GCIP/GAPP Missouri River Water Resources Demonstration Project

Progress Report

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1. Introduction

This report constitutes a final report on our activities on the above project. Reflecting our progress on the project, we have produced five peer-reviewed journal articles (Maurer et al. 2001; 2002; 2003a; 2003b; 2003c), with the last two being completed during this past year. These most recent two journal articles are related to Task 7 in the original proposal. Several conference presentations have been made related to this work, including the three listed in section 5 below that were made during the past year. During the past year, our primary efforts were related to the investigation of the sources of predictability in the Missouri (and the wider Mississippi) River basin, and in quantifying the potential benefits related to long-lead hydrologic predictability. We also published the original data (produced as part of Task 1) on-line, to make it available to other scientists interested in continental-scale land surface hydrology.

2. Identification of seasonal hydrologic predictability

A foundational data set of water and energy budget fluxes and states at the land surface was developed by Maurer et al. (2002), and formed the basis of the subsequent studies included in this project. This unique dataset has also been of interest to many others in the climate modeling, forecasting, and hydrologic modeling communities. For this reason, we made the dataset available to others through a web-based interface, with the data stored at the San Diego Supercomputer Center at the University of California at San Diego. Since the publication of the journal article in November 2002, over 40 unique users have registered, and several studies are in review that utilize this data (e.g., Marshall et al., 2003; Betts et al., 2003; Roads et al., 2003).

Using this derived long-term hydrologic data set, Maurer and Lettenmaier (2003b) computed for each season the r^2, representing predictability, associated with a multiple linear regression between selected initial conditions (i.e., different combinations of knowledge of climate or land surface conditions) and the seasonal average runoff at each of 1532 _-degree grid cells in the Mississippi River basin. The 51-year (1950-2000) time series of derived seasonal soil moisture, snow, and reported climate indices were regressed against the corresponding seasonal average runoff data for the specified lead time at each grid cell. All data were used in developing the regression relationship; e.g., all 51 years of spring runoff values at a single grid cell were correlated with the values of the climate indicators, soil moisture, and snow at that grid cell at the specified lead time. r^2 values were computed for seasons at leads of 0-4 seasons (where lead 0 would be a forecast of a season's runoff using initial conditions of the first day of the season, or an average of 1.5 month lead time). One example of the predictability levels derived by Maurer and Lettenmaier (2003b) is illustrated in Figure 1.

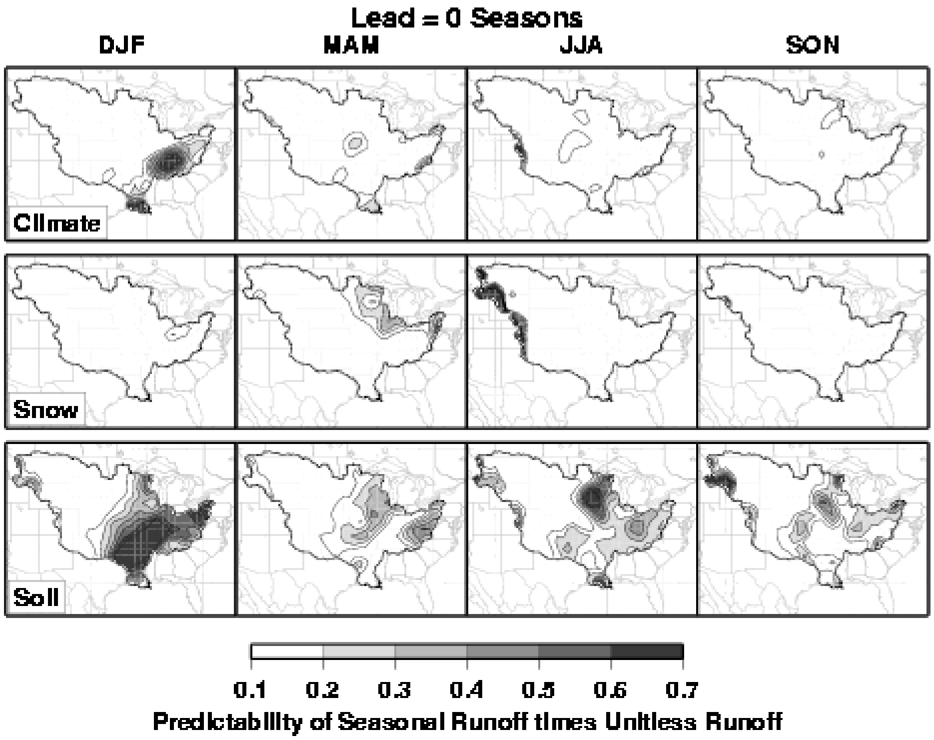

Figure 1 - Importance of predictability due to climate, snow, and soil moisture for a lead of zero seasons, equivalent to an average 1.5 month lead time, as indicated by the variable of unitless runoff times r^2. See Maurer and Lettenmaier (2003b) for details.

The summary findings were that, for the western basin, the land surface state has a stronger predictive capability than climate indicators through leads of two seasons; climate indicators are more important for eastern areas at lead times of one season or greater. Modest winter runoff predictability exists at a lead time of 3 seasons due to both climate and soil moisture, but this is in areas producing little runoff, and is therefore of lessened importance. Local summer runoff predictability is limited to the western mountainous areas (generating high runoff) through a lead of 2 seasons. This could be useful to water managers in the western portion of the Mississippi River basin, since it suggests the potential to provide skillful forecast information earlier in the water year than currently used operational forecasts.

3. The Value of Hydrologic Predictability in the Missouri river basin.

The potential seasonal predictability of runoff identified by Maurer and Lettenmaier (2003b) for the Mississippi River basin implied an inherent benefit to water resources management. In order to quantify this benefit for the Missouri River main stem reservoir system, and to reveal the impact of increased predictability at long lead times on water resources management, a simulation model of the system of reservoirs was developed. The Missouri River is a large continental river with a main stem reservoir system consisting of six dams operated by the U.S. Army Corps of Engineers (Figure 2). A simulation model of the system of reservoirs was developed to demonstrate the potential effect of adding forecast knowledge at lead times of up to one year.

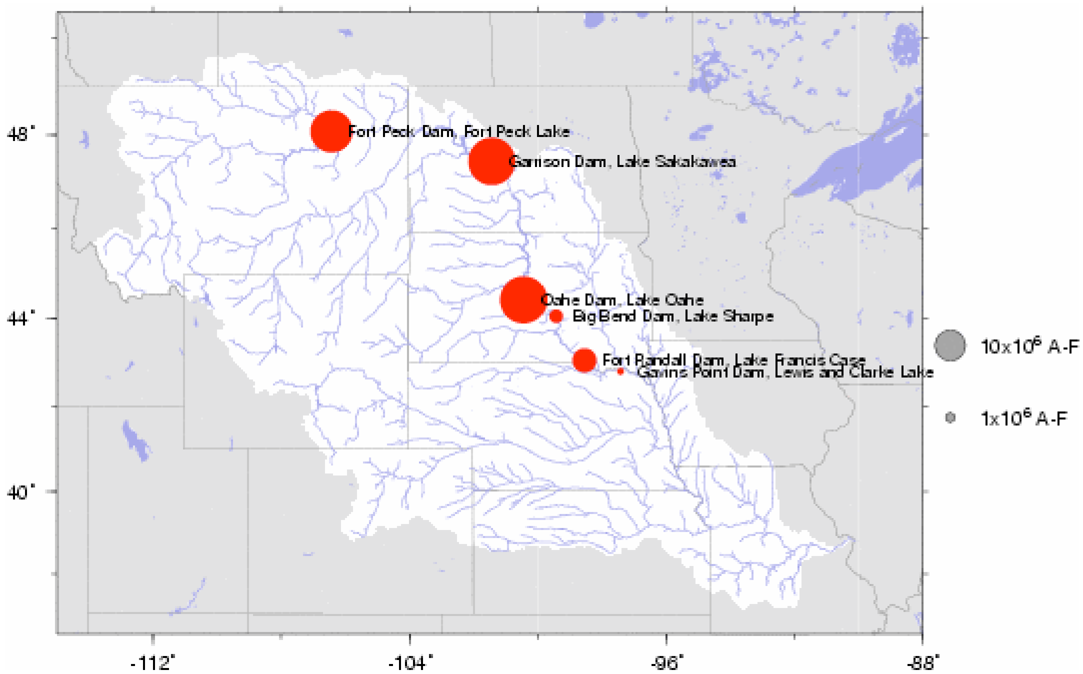

Figure 2– Illustration of the Missouri River basin, with dams operated by the U.S. Army Corps of Engineers (COE), with the size of the symbol scaled for the reservoir volume in acre-feet.

3.1 Missouri River main stem reservoir simulation model

The U.S. Army Corps of Engineers (COE) operates a series of six reservoirs along the main stem of the Missouri River, shown in Figure 2. The operation of the reservoirs is governed by a master water control manual (COE, 1979), which has been under review for several years to adapt the management of the main stem system for ecological and other concerns (National Research Council, 2002; COE, 2001). As part of the review, extensive studies by the COE have been made on the operation of the system, using a system simulation model operating at a monthly time step, under different scenarios and constraints (COE, 1994a). The COE monthly simulation model does not include an explicit ability to include forecast knowledge, and thus could not be used directly for our investigation.

Our desire was to maintain the simplicity of a monthly model, to take advantage of the flexibility of simulation software, and to emulate the current operations relatively closely. To achieve this, we constructed a system model, MOSIM, using the Extend simulation software (Imagine That, Inc., 2001). MOSIM uses the physical reservoir data and minimum releases for hydropower and environmental constraints from the long-term study model described by the COE (), which are shown in Table 3. We include the simplification used by Jorgensen (1996) and COE (1991) that combines local inflow to Big Bend and Ft. Randall reservoirs. This assumption is justified by the small contributing area between Big Bend and Oahe Dams.

The three upstream reservoirs contain about 90% of the total system storage, and therefore provide the majority of the capacity to operate the system by draining during the Fall and Winter and refilling during Spring. Therefore, in our system model the downstream three reservoirs are operated in a run-of-river mode, where for each month the inflow is equal to the outflow. Details of the model are available in Maurer and Lettenmaier (2003c). The performance of the MOSIM model, compared to historic system operation, is illustrated in Figure 2.

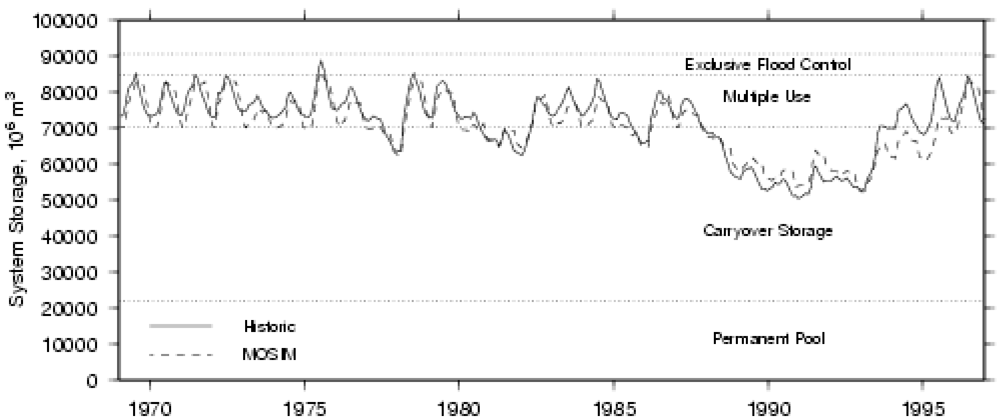

Figure 3 - Historic and MOSIM simulated system-wide storage in the six main stem reservoirs.

3.2 Adapting the MOVIC system model to assess the value of hydrologic predictability

To contrast the effects of different levels of predictability on the system operation, it was necessary to develop forecasted inflow sequences that reflect each predetermined level of predictability. This was accomplished by stochastically adding error to observed system inflow sequences, with larger errors reflecting lower levels of predictability, and perfect predictability resulting in forecasted flows equal to observed. The method used was based on Lettenmaier (1984). In order to extend this analysis further into the past, we used as a surrogate for the historic record the 100-year reconstructed historic reservoir inflows developed by COE (), which remove the effects of upstream water management and set a constant depletion level at the relatively low level present in 1949.

The annual operation in MOSIM was based on COE (), which uses a target of draining all reservoirs (in the case of MOSIM, the three upper reservoirs only, as the lower three are run-of-river) to the target elevation corresponding to the base of the annual flood control zone (also referred to as the flood control and multiple use zone) by March 1. In order to permit the use of long-lead forecast information, this rule was altered to use two forecast volumes, both derived at the 90th percentile level (e.g., high flow scenarios). First, rather than fix the March 1 level to the base of the multiple use zone, the level was set to allow storage of the forecasted volume of spring and summer inflow (March through July) less the maximum amount that could be released through the turbines, in order to minimize spill. Second, the forecasted inflow volume from the current month through March 1 was compared against the maximum volume that could be released through the turbines by March 1. This modification in operating procedures to incorporate forecast knowledge produces patterns of system-wide storage that differ from the historic, as shown in Figure 4.

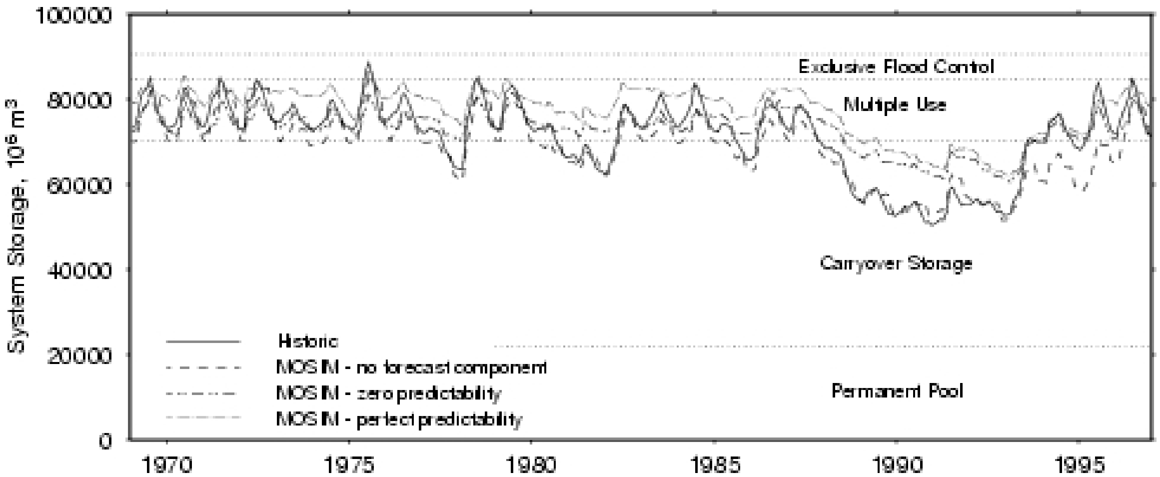

Figure 4 - Monthly historic and simulated main stem system storage, as in Figure 3, but including the system operation under the flexible rule curve adopted in this study to adapt operations to different levels of predictability. MOSIM – no forecast component corresponds to the MOSIM model.

3.3 The value of predictability for the Missouri River mainstem system

As a bounding case, the annual system-wide hydropower benefits under a perfect forecast scenario (complete knowledge of future flows) are compared to those resulting from no predictability. The average annual hydropower benefits for the no predictability scenario were $530 million, while the perfect forecast scenario produced $540 million, representing an increase of 1.8%. (For comparison, MOSIM without a forecast component, which more closely follows the historic system operation illustrated in Figure 4, produces $510 million in hydropower benefits). This suggests a relative maximum potential benefit in the Missouri River basin, due to hydropower alone, with improved predictability that amounts to several million dollars but is small on the scale of the benefits already produced by the project.

Although the current storage capacity of the Missouri River main stem reservoirs is too large to show a substantial difference in hydropower benefits between different levels of predictability, for reasons discussed above, a smaller system in the same geographical setting could show greater sensitivity. To investigate this, the MOSIM model was altered by reducing the total capacities of the carryover storage and permanent pool zones of the three upstream reservoirs, resulting in a hypothetical system with smaller reservoir storage capacities that is more sensitive to changes in forecasted inflows. The reduced-volume system showed a difference of 7.1% in hydropower benefits between the perfect and zero predictability alternatives, representing a difference of $25.7 million in annual average hydropower benefits. A summary of the benefits, using this reduced-volume system under a variety of predictability levels, is shown in Table 1.

Table 1 - Total system hydropower benefits for reduced-volume Missouri River main stem dams under different levels of predictive skill.

Scenario/Forecast Knowledge	Average Annual Hydropower Benefits, millions of dollars
Zero forecast skill	$359.8
Climate state	$363.2
Climate state and snow water content	$364.5
Climate, snow, and soil moisture	$366.6
Lag flow forecast	$363.5
Perfect forecast skill	$385.5

With the reduced main stem system, incorporating both a knowledge of the climate state as well as perfect knowledge of snow and soil moisture states in the forecast resulted in an increase of 1.9% in system hydropower benefits, representing $6.8 million annually. Of this $6.8 million total, use of currently available climate indicators provides the largest portion at $3.4 million, which is approximately the same as the value of predictability provided by historically observed inflows. Of the additional benefits above that already provided due to climate knowledge, soil moisture adds the greatest value, at $2.1 million. This provides an important context for operational implementation of hydrologic predictability, where for large water resources systems the benefits of added predictability may amount to modest sums, but represent a small percentage of additional benefits.

4. References

Betts, A.K., J.H. Ball,, M. Bosilovich, P. Viterbo, Y. Zhang, and W.B. Rossow, 2003, Intercomparison of Water and Energy Budgets for Five Mississippi Sub-basins between ECMWF Reanalysis (ERA-40) and NASA-DAO fvGCM for 1990-1999, *J. Geophys. Res. (in review)*.

Imagine That, Inc., Extend professional simulation tool, version 5, Imagine That, Inc., 6830 Via del Oro, Suite 230, San Jose, CA 95119.

Jorgensen, S.F., 1996, Hydrologic modeling of Missouri River reservoirs in a climate change model, M.S. thesis, University of Nebraska, Lincoln Nebraska, December 1996.

Lettenmaier, D.P., 1984, Synthetic streamflow forecast generation, ASCE Journal of Hydraulic Engineering 110, 277-289.

Marshall, C.H. Jr., R.A. Pielke, Sr., LT. Steyaert, and D.A. Willard, 2003, The Impact of Twentieth Century Anthropogenic Land-Use Change on Sea Breeze Generated Convective Rainfall and Sensible Weather over the Florida Peninsula, *Monthly Weather Review (in review)*Maurer, E.P., J.D. Rhoads, R.O. Dubayah, and D.P. Lettenmaier, 2003a, Evaluation of the Snow-Covered Area Data Product from MODIS, *Hydrol. Processes* 17(1), 59-71.

Maurer, E.P. and D.P. Lettenmaier, 2003b, Predictability of seasonal runoff in the Mississippi River basin, *J. Geophys. Res.* (in press).

Maurer, E.P. and D.P. Lettenmaier, 2003c, Potential effects of long-lead hydrologic predictability on Missouri River main-stem reservoirs, *J. Climate* (in revision).
Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen, 2002, A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and States for the Continental United States, *J. Climate* 15(22), 3237-3251.
Maurer, E.P., G.M. O'Donnell, D.P. Lettenmaier, and J.O. Roads, 2001, Evaluation of the Land Surface Water Budget in NCEP/NCAR and NCEP/DOE Reanalyses using an Off-line Hydrologic Model, *J. Geophys. Res.* 106(D16), 17,841-17,862.
National Research Council, 2002, The Missouri river ecosystem: exploring the prospects for recovery, Water Science and Technology Board, Division on Earth and Life Sciences, Washington, D.C.
Roads, J., E. Bainto, M. Kanamitsu, T. Reichler, R. Lawford, D. Lettenmaier, E. Maurer, D. Miller, K. Gallo, A. Robock, G. Srinivasan, K. Vinnikov, D. Robinson, V. Lakshmi, H. Berbery, R. Pinker, Q. Li, J. Smith, T. von der Haar, W. Higgins, E. Yarosh, J. Janowiak, K. Mitchell, B. Fekete, C. Vörösmarty, T. Meyers, D. Salstein S. Williams, 2003, GCIP Water and Energy Budget Synthesis, *J. Geophys. Res. (in review)*. U.S Army Corps of Engineers, 2001, Missouri River master water control manual review and update, revised draft environmental impact statement, Northwestern Division, Omaha, Nebraska, August 2001.
U.S Army Corps of Engineers, 1994, Missouri River master water control manual review and update, Volume 2: reservoir regulation studies, long range study model, Missouri River Division, July 1994.
U.S Army Corps of Engineers, 1991, Missouri River system analysis model – phase I, Hydrologic Engineering Center, Davis, CA, February 1991.
U.S Army Corps of Engineers, 1979, Missouri River main stem reservoir system reservoir regulation manual: Vol. 1, master manual, Missouri River Division, Omaha, Nebraska.

5. Presentations

Maurer, E., (*invited*) Publication of a large-scale hydrologic data set using the SDSC SRB, National Partnership for Advanced Computational Infrastructure (NPACI) All-Hands Meeting, San Diego, CA, March 19, 2003.

Maurer, E.P. and D.P. Lettenmaier, Potential benefits of long-lead hydrologic predictability on Missouri River main-stem reservoirs, American Meteorological Society 83rd Annual Meeting, 17th Conference on Hydrology, Long Beach, California, February 11, 2003.

Maurer, E.P. and D.P. Lettenmaier, Predictability of seasonal runoff in the Mississippi River basin, AMS/GAPP Mississippi River Climate and Hydrology Conference, New Orleans, May 14, 2002.