Multi-Model Ensemble Combination and Conditional Stochastic Weather Generation Tool for Improved Streamflow Forecast

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Results and Accomplishments:

In the last report we proposed the following tasks

- Run the MTOM for the San Juan River basin for each year from 2000-2010 in three modes
    - Unconditional – based on historical data
    - Conditional – based on NOAA seasonal climate forecast
    - ESP – current forecasting method used by CBRFC

- Presently, for conditional weather simulation mode only winter precipitation forecasts issued from NOAA are used. We plan to enhance this by also using spring temperature forecasts. The idea is that spring temperature forecasts play an important role in the timing of snow melt and consequently, the timing of the peak flow in the River. This timing is critical for reservoir operations on this river. To this end, we plan to enhance the stochastic weather generator by incorporating spring temperature forecasts in the conditional weather simulation.
- Obtain suite of water resources system metrics such as Navajo reservoir operations, environmental flow and other metrics; perform detailed analysis of the statistics and compare them for the three forecasting methods
- This forms Lianne Daugherty's (the MS student currently working on the project) MS thesis, that she will write up and defend in Fall 2013.
- We also plan to write it up for submission to a peer reviewed journal article
- We are closely collaborating with researchers at CBRFC, as mentioned earlier they are using the integrated approach developed in this project. The extension will enable us to make progress on this collaboration and build on the results for future collaboration.

We are happy to report that we have accomplished almost all of the tasks.

We made progress in working with water managers (USBR) in the Colorado River Basin to implement the forecasts for operations and management.

Incorporate Spring Temperature Forecasts

Conditional weather generation was performed based on NOAA's winter seasonal precipitation forecasts as was developed in *Caraway et al.* (2014) accomplished in this project in previous years. However, spring temperatures are important in modulating the snowmelt and consequently, the timing of the peak flow, which can be crucial for water resources management. To this end, we modified the weather generator of *Caraway et al.* (2014) to incorporate Mar-Apr temperature forecasts in addition to the winter seasonal forecasts. In years when the forecasts were skilful these influenced the peak flow timing. For example, in 2002 the spring temperatures enable a skillful projection of peak flow timing at several locations in the San Juan River Basin (Figure 1 below). For details see Lianne's M.S thesis – *Daugherty* (2013). The peak flow timing is used in coordinating releases from the Navajo reservoir for environmental flows. If the timing is not projected skillfully water has to be released from the reservoir thus having a reduced supply for summer irrigation.

Demonstration of Skill in Water Resources Management

As mentioned before we coupled the weather generator ensembles with a mid-term probabilistic operations model (MTOM) on the San Juan River Basin. This is a demonstration of the utility of this new ensemble generation approach in improving the skill of water resources management variables. Bureau of Reclamation's mid-term probabilistic operations RiverWare (*Zagona et al.*, 2001) model (MTOM) was developed for the entire Colorado River Basin (outlined in *Grantz* (2011) and described in detail in *Bracken* (2011)). The MTOM simulates all major basin reservoirs and flows throughout the basin, shown in Figure 2a. The model requires unregulated reservoir inflows (forecasts), initial reservoir pool elevations and storages, and upper and lower basin demands. The CBRFC's 60-month ESP forecast ensemble drives the monthly timestep model. The model runs each of the forecast traces in the ensemble and analyzes the output of all runs collectively to provide the probability distributions of forecasted operational variables. In *Daugherty* (2013) we demonstrated this on a small part of the Colorado River model covering San Juan River she found good long lead skills in several water resources management variables shown in Figure 2b. This indicated that the skill in streamflow forecasts

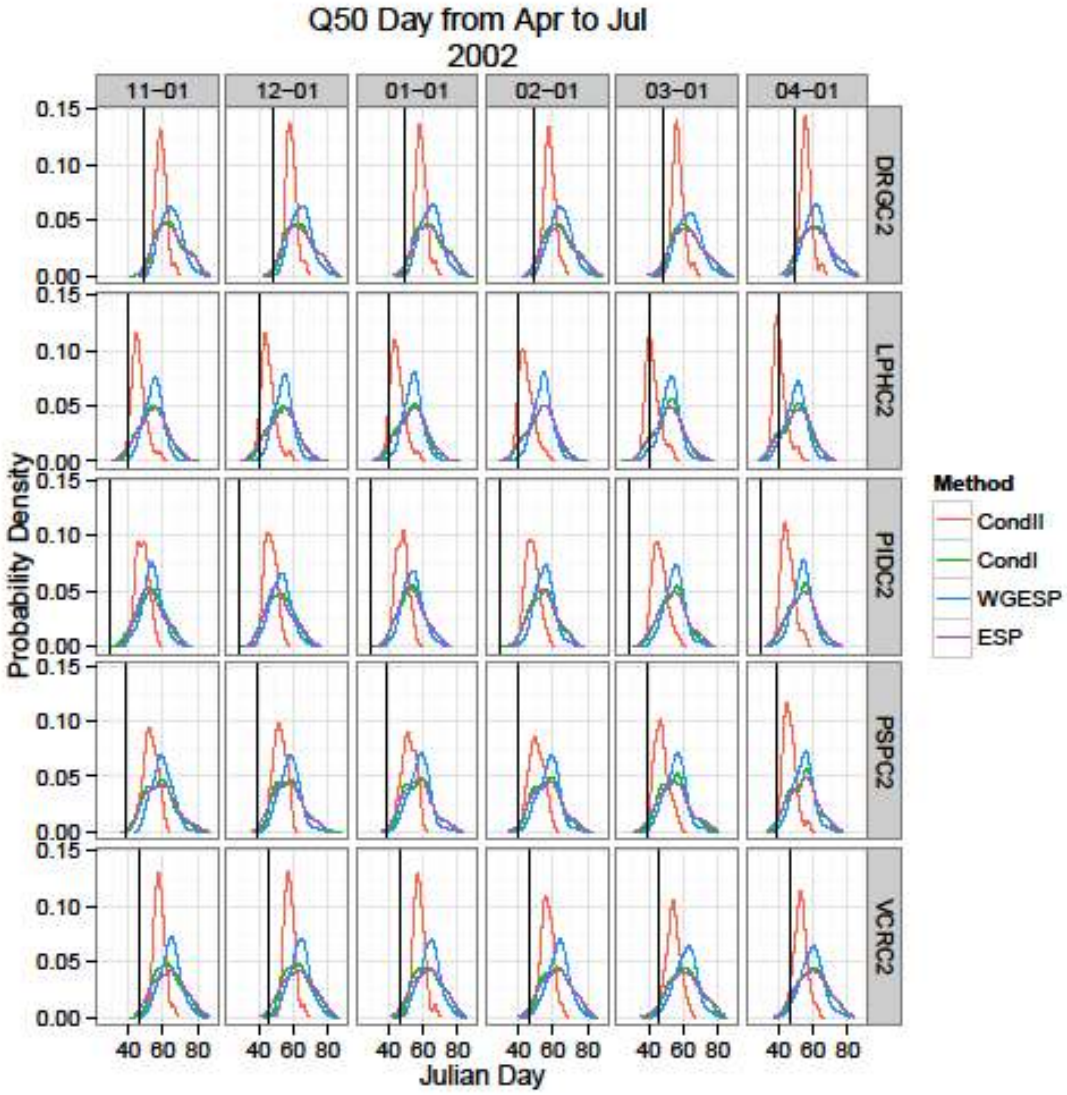

Figure 1 PDF of projection of peak flow timing (defined as the Julian day when 50% of the flow occurs during Apr - May) for 2002. Rows are various streamflow locations in the San Juan Basin and columns are projections made on the 1st of each month starting Nov 1st . Projections based on stochastic weather generator conditioned on winter precipitation forecast (CondI), and spring temperature forecast (CondII), unconditional (WGESP) and the standard ESP.

translate quite well through the water resources decision process.

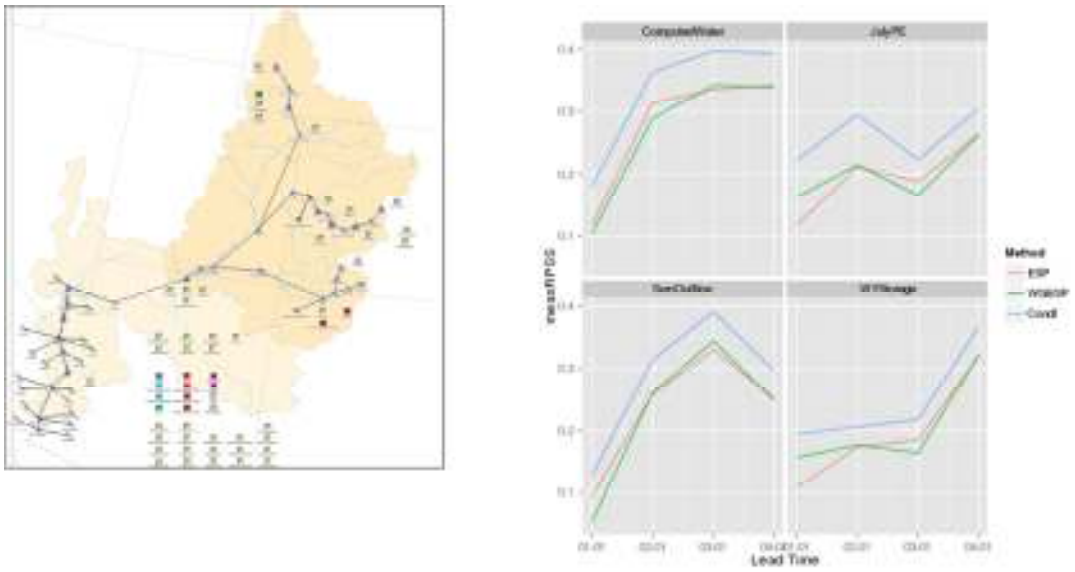

Figure 2 (a) Colorado River System Simulation (CRSS) model screen shot. (b) RPSS scores of four water resources management variables on the San Juan River Basin at four lead times starting Jan 1st. Computed available water, July pool elevation in the reservoir, summer outflow, and end of Water Year storage. The blue lines are the skills from stochastic weather generator ensembles forecasts but with conditional from seasonal climate forecast; WGESP is based on unconditional ensembles and ESP is the standard approach used by NOAA/CBRFC.

Highlights of Accomplishments from the Project

- The enhanced stochastic weather generator developed in prior years has been published *Caraway et al.* (2014).
- The coupling of stochastic weather generator with CHPS to produce skillful streamflow forecasts, especially when combined with seasonal climate forecast is currently being prepared for submission to Journal of Hydrometeorology.
- The above two components are described in detail in the MS thesis of Ms. Nina Caraway (*Caraway*, 2012) – that is linked below.
- We demonstrated the translation of skills in streamflow forecasts to water resources management variables (*Daugherty,* 2013). This is being prepared for submission to Journal of American Water Resources Association.
- We worked *closely* with Colorado Basin River Forecasting Center, Salt Lake City – Drs. Paul Miller and Kevin Werner. They have successfully implemented the above integrated framework for the entire Colorado River Basin and are testing them in their operational forecasting mode using computational resources from NASA.
- This collaboration has led to a follow up proposal to NASA – to apply the developed framework to the entire Colorado River Basin.

References (in italics) and Publications/Presentations from this Project:

Bracken, Cameron W. (2011), Seasonal to Inter-Annual Streamflow Simulation and Forecasting on the Upper Colorado River Basin and Implications for Water Resources Management. Masters thesis, University of Colorado, Boulder, CO, 113p.

Caraway, N., J. McCreight and B. Rajagopalan, Multisite Stochastic Weather Generation Using Cluster Analysis and K-nearest neighbor Time Series Resampling, Journal of Hydrology, 598(16), 197-213, 2014.

Caraway, N., Stochastic Weather Generator Based Ensemble Streamflow Forecasting, MS thesis, University of Colorado at Boulder, 2012.

Caraway, N., A. Wood and B. Rajagopalan, Advancing Ensemble Streamflow Prediction with Stochastic Meteorological Forcings for Hydrologic Modeling, presented at the AGU Chapman Conference, in Portland, OR, Jul 28-31, 2013

Caraway, N., A. Wood, B. Rajagopalan, E. Zagona, and L. Daugherty, Advancing Ensemble Streamflow Prediction with Stochastic Meteorological Forcings for Hydrologic Modeling, presented at the AGU Fall Meeting, San Francisco, CA, Dec 3-7, 2012.

Daugherty, Lianne (2013). An End-to-End Framework for Seasonal Forecasting in Water Resources Management in the San Juan River Basin Using Stochastic Weather Generator based Ensemble Streamflow Predictions. Civil, Environmental, and Architectural Engineering M. S. Thesis, University of Colorado, Boulder, CO.

Daugherty, L., E. Zagona and B. Rajagopalan, Application of Stochastic Weather Generator based Seasonal Ensemble Streamflow Forecasts to Water Resources Management, presented at the AGU Hydrology Days conference, Fort Collins, CO, Mar 25-27, 2013.

Daugherty, L., E. Zagona, B. Rajagopalan, K. Grantz, W. P. Miller and K. Werner, Probabilistic Operational Forecasting in the San Juan Basin using Stochastic Weather Generator based Seasonal Ensemble Streamflow Forecasts, presented at the AGU Chapman Conference, Portland OR, Jul 28-31, 2013.

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Grantz, K. (2011, March 21{22). Reclamation mid-term operational modeling. In Seasonal to Year-Two Colorado River Streamow Prediction Workshop, Salt Lake City, Utah. Colorado Basin River Forecast Center.

Zagona, Edith A., T.J. Fulp, R. Shane, T. Magee, H.M. Goranflo (2001). Riverware: A Generalized Tool For Complex Reservoir System Modeling. Journal of the American Water Resources Association 37(4), 913-92

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