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LAKE CHAMPLAIN WATERSHED FORECASTING

Edward J. Capone, Thomas W. Econopouly, Robert C. Shedd*
NOAA/NWS/Northeast River Forecast Center

1. Introduction

The National Weather Service (NWS) Northeast River Forecast Center (NERFC) has developed a forecast model for the Lake Champlain watershed. The 21, 326 km^2 basin, includes contributing area in Vermont (56%), New York (37%) and Quebec (7%). Daily river stage forecasts are produced on tributaries to Lake Champlain including the Great Chazy, Saranac, Ausable, Bouquet, Mettawee, Poultney, Lamoille, Winooski, and Missisquoi Rivers and Otter Creek. Lake level forecasts are also provided at Rouses Point, on the northern end of the Lake, and at St. Jean's Shoal at the control downstream on the Richelieu River in Canada.

Flooding has been a great concern, especially in the spring snow melt season on the lake along the Richelieu River in Canada and along the shoreline of Burlington, VT as well as other shoreline communities. Low flow conditions have also provided problems along the Richelieu River at Saint Jean's Shoal. Since the 1970's, the International Joint Commission (IJC) has been interested in a short and long-term tool for forecasting Lake Champlain lake levels. For long-term lake level forecasting, the NERFC has implemented the Advanced Hydrologic Prediction Service (AHPS) that includes ensemble stream flow predictions 15 to 45 days in the future.

Forty years of precipitation and temperature data from NWS stations were obtained and quality controlled. United States Geological Service (USGS) stream flow data was obtained and quality controlled for each sub-watershed. Nineteen sub-watersheds were calibrated using the NWS River Forecast System (NWSRFS). The NWSRFS includes the Sacramento Soil Moisture Accounting model (SAC-SMA), unit hydrograph analyses, a snow accumulation and depletion model, reservoir operations and routing schemes, and channel routing. The channel and reservoir/lake routing routines use both hydrologic and dynamic routing methods.

Dynamic routing of each sub-watershed hydrograph into Lake Champlain was completed using the NWS Flood Wave (FLDWAV) model. Lake Champlain bathymetry and Richelieu River cross section information was obtained to route each sub-watershed lateral inflow hydrograph through Lake Champlain to the Richelieu River. The use of the dynamic routing technique allows for a forecast water level at each cross section location along the lake, including Burlington, VT.

Data from the backwater analysis completed by the International Joint Commission (IJC) was input into the Hydrologic Engineering Center's River Analysis System (HEC-RAS) to develop the backwater profiles along and through the controlling sections at Saint Jean's shoal.

The lake's geometric configuration including the location and size of the outlet at the north end of the lake enhance wind developed setup conditions that affects lake levels. An inland version of the Sea, Lake, and Overland Surge from Hurricanes (NWS-SLOSH) is in the development stage and is being coupled with the National Center for Environment Prediction Aviation model (NCEP -AVN) for its site specific forecast wind data. This model will be used to further refine the hydrologic/hydraulic model output for Lake Champlain levels in the short-term. The NERFC is also working with the Great Lakes Environmental Research Laboratory (GLERL) that currently has a working hydrodynamic model of Lake Champlain.

2. Forecast Models

Several NWS models were used to develop the forecast tool that include aspects of hydrology, river mechanics, statistics, and meteorology. The hydrologic component was completed using the Sacramento Soil Moisture Accounting Model (SAC-SMA) that incorporates calibrated watershed specific runoff parameters. River mechanics/hydraulics was accomplished by using the FLDWAV model which includes dynamic reach routing using the Saint Venant equations. The Extended Stream flow Prediction (ESP) compares the historic simulation with a conditional simulation based on the current forecast conditions of each sub-watershed. Lake setup due to wind is being completed using an Inland lake version of the SLOSH model that will use the

* Corresponding author address: Edward J. Capone, National Weather Service, Northeast River Forecast Center, Taunton, MA. 02780

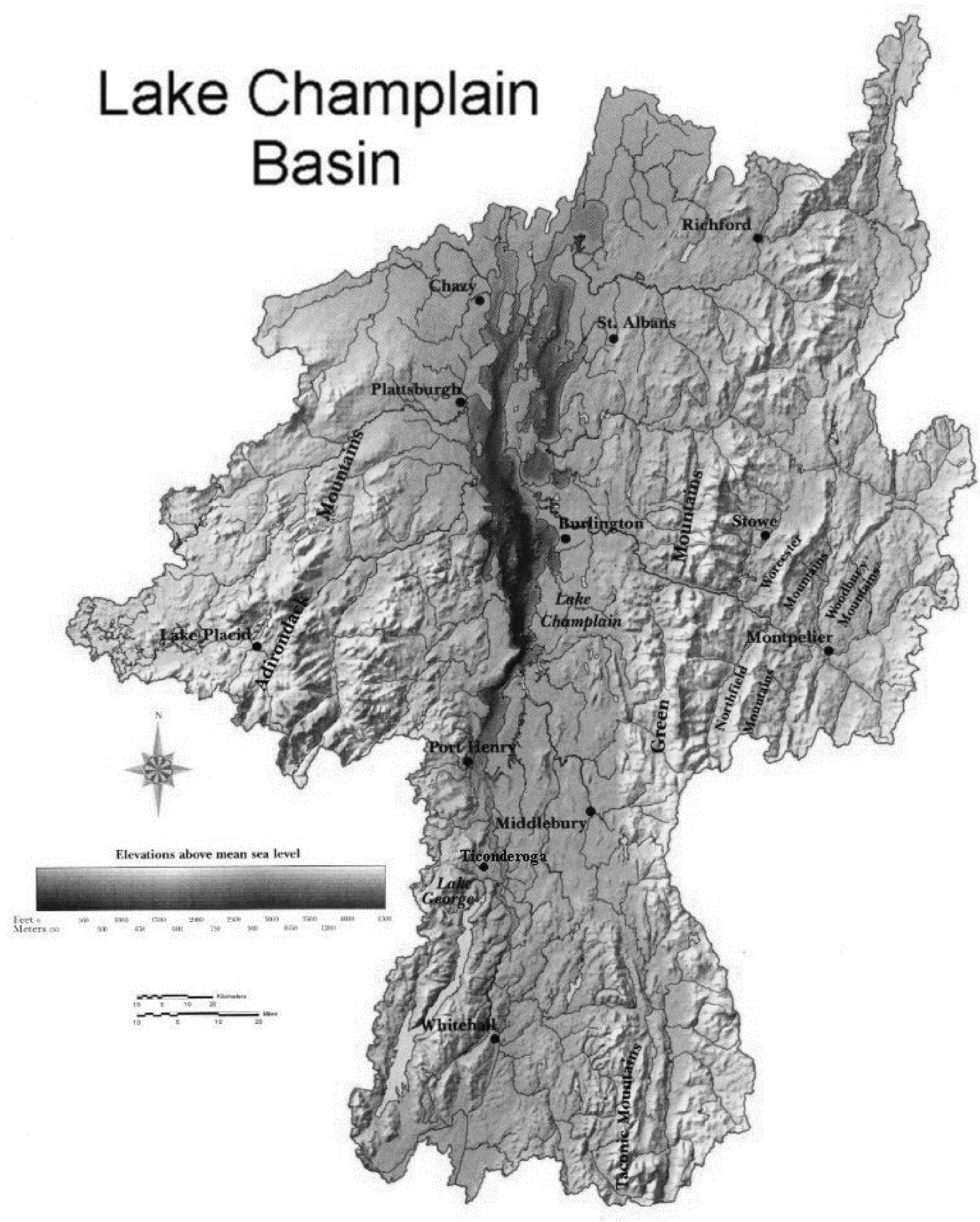

Figure 1-Lake Champlain Watershed

20km grid AVN wind data to develop lake level changes due to the wind direction, speed, duration and fetch.

3. Hydrologic Modeling

Nineteen sub-watersheds were calibrated using the SAC-SMA model and the snow melt model (SNOW-17). Telemetered sub-watersheds comprise approximately 60% of the Lake Champlain watershed. The calibration completed by the NERFC is designed to simulate natural flows. Several sub-watersheds, including the Saranac, Poultney, Lamoille, Winooski, and Missisquoi Rivers and Otter Creek are affected by reservoir and hydropower operations upstream of the forecast point. Fluctuations during low flow periods become very apparent at these forecast locations due to some hydro power operation..

The generation of precipitation and temperature time series data was completed for the historic record for each sub-watershed. Because of the significant range in elevation in several Adirondack and Green Mountain sub-watersheds and the differences in snow accumulation and ablation, several sub-watersheds were divided at the 2000 foot contour. A Mean Areal Precipitation (MAP) analysis was completed for each sub-watershed that was based on the PRISM isohyetal maps. Annual predetermined weights were used to compute MAP. A Mean Areal Temperature (MAT) analysis was based on temperature-elevation relationships developed for the basin. Stream flow data were obtained from the USGS web site. Both mean daily flow and peak flow data were used. Where appropriate, the entire historic database (1948 to 1994) was utilized with calibration pertaining to a common ten year period for most sub-watersheds. A stream gage historic record of at least 10 years determined if a station was useful to the calibration effort.

The Lake Champlain Basin contains a variety of conditions as the headwaters approach 4000 feet in the Adirondacks down to near 100 feet Mean Sea Level near Burlington on Lake Champlain(Fig. 1). A vast majority of the watershed is wooded and undeveloped, but urban development is expanding in the lower reaches of the watershed near the lake. The hydrologic variability was evaluated by comparing hydrographs from the various sub-watersheds and by performing water balance computations to examine precipitation, runoff, and evaporation variations.

Water balance computations were completed for all headwater sub-watersheds. Monthly and annual ET-Demand values were computed and analyzed for their variations. Elevation, latitude, available evaporation pan data, and the ET-Demand for nearby basins with similar conditions were evaluated.

The SAC-SMA model is a conceptual water balance model which simulates the land phase of the hydrologic cycle. The movement and storage of water in the soil column is accomplished by using two soil layers: the upper zone, or top soil layer, and the lower zone, or deep soil layer(Fig. 2). The SAC-SMA model relates closely to the watershed's physical features. The SAC-SMA model is a continuous model with a longer memory of rainfall and water storage than the previous Antecedent Precipitation Index (API) that was used at the NERFC. The use of the SAC-SMA model is also necessary to support probabilistic river forecasting using Ensemble Streamflow Prediction (ESP).

The SAC-SMA model has 18 parameters which must be calibrated using historical precipitation, temperature, and stream flow data. In addition, 12 SNOW-17 parameters, 7 frozen ground model parameters, and evapotranspiration parameterization further complicate the calibration process. This approach is labor intensive and complex because there are so many parameters and many of them are interrelated.

Manual calibration of the Lake Champlain watershed area of forecast responsibility for the NERFC was completed in about a year. In order to speed up the calibration process, regionalization of calibrated sub-watersheds was accomplished on 1 or 2 sub-watersheds as an initial phase of the calibration. Regionalization is the process in which a headwater point is intensively calibrated, and the parameters are transferred to similar areas in the river basin. The parameters can be applied from one calibrated area to several nearby areas with similar topography, soil and land use conditions.

Another method of calibration used on a couple of Lake Champlain basins was the automated parameter estimation technique, which was used as a first "cut" basin calibration technique.

In order to handle runoff from snow melt, the NWS SNOW-17 model was used and calibrated. The driving mechanism for lake level rise each spring is snow melt, which can approach 7 feet of rise in a 4 week period. The need for real-time or near real-time snow water equivalent data is essential for forecasting the Lake Champlain lake level. Snow pack data is supplied by local water agencies including the Corps of Engineers on a bi-monthly basis. Supplemental data is gathered from the National Operational Hydrologic Remote Sensing Center (NOHRSC) using their gamma radiation technique. The NERFC supplies "flight lines" in remote, data sparse areas, to NOHRSC in order to supplement snow water equivalent data in the watershed.

The SNOW-17 model uses air temperature as the sole index to energy exchange at the snow-air interface. Nine parameters required calibration on each watershed and the major parameters used in the Lake Champlain basin are briefly discussed. Where there might be a mean gage catch deficiency, a snow correction factor was applied. Typically the information at the specific gage in terms of its exposure and susceptibility to high winds was examined. Surface snow melt is affected by many climatic and physiographic factors. In the Champlain watershed, such factors as forest cover and type of cover, southerly versus northerly exposures, large open areas, and wind prone areas were taken into account to develop the maximum and minimum melt factors. Forecast wind conditions over a specific sub-watershed was also accounted for using the wind function parameter which can be adjusted for the current and future sub-watershed conditions. Another important parameter that requires updating is the areal extent of snow cover versus the mean areal water-equivalent, or areal depletion curve. The areal extent of snow cover estimates are provided by using NOHRSC data and high-resolution GOES and NOAA Polar Orbiter imagery. The NERFC has also looked into the Defense Department satellites (DMSP) for indications of the areal extent of snow cover from both their day and night visible imagery channels.

During the first full snow melt season using the NWSRFS model, the Spring of 2001, the NERFC forecast called for a rise in Lake Champlain level between 6 and 7 feet. The forecast rise would have brought Lake Champlain close to record flood. Due to a very dry April 2001, the 3rd driest in 100 years at Burlington, VT., a rise of 6 feet to major flooding occurred on the lake and not the ESP record flooding near 7 feet.

4. Dynamic Hydraulic Routing

Routing of all calibrated sub-watershed flows through Lake Champlain was completed using NWS Floodwave (FLDWAV). The FLDWAV model has the capabilities of both the NWS Dambreak (DAMBRK) model and the Dynamic Wave Operational (DWOPER) model. The resultant flood wave from the multi-positioned lateral inflows from the sub-watersheds is routed through the lake. FLDWAV has the capability, dependent on flow and lake/channel geometry, to move the resultant wave (hydrograph), in both the upstream and downstream directions. This routing through the lake and downstream channel/valley uses a four-point implicit finite-difference numerical solution of the complete Saint-Venant equations of one dimensional unsteady flow (conservation of mass and momentum) along with appropriate internal boundary equations. The model was run completely in the sub-critical flow algorithm due to the flatness in slope of the

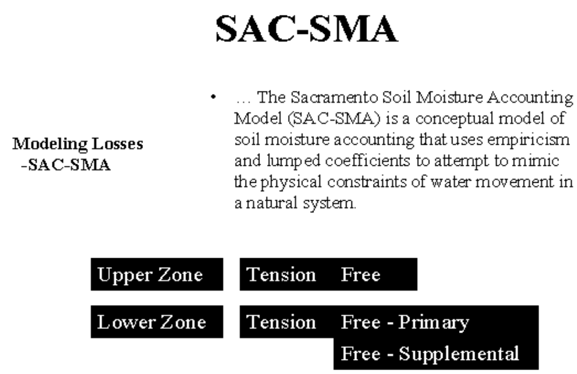

Figure 2. - Schematic of SAC-SMA zones

reach of interest. Twenty transects where located along appropriate Lake Champlain reaches and into Canada along the Richelieu River for a total model length near 130 miles. This includes the riverine sections of the lake near Whitehall, through Burlington and Rouses Point, and then downstream where the lake become more channelized into the Richelieu River at St. Jean's shoal. The natural geologic formation at the shoal becomes the downstream boundary for the model. Information from the IJC, including the step backwater model, HEC-2, cross sections and field verified hydraulic information was used to study the river from Rouses Point to Fryers Island Dam, just downstream of the controlling St. Jean shoal. In order for the model to develop a correct numerical solution in rapidly varying geometric configurations, FLDWAV will automatically decrease the time and distance steps of a computational reach.

Sub-watershed calibrated flows were used as lateral inflows to the FLDWAV model. These inflows were positioned into the model at or near their appropriate transect location. A six hour time series is used in the model for input flows and stages and forecast output flows and stages. Other initial boundary condition data included in the model are stage data from Whitehall, Burlington, and Rouses Point. The existing, long-term USGS rating curve at Rouses Point only has a history of stage values without a relating history of discharge values. Discharge information was not available at the USGS gage at Rouses Point, but is available 26 miles downstream at the Fryers Island Dam site. Additional information provided by Environment Canada included a relationship of stage to discharge at the dam and at the St. Jean's shoal area based on 1970's HEC-2 information. A set of seasonal stage-discharge relationships was developed by the IJC for the Richelieu River based on a summer weed growth condition, a winter ice cover condition, and a spring/fall "free outlet" condition. The NERFC further developed these three seasonal curves based on the historic data supplied by Environment Canada. Field investigations revealed the summer weed growth problem with low flows changing the channel's Manning "n" condition is not significant. Ice cover is significant and forecasts of the lake level during these periods of time is used with some caution. Using the available information from the historic record, and using the step backwater program for the entire reach of Richelieu River to Rouses Point, has allowed the NERFC to establish a good downstream boundary condition for the model. The "free outlet" downstream boundary condition is therefore being used for all non-ice covered forecasts.

5. Ensemble Stream flow Prediction (ESP)

One of the benefits of the forecast modeling of the Lake Champlain watershed is to disseminate the Ensemble Streamflow Prediction (ESP) forecast which is a probabilistic forecast of stream flow/stage and variables for periods up to 12 months. ESP uses multiple years of historical time series of precipitation and temperature as possible future meteorological realizations to create an ensemble of stream flow traces. These traces are then analyzed statistically to make a probabilistic forecast of any stream flow related variable.

Products available at the NERFC website include the medium range mean and maximum flows (7-14 days), the long range mean and maximum flows (15-45 days), and the expected value plot. These probability forecasts are presented in terms of exceedence probabilities, or probabilities that a given flow (stage in the case of the Lake Champlain level) will be exceeded in a given time frame. The forecasts assume that meteorologic conditions which have occurred over the forecast period during each of the past 20 to 40 years are equally likely to occur during this coming year. The different forecasts represent conditions anticipated over the given time periods, i.e. 7-14 day, 15-30 day, or 30-45 day forecast periods. The forecast graphics are labeled "OBS" for the exceedence probabilities based on observed data obtained over a 20 to 40 year period. Another label, "HS", represents exceedence probabilities based on a historic simulation of flows/stages over that same 20 to 40 year period. The third label, "CS", represents the exceedence probabilities based on a conditional simulation(Fig. 3). A conditional simulation is a forecast based on the current hydrologic conditions (i.e. flow, soil moisture, snow, etc) in a river watershed, using different historical time series of meteorological variables (precipitation and temperature) to drive the simulation. The difference between the historic simulation and the conditional simulation is that the historical simulation uses the historical hydrologic conditions at the start of the forecast run, while the conditional simulation uses the current hydrologic conditions at the start of the forecast run. The OBS trace can be compared to the HS trace to determine the skill of the hydrologic model at simulating historical river flow conditions.

6. Future Enhancements

During the NERFC calibration and forecasting efforts for the past year, several future enhancements are appropriate. The Great Chazy sub-watershed requires development of a new rating curve due to a split flow occurring approximately 50% of the time. The upstream channel conveys water under moderate to high flow conditions around the gage into the Village of Champlain below the gage. We are currently looking into modeling this split flow with the HEC-RAS model. Reservoir operations on the Saranac, Poultney, and Lamoille Rivers and Otter Creek influence our forecasts greatly during low to moderate flows and incorporation of these operations is being investigated. It was noted from high resolution imagery during the Year 2001 snow melt season that Lake Champlain may have a dual outlet system where some flow bypasses the Rouses Point gage, which may have an affect on the forecasts when the lake exceeds its flood stage level of 100 feet. Future cooperation with Environment Canada and incorporating more Richelieu River data will improve the St. Jean shoal area forecasts. This area supports a well used marina at the hydraulic control section for the lake with the greatest influences from wind effects.

The future Advanced Hydrologic Prediction Service (AHPS) will also involve adding 1 to 5 day, 6 to 10 day, and monthly/season precipitation and temperature outlooks from the Hydrometeorologic Prediction Center (HPC) of the National Center for Environmental Prediction (NCEP).

Future expansion of the snow measuring network including local watershed commissions and close coordination with NOHRSC will further enhance the NERFC's snow water equivalent database.

An inland version of the Sea, Lake, and Overland Surge from Hurricanes (SLOSH) model similar to Lake Okeechobee is being developed in cooperation with NOAA's Great Lakes

Environmental Research Laboratory (GLERL). This will enable fine tuning the FLDWAV lake level routing. In the past year since the models inception, NERFC forecaster's have already noted a 6 inch change in lake level during winds paralleling the long dimension of the lake for at least 6 hours at speeds of 20 knots. This portion of the forecasting tool will become very important during lakes levels near flood stage or higher. AHPS will also include some reach routing inundation maps, when refined mapping data becomes available, for certain critical reaches of the sub-watersheds as well as along the lake shore communities themselves.

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Morin, Guy ; Environment Canada, Civil Service Montreal, Richelieu River Stage Data

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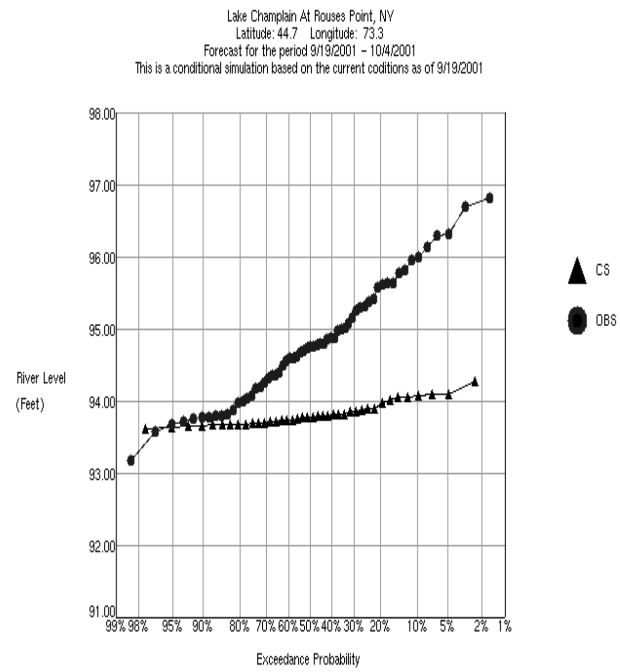

Figure 3 - ESP Exceedence Probability Plot