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PROBABILISTIC GREAT LAKES HYDROLOGY OUTLOOKS[1]

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ABSTRACT: The Great Lakes Environmental Research Laboratory developed a semiautomatic software package for making hydrological outlooks for the Great Lakes. These include basin moisture storages, basin runoff, lake heat storage, lake evaporation, heat fluxes, and net lake supplies, one or more full months into the future. The package combines GLERL's rainfall-runoff and lake evaporation models with near real-time data reduction techniques to represent current system states. Users select historical meteorologic record segments as candidate future scenarios to generate deterministic near real-time hydrological outlooks. GLERL has extended the package to make probabilistic outlooks for a decision-maker who must estimate the risk associated with his decisions. GLERL matches National Weather Service meteorologic outlook probabilities by selecting groups of historical meteorologic sequences, and constructs embedded outlook intervals for each hydrologic variable of interest. Interval probabilities are assigned from comparisons over a recent evaluation period. This physically-based approach for generating outlooks offers the ability, as compared to other statistically-based approaches, to incorporate improvements in the understanding of process dynamics as they occur in the future and to respond reasonably to conditions initial to a forecast (such as heat and moisture storages), not observed in the past.
(KEY TERMS: forecasting; hydrology; probabilistic outlooks; Great Lakes; run off; evaporation; water supply.)

INTRODUCTION

The Great Lakes Environmental Research Laboratory (GLERL) developed a software package for making short-term operational hydrology forecasts in the face of uncertain meteorology. GLERL developed it on all Great Lakes for the U.S. Army Corps of Engineers (USACE) Detroit District, USACE Buffalo District, USACE Hydrologic Engineering Center, the New York Power Authority, and the Illinois State Water Survey's Midwest Climate Center. GLERL also developed it on Lake Champlain for use by the National Weather Service Northeast River Forecast Center. The package uses real-time information to consider both the existing states of each basin and lake and the anticipated meteorology.

GLERL's software package has been used so far to generate six-month deterministic outlooks of net supplies to each lake, including basin runoff and lake evaporation, for use in predicting six-month lake levels. Work continues on alternate deterministic outlooks and their evaluation and comparison with other methods; these are discussed elsewhere (Croley and Lee, 1993). Unfortunately, a single deterministic outlook over the next six months is unreliable and contains no information on its likelihood. Alternatively, probabilistic outlooks express the potential diversity and inherent uncertainty of future conditions, and the uncertainty of the forecasting process itself.

The purpose of this paper is to develop probabilistic outlooks by extending GLERL's forecast package. First, a user's perspective is presented on the package and its use to generate deterministic outlooks. Then, a new probabilistic outlook method is developed that forecasts successive ranges of values for each variable of interest; each range is contained within its predecessor. These embedded intervals are assigned containment probabilities and evaluated to partially assess their worth. Finally, the use of embedded intervals and associated probabilities is discussed and interpreted as a risk measure for a decision maker.

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FORECASTING WATER SUPPLIES

Forecasts are integrations of modeling and efficient data handling. Deterministic and probabilistic forecasts of water supply several months into the future are possible in "near real-time" (calculations are performed quickly enough to track events as they occur). GLERL accomplishes this by using their Large Basin Runoff Model and lake evaporation and heat storage model with forecasted meteorology. GLERL applies the runoff model to each of the 121 subbasins about the Great Lakes and the evaporation model to each of the five Great Lakes and to Lake St. Clair. Calibrated models (Croley, 1983a, b; 1989; 1992) are used from the end of archived climatic data to the present and then provisional data are used from a near real-time data network, spatially-averaged over each subbasin and lake surface as appropriate (Croley and Hartmann, 1985). Thus, one can model current basin moisture and lake heat conditions for use as initial conditions in a forecast. Then, forecast meteorology is used with the models to estimate basin runoff, basin storages, lake evaporation, and heat storages over the next few months. These estimates are included with other water supply components (precipitation over the lake and net ground water flux to the lake) to generate a water supply forecast. Hydraulic routing of a water supply forecast enables a lake level forecast to be made. The forecast package produces an outlook from the end of the available provisional data through the next one or more full months (length set by user). It also computes basin storages over the preceding 18-month period for a perspective on recent basin moisture conditions. This physically-based approach for generating outlooks offers the ability, as compared to other statistically-based approaches, to incorporate improvements in modeling, theory, or data as they occur in the future.

The outlook procedure, outlined schematically in Figure 1, consists of six modules. The first module prepares climatic subbasin files of areally-averaged historical meteorologic and hydrological data. The second module calibrates the runoff model for each subbasin and the evaporation model for each lake. The third module prepares initial data bases for the forecast module including climatic hydrometeorologic quantiles to aid in selecting a forecast meteorologic scenario and to provide historical perspective for the water supply forecasts. The fourth module updates provisional data bases with near real-time meteorologic data, and updates basin moisture and lake heat storage conditions with the models applied to provisional data or field measurements. The fifth module selects a meteorologic forecast scenario. The sixth module transforms forecasted meteorology into basin runoff, net basin supply, and lake level forecasts.

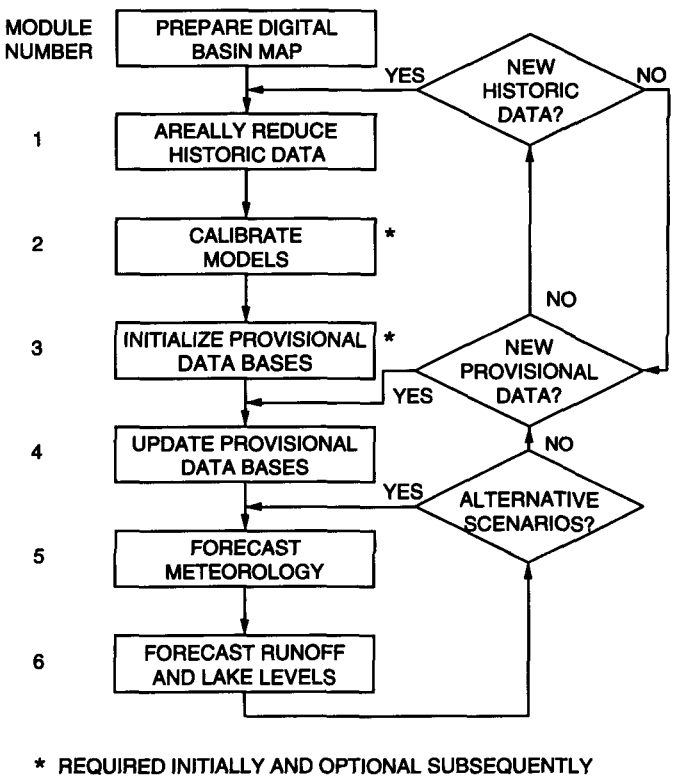

Figure 1. Logic Diagram of GLERL's Automated Outlook Procedure.

While Croley and Hartmann (1987, 1990) detail all modules identified in Figure 1, a user agency is most concerned with modules four, five, and six. GLERL transfers these three modules to the user agencies responsible for the forecast. The user provides up to four types of information to the package; two of them are optional. First, a near real-time data acquisition network must deliver daily meteorologic provisional data additions, deletions, or changes, from stations in and around the lake basin. The user must place these data into individual station files on the computer. [Currently, the Midwest Climate Center (Kunkel *et al.*, 1990) provides data, specifically chosen and formatted for use with GLERL's forecast package, available for down load and immediate use in the package.] Second, the user may provide field measurements of basin moisture conditions and water surface temperatures if they are available; otherwise, he uses model estimates. Third, the user may also provide an initial lake level if lake levels are to be forecast in addition to runoff, basin storages, and net

basin supplies. Fourth, the user must provide meteorologic time series representing forecasted meteorology. If a deterministic water supply forecast is desired, the user may need only to provide a single sequence of forecasted meteorology. Sophisticated deterministic or a probabilistic water supply forecast requires multiple input forecasted meteorologic sequences.

The fourth module in Figure 1 accepts new provisional data and adds it to provisional data bases, culminating with areal averages for each subbasin and lake surface. It then uses these files with the runoff and evaporation models to update direct-access files of subbasin and entire-basin daily moisture storages and daily lake heat storage, respectively. The updates are made only from the date of the earliest change or addition of provisional data to the end of the provisional data. Field measurements (including basin moisture conditions or water surface temperatures) available from snow course, aerial, or satellite monitoring, may be incorporated in this module. Overall, the fourth module estimates current storages by using the most recent provisional data and available field measurements. These storages serve as initial conditions for a forecast.

To make forecasts of basin runoff and lake evaporation, one can apply the runoff model for each subbasin and the lake evaporation model for each lake to a forecasted meteorologic sequence. Module 5 in Figure 1 builds a biased sample of forecasted meteorologic sequences, identified in some appropriate manner (the subject of the next section) as segments of the historical record. The historical data consists of daily values of areally-averaged minimum, maximum, and average air temperatures, precipitation, windspeed, humidity, and cloudcover corresponding to the forecast period of interest for each subbasin.

The sixth module in Figure 1 accepts a single forecasted meteorologic sequence from module 5. It uses the sequence as input to the runoff model, for all subbasins, and the lake evaporation model, for all lakes, to automatically simulate the resulting basin runoff and lake evaporation. Thus, the forecasted meteorology and the beginning basin storages (existing at the end of the provisional data period as computed in module 4) determine the forecasted basin runoff. Likewise, the forecasted meteorology and the lake heat storage that exists at the beginning of the forecast period determine the forecasted lake evaporation. This module aggregates the subbasin runoff and moisture storages outlooks over the entire basin and combines the total basin runoff, lake precipitation, and lake evaporation to forecast net basin supply for a lake. Module 6 forecasts lake levels by using net basin supply in conjunction with hydraulic routing models and the user-supplied initial lake level. For probabilistic forecasts, module 6 in Figure 1 then is repeated for every segment of the historical record selected in module 5.

The six modules of Figure 1 are reused as required for successive product updates, climatic or provisional data updates, and forecasts. Modules 5 and 6 are re-executed for each selected meteorologic record segment to form a forecast. As new provisional data become available in near real-time, modules 4-6 are re-executed to include the data and to make revised forecasts. As data-collection agencies revise their provisional data and make it available to add to the historical records, the entire package of Figure 1 may be re-executed. This revision allows one to update historical data bases, recalibrate the runoff model on each subbasin and the evaporation model on each lake, and reinitialize the forecast data bases (replacing limited provisional data with more comprehensive historical data as it becomes available). Modules 1-3 are executed infrequently (every 2-5 years) as historical data are available on machine-readable media. Modules 4-6 are executed frequently (every day, week, or month) as provisional data are received in near real-time and as forecasts are desired. Modules 4-6 are encoded to run conveniently on small computers with 5 to 15 megabytes of disk storage using standard FORTRAN.

SELECTING METEOROLOGIC OUTLOOKS

The package may be used to make a deterministic or a probabilistic forecast. Ostensibly, Great Lakes users demand a single time series of forecasted net basin supplies or lake levels for their decision making. Such preferences may reflect overconfidence in existing forecast technology or a lack of experience in using probabilistic concepts in decision making. Regardless, some uses, such as the regulation plans for Lakes Superior and Ontario, presently require a single forecast of net basin supplies. Monthly water level forecasts are presently issued as deterministic sequences by the USACE (1990). The Canadian Hydrographic Service (1991) now issues a forecast they call their "most probably range" which is based on the 10 percent and 90 percent supply sequences.

In the past, the GLERL package has been used to make deterministic forecasts by simply selecting a single meteorologic time series as input (in module 5) and calculating the resulting hydrological time series (in module 6). It has also been used at the USACE by selecting 3 to 5 series and averaging the package outputs. The selection of these meteorologic times eries as a forecast is important, but difficult; the resulting forecast of runoff and evaporation depend to some

extent on the forecasts of air temperatures, precipitation, windspeed, humidity, and cloudcover which are used in the simulation.

An alternate standard method uses climatological medians, calculated from the historical record, as the estimate of the most-likely meteorology for the future. That method does not recognize the limited expertise that exists for predicting the weather and ignores the interdependencies that exist between meteorologic variables. Since medians for the various variables usually do not occur at the same time, their use together introduces bias into the forecasts. Likewise, medians are computed by assuming that meteorologic variables are serially independent, as well as mutually independent, introducing other biases into a forecast.

Another alternative involves the estimation of statistical models of the time series for these variables. However, this approach involves considerable uncertainty in the selection of an appropriate multivariate model which could adequately relate the meteorologic processes at many points over the basin. The spatial and temporal interdependencies of all meteorologic variables would be difficult to capture with any confidence. A workable method was sought that preserves the spatial and temporal interdependencies of all meteorologic variables and that recognizes the limited expertise available in forecasting meteorology.

Using Available Expertise

The U.S. National Weather Service (NWS) provides weather outlooks semimonthly for the next month and monthly for the next three months for the North American Continent (Climate Analysis Center, 1990). The outlooks consist of maps of probabilities of exceeding the 70 percent quantiles or of not exceeding the 30 percent quantiles for air temperature and precipitation for the coming month and three-month season (O'Lenic, 1990). The NWS has limited skill in forecasting these quantities. O'Lenic (1990) estimates that the average skill (interpreted as improvement over climatology) is between 2.3 percent and 15.2 percent (see Table 1). Skill is measured as the difference between expected correct and actual correct number of forecasts divided by the difference between total and expected correct number of forecasts. Locally higher and lower scores exist in the Great Lakes area than are indicated in Table 1 for the U.S. The NWS has the most skill in forecasting monthly air temperature. They have limited skill in forecasting monthly precipitation and seasonal temperature in the wintertime. They have only marginal skill in forecasting otherwise.

TABLE 1. U.S. Average Skill of Forecasts by Season* (percent).

Season	Monthly Forecasts		Seasonal Forecasts	
	Temp.	Precip.	Temp.	Precip.
Winter	13.8	10.7	10.6	6.3
Spring	12.2	7.4	2.7	2.3
Summer	15.2	3.7	8.8	4.2
Autumn	8.0	6.1	6.2	4.4

*Interpreted as percent better than climatology (O'Lenic, 1990).

Module 5 in Figure 1 uses these outlooks either to select a single meteorologic forecast time series or to construct a biased sample of such sequences for input. The meteorologic quantile exceedance frequency tables, compiled in module 3, are scanned to identify one or more segments of the historical record for the entire basin with exceedance frequencies similar to forecast weather probabilities over the period of interest. These segment(s) are then used as the forecasted meteorologic sequence(s). Thus, the spatial and temporal interdependencies of the meteorologic processes are preserved.

Previous Deterministic Selection

The manner in which these historical record segments are identified affects, of course, the goodness of the resulting forecast. Previously, Croley and Hartmann (1987, 1990) selected record segments with relative frequencies, of not exceeding the 30 percent or of exceeding the 70 percent quantiles of precipitation and temperature, that were arbitrarily close to the NWS one-month and three-month outlook probabilities. This entailed computing (in module 3) the 30 percent and 70 percent precipitation and air temperature quantiles for each month of the year for each basin, estimating the relative frequencies of exceedance for these quantiles (from daily order statistics) for each month (beginning semimonthly) and for each three-month period (beginning monthly), and inspecting all estimates to find the best overall agreement with the NWS outlook probabilities for four simultaneous parameters (one-month and three-month precipitation and one-month and three-month air temperatures).

No unique "best" match is guaranteed; for example, a record segment with a first-month precipitation relative frequency close to the outlook probability may not be the same segment with a first three-month air temperature relative frequency close to the outlook probability. While many segments of the historical

record have relative frequencies that are within 3 percent of the NWS probability outlooks (defined as a "match") for a single category (one-month precipitation, one-month air temperature, three-month precipitation, or three-month air temperature), few segments do so for all categories. Often, compromises were required (e.g., sacrificing a close match on the three-month precipitation probability, but getting matches within 3 percent for the remaining categories) in selecting the record segment which best reflects the NWS meteorologic outlook. Further, some NWS outlooks called for conditions so extreme that they were unprecedented in the available historical record; for those cases, the "best" match compromises in typically several categories. The selection was made subjectively to allow employment of hydrological judgment.

NEW PROBABILISTIC METHOD

Deterministic outlooks have inherent limitations since they provide only a single forecasted time series. Whether considering one or several possible futures in making the single forecast, the final expression of a forecast as a "single best" time series simply cannot convey all the information that is available to make a forecast. If only a single possible future is considered, the potential impacts of other, perhaps almost equally-likely, futures are being ignored. If several possible futures are collapsed into a single time series, any expression of their diversity is lost.

Alternatively, probabilistic approaches explicitly communicate the potential diversity and inherent uncertainty of future hydrometeorologic conditions. Probabilistic outlooks may be generated by using multiple meteorologic sequences to produce multiple net basin supply forecasts, and then performing frequency analyses to define a probability distribution. The NWS uses such an approach, known as Extended Streamflow Prediction (ESP), with their conceptual runoff models (Day, 1985). However, that approach assumes that all the meteorologic sequences are equally likely to occur, and does not consider the limited ability of the NWS to forecast meteorology one to three months in advance. Suggested improvements to ESP include objectively assigning weights to historical sequences according to their similarity to meteorologic conditions of the current year (Day, 1985); this represents an alternative meteorologic forecast not consistent with the NWS outlooks. GLERL sought an approach that would explicitly consider the NWS weather forecast skill, yet also reflect the significant uncertainty of their outlooks and the recurring difficulty of finding few historical meteorologic sequences that closely match all categories of the NWS probability outlooks.

Embedded Intervals Forecasts

In selecting historical meteorology to use as forecast scenarios, we now distinguish among successively narrower classes of historical record segments, such that each class contains all successive classes. Historical record segments within a given class are used with the hydrological outlook package to produce multiple net basin supply time series, and the extremes are plotted, as in Figure 2. Since the classes contain all successive classes, the extremes associated with classes contain the extremes associated with all successive classes. These are referred to as embedded intervals.

After much experimentation, the following five sequential classes were defined for derivation of embedded intervals. Class "A" consists of ALL segments of the historical record that begin at the same time of the year as the desired forecast and that last for the forecast length. Class "B" consists of all such segments that "match" (redefined shortly) NWS one-month air temperature probabilities. Class "C" consists of all segments that "match" NWS one-month air temperature probabilities and one-month precipitation probabilities for winter or spring starts or one-month air temperature probabilities and three-month air temperature probabilities for summer or fall starts. Class "D" consists of all segments that "match" NWS one-month air temperature probabilities, one-month precipitation probabilities, and three-month air temperature probabilities. Class "E" consists of all segments that "match" all four: one- and three-month air temperature probabilities and one- and three-month precipitation probabilities. Note that these definitions are embedded; i.e., all class B segments are contained in Class A, all Class C segments are contained in Class B, and so forth.

A record segment is defined as "matching" when: (1) more than 30 percent of its daily values (in the first 30 or 90 days, as appropriate) are less than the 30 percent quantile if so forecast by NWS, (2) more than 30 percent of its daily values exceed the 70 percent quantile if so forecast by NWS, or (3) more than 40 percent of its daily values are between the 30 percent and 70 percent quantiles if neither of the first two forecasts are made by NWS. The essential difference between this and the earlier definition of "matching" is that the earlier used an arbitrarily small probability interval to establish agreement with the NWS forecast. This one simply identifies meteorology as wet, dry, warm, cool, or normal in the same sense as the NWS forecasts.

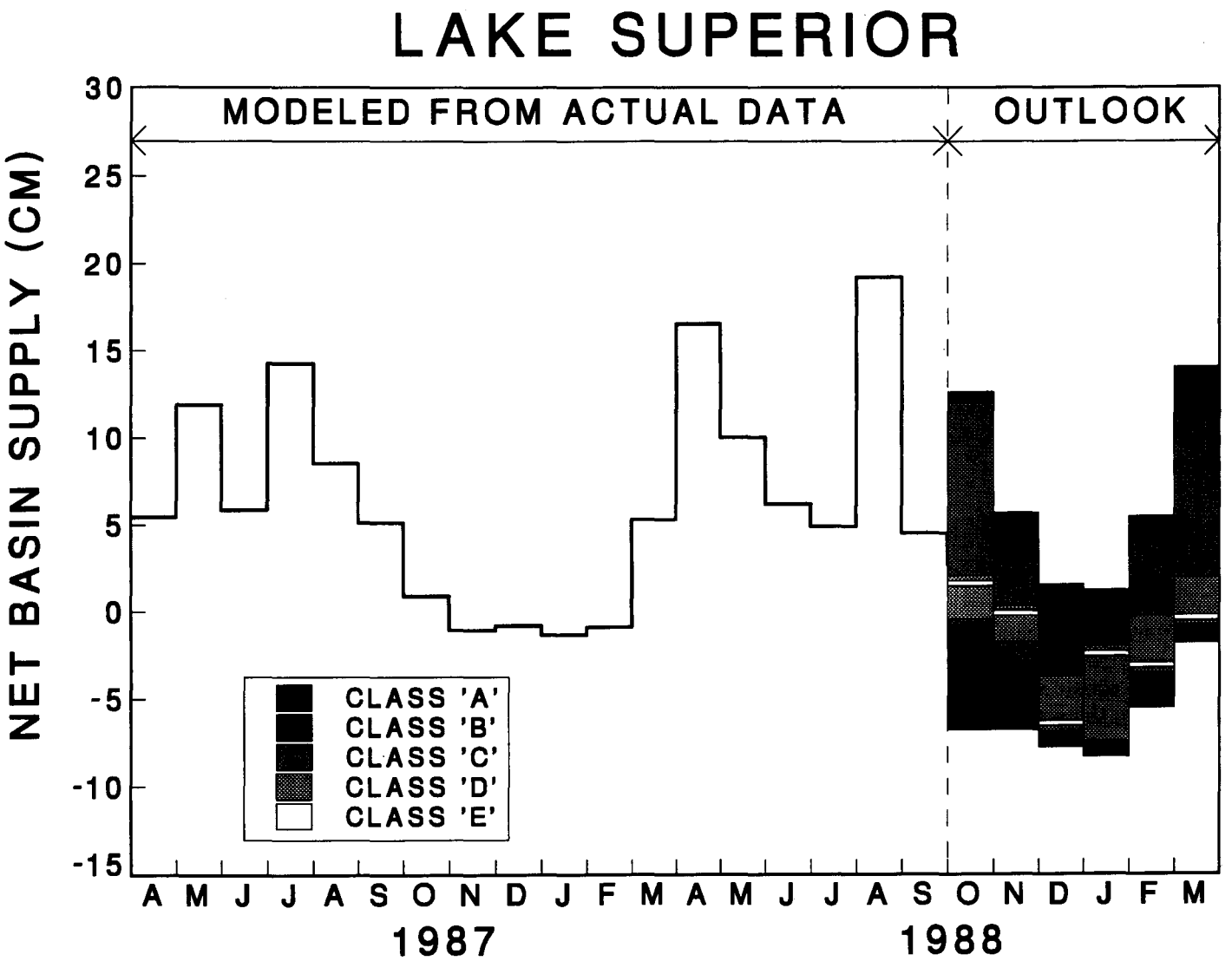

Figure 2. Example Probabilistic Outlook for Lake Superior Net Basin Supplies.

Embedded Interval Probabilities

At times, there are classes with no historical record segments that match the NWS outlooks. In such cases, no limits are derivable, reflecting greater uncertainty in potential net basin supplies over the forecast period because there is no historical precedent for the forecasted meteorology. The broadest class (class A) reflects use of all historical meteorologic record segments and is equivalent to the NWS ESP approach. All historical record segments are considered equally likely to recur. This class represents no confidence in the NWS outlook since no NWS forecast information is used to define the class. Successive classes use progressively more and more of the NWS forecast information, but each is a smaller subset of the previous. The resulting limits on potential net basin supplies are plotted from the widest to the narrowest in Figure 2. These limits define embedded intervals that represent incremental decreases in the uncertainty about future meteorologic and hydrological conditions since more NWS forecast information is utilized. But they also represent incremental increases in sampling or estimation uncertainty because of the decreasing sample size used for each pair of limits.

For each forecast month within an evaluation period from August 1982 through December 1988, the actual net basin supplies and supply components were observed in the intervals associated with each class of historical record segments. The frequencies of agreement, expressed as non-exceedance probability

TABLE 2. Great Lakes Autumn Non-Exceedance Probabilities on First-Month Forecasts for Embedded Classes of Historical Record Segments (percent).

Class*	A	B	C	D	E
			BASIN RUNOFF		
Superior	(5, 81)	(5, 76)	(14, 76)	(33, 52)	(47, 47)
Michigan	(0, 81)	(0, 81)	(0, 76)	(14, 71)	(27, 67)
Huron	(14, 86)	(14, 76)	(24, 62)	(35, 60)	(44, 56)
St. Clair	(0, 90)	(0, 90)	(0, 71)	(21, 53)	(35, 41)
Erie	(10, 95)	(14, 81)	(19, 67)	(53, 68)	(56, 69)
Ontario	(5, 95)	(5, 86)	(10, 86)	(42, 74)	(60, 60)
			OVER-LAKE PRECIPITATION		
Superior	(0, 90)	(0, 81)	(0, 81)	(19, 57)	(29, 41)
Michigan	(0, 86)	(0, 86)	(5, 76)	(10, 67)	(33, 60)
Huron	(0, 95)	(5, 90)	(5, 76)	(10, 70)	(19, 56)
St. Clair	(0, 86)	(0, 86)	(5, 67)	(26, 47)	(29, 35)
Erie	(0, 90)	(0, 81)	(5, 52)	(32, 53)	(31, 44)
Ontario	(0, 90)	(0, 86)	(5, 81)	(26, 58)	(47, 47)
			LAKE EVAPORATION		
Superior	(0,100)	(14, 86)	(38, 86)	(43, 67)	(47, 65)
Michigan	(0,100)	(24, 95)	(33, 76)	(43, 67)	(47, 67)
Huron	(0,100)	(14,100)	(19, 86)	(20, 70)	(44, 75)
St. Clair	(10,100)	(24,100)	(52, 90)	(63, 89)	(71, 88)
Erie	(10, 95)	(19, 95)	(29, 90)	(42, 74)	(44, 50)
Ontario	(0,100)	(10,100)	(14, 76)	(11, 58)	(27, 47)
			NET BASIN SUPPLY		
Superior	(0, 90)	(0, 86)	(0, 76)	(10, 62)	(24, 53)
Michigan	(0, 90)	(0, 90)	(5, 86)	(14, 76)	(27, 67)
Huron	(0, 90)	(0, 81)	(10, 71)	(15, 70)	(25, 56)
St. Clair	(0, 90)	(0, 90)	(0, 71)	(21, 53)	(35, 41)
Erie	(0, 95)	(0, 81)	(5, 67)	(32, 58)	(44, 63)
Ontario	(0, 90)	(0, 86)	(0, 86)	(32, 74)	(60, 60)
			OVER-LAKE AIR TEMPERATURE		
Superior	(5,100)	(29,100)	(43,100)	(57,100)	(65, 94)
Michigan	(10,100)	(33,100)	(48,100)	(76,100)	73, 93)
Huron	(0,100)	(19,100)	(43,100)	(65,100)	(75, 100)
St. Clair	(0,100)	(14,100)	(48, 95)	(74, 95)	(76, 88)
Erie	(0,100)	(14,100)	(52,100)	(68,100)	(69,100)
Ontario	(0,100)	(14,100)	(33,100)	(89, 95)	(100,100)

*Group A corresponds to use of all historical meteorologic sequences in the outlook generation; Group B sequences match the National Weather Service 30-day temperature (T) outlooks; Group C sequences match 30-D T and precipitation (P) (Winter and Spring forecasts) or 30-D T and 90-D T (Summer and Fall); Group D sequences match 30-D T, 30-D P, and 90-D T; Group E sequences match 30-D T, 30-D P, 90-D T, and 90-D P.

estimates, are given in a series of tables exemplified by Table 2 for autumn forecasts. These probabilities are estimates, based on past performance, that future forecasted supplies will fall within the intervals predicted for each of the forecast classes. For example, in Table 2, the use of all historical record segments (Class A) suggests that actual net basin supplies will not exceed the associated maximum 90 percent of the time on Lake Superior for the first month of a forecast beginning in the autumn. Likewise, a 0 percent chance exists that actual supplies will not exceed the associated minimum. Thus, we estimate a 90 percent probability (90 percent – 0 percent) that actual net basin supplies will fall within the outermost interval in Figure 2, for the first month of the autumn forecast period. Likewise, embedded intervals associated with the remaining successive classes give rise to respective containment probability estimates of 86 percent, 76 percent, 52 percent, and 29 percent.

Goodness of Probability Estimates

Table 2 is actually a summary table of limit probabilities; originally, estimates were constructed based on the season of the beginning of the forecast and on the forecast month of a 12-month forecast; Table 3 is for all record segments (Class A) on Lake Superior. There are 77 months of actual conditions in the entire evaluation period (August 1982 through December 1988) for comparisons with first-month forecasts (76 for second-month, 75 for third-month, and so forth). By categorizing these comparisons by three-month season (winter is December through February), 15 to 21 comparisons are available for each season and forecast month, revealing a pronounced seasonality in each category across the forecast months (see Table 3). For example, actual runoff appears higher than historical most often in the autumn and least often in the spring in Table 3. This seasonality results solely from meteorologic differences between the historical period (1948 up to the forecast date, used for the forecast) and the evaluation period (1982-1988, used for actual outcomes). Inspection of Table 3 also shows some repetition of probability estimates among corresponding forecast months; e.g., compare basin runoff for the eighth month of a forecast beginning in the autumn, the fifth month of a forecast beginning in the winter, and the second month of a forecast beginning in the spring. This correspondence is more approximate for other months due to sampling errors (associated with small seasonal samples), variable sample sizes, and the effects of initial conditions which diminish with forecast length. The 30 tables represented by Table 3 (six lakes and five classes of record segments) where thus collapsed into tables, like Table 2 for first-

TABLE 3. Lake Superior Non-Exceedance Probabilities for Class A (all historical record segments) as a Function of Season and Forecast Month (percent).

Forecast Month	1	2	3	4	5	6	7	8	9	10	11	12
						BASIN RUNOFF						
Winter	(16, 89)	(6, 89)	(6, 100)	(11, 100)	(28, 100)	(33, 100)	(39, 94)	(28, 94)	(17, 89)	(6, 83)	(0, 83)	(0, 82)
Spring	(0, 100)	(28, 100)	(33, 100)	(33, 94)	(22, 94)	(17, 89)	(6, 83)	(0, 83)	(0, 82)	(0, 94)	(0, 93)	(7, 93)
Summer	(37, 95)	(21, 100)	(11, 84)	(5, 79)	(0, 79)	(0, 78)	(0, 94)	(0, 94)	(6, 100)	(13, 94)	(25, 94)	(31, 100)
Autumn	(5, 81)	(0, 71)	(0, 75)	(0, 79)	(0, 83)	(6, 100)	(11, 100)	(28, 100)	(33, 100)	(33, 94)	(28, 94)	(17, 89)
ENTIRE	(14, 91)	(13, 89)	(12, 89)	(12, 88)	(12, 89)	(14, 92)	(14, 93)	(14, 93)	(14, 93)	(13, 91)	(13, 91)	(14, 91)
						OVER-LAKE PRECIPITATION						
Winter	(0, 95)	(0, 100)	(0, 100)	(0, 100)	(6, 100)	(6, 100)	(6, 94)	(0, 89)	(0, 89)	(0, 83)	(0, 83)	(0, 82)
Spring	(0, 100)	(6, 100)	(6, 100)	(6, 94)	(0, 89)	(0, 89)	(0, 89)	(0, 89)	(0, 88)	(0, 94)	(0, 100)	(0, 100)
Summer	(5, 95)	(0, 89)	(0, 89)	(0, 89)	(0, 89)	(0, 89)	(0, 94)	(0, 100)	(0, 100)	(0, 100)	(6, 100)	(6, 100)
Autumn	(0, 90)	(0, 90)	(0, 90)	(0, 95)	(0, 100)	(0, 100)	(0, 100)	(6, 100)	(6, 100)	(6, 94)	(0, 89)	(0, 89)
ENTIRE	(1, 95)	(1, 95)	(1, 95)	(1, 95)	(1, 95)	(1, 94)	(1, 94)	(1, 94)	(1, 94)	(1, 93)	(1, 93)	(2, 92)
						LAKE EVAPORATION						
Winter	(11, 95)	(6, 100)	(6, 100)	(0, 100)	(0, 94)	(0, 89)	(0, 78)	(0, 83)	(0, 94)	(0, 100)	(6, 94)	(0, 94)
Spring	(0, 100)	(0, 100)	(0, 94)	(0, 100)	(0, 100)	(0, 94)	(0, 100)	(11, 94)	(12, 94)	(13, 94)	(7, 100)	(7, 100)
Summer	(5, 95)	(5, 100)	(0, 100)	(0, 100)	(11, 95)	(11, 94)	(18, 94)	(6, 100)	(6, 100)	(0, 100)	(0, 88)	(0, 81)
Autumn	(0, 100)	(14, 95)	(10, 95)	(11, 95)	(6, 100)	(6, 100)	(0, 100)	(0, 89)	(0, 83)	(0, 78)	(0, 89)	(0, 94)
ENTIRE	(4, 97)	(7, 99)	(4, 97)	(3, 99)	(4, 97)	(4, 94)	(4, 93)	(4, 91)	(4, 93)	(3, 93)	(3, 93)	(2, 92)
						NET BASIN SUPPLY						
Winter	(0, 95)	(0, 100)	(6, 100)	(6, 100)	(11, 100)	(6, 100)	(6, 94)	(0, 94)	(0, 94)	(0, 94)	(0, 89)	(0, 94)
Spring	(0, 100)	(11, 100)	(6, 100)	(6, 94)	(0, 94)	(0, 94)	(0, 94)	(0, 89)	(0, 88)	(0, 94)	(0, 100)	(7, 100)
Summer	(5, 95)	(0, 95)	(0, 89)	(0, 95)	(0, 89)	(0, 89)	(0, 94)	(0, 100)	(6, 100)	(6, 100)	(13, 100)	(6, 100)
Autumn	(0, 90)	(0, 86)	(0, 90)	(0, 95)	(0, 100)	(6, 100)	(6, 100)	(11, 100)	(6, 100)	(6, 94)	(0, 94)	(0, 94)
ENTIRE	(1, 95)	(3, 95)	(3, 95)	(3, 96)	(3, 96)	(3, 96)	(3, 96)	(3, 96)	(3, 96)	(3, 96)	(3, 96)	(3, 97)
						OVER-LAKE AIR TEMPERATURE						
Winter	(5, 100)	(0, 100)	(0, 100)	(0, 100)	(0, 100)	(0, 100)	(0, 100)	(6, 100)	(6, 100)	(6, 100)	(6, 100)	(6, 100)
Spring	(0, 100)	(0, 100)	(0, 100)	(0, 100)	(6, 100)	(6, 100)	(6, 100)	(6, 100)	(6, 100)	(6, 100)	(0, 100)	(0, 100)
Summer	(0, 100)	(5, 100)	(5, 100)	(5, 100)	(5, 100)	(6, 100)	(6, 100)	(0, 100)	(0, 100)	(0, 100)	(0, 100)	(0, 100)
Autumn	(5, 100)	(5, 100)	(5, 100)	(5, 100)	(0, 100)	(0, 100)	(0, 100)	(0, 100)	(0, 100)	(0, 100)	(6, 100)	(6, 100)
ENTIRE	(3, 100)	(3, 100)	(3, 100)	(3, 100)	(3, 100)	(3, 100)	(3, 100)	(3, 100)	(3, 100)	(3, 100)	(3, 100)	(3, 100)

month autumn probabilistic outlooks, for each class of record segments, and for each forecast component.

For 33-39 years of historical record (1948-1982 to 1948-1988, or all years preceding a forecast), a simple ranking of historical record segment outputs would produce non-exceedance probability estimates of 3 percent (1/33 = 0.03 or 1/39 = 0.03) and 97 percent (32/33 = 0.97 or 38/39 = 0.97) to be associated with the lower and upper range limits, respectively, in Class A. Larger lower probabilities and small upper probabilities associated with this broadest class in Tables 2 and 3 reflect the effects of several factors: extreme conditions occurring during the evaluation period, use of a limited historical record for creating forecasted meteorologic scenarios, modeling error, and error in the estimation of actual conditions. On the other hand, smaller lower probabilities and larger upper probabilities reflect a combination of the lack of exceptional actual conditions and, for the early months of the forecast, additional initial-boundary-condition information provided by the near real-time estimation of basin moisture and lake heat storage conditions, which subsequently influence hydrological response to varied meteorologic conditions (Hartmann and Croley, 1990).

Differences from the 3 percent and 97 percent probabilities for precipitation directly reflect the extreme conditions experienced during the evaluation period,

especially for the upper lakes. Actual precipitation (during the evaluation period) was more extreme than reflected in the historical record since 1948; fully 32 percent of the evaluation period for Lake Huron and 31 percent for Lake Superior had extremes exceeding the historical record. Lakes St. Clair and Erie had relatively few occurrences of precipitation more extreme than in the previous 33-39 years. The reduced range of probabilities for basin runoff, compared to precipitation, probably reflects the influence of higher-than-usual initial basin moisture storage conditions during the evaluation period. Likewise, the probability ranges for lake evaporation are probably biased by higher-than-usual initial heat storage conditions during the evaluation period.

This unrepresentativeness of the evaluation period, used to estimate the probabilities associated with the embedded intervals, is a problem. Since this period contains extremes and the data do not appear statistically homogeneous when compared to the longer historical period, then the probability estimates are biased. This would not be a problem if the standard ESP approach were used to derive probabilities by ranking of all forecast scenarios. Again, the tradeoff is that this method allows assignment of probabilities for the embedded classes whereas the ESP approach only works for the broadest class which does not use the NWS meteorologic forecasts.

If we expect that there will be no changes in the meteorology in general between the historical period and the future (that is, the meteorology is stationary), then we could ignore the seasonal effects, associated with our small evaluation period, as sampling error. This is done by estimating probabilities without regard to starting season of the forecast, as in the rows labeled "ENTIRE" in Table 3. Note that there are very little differences in these probability estimates across the month of forecast for each forecast variable. Their average is thus regarded as representative across all forecast months and are summarized in Table 4 for all lakes and forecast classes. Table 4 may be used in place of Table 2 to assign probabilities to the embedded intervals of a probabilistic forecast, for all months of the forecast, if the evaluation period is regarded as being anomalous (not representative of the future). If the evaluation period is regarded as being representative of the future, then Table 2 should be used to assign probabilities for the first-month forecast (only); similar tables would be used for the other-month forecasts.

Both the actual process and our forecast of it have some memory of initial conditions for one to three months. This can be seen by comparing each month of a deterministic outlook with actual conditions. One may observe then that the first-month outlook is "closer" to the actual first-month value (smaller

TABLE 4. Great Lakes Non-Exceedance Probabilities on All Forecast Months for Embedded Classes of Historical Record Segments (percent).

Class*	A	B	C	D	E
			BASIN RUNOFF		
Superior	(13, 91)	(15, 85)	(19, 77)	(26, 65)	(34, 57)
Michigan	(6, 91)	(9, 87)	(13, 80)	(21, 68)	(30, 58)
Huron	(11, 90)	(15, 86)	(21, 77)	(30, 68)	(36, 62)
St. Clair	(2, 95)	(4, 88)	(10, 80)	(24, 65)	(32, 56)
Erie	(2, 98)	(6, 90)	(14, 82)	(26, 71)	(38, 62)
Ontario	(4, 92)	(6, 89)	(14, 82)	(25, 74)	(37, 65)
			OVER-LAKE PRECIPITATION		
Superior	(1, 94)	(4, 91)	(9, 84)	(21, 74)	(33, 62)
Michigan	(3, 97)	(6, 94)	(12, 86)	(22, 75)	(32, 63)
Huron	(1, 96)	(4, 91)	(9, 81)	(18, 66)	(28, 59)
St. Clair	(1, 95)	(3, 90)	(10, 82)	(25, 67)	(34, 57)
Erie	(4, 98)	(6, 95)	(13, 85)	(24, 72)	(37, 63)
Ontario	(0, 95)	(2, 93)	(11, 85)	(22, 74)	(35, 63)
			LAKE EVAPORATION		
Superior	(4, 95)	(8, 91)	(15, 83)	(25, 75)	(36, 66)
Michigan	(5, 97)	(9, 94)	(19, 85)	(31, 76)	(40, 68)
Huron	(2, 99)	(6, 94)	(13, 85)	(25, 77)	(31, 66)
St. Clair	(3, 96)	(9, 93)	(20, 86)	(36, 75)	(44, 68)
Erie	(3, 85)	(7, 79)	(11, 71)	(22, 62)	(28, 52)
Ontario	(1, 95)	(5, 90)	(12, 81)	(20, 71)	(30, 58)
			NET BASIN SUPPLY		
Superior	(3, 96)	(4, 91)	(8, 84)	(20, 72)	(32, 62)
Michigan	(4, 93)	(5, 89)	(10, 81)	(19, 70)	(29, 58)
Huron	(2, 93)	(5, 89)	(11, 81)	(22, 69)	(31, 61)
St. Clair	(2, 96)	(4, 89)	(11, 81)	(23, 66)	(32, 56)
Erie	(3, 98)	(4, 92)	(11, 86)	(26, 74)	(40, 67)
Ontario	(3, 95)	(5, 90)	(13, 82)	(24, 74)	(38, 63)
			OVER-LAKE AIR TEMPERATURE		
Superior	(3, 100)	(6, 95)	(12, 86)	(25, 74)	(35, 61)
Michigan	(4, 100)	(7, 98)	(15, 91)	(27, 77)	(36, 66)
Huron	(0, 100)	(2, 98)	(10, 89)	(19, 75)	(29, 67)
St. Clair	(0, 100)	(3, 99)	(9, 88)	(23, 73)	(30, 60)
Erie	(0, 100)	(3, 99)	(11, 91)	(25, 77)	(31, 64)
Ontario	(0, 100)	(2, 99)	(9, 92)	(23, 80)	(34, 65)

*Group A corresponds to use of all historical meteorologic sequences in the outlook generation; Group B sequences match the National Weather Service 30-day temperature (T) outlooks; Group C sequences match 30-D T and precipitation (P) (Winter and Spring forecasts) or 30-D T and 90-D T (Summer and Fall); Group D sequences match 30-D T, 30-D P, and 90-D T; Group E sequences match 30-D T, 30-D P, 90-D T, and 90-D P.

average differences, root mean square error, and so forth) than are successive outlook months to their respective actual months. This is addressed in some detail by Croley and Lee (1993). However, this effect is not revealed in the non-exceedance frequencies computed here (Table 3). While both the forecast and actual conditions are tied to initial conditions at the beginning (and the forecast is closer to actual), the frequency of containment of actual conditions by the forecast is not necessarily higher near the beginning. However, the information content is higher near the forecasting beginning, discussed next.

PROBABILISTIC OUTLOOKS

Forecast Information Use

The difference in the probability estimates associated with a class' interval limits represents the probability of containment in the interval. By dividing this difference (in percent) by the interval width (in centimeters for runoff, precipitation, evaporation, or net basin supply, or in °C for air temperature), the resulting ratio gives a measure of the relative utilization of the available information. We expect this ratio to be large if the forecast has a lot of information in it (large probability associated with a small range of values) and small if the forecast tells us little (small probability or large range of values). We can compare forecasts to some extent by looking at their ratios. For example, while embedded intervals have successively smaller probabilities associated with them, if the outermost interval in Figure 2 for the first-month forecast has a ratio of 0.58 percent/cm and the next embedded interval has a ratio of 0.70 percent/cm, a little more assurance can be placed on the inner interval. This increase in assurance results because a little more information was used in derivation of the embedded interval, as reflected by the matching to more of the NWS meteorologic forecast.

Table 5 presents an example table of probability-interval width ratios for all historical record segments (Class A) on Lake Superior for each season of the beginning of the forecast and for each forecast month, similar to the presentation in Table 3. As in Table 3, there is a pronounced seasonality across the forecast months in Table 5. For example, basin runoff forecasts have maximum information in the winter and minimum in the spring. This behavior results from the seasonality present in natural variability; runoff is small (with small range) in the winter and large (with large variability from year to year) during the spring snow melt. Note that this seasonality is evident in all hydrological components and the cycle is present, but shifted in forecasts beginning in all four seasons. This seasonality is so pronounced that it is difficult to ascertain the effects of initial conditions throughout a forecast, which are more subtle. By estimating interval width and containment probabilities regardless of season, as in the rows labeled "ENTIRE" in Table 5, the seasonality is filtered and the effects of initial conditions are more apparent. For example, Table 5 reveals that Lake Superior first-month runoff, evaporation, and net basin supply forecasts generally contain more information than subsequent months while precipitation and air temperature generally do not. This is expected since initial conditions of basin moisture and lake heat storage are used by the runoff and evaporation models, respectively, in making a forecast and the effect of initial conditions diminishes with forecast length. Similar observations on seasonality and initial condition effects were made for the other Great Lakes, not shown here.

Summaries of first-month forecast statistics for all classes are given in Table 6 for Lake Superior. Note in Table 6 that the use of more information, as reflected in the consideration of embedded Classes A through E, generally improves the probabilistic outlook (ratios increase). (Again, seasonal effects can be ignored by looking at the rows labeled "ENTIRE" in Table 6.) Improvement in first-month forecasts that use more weather outlook information is evident for most seasons and forecast variables in Table 6. However, sometimes the later embedded classes (D and E) do not improve the outlooks since they restrict the forecasts based on 90-day climatic outlooks and Table 6 is for first-month forecasts only. What happens over 90 days sometimes has little effect on the first 30 days. Additionally, the NWS has almost no skill in predicting precipitation three months in advance (see Table 1). Class B runoff forecasts are lower in the winter and summer than Class A since 30-day temperature outlooks (on which Class B is based) have little effect on runoff at those times. Class B evaporation forecasts are always better than Class A since 30-day temperatures are very important in determining first-month forecast evaporation and are predicted with some skill by the NWS (see Table 1). Class C evaporation forecasts are poorer than Class B in the summer and autumn, since Class C considers 90-day temperature outlooks instead of 30-day precipitation in addition to 30-day temperature at those times. While precipitation has no effect on evaporation, further limiting the group for 90-day temperatures can remove some historical sequences with matching 30-day temperatures.

Note in Table 6 that the ratios are generally high for air temperature and, among the net basin supply components (runoff, precipitation, and evaporation),

TABLE 5. Lake Superior Non-Exceedance Probability-Interval Ratios for Class A (all historical record segments), as a Function of Season and Forecast Month.

Forecast Month	1	2	3	4	5	6	7	8	9	10	11	12
					BASIN RUNOFF (percent/cm)							
Winter	5.36	2.71	1.81	1.16	1.00	1.13	1.81	1.77	1.67	1.57	2.05	2.57
Spring	2.03	1.28	1.35	2.04	1.94	1.69	1.57	2.03	2.52	3.45	2.76	1.73
Summer	2.65	2.05	1.70	1.51	2.00	2.51	3.48	2.64	1.81	1.05	0.98	1.21
Autumn	2.26	2.01	2.65	3.31	2.44	1.84	1.18	1.01	1.14	1.86	1.79	1.65
ENTIRE	2.60	1.90	1.80	1.70	1.68	1.69	1.71	1.68	1.68	1.68	1.71	1.71
					OVER-LAKE PRECIPITATION (percent/cm)							
Winter	1.56	1.52	1.45	1.13	1.05	0.94	0.90	0.82	0.83	0.85	1.04	1.19
Spring	1.09	1.00	0.91	0.88	0.82	0.83	0.91	1.10	1.29	1.55	1.52	1.44
Summer	0.89	0.82	0.84	0.92	1.11	1.30	1.57	1.50	1.44	1.12	1.05	0.92
Autumn	0.92	1.11	1.31	1.56	1.52	1.45	1.14	1.05	0.94	0.90	0.81	0.83
ENTIRE	1.06	1.06	1.08	1.08	1.08	1.08	1.08	1.07	1.06	1.04	1.05	1.04
					LAKE EVAPORATION (percent/cm)							
Winter	1.53	1.56	1.85	2.69	5.42	8.27	5.07	2.61	1.61	1.43	1.30	1.54
Spring	2.57	4.90	8.00	6.31	3.19	1.68	1.50	1.22	1.32	1.37	1.49	1.81
Summer	4.92	3.13	1.79	1.53	1.26	1.39	1.32	1.50	1.87	2.72	5.20	8.23
Autumn	1.68	1.28	1.49	1.48	1.57	1.85	2.65	5.10	8.24	5.25	2.59	1.59
ENTIRE	2.15	2.09	2.10	2.17	2.10	2.03	2.00	1.96	1.97	1.99	1.96	1.97
					NET BASIN SUPPLY (percent/cm)							
Winter	1.17	0.87	0.74	0.66	0.72	0.74	0.73	0.64	0.54	0.53	0.64	0.94
Spring	0.73	0.70	0.73	0.72	0.63	0.53	0.54	0.63	0.89	1.04	0.86	0.76
Summer	0.72	0.63	0.51	0.55	0.67	0.93	1.05	0.84	0.77	0.68	0.74	0.74
Autumn	0.58	0.65	0.97	1.10	0.87	0.77	0.69	0.74	0.74	0.73	0.63	0.53
ENTIRE	0.75	0.70	0.70	0.71	0.71	0.71	0.71	0.70	0.70	0.70	0.70	0.71
					OVER-LAKE AIR TEMPERATURE (percent/°C)							
Winter	3.43	3.90	4.45	5.37	6.44	7.05	7.41	6.42	5.85	5.44	4.44	3.90
Spring	5.37	6.44	7.05	7.40	6.42	5.85	5.44	4.44	3.90	3.39	3.91	4.46
Summer	7.41	6.38	5.83	5.47	4.37	3.89	3.41	3.93	4.52	5.44	6.49	7.07
Autumn	5.48	4.48	3.93	3.42	3.90	4.45	5.37	6.45	7.06	7.41	6.42	5.85
ENTIRE	5.06	5.04	5.03	5.02	5.01	5.04	5.07	5.10	5.11	5.11	5.09	5.06

are lowest for precipitation forecasts. The dominance of runoff and evaporation ratios over precipitation ratios agrees with currently perceived ideas of the NWS ability to forecast these quantities. While the NWS has marginal skill in predicting one-month precipitation, its skill is greater for air temperatures. Likewise, GLERL's predictions of runoff and of evaporation show better skill than for precipitation (compare ratios in Table 6), since these component forecasts utilize information on currently-available (initial) conditions.

The ratios for the components of net basin supply are somewhat comparable since the components are all of the same order of magnitude. GLERL shows skill in forecasting the components of net basin supply, but Table 6 indicates that the ratios for net basin supply are much lower. However, net basin supply ratios are not directly comparable to the components because net basin supply is the algebraic sum of the components, and its range (and variance) is much greater than that of each of the components. Finally, skill in forecasting components on each lake appears to be parallel to calibration success in applying the models to each lake.

TABLE 6. Lake Superior Non-Exceedance Probability-Interval Ratios on First-Month Forecasts for Embedded Classes of Historical Record Segments as a Function of Season.

Class*	A	B	C	D	E
		BASIN RUNOFF (percent/cm)			
Winter	5.36	4.80	7.07	6.68	8.70
Spring	2.03	2.42	2.86	3.27	5.32
Summer	2.65	2.04	2.31	1.83	2.16
Autumn	2.26	2.56	2.55	1.55	0.00
ENTIRE	2.60	2.69	2.99	2.78	3.36
		OVER-LAKE PRECIPITATION (percent/cm)			
Winter	1.56	1.75	1.81	2.06	2.35
Spring	1.09	1.24	1.24	1.11	1.46
Summer	0.89	0.92	0.90	0.84	0.65
Autumn	0.92	0.92	1.09	1.38	1.11
ENTIRE	1.06	1.13	1.15	1.25	1.22
		LAKE EVAPORATION (percent/cm)			
Winter	1.53	1.74	1.74	2.04	2.37
Spring	2.57	3.57	3.70	4.61	4.37
Summer	4.92	6.70	6.37	9.63	8.41
Autumn	1.68	1.97	1.69	1.30	3.33
ENTIRE	2.15	2.76	2.76	3.10	3.75
		NET BASIN SUPPLY (percent/cm)			
Winter	1.17	1.26	1.60	1.56	1.54
Spring	0.73	0.89	0.97	0.94	1.19
Summer	0.72	0.74	0.76	0.68	0.35
Autumn	0.58	0.70	0.78	1.57	2.45
ENTIRE	0.75	0.85	0.92	1.09	1.09
		OVER-LAKE AIR TEMPERATURE (percent/°C)			
Winter	3.43	3.96	3.75	3.41	3.30
Spring	5.37	6.23	5.72	7.26	7.71
Summer	7.41	8.81	9.31	12.14	13.46
Autumn	5.48	5.27	5.61	6.87	11.80
ENTIRE	5.06	5.62	5.62	6.43	7.80

*Group A corresponds to use of all historical meteorologic sequences in the outlook generation; Group B sequences match the National Weather Service 30-day temperature (T) outlooks; Group C sequences match 30-D T and precipitation (P) (Winter and Spring forecasts) or 30-D T and 90-D T (Summer and Fall); Group D sequences match 30-D T, 30-D P, and 90-D T; Group E sequences match 30-D T, 30-D P, 90-D T, and 90-D P.

Interpretation of Risk

The decision maker can use probabilistic forecasts to interpret some of the risk associated with consequences of his decisions. For example, the interpolation of a probabilistic forecast may suggest a 20 percent chance that net supplies to a lake will be below a critical value resulting in expensive consequences to a decision maker if he plans on certain water levels in the next month. He can decide that this chance of that consequence is unacceptable and, therefore, he plans on lower water levels with smaller, but acceptable, benefits. Of course, he must understand his own set of tradeoffs in evaluating consequences and their associated chances of occurrence, but he will at least have estimates of these chances available for his consideration.

A fuller evaluation of risks associated with use of the methodology presented herein involves estimates of errors and confidence limits. This is impeded here since data available for evaluation were used in estimating the hydrological probabilities of the methodology; these data are thus unavailable for unbiased assessments of the resulting methodology. However, some evaluation and, in particular, comparisons with other methods have been made for a deterministic version of this methodology (Croley and Lee, 1993). The evaluation data were used for these comparisons instead of for assigning probabilities; the comparisons enable some understanding of the information contained in each of the classes (A through E) used in the probabilistic method presented here.

CONCLUSIONS

GLERL's Large Basin Runoff Model and lake evaporation model have been extended in a software package allowing near real-time forecasts of water supplies for large lakes. The models are calibrated with the most recent climatic data for all subbasins and lakes in the Great Lakes and run from the end of the climatic data sets to the present by using provisional data. Forecasted meteorology is then used to estimate basin runoff and basin storages over the next one or more months. Probabilistic forecasts use a biased sample of meteorologic forecasts, matching the monthly and seasonal NWS outlooks. GLERL has automated all climatic data reduction, model calibration, provisional data reduction, and forecast procedures to enable the application of the model at GLERL and of the forecast package by agencies responsible for operational forecasting of large lake supplies.

Deterministic outlooks have inherent limitations since they provide only a single forecasted time series. If only a single possible future is considered in making deterministic outlooks, the potential impacts of other, almost equally-likely, futures are being ignored. If several possible futures are collapsed into a single time series, any expression of the diversity of potential future conditions is lost. Additionally, measures of performance of deterministic outlooks do not usefully express the confidence level to be accorded to future outlooks. Alternatively, probabilistic outlooks explicitly communicate the potential diversity and inherent uncertainty of future hydrometeorologic conditions. They also give the decision-maker an expression he may interpret as confidence or risk associated with his own tradeoffs.

GLERL's Hydrologic Outlook Package presently produces forecasts for the Great Lakes, especially for the first month of the forecast period, that incorporate useful information provided by good extended weather outlooks. However, both deterministic and probabilistic net basin supply outlooks are hindered by notably poor NWS precipitation forecasts, which directly and adversely affect forecasting of basin runoff and overlake precipitation. Lake evaporation outlooks are sensitive to errors in air temperature forecasts. Use of a limited historical record particularly affects selection of historical meteorologic sequences during the "dry" part of the evaluation period; no conditions since 1948 were of the same character as those forecast by the NWS during that part of this period.

However, initial conditions are found to be more important than meteorology in predicting one- to three-month extremes. GLERL's Hydrologic Outlook Package captures the effect of initial conditions very well since physically-based models are used both to keep track of heat and moisture storages (to estimate initial conditions) and to estimate the storage changes in a forecast, as affected by forecast meteorology. The advantage of conceptual, physically-based models over stochastic or statistical ones is that they can respond reasonably to initial conditions not observed in the past. While forecast meteorology is limited to sequences that have occurred in the past, the resulting heat and moisture storages are not.

Forecast errors fall into two broad categories: those associated with the NWS meteorologic probability forecasts and those associated with water supply estimation procedures. The former includes errors associated with the NWS forecasts, with the sampling of historical periods that "match" the NWS outlooks to some extent, and with selecting from a limited sample (only 33-39 years are used). The latter includes conceptual modeling errors for each component of net basin supplies (runoff, overlake precipitation, lake evaporation) and data errors associated with measurements (air temperatures, precipitation) and basic computations (e.g., overlake meteorology is estimated by overland meteorology, ignoring many lake effects). Additional analyses are described elsewhere (Croley and Lee, 1993) to assess these forecast error components.

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LITERATURE CITED

Canadian Hydrographic Service, 1991. Monthly Water Level Bulletin, Great Lakes and Montreal Harbour, December 1991. Canadian Hydrographic Service, Department of Fisheries and Oceans, Burlington, Ontario, Canada.

Climate Analysis Center, 1990. Monthly and Seasonal Weather Outlook for May 1990. National Weather Service, Washington, D.C., Monthly and Seasonal Weather Outlook 44(9).

Croley, T. E. II, 1983a. Great Lakes Basins (U.S.A.-Canada) Runoff Modeling. Journal of Hydrology 64:135-158.

Croley, T. E. II, 1983b. Lake Ontario Basin (U.S.A.-Canada) Runoff Modeling. Journal of Hydrology 66:101-121.

Croley, T. E. II, 1989. Verifiable Evaporation Modeling on the Laurentian Great Lakes. Water Resources Research 25(5):781-792.

Croley, T. E. II, 1992. Long-Term Heat Storage in the Great Lakes. Water Resources Research 28(1):69-81.

Croley, T. E. II and H. C. Hartmann, 1985. Resolving Thiessen Polygons. Journal of Hydrology 76:363-379.

Croley, T. E. II and H. C. Hartmann, 1990. GLERL's Near Real-Time Hydrological Outlook Package. Proceedings of the Great Lakes Water Level Forecasting and Statistics Symposium, Great Lakes Commission, Windsor, Ontario, May 17-18, pp. 63-72.

Croley, T. E. II and D. H. Lee, 1993. Evaluation of Deterministic Great Lakes Hydrology Forecasts. Water Resources Bulletin 29(2):267-282.

Day, G. N., 1985. Extended Streamflow Forecasting Using NWSRFS. Journal of Water Resources Planning and Management 111:157-170.

Hartmann, H. C. and T. E. Croley II, 1990. An Evaluation of GLERL's Hydrological Outlook Package. Proceedings of the Great Lakes Water Level Forecasting and Statistics Symposium, Great Lakes Commission, Windsor, Ontario, May 17-18, pp. 177-196.

Kunkel, K. E., S. A. Changnon, C. J. Lonnquist, and J. R. Angel, 1990. A Real-Time Climate Information for the Midwestern United States. Bulletin of the American Meteorological Society 71:1601-1609.

O'Lenic, E. A., 1990. Short-Term Climate Prediction in the Great Lakes Region. Proceedings of the Great Lakes Water Level Forecasting and Statistics Symposium, Great Lakes Commission, Windsor, Ontario, Canada, May 17-18, pp. 27-40.

U.S. Army Corps of Engineers, 1990. Monthly Bulletin of Lake Levels for the Great Lakes, May 1990. Detroit District, Corps of Engineers, Detroit, Michigan.