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Forecasting Long-term Water Supply Using Stochastic Methods with Trend Consideration: A Study on Lake Meredith in the Canadian River Basin in Texas

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1. Introduction

How much water supply can come from a certain reservoir in 2020, 2030, 2040, 2050 and 2060? This is a key question that must be answered for the water planning process in Texas. Currently, the state's water planning rules request regional planning groups to use the firm yield computed by the Texas Commission of Environmental Quality (TCEQ) updated Water Availability Model (WAM) Run3 (full permit diversion and no return flow) as available supply, plus consideration of future sedimentation effects which would reduce water supply. WAM is the official water accounting model used for water rights permitting, regulation, and water planning purposes in Texas. The WAM uses the Water Right Analysis Package (WRAP) developed by Texas A&M University (Wurbs 2015). WRAP simulates management of water resources of river basin(s) under a priority-based water allocation system with river basin hydrology represented by sequences of naturalized stream flows and reservoir net evaporation rate at pertinent locations. Naturalized flows are sequences of monthly flows representing natural hydrology and are typically developed by adjusting historical gauged streamflow data to remove the impacts of reservoir construction, water use, and other human activities. Currently, most of TCEQ's WAMs use hydrologic input from 1940s to 1990s. That means the firm yield computed by such a model is only applicable for the period from 1940s to 1990s. One effort now is to extend the input hydrologic data to recent years to include 2011, which is the worst one year drought in the observational record going back to 1895. Using an extended hydrology reveals potentially critical issues with respect to water availability. For example, some river basins have decreasing streamflow and some reservoirs have had lower storage in the past decade (*i.e.*, Lake Meredith since 2000) and some have even run dry (*i.e.*, O.C. Fisher Lake in 2013). The firm yields from reservoirs decrease with the extended hydrologic input. This is an indication that the firm yield values used presently are probably not applicable for the future because future hydrological conditions will differ from present hydrology.

In this study we investigate the potential of using stochastic hydrological forecasting with an incorporation of observed long-term trends in streamflow. The Monte Carlo method and the best trend line through regression are employed to generate a synthetic hydrology input for the future period (2020 through 2069), which is the time horizon needed in water resource planning. A constraint for limiting the number of wet and dry years that can cluster together is also incorporated in the process for generating the synthetic hydrology to maintain the observed patterns of wet and dry year clustering. In this study, we take Lake Meredith in the Canadian River basin (Fig. 1) as an example, because a clear downward trend has been observed at the Amarillo gauge, which is located upstream of Lake Meredith on the Canadian River. Finally,

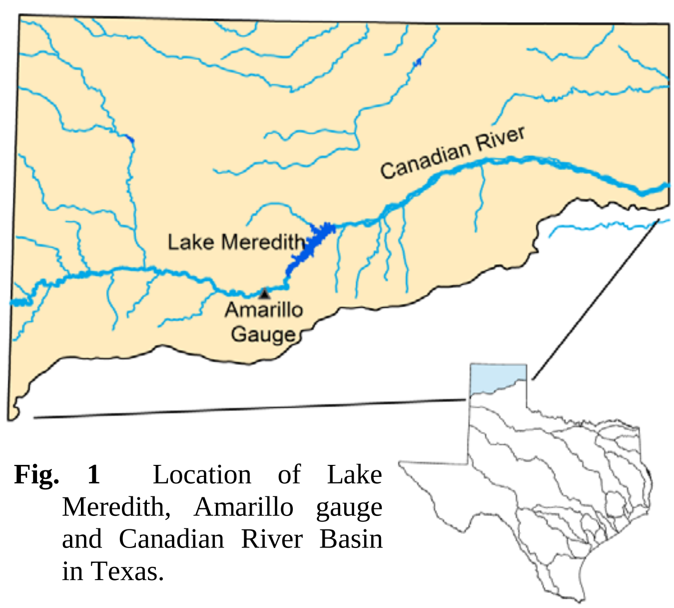

Fig. 1 Location of Lake Meredith, Amarillo gauge and Canadian River Basin in Texas.

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we forecast the available water supply for Lake Meredith over the next 50 year time horizon (*i.e.* for 2020, 2030, 2040, 2050, and 2060) at various given confidence intervals or certain criterion, such as 65-percent and 85-percent exceedance probabilities.

2. Methodology

As stated above, the existing WAM model is only applicable to the existing hydrologic condition from 1940s to 1990s, because the future hydrologic condition is not as the same as existing conditions. Therefore, for that specific future time (up to 2060 or beyond), we must extend the hydrologic input and the simulation period to a future time (up to 2060 or beyond), if we are to use the WAM model to compute firm yield from reservoir. In this case, the future naturalized streamflow, which is generated by precipitation, has a random nature. Therefore, the Monte Carlo method is applied to generate a synthetic hydrology. However, trend in the existing hydrology should also be considered if there is a clear trend, especially a non-linear trend. Moreover, we must consider the maximum length of continued dry or wet period, because naturally a dry period must finally end with a wet period, and vice versa. In other word, naturalized streamflow also has a cyclical nature (*i.e.* not pure random process). This factor affects reservoir firm yield, which is determined for drought conditions. If we inadvertently generate an extremely long dry period through the random selection process, an unrealistically lower firm yield would be generated. Therefore, a constraint of maximum dry period and maximum wet period is introduced in our random selection process, based on the available historical record. As an example in this study, future firm yields from Lake Meredith in the Canadian River Basin are simulated by TCEQ's WAM Model for the Canadian River Basin (Espey Consultants, Inc. 2002). The model has been updated by extending its hydrologic input data from 51 years (1948-1998) to 65 years (1948-2012) to obtain a better representation of the hydrology in the Canadian River Basin. The recent drought (2011-2013) event is included in this extended hydrology. Extending the hydrology also enables us to increase the population available for random sampling. The inflow to Lake Meredith is represented by the adjusted gauge flow (*i.e.* naturalized) at the U.S. Geological Survey gauge at Amarillo. Adjusted gauge flow refers to accounting for, and removing, diversions above the gauge.

Stochastic models, which are often known as time series models have been used in scientific, economic and engineering applications for the analysis of time series data (Barndorff-Nielsen *et al.* 1998; Srikanthan and McMahon 2000; U.S. Bureau of Reclamation 2003). Time series modeling techniques have been shown to provide a systematic empirical method for simulating and forecasting the behavior of uncertain hydrologic systems and for quantifying the expected accuracy of the forecasts (Machiwal and Jha 2006). If there is a systematic linear trend in seasonal inflow, this could be incorporated in the simulated time series (Ward *et al.* 2012). Streamflow at the Amarillo gauge has a non-linear recession trend. We, therefore, propose a new methodology for generating the synthetic hydrology that incorporates the non-linear trend. Steps for generating the synthetic streamflow and modifying the model for simulation are discussed below:

1. Analyze existing annual naturalized flows to see if there is an obvious trend. If there is a trend, make the best fit trend line and its formulation. In this case, we found the best fit (highest R-square value) curve is exponential (Fig. 2).

2. Find out the maximum length (year) of high flow and maximum length (year) of low flow by computing exceedance probability below 25-percent and above 75-percent, respectively (Fig. 3). These maximum lengths will be used in the synthetic process by random selection as a constraint to maintain the cyclic nature of naturalized flows. If the selected year exceeds the maximum limit,

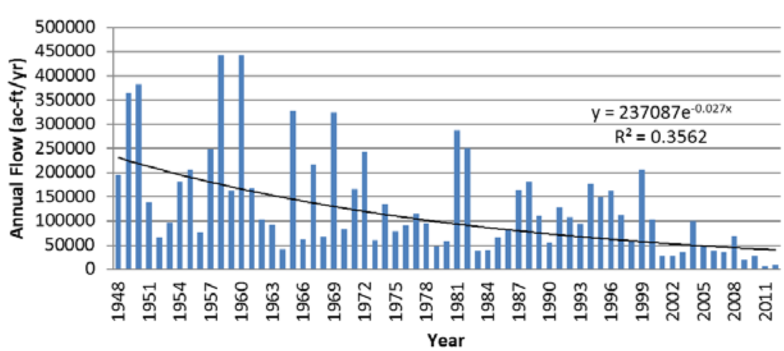

Fig. 2 Existing annual naturalized flows and its best fitted trend line at the Amarillo gauge.

it would be skipped and a year of different type will be selected to construct the synthetic hydrologic sequence. In this case, the maximum length for a clustering wet period is 3 years and 4 years for dry period (Fig. 3).

3. Select a year randomly from the existing naturalized flow to construct year by year the future flows till 2069 by following the trend line (or value of the slope for those years). This task is done using the following methodology:

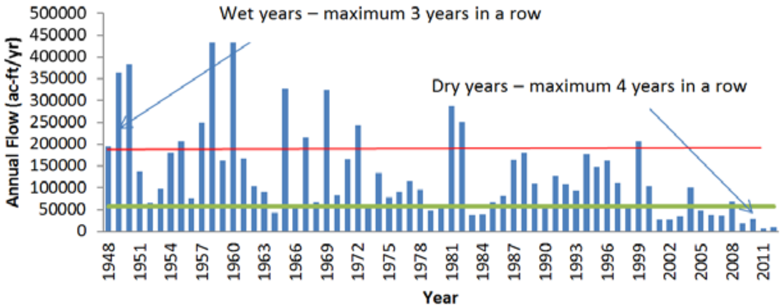

Fig. 3 Identify wet and dry pattern from existing flows.

3a. Randomly select a year (t_1) from the existing naturalized flow (Qt_1) and compute the naturalized flow (Qt_2) for a future year (t_2) (Fig. 4) by the formulation:

$$\mathbf{Qt_2 = (Vt_2 / Vt_1) * Qt_1}$$

where Vt_1 and Vt_2 are the value of trend line at year t_1 and t_2, respectively.

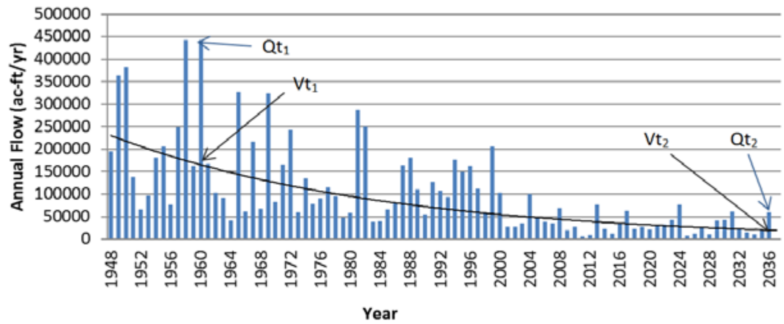

Fig. 4 Construct flow at future time (t2) by randomly selecting existing time (t1) and by using the above formulation.

3b. Repeat step 3a for next future year until all flows for the future years (up to 2069) are done.

3c. If the maximum length of 4-year dry period defined in step 2 is exceeded at step 3b, the 5th dry year is skipped until a different type (wet or neutral) of year's hydrology occurs. This will guarantee that the constructed hydrology does not exceed the known maximum length of drought. This step is important because too many years drought clustering together would be unrealistic and would lead to extreme low firm yield.

3d. To preserve the trend in the existing streamflow, the newly constructed synthetic dataset should be adjusted to ensure that the existing trend is maintained exactly. The original trend line may be altered a little bit (less than 1%) in the above random process. This adjustment is done by comparing the difference between the existing and new trend line for the period from the beginning year (*i.e.*, 2013) to the last year (2069) of new flows year by year. Then the differences are distributed to the month flows proportionally based on the flow of each month in the entire calendar year. After applying the differences, the original regression equation is preserved.

4. Repeat step 3 to make a series of 1000 natural hydrology input datasets. The decision to use 1000 input datasets is based on another study on the reliability of reservoir firm yield, which indicates that 500 datasets are sufficient for a convergence of firm yield mean value (Yang *et al.* 2017). Figure 5 shows the distribution of these 1000 simulated firm yields, which reveals a normal distribution.

5. Modify the model input file for the sediment condition at 2020, 2030, 2040, 2050 and 2060. Sedimentation in reservoir reduces its capacity and affects storage volume and gives lower firm yield. We use an elevational sedimentation rate, derived from volumetric surveys undertaken by the Texas Water Development Board in 1965 and 1995 (1,330 acre-feet per year or 0.15 percent of 1965 capacity), to construct the projected capacities and elevation-area-capacity rating curves of above planning decades for Lake Meredith (Zhu *at al.* 2018).

6. Run the modified model of 2020, 2030, 2040, 2050 and 2060 by using the newly constructed 1000 hydrologic dataset for the simulation periods, respectively. For each decade, 1000 firm yields are computed for Lake Meredith.

7. Analyze statistical properties of the computed 1000 firm yield results at each simulated decade (*i.e.*, 2040; Fig. 5). Results indicate that firm yields are normally distributed, so mean, median and standard deviation are derived per normal distribution. The exceedance probability of the computed 1000 firm yield results for each simulated decade is plotted too (Fig. 6).

8. Evaluate available water supply for each decade simulated by selecting the best criteria, such as an exceedance probability, a certain percentile, or confidence interval. In this experimental study, we selected Confidence Intervals, 99-percent, 95-percent, 90-percent, and 80-percent to examine the magnitude of the simulated firm yields for all decades designed.

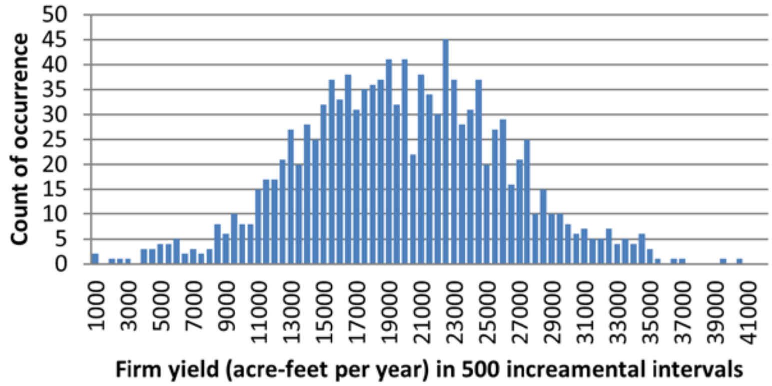

Fig. 5 Distribution of firm yields for result of simulation for 2040.

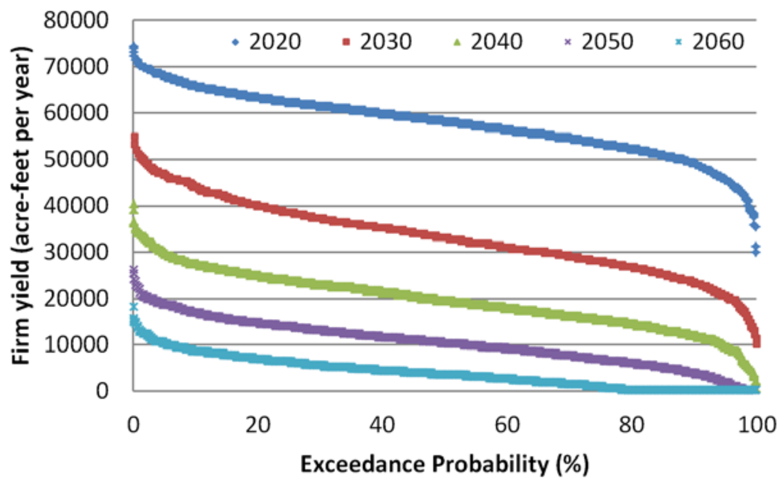

Fig. 6 Exceedance probability of firm yield for simulations for 2020, 2030, 2040, 2050, and 2060.

3. Preliminary results for Lake Meredith in Canadian River Basin

Results for Lake Meredith indicate that firm yield in the future decreases as the simulation period increases. The original TCEQ Canadian WAM (1948-1998) firm yield for Lake Meredith is 79,970 acre-feet per year at exceedance probability of 65-percent. The firm yield for 2010 (period of simulation is from 1948 to 2010) is 75,280 acre-feet per year (also bears 65-percent exceedance probability). If one does not want to change the current exceedance probability (65-percent), the simulated firm yield is approximately 55,390, 30,280, 17,040, 8,350, and 1,970 acre-feet per year for 2020, 2030, 2040, 2050, and 2060, respectively. Alternatively, at 85-percent exceedance probability, simulated firm yield is approximately 50,780, 25,180, 13,170, 5,040, and zero (0) acre-feet per year for 2020, 2030, 2040, 2050, and 2060, respectively.

Exceedance probability of firm yields in all simulated decades (2020, 2030,…..2060) are plotted in Figure 6. Results indicate that firm yield declines from 2020 to 2060. For planning purposes, a planner could set a certain exceedance probability limit as a standard (criterion) for selecting the firm yield. As indicated in Figure 6, a higher exceedance probability would lead to a lower firm yield and a cautious approach (i.e. avoiding over-allocation of available water supply) for water allocation in the future. However, one should avoid selecting too high an exceedance probability (meaning extremely lower firm yield) because it would result in unrealistically low water supply projections for the future. This could lead to unmet water demands in the future resulting in adverse socio-economic impacts. It could also result in water loss to evaporation if the reservoir water is not allocated for beneficial use during the non-drought periods.

A planner can also select a certain Confidence Interval for determining the future firm yield. A confidence interval is the probability that a value will fall between an upper and lower bound of a probability distribution. The lower bound is of interest to the designer or planner interested in adopting a cautious approach to water planning. For example, at the 99-percent Confidence Interval, the lower bound of firm yield is 57,051, 32,748, 19,109, 9,966, and 3,683 acre-feet per year for 2020, 2030, 2040, 2050, and 2060, respectively (Fig. 7). These are greater than the above mentioned firm yields at 65-percent and 85-percent exceedance probabilities. For some decades, simulated firm yields become larger with decreased confidence interval. For instance, at 99-percent Confidence Interval, firm yield is 57,051 acre-feet per year for 2020, while at 80-percent Confidence Interval, firm yield is 57,301 acre-feet per year for 2020. Table 1 provides some typical Confidence Intervals and their associated firm yields.

Table 1 Selected confidence intervals and their associated firm yield for decades from 2020 to 2060.

Key criterion		Firm yield (acre-feet per year) at given year				
		2020	**2030**	**2040**	**2050**	**2060**
Mean		57,551	33,338	19,569	10,336	3,943
Standard deviation		6,715	7,868	6,192	4,994	3,414
Median		58,105	33,145	19,475	10,315	3,520
Lower bound of given Confidence Interval (percent)	**99**	57,051	32,748	19,109	9,966	3,683
	95	57,171	32,888	19,219	10,056	3,753
	90	57,231	32,958	19,269	10,096	3,783
	80	57,301	33,048	19,339	10,146	3,813

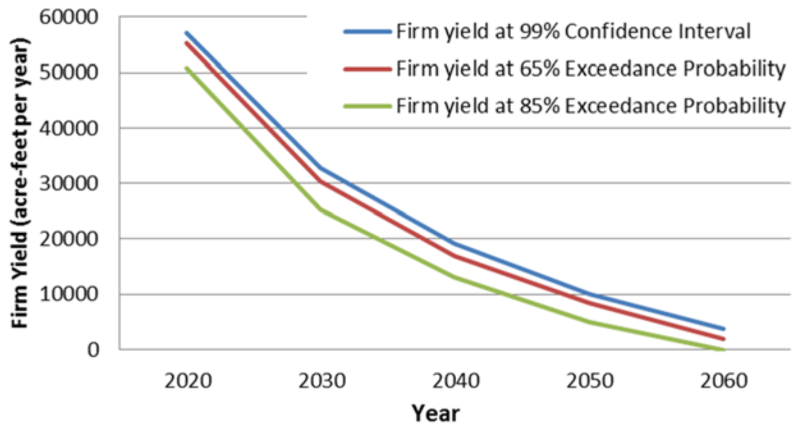

Fig. 7 Simulated firm yields for decades 2020 through 2060 at 99-percent Confidence Interval, 65-percent Exceedance Probability and 85-percent Exceedance Probability.

In this particular study, it appears that exceedance probability around 80-90 percent is a reasonable selection of future firm yield, because the slope drops sharply on curves of firm yield vs. exceedance probability in Fig. 6 above 90 percent exceedance probability, meaning the occurrence is poor (probability of occurrence is low). If we pick exceedance probability at a higher percent (*i.e.* 99 percent), it would lead to a lower firm yield picked which may be never occurring. If we pick a lower exceedance probability, it means higher firm yield but it would cause over allocation and unmet shortage in the future. In this particular case, it appears that firm yields at around 85 percent exceedance probability is safe enough for planning purpose (green line in Fig. 7). Confidence Interval is another criterion that can be used in this type of stochastic study. The higher Confidence Interval means higher probability for the corresponding firm yield in this stochastic forecasting. A normal distribution with known mean and standard deviation of simulated firm yield is tested in this study. It appears firm yield does not change significantly from mean value with increased Confidence Intervals (Table 1).

4. Conclusion and recommendation

As an experimental study, we combine a stochastic approach (Monte Carlo method) and the incorporation of trend to forecast firm yield for the 2020, 2030, 2040, 2050, and 2060 planning decades for Lake Meredith in Canadian River Basin. A constraint (limit of dry and wet periods) for maintaining the cyclic nature of natural hydrology is also incorporated in the synthetic processes. Simulated results indicate that firm yields will decline significantly in future decades from 2020 to 2060. This can be a good reference for water resource planning. It appears that, with a sufficient population for sampling and proper consideration for future trends, simulated firm yields reveal a clear statistical distribution for planners to determine future projected water supply.

Based on this study, we believe that the 2016 Regional Water Plan for the Panhandle Region (Freese and Nichols, Inc. 2016) can be improved in future planning cycles. The 2016 Plan gave a constant (static) estimated firm yield (37,505 acre-feet per year), safe yield (32,928 acre-feet per year), and zero available supply from 2020 to 2060. Safe yield is safer than firm yield because the 2016 Plan assumed a longer drought than the drought of record. Lake Meredith is an important source of water supply for 11 cities, including Amarillo and Lubbock in the Texas Panhandle. Drought in recent years had significantly affected the storage in this reservoir and drawn attention to water supply issues in the region. It forced the Canadian River Municipal Water Authority to develop groundwater resources from the Ogallala Aquifer to meet their supply shortage. Therefore, earlier planning for the worst case scenario is vitally important to overcome potential future shortages. This study demonstrates a methodology that could be applied to water planning in Texas to improve the reliability of water availability estimates over the next fifty year planning horizon. The study is particularly applicable to other locations in the state that have declining streamflow trends. Modifications to the methodology presented here would be needed if it is to be applied to locations that do not have declining streamflow trends in the observational record.

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