GREAT LAKES ADVANCED HYDROLOGIC PREDICTION SYSTEM

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Abstract: The Great Lakes Environmental Research Laboratory's hydrology research over the past decade and a half addressed the Great Lakes community's forecasting needs and has culminated in a mature and tested Great Lakes *Advanced Hydrologic Prediction System*. Recently designed and tested technology properly incorporates multi-agency, multi-area, multi-period climate outlooks of meteorology probabilities into the package. This allows provision of 1- to 12-month (and longer) outlooks of probabilities for 25 hydrology variables over the entire Great Lakes basin, including simultaneous water levels on all lakes. It is important not to confuse probabilistic hydrology outlooks with currently available deterministic forecasts of lake levels, and to realize the much greater utility of the probabilistic hydrology outlooks. Probabilistic outlooks allow decision makers to incorporate some of the uncertainty inherent in forecasts, to properly consider the wide range of possibilities always present, and *to consider the risk associated with their decisions*, not possible with deterministic forecasts.

BACKGROUND

Extreme Great Lakes water levels cause extensive flooding, erosion, and damage to shorelines, shipping, and hydropower. Knowledge of even near-normal level expectations is important to riparians, recreational users, shipping, fishing, and many others. The International Joint Commission, at the request of the US and Canadian governments, recommended improving forecast methodologies, hydrological models, data collection, and communication of hydrological forecast information (IJC, 1993). While forecasts of meteorology, riverine flooding, and water level fluctuations are available for several hours to several days, the Great Lakes community requires water resource forecasts over large areas and time periods. Products must include nowcasts and 1-day to 3-month and future seasonal probabilistic outlooks of lake supplies, lake levels, and connecting channel flows. These require careful tracking of moisture storage variables and heat storage variables. The products must be relevant to users and delivered in a clear and understandable manner that aids in planning and decision making. They must make maximum use of all available information and be based on efficient and true hydrological process models.

Fortunately (for forecasters), the Great Lakes possess tremendous capacities for storage of mass and energy and respond slowly to changes in meteorology, making them amenable to hydrological forecasting. The dynamics of water supply components and basin and lake storages of water and heat must be understood before hydrological changes can be forecast. The Great Lakes Environmental Research Laboratory (GLERL) developed, calibrated, and verified conceptual model-based techniques for simulating hydrological processes in the Laurentian Great Lakes (including Georgian Bay and Lake St. Clair, both as separate entities). GLERL integrated the models into a system to estimate lake levels, whole-lake heat storage, and water and energy balances (Croley, 1990, 1993a,b; Croley and Hartmann, 1987, 1989; Croley and Lee, 1993; Hartmann, 1990). These include models for rainfall-runoff, evapotranspiration, and basin moisture storage [121 daily watershed models (Croley, 1982, 1983a,b; Croley and Hartmann, 1984)], overlake precipitation (a daily estimation model), one-dimensional (depth) lake thermodynamics [7 daily models for lake surface flux, thermal structure, evaporation, and heat storage (Croley, 1989a,b, 1992; Croley and Assel, 1994)], net lake supplies, channel routing [4 daily models for connecting channel flow and level, outlet works, and lake levels (Hartmann, 1987, 1988; Quinn, 1978)], lake regulation [a monthly plan balancing Lakes Superior, Michigan, and Huron and a quarter-monthly plan balancing Lake Ontario and the St. Lawrence Seaway (International St. Lawrence River Board of Control, 1963)], and diversions and consumption (International Great Lakes Diversions and Consumptive Uses Study Board, 1981). Details of these models are conveniently summarized by Croley et al. (1996). The modeling system is modularly-built, allowing model upgrades to be "dropped in" as developed and tested. It is coupled with near real-time data acquisition and reduction to enable representation of current system states. A new generation of interactively coupled models of the hydrosphere and atmosphere is forthcoming.

Forecasting efforts in the Great Lakes include the former US Lake Survey of the US Army Corps of Engineers, which began 6-month lake level forecasts in 1952. Since 1975, the Detroit District of the Corps has continued on a monthly basis. The Canadian Hydrographic Service (CHS) of the Department of Fisheries and Oceans began publishing monthly forecasts of levels in 1973. The Canadian forecasts are generated currently by the Great Lakes - St. Lawrence Regulation Office of Environment Canada and published by the CHS. See Table 1 for a chronology of recent Great Lakes forecasting developments. Both the US and Canadian monthly forecasts project water levels for each of the Great Lakes six months into the future. These forecasts are generated separately by each agency and then are coordinated to remove any differences. The Corps deterministic forecast is based upon extrapolations of recent

Table 1. Chronology of Recent Great Lakes Forecasting Developments.

	Great Lakes Water Level Forecasting
1952:	US Lake Survey 6-month lake level forecasts
1964:	US Lake Survey develops "Trend Regression"
1973:	Canadian Hydrographic Service estimates levels from probabilistic supplies
1975:	US Army Corps estimates levels from supply statistics with Trend Regression
1977:	Environment Canada & Corps both publish combined levels forecasts
1996:	Bulletin distribution via the Internet
Now:	6,800 US & 2,600 Canadian bulletins coordinated by IJC
	GLERL Advanced Hydrologic Prediction System (AHPS)
1982:	adapted runoff models to estimate supplies
1983:	Lake Superior installed for US Army Corps
1984:	Lake Champlain installed for NWS NERFC
1985:	identified weak evaporation estimates
1987:	all Great Lakes installed for 3 Corps offices
1988:	installed for New York Power Authority
1988:	delivered to Ontario Hydro
1990:	added improved 1-D evaporation models
1993:	altered deterministic outlooks,
	added an early form of probabilistic outlooks,
	re-evaluated & identified meteorology outlook as weakest part
1994:	installed for Midwest Climate Center
1995:	defined **AHPS** Product
	incorporated NOAA meteorology outlook probabilities
	built front-end **AHPS Graphical User Interface (GUI)** & public **GUI**
	built back-end **AHPS GUI**
	updated installation for Corps, NYPA, & MCC
1996:	expanded outlook products
	mixed agency outlook meteorology probabilities
	enhanced front-end **AHPS GUI** & public **GUI**
	assembled primitive back-end **AHPS GUI**
	demonstrated NRT **AHPS** at MCC on the WWW
	automated data downloading
1997:	**AHPS** outlooks produced at MCC & distributed via the Internet
	mixed multiple-area outlook meteorology probabilities
	developed method for lake-levels and connecting channel outlooks
	reinstalled for Ontario Hydro, NYPA, MCC, Corps
	demonstrated daily updates
Future:	development of improved **AHPS** distributed-parameter hydrology models
	incorporation of new & improved data streams
	expanded **AHPS** product dissemination
	revision & expansion of **AHPS GUI** & public **GUI**
	update Great Lakes **AHPS** lake regulation and channel routing routines

trends in water supplies for each of the lakes. Environment Canada's probabilistic forecast is computed from statistical analysis of historical water supplies. Neither the Corps nor Environment Canada use weather forecasts or antecedent hydrological conditions (current moisture and heat storages in the basins and lakes) in making their outlooks.

GLERL adapted runoff models to estimate supplies in 1982, installed their forecast package for the US Army Corps of Engineers on Lake Superior in 1983, for the NWS Northeast River Forecast Center on Lake Champlain in 1984, for 3 Corps offices on all Great Lakes in 1987, 1996, and 1997, for the New York Power Authority and Ontario Hydro in 1988, 1995, and 1997, and for the Midwest Climate Center in 1994, 1996, and 1997. GLERL identified weak evaporation estimates in 1985, added improved one-dimensional evaporation models in 1990, altered deterministic outlooks, added probabilistic outlooks, and identified meteorology outlooks as the weakest component in 1993.

GREAT LAKES AHPS

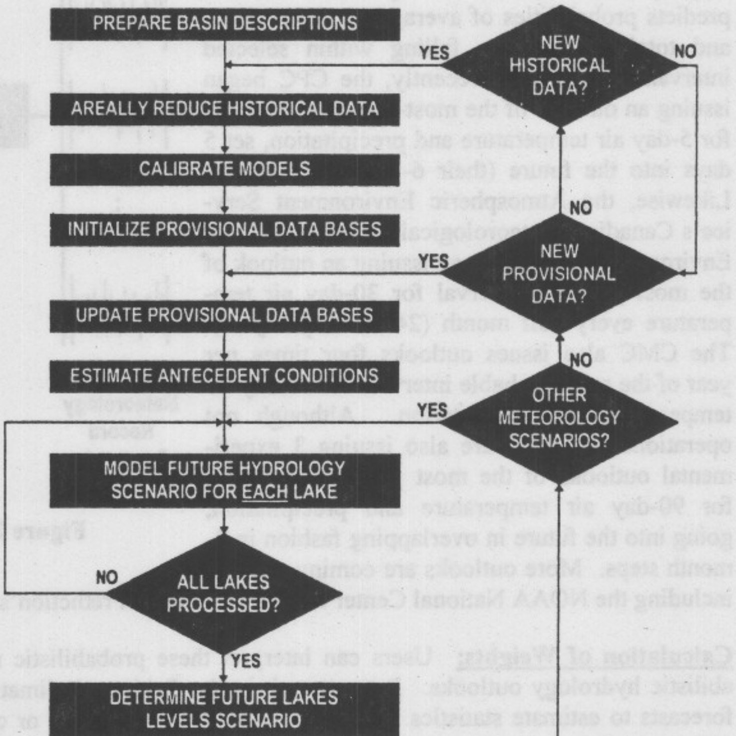

Figure 1. GLERL's Deterministic Hydrology Forecast.

<u>Deterministic Hydrology Forecasts:</u> GLERL developed the precursor to their present-day *Advanced Hydrologic Prediction System* (AHPS) as a semiautomatic software package to make deterministic forecasts of basin moisture storage, basin runoff, lake heat storage, surface water temperatures, lake surface evaporation, and lake water supplies (Croley, 1993b). These forecasts take advantage of the long-term memory of the Great Lakes system in the face of uncertain meteorology, and can be made for any number of months into the future. The package integrates modeling and near real-time data handling, is implemented in FORTRAN and PASCAL, and has been ported to several versions of MS-DOS, Windows, and UNIX. Inputs are daily meteorology (air temperature, dewpoint temperature, precipitation, wind speed, and cloud cover) for all available stations. Optional inputs are snow water equivalent, soil moisture, lake water temperature, and lake levels. Daily provisional point data are converted to areal averages for each watershed and lake surface by Thiessen weighting over digital maps of the areas (Croley and Hartmann, 1985). The areal averages are used by GLERL's runoff model (applied to all 121 Great Lakes watersheds) and their lake thermodynamics model (applied to each lake), to estimate basin moisture and lake heat as antecedent (initial) conditions to a forecast. A deterministic "forecast" of all hydrology variables, including lake supply, may be made then by simulating the hydrology from the point of estimated initial conditions forward with a meteorology scenario (taken from the historical record, for example). The resulting lake supply scenarios, one for each lake, then are used with connecting-channel routing and lake regulation models to determine a lake levels scenario. This can be repeated for alternate meteorology scenarios. New provisional data are used as they become available; new historical data are also used as available to update models and databases. See Fig. 1.

<u>Probabilistic Hydrology Forecasts:</u> GLERL adapted this deterministic hydrology forecasting methodology to make probabilistic forecasts by considering historical meteorology as possibilities for the future. An *operational hydrology* approach [used also by the National Weather Service in their Extended Streamflow Prediction (ESP) forecasts] segments the historical record and uses each segment with models to simulate a possible "scenario" for the future. Sections of the historical meteorology record are input to hydrological, limnological, and other models, as in Fig. 1, as alternate meteorology scenarios, preserving observed spatial and temporal interrelationships. Corresponding hydrology variable scenarios are computed for the future, including lake supply scenarios. The resulting set of scenarios serves as a statistical sample for inferring probabilities and other parameters associated with both meteorology and hydrology; see Fig. 2. Probabilistic hydrology outlooks then are made from the sample for each variable of interest. Thus, the resulting probabilistic hydrology outlooks properly consider antecedent hydrological conditions, but they do not consider other-agency predictions of meteorology.

<u>Probabilistic Meteorology Outlooks:</u> Multiple long-lead probabilistic meteorology outlooks of improving skill (climate outlooks) are now available to the water resource engineer or hydrologist. They are defined over different time periods at different time lags; they forecast either event probabilities or most-probable events. The National Oceanic and Atmospheric Administration's Climate Prediction Center (CPC) recently (1 January 1995) changed from issuing a few relatively short-term outlooks of meteorology probabilities to a new multiple long-lead "climatic

outlook." The outlook consists of a 1-month forecast for the next (full) month and thirteen 3-month forecasts, going into the future in overlapping fashion in 1-month steps. Each forecast predicts probabilities of average air temperature and total precipitation falling within selected intervals. Even more recently, the CPC began issuing an outlook of the most-probable intervals for 5-day air temperature and precipitation, set 5 days into the future (their 6-10 day outlooks). Likewise, the Atmospheric Environment Service's Canadian Meteorological Center (CMC) of Environment Canada began issuing an outlook of the most probable interval for 30-day air temperature every half month (24 times per year). The CMC also issues outlooks four times per year of the most probable intervals for 90-day air temperature and precipitation. Although not operational yet, they are also issuing 3 experimental outlooks of the most probable intervals for 90-day air temperature and precipitation, going into the future in overlapping fashion in 3-month steps. More outlooks are coming on-line, including the NOAA National Center for Environmental Prediction's ensemble forecasts.

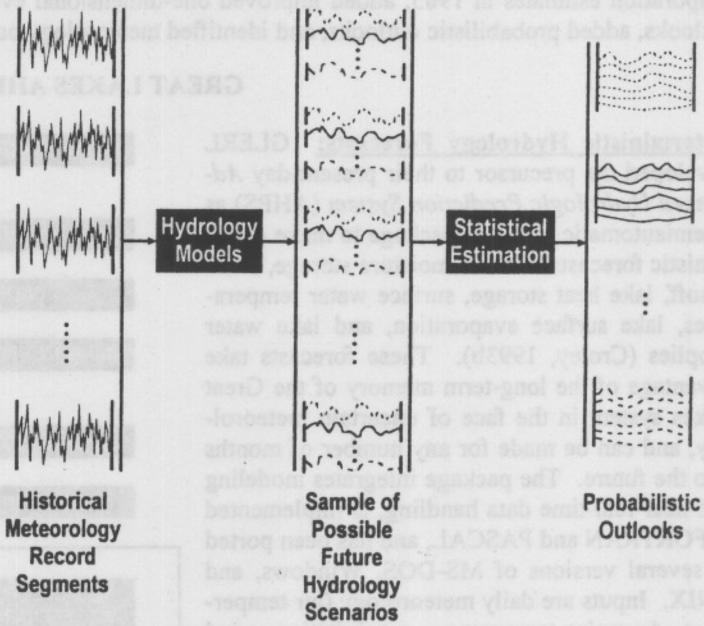

Figure 2. Operational Hydrology Approach.

<u>**Calculation of Weights:**</u> Users can interpret these probabilistic meteorology outlooks in improving their probabilistic hydrology outlooks. Recent work in the field used climatic indices from (other) long-range meteorology forecasts to estimate statistics subjectively (Smith et al., 1992) or coupled historical precipitation record segments with precipitation forecasts (Ingram et al., 1995). However, the relative frequencies of selected events (in the statistical sample of scenarios used in the operational hydrology approach) are fixed at historical values that are incompatible (generally) with those specified in the CPC's or CMC's probabilistic meteorology outlooks. Only by restructuring the set of scenarios can one obtain relative frequencies of selected events for a lake that match the CPC and CMC probabilistic meteorology outlooks over the lake. Recently, GLERL properly incorporated multi-agency, multi-period forecasts of meteorology probabilities by modifying their operational hydrology approach to generate probabilistic hydrology outlooks compatible with the meteorology outlooks. The hydrology variable scenarios, generated from corresponding segments of the historical meteorology record, are still used as a statistical sample for inferring probabilities, but the sample is first restructured. Croley (1996, 1997a,b) introduced a restructuring method that weights the scenarios and identifies boundary condition equations for the weights that correspond to probabilistic meteorology outlooks. The solution for the general case is shown to be an optimization problem. Now probabilistic hydrology outlooks consider both antecedent hydrological conditions <u>and</u> predictions of meteorology!

<u>**Simultaneous Spatial Outlooks:**</u> The probabilistic outlook of lake levels involves an additional complication. In a deterministic forecast, the forecast lake supply scenarios for each and all of the Great Lakes can be used as inputs to the connecting-channel routing and lake regulation models to determine the (simultaneous) lake level forecast scenarios on each lake. The connecting-channel routing and lake regulation models require water supplies on all lakes simultaneously to determine levels and outflows jointly on all lakes because all levels and outflows are interdependent. In a probabilistic outlook, the direct application of such a methodology might not be suitable for two reasons. 1) One <u>cannot</u> simply take the (say) 95<u>th</u> exceedance time series for water supplies as input to the connecting-channel routing and lake regulation models to determine the 95<u>th</u> exceedance time series for lake levels or outflows. There is not a simple one-to-one transform between quantiles of water supplies and lake levels. It is more appropriate to use the entire sample of water supply scenarios to create a sample of lake level scenarios from which to make probability outlooks. 2) However, since each lake (application area) involves a (generally) different set of probabilistic meteorology outlooks and set of weights, the water supply scenarios do not correspond to the same statistical sample from lake to lake. The use of all of the water supply scenarios for all of the Great Lakes, derived independently, as simultaneous inputs to the connecting-channel routing and lake regulation models then would not be representative of the same statistical sample when calculating lake level scenario forecasts.

As discussed earlier, the calculation of weights solves a set of equations representing multiple meteorology outlooks for a single lake to determine weights used in the solution for hydrology scenario probabilities. Because each lake's levels are not independent of the others, this method precludes the use of the independently derived weights in determining lake level probabilities. GLERL has been considering this issue for the past several years, and now have determined an appropriate method for determining joint lake level probabilities. The new extended methodology involves determining water supply (and other hydrology variable) scenarios on all lakes from the same historical record segments (as they existed on each of the lakes) and then solving all sets of equations (over all application areas) simultaneously to determine one set of weights that preserves all of the multiple meteorology outlooks over all of the Great Lakes. This of course requires that forecast parameters (such as start date and length of forecast) and historical meteorology record periods are the same over all application areas. The resulting weights can therefore be used directly in the solution for lake level probabilities, where the sample of lake level scenarios is derived from the appropriate simultaneous water supply scenarios on all the lakes; see Fig. 3. It is also useful to note here that, in Fig. 3, alternate meteorology outlooks (forecasts) may be considered without having to repeat provisional data updates, estimates of antecedent conditions, or any of the hydrology modeling required in sample building.

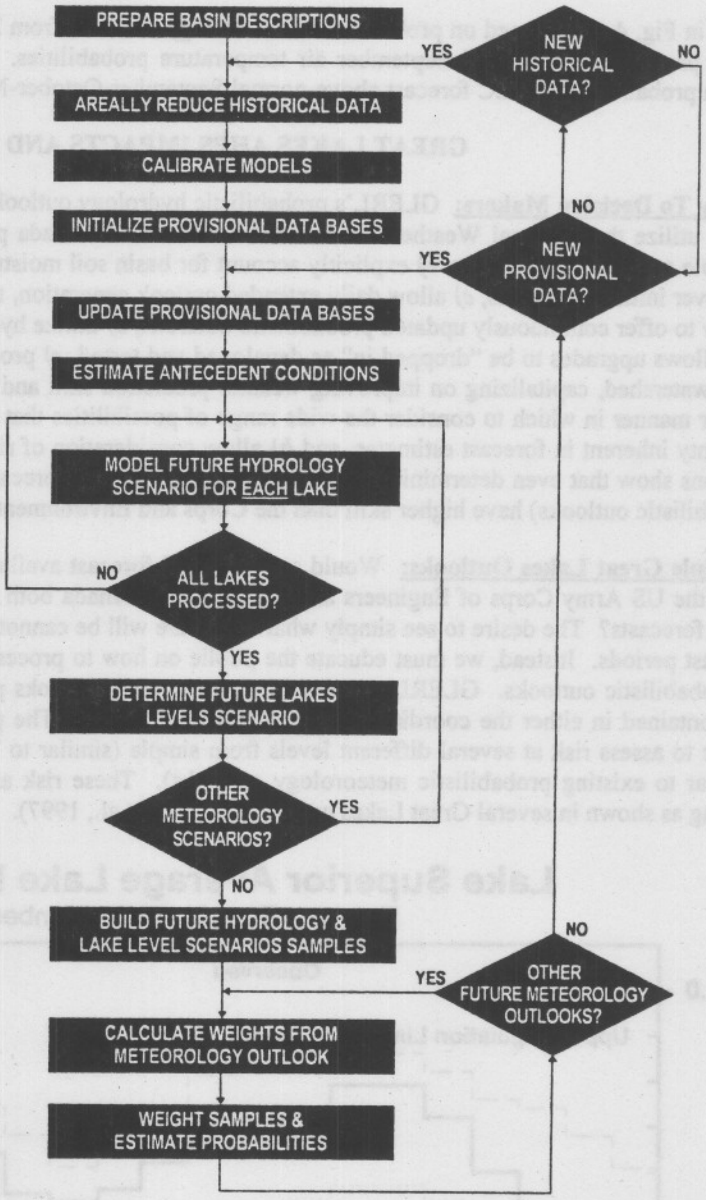

Figure 3. GLERL's Probabilistic Hydrology Forecast.

The methodology provides an objective and open-ended means of matching forecast meteorology probabilities in other forecasts besides the water resource forecasts considered here. This has opened the door on jointly considering additional multiple agency forecasts over multiple areas for multiple (different simultaneous) periods as they become available in the future.

<u>**Probabilistic Outlooks from Great Lakes AHPS:**</u> 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. This allows GLERL to provide 1- to 12-month (and longer) outlooks of probabilities for 25 hydrology variables over the entire Great Lakes basin, including simultaneous lake levels on all Great Lakes, that consider meteorology outlooks. Probabilistic outlooks allow decision makers to *consider the risk associated with their decisions*, not possible with deterministic outlooks. Probabilistic outlooks for all variables, except for lake levels, currently are made with GLERL's technology on an operational basis by the Midwest Climate Center, available to the public via the Internet. Probabilistic outlooks for lake levels currently are made experimentally at GLERL, as part of their *Advanced Hydrologic Prediction System*. The methodology is also used operationally by the Midwest Climate Center, the New York Power Authority, and Ontario Hydro, and experimentally by the US Army Corps of Engineers in Buffalo and Detroit. A recent probabilistic lake level outlook is pro-

vided in Fig. 4. It is based on probabilistic meteorology outlooks from NOAA and Environment Canada. Both generally predicted near-normal September air temperature probabilities. NOAA forecast normal September precipitation probabilities and EC forecast above-normal September-October-November air temperature probabilities.

GREAT LAKES AHPS IMPACTS AND ASSESSMENT

Utility To Decision Makers: GLERL's probabilistic hydrology outlooks are state-of-the-art. They ***a)*** fully and correctly utilize the National Weather Service and Environment Canada probabilistic long range climate outlooks for multiple areas simultaneously, ***b)*** explicitly account for basin soil moisture and snow pack and lake heat storage and ice cover initial conditions, ***c)*** allow daily extended outlook generation, taking advantage of near-real-time data availability to offer continuously updated probabilistic outlooks, ***d)*** utilize hydrology models in a modularly-built package that allows upgrades to be "dropped in" as developed and tested, ***e)*** provide probabilistic outlooks for each lake and river watershed, capitalizing on improving weather prediction skill and hydrometeorology observations, ***f)*** offer the proper manner in which to consider the wide range of possibilities that always exist, ***g)*** incorporate some of the uncertainty inherent in forecast estimates, and ***h)*** allow consideration of risk by decision makers, as mentioned. Comparisons show that even deterministic outlooks from the GLERL forecast package (constructed by simply averaging probabilistic outlooks) have higher skill than the Corps and Environment Canada outlooks (Croley and Lee, 1993).

Multiple Great Lakes Outlooks: Would an additional forecast available to the public cause confusion, especially since the US Army Corps of Engineers and Environment Canada both concurrently publish "coordinated" deterministic forecasts? The desire to see simply what the future will be cannot be accommodated, particularly for extended forecast periods. Instead, we must educate the public on how to process a range of possibilities through expression as probabilistic outlooks. GLERL's probabilistic hydrology outlooks provide additional information to the public, not contained in either the coordinated or component forecasts. The probabilistic information can be used by the public to assess risk at several different levels from simple (similar to TV weather forecasts) to more sophisticated (similar to existing probabilistic meteorology outlooks). These risk assessments may be associated with decision making as shown in several Great Lakes case studies (Lee et al., 1997).

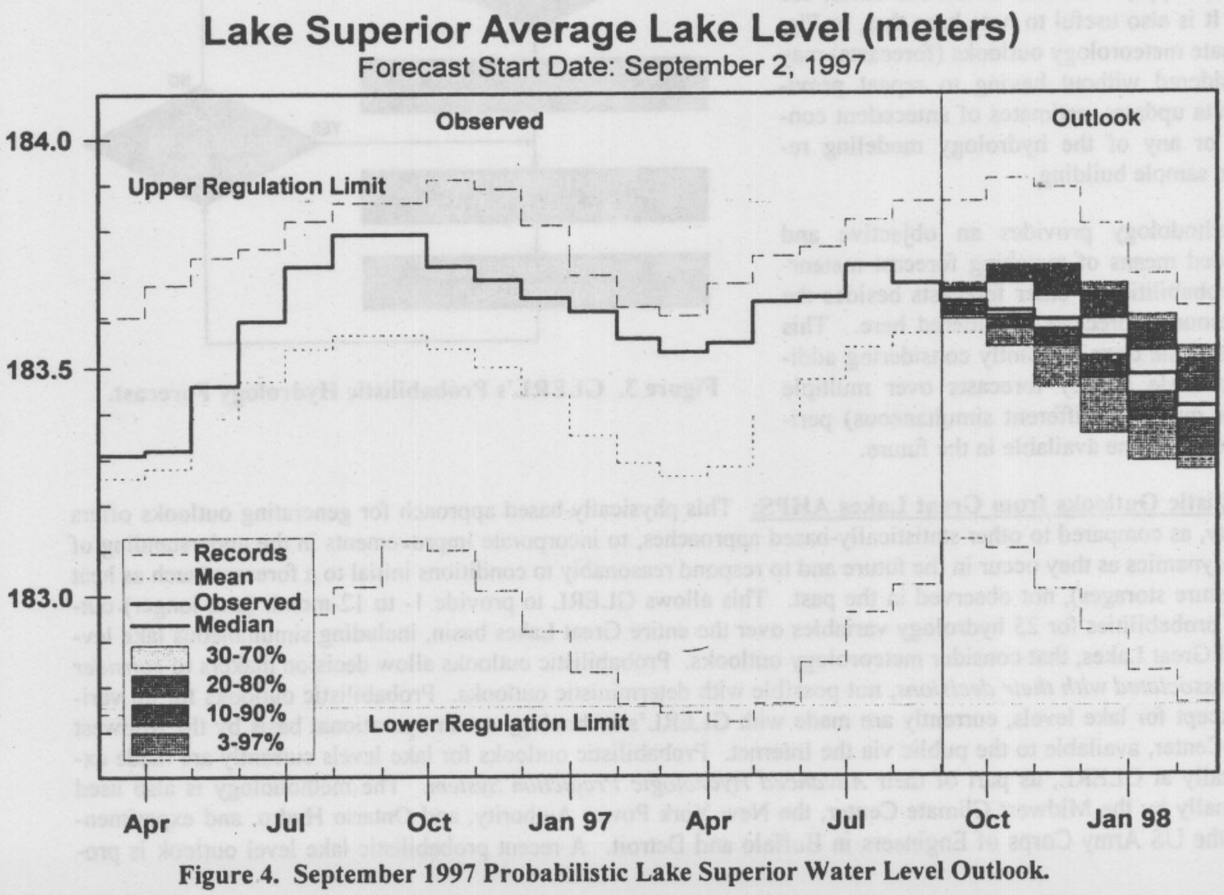

Figure 4. September 1997 Probabilistic Lake Superior Water Level Outlook.

It behooves all parties to ease possible confusion by introducing GLERL's probabilistic outlooks along side of the current deterministic ones, with appropriate explanation on the interpretation and use of outlook probabilities. This would help to educate decision makers on using outlook probabilities to assess risk in their decision making. This would also clarify the role of all of these outlooks in relation to one another. This is much preferable to forcing users to wonder if the different outlooks, that they discover independently available, are conflicting or are related to one another.

Responding To User Needs: Probabilistic hydrology outlooks address NOAA's 1995-2000 *Strategic Plan* component for the enhancement of environmental prediction. The plan calls for an integrated environmental observation, assessment, and forecast service that supports the Nation's economic and environmental agenda both by significantly improving short-term (immediate to 60 days) forecasts, and by implementing reliable seasonal to interannual (60 days-10 years) forecasts. GLERL has been providing that service on the Great Lakes, in terms of water quantity, through its AHPS program (see Table 1) for predicting Great Lakes hydrology variables, and through its Great Lakes Forecast System for predicting short-term wind-driven waves and setup on Lake Erie. Other NOAA offices (National Weather Service) have been providing both 1-2 day level outlooks (related to storm and wind setup) and 1 week level outlooks on all Great Lakes.

GLERL's probabilistic hydrology outlooks also address recommendation number 31 of the International Joint Commission to the US and Canada as a result of their Levels Reference Study (IJC, 1993). The 5-year study examined methods to alleviate problems associated with Great Lakes-St. Lawrence River Basin fluctuating water levels and outflows. They recommended development of improved lake operation and management tools, "[to] upgrade models used for simulation, forecasting and regulation in order to formulate a comprehensive water supply and routing model that includes the whole basin." In its report to the governments, the IJC supported the development of risk analysis techniques for application in management of water levels issues. The IJC recognized the usefulness of risk analysis techniques in its work under the Great Lakes Water Quality Agreement and supported their extension to lake level management.

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Tropicana Hotel
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Prepared by the Subcommittee on Hydrology of the Interagency Advisory Committee on Water Data

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