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**EDITED BY**

Sajjad Ahmad, Ph.D.
Regan Murray, Ph.D.

ASCE
EWRI
ENVIRONMENTAL & WATER RESOURCES INSTITUTE

# Extension of Naturalized Flow Using Linear Regression

John Zhu, Ph.D., P.G., M.ASCE[1]; Nelun Fernando, Ph.D.[2]; and Carla Guthrie, Ph.D.[3]

[1]Texas Water Development Board, Austin, TX. E-mail: john.zhu@twdb.texas.gov
[2]Texas Water Development Board, Austin, TX
[3]Texas Water Development Board, Austin, TX

## ABSTRACT

Naturalized flow, which is streamflow representing natural hydrology, is one of the hydrologic input datasets for Texas' water availability models (WAMs) that are used for the water rights permitting process, regional and statewide water planning, and other water management activities in Texas. The existing naturalized flow input for most of these models covers the period extending from the 1940s to the 1990s. Given that some river basins in Texas have, in recent years, experienced record low streamflow associated with the 2010–2015 drought event, having updated naturalized flows is essential for reliable estimates of water availability from surface water sources. We find that for some river basins, or some part of a river basin, naturalized flows have a close correlation with observed flows. Furthermore, monthly naturalized flow in upstream watersheds and downstream watersheds, and vice versa, are also correlated, since streamflow under natural condition typically increases gradually downstream. Adjacent watersheds may also have similar flow characteristics. Therefore, it is relatively easy and fast to extend the WAM's naturalized flow input using a regression method. We introduce a simple and convenient methodology for updating naturalized flows using linear regression between historical gauged flow and existing naturalized flow, between upstream and downstream naturalized flow, and between naturalized flow in adjacent watersheds. Naturalized flows updated using this methodology can be used as an auxiliary dataset for water planning purposes until the Texas Commission on Environmental Quality (TCEQ) releases official updated naturalized flow datasets for the state. We present an evaluation of the extended naturalized flows for the Canadian River Basin WAM and Sulphur River Basin WAM where the datasets used to develop the regression equations are highly correlated (correlation coefficient, $R>0.93$ and standard error $<0.12$). A comparison of extended naturalized flows for the Sulphur River Basin WAM derived using our methodology with the recently-released official update to the Sulphur River Basin WAM indicates that the average monthly mean flow is only 0.3% higher than the official average at a selected control point (i.e., model node). Simulated firm yield and overall water right reliability are within 2% of the same metrics derived using the official dataset. This result provides a validation of our dataset and justification for using such extended naturalized flows as auxiliary datasets for research and surface water resources planning in Texas.

## INTRODUCTION

Texas' Water Right Analysis Package (WRAP) System Models (known as Water Availability Models or WAM) were initiated following the passage of Senate Bill 1 in 1997 by the Texas Legislature in support of the water rights permitting process, regional and statewide water planning, and other water management activities in Texas. Official WAMs are maintained by the Texas Commission on Environmental Quality (TCEQ) and consist of 20 individual models (Fig.1), which all together represent the 23 river basins in Texas. Hydrologic input data for the original models include estimates of naturalized streamflow and net reservoir evaporation for a 50- to 60-year period, beginning in the 1940s and ending in the 1990s, depending on the basin. Naturalized streamflow represents the natural hydrology and is estimated by adjusting historical gauged streamflow data to remove the impacts of reservoir construction, water use, and other human activities. Simulated WAM results have served as the basis of water supply planning and have informed Texas' State Water Plans since 2002.

**Figure 1 Water Availability Models (WAMs) for Texas River and Coastal Basins**

Prior to 2011, the period of record used for the input hydrologic data (known as the "simulated period") was considered to be adequate because it included the most significant recorded drought in Texas—the 1950s drought-of-record or other specific drought periods before 2000 in specific regions in Texas. However, following another significant drought period from 2010–2015, in which 2011 was identified as the single worst one-year drought in Texas, streamflow and reservoir storage in some river and sub-river basins experienced new record low levels. Consequently, there is a need for extending the hydrologic input data so that recent record drought events are incorporated in the WAM runs (Texas House Committee on Natural Resources, 2018), thus allowing for a better estimation of water availability for surface water resource planning in Texas.

There are several methods for producing or extending a hydrologic input dataset. The existing naturalized flow input dataset for the WAMs [i.e., TNRCC, 2001] were constructed by adjusting observed stream flow to remove the influence of human water management and use. Typical adjustments include correcting for water supply diversions, return flows, changes in reservoir storage, and precipitation and evaporation over a reservoir surface. Although this method is considered the most reliable method, it requires detailed datasets for the above listed items and is time-consuming. This study, therefore, evaluated other available methods to identify an effective and time-efficient method to extend the datasets for Texas.

The California Department of Water Resources (2016) updates their naturalized streamflow using historical snow melt record through the Cooperative Snow Surveys Program. Unfortunately, this method does not work in Texas, as watersheds are not fed by permanent or seasonal snowpack. Prairie and Callejo (2005) used the Colorado River Simulation System (CRSS) (run using RiverWare software) to systematically (re-) construct historical naturalized flow. However, the required water usage data can be incomplete or delayed by several years, limiting this method’s applicability in Texas. Wurbs and Kim (2008) developed a procedure to adjust gauged streamflow corresponding to the difference between naturalized (unregulated) flows and regulated flows using a simulation with a modified current water use/diversion dataset (Kim et al., 2011). Although the method has been applied to the Brazos River Basin WAM, it has not been widely used by others, because it requires recent water use/diversion datasets, which are not easily obtainable. Additionally, the accuracy of the results depends upon the accuracy of the flow difference, rather than the accuracy of the naturalized and regulated flows themselves. This method is also time-consuming. Wurbs and Chun (2012) then developed another method to generate naturalized flows by using concurrent monthly precipitation and lake evaporation data compiled by the Texas Water Development Board (TWDB). Several parameters were calibrated through automated enumeration and gradient search optimization algorithms. Additional parameters were adopted for more adjustments. This method assumes that naturalized flow is purely a response to monthly precipitation and lake evaporation. Studies in the Texas Panhandle and the Upper Colorado River Basin in Texas have identified declines in streamflow in recent years independent of changes in precipitation (TWDB 2011, TWDB 2017, and TWDB, 2019). Therefore, calibrated naturalized flow may be over-estimated. Furthermore, this method has not been widely used by others.

## METHODOLOGY

This study takes advantage of the existing ~50-year period of record of naturalized flows that have been developed for Texas river basins to identify hydrologic correlations that provide information on the (1) relationship between naturalized flow and historical observed flow; (2) the relationship between the existing naturalized flow at upstream and downstream locations, and vice versa; and, (3) the relationship of existing naturalized flows in adjacent watersheds. Once these relationships are identified, new estimates of naturalized flow can be generated for an extended period of record.

**Gauged-to-Naturalized Flow Regression method:** In many upstream and rural locations in Texas, naturalized flows in the existing WAMs have a close correlation with gauged streamflow, especially when there are no upstream reservoirs. In this approach, human uses/diversions, if they exist, are relatively small and/or stable, so fluctuations in naturalized flow are similar to that of observed streamflow. The assumption is that naturalized flow and gauged streamflow are highly correlated. If so, the naturalized flow for the extended period can be estimated using a regression equation and current observed streamflow data available from the U.S. Geological Survey (USGS). Moreover, this correlation may be applicable to gauged locations at lower reaches in the basin under conditions such as, when diversions are small compared to total streamflow, when reservoirs remain consistently full (inflow equals to outflow), and when withdrawals and return flows balance out to minimize the net effect of diversions.

The regression equation used is:

$$Q_{nat} = a * Q_{obs} + C \tag{1}$$

Where, $Q_{nat}$ is the naturalized flow to be computed; $Q_{obs}$ is observed flow; and, $a$ and $C$ are slope and constant (intercept), respectively.

If there is little or no human influence, observed flow is naturalized flow, and the equation can be simplified to: $Q_{nat} = Q_{obs}$. The intercept in Equation (1) can be either positive or negative and is retained to preserve the original relationship, especially when it is relatively small (less than 5 percent of mean flow). A positive intercept may represent a relatively steady diversion (such as municipal diversion). A negative intercept occurs when naturalized flow is less than observed flow for reasons such as, the existence of return flows from other sources (*e.g.*, irrigation or municipal return flows sourced by groundwater pumping), or if the existing naturalized flow is not fully naturalized. For an unreasonable intercept, such as negative value at a location with little human impact or when it is greater than five percent of extended naturalized flows, we force the regression through the zero intercept. In which case, the equation is simplified to: $Q_{nat} = a * Q_{obs}$.

**Naturalized-to-Naturalized Flow Regression method:** Streamflow under natural conditions usually increases gradually from upstream to downstream. Therefore, there is a good correlation between the streamflow from upstream to downstream, and vice versa, especially on a monthly timestep as is used in the WAMs. In fact, this method was used extensively in the construction the original/existing naturalized flows, when observed flows were not available (TNRCC, 2001). The regression equation is similar to Equation (1):

$$Q_{nat1} = a * Q_{nat2} + C \tag{2}$$

Where, $Q_{nat1}$ is the naturalized flow to be estimated/extended; $Q_{nat2}$ is naturalized flow at an upstream or downstream location or in a nearby watershed and has been extended; and $a$ and $C$ are slope and constant (intercept), respectively. Obviously, the prerequisite for this method is that naturalized flow at a given location ($Q_{nat2}$) has been extended before naturalized flow at another location ($Q_{nat1}$) can be extended, using the regression on the existing datasets.

The naturalized flow ($Q_{nat2}$) on the right side of Equation (2) may be a single naturalized flow or a combination of several naturalized flows, depending on the geography of the basin. For example, $Q_{nat2}$ may be derived by adding together known estimates for two upstream locations, thus representing where the system forms one stream. The intercept in Equation (2) can be either positive or negative and is retained to preserve the original relationship, especially when it is relatively small (less than 5 percent of mean flow). However, extra attention must be given to negative values of the intercept as this may indicate that the computed naturalized flow ($Q_{nat1}$) is smaller than known naturalized flow ($Q_{nat2}$), such as could occur if $Q_{nat1}$ is located upstream of $Q_{nat2}$. If the negative intercept is relatively small and does not generate many negative naturalized flows in the extended period, the negative intercept may be retained for a better estimation with any negative values of extended naturalized flow adjusted to zero. However, due to inaccuracies in the existing naturalized flows, an unreasonably large negative intercept may occur. In such instances, we force the regression through the zero intercept, simplifying Equation (2) to $Q_{nat1} = a * Q_{nat2}$ . We find that a common cause for a negative intercept of the regression line is an inaccuracy in the existing naturalized flow.

In this study, the application of the gauged-to-naturalized flow regression Equation (1) is the preferred or primary method. However, using known and extended naturalized flow to generate new naturalized flow for nearby control points (model nodes) by Equation (2) is necessary (but secondary) either when observed flow has been severely impacted or when there is no observed flow for the past and or recent period. As noted above, regression Equation (2) was originally used to estimate existing naturalized flows from available upstream or downstream naturalized flows in the same watershed/basin, when suitable gauged streamflow data were unavailable. In some rare cases, suitable upstream or downstream naturalized flow may not be available. Then, we have to select available naturalized flow from adjacent watersheds with similar climate, geographic, and geologic conditions. Although this method can be easily explained by comparative hydrology, it is deemed as our last choice for generating new naturalized flows.

**Criteria for Selection:** The regression methodology applied was selected based on goodness of fit, which was determined based on the correlation coefficient (R), the standard error (SE) of the slope coefficient, and p-value. The p-value is the two-sided p-value for a hypothesis test whose null hypothesis is that the slope is zero. If the regression is based on data from within the same river basin, the correlation coefficient should be greater than 0.9; however, if the regression is based on data from adjacent watersheds, the R value may be greater than or equal to 0.85. The standard error (SE) of the slope coefficient should be less than 0.1. In some rare cases when there are heavily human-influenced locations, our criteria were relaxed such that only one of the above criteria must be met. We note in our discussion a few exceptions to these rules. In our cases, p-value must be statistically highly significant ($p < 0.0005$).

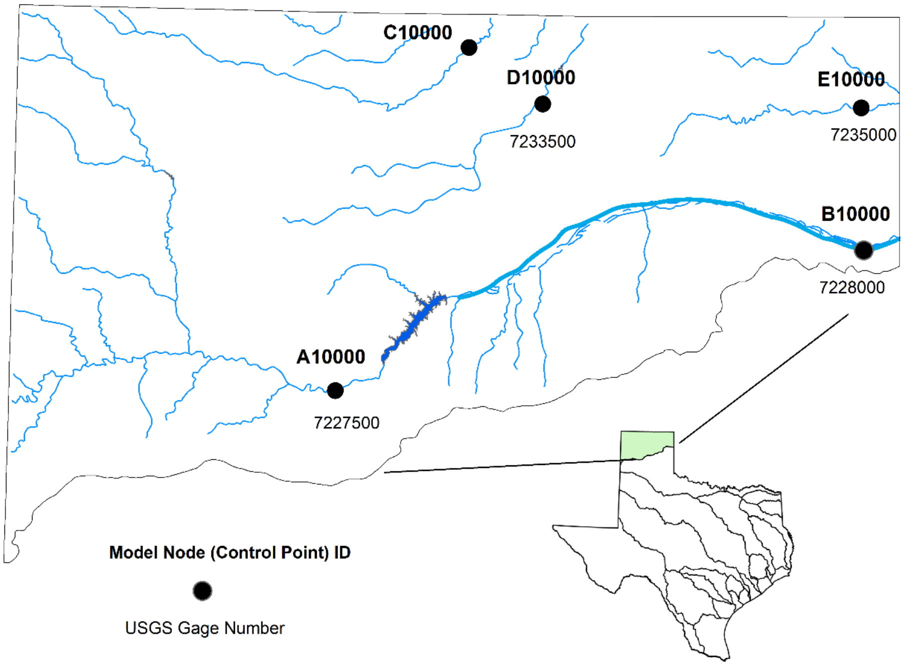

**Figure 2: Location of control points (*in bold*) in the Canadian River WAM and corresponding USGS Gauge Stations (*7-digit numbers*) in the Canadian River Basin.**

We selected Canadian River Basin WAM and the Sulphur River Basin WAM to apply the above methodology.

**Canadian River Basin:** The Canadian River Basin WAM (Espey Consultants, Inc., 2002) was updated by extending the hydrologic input data (naturalized flow and net lake evaporation) from 51 years (1948 – 1998) to 71 years (1948 – 2018). There are five primary control points (model nodes) in this WAM (Fig. 2).

Naturalized flows at three control points (A10000, D10000, and E10000) were extended using the gauged-to-naturalized flow regression methodology ($R > 0.99$ and $SE < 0.00001$ for each control point using USGS gauge data at stations 7227500, 7233500, and 7235000, respectively; Table 1). Control point B10000 (corresponding to USGS gauge station 07228000, Canadian River at Canadian, TX) is heavily influenced by human activity since the completion of Sanford Dam (Lake Meredith) in 1965. Extended naturalized flow for this control point was therefore based on the naturalized-to-naturalized flow relationship derived at the upstream control point, A10000, which has been extended from observed flow. There is no observed flow data available for control point, C10000 so naturalized flow was extended using the relationship derived for control point, D10000, in an adjacent watershed.

**Table 1: Location of WAM control points for which extended naturalized flows were developed for the period 1998 – 2018 in the Canadian River basin. Results are based on the relationship of USGS Gauge Station data and existing naturalized flows for the period of record shown. p-values for all regressions are smaller than 0.0005**

| WAM Control Point | USGS Gauge Station | Regression Equation for Extending Naturalized Flow | Period of Regression | Slope | Intercept (cubic meter) | R | SE |
|---|---|---|---|---|---|---|---|
| A10000 | 7227500 | Equation (1) | 1948-1998 | 1.001 | 81,039 | 1.0 | 0.000 |
| D10000 | 7233500 | Equation (1) | 1948-1978 | 1 | 5,180 | 1.0 | 0.000 |
| E10000 | 7235000 | Equation (1) | 1962-1998 | 0.999 | 740 | 1.0 | 0.000 |
| B10000 | 7228000* | Equation (2)<br>(A10000 to B10000) | 1948-1998 | 1.174 | 894,149 | 0.941 | 0.017 |
| C10000 | no data | Equation (2)<br>(D10000 to C10000) | 1948-1998 | 1.44 | 0 | 0.97 | 0.013 |

*USGS Gage Station 7228000 on the Canadian River is influenced by the upstream reservoir; therefore, naturalized flows at control point B10000 is developed from regression with upstream naturalized flow at A10000.

**Sulphur River Basin WAM:** The Sulphur River Basin WAM was officially updated by the TCEQ in 2019 to include updated hydrologic datasets (naturalized flow and net reservoir evaporation; TCEQ, 2019). The update extended the simulation period from 57 years (1940 – 1996) to 78 years (1940 – 2017). To validate the regression methodology described herein, we conducted an extension of the naturalized flows using methods outlined above.

There are six primary control points in the existing TCEQ WAM (Fig. 3). Among these six primary control points, four control points (A10, B10, C10, and D10) demonstrate good correlation between naturalized flow and observed flows ($R > 0.963$ and $SE < 0.012$ for each control point using USGS gauge data at stations 7342500, 7343000, 7343200, and 7343500, respectively; Table 2). The remaining two control points are either heavily influenced by reservoir construction (E10) or do not have gauged flow available (F10). For these two locations, we derived the naturalized-to-naturalized flow relationship based on an upstream control point (C10 and E10, respectively).

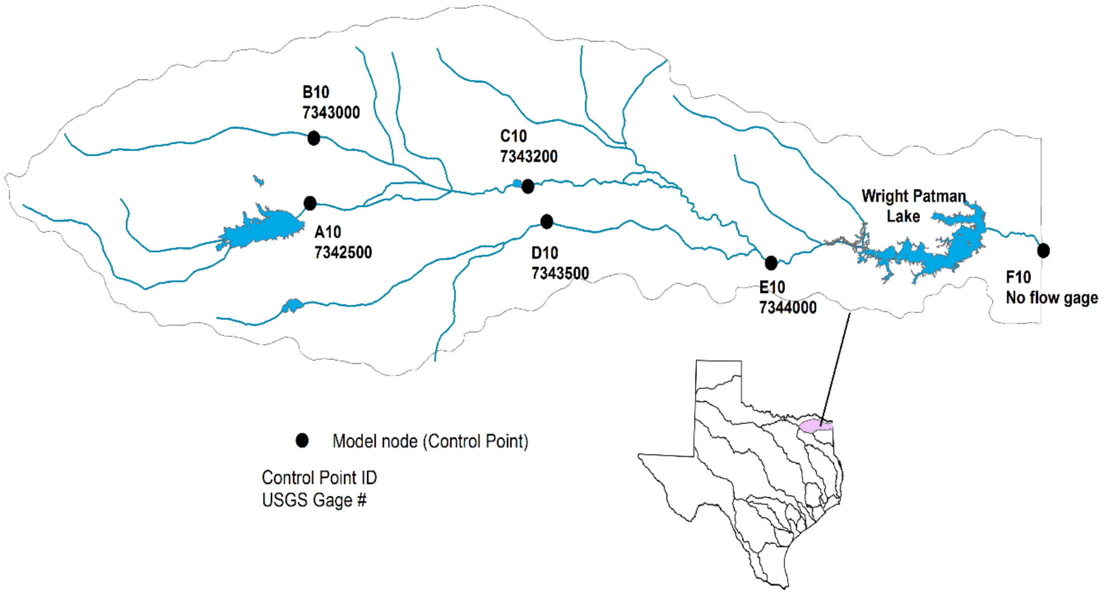

**Figure 3: Location of control points (*first identifier in bold*) in the Sulphur River Basin WAM and corresponding USGS Gauge Stations (*7-digit numbers in second line*) in the Sulphur River Basin.**

**Table 2: Location of WAM control points for which extended naturalized flows were developed for the period 1997 – 2018 in the Sulphur River Basin. Results are based on the relationship of USGS Gauge Station data and existing naturalized flows for the period of record shown. p-values for all regression are smaller than 0.0005.**

| WAM Control Point | USGS Gauge Station | Regression Equation for Extending Naturalized Flow | Period of Regression | Slope | Intercept (cubic meter) | R | SE |
|---|---|---|---|---|---|---|---|
| A10 | 7342500 | Equation (1) | 1942-1995 | 0.984 | 0.0 | 0.964 | 0.011 |
| B10 | 7343000 | Equation (1) | 1950-1996 | 1.000 | 10,978 | 1.000 | 0 |
| C10 | 7343200 | Equation (1) | 1957-1996 | 1.002 | 0.0 | 0.995 | 0.005 |
| D10 | 7343500 | Equation (1) | 1950-1996 | 0.99 | 0.0 | 1.000 | 0.001 |
| E10 | 7344000 (heavily interrupted) | Equation (2) (C10 to E10) | 1940-1996 | 1.901 | 0.0 | 0.932 | 0.027 |
| F10 | no data | Equation (2) (E10 to F10) | 1940-1996 | 1.260 | 0.0 | 0.993 | 0.006 |

## RESULTS AND VALIDATIONS

Using the extended period of naturalized flows and updated net lake evaporation data for the period 1998 – 2018 (Fig.4), we simulate 71 years of water availability conditions with the

Canadian River basin WAM. The updated record includes the most-significant drought of recent years in the Panhandle region of Texas.

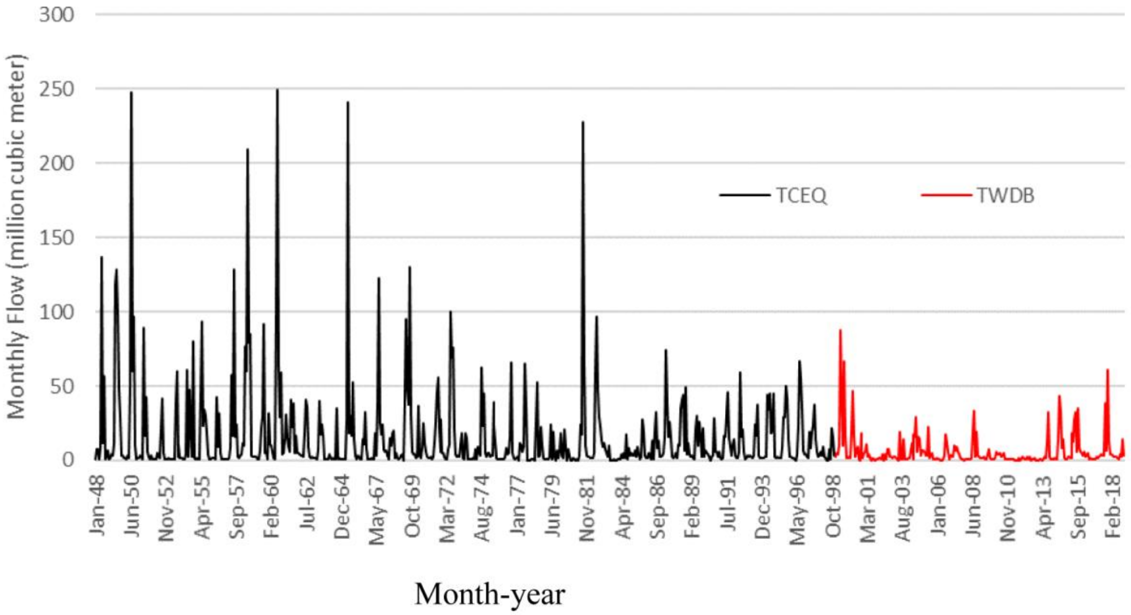

**Figure 4: Extended naturalized flow (*red*) provides significant addition to existing naturalized flow (*black*) for control point (model node), A10000 (@USGS Amarillo gauge) in the Canadian River Basin**

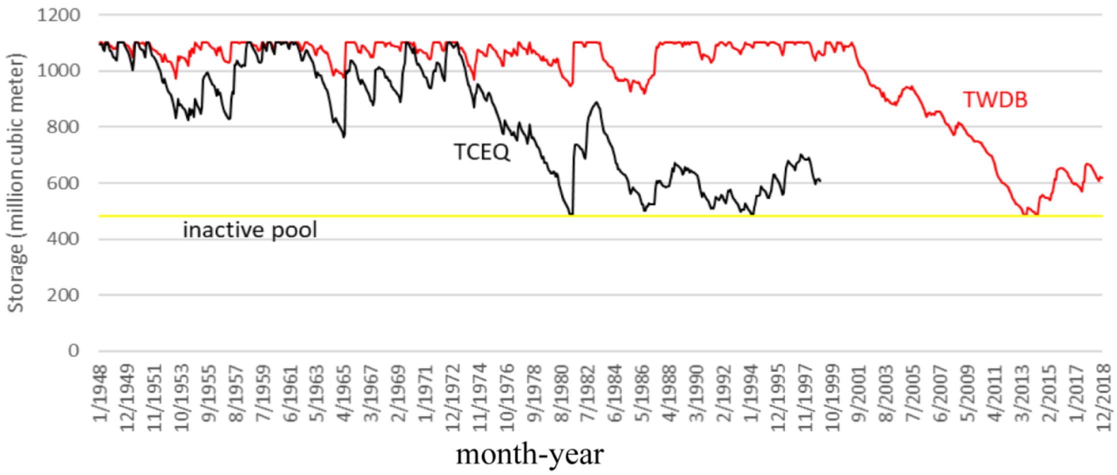

**Figure 5: Storage in Lake Meredith by firm yield diversion under the TCEQ's 51-year hydrologic input (*black*) and under TWDB's extended 71-year hydrologic input (*red*)**

Simulation results from the extended model (Canadian WAM) indicate that the most recent drought (2001 to 2013) is the worst since 1948. When the extended period is included in the simulation, the overall volumetric reliability of water rights decreases from 71.89%, as derived with the existing Canadian WAM which covers a 51-year period (1948 – 1998), to 56.27%. The firm yield — that is the maximum amount of water a reservoir can supply annually during a repeat of the worst drought experienced in the area of concern — of Lake Meredith decreases from 98.64 million cubic meters per year (79,970 acre-feet per year) to 18.53 million cubic meters per year (15,020 acre-feet per year). The periods determining the firm yield are also changed from 1973-1981 to 2001-2013 (Fig. 5). The simulation results indicate that it is necessary to extend the existing naturalized flow to recent years to capture the recent drought, which is the worst drought in the instrumental record for the Canadian River Basin.

Taking the WAM control point (i.e., model node) E10 in the Sulphur River Basin, as shown in Figure 6, naturalized flows extended using the regression method (*red line*) for control point E10 are consistent with the official TCEQ dataset (*black line*) during the period 1997 – 2017. Average monthly flow using the regression method is 172.69 million cubic meters (140,006 acre-feet), while average monthly flow using the official TCEQ estimate is 172.12 million cubic meters (139,537 acre-feet) during this period. Thus, the average monthly flow derived using the extended naturalized flow is only 0.3% higher than the official monthly average flow.

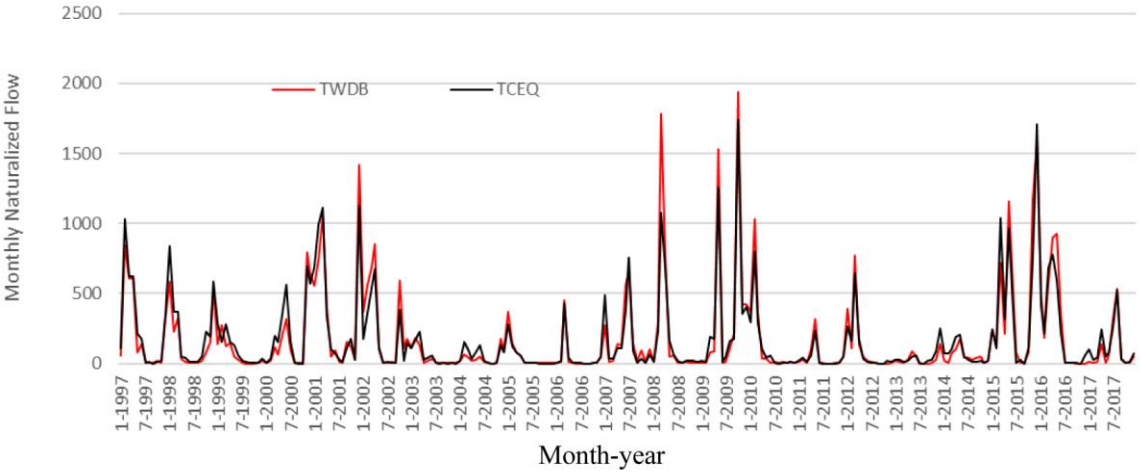

**Figure 6: Regression-based extended monthly naturalized flow (million cubic meter) (*red*) as compared to the official TCEQ dataset (*black*) for control point, E10 (upstream of Wright Patman Lake) in the Sulphur River Basin.**

Using the Sulphur River basin WAM to calculate reservoir firm yield for Wright Patman Lake, also shows good correspondence between the two methods for estimating naturalized flows. Firm yield simulated by using the naturalized flow from regression method is 427.73 million cubic meters per year (346,770 acre-feet per year) in comparison to that from the TCEQ method (436.65 million cubic meters per year or 354,000 acre-feet per year), or about a 2% difference. Prior to either update of the naturalized flows (when the period of record simulated was (1940 – 1996), the firm yield was 578.86 million cubic meters per year (469,290 acre-feet per year), indicating the importance of updating naturalized flows to capture significant historical hydrological conditions, or recent drought. The period for determining the firm yield from full to empty (aka, critical period) also is the same for these two naturalized flow datasets (Fig. 7). Reservoir storage simulated using the Sulphur River Basin WAM with extended naturalized flows that were developed using the regression method (Fig. 7, *red*) generally exhibits less storage between 1996 – 2017 than the updated TCEQ WAM (Fig. 7, *black*). However, the period determining the firm yield where storage from full to empty is almost the same and both models simulate reservoir storage at empty in August 2006. The overall water right volumetric reliability simulated by using naturalized flow from the regression method is 96.3% in comparison to 98.0% simulated by the updated TCEQ WAM, or a 1.4% difference.

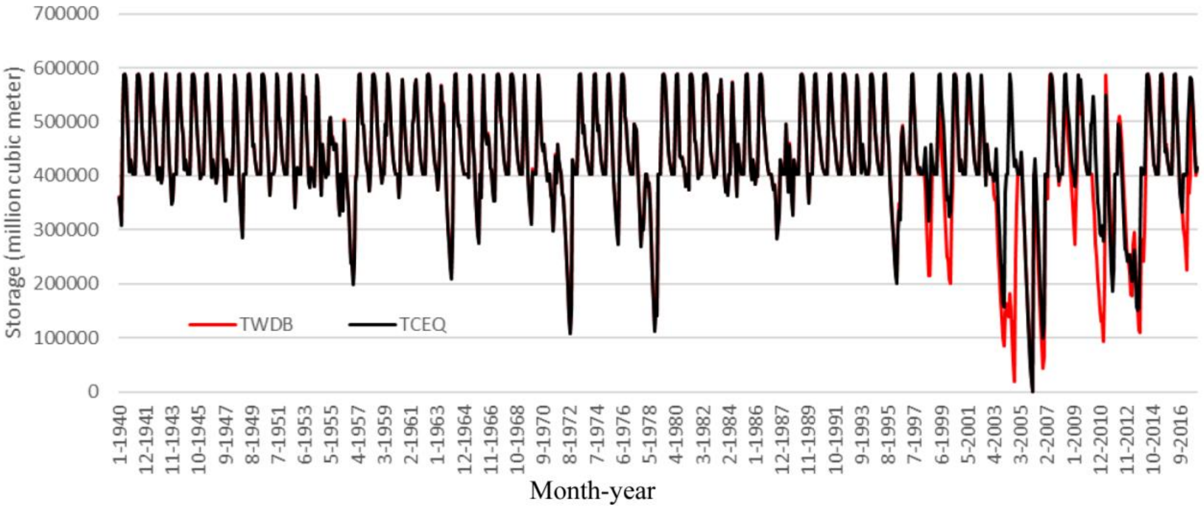

**Figure 7: Comparison of storage in Wright Patman Lake simulated under the firm yield condition using the regression-based extended naturalized flows (*red*) at E10, as compared to the updated TCEQ naturalized flow at E10 for the Sulphur River Basin (*black*) .**

## CONCLUSIONS

Updated hydrologic input dataset for water availability model is important, especially for drought-prone Texas. We demonstrated in this study that existing naturalized flow can be easily extended through linear regression with the existing dataset. These datasets include historic observed or gauged flows, and existing naturalized flows from nearby or adjacent watersheds. This regression method is particularly useful or applicable to river basins where the influence of human activity is minimal and naturalized flows are closely correlated with observed (gauged) streamflow. The method is also effective when a basin is partially interrupted by human activities. Under this situation, we can use the correlation between naturalized flows from upstream to downstream, and vice versa, since monthly naturalized flow from upstream to downstream (or vice versa) tend to be closely correlated. Once extended naturalized flow is created for a control point, using regression between existing observed flow and naturalized flow in a basin, other naturalized flows either downstream or upstream in the same basin or in an adjacent watershed can be generated by regression between the naturalized flows. Hence, the regression method can be useful for extending naturalized flow datasets using observed and existing naturalized flows within a watershed or an adjacent watershed for the entire basin. The method can be continuously or repeatedly used annually for the timely extension of naturalized flows. Using python programming tools, it is relatively easy and fast to extend the hydrologic inputs for many river basin WAMs in Texas.

As demonstrated with Canadian River Basin, extended naturalized flows are extremely useful for discovering new critical drought conditions. The differences in simulated firm yield and water right reliability, computed using the extended naturalized flows from the methodology we demonstrate above and the official version of naturalized flows for the Sulphur River Basin, are less than two percentage points. This result indicates that accurate naturalized flows for the Sulphur River Basin can be produced using our methodology.

We intend to extend the WAM hydrologic input data (i.e., naturalized flow and net reservoir evaporation) for most river basins in Texas through 2019 so that we can provide a current and reliable data set on surface water availability for water resources planning purposes. These datasets can be used for planning purposes until the TCEQ releases official extended naturalized flows for all river basins in Texas. For heavily influenced river basins or sub-basins (such as the Lower Colorado River basin or Lower Brazos River basin) in Texas, the methods proposed herein may not be suitable, and we continue to investigate a suitable method for estimating naturalized flow in recent years. Fortunately, local authorities in both these basins have extended the respective hydrologic input series to 2017 using official methods to meet their water management needs.

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