Framework for the application of seasonal rainfall forecasts for reservoir storage forecasts: *proof of concept for three reservoirs in the Brazos River Basin*

D. Nelun Fernando, Ph.D., John Zhu, Ph.D., P.G., and Solomon Negusse

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1) Need for improved drought information for drought contingency planning

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 through July, May–July) 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 May–July 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) Applying seasonal rainfall forecasts to forecast reservoir storage

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 for a particular season could be useful for the generation of skillful reservoir storage forecasts for that season. 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 the Brazos River Authority indicates that some large reservoirs in the Brazos river basin 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) — managed by the Brazos River Authority.

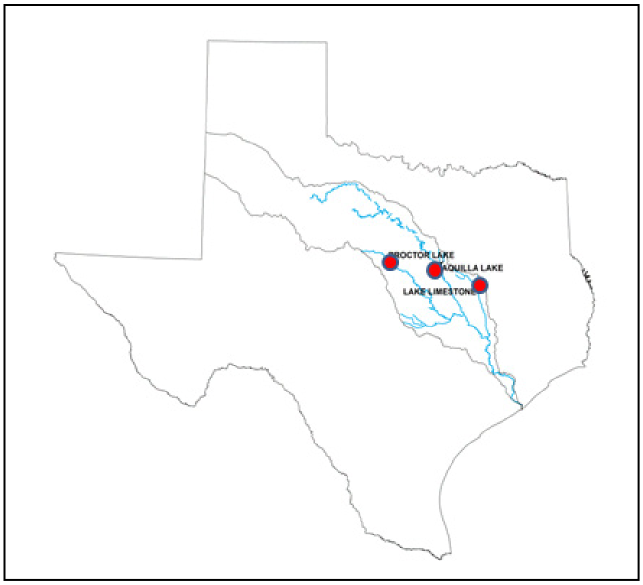

Figure 1: The location of the three reservoirs in the Brazos river basin for which experimental storage forecasts were issued in May 2017

Questions that needed to be addressed when applying the rainfall forecast to inform forecasts of reservoir storage were: 1) How can the forecast be applied to the Water Rights Analysis Package (WRAP)[1]?; and 2) How can probabilistic categorical seasonal forecasts (i.e. whether rainfall in the coming season will be above-, near-, or below normal) be translated to information that reservoir operators can use?

2.1: Working with WRAP for reservoir storage forecasts

To address the first question, we utilized Conditional Reliability Modeling (CRM), which is a 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.

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

[1] 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).

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.

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, 2017. For unmonitored reservoirs, they are divided into upper and lower sub-basin and are assigned the percent full as same as 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 from the TWDB. The diversion from reservoirs is updated to reflect 2016 projected conditions. 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. The correlation between historical rainfall and simulated storage over the summer demonstrates this relationship and concept (Figure 2). 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 exceedance frequency of the summer rainfall forecast over the reservoir.

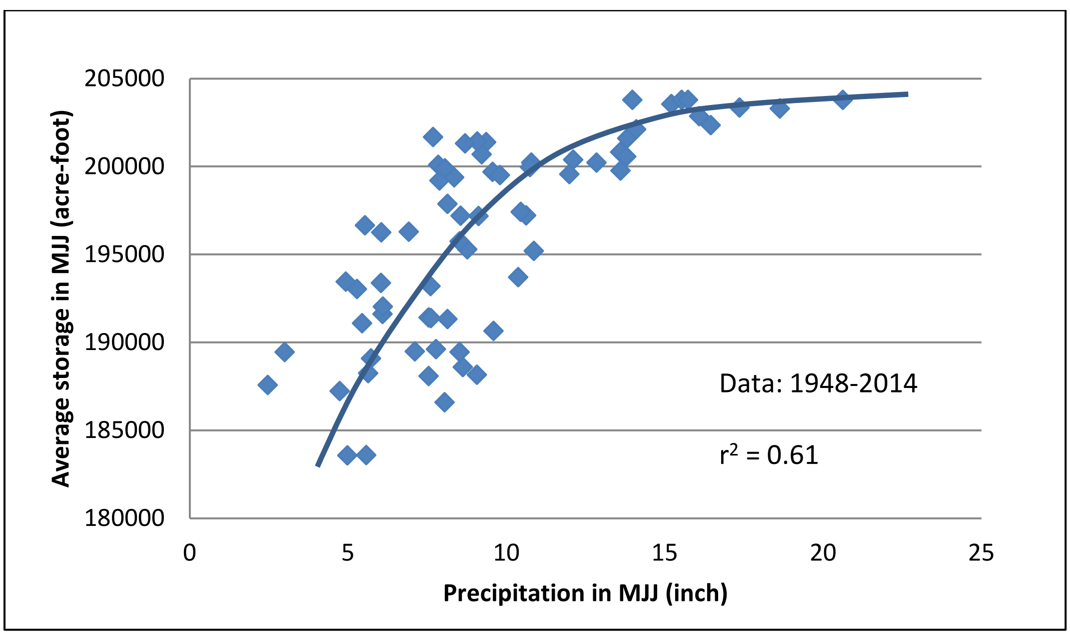

Figure 2: Correlation between average simulated storage in Lake Limestone and Precipitation in its watershed during summer period (assuming full storage in the end of April)

2.2: Factoring in the rainfall forecast

Given that the probabilistic forecasts of May–July rainfall cannot directly be applied in the selection of a storage percentile, we consult exceedance probability curves for the rainfall forecast to guide the selection of the storage percentile. Specifically, the deterministic forecast of rainfall (i.e. the point forecast of the actual quantity of rainfall) for each grid point overlying each lake was used in conjunction with an exceedance probability curve of forecast rainfall (green curve in the probability of exceedance graphs) to obtain the exceedance frequencies for the point forecast and for the upper and lower limits of the point forecast using a confidence interval of 60 percent. The option to use the confidence interval of 95 percent was also investigated. We only report on the results using the confidence interval of 60 percent.

A multiplication factor (known as Qx, which reflects the anticipated influence of near-term climatic conditions on streamflow, Wurbs et al., 2012) was applied to the probability array option used in the analysis of output from the Conditional Reliability Model run. Given that the point forecasts of rainfall over each reservoir were very close to the historical mean values for May–July rainfall for each location, we set the multiplication of Qx to 1. This implies that we anticipate inflow conditions to all three reservoirs to be around their long-term average inflow conditions. The output from the Conditional Reliability Model run was ranked in ascending order and the forecast storage value was selected using the exceedance frequency value for the point rainfall forecast over each reservoir. The upper and lower bound storage values were selected using the exceedance frequencies for the 60 percent confidence interval for the point rainfall forecast.

2.3: Framework for applying rainfall forecasts for reservoir storage forecasts in Texas

We developed a schematic (Figure 3) of the steps that reservoir operators in Texas could take if they opt to use forecasts of seasonal rainfall to inform reservoir storage forecasts.

1) Obtain point forecast for reservoir county (including exceedance frequency and upper/lower limit forecast)

2) Multiply CRM output by Qx multiplication factor (Wurbs et al., 2012)
Qx < 1 (less than average streamflow); Qx = 1 (average); Qx > 1 (greater than average)

3) Rank storage in ascending order, obtain storage exceedance frequencies

4) Select storage based on exceedance frequency for point rainfall forecast

5) Obtain upper and lower limit of forecast storage based on exceedance frequency for 60% confidence interval for the point forecast

Figure 3: Schematic of steps to take when factoring in a rainfall forecast when generating reservoir storage forecasts

3) May–July 2017 storage forecasts for Aquilla Lake, Lake Limestone, and Proctor Lake

The TWDB issued experimental forecasts of May–July 2017 reservoir storage for Aquilla Lake, Lake Limestone, and Proctor Lake at the beginning of May 2017. The forecast utilized information from the TWDB's May–July forecasts of seasonal rainfall (https://waterdatafortexas.org/drought/rainfall-forecast) and the CRM routine. The flood pool was included in the storage calculations for each reservoir.

Comparison of forecast reservoir storage with observed storage for May–July 2017 shows that for Aquilla Lake, observed storage (thick black line) at the end of July was in the flood pool (above blue line, Figure 3.1) while the forecast had it dropping below conservation storage. The forecast for Lake Limestone had storage dropping below conservation storage and observed storage also drops below conservation storage by the end of July 2017 (Figure 3.2). However, the observed storage at end July 2017 in Lake Limestone is slightly higher than the forecast storage. The forecast for Proctor Lake shows storage at conservation capacity by end July 2017. Observed storage at end July 2017 is also at conservation capacity. However, in May 2017, forecast storage for Proctor Lake was much higher than observed storage at end May 2017 (Figure 3.3). This discrepancy is very likely due to flood releases from Proctor Lake by the U.S. Army Corps of Engineers, in May 2017, that were not accounted for in the forecast methodology.

3.1: Observed and forecast storage and exceedance probability plots for Aquilla Lake

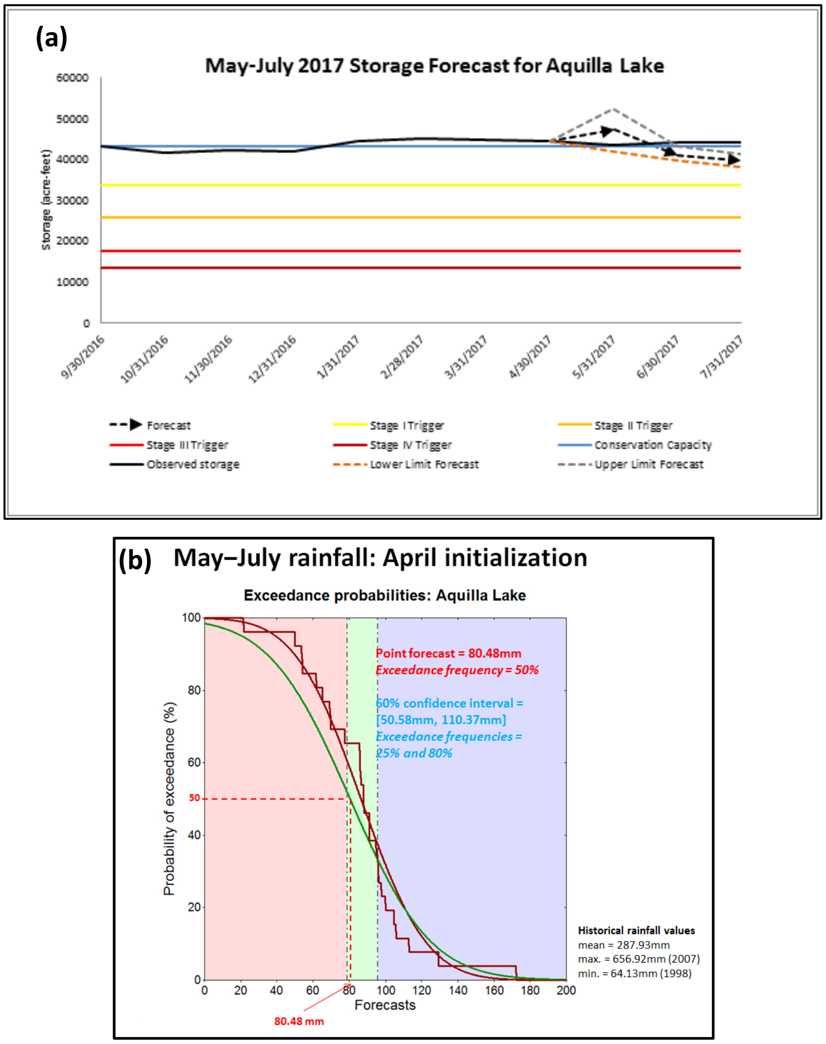

Figure 3.1: (a) May–July 2017 storage forecasts for Aquilla Lake. Thick dashed black arrows in (a) indicate the storage forecast generated using the point rainfall forecast. Thick black line indicates observed storage. Thin dashed grey indicates the upper limit of the storage forecast generated using the upper limit of the 60% confidence interval. Thin dashed brown line indicates the lower limit of the storage forecast generated using the lower limit of the 60% confidence interval. Solid horizontal blue line indicates reservoir conservation capacity. Solid horizontal yellow, light brown, red, and dark brown lines are Stage I, Stage II, Stage III, and Stage IV drought contingency trigger levels, respectively, for Lake Aquilla as listed in the Brazos River Authority's Drought Contingency Plan available at: https://www.brazos.org/Portals/0/generalPdf/DCP_10-2012.pdf; and (b) Exceedance frequency curve for May–July rainfall over Aquilla Lake. The stepped brown curve shows exceedance probabilities associated with climatological rainfall values, the smooth brown curve shows a log-normal fit to the climatological rainfall exceedances, and the green smooth curve shows a log-normal fit to the forecast rainfall exceedances. The red dashed line indicates the point forecast of 80.48mm and its associated exceedance probability of 50%. The point forecast falls within the green shaded area of the plot indicating that the forecast rainfall is likely to be near the climatological average for that location.

3.2: Observed and forecast storage and exceedance probability plots for Lake Limestone

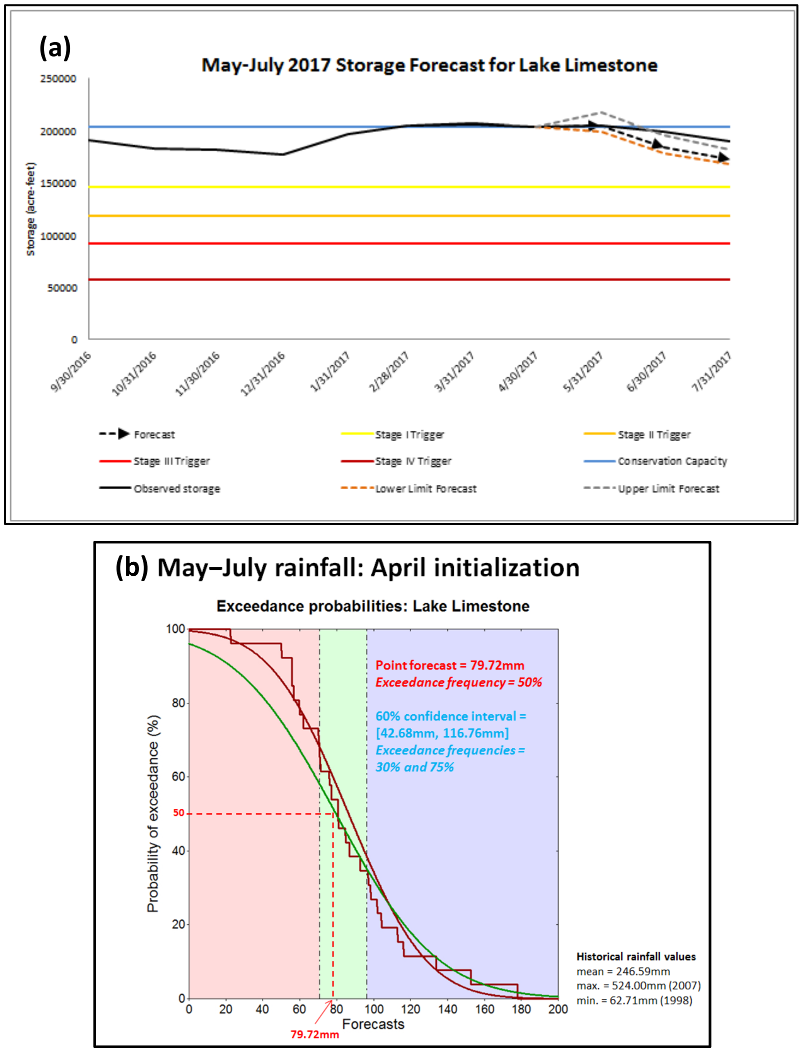

Figure 3.2: (a) May–July 2017 storage forecasts for Lake Limestone. Thick dashed black arrows in (a) indicate the storage forecast generated using the point rainfall forecast. Thick black line indicates observed storage. Thin dashed grey indicates the upper limit of the storage forecast generated using the upper limit of the 60% confidence interval. Thin dashed brown line indicates the lower limit of the storage forecast generated using the lower limit of the 60% confidence interval. Solid horizontal blue line indicates reservoir conservation capacity. Solid horizontal yellow, light brown, red, and dark brown lines are Stage I, Stage II, Stage III, and Stage IV drought contingency trigger levels, respectively, for Lake Limestone as listed in the Brazos River Authority's Drought Contingency Plan available at: https://www.brazos.org/Portals/0/generalPdf/DCP_10-2012.pdf; and (b) Exceedance frequency curve for May–July rainfall over Lake Limestone. The stepped brown curve shows exceedance probabilities associated with climatological rainfall values, the smooth brown curve shows a log-normal fit to the climatological rainfall exceedances, and the green smooth curve shows a log-normal fit to the forecast rainfall exceedances. The red dashed line indicates the point forecast of 79.72mm and its associated exceedance probability of 50%. The point forecast falls within the green shaded area of the plot indicating that the forecast rainfall is likely to be near the climatological average for that location.

3.3: Observed and forecast storage and exceedance probability plots for Proctor Lake

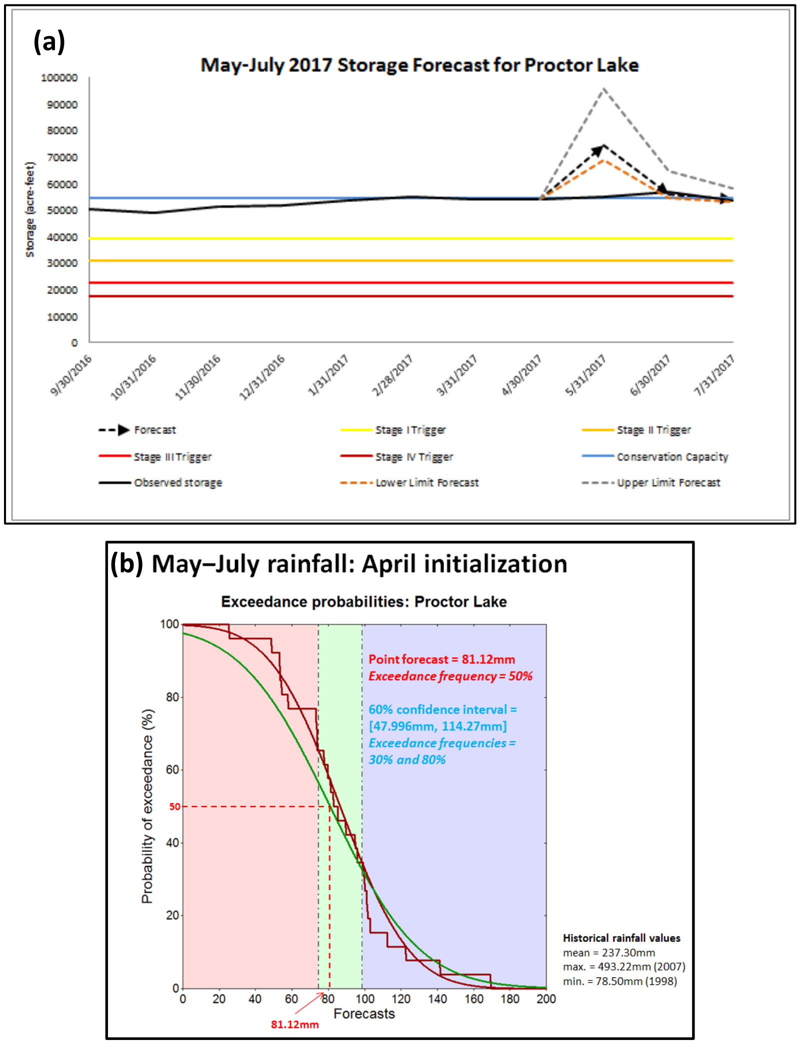

Figure 3.3: (a) May–July 2017 storage forecasts for Proctor Lake. Thick dashed black arrows in (a) indicate the storage forecast generated using the point rainfall forecast. Thick black line indicates observed storage. Thin dashed grey indicates the upper limit of the storage forecast generated using the upper limit of the 60% confidence interval. Thin dashed brown line indicates the lower limit of the storage forecast generated using the lower limit of the 60% confidence interval. Solid horizontal blue line indicates reservoir conservation capacity. Solid horizontal yellow, light brown, red, and dark brown lines are Stage I, Stage II, Stage III, and Stage IV drought contingency trigger levels, respectively, for Proctor Lake as listed in the Brazos River Authority's Drought Contingency Plan available at: https://www.brazos.org/Portals/0/generalPdf/DCP_10-2012.pdf; and (b) Exceedance frequency curve for May–July rainfall over Proctor Lake. The stepped brown curve shows exceedance probabilities associated with climatological rainfall values, the smooth brown curve shows a log-normal fit to the climatological rainfall exceedances, and the smooth green curve shows a log-normal fit to forecast rainfall exceedances. The red dashed line indicates the point forecast of 81.12mm and its associated exceedance probability of 50%. The point forecast falls within the green shaded area of the plot indicating that the forecast rainfall is likely to be near the climatological average for that location.

4) Conclusions and lessons learned

We demonstrated how rainfall forecasts for the May–July season could be used to guide the implementation of drought contingency triggers in water supply reservoirs in Texas.

Tercile categorical rainfall forecasts (i.e. forecasts providing probabilistic information on whether an upcoming season will be above-, near-, or below-normal) cannot be applied directly to reservoir storage forecasts. There is a need to use deterministic forecasts (i.e. point rainfall forecasts) and the associated probabilities of exceedance for these deterministic forecasts. The latter provide an assessment of the uncertainty associated with the point forecast.

Storage forecasts must account for local basin conditions, such as reservoir diversions, capacity, inflow, etc. A generalized storage forecast formula cannot be applied uniformly to all reservoirs in a given state or region. Given this key factor, the purpose of generating experimental storage forecasts for three reservoirs on the Brazos river basin was to demonstrate a proof of concept by which reservoir operators could utilize seasonal rainfall forecast information to inform the implementation of drought contingency triggers on surface water supply reservoirs.

Reservoir storage forecasts for the May through July 2017 season indicated that the odds of storage in Lake Aquilla, Lake Limestone, and Proctor Lake reaching drought contingency trigger levels were low because for each reservoir the forecast indicated that storage would be at or just below conservation capacity. In terms of guiding the implementation of drought contingency triggers in these reservoirs, the forecast was able to provide reasonably accurate information that there was little likelihood of a need to implement drought contingency trigger levels in any of the three reservoirs studied. The forecasts show an increase in storage in May for all three reservoirs not seen in observed storage. This discrepancy could stem from historical diversion and naturalized flow data used in training the Conditional Reliability Model run of the Water Rights Analysis Package. It could also stem from the non-incorporation of May flood release estimations in the forecast methodology. We will work on identifying what steps we could take to correct this discrepancy going forward.

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