Great Lakes Sensitivity to Climatic Forcing

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Overview

The Great Lakes Environmental Research Laboratory simulated Great Lakes hydrology for hypothetical climate scenarios to understand the extremes necessary to cause closed (terminal) lakes, believed to have occurred about 7,500 years ago (by carbon dating).

- We used GLERL's Advanced Hydrologic Prediction System with some conditions estimated for this period.
- We used dynamic lake areas (which vary with lake depth) to correct modeled over-lake precipitation, runoff, and lake evaporation, and did not remove existing diversions and consumptions, as they are negligible.
- We used simple shifts in precipitation, air temperature, and humidity with 52 years of daily historical meteorology. For steady-state analysis of the interconnected Great Lakes, GLERL employed lake outflow-depth rating curves (using estimated sill elevations) reasonable for a natural system and combined with a water balance for all the lakes connected by their channels.
- We identified candidate climates that result in closed lakes (see Figure 1) by looking at lake outflows and levels, demonstrating that climate may have been the mechanism creating terminal lake status in the past.

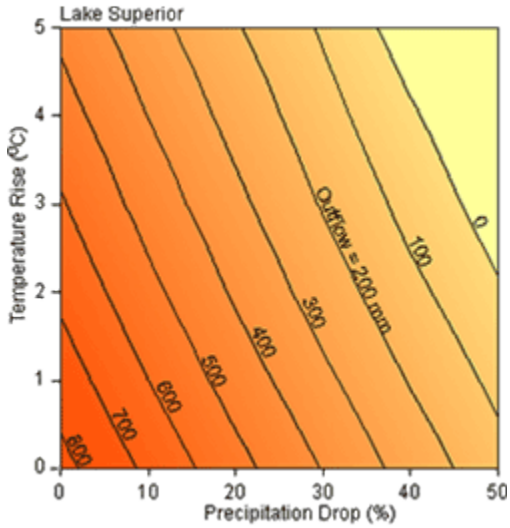

Figure 1: *Variation of Lake Superior Average Outflow with Changes Climate*

Scientific Rationale

The purpose of this project is to increase understanding of Great Lakes' sensitivity to climate change by looking at the paleontological record. Previous reconstructions of late glacial and post-glacial lake phases in the Great Lakes have attributed major changes in lake levels to non-climatic processes (e.g. isostatic rebound and shifts in outlet elevation). New findings of early-middle Holocene lake closure events that could only have been forced by abrupt periods of severe dry climate contrast with relatively small changes in lake levels recorded within the last two centuries. Knowledge of past occurrences of high-amplitude rapid hydrological change is relevant as some scenarios of future climate driven by global warming, suggest lake-level reductions below presently-known variability may be possible in the important watershed of the Laurentian Great Lakes.

A group of researchers from several agencies (see Scientific Collaborations, above) hypothesize that the lakes were driven below their outlets after 9000 cal BP (8 ka) by the combined effects of enhanced southward incursions of dry Arctic air during late deglaciation in Hudson Bay and the intensification of eastward flows of warm-dry Pacific air. The latter effect was associated with shifting atmospheric circulation about 8200 cal BP that is manifested for example in the eastward expansion of prairie vegetation in the latitudes of southern Lake Michigan and Lake Erie. This effect is thought to have delayed recovery of lakes Michigan and Huron from closed status until about 7800 cal BP (7 ka). These closed-lake events afford a useful example of past high-amplitude climate-hydrology variation because the hydrology of the Great Lakes basin had already entered its present non-glacial state.

Proposed Work

- Corroborate and test Great-Lake closed lowstands. Sediment cores and seismic pro-files available from previous studies in the Great Lakes will be used to corroborate past altitudes of water surfaces (large lake response to climate change), and to ensure that lake water sources in the modeled periods were mainly a result of local hydrological processes, as at present. Limited new seismic surveys and coring will be undertaken using NOAA's vessels. These records will be supplemented by dendroclimatological studies of fossil wood from submerged in situ tree stumps.
- Evaluate paleoclimate change using multi-proxy data from small lakes in the Great Lakes watershed. Limited fieldwork is proposed to survey and sample sediments in selected small lakes distributed around the periphery of the Great Lakes drainage basin to determine past atmospheric conditions and their gradients across the Great Lakes basin. Laboratory studies will identify the targeted time interval in cores using paleomagnetic and AMS 14C methods. Lake sediments will be analyzed using paleoecological transfer functions and isotopic geochemical methods to derive proxy records of changes in former atmospheric and hydrological conditions associated with the oscillations of the Great Lakes water levels
- Reconstruct paleogeography and model the paleoclimate-hydrologic relationship of the Great Lakes. Data generated in (1) and (2) above will constrain modeling of the climate-

lake hydrology relationship using both an operational hydrological process model (NOAA) and an isotopic hydrological model (University of Michigan) for the Great Lakes. Both will be modified for paleogeographic conditions in the targeted time interval. These approaches will determine hydrological sensitivity of the lake system to abrupt high-amplitude climate change.

GLERL will focus on simulation of the hydrology under several candidate climate scenarios for alternative assumptions on lake and connecting channel conditions.

This year, GLERL looked at climate scenarios to identify some that would drive present Great Lakes hydrology to produce terminal lakes. This is not an attempt to simulate past hydrology but to demonstrate the possibility that changed climates could produce terminal Great Lakes.

Data Preparation

GLERL used daily data from 1948-1999 from about 1800 overland stations for precipitation and air temperature and about 40 lakeside stations for air temperature, humidity, wind speed, and cloud cover.

- We Thiessen-weighted the data to determine time series for each of 121 watersheds and 7 lake surfaces.
- We used the historical meteorology with a system of models for watershed runoff, lake evaporation, connecting channel flows, lake outflows, and lake water balances to represent a “base case” scenario. These models have been used in many past studies for the EPA, IJC, and NOAA.
- We applied precipitation ratios and temperature differences, representing alternate climates, to the historical data to construct changed climate meteorology and used it with the models to calculate changed climate scenario hydrology.
- We repeated each simulation (base case or changed climate) with the 52 years of daily data with initial conditions set equal to end conditions until model results were unchanging, to estimate steady-state conditions.

GLERL built hypsometric curves (plots of volume and area with elevation) for each of the lakes (see Figure 2) and translated equations of lake outflow vs. elevation for “natural/pre-project” conditions to the IGLD 1985 water datum. This avoids regulation and channel changes of the recent past. We further adjusted outflow equations to make physical sense for backwater effects and for equal levels on connected lakes (no flow).

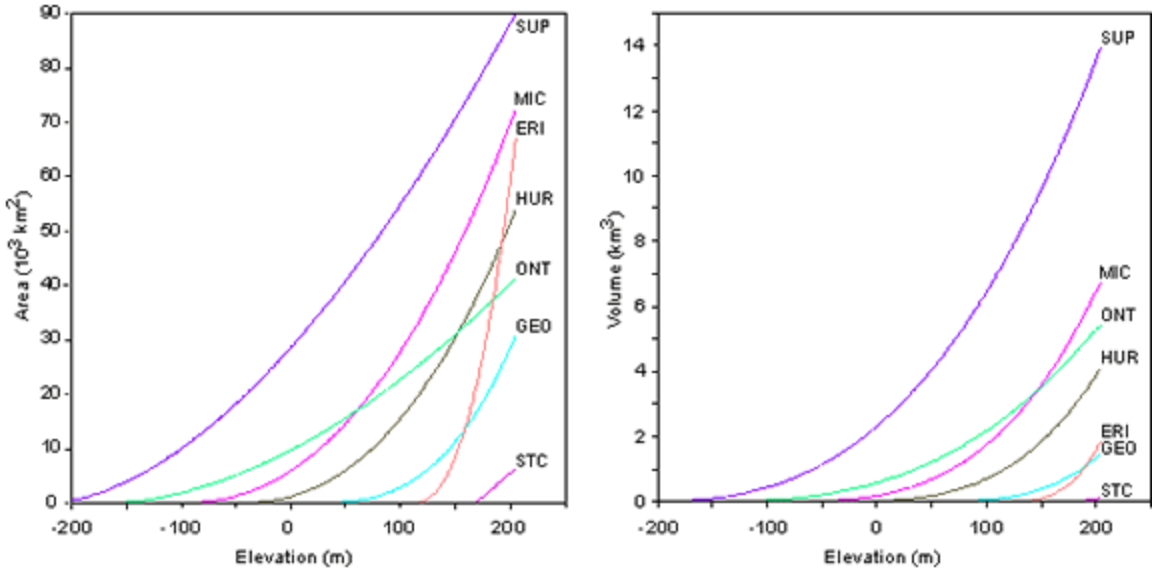

Figure 2*: Hypsometric Curves for the Great Lakes.*

GLERL simulated overlake precipitation, runoff, and evaporation in a water balance based on the arrangement of lakes and their connecting channels; see Figure 3. We must compute the outflows from all lakes as inflows to downstream lakes as part of the simulation. This requires using outflow and connecting channel relationships and hypsometric relationships and calculating lake levels as part of the simulation.

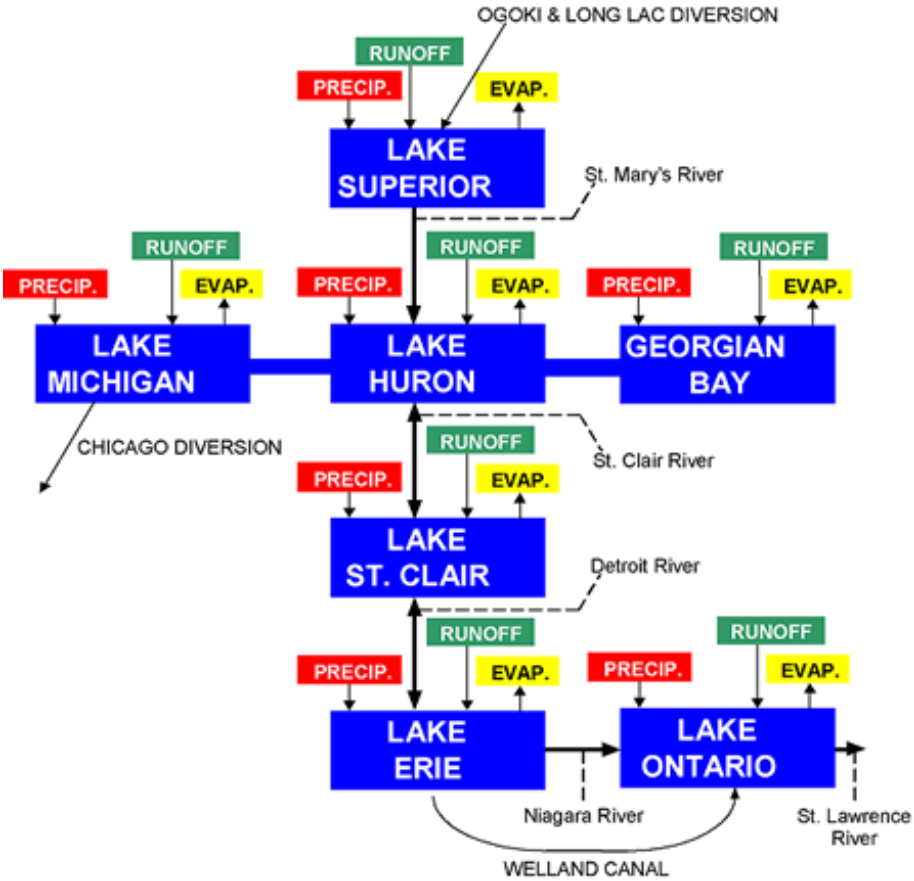

Figure 3: *Arrangement schematic of Great Lakes Connecting channels, and all water flows*

Verification. First, GLERL compared the "base case" net basin supplies (precipitation + runoff - lake evaporation) with historical net basin supplies (computed as a water balance residual from historical lake levels and flows). Annual NBS actually show good agreement, as expected since historical meteorology is used in the simulation; see Figure 4. Differences can be ascribed to water balance errors in the computation of residual NBS and to modeling errors in the computation of the NBS components. The biggest differences occur on Lake Ontario, suggesting they arise from water balance errors in computing the historical residual NBS.

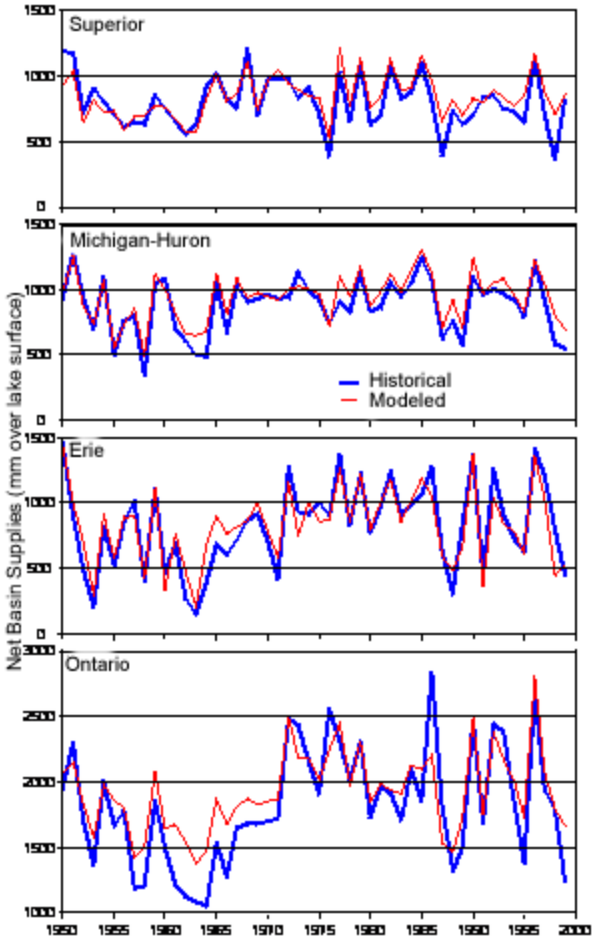

***Figure 4**: Net Basin Supply Comparison*

Next, GLERL compared “base case” lake levels with historical levels. We included all diversions but used “natural/pre-project” outflow/channel relationships. There is fair agreement, but with expected deviations. On Superior, levels match well with historical data after about 1965 but differ before; this is probably due to differences between the natural/pre-project outflow/channel relationships that were simulated and the actual conditions. Water was released from Superior in 1965 to alleviate low levels downstream; there were also changes in the Superior regulation plan between 1970-77. On Michigan-Huron, historical levels are below the simulated, probably due to changing Lake Superior operations and to changes made in the St. Clair River. Lakes St. Clair and Erie are very similar to the simulation but Ontario is lower historically, probably due to differences between regulated Niagara flows and the natural/pre-project outflow/channel conditions. The model appears to simulate the system reasonably when all sources of differences between the simulations and historical flows are considered.

GLERL then separated the upper lakes from the lower lakes with no inflow from the upper Great Lakes as they were during the early Holocene; i.e., no outflow from the Huron basin to the St. Clair-Erie basin. We used a weir equation for Michigan-Huron outflow, as suggested by the natural/pre-project equations for some of the lakes, but with a sill elevation taken from the

natural/pre-project equation for Michigan-Huron. (Below the sill elevation, there are no outflows from the lake.) We experimented with the coefficient until the water balance roughly matched simulated base-case Michigan-Huron levels with historical. Present-day diversions were included but are negligible compared to simulated climate change net basin supply changes or water level drops; their effects are safely ignored.

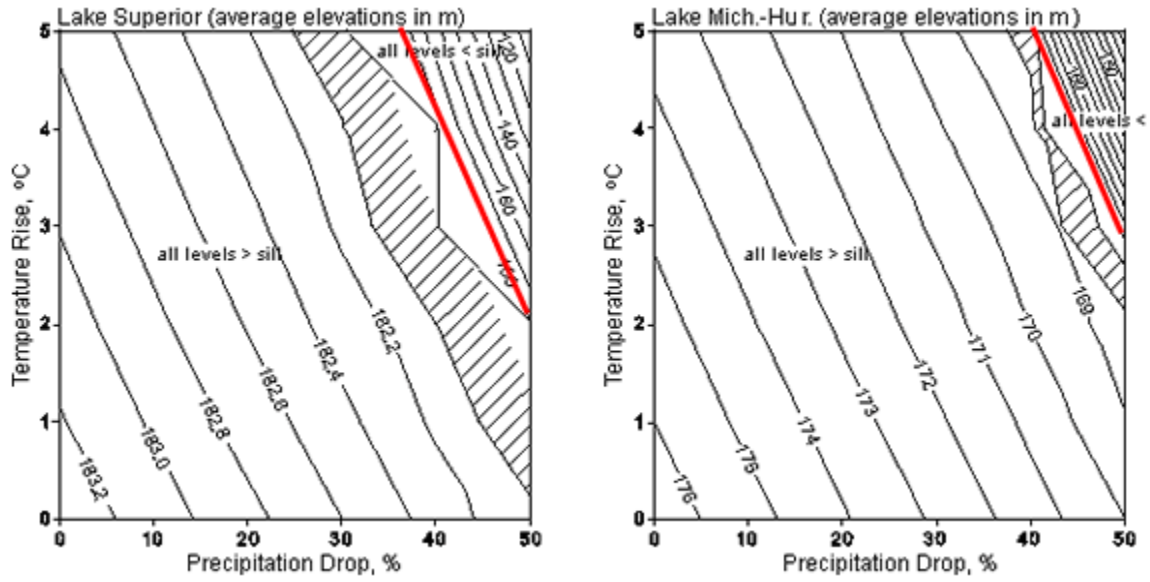

Figure 5: *Steady-State Upper Lake Average Water Levels As A Function of Climate*

Upper Lakes

GLERL looked at 36 climate scenarios, each defined in terms of the precipitation drop (%) from the base case (0, 10, 20, 30, 40, 50) and the temperature rise (oC) above the base case (0, 1, 2, 3, 4, 5). We calculated the steady-state average water level resulting from each lake and plotted it with precipitation drop and temperature rise as shown in Figure 5 for Lakes Superior and Michigan-Huron-Georgian Bay. (Average Lake Superior outflow is shown in Figure 1.) Three regions are identified for each lake's graph: where levels are all above the sill, where levels are all below the sill, and where they are both above and below (an intermediate region). GLERL found these regions by looking at maximum and minimum levels in a simulation and comparing them to the sill elevations. Of course, the lakes are terminal when all levels are below the sill. As the climate gets dryer or warmer, the average steady-state water level drops. It appears that, for Lake Superior, a 1oC rise in temperatures is roughly equivalent to a 4.7% drop in precipitation and, for Lake Michigan-Huron, a 1oC rise in temperatures is roughly equivalent to a 4.5% drop in precipitation; climates to the right of the red lines produce terminal lakes.

Lower Lakes

For the lower lakes, GLERL took inflow to Lake St. Clair as zero as existed uring the early Holocene. Lake St. Clair's bottom elevation is above its sill elevation, meaning that St. Clair can be empty but still have flow into Lake Erie. Thus, St. Clair is never a terminal lake but simply part of the Lake Erie watershed as Lake Erie water levels drop. GLERL looked again at the 36 climate scenarios considered for the upper lakes and found that while Erie became terminal, Ontario did not. So we looked at 99 climate scenarios, each defined in terms of the precipitation drop (%) from the base case (0, 10, 20, 30, 40, 50, 60, 70, 80) and the temperature rise (oC) above the base case (0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10). We calculated the steady-state average water level resulting from each lake and plotted it with precipitation drop and temperature rise as shown in Figure 6 for Lakes Erie and Ontario. Three regions are again identified for each lake's graph: all levels above the sill, all levels below the sill, and levels both above and below. For Lake Erie, a 1oC rise in temperatures is roughly equivalent to a 4.7% drop in precipitation and, for Lake Ontario, a 1oC rise in temperatures is roughly equivalent to a 3.5% drop in precipitation; climates to the right of the red lines produce terminal lakes.

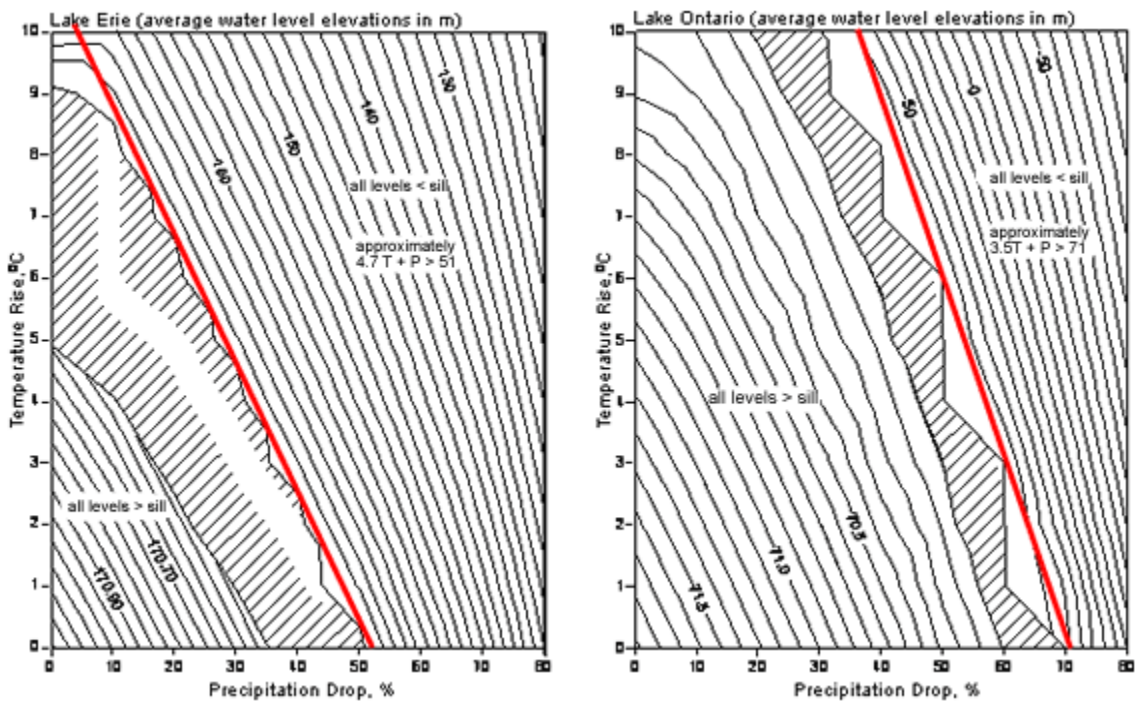

Figure 6: *Steady State Lower Lake Average Water Levels as A Function of Climate*

Summary

Geologic evidence of terminal Great Lakes about 7,500 years ago (carbon dating) motivated GLERL to explore the feasibility of climate change closing the Laurentian Great Lakes.

- We demonstrated the possibility that changed climates could produce terminal Great Lakes by using present hydrology but natural channel and outflow conditions.
- We first integrated existing comprehensive models for present-day large basin runoff applied to each of the 121 watersheds draining into the Great Lakes, models of present-day large-lake thermodynamics applied to the seven water bodies of the Great Lakes, water balances of the lakes and their connecting channels, lake area adjustments relating supplies (lake precipitation, runoff, and evaporation) to the water balance, models of natural outflows and channel flows, present-day hypsometric relations, and a water balance of all lakes and connecting channels.
- We tested the integrated model with historical meteorology and found it to be a reasonable model of Great Lakes water levels.
- We built alternate climates from the historical meteorology record by reducing precipitation by fixed ratios and increasing temperature by fixed increments.
- We applied the integrated hydrology model to these alternate climates, producing associated alternate lake level time series.

GLERL ran each alternate climate through the models with initial conditions set equal to final conditions until there were no changes in an effort to simulate steady-state conditions. It appears that Lake Superior would be a terminal lake if precipitation dropped 60% or more from the present or if air temperature increased 60/4.7 = 13°C or more above the present or some linear combination of the two, 4.7 T + › 60 where T and P and are temperature rise (^{o}C) and precipitation drop (%), respectively. Likewise, it appears Michigan-Huron would be a terminal lake for P › 63% or T › 14°C or 4.5 T + P › 63. Erie would be a terminal lake for P › 51% or T ›11°C or 4.7 T + P › 51. Ontario would be a terminal lake for P › 71% or T › 20°C or 3.5 T + P › 71.

The changed climate scenarios used in this study were simple: spatially and temporally constant adjustments were applied to historical meteorology for each watershed and lake surface to estimate changed-climate meteorology for each watershed and lake surface. More complex climate change considerations in the study of terminal Great Lakes wait on improved paleoclimatic considerations. Our results are biased by the length of the historical meteorology record we used. Errors of approximation include linear adjustment of supplies for lake area, power equation hypsometric relations, and approximation of natural flow conditions and sill elevations for each Great Lake.

The study addresses only the question of climate change necessary to close the Great Lakes and does not represent past hydrology. GLERL endeavored not to model the hydrology of the lakes 7,500 years ago, but to demonstrate that alternate climates could cause the present lakes to drop so low as to become “terminal” lakes (with no outflow). We were able to do this and it is

significant because other mechanisms for explaining the formerly low water levels are largely discounted today; climate could have been the mechanism.

Products

Croley, T. E., II, and C. F. M. Lewis, 2006. Warmer and drier climates that make terminal Great Lakes. *Journal of Great Lakes Research*, IAGLR, (in review).

Croley, T.E. II. Using climatic predictions in Great Lakes hydrologic forecasts. A*SCE Task Committee Report on Climate Variability, Climate Change, and Water Resources Management.* Garbrecht, J., and U. Lall (Eds.). American Society of Civil Engineers, Arlington, VA, 164-185 (2006).

Croley, T. E., II, 2005. Recent Great Lakes Evaporation Model Estimates. *Proceedings of World Water and Environmental Resources Congress* 2005, May 15-19, 2005, Anchorage, Alaska, Environmental Water Resources Institute, American Society of Civil Engineers, Washington, DC, 10 pp., Compact Disc.