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Great Lakes Water Level Extremes and Risk Assessment

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Abstract

A method for developing Great Lakes probabilistic monthly water level forecasts, adapted from the Extended Streamflow Prediction technique, is presented. The method is applied retrospectively to quantify the risk of flooding at Milwaukee, Wisconsin and assess the need to enhance flood control measures during a period of record high water levels. The results show that during the 24 months following October, 1986 when Lake Michigan reached an all time high, the risk of exceeding the maximum flood protection level of 177.76 m was less than 2%. This information would have reduced the uncertainty regarding the need to prepare a high lake level protection plan for downtown Milwaukee. Further refinements to the probabilistic forecast technique are discussed.

Introduction

The adverse consequences of extreme Great Lakes water level fluctuations on public and private interests are well documented. During low water level periods, such as those experienced in the 1920's, 1930's, and 1960's, 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 1950's, 1970's, and most recently in 1985 and 1986, riparians suffer property damage due to flooding and increased erosion, metropolitan sewer outfalls are submerged, and recreational use of beaches and marinas is impaired.

During periods of extreme water levels, governments (local, state, and federal) and commercial and private interests are faced with making decisions

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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. Also, they must make these decisions with little certainty of future water levels. Recent analyses (Croley and Lee 1993, Lee 1992) of state-of-the-art deterministic Great Lakes water supply and lake level forecasts have shown that these forecasts are only marginally better than climatology for a 1-month outlook, and that their skill declines to the same or worse than climatology for a 6-month outlook. Probabilities of exceedance or non-exceedance are not explicitly given. How, then, can interests 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. 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.

The ESP technique is adapted here to illustrate the use of Great Lakes probabilistic water level forecasts to assess 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. Refinements to the forecast technique are suggested.

Adaptation of the ESP Forecast Approach

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 the following case study, 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.

The alternative water supply scenarios were routed through a hydrologic response model obtained from Environment Canada. This model embodies the Lake Superior regulation plan and middle lakes stage-discharge relationships. The hydraulic conditions of the system (lake outlet conditions, diversion rates, and ice and weed retardation) represent those of the present system. Initial conditions of lake levels and outflows were taken from forecast summary sheets from the U.S. Army Corps of Engineers.

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

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

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 empirical distribution for each month of the outlook was then interpolated to determine water levels associated with even intervals of exceedance probabilities, and the results plotted to produce a probabilistic forecast.

Risk Assessment: A Case Study

Throughout 1986, Lake Michigan set record high monthly mean water levels. 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 rising lake levels included flooding 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.

The completed prospectus (Southeastern Wisconsin Regional Planning Commission, 1987) concluded that as long as lake levels did not exceed 177.76 m, damages from direct overland flooding problems would be localized and no large harborwide flood control projects, such as elevating the breakwater, needed to be considered. However, if lake levels were to continue to rise, the preparation of a contingency plan for flood protection was recommended. The prospectus estimated the cost of preparing this plan at $253,200.00. The Milwaukee County Board of Supervisors was faced with the decision as to whether the plan should be prepared. They could have used their knowledge of the probability that the level would exceed 177.76 m in the 12 to 24 months following October, 1986 to assess the imminent risk of flooding and aid them in making their decision.

The adapted ESP method was applied to estimate these risks. Alternative water supplies for 24-month periods, beginning in November for 1940 through 1985 [a relatively wet climate period as identified by Quinn (1981)] were routed using the Great Lakes hydrologic response model and recorded initial conditions of lake levels and outflows for November, 1986. Probabilities of exceedance were computed based on the resulting lake level scenarios; the results are shown in Figure 1.

These results show that during the next 24 months, the probability of Lake Michigan's level exceeding 177.36 m 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 critical flood level. Thus, the Milwaukee Board of Supervisors could have made the decision with a high level of confidence at a time of record high levels, that a contingency flood plan was not needed .

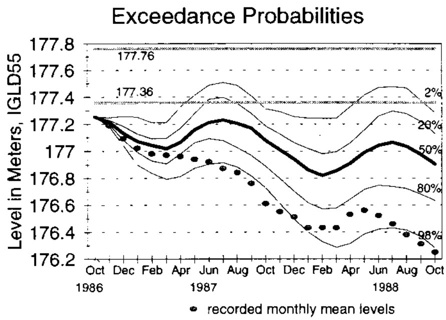

Figure 1. Probabilistic forecast of Lake Michigan water levels from October, 1986 to October, 1988.

The prospectus commissioned in November, 1986 by the Board of Commissioners to review the need for a flood protection plan was completed 1 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 began 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. This was an unprecedented drop in lake levels. Figure 1 shows that the actual 1987 and 1988 lake levels at times fell near the 2% non-exceedance (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.

Conclusion

We have adapted a simple technique to produce Great Lakes probabilistic water level forecasts for risk assessment and have demonstrated its use in assessing the need for flood protection at Milwaukee, Wisconsin during a period of record high lake levels. The technique has many other potential applications, including lake regulation and use by hydropower and commercial navigation interests. The forecast method is simple and practical, however, several improvements to the method 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. 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 stochastic generation of alternate water supply scenarios. A final suggestion is that various distribution functions be explored and compared to the results obtained using the empirical function given in equation 1. A formal assessment of probabilistic water level forecast skill should also be made.

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