December 4, 2008

Re: Evaluating Scientific Uncertainty in the International Upper Great Lakes Study (IUGLS)

In its earlier reviews of two methodological papers produced by the IUGLS Study Team – *Hydraulic and Sediment Modelling Strategy* and *Hydrology and Climate Modelling Strategy* – the Independent Review Group (IRG) identified a need to develop a more comprehensive scientific uncertainty framework to better understand and present the scientific findings. The Study Team therefore produced a methodological paper, *Evaluating Scientific Uncertainty in the International Upper Great Lakes Study (IUGLS).* The review team convened by the IRG has assessed the uncertainty paper and engaged in a thorough discussion with the Study Directors/Managers concerning the paper.

The paper presented the IUGLS strategy for dealing with the scientific uncertainty in their investigations concerning the cause of the lower levels of Lakes Michigan-Huron relative to Lake Erie in recent decades. That is, the paper discussed methods for evaluating the importance and impact of uncertainty related to the findings pertaining to hydraulic and sediment modeling of the St. Clair River and to the determination of Net Basin Supply (NBS) in the upper lakes. The paper does not deal with matters concerning Lake Superior regulation.

Evaluating the uncertainty in any scientific modeling endeavor is a difficult and challenging task, due to the myriad of sources of uncertainty concerning measurements, models and model parameters. The review team has assessed the proposed methodologies and considered the needs related to public understanding of study findings. It is the consensus of the review team that:

- A number of the proposed methods are not described with enough detail to enable the review team to be able to fully evaluate the recommended approach
- The proposed methods are not always appropriate to the task
- There are other approaches that should be considered

Since some of the methods outlined in the paper do not give adequate guidance or details concerning how the uncertainty analysis will be applied, the review team sought to introduce, on several occasions, detailed recommendations on appropriate methods. Based largely on the technical discussions, the review team makes the following observations and recommendations:

1. **Sensitivity Analysis:** Uncertainty analysis requires numerous assumptions regarding which factors in the overall system are subject to variability. To guide the ultimate uncertainty analysis we suggest using sensitivity analyses to determine which elements of each analysis are most critical and thus warrant further analyses using uncertainty analysis. Sensitivity analysis concerning measurement error, model parameter error, and model error should

be considered for each project element. For example, in the hydraulic studies the focus thus far has been almost exclusively on determining the impact of uncertainty in bathymetry on resulting river and lake levels. Sensitivity analysis is needed to confirm that other elements or components of the hydraulic analyses can be neglected. Good examples of graphical tools that can be used to summarize such sensitivity analyses include the use of Pareto charts, Spider Plots or Tornado Diagrams (Eshenback, 1992). Another suggestion is to investigate the adjoint model parameter sensitivity method, which would enable you to evaluate the sensitivity of all model parameters to the differences in Huron-Erie lake levels. The adjoint sensitivity method combined with parameter uncertainty (variances), can be used to determine the uncertainty in lake level differences using the First Order Second Moment method (FOSM), instead of using a Monte Carlo approach. Further information on the adjoint sensitivity method is found in Sykes et al. (1985), Sykes and Thomson (1988), and Lu (1991).

2. **Uncertainty Analysis:** The study team was unable to discern exactly what methods of uncertainty analysis would be used for evaluating uncertainty in the net basin supply. For example, it is not enough to say that Monte Carlo methods will be used, because they can be applied in a myriad of ways. In general, the review team recommends that the study give greater emphasis and clarification in each of the analyses to identify the various sources of uncertainty that are being considered. In particular, it should be clear whether the methods used account for measurement error, model parameter error, and/or model structural error, or all three. This does not mean that the study must consider all three components of error, but it should be clearer in identifying what components are being considered in each analysis. The study should also state more clearly how errors will be generated for each of the Monte Carlo analyses. For example, when generating synthetic time series of hydrological variables, one must be careful to account for the fact that errors behave differently across space and time due to physical issues such as seasonality and storage processes and due to statistical issues associated with model errors such as nonnormality, serial correlation and heteroscedasticity.

3. **Value of Uncertainty Analysis:**

   The review team takes the view that the uncertainty analyses are fundamentally important to a successful study outcome. A thorough and clear representation of uncertainty in each of the study components will increase public understanding and help identify priorities for future action. Limited resources can be applied most effectively to reduce uncertainty in parameters that contribute the greatest uncertainty to, for example, the difference in Huron-Erie lake levels.

4. **Uncertainty Analysis for Hydraulic Conveyance**:

a. **Hydraulic Model Complexity:** Initial results indicate that, given the consistency among the various model results, the uncertainty analysis associated with resulting water surface elevations may be achieved using a one-dimensional HEC-RAS model. There may be no need to replicate the hydraulic and bathymetric analysis using two-dimensional models.
b. **Synthetic Bathymetry:** The current approach for generating synthetic bathymetric profiles may lead to profiles that are not physically realistic. To address this issue, consider using geostatistical methods for generating synthetic grids. For example, estimation of the empirical variogram (or semivariogram) of the 2007 bathymetry, would enable one to obtain an estimate of the 'correlation distance'. The 'correlation distance' is a measure of how far away a 'synthetically' generated point must be, so that it is independent of the initial point. The current approach assumes all points in the grid are independent of one another, regardless of their distance. The variogram can be used to assess this assumption. If the variogram indicates spatial correlation structure to the bathymetry, as the review team expects it will, then geostatistical methods such as kriging should be used to generate synthetic bathymetry instead of the methods outlined in the paper.
c. **Synthetic HEC-RAS Profiles:** It is possible that the hydraulic profiles in HEC-RAS may already be located sufficiently far apart from one another to be independent of one another (which can be evaluated in 2a above). If that is the case a simple yet reasonable Monte Carlo approach would involve adding independent measurement and smoothing error to each cross section in HEC-RAS using the 2007 bathymetry. It should be noted that correlation lengths across the river are not the same as correlation lengths along the river's length. The river may need to be "straightened" in order to ensure independence of correlation lengths.

5. **Residual Net Basin Supply (NBS) Estimation Method**:

The review team was unable to discern exactly what approach would be used to implement uncertainty analysis in a Monte Carlo framework. In general the components of the residual NBS method can be handled for each term independently. However, it is not possible to ignore the important seasonal, spatial and other temporal dependencies associated with each term. Below the review team suggests a specialized Monte-Carlo method, known as the bootstrap for generating each synthetic term in the residual NBS method using observations and observed errors from existing models. The bootstrap approach is advantageous here because it enables a very simple generation of synthetic sequences, without resorting to complex stochastic hydrological models.

a. **Storage Change Term:** To address the primary error involving the fact that the spatial distribution of storage levels in each month is not known, the review team suggests using at least three reasonable but different spatial averaging methods for estimating the mean lake level in each month. Examples of such methods include the isohyetal, Thiessen polygon, inverse distance, and/or kriging methods. Now, to generate a synthetic lake storage level in a given month, simply resample, with replacement, from one of the selected methods. For example, with 3 methods, select one method, with equal probability, in each month, with replacement. This is known as the bootstrap.

b. **Inflow and Outflow Terms:** For each month, the synthetic inflows would be the observed inflows plus randomly selected empirical errors obtained from the original rating curve model or other such model used for estimating the observed flows. For example, when a rating curve is constructed from *n* observations, it results in *n* model residuals (errors). Ideally one can sample, with replacement, from those residuals to capture the uncertainty associated with the rating curve model. The same idea can be applied to any model, fit using data. The same approach can also be applied to the outflows.

c. **Ice and Weed Growth:** There will be a need to consider an analogous approach to account for uncertainty related to ice and weed growth effects.

6. **Component NBS Estimation Method:** the review team is concerned with the suggestion to generate error estimates for each component of NBS based on literature values and on the assumption of independence among the component errors. The suggested approach to add an error term to each individual NBS component is not appropriate as these components are themselves strongly correlated in both space and time. The review team suspects that actual errors for the NBS Component method would be highly seasonal (mean error changes from month to month), heteroscedastic (variance changes from month to month), and serially correlated in complex ways. The review team could not arrive at an acceptable strategy to offer, because in part, the proposed approach is unclear. However, some form of the bootstrap may offer opportunities for generating alternative, yet likely sequences of lake levels.

7. **Overall Experiments on Impact of Uncertainty:** Given that numerous factors influence lake levels over long periods of time, there may be some value to performing resampling (bootstrap) experiments, where years, or 2-3 year blocks of years of lake levels, are resampled with replacement from the historical records resulting in a rich variety of different time-sequences of lake level fluctuations. In the process of reshuffling or resampling the time-series of lake levels, it may be possible to determine, in a controlled experimental fashion, which factors (NBS supply, River hydraulics, etc.) govern resulting variations in lake levels. Such resampling can only be done over time blocks which are relatively independent of one another, hence one would first need to select a suitable block length for resampling. See Vogel and Shallcross (1996) for further details on the moving blocks bootstrap method. While the

review team has not thought through all the details of this approach completely, we are simply suggesting this idea for further consideration.

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