GLERL'S NEAR REAL TIME HYDROLOGICAL OUTLOOK PACKAGE[1]

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ABSTRACT: The Great Lakes Environmental Research Laboratory developed a semiautomatic software package for making deterministic or probabilistic outlooks of basin moisture storage conditions, basin runoff, lake heat storage, lake evaporation and other heat fluxes, net lake supplies, and lake levels six or more full months into the future for large lakes. We designed the package especially for use on small computers with a standard FORTRAN-77 compiler, 5-15 megabytes of disk storage (per application), and a minimum of processor and memory resources. The package combines our Large Basin Runoff Model applications on each of the subbasins about a lake to represent the entire basin's current moisture storage and our lake evaporation model applications on each of the Great Lakes to represent each lake's current heat storage. Our near-real-time data reduction system uses new algorithms to efficiently determine daily areal averages of meteorologic variables over each of the subbasins. We select historic meteorologic sequences, representing anticipated meteorology, based on the National Weather Service monthly and seasonal forecasts of precipitation and air temperature probabilities, for use with the runoff and evaporation models to generate our near real-time outlooks. The package construction is presented and the use of its modules are detailed.

Introduction

With the intrinsic memory of large basins and lakes (large storages of water and heat), there is much potential for developing useful short-term operational hydrology forecasts in the face of uncertain meteorology. The Great Lakes Environmental Research Laboratory (GLERL) developed a conceptual model-based software package that uses near real-time information to establish forecasts which consider both the existing basin storages and anticipated meteorology. GLERL developed the forecast package on all Great Lakes for the U.S. Army Corps of Engineers Detroit District, USCOE Buffalo District, USCOE Hydrologic Engineering Center, and the New York Power Authority, and on Lake Champlain for use by the National Weather Service Northeast River Forecast Center (Croley and Hartmann, 1985b).

Forecasts are integrations of modeling and near real-time data handling. Deterministic and probabilistic forecasts of water supply several months into the future are possible in near real-time by using GLERL's Large Basin Runoff Model and lake evaporation and heat storage model with forecast meteorology. The calibrated models (Croley 1983a,b, 1989a,b) are used from the end of archived climatic data to the present by using provisional data from a near real-time data network. Thus, we 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. Finally, estimates of the other components of water supply

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(precipitation over the lake and net groundwater flux to the lake) are included to generate a water supply forecast; hydraulic routing enables a lake level forecast. While our forecast package produces an outlook from the end of the available provisional data through the next six or more full months, we also compute basin storages over the preceding 18-month period for a perspective on recent basin moisture conditions.

Three components of the forecast package are described first: 1) the runoff model and its application, 2) the lake evaporation model and its application, and 3) the near real-time data acquisition and reduction system. The forecast package then is outlined from a user's perspective.

Runoff Modeling

The GLERL Large Basin Runoff Model (LBRM) consists of moisture storage tanks arranged in a serial and parallel cascade (Croley 1983a,b). Daily, water enters the snowpack (if present) and some then is available to the watershed surface based on degree-day determinations of snowmelt. Infiltration is proportional to snowmelt or precipitation and to the areal extent of the unsaturated portion of the upper soil zone. The tanks are modeled as linear reservoirs; the outflow rate from each tank is proportional to the moisture in storage. Evapotranspiration rates from the upper and lower soil zones are proportional to available moisture and to the heat rate available for evapotranspiration; the daily evapotranspiration volume is also complementary to the total daily heat available for evapotranspiration (Croley 1985) which is estimated empirically from the average air temperature.

Mass continuity and the concepts for snowmelt, infiltration, linear reservoirs, and evapotranspiration yield a first-order linear differential equation for each moisture storage; outputs from one tank are used in lower tanks where they appear as inputs. There are 30 different analytic results (Croley 1982), depending upon the relative magnitudes of all inputs, initial storages, and model parameters. Since the inputs and initial storages change each day, the appropriate analytic result, as well as its solution, varies with time; mathematic continuity between solutions is preserved, however. The analytic solutions preclude the approximation and convergence problems of numeric solutions.

Daily precipitation, daily maximum and minimum air temperatures, a climatic summary of daily extraterrestrial solar radiation, the area of the watershed, and daily basin outflows are used to determine the nine parameters in an automated systematic search of the parameter space that minimizes the sum-of-squared-errors between actual and model outflow volumes (Croley and Hartmann 1984, 1985c). We divided the Great Lakes basin into 121 subbasins, each draining directly into a lake and calibrated the model for each of them. Daily meteorologic data for 1900-88 from 1,581 stations (672 U.S. and 909 Canadian) about the Great Lakes were combined through Thiessen weighting to produce areally-averaged daily time series for each subbasin. Distributed-parameter applications, in which the LBRM is calibrated for each subbasin and model outflows are combined to represent an entire lake basin, make use of information that is lost in a lumped-parameter approach; the integration then filters individual subbasin model errors. Calibration and independent verification statistics are summarized in Table 1.

Evaporation Modeling

Conceptual formulations of mass transfer through the air layer in contact with the water surface, that include atmospheric stability effects on the evaporation bulk transfer coefficients, are applied to daily data in a heat balance with models for over-water meteorology, ice cover, various heat fluxes at the water surface, and heat storage (Croley 1989a,b). As over-water meteorology are not available generally, over-land meteorology are used by adjusting for over-water conditions. Air temperatures and specific humidities over ice are used for over-ice evaporation calculations and over water for the over-water calculations; the two estimates are combined by weighting for the fraction of the surface covered in ice. Existing empirical relations between ice cover extent and air temperatures are used as determined during the International Field Year for the Great Lakes. Standard models are used for over-water and over-ice short-wave radiation, short-wave reflection, long-wave radiation exchange, sensible heat transfer, evaporative advection, latent heat transfer, energy advected with precipitation, snowmelt, energy advected with other water flows, and heat delivered to the ice pack.

Table 1. Runoff Model Calibration & Verification Statistics.[a]

Lakes	Number of Sub-Basins	Mean 1-Day Flow[b]	Flow Std. Dev.[b]	Root Mean Square Error[b]	Correlation Cal.	Correlation Ver.
Lake Superior	22	1.12	0.67	0.25	0.93	0.77
Lake Michigan	29	0.89	0.47	0.18	0.93	0.86
Lake Huron	27	1.06	0.69	0.26	0.92	0.69
Lake St. Clair	7	0.90	1.36	0.62	0.89	0.87
Lake Erie	21	1.01	1.28	0.54	0.91	0.90
Lake Ontario	15	1.41	1.13	0.43	0.93	0.89

[a]Calibration over 1966-83, verification over 1956-63.
[b]Equivalent depth over land portion of basin in millimeters.

Mixed-layer thermal structure models developed for oceans are extended for the Great Lakes , based on concepts for mixed-thermal layer development and spring and fall water column turnovers, in a one-dimensional heat storage model where surface temperature increments or decrements are defined in terms of past heat additions or losses, respectively (Croley 1989a,b). The effects of past additions or losses are superimposed to determine the surface temperature on any day as a function of heat in storage; each past addition or loss is parameterized by its age as a proxy for the wind history or accumulated mixing. Turnovers can occur as a fundamental behaviour of this superposition model and hysteresis between heat in storage and surface temperature, observed during the heating and cooling cycles on the lakes, is preserved.

Daily meteorological over-land data for air temperature, humidity, windspeed, and cloudcover at from five to ten near-shore stations about each Great Lake were assembled and spatially averaged. The lake evaporation and heat balance model then was calibrated to water surface temperatures available from the National Oceanic and Atmospheric Administration's Polar Orbiting Satellite Advanced Very High Resolution Radiometer to determine values of the five model parameters that give the smallest sum-of-squared-errors (Croley 1989b). Calibration and independent verification statistics are summarized in Table 2.

Table 2. Evaporation Model Calibration & Verification Statistics.[a]

Lake	Means Ratio[b] Cal.	Means Ratio[b] Ver.	Var. Ratio[c] Cal.	Var. Ratio[c] Ver.	Correlation[d] Cal.	Correlation[d] Ver.	Root Mean Square Error[e] Cal.	Root Mean Square Error[e] Ver.
Superior	0.99	0.92	0.98	1.02	0.98	0.94	1.17	1.46
Michigan	1.02		0.92		0.97		1.50	
Huron	1.00	1.02	1.00	0.97	0.98	0.98	1.30	1.34
St. Clair	1.09		1.71		9.97		3.69	
Erie	0.99	1.09	1.06	1.25	0.98	0.97	1.76	2.38
Ontario	1.00	1.09	0.97	0.99	0.98	0.97	1.35	1.79

[a]Calibrations cover 1979-85 for all Great Lakes and 1979-83 for Lake St. Clair. Verifications cover 1966-78.
[b]Ratio of mean model surface temperature to data mean.
[c]Ratio of variance of model surface temperature to data variance.
[d]Correlation between model and data surface temperature.
[e]Root-mean-square error between model and data surface temperatures in C.

Near Real-Time Data Reduction

To use the LBRM in an operational mode, near real-time meteorologic station data (daily precipitation and minimum and maximum air temperature) must be rapidly reduced to daily areal averages for each of the many subbasins about a lake. Likewise, daily near real-time average air temperature, windspeed, humidity, and cloudcover must be rapidly reduced for the lake surface. These data reduction processes consist of three elements: 1) the acquisition of point measurements in individual station files, 2) the automatic update of master point-measurements data bases, and 3) the automatic update of areal-averages data bases. While the processing of meteorologic data is described herein, the routines offer advantages for any application requiring rapid conversion of point measurements to areal averages, especially for high-density data-observation networks. The routines are described in detail by Croley and Hartmann (1986) and can be implemented independently of the forecast package.

Data Acquisition

Meteorologic data available for use in forecasting Great Lakes Basin runoff currently include daily precipitation and minimum and maximum daily air temperatures from about 880 stations in the U.S. and Canada. Provisional data are available in near real-time (within a week of measurement) from about 85 stations (44 U.S. and 41 Canadian), within 6 weeks from an additional 445 U.S. stations from the U.S. National Climatic Data Center (1985), and within 6 months from an additional 350 Canadian stations. Likewise, meteorologic data for evaporation forecasting include daily temperature, windspeed, humidity, and cloudcover from about 31 stations (14 U.S. and 17 Canadian) and all are available in near real-time. Operational water supply outlooks require all data (for all data-reporting lags) to be processed within a few minutes each month to produce daily areal-average precipitation, minimum, maximum, and average air temperatures, windspeed, humidity, and cloudcover for 121 subbasins and six lake surfaces about the Great Lakes. As the provisional data network becomes more responsive and as the requirements for timely water supply or flooding outlooks grow, outlooks may be generated daily or hourly. For Great Lakes applications, a daily reduction of data is acceptable (currently done once a month) and so microcomputers may be used (Croley and Hartmann 1985d).

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The extreme variability of the meteorologic network can pose data reduction problems. Procedures for reducing data that consider only a single network containing all stations and then make simple adjustments for missing data introduce data errors into the water supply outlooks; however, data reduction procedures that consider all networks must be fast enough to use in an operational setting. For example, over the period 1 January 1984 through 31 August 1985 (609 days), 71,349 station-datum-days (daily precipitation and daily minimum and maximum air temperatures) were received from 57 stations about Lake Superior as GLERL operated in an experimental outlook mode. Inspection reveals that there were 644 unique network configurations but that as some of these networks recur, 3,553 network changes took place as the data were processed in 13 reduction sessions; the averages per session were 273 network changes with 50 new network configurations. The actual numbers for the last reduction were 469 network changes with 170 new network configurations. The continuing data reduction requirements on each Great Lake consist of about 400-600 network changes with about 100-200 new network configurations each month.

Point-Measurements Data Base Management

The user provides a file for each station, containing new and changed data, each time the data bases are to be updated. Procedures for creating the station files are the responsibility of the user; data acquisition systems must be designed for each specific installation to most efficiently place near real-time data into individual station files. These station files are processed with an error-checking program to trap units, range, and consistency errors. All errors are identified in detail so the user may easily correct them and rerun the error-checking program; subsequent programs will terminate immediately, with appropriate error messages, if the error-checking program has not approved all station files. New data are simply appended to the physical end of a point-measurements data base, as they are encountered in reading the individual station files, and appropriate links within the data base are changed to include the new data in logical order. Changed data simply replace old data in the file. The data base is rewritten to recover dead space from removed data and reordered for efficient processing.

Areal-Averages Data Base Management

Thiessen weighting is used to transform the near real-time point measurements from the meteorologic network to areal averages for each subbasin. The area of the "Thiessen polygon" about each station that encompasses all points closest to that station is found first. The intersection of this area with a subbasin area determines the fraction of the subbasin governed by that station. These fractions (Thiessen weights) are multiplied with the station's data and summed to give an areally averaged value for the subbasin. We developed a new algorithm for quickly computing Thiessen weights for all stations in a collection network for each of several subbasins of interest. The algorithm is presented in sufficient detail by Croley and Hartmann (1985a) for its implementation on any computer.

Separate files of areal averages are maintained for each subbasin and lake surface for both the basin runoff and evaporation models. Efficiencies in the update of the areal averages data bases result from: 1) processing only those dates with new or changed data, 2) recycling, rather than recomputing, Thiessen weights for recurring networks, and 3) efficiently computing Thiessen weights (discussed previously) for new networks. As each network's Thiessen weights are computed and used, they are saved in separate data bases; this enables fast recall of any network's Thiessen weights. As the areal-averages data bases are updated, each block in the point-measurements data bases are marked as "old" so that they are not processed in subsequent reductions unless changed by the addition of new or different data. Also, the management of the areal-averages data bases includes the recording of the date of the earliest changed or added data for use by subsequent programs. This date is used to initiate further updates of additional data bases of basin moisture and lake heat storages with the runoff and evaporation models respectively.

Forecasting Water Supplies

The outlook procedure, outlined schematically in Figure 1, consists of 6 modules for: 1) preparing climatic subbasin files of areally-averaged historic meteorologic and hydrologic data, 2) calibrating the runoff model for each subbasin and the evaporation model for each lake, 3) preparing initial data bases for the forecast module, including climatic hydrometeorologic quantiles to aid in selecting a forecast meteorologic scenario and to provide historic perspective for the water supply forecasts, 4) updating provisional data bases with near real-time meteorologic data and updating basin moisture and lake heat storage conditions with the models applied to the provisional data or with field measurements, 5) selecting a forecast meteorologic scenario, and 6) transforming forecast meteorology into forecast basin runoff, net basin supply, and lake levels.

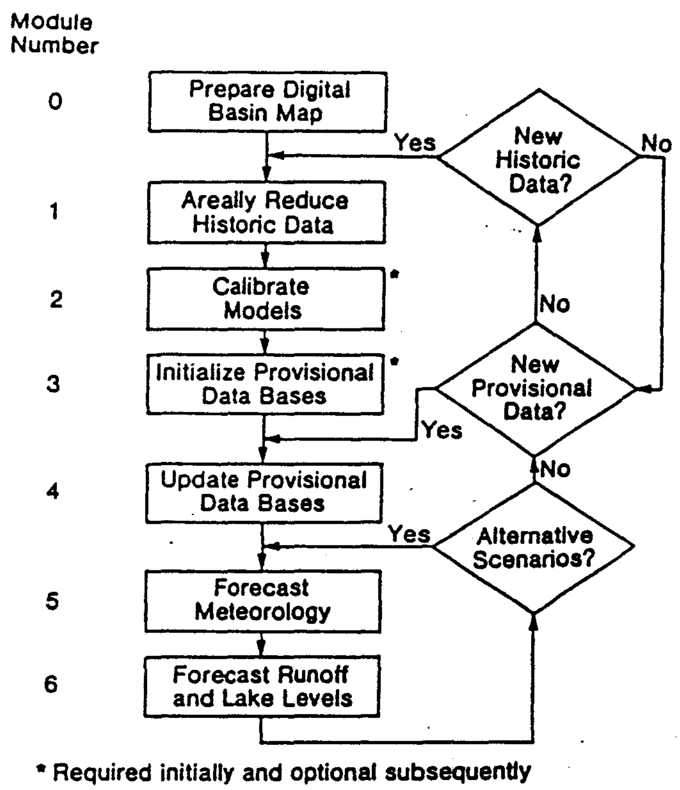

Figure 1. Logic diagram of the automated outlook procedure.

While all modules identified in Figure 1 are detailed elsewhere (Croley and Hartmann 1986), a user's perspective on use of the forecast package consists of the last three modules in Figure 1; these are transferred 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, daily meteorologic provisional data additions, deletions, or changes must be obtained from stations in and around the lake basin through a near real-time data acquisition network and placed into individual station files as described above. Second, the user may provide field measurements of basin moisture conditions if they are available; otherwise, model storages are used. 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 forecast meteorology. If a deterministic water supply forecast is desired, the user need only provide a single sequence of forecast meteorology; a probabilistic water supply forecast requires multiple forecast meteorologic sequences.

The fourth module in Figure 1 accepts new provisional data and adds it to the provisional data bases as detailed in the above section, culminating with areal averages for each subbasin. The subbasin files are then used with the LBRM to update direct-access files of subbasin and entire-basin daily moisture storages; 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 of basin moisture conditions, available from snow course, aerial, or satellite monitoring (Gauthier et al. 1984), may be incorporated for the LBRM in this module; these measurements can be for any date later than the end of the climatic data bases. Overall, the fourth module estimates current subbasin storages with the model as applied to the most recent provisional data and available field measurements, and these storages serve as initial conditions for a forecast.

Basin runoff and lake evaporation are forecast by applying the LBRM for each subbasin and the lake evaporation model for each lake to a forecast meteorologic sequence. The selection of this sequence is important and difficult; the resulting forecast of runoff will be no better than the forecast of air temperatures, precipitation, windspeed, humidity, and cloudcover used in the simulation. A standard method involves using medians, selected from the historic 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. An alternative method 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.

The U S. National Weather Service (NWS) provides monthly and seasonal weather outlooks semimonthly for the North American Continent (Climate Analysis Center 1985) which consist of maps of air temperature and precipitation probabilities for the coming month and 3-month season. Module 5 in Figure 1 uses these outlooks to construct a biased sample of forecast meteorologic sequences; meteorologic quantile non-exceedance probability tables, compiled in module 3, are scanned to identify several years of the historic record for the entire basin which best match the probabilistic weather outlooks (non-exceedance probabilities forecast for the 30% or 70% quantiles of daily air temperature and precipitation over the next month and 3 months) over the water supply forecast period of interest. For each subbasin, the historic daily values of areally-averaged minimum, maximum, and average air temperatures, precipitation, windspeed, humidity, and cloudcover corresponding to the forecast period of interest then are taken from the identified years of record and used as the forecast meteorologic sequences. Thus, the spatial and temporal interdependencies of the meteorologic processes are preserved. Admittedly, the extremes are limited to only those of record, but this is not considered a problem since subbasin areal averages are used, corresponding to very large areas which do not have as extreme data values as small areas.

The sixth module in Figure 1 accepts a single forecast meteorologic sequence from module 5 and uses it with the LBRM, for its respective subbasins, and the lake evaporation model, for each lake, to automatically simulate the resulting basin runoff and lake evaporation; the forecast basin runoff is then predicated on the forecast meteorology and the basin storages that exist at the beginning of the forecast period (end of the provisional data period as computed in module 4) and the forecast lake evaporation is predicated on the forecast meteorology and the lake heat storage that exist at the beginning of the forecast period. The subbasin runoff and storages outlooks each are aggregated over the entire basin, comparison historic quantiles are extracted and tabulated, and the total basin runoff, lake precipitation, and lake evaporation are combined to forecast net basin supply for the lake. Net basin supply is used in conjunction with hydraulic routing models and the user-supplied initial lake level to calculate forecasted lake levels. For probabilistic forecasts, module 6 in Figure 1 is then repeated for every year of the historic record selected in module 5. Various forecast statistics are computed and various forecast entire-basin storage conditions are plotted with (optional) historic quantiles for perspective. An example is pictured in Figure 2.

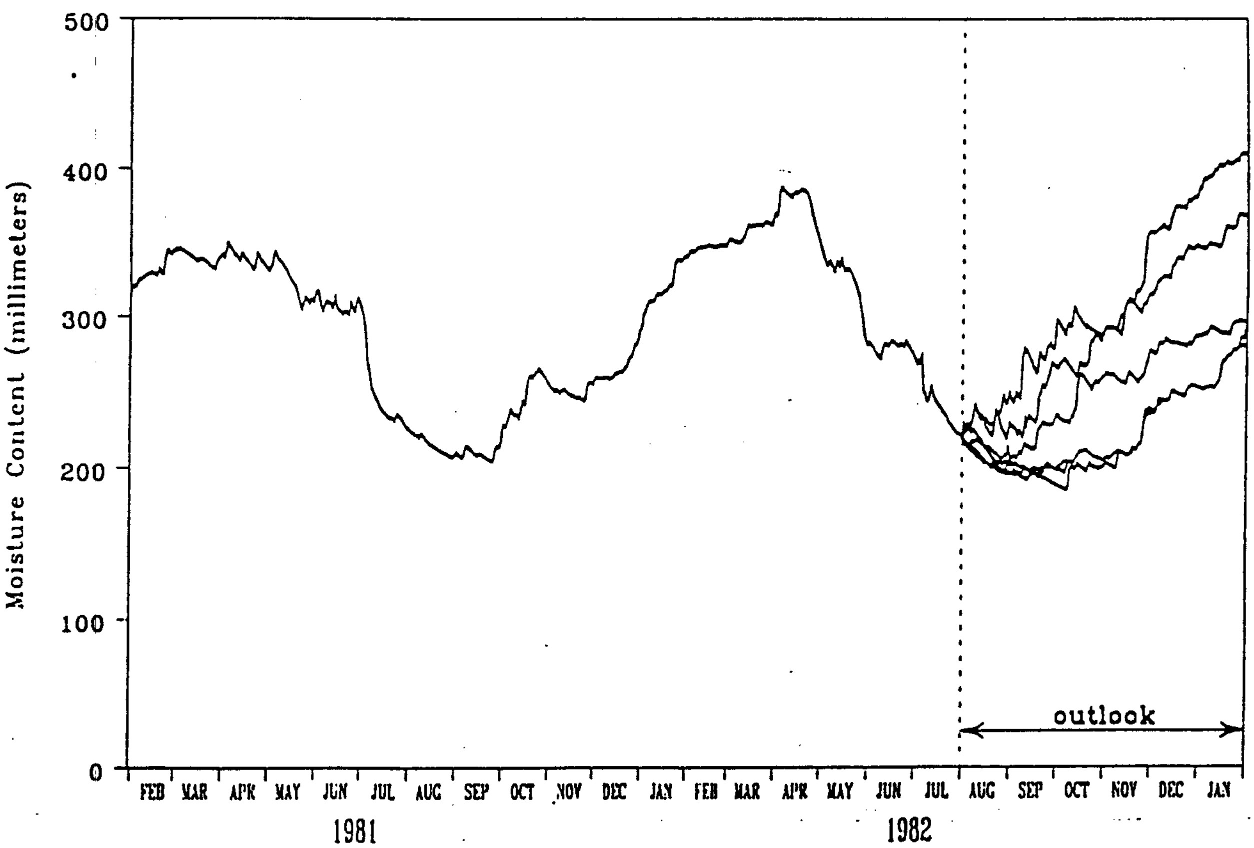

Figure 2. Example outlook for Lake Superior.

The six modules of Figure 1 are reused as required for successive product updates, climatic or provisional data updates, and forecasts as illustrated thereon. Modules 5 and 6 are re-executed for each selected year of record to form a forecast sample average. As new provisional data become available in near real-time, modules 4-6 are re-executed to include the data and make revised forecasts. As data collection agencies revise their provisional data and make it available to add to the historic records, the entire package of Figure 1 may be re-executed to revise the historic data bases, recalibrate the runoff models on each subbasin, recalibrate the evaporation model on each lake, and reinitialize the forecast data bases (also replacing the limited provisional data in those data bases with the more comprehensive historic data). Modules 1-3 are executed infrequently (every 2-5 years) as historic 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 realtime 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.

Conclusions

GLERL's Large Basin Runoff Model and lake evaporation model have been extended in a software package allowing both probabilistic and deterministic 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. Forecast meteorology then is used to estimate basin runoff and basin storages over the next six 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 and forecast package by agencies responsible for operational forecasting of large lake supplies.

Integral to the package are data handling routines designed especially for use on small computers with a FORTRAN compiler and a minimum of processor and memory resources. The user can change or delete prior data as well as add new data with no restrictions on continuous or chronologic order. The routines check new and changed data for format and range errors and add it to a master data base structured as a linked list. The software is available in FORTRAN-77 for PCDOS or MSDOS. The routines have been transferred to the U.S. Army Corps of Engineers Detroit District, Buffalo District, and Hydrologic Engineering Center and the New York Power Authority for use on the Great Lakes and to the National Weather Service Northeast River Forecast Center for use on Lake Champlain.

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