Project Title: Integrated Seasonal Drought Forecast-Adaptive Management System for the Lower Colorado River Basin in Texas (Collaborative: Part I of II)

Investigators:

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Project years: 2013-2016

Time Period addressed by Report: June 1, 2014 – May 31, 2015

I. PRELIMINARY MATERIALS

A. Research project objective

The project objective is to develop an integrated seasonal forecast-adaptive management system for drought management decision-making by the Lower Colorado River Authority (LCRA) in Texas, based on a number of NOAA-supported climate models and data products. We will apply climate and hydrologic data to in expectation of generating skillful hydroclimatic forecasts at relevant time scales (3-6 months lead time); assess the potential value of using the forecasts in conjunction with risk-sharing policies and financial instruments; identify residual risk; and work with the LCRA to incorporate forecasts into operational water resource management models.

B. Stakeholders and decision makers

Project collaborators include Ron Anderson, Chief Engineer, and Bob Rose, Chief Meteorologist of the Lower Colorado River Authority (LCRA) in Austin, Texas. The LCRA manages the Highland Lakes reservoir system in central Texas, a series of six lakes on the Lower Colorado River. This system provides water to approximately 1.1 million people in central Texas, supplies hydropower to a 55-county area, supports rice farming along the Texas Gulf Coast, and sustains in-stream flows in the Lower Colorado River and freshwater inflows to Matagorda Bay.

C. Approach

The project approach involves the following steps:

1) Apply climate and hydrologic data to develop a hybrid statistical-dynamical forecast model for reservoir inflows at relevant time scales (3-6 month lead time);
2) Perform hindcast simulations to assess the potential value of using the forecasts in conjunction with risk-sharing policies and financial instruments, and identify residual risk; and
3) Work with LCRA staff to incorporate forecasts into operational water resource management models.

The hydroclimatic forecast model utilizes predictors from multiple sources, including seasonal climate forecasts from NOAA's CFS model and National Multi-model Ensemble Forecast program, as well as satellite remote sensing estimates of relative soil moisture and land cover (e.g., SAR-based soil moisture indices, Landsat and MODIS-based indices). These predictor data will be optimally combined in a hybrid statistical-dynamical forecast model. Both parametric and non-parametric methods will be evaluated in developing the statistical components of the forecasts, and the Variable Infiltration Capacity (VIC) land surface model will generate the dynamic hydrologic forecast. Hydrologic forecasts will be generated in the form of probabilistic (ensemble) forecasts with 3-6 month lead times.

The ensemble hydrologic forecasts will first be evaluated in the LCRA's existing decision support system (DSS), based on stochastic simulation. This model generates forecast scenarios by Markov chain sampling from the historical record of monthly reservoir inflows according to a simple categorical forecast of ENSO phase. The DSS is capable of evaluating the impacts of different drought "trigger" levels and curtailment policies, and it generates convenient displays of the forecast probability distribution of monthly reservoir storage levels up to 5 years in the future. Further, an enhanced DSS will be developed based on a stochastic optimization model. This model will be run with a rolling horizon, prescribing "open-loop" operating decisions which can then be evaluated to quantify the potential benefits of using forecasts. The enhanced DSS will also include features to analyze a select set of risk-sharing instruments that may be valuable in mitigating residual risk, including the risk associated with a poor forecast. Examples include transfer options and index-based drought insurance programs.

Water managers at the LCRA will be actively engaged throughout the project, providing regular feedback on interim forecast and decision support products. In addition to regular video conferences, two face-to-face workshops will be held with water management decision-makers. The objectives of these one-day workshops will be to provide decision-makers with more detailed information about project outcomes and to enable them to participate in project outcome evaluation. The first workshop, held in September 2014, focused on preliminary evaluation of the seasonal forecast model. Feedback from LCRA staff was critical to enhancing and tailoring the forecasts. The second workshop, held at the end of Year 2, will involve evaluation of the tailored forecast product in combination with the adaptive management support system, along with a virtual drought exercise. Feedback from this workshop will be used for final product enhancements and revisions. All software tools developed in this project will be provided to LCRA staff at the end of the project, along with tutorials on use of the software.

Project evaluation will be based on quantitative measures of forecast skill and value, and qualitative measures of capacity building, and contributions in direct support of the National Integrated Drought Information System (NIDIS). Quantitatively, the ensemble streamflow forecasts will first be evaluated using a range of distribution-oriented metrics. Next, the value of the proposed approach, in comparison to the status quo, will be assessed through hindcast simulations with the integrated forecast-decision support system for an extended period, e.g., 1940-2012. Capacity building will be evaluated based on assessment of training and education objectives, specified for each workshop and technology transfer activity. Finally, we will evaluate project success by identifying outcomes that fundamentally contribute to NIDIS.

D. Matching funds/activities

One graduate student working on the project, Brian Zimmerman, has received partial support from a Graduate Engineering Research Scholars Fellowship awarded by the University of Wisconsin during the 2014-15 academic year.

One month of academic year salary was provided by Michigan Tech University for David Watkins for the 2014-15 academic year. Travel costs for the annual meeting in Austin, TX in September 2014 were also provided by Michigan Tech.

E. Partners

We are partnering with the Lower Colorado River Authority (LCRA) in Austin, Texas, with Ron Anderson, Chief Engineer, and Bob Rose, Chief Meteorologist, expressly identified as project collaborators and agency contacts. Mark Svoboda, Climatologist, National Drought Mitigation Center at the University of Nebraska-Lincoln, is also serving as a project collaborator to assist in coordination with NIDIS. In addition, we are collaborating with the Texas Soil Observation Network program led by Todd Caldwell at the University of Texas at Austin, though exchange of soil moisture measurements.

II. ACCOMPLISHMENTS

A. Project timeline and tasks accomplished

Work in Quarters 4-7 of the project has focused on validating satellite-based data products (e.g., soil moisture, land cover indices), developing statistical forecasts models, generating dynamical forecasts from GCMs, and calibrating and verifying the VIC hydrologic model. In addition, work has begun to integrate forecasts in the existing and enhanced DSS.

i) Satellite-Based Data Products

A field campaign was carried out in Summer 2014 to acquire *in situ* soil moisture data for use in deriving satellite-based data products. Five soil moisture data loggers were installed in the Mason Mountain Wildlife Management Area to record soil moisture conditions that were representative of the Lower Colorado River Basin study area. Moisture probes for each data logger were installed at 10-cm, 18-cm, and 30-cm depths and collected data from the beginning of August until the end of September. The data loggers were in place for three Radarsat-2 overpasses which occurred on August 10, September 3, and September 27.

Radarsat-2 is a C-band Synthetic Aperture Radar (SAR) satellite. C-Band SAR data has been shown to be useful for estimating soil moisture in low-biomass areas, such as the shrub and pastureland found in the study area. The Radarsat-2 images collected are fully polarimetric, which enables the characterization of the backscattered energy in addition to providing polarized backscatter images. This characterization was conducted by performing polarimetric decompositions and calculating several polarimetric discriminators. The Freeman-Durden and Van Zyl decompositions both decompose backscattered energy into three categories, volume scattering, surface scattering, and double bounce. The Cloude-Pottier decomposition has three outputs which measure the importance of each of the three types of scattering mechanisms. Figure 1 shows the Van Zyl decomposition of the August 10 image.

Preliminary results show that some of the parameters will be useful for developing a SAR based moisture map for the study area. For example, there is a strong relationship (r^2 = 0.78) between the surface scattering parameter from the Van Zyl decomposition and percentage of volumetric water content at 10-cm depth. Once completed, the remotely sensed soil moisture products will be incorporated into both the statistical and dynamical forecast models.

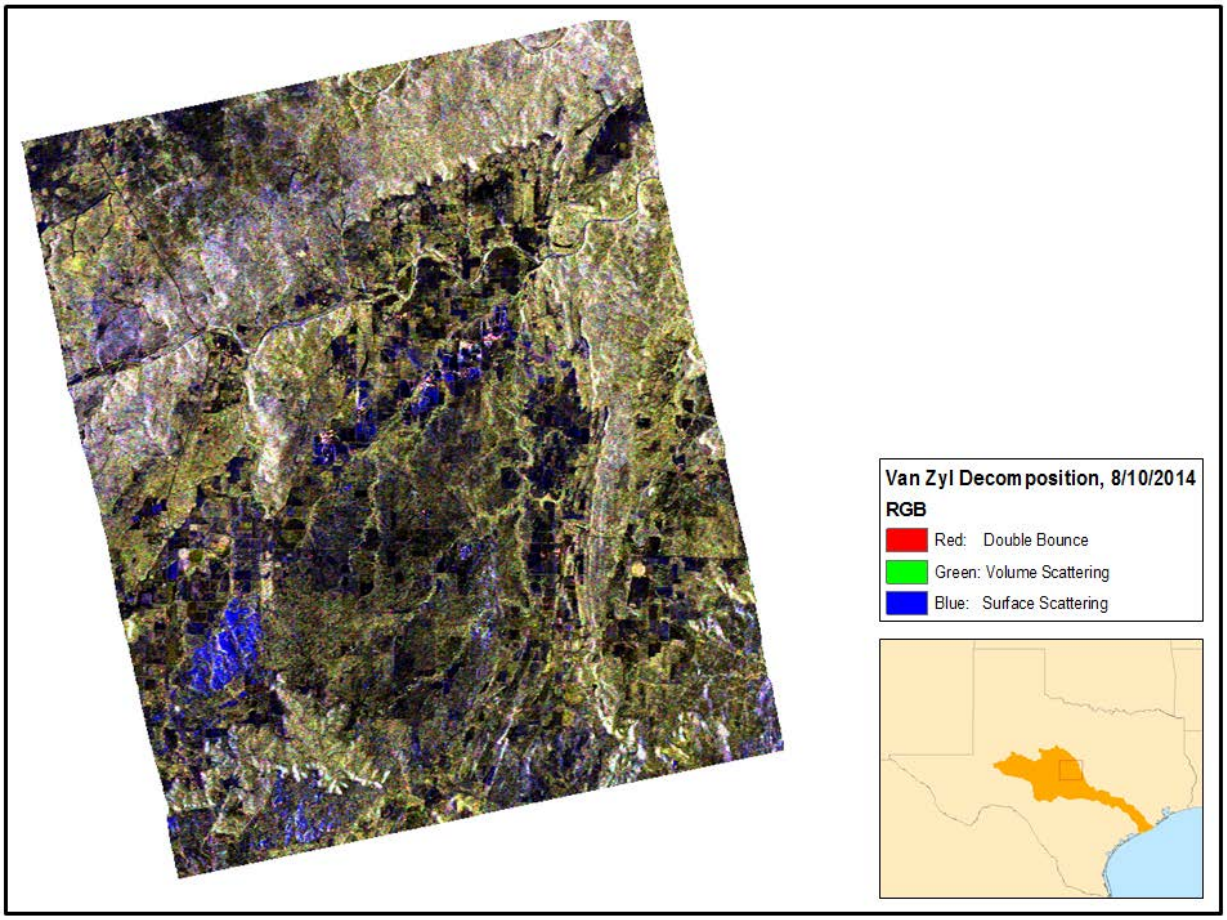

Fig. 1. *Van Zyl decomposition of the August 10, 2014 Radarsat-2 image.*

ii) Statistical Forecast Models

For different seasons of the year, the relationship between various rainfall characteristics and inflow was examined. Of particular interest was to investigate the role of intense precipitation events on inflows. To do this, the log of inflows was first compared with the total precipitation as a baseline. Next a daily severity index (DSI) was computed which is a basin-wide indicator indicating the frequency of daily rainfall exceeding the 90^{th} percentile. Seasonal inflows and DSI values were then analyzed. The results are shown in Figure 2. A key finding is that *a large fraction of the variance in inflow can be attributed to the occurrence (or non-occurrence) of heavy rainfall events in the LCRA watershed*. Recent heavy rains in Texas have shown how quickly the water supply system can recover from drought.

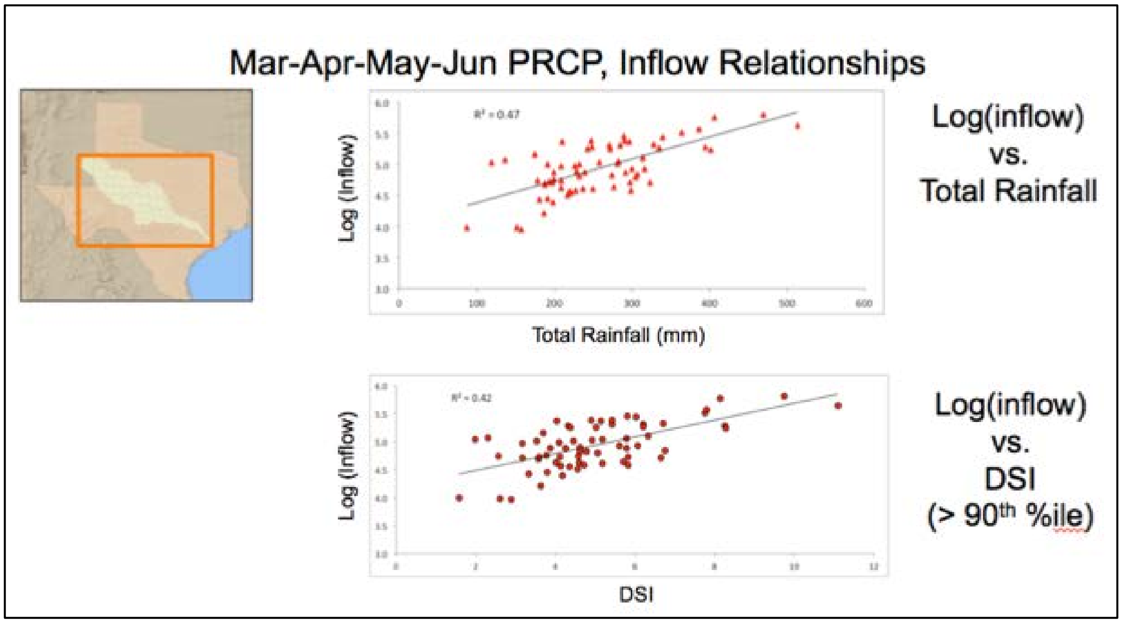

Fig. 2. *(top) Relationship between the log of inflows to the LCRA watershed and total rainfall received during the March-June season, the black line showing the least squares linear fit. (bot.) As in the top plot, but using the DSI rather than total rainfall. The DSI accounts for nearly as much of the explained variance ($r^2 = 0.42$) as does total rainfall ($r^2 = 0.47$).*

Season-ahead statistical forecast models have been developed for precipitation and streamflow. In each case, a suite of large-scale (e.g. sea surface temperatures, sea level pressures) and local (e.g. soil moisture) season-ahead predictors from the historical record have been evaluated for use in a hybrid Principal Components-Autoregressive model.

The seasonal precipitation forecast model uses a Niño Index Phase Analysis (NIPA) framework for forecasting total MAMJ and JASO precipitation in the Lower Colorado River Basin from NDJF and MAMJ global SSTs and SLPs, respectively (Zimmerman et al., in review). NIPA has been shown to improve seasonal forecasts significantly over the most 'typical' approach for seasonal forecasting, as shown in Figure 3. The NIPA methodology performs especially well at forecasting dry/wet years, as indicated by high Ranked Probability Skill Scores for the 20 driest (RPSS = 0.68) and 20 wettest (RPSS = 0.96) years.

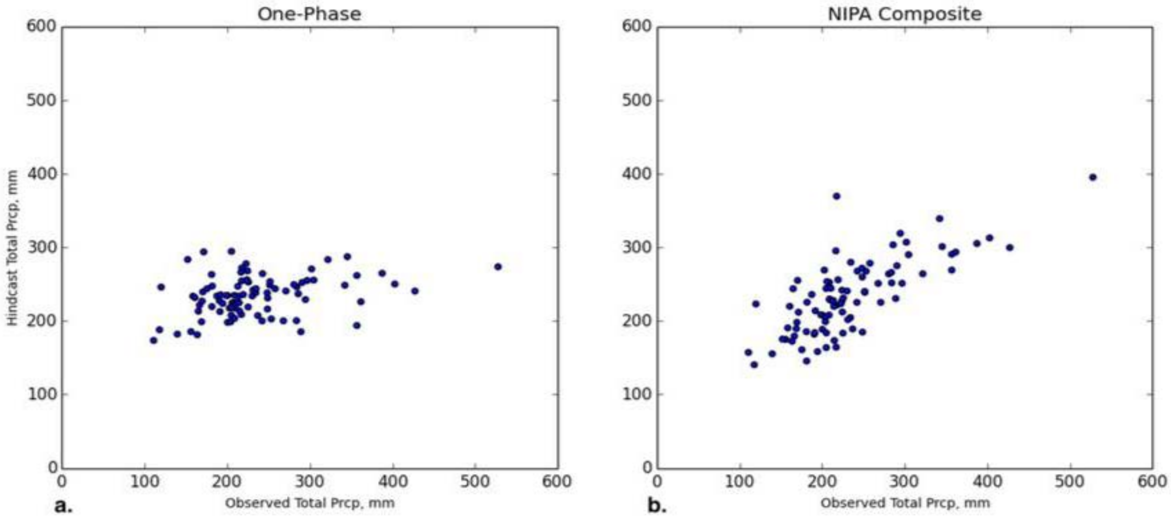

Fig. 3. *Scatter plots of (a) season-ahead hindcasts from a traditional "one-phase" model and (b) composite hindcasts from NIPA.*

Initially, a deseasonalized Autoregressive Moving Average (ARMA) model was developed for the Lower Colorado River basin with a correlation of 0.50 at the seasonal time-scale. In order to improve the predictive skill of the forecast, a suite of large-scale (e.g., sea surface temperatures (SSTs), sea level pressures (SLPs), climate indices) and local (e.g., soil moisture) season-ahead predictors from the historical record and dynamical models (i.e., GCMs) were evaluated. The selected predictors, along with the forecast from the ARMA model, are combined in a hybrid autoregressive-principal component regression framework, which uses principal components analysis to isolate dominant modes of variability in the historical data. Results demonstrate significant overall forecasts skill, particularly for the MAMJ inflow season (r = 0.70, RPSS = 0.72) (Figure 4), where ARMA, soil moisture, CFSv2 precipitation forecasts, and SSTs were selected as predictors. Forecasts of JASO inflows also exhibit increased predictive skill over climatology (r = 0.63, RPSS = 0.64). The ARMA results, CFSv2 precipitation forecasts, and SLPs provided the strongest predictive skill for the JASO season.

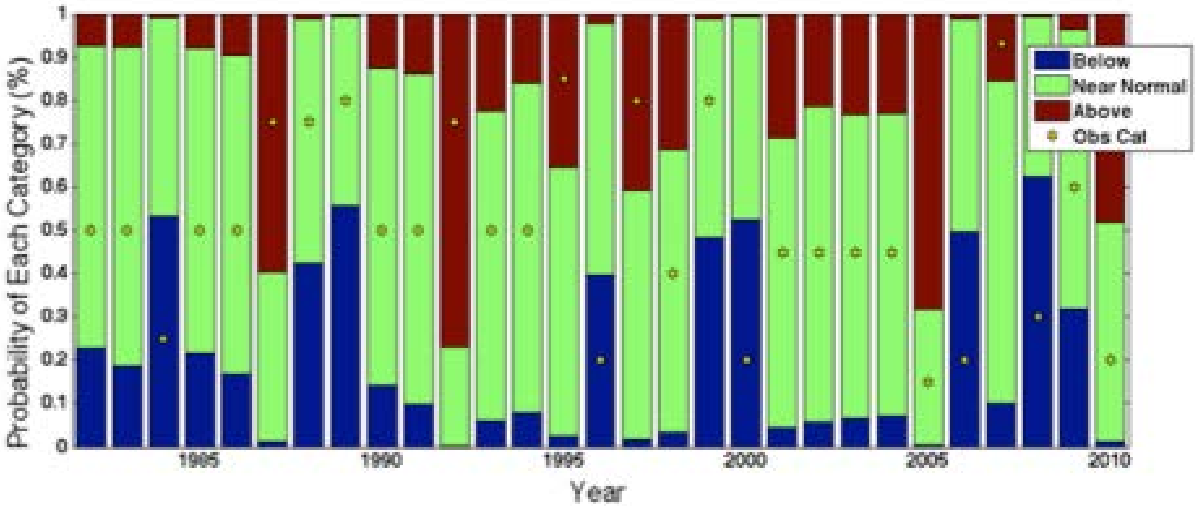

Fig. 4. *Categorical model results for MAMJ Inflows. Each color (category) represents the expected probability of the observation falling in that category. Observed category denoted by a star.*

iii) Dynamical Forecast Models

Independent of the statistical forecast models, dynamical and hybrid statistical-dynamical precipitation and streamflow forecasts were developed using the National Multi-Model Ensemble (NMME). The methodology is outlined in Figure 5 and essentially involves using principal components analysis (PCA) to extract a common precipitation signal from multiple models within the NMME (CanCM3, CanCM4, GFDL, NASA, and CFSv2). This information is then used as input to a statistical model that utilizes historical inflows to evaluate the relationship between the two over the hindcast period 1982-2010. The statistical model generates probabilistic forecasts of inflow values, i.e., probabilities either of falling into specified categories or of exceeding specified absolute values.

The skill of the inflow forecasts was evaluated using multiple metrics. An example is shown in Figure 6, which shows the relative operating characteristics (ROC) scores for four different seasons. Overall forecast skill is modest, but is statistically significant in three out of the four seasons. September-November forecasts show the highest skill. No statistically significant skill is identified for the June-August season.

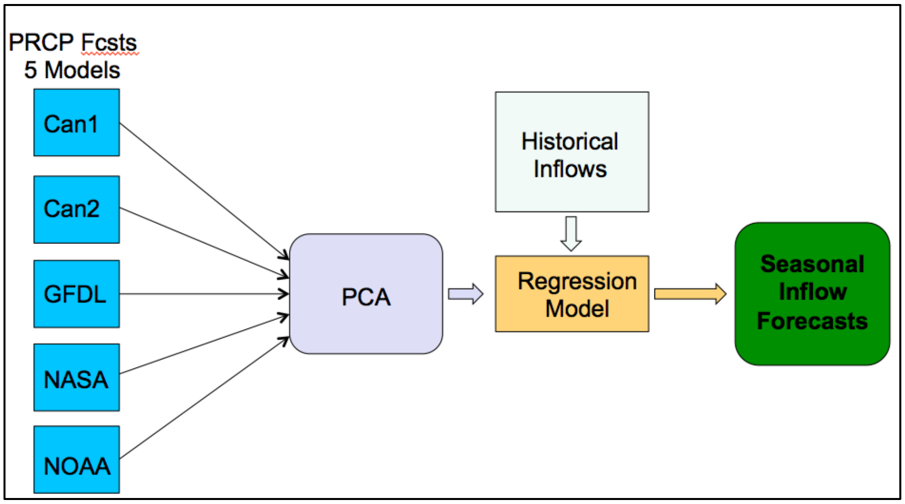

Fig. 5. *Inflow forecast methodology. Precipitation hindcasts (1982-2010) from five climate models are combined using PCA, the results used as input to a regression model where the relationship with historical inflows is evaluated. The regression model then generates the seasonal inflow forecast.*

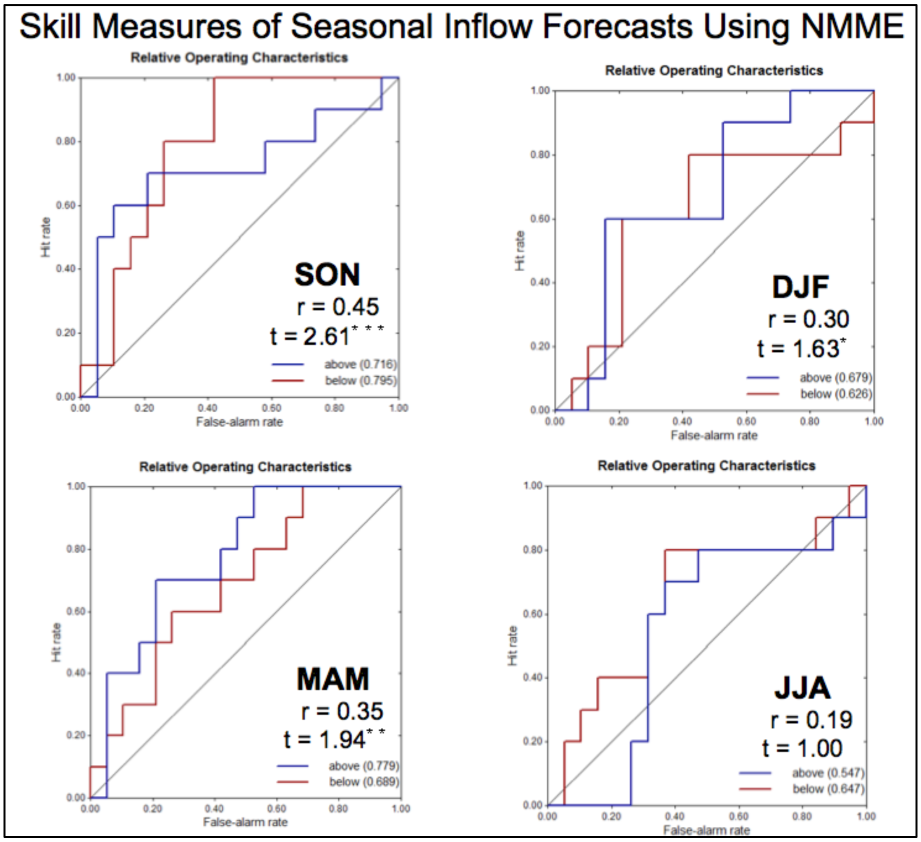

Fig. 6. *ROC scores of hindcast inflow predictions for different seasons over the period 1982-2010. Red (blue) lines are for forecasts of below-average (above-average) inflows. ROC values above and to the left of the black diagonal line in the plots indicates skill. Correlation values and t-statistic scores are also indicated on each plot.*

For those seasons where the NMME precipitation forecasts provide statistically significant skill, the precipitation forecasts will be temporally disaggregated to generate several sets of plausible daily sequences of precipitation (and temperature) to be used as input into a land surface model. The latter will also be used to generate inflow forecasts, the results to be compared with those described above.

The land surface model selected for generation of physically based inflow forecasts is the Variable Infiltration Capacity (VIC) hydrologic model. The VIC model simulates runoff and baseflow on a 1/8th-degree grid and daily time step and routes flows to the LCRA water supply reservoirs. Model extents and inputs from the Gulf Region were clipped to represent only the contributing areas of the Highland Lakes in order to decrease model run times.

After defining the watershed extent, VIC was calibrated to best match observed flows into the Highland Lakes for the period 1940 through 2011. VIC calibration is done through adjusting five soil parameters: (1) *b_infilt*, which describes the available infiltration capacity over the grid cell; (2) *Ds_max*, the maximum baseflow from the bottom soil layer; (3) *Ds*, the fraction of *Ds_max* where non-linear baseflow is observed; (4) *Ws*, the fraction of largest soil moisture at which nonlinear baseflow occurs; and (5) *Soil Depth* for each of three layers used in VIC (though we focused on the top layer initially). Of these, *b_infilt*, *Ds*, and *Ws* are conceptual parameters that were adjusted within recommended ranges. The parameters *Ds_max* and *Soil Depth* have a direct physical interpretation, and were thus estimated spatially based on data from the USDA-NRCS SSURGO database.

These parameters were adjusted in order to maximize the Nash-Sutcliffe Efficiency (NSE) while maintaining a high correlation coefficient (r) and low percent error in total volume. A sensitivity-based radio tuning calibration procedure was conducted (which assumes linearity and additivity), with additional runs of the VIC model to test for nonlinear behavior and parameter interactions. A final quantile-matching bias correction was applied to the monthly flows, resulting in an overall r^2 value of 0.70 and NSE of 0.77 for total monthly inflows into the Highland Lakes. Results are shown in Figures 7 and 8. Although calibration and verification will continue during the final year of the project, large improvements in goodness-of-fit statistics are not expected due to rainfall sampling errors, i.e., large flows are often produced by intense rainfall over small geographical areas in central Texas. However, model calibration may improve with respect to low flows, which is of more interest for this project.

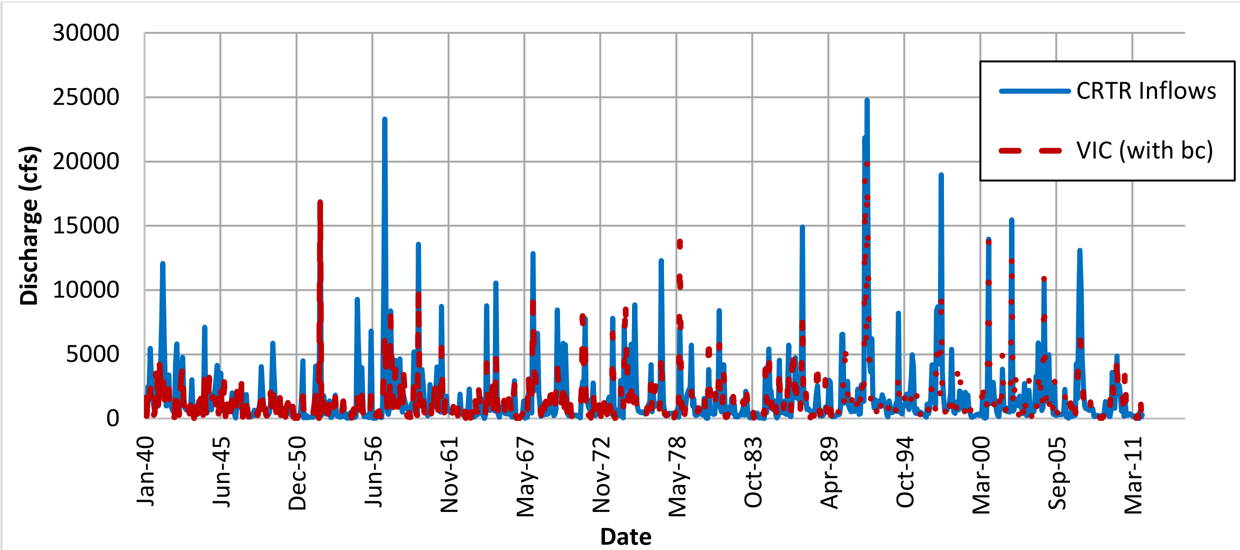

Fig. 7. *Total monthly simulated (VIC) and observed (CRTR) inflows to the Highland Lakes, 1940-2011.*

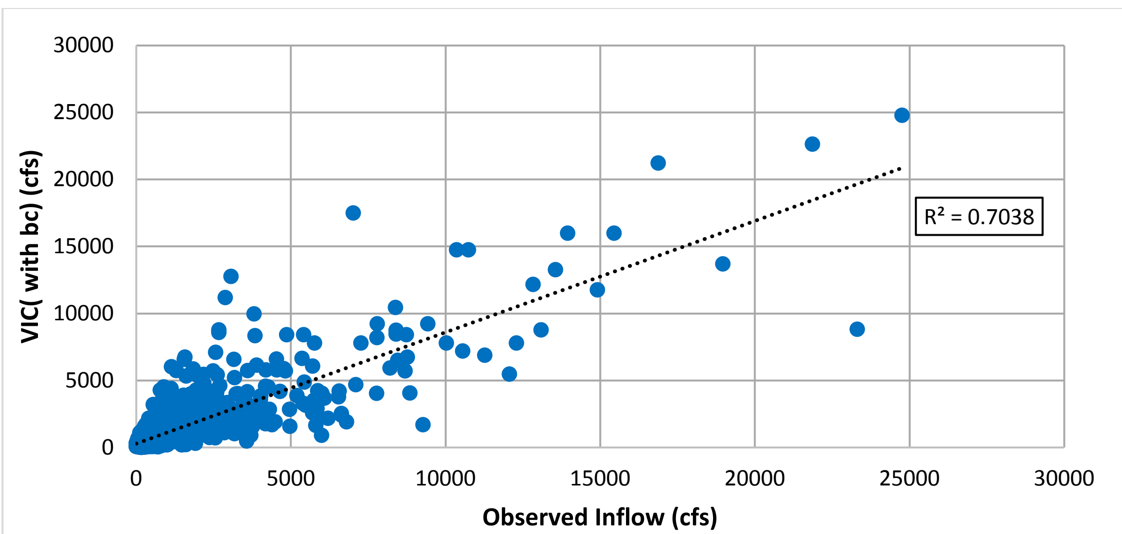

Fig. 8. *Monthly simulated (VIC) vs. observed inflows to the Highland Lakes, 1940-2011.*

iv) Decision Support System

Progress has been made in developing a Highland Lakes reservoir simulation/optimization model to understand the impact of incorporating forecasts into the LCRA's decision making process, primarily in terms of amount of water made available to interruptible water customers. Preliminary simulation results indicate larger variability in interruptible water contracts, fewer curtailments, and lower spill volumes when using seasonal forecasts. Further work on this model will be undertaken in the final project year.

B. Application of findings to inform decision making

Application of findings to inform decision making is primarily planned for the final year of the project. However, our research group presented our project and current accomplishments at the recent ASCE-EWRI Congress in Austin, TX, and several LCRA staff were in attendance and provided feedback. We also met with LCRA staff to plan the next steps of the project. In addition, we have maintained regular correspondence with Ron Anderson of the LCRA, including exchanges of preliminary research results and related work that has appeared in the literature.

C. Planned methods to transfer knowledge

LCRA water managers have been engaged throughout the project through frequent emails, occasional web conferences, and annual face-to-face workshops. Although we feel we have been reasonably successful in transferring knowledge to date, we have been made more keenly aware of the “gap” between research and practice and the need to tailor data products and tools for use by water managers. It may be that not all of the data products being developed are “usable” by the LCRA, for reasons such as limited staff time, computer resources, and experience with different models, and thus we will need to focus on a smaller set of products that have a greater chance of gaining acceptance and being used in practice.

All forecast models and data products will be shared with NIDIS. In addition, we intend to explore the generalizability of our findings for central Texas to other climate divisions in the U.S.

D. Significant deviations from proposed work plan

The project end date has been extended (at no additional cost) to August 31, 2016. This will provide additional time for completion of the dynamical forecast model (expected completion by December 2015), refinement of the statistical forecast models (December 2015), and incorporation of forecasts in the enhanced DSS (April 2016).

Along with a second decision maker workshop in late Summer or early Fall 2015, an additional workshop is planned near the end of the project in Summer 2016.

E. Completed publications, white papers, or reports

There are no publications to date. Two journal papers are in review.

III. GRAPHICS: PLEASE INCLUDE THE FOLLOWING GRAPHICS AS SEPARATE ATTACHMENTS TO YOUR REPORT

A Powerpoint slide is attached, depicting the overall framework for this project.

Additional information and graphic are available from the research team's EWRI conference presentations, posted on-line:

- https://docs.google.com/file/d/0Byz8QM_b4b4qZFZPRUFUSEpTczA/edit
- https://docs.google.com/presentation/d/1wtNFoNzDHjKF05WFdXkPiyPDvQxlweAwfgbiPXvhN1Q/edit?usp=sharing
- https://drive.google.com/file/d/0B9MZjFxMoYKSanVFUnZGNVJXRzQ/view?usp=sharing

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