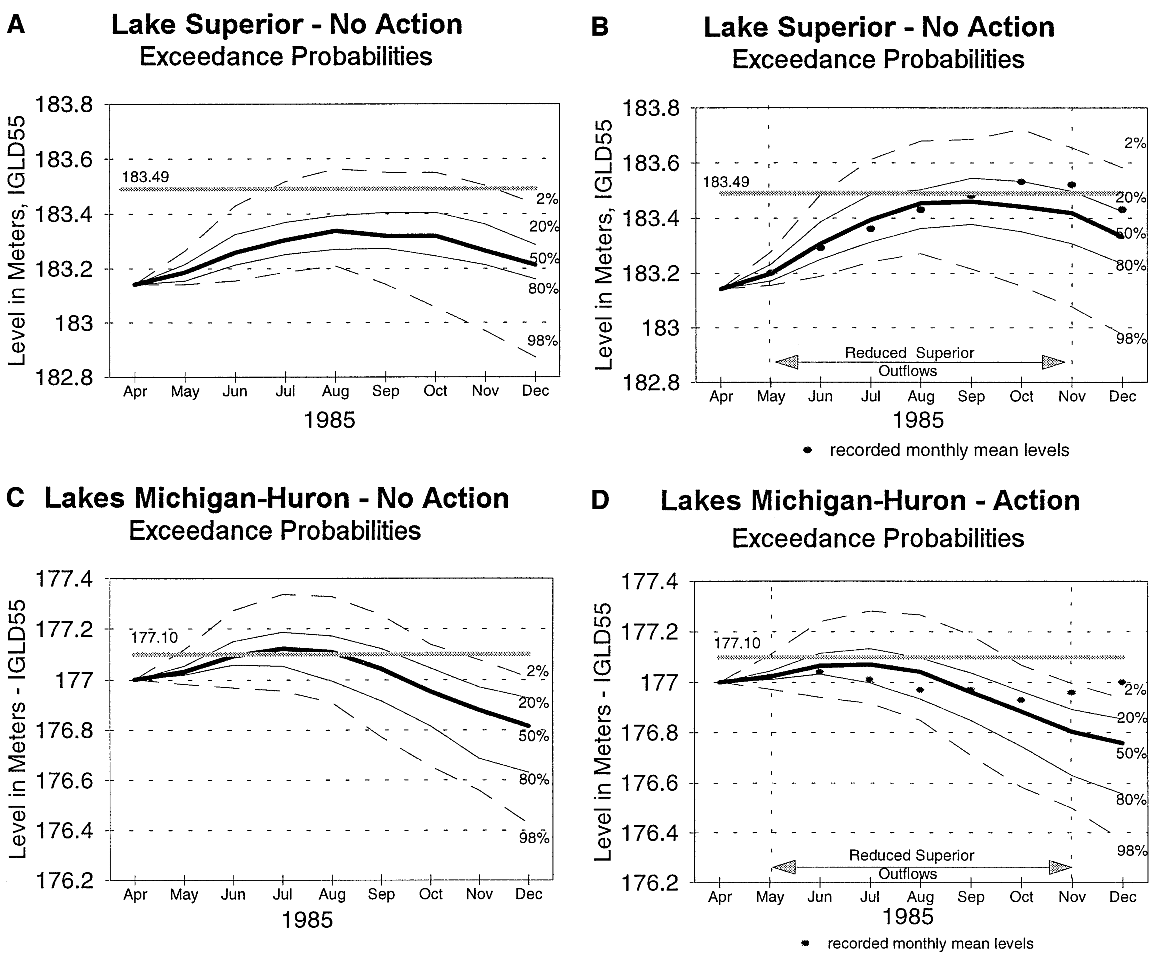

Figure 3. Probabilistic forecasts (case study 1) of Lake Superior and Lakes Michigan–Huron water levels for April to December 1985, with (action) and without (no action) reduced Lake Superior outflows: (**A**) Lake Superior—no action, (**B**) Lake Superior—action, (**C**) Lakes Michigan–Huron—no action, and (**D**) Lakes Michigan–Huron—action.

Table 3. Probabilities of exceeding Lake Superior's upper regulation limit (183.49 m) and Lake Michigan–Huron's 1973 record high level (177.10 m) for May–December 1985[a]

	Lake Superior, probability of exceeding 183.49 m (%)			Lakes Michigan–Huron, probability of exceeding 177.10 m (%)		
Month	No action	Action	Increase in risk	No action	Action	Decrease in risk
May	<2	<2	0	3	3	0
June	<2	<2	0	42	27	15
July	3	14	11	59	34	25
August	5	30	25	52	18	34
September	6	40	34	24	8	16
October	5	37	32	12	<2	$10 > P < 12$
November	4	24	20	<2	<2	0
December	<2	9	$7 > P < 9$	<2	<2	0

[a]Action—with the IJC's decision to store water on Lake Superior; no action—with no storage on Lake Superior.

of lake regulation alternatives. The five-year study examined methods that could alleviate problems associated with Great Lakes–St. Lawrence River system fluctuating water levels and outflows. Functions were developed that express the value of a particular water level to an interest group (Task Group 1 1993). One set of relationships, the riparian inundation value functions, relates inundation damage to still-water levels. For the pur-

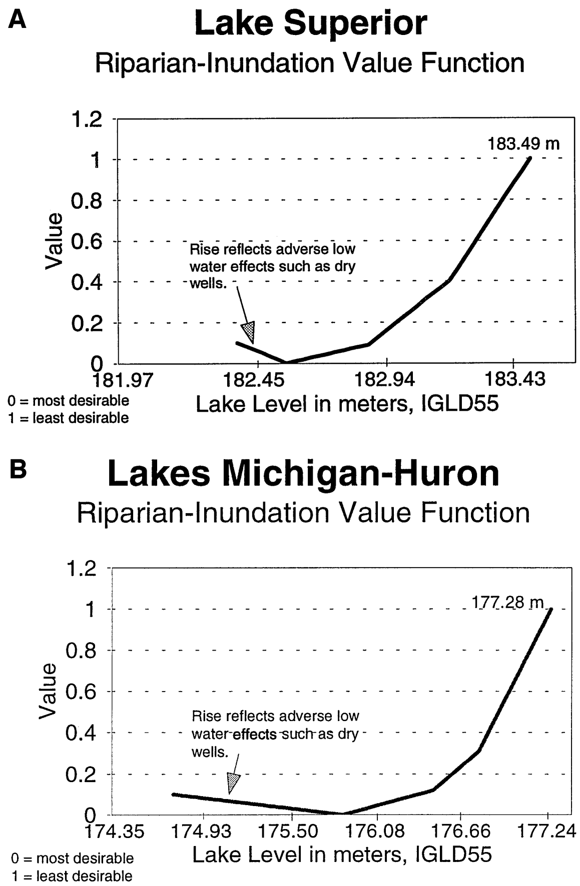

Figure 4. Riparian-inundation value functions relating inundation damage to monthly mean lake levels: (**A**) Lake Superior, and (**B**) Lakes Michigan–Huron (Task Group 1 1993).

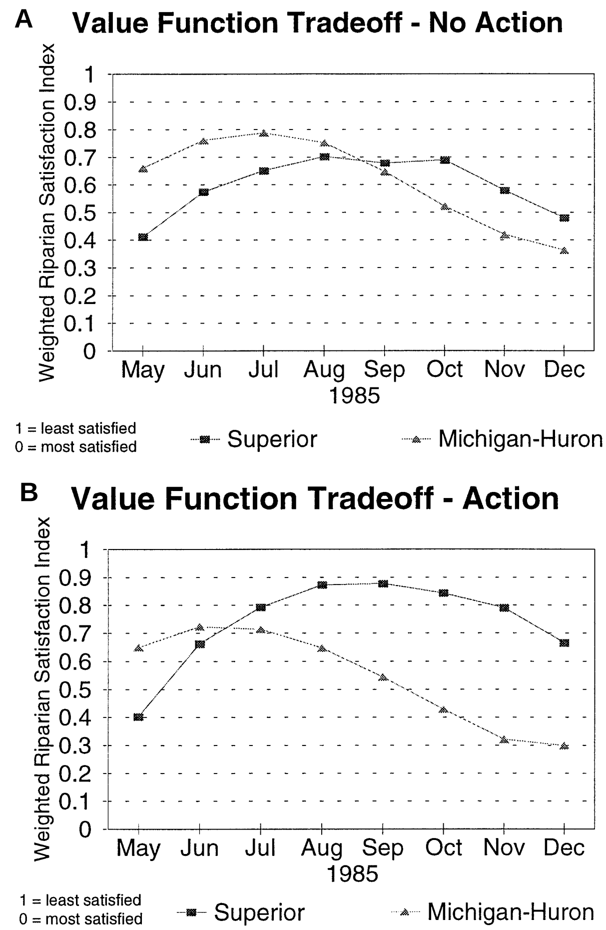

Figure 5. Weighted riparian satisfaction index relating riparian satisfaction with probable lake levels for May to December 1985 for Lake Superior and Lakes Michigan–Huron: (**A**) without (no action), and (**B**) with (action) reduced Lake Superior outflows.

poses of the study, a riparian was defined as "any individual who owns property that borders on the Great Lakes–St. Lawrence River system." Figures 4A and B show the riparian inundation value functions developed for Lake Superior and Lakes Michigan–Huron, respectively. The values range from 0, the most desired condition, to 1, the least desired condition. These functions can be used with the probabilistic forecasts to develop a weighted riparian satisfaction index (WRSI) to assess the impact of a policy decision on an interest. The WRSI provides a normalized comparison of the impacts on riparians of potential changes in lake levels and represents probable levels of satisfaction, with values ranging from 0 (satisfied) to 1 (least satisfied). The index, calculated for each month, i, of a probabilistic forecast, is expressed as

$$WRSI_i = \sum_x V(x)p'_i(x) \qquad (2)$$

where $p'_i(x)$ is the probability of occurrence of water level, x, for month, i, and $V(x)$ is the value of the riparian inundation value function at water level x. Value functions for other Great Lakes interests could be substituted in equation 2 to assess impacts on them. In the cases of navigation and recreational boating interests, $V(x)$ is a function of the month and would be represented in equation 2 as $V_i(x)$. The probability of occurrence, $p'_i(x)$, was determined numerically from the empirical cumulative probability function $p_i(x)$ (equation 1).

Figures 5A and B show the Lake Superior and Lakes Michigan–Huron WRSI, without (no action) and with reductions (action) in Lake Superior outflows, respectively, for May through December 1985. With no action, Lake Superior's WRSI would have been less than that of Lakes Michigan–Huron for May through August. Lakes Michigan–Huron property owners would have most likely been less satisfied than Lake Superior property owners. For these months, Lake Superior's WRSI increases from a value of 0.40 to 0.70, while Lakes Michigan–Huron's ranges from 0.65 to 0.79. The situation reverses for September through December, with Lake Superior's WRSI higher (and Lake Superior property owners less satisfied) than those of Lakes Michigan–Huron's. For these months, Lake Superior's values range from 0.69 to 0.48, while Lakes Michigan–Huron's range from 0.65 to 0.36. With the action to reduce Lake Superior outflows, Lake Superior's WRSI remains lower than that of Lakes Michigan–Huron's for only two months, May and June. Lake Superior's WRSI quickly rises from 0.4 in May to nearly 0.9 for August–October. In contrast, Lakes Michigan–Huron's WRSI rises from 0.65 in May to 0.72 in June, then falls below Lake Superior's WRSI for July to December, ranging from 0.71 to 0.30. The largest divergence between Lake Superior's and Lakes Michigan–Huron's WRSI values occurs in November, with Lakes Michigan–Huron's value (0.32) half that of Lake Superior's value (0.79). Figures 5A and B help to illustrate clearly the trade-offs inherent in the IJC's decision to store water on Lake Superior.

No judgement is made here on the action that was taken. Impacts of the action on the Lake St. Clair and Lake Erie water levels also have to be considered, as well as other complex factors the decision makers had to evaluate that have not been discussed here. What is offered here is another tool to add information to the decision-making process.

Case Study 2: Flood Protection

Despite the actions taken in 1985 to reduce Lakes Michigan–Huron water levels, as discussed in the previous case study, Lakes Michigan–Huron's levels continued to rise and set record high water levels throughout 1986. As recorded at Milwaukee, Wisconsin, the maximum monthly lake level of 177.36 m occurred in October of that year. In November, concerned that the trend of rising lake levels would continue, the Milwaukee County Board of Supervisors requested the Southeastern Wisconsin Regional Planning Commission to prepare a prospectus for a possible study of the impacts of high Lake Michigan water levels on the area surrounding the Milwaukee Harbor (downtown Milwaukee). Potential problems from increasing lake levels, as cited in the completed prospectus (Southeastern Wisconsin Regional Planning Commission 1987), included the flooding of lands in the Menomonee River Valley and other riverine areas along the Milwaukee Harbor estuary; the flow of inner harbor estuary waters back over diversion gates into intercepting sewers and, through sewer surcharging, into basements; impaired flows from storm sewers and industrial and other clearwater discharge pipes; very high groundwater levels affecting the infiltration and inflow of clear waters into sewers, utility tunnels, and basements; the flooding of transportation facilities; and overland flooding of major utility installations such as the Jones Island sewage treatment plant.

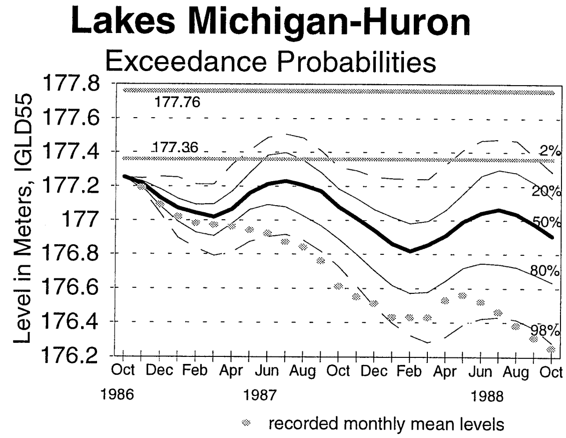

Figure 6. Probabilistic forecast (case study 2) of Lake Michigan water levels for October 1986 to October 1988.

Another of the planning commission's ongoing studies, the Milwaukee Harbor Estuary Study, concluded that as long as lake levels did not exceed 177.76 m, damages from direct overland flooding problems would be localized. At that level, the flood hazard area would encompass about 85 ha and 168 structures. If Lakes Michigan–Huron levels were to continue to rise above 1985 levels, the preparation of a contingency plan for flood protection was recommended. The commissioning of the prospectus was in effect the first step in fulfillment of that contingency plan recommendation. The prospectus estimated the cost of preparing this plan would be $253,200. The Milwaukee County Board of Supervisors was faced with the decision as to whether the plan should be prepared. Knowledge of the probability of the lake exceeding 177.76 m in the 12–24 months following October 1986 could have been useful in assessing the imminent risk of flooding and aided the board in making its decision.

The adapted ESP method was applied to estimate these risks. Because the decision makers were risk averse to rising water levels, the alternative water supplies were selected from the wet climate regime. Water supplies for 24-month periods, beginning in November for the years 1940 through 1985 (the data that would have been available in 1986), were routed using the Great Lakes hydrologic response model and recorded initial conditions of lake levels and outflows for the month of November 1986. Probabilities of exceedance were computed based on the resulting lake level scenarios; the results are shown in Figure 6.

These results show that during the next 24 months, the probability of exceeding 177.36 m (recall that this was the record high of October 1986) was 21%, 22%, and 19% for the upcoming months of June, July, and August, respectively. For the remainder of the 24 months, the probability of exceedance was substantially less. The probability of exceeding 177.76 m was much less than 2%. The 2% exceedance line peaked in July 1987 at 177.5 m, 26 cm below the prospectus' critical flood level. With this information, the Milwaukee Board of Supervisors could have made the decision that a contingency flood plan was not needed with a high level of confidence at a time of record high levels. Of course, as in the first example, these estimates of risk are biased by the limited number of water supply scenarios available. Ideally, a better understanding of climate trends is required to assist in selecting or simulating the water supply scenarios.

The prospectus commissioned in November 1986 by the Milwaukee Board of Supervisors to review the need for a flood protection plan was published a year later in December 1987. The prospectus recommended the development of the flood protection plan if levels were to continue rising. Ironically, Lake Michigan levels had begun to decline in response to below average precipitation in the winter and spring of 1987, and by December 1987, the lake was at an elevation of 176.51 m, 0.85 m below the October 1986 high, and 1.25 m below the proposed flood level. In fact, this was an unprecedented drop in lake levels. Figure 6 shows that the actual 1987 and 1988 lake levels at times fell near the 2% nonexceedance (98% chance exceedance) line of expected probabilities. This shows that the adapted ESP approach also provides a good estimate of the probable range (with 96% probability of occurrence) of expected lake levels.

Case Study 3: Municipal Waterworks Operation

In early 1964, Lakes Michigan–Huron began setting record low levels, and Lakes Erie, St. Clair, and Ontario were approaching their record low levels established in the mid-1930s (1934–1936). The Great Lakes were experiencing a downward trend in lake levels that had begun after record high levels occurred in 1952. Critically low levels were experienced during the winter months at the end of 1964 and the beginning of 1965. Late in 1964, the International St. Lawrence River Board of Control requested the Ontario Water Resources Commission to conduct a survey of the impacts of low water levels on the operation of major Canadian water works intakes and wastewater outfalls (Ontario Water Resources Commission 1965). Initially, the survey focused on Lake Ontario and the St. Lawrence River but was expanded in early 1965 to include the entire Canadian Great Lakes shoreline.

The survey resulted in information for 75 municipal water works installations, 24 of which were experiencing problems due to low lake levels. Although included in the survey, no problems were reported for Lake Superior as levels were not as critical as on the downstream lakes. Three types of problems were being experienced: (1) reduced intake capacities due to loss of available head, and the associated problems of increased pumping costs and pump cavitation; (2) deterioration in water quality near intakes located in shallow depths due to reduced dilution of surface runoff and increased turbidity from wave action; and (3) increased frazil ice development on intakes due to reduced water depths. More than 500,000 people were affected by these problems. Table 4 summarizes the information collected from the 24 water works installations experiencing problems.

Reduced intake capacity, resulting in water shortages and failure to meet maximum demand, was the most prevalent problem. Many of the facilities installed inline intake pumps, installed new or temporary intakes, or modified existing intakes. A probabilistic water level forecast may have assisted many of the facility operators in anticipating the problems and preparing for them ahead of time. After experiencing the low water levels in the winter of late 1963/early 1964, the operators may have been concerned that water levels in late 1964/early 1965 would be even more critical (lake levels usually reach their seasonal minimums during the period of November to March). As mentioned earlier, Potter (1990) and Buchberger (1991) have demonstrated that the traditional frequency analysis approach overestimates risk when lake levels are low. A probabilistic forecast made at the beginning of the seasonal decline in levels (about the end of July) would have enabled decision makers to estimate the risk of experiencing reductions in intake capacity and provided them with the time to take the necessary actions during the fall months.

For this case study, we made probabilistic water level forecasts for Lakes Michigan–Huron, Lake St. Clair, Lake Erie, and Lake Ontario for August 1964 to July 1965. The forecasts were produced as previously described, with some modifications. Because the decision makers would be risk averse to falling lake levels, the alternate water supply scenarios used were those of 1900–1939, the dry climate regime. Several of the hydraulic regime conditions summarized in Table 1 were changed to be representative of the conditions that existed in the 1960s. Because a different Lake Superior regulation plan than Plan 1977-A was in

Table 4. Water intake problems at 24 Canadian municipal water works[a]

Municipality	Population	Maximum demand: Flow (liters/sec)	Maximum demand: Water elev. required (m, IGLD 55)	Problem experienced
Lake Ontario and St. Lawrence River				
Deseronto	1,800	NR[b]	NR	water quality problem
Belleville	32,100	358	73.69	reduced intake capacity
Picton	7,000	126	73.27	reduced intake capacity
Port Hope	8,200	79	73.73	reduced intake capacity
Metro Toronto/New Toronto Station	1,700,000[c]	631	74.98	reduced intake capacity
Port Credit	7,100	79	73.76	water quality problem
Hamilton	300,000	4,473	73.76	reduced intake capacity
Vineland	750	47	74.37	reduced intake capacity
Town of Niagara	3,500	NR	NR	reduced intake capacity
Lake Erie				
Fort Erie	9,200	263	172.82	reduced intake capacity
Crystal Beach	15,000	90	173.25	reduced intake capacity
Port Colborne	17,400	237	173.74	reduced intake capacity
Dunnville Area	8,000 + industry	1,316	171.90	frazil ice problem
Port Rowan	834	34	173.74	reduced intake capacity
Lake St. Clair				
Belle River	1,920	158	173.19	reduced intake capacity
Stoney Point	2,000	NR	NR	reduced intake capacity
Tilbury	2,000	NR	NR	reduced intake capacity
Lake Huron–Georgian Bay				
Kincardine	2,850	116	NR	reduced intake capacity
Port Elgin	7,000	50	173.27	frazil ice problem
Wiarton	2,030	55	175.50	reduced intake capacity
Waubaushene	1,200	NR	NR	reduced intake capacity
Parry Sound	6,100	105	175.56	reduced intake capacity
Little Current	1,600	38	175.56	reduced intake capacity

[a]Problems due to low lake levels and supporting data reported to the Ontario Water Resources Commission (1965).

[b]NR, not reported.

[c]The New Toronto Station was one of five stations serving this population. The population served by each station was not given.

operation, and this plan was not available to us, recorded Lake Superior outflows for this period were used as input to Lakes Michigan–Huron. This is not a perfect solution because the 1900–1939 Lake Superior outflows reflect the changes made to its outlet during this period and the implementation of regulation. However, we believe the outflows still correlate to a high degree with the lake's water supplies. Using Plan 1977-A with the recorded 1900–1939 water supplies is deemed less desirable because of the plan's consideration of Lakes Michigan–Huron's levels in determining Lake Superior outflows. The first regulation plan that considered Lakes Michigan–Huron's levels was implemented in 1973. Using recorded August 1964 to July 1965 Lake Superior outflows with the alternate water supply scenarios for the lower lakes was also considered, but that would bias the probabilistic forecast results by reducing the variability of the forecast lake levels. Changes in Lake Erie outflow conditions were also required. The Niagara River stage–discharge relationship and ice and weed retardation values were replaced with those representative of the time prior to 1974, and the Welland Canal diversion was reduced from an average of 261 m^3/sec to 224 m^3/sec, a value more representative of the 1960s.

Developing the initial conditions for Lake Ontario's regulation plan, Plan 1958-D, also required some consideration. Because the plan considers other information beyond the initial lake level and inflow from Lake Erie (weighted previous months' total water supplies), we initialized the plan with the information obtained by routing recorded total water supplies through the plan up to the end of July 1964.

The resulting probabilistic forecasts are shown for Lakes Michigan–Huron, Lake St. Clair, Lake Erie, and Lake Ontario in Figures 7A–D, respectively. From the Lakes Michigan–Huron forecast shown in Figure 7A and the data presented in Table 4, the municipalities of Parry Sound and Little Current on Georgian Bay could have expected to be unable to meet their maximum

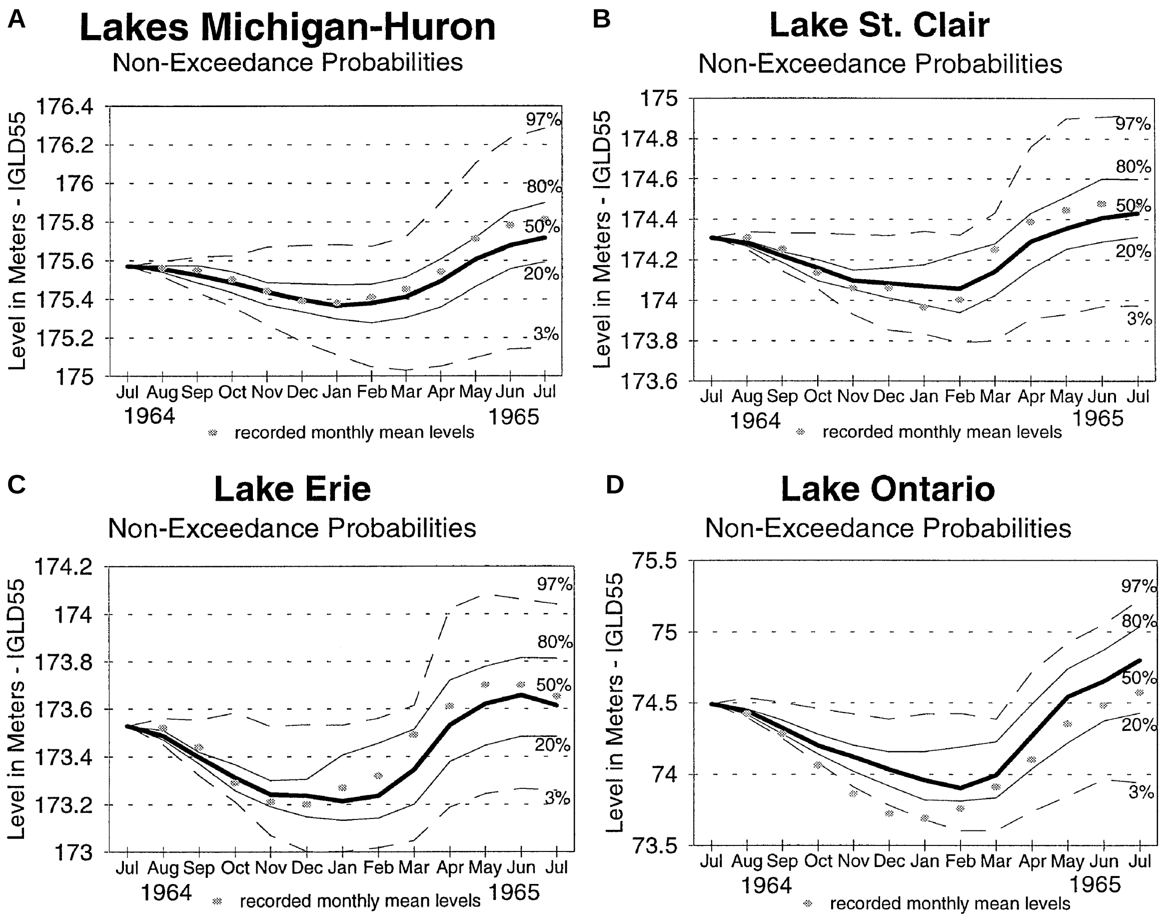

Figure 7. Probabilistic forecasts (case study 3) of water levels for August 1964 to July 1965 for (**A**) Lakes Michigan–Huron, (**B**) Lake St. Clair, (**C**) Lake Erie, and (**D**) Lake Ontario.

demand from August 1964 to April 1965. For these months, the probability of not exceeding the lake level required to meet maximum demand, 175.56 m, is greater than 50%. Similarly, the municipality of Wiarton could have expected to be unable to meet its maximum demand (requiring a level of 175.50 m) from October 1964 to April 1965. The monthly nonexceedance probabilities for the maximum demand levels of 175.56 m and 175.50 m, interpolated from Figure 7A, are summarized in Table 5. The municipality of Elgin could have expected to have similar or more severe problems with frazil ice on the intakes because probabilities of not exceeding the previous winter's levels (December 1963, 175.51 m; January 1964, 175.42 m; and February 1964, 175.40 m) were 89%, 69%, and 61%, respectively. The municipalities of Kincardine and Waubaushene did not report a water elevation required to meet maximum demand, but considering that the probability of experiencing the previous winter's lake levels or lower was

Table 5. Probabilities of not exceeding maximum demand levels for selected municipal water intakes

	Nonexceedance probability (%)					
	Lakes Michigan–Huron		Lake Erie		Lake Ontario	
Month	175.56 m	175.50 m	173.74 m	173.25 m	74.37 m	73.76 m
August 1964	56	<3	>97	<3	<3	<3
September	73	27	>97	<3	79	<3
October	88	63	>97	17	94	<3
November	91	82	>97	57	96	<3
December	93	88	>97	61	97	<3
January 1965	95	90	>97	57	95	10
February	95	90	>97	55	95	17
March	90	73	>97	29	96	10
April	63	51	85	5	63	3
May	40	31	78	3	28	<3
June	22	14	72	<3	20	<3
July	15	10	71	<3	14	<3

significant, they could have expected their problem of reduced intake capacity to continue or worsen.

The municipalities along Lake St. Clair (Belle River, Stoney Point, and Tilbury) had experienced problems from reduced intake capacity previous to the forecast period and had installed new intakes to remedy their problems. The municipality of Belle River reported to the Ontario Water Resources Commission its new elevation required to meet maximum demand as 173.19 m. From Figure 7B, it can be seen that the municipality was assured of being able to meet its maximum demand. The other two communities did not report their new maximum demand level.

At the beginning of the forecast period, as shown in Figure 7C, the water level of Lake Erie was already below the required level of 173.74 m to meet maximum demand for two of its shoreline municipalities, Port Colborne and Port Rowan. There remained throughout the forecast period a high probability (greater than 71%) that their maximum demand level of 173.74 m would not be exceeded. For the municipality of Crystal Beach, a 50% probability or greater existed that its maximum demand level, 173.25 m, would not be exceeded for November to February. The monthly nonexceedance probabilities for these maximum demand levels, interpolated from Figure 7C, are summarized in Table 5. The Dunnville area could have anticipated similar or worse problems due to frazil ice because the probabilities of not exceeding the previous winter's levels (December 1963, 173.28 m; January 1964, 173.26 m; and February 1964, 173.29 m) were 72%, 64%, and 60%, respectively. Fort Erie would have most likely been able to meet its maximum demand as there was a less than 3% probability of its critical level, 172.82 m, not being exceeded. Fort Erie reported to the Ontario Water Resources Commission that it only experienced water shortages during short-term low water levels during seiches. To accurately estimate this municipality's risk, the joint probability of still lake levels and short-term drawdowns due to seiche activity would have to be computed. The reader is referred to Chow and others (1994) for illustration of this procedure.

The probabilistic forecast for Lake Ontario, shown in Figure 7D, shows that the New Toronto Station serving Metropolitan Toronto would continue to experience significant reduction in intake capacity. For the forecast period, a probability near or greater than 97% existed that its maximum demand water level, 74.98 m, would not be exceeded. The municipality of Vineland also could have expected to experience reduced intake capacity for September 1964 to April 1965, with monthly probabilities of not exceeding its maximum demand level of 74.37 m ranging between 63% and 97%. The municipalities of Hamilton, Port Credit, Port Hope, and Belleville had very small forecast probabilities of not exceeding their required maximum demand levels of 73.76 m (Hamilton and Port Credit), 73.73 m (Port Hope), and 73.69 m (Belleville). Their largest risk of not exceeding their demand levels occurred in February and was less than 17%. However, in December and January, Lake Ontario levels did fall below their maximum demand levels, and these municipalities experienced reduced intake capacities. The recorded levels were very near the forecast 3% nonexceedance levels. In this circumstance, the municipalities may have postponed their decision to take action because of their low forecasted risk. They could have waited to make their decision until new forecasts were made in August or September, reflecting the continued trend in decreasing lake levels. These new forecasts would have shown that their risk was substantially increased and they would still have had time remaining in the fall season to take action. The monthly probabilities of nonexceedance for the maximum demand levels of 74.37 m and 73.76 m are shown in Table 5. The municipality of Picton could have expected no reduced intake capacity based on their maximum demand level of 73.27 m. They reported to the Ontario Water Commission that they would only experience a problem due to low lake levels if a heavy fire demand occurred. The Town of Niagara did not report a maximum demand level, and the municipality of Deseronto was concerned with water-quality problems. Both municipalities could have anticipated continued problems because a 50% or greater probability was forecast for August through March of not exceeding the previous year's recorded lake levels.

All of the municipalities that reported problems due to low water levels could have benefitted from the risk information contained in these probabilistic forecasts. Whether used to assess the need for additional intake capacity, prepare emergency contingency plans, or estimate potential water quality, the probabilistic forecasts could have been very valuable to local decision makers.

Discussion

Suggested Improvements

Because the focus of this paper is to illustrate the assessment of risk in Great Lakes operational decision making, the simple procedure outlined here was employed for the development of probabilistic forecasts.

Several improvements are suggested. First, physically based hydrology and lake evaporation models should be used to generate the alternate water supply scenarios, driven by historical or stochastically generated meteorology. Such models exist, and Croley (1993) has demonstrated their use in the development of probabilistic forecasts of water supply. The benefits of this approach are that initial basin moisture and lake heat conditions are considered, and information contained in long-range weather outlooks can be incorporated.

A second suggestion is to develop a more sophisticated approach to identifying climate regimes and trends (decadal to interdecadal) and to relate this to the selection or generation of the alternate water supply scenarios. Linking low-frequency climate variability to global ocean–atmosphere dynamics is an active area of research. For example, the influence of the El Niño Southern Oscillation on precipitation and streamflow is now being recognized.

A final suggestion is that various distribution functions be explored and compared to the results obtained using the empirical function given in equation 1. Fitted distributions would provide estimates of lake levels associated with extreme probabilities of exceedance and nonexceedance (less than 2% chance of exceedance). Chow and Watt (1992) and Chow and others (1994) have explored seven probability distributions and two tests to determine the best-fit distributions for Great Lakes water levels. Their work should form the basis for further research.

Of course, a formal assessment of probabilistic water level forecast skill should also be made. Many techniques exist that have been developed for the assessment of probabilistic meteorological forecasts that could be applied to probabilistic water level forecasts. A large body of literature exists on this subject. Brier (1950) presented one of the first measures of skill for probabilistic forecasts. Stanski and others (1989) provide a comprehensive survey of verification techniques, advantages and disadvantages of each, and provide numerous examples of their application. Kryzsztofowicz (1992) presents a new and interesting measure of utilitarian forecast skill, the Bayesian correlation score, and applies it to snowmelt forecasts.

Other Applications

In addition to making the types of decisions illustrated here by the three case studies, there are many other potential applications. Chief among these would be the dissemination of probabilistic forecasts to the public. As the Great Lakes shoreline approaches full development, it will become extremely useful for riparian landowners to have access to this type of probabilistic information. Such forecasts communicate their inherent uncertainty and may help regain public confidence in lake level forecasts—confidence that was eroded by the unpredicted high water levels in 1985–1986, followed by the equally unprecedented drop in levels during 1987–1988. O'Grady and Shabman (1990) offer some general guidelines for governments on regaining trust among Great Lakes water level forecast users: (1) restrict the message to probabilities and physical consequences; (2) share the uncertainty of the estimates with the audience; (3) do not avoid probability distribution information just because the audience finds it hard to interpret; and (4) information should be designed to inform, not to modify behavior.

It is important that no value judgements be embedded in the probability information. The user needs to make his own value judgements based on the facts. Although most people can more readily interpret a deterministic water level forecast, a probabilistic forecast provides more information and gives users a better understanding of both the nature and uncertainty of the physical system. It allows the user to make his own judgement about how much risk he is willing to accept.

Another important application of probabilistic outlooks could be in anticipating and preparing for crisis conditions (either extreme high or low levels). In the case studies above, actions were not taken until crisis conditions prevailed. Probabilistic forecasts offer a means of assessing the risk of reaching crisis water levels prior to their occurrence and implementing emergency measures based on the level of risk. During the IJC Levels Reference Study, ''crisis threshold limits'' were defined for the Great Lakes–St. Lawrence River system. These water levels are those beyond which major damages and adverse impacts begin to occur to Great Lakes interest groups (Crises Conditions Task Group 1993). Alerts could be issued and emergency actions initiated based on the risk of obtaining these crisis threshold limits. The risk threshold limit would have more meaning to people affected by Great Lakes water levels, and the acceptable risk is a value that could be negotiated between conflicting interest groups and government.

The probabilistic outlooks could also have several commercial applications, in addition to lake level and emergency management applications. Hydroelectric power utilities could use probabilistic forecasts of levels and flows in anticipating power production for devising preliminary load schedules, and in the case of low flows, for sending notifications of possible reductions in power delivery. They could also use them for producing short-term revenue forecasts. Commercial navigation could use such outlooks for anticipating loading capacities and transportation costs. The information may be useful to shippers in making routing decisions. For example, the decision may be made to ship grain from Minnesota via the Mississippi River rather than through the Great Lakes system. Anyone who must make decisions based on Great Lakes water levels would find the probabilistic forecasts of use.

Conclusions

As phase I of the IJC's Levels Reference Study drew to a close, one conclusion was that "there remains a limited ability of governments to adequately describe in probabilistic terms the physical conditions and their implications for interests' investments in the Basin" (Functional Group 3 1989). In its report to the governments after completion of phase II (International Joint Commission 1993), the IJC stated its support for the development of risk analysis techniques for application in management of water levels issues. The IJC recognized the usefulness of risk analysis techniques applied to its work under the Great Lakes Water Quality Agreement and supported their extension to lake level management.

We have developed such a technique for risk assessment and have demonstrated its application to lake level management and operational decision making. The probabilistic water level forecast method is simple and practical; we have suggested some potential refinements for its improvement. A formal assessment of the forecast skill also remains to be conducted.

However, until the skill of deterministic water level forecasts significantly improves beyond that of climatology (and this depends on improved long-range weather forecasts), probabilistic water level forecasts should be used for lake level management, anticipation of and preparation for crisis conditions, and disseminating information to those affected by Great Lakes water levels. The method should be adopted and evaluated by government agencies and introduced to the public as soon as possible while the Great Lakes are near their long-term averages, prior to future occurrences of extreme lake levels.

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