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Application of Seasonal Rainfall Forecasts to Inform the Implementation of Drought Contingency Triggers in Selected Water Supply Reservoirs in Texas

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1. Introduction

In response to the exceptional drought of 2011, the Texas Water Development Board (TWDB) adopted new rules for its water planning process in 2012. The new rules require all regional water planning groups to include a chapter on drought management in their respective 5-year water plans with the aim of implementing short-term water demand reductions in the face of impending or existing drought conditions. Each water user group in a water planning region is required to develop drought contingency plans and drought action triggers for their respective water supply sources. Water user groups need to consult existing information on impending or current drought conditions before making a decision on whether to implement drought contingency triggers, which set in place voluntary or mandatory water use restrictions.

Reliable forecasts of summer (May, June and July; MJJ) reservoir storage issued at the end of April is vitally important for reservoir operators in Texas because such forecasts could help reservoir operators decide on whether the implementation of drought contingency triggers is warranted for the upcoming summer season.

In this study we report on how we applied improved forecasts of MJJ rainfall, issued at the end of April in a given year, for seasonal storage forecasts at three reservoirs managed by the Brazos River Authority (BRA) on the Brazos river basin in Texas. The objective of the study was to develop a framework by which the BRA could use seasonal rainfall forecasts to inform the implementation of drought contingency triggers on their reservoirs.

2. Improved May-July seasonal rainfall forecasts and the TWDB drought forecast tool

The MJJ season is the critical rainfall season over much of Texas. Failure of this rainfall season tends to result in intense summer drought over Texas (Fernando *et al.*, 2016). Seasonal rainfall forecasts from dynamic climate models are unable to provide more skill than that provided by the autocorrelation of rainfall anomalies, particularly during the summer over the U.S. Great Plains (Quan *et al.*, 2012).

We developed a process-based statistical forecast tool to generate improved forecasts of May-July (MJJ) rainfall over Texas and the South Central U.S. based on our understanding of key processes that drive the failure of late-spring/early-summer rainfall over the region (Fernando *et al.*, 2015). The key processes active in the spring (April) that drive summer rainfall deficits over the South Central U.S. are: mid-tropospheric high pressure, enhanced convective inhibition energy, and low soil moisture. We used geopotential height at 500 hPa, the difference in temperature between 700 hPa and surface dewpoint (as a proxy for convective inhibition), and soil moisture in April as the predictor variables and MJJ rainfall as the predictand in the empirical forecast tool. We find that the skill of rainfall forecasts from the statistical forecast tool exceeds skill due to persistence (*i.e.* autocorrelation) over most of Texas and Oklahoma (Fernando *et al.*, 2015). Given that the failure of the MJJ rainfall season tends to result in intense summer drought over Texas, seasonal forecasts of MJJ rainfall are, in effect, early warnings of impending summer drought.

The TWDB launched a 'Drought Forecast Tool' in May 2016 at http://waterdatafortexas.org/drought/drought-forecast to provide automated probabilistic forecasts of MJJ rainfall for each county in Texas. These forecasts provide information on the likelihood that rainfall in the MJJ season will be above-, near-, or below-normal in a given county.

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3. Water availability modeling in Texas

The Water Right Analysis Package (WRAP) from Texas A&M University is the official water availability modeling (WAM) tool adopted within Texas for the simulation of water use in Texas, where water rights are governed by the Prior Appropriations Doctrine. A conventional WRAP simulation run extends over the entire hydrological record in a single (aka, long-term) simulation. Conditional Reliability Modeling (CRM) is another feature (or mode) that was implemented in the WRAP modeling system to support drought management and operation planning activities. CRM provides the capability to truncate long-term simulations into many short periods by specifying starting month, length of simulation and initial reservoir storage. The CRM output can be used in conjunction with seasonal rainfall forecasts to derive climate-informed reservoir forecasts. In this study we adopt the CRM feature to generate experimental reservoir forecasts for three reservoirs on the Brazos river basin.

3.1 Brazos River Basin and Brazos Water Availability Model

The Brazos River Basin, located in the middle of Texas and runs southeasterly, has a total area of 44,620 square miles. The climate, hydrology, and geography of the basin vary greatly as it extends across Texas from New Mexico to the Gulf of Mexico. Mean annual precipitation varies from 19 inches in the upper basin that lies in the High Plains to 45 inches in the lower basin in the Gulf Coast region. The extreme upper end of the basin in and near New Mexico is an arid flat area that rarely contributes to stream flow.

The Texas Commission on Environmental Quality (TCEQ) maintains water availability models for every river basin in Texas. The TCEQ Brazos WAM Run 8 (current use scenario at monthly time step) is updated and employed in this study. The Brazos WAM model is one of the largest models maintained by the TCEQ. The Brazos WAM RUN 8 has 3,834 control points (77 primary control points with naturalized flow and 66 control points with reservoir net evaporation), 711 reservoirs, 1,725 water rights, and 144 instream flow water rights. The current use scenario consists of diversions being made based on maximum annual amount used in a ten year period (approximately 1991–2000), return flow coefficients and reservoir storage capacities reflecting sedimentation conditions for the year 2000.

The official Brazos WAM model covers a hydrologic period of analysis from January 1940 to December 1997. The extended hydrologic (naturalized flow and reservoir net evaporation) input (1900-1939 and 1998-2014) for the Brazos WAM, produced by Prof. Ralph Wurbs (Texas A&M), is combined with the existing hydrologic input (1940-1997, Wurbs and Kim, 2008; Wurbs, 2015) for the CRM simulation used in this study. We used the full hydrology, extending from 1900–2014, because frequency (or percentile) estimates are improved as sample size increases.

3.2 Reservoirs selected for this study

The United State Army Corps of Engineers, BRA or local municipalities, operate most large reservoirs in the Brazos River Basin. As stated in previous section, reservoir storage is mainly related to inflow and diversion. If diversion varies greatly from year to year, it is difficult to predict reservoir storage even though the inflow is predicted with a higher degree of accuracy. Water usage information from BRA indicates that some large reservoirs have irregular industrial usage that is less predictive. Therefore, this study focuses on three small reservoirs — *i.e.* Lake Limestone, Aquilla Lake, and Proctor Lake (Figure 1).

Fig. 1 Brazos River Basin and selected reservoirs in this study.

In this study, CRM simulation starts from May 1 and last for 3 months for 115 (1900-2014) years. Initial reservoir storage for monitored major reservoirs is set to the actual storage condition on April 30, 2016. For unmonitored reservoirs, they are divided into upper and lower sub-basin and are assigned the percent full to be equal to the overall percent full of all monitored reservoirs in the sub-basin on the same date. Reservoir capacity and area-volume rating curves are updated using the latest available hydrographic surveys. The diversion from reservoirs is updated to reflect 2016 projected conditions.

4. Methodology for applying rainfall forecasts for reservoir storage forecasts

Many factors affect reservoir storage. Among these factors, inflow and diversion generally play important roles in reservoir storage. If diversion can be projected with some degree of certainty, reservoir storage would largely depend on inflow. Inflow or natural river flow in turn is generated by precipitation. Thus, skillful rainfall forecasts could be useful for the generation of skillful reservoir storage forecasts.

We employ two methods to derive reservoir storage forecasts based on information from the seasonal rainfall forecast.

a) Conceptual method

The sequential output from Conditional Reliability Modeling (CRM) reflects all possible situations for storage under assumed water use scenarios. With a sufficiently long period of analysis, simulated storages reflect all possible storage situations related to all historical rainfall situations. In other words, the maximum storage is a reflection of the highest rainfall, while the minimum storage is a reflection of the lowest rainfall. Therefore, the basis of this method is to forecast summer reservoir storage by ranking (percentile) the sequential storage output from the CRM simulation, and by selecting storage at a certain percentile to match the summer rainfall forecast. Given that the probabilistic forecasts of MJJ rainfall cannot directly be applied in the selection of a storage percentile, we use the exceedance probability curve for the rainfall forecast to guide the selection of the storage percentile. We obtain the exceedance probability curve for the grid point in which each reservoir falls. If the probabilistic forecast shows higher probabilities of below normal rainfall, for example as in the hindcast for 2011, we would consult the exceedance probability curve for the selected grid point to obtain the probability for rainfall being less than 50% of normal (Figure 2). The correlation between historical rainfall and simulated storage over the summer demonstrates this relationship and concept (Figure 3).

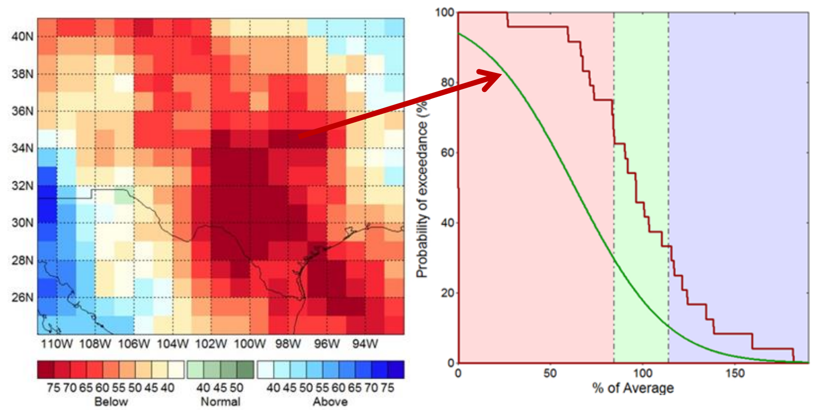

Fig. 2 Probabilistic forecast of 2011 MJJ rainfall (left) and the forecast exceedance probability curve (green) versus the climatological exceedance probability (red) for the grid point over Lake Limestone.

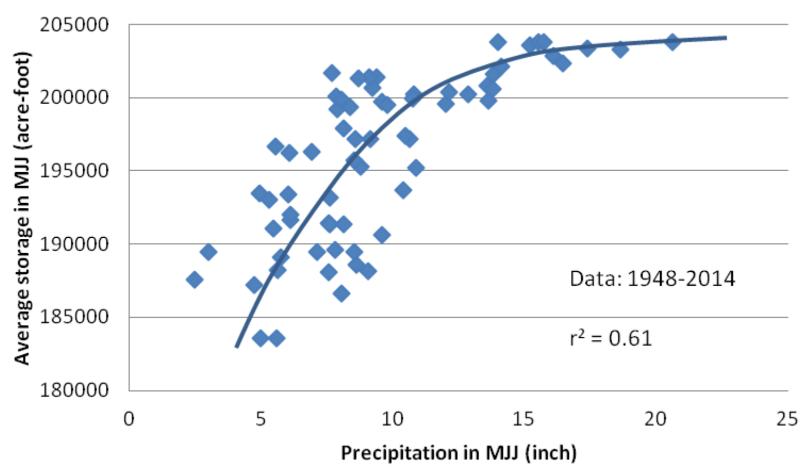

Fig. 3 Correlation between average simulated storage in Lake Limestone and precipitation in its watershed during summer period (assuming full storage in the end of April).

b) Selective method

The Selective method for forecasting reservoir storage requires the identification and use of years in which rainfall is similar to that predicted using the Texas Water Development Board's May–July rainfall forecast tool. By word "similar" we actually mean that the rainfall amount for a given month is within a certain predetermined range (such as from 85% to 115% of forecasted rainfall). The philosophy of this method is based on the assumption that the reservoir storage in a particular month (such as May) should be similar if rainfall in that month is similar. Therefore, using storages of selected historical years should provide a reasonably good prediction of storage for a coming year if the rainfall is similar.

5. Forecast results for 2016

For the Conceptual Method, reservoir storages at typical (1, 10, 20… 100) percentiles are computed for each simulation sequence. The reservoir storage for the summer months (end of MJJ) at the 90th percentile is selected as the forecast storage for each reservoir. The selection of the 90th percentile was informed based on the exceedance probability for 2016 MJJ rainfall being above 100% of normal and the categorical forecast indicating high probabilities (above 95%) for above normal rainfall (Figure 4). Forecast reservoir storage curves for end of May, June and July show no change from May to June and decrease slightly in July for Lakes Limestone (Figure 5) and Proctor (not shown). Forecast reservoir storage at Lake Aquilla was at full capacity for May, June and July (not shown). Observed storage in all three reservoirs were way above any of the drought contingency trigger levels, indicating that there was no necessity to adopt drought management strategies in the summer of 2016.

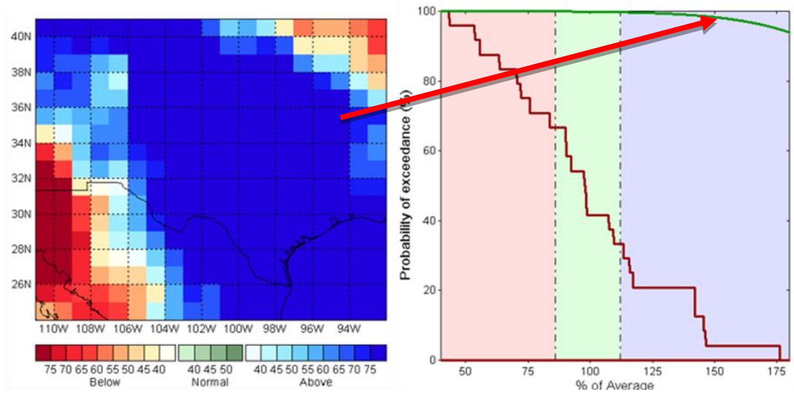

Fig. 4 Probabilistic forecast of 2016 MJJ rainfall (left) and exceedance probability curve for grid point over Lake Limestone.

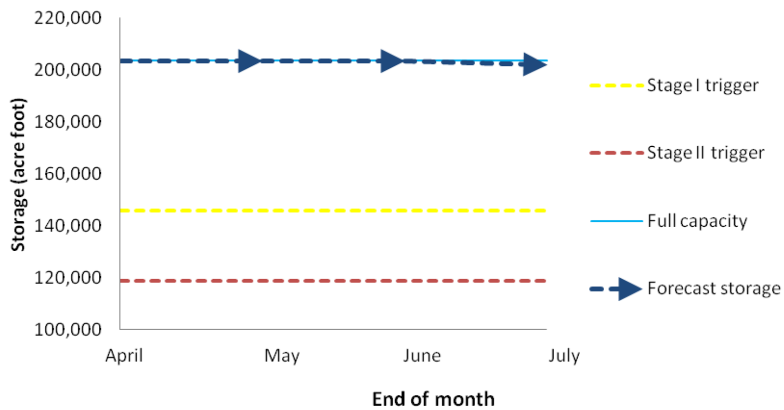

Fig. 5 2016 Storage forecast for Lake Limestone by Conceptual method.

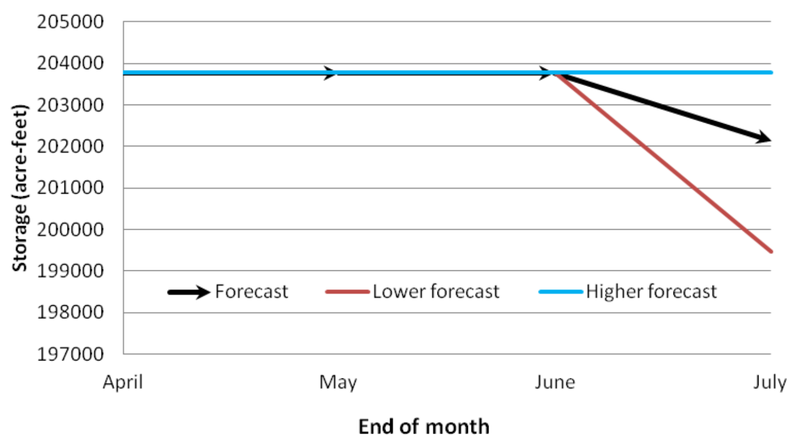

Fig. 6 2016 Storage forecast for Lake Limestone by Selective method.

For the Selective method, several years are selected for each month of May, June and July for each reservoir based on similarity of historical rainfall to the forecast rainfall. The criterion for selection of years is that rainfall of selected years must fall within the range of 0.85 to 1.15 times of forecast rainfall. Simulated storages of those selected years are picked from the CRM sequential output and their average is denoted as the "storage forecast". The minimum and maximum historical storage values selected by this method indicate the uncertainty range of this forecast (see Figure 6 for results for Lake Limestone; results for Lakes Aquilla and Proctor are not shown).

For Lake Limestone, both Conceptual and Selective methods forecast no change or little change to full storage in the end of June and July, while observed storage was slightly lower than the forecast in June and July. The maximum error of this forecast for July was 5.6% higher than observed (Figure 7). For Lake Aquilla, the Conceptual method forecasts full storage for May, June, and July, which happens to be the same as was observed in those three months (not shown). The forecast from the Selective method for Aquilla is very close to observed values and is only one percent less than observed storage for July (not shown). For Proctor Lake, both the Conceptual and Selective methods forecast no change or little change to full storage at the end of June and July, while actual observed storage went down slightly in July. The maximum error in July was only 1% higher than observed (not shown). Overall, both methods give a good accuracy of forecast.

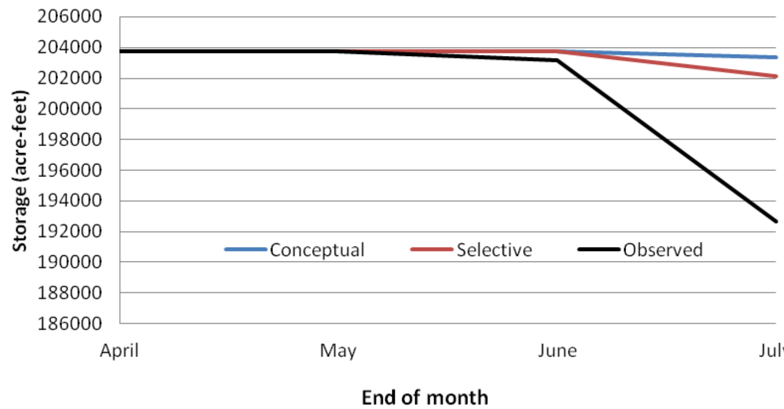

Fig. 7 Comparison of forecasted and observed storages for Lake Limestone.

6. Conclusion and discussion

We operated Conditional Reliability Modeling (CRM) capabilities of the Water Rights Analysis Package (WRAP) and applied 2016 May–July rainfall forecasts to derive storage forecast using the Conceptual method and the Selective method. The storage forecasts for Lake Limestone, Aquilla Lake, and Proctor Lake in the Brazos river basin for the 2016 summer (MJJ) were derived using the 90th percentile curves for these three reservoirs. The wet conditions forecast for MJJ 2016 from the Texas Water Development Board's (TWDB's) rainfall forecasting tool (http://waterdatafortexas.org/drought/drought-forecast) provided input to the selection of the percentile curves. Forecasted reservoir storage curves for end of May, June, and July exhibit no change from May to June and slight decreases in July, indicating low drought management trigger probability. The comparison of the forecast storage with observed storage at the end of July indicates our forecast has good accuracy.

The Selective method may not provide adequate room for risk management given that the uncertainty in the forecast is limited by the number of "similar" cases available for selection from the historical record. More work is needed on the Conceptual method to ascertain the exact relationship between rainfall and reservoir storage. Furthermore, the current model only simulates storage up to the conservation pool and does not account for water stored in the flood pool. Therefore, extending our simulation into the flood pool in a wet year (such as in 2016) is needed for improved reservoir forecasts. Further investigation is also needed to assess the impact of antecedent rainfall in April on storage in May to better understand the role of hydrological persistence in reservoir storage.

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