

Changing Hydrology and Impacts on Water Planning In the Highland Lakes Watershed, Central Texas

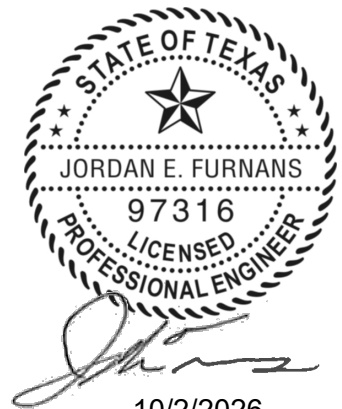
Or

“Would Central Texas have sufficient water supplies if current rainfall patterns equaled those from the 1950s Drought?”

Technical Report By:



Jordan Furnans, PhD, PE, PG
Principal Engineer & Hydrogeologist
Windward Water Resources Engineering & Geoscience, PLLC
Jordan@Windward-Water.com
512-736-6485



10/2/2026
TBPE Firm #28401

Supported By:



October 2, 2026

Would Central Texas have sufficient water supplies if
current rainfall patterns equaled those from
the 1950s Texas Drought?

Notes:

Windward Water Resources Engineering & Geoscience (“Windward Water”) is responsible for the technical content of this report, and the Central Texas Water Coalition (CTWC) contributed to forming and developing the technical content.

A draft version of this report was reviewed by three professionals and recognized experts in water resources engineering in Texas. Their comments, ideas, and suggestions contributed to and strengthened the final manuscript. The reviewers provided valuable technical feedback; however, responsibility for the statements, methods, interpretations, and conclusions presented in this report remains solely with the author.

Table of Contents

Acknowledgements	2
Technical Abstract	3
1. Introduction and Purpose	5
2. Rainfall on the Highland Lakes Watershed	10
PRISM Data Analysis	23
3. Analysis of Inflow Data	26
4. Watershed Productivity – Capture Rate Analysis	28
5. Naturalized Flows, Rainfall, and Small Ponds	35
6. Water Availability Modeling & Capture Rate Adjustments	41
Application of Naturalized Flow Adjustments	41
Method #1 – Simple Reduction in Dry Years	46
Method #2 – Direct Year to Year Comparison	46
Method #3 – Random Adjustments within a Defined Range	48
Method #4 – Median Capture Rates by Rainfall Category	49
7. WAM Modeling Results	50
Firm Yield Modeling	50
LCRA 2032 WMP Modeling	53
8. Conclusions & Implications	54
Implications for Water Management	56
9. Recommended “Next Steps”	57
Recommended Study #1 – Highland Lakes Safe Yield Analysis	57
Recommended Study #2 – Rainfall-Runoff Analysis to assess small pond affects	58
Recommended Study #3 – Rainfall Intensity Analysis	58
Recommended Study #4 – Evaporation Rate Change Analysis	59
10. References	61

Acknowledgements

This report has been under development for as long as the Central Texas Water Coalition (CTWC) and I have collaborated to better understand water management policies in Texas. Since 2012 we have been continuously researching, debating, and developing ideas that we believe result in better water management policies for the Highland Lakes region. This study benefited from the time, expertise, and support of many individuals. I would especially like to recognize several whose passion, dedication, and contributions helped make this work possible:

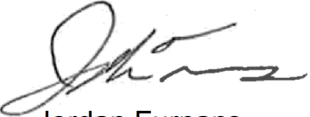
- **David Lindsay** – Dave has put in enormous effort and time toward understanding and analyzing the water supplies for Central Texas, in his roles as a concerned citizen, a Board member of CTWC, and through his years of service in the Region K water planning group activities. With his chemical engineering and business experience, Dave brings new ideas and perspectives into the water world, along with an ability to explain difficult water concepts in comprehensible ways. Our interactions over the years have directly led to the concepts discussed in this report, and Dave's insights have been invaluable.
- **Dr. Bill McNeese** – Dr. McNeese is the founder and developer of SPC for Excel, an analysis tool that CTWC has used over the years to demonstrate how recent low inflows are anomalous and potentially indicative of process changes. This work has led to the development of many of the concepts presented in this report, including the rainfall analyses and development of capture rates.
- **Shaun Comfort, MD** – Dr. Comfort brought his medical expertise and statistical knowledge to CTWC discussions and demonstrated how CUMSUM statistical analyses support the inflow trend observations from SPC and other sources. These discussions were instrumental in developing the watershed productivity and capture rate concepts detailed in this report.

CTWC Executive Director Shannon Hamilton and legal counsel Cindy Smiley were also instrumental in making this report technically sound while still remaining comprehensible to non-engineers and scientists. Additional significant contributions were made by Dr. John Nielsen-Gammon (Texas' State Climatologist), Dr. Kathy Alexander (Texas Commission on Environmental Quality), and Leonard Oliver and others from the Lower Colorado River Authority.

Lastly, this report was vastly improved based on the ideas and recommendations provided by the following independent technical reviewers:

- **Dr. Barney Austin** – Vice President, Hazen and Sawyer
- **Dr. Francisco Olivera** – Retired Professor of Civil Engineering, Texas A&M University
- **Dr. Spencer Schnier** – Water Resources Engineer at Rivulous, LLC

I am extremely grateful for everyone's contributions – team efforts are the best pathways to success.



Jordan Furnans

Technical Abstract

The Highland Lakes watershed, defined here as the land area between the outlet from OH Ivie Lake and Lake Travis on the Colorado River, provides the primary water supply for millions of residents in Central Texas. The agencies responsible for managing that supply, namely the Lower Colorado River Authority (LCRA) and the Texas Commission on Environmental Quality (TCEQ), utilize sophisticated models to assess how current water policies would dictate water availability under historically observed hydrologic conditions. These water availability models (WAMs) use naturalized streamflow data as input, which are computed approximations of the historical streamflow that would have occurred within the watershed without human interference (through reservoir construction, diversions, return flows, and other discharges). The WAMs use the naturalized flows to distribute available water to end users with state-issued water rights (including municipalities, agricultural producers, industrial users, and other water users). For each user, the WAMs compute how much water each entity would have historically received given the simulated water allocation policies.

Recent observations have shown that the lowest inflows to the Highland Lakes (specifically Lakes Buchanan and Travis) have occurred within the 2006-2025 time period, yet the lowest historical rainfall totals occurred during the 1945-1957 drought period. To determine current water availability from the Highland Lakes watershed under the 1945-1957 low rainfall pattern, adjustments to the naturalized flows were made, based on comparisons between current and historical "Capture Rates." The capture rate, defined as the ratio of watershed outflow to rainfall over a specific time interval, is a measure of the watershed productivity and demonstrates the efficiency with which the watershed creates streamflow from rainfall. Four different methods were evaluated for adjusting naturalized flows based on relative capture rates, and WAMs using the adjusted flows were compared to original WAMs developed by LCRA during its 2032 Water Management Plan (WMP) revision process. Model results from all WAMs run with modified naturalized flows datasets indicate lower water availability and suggest lower reservoir storage levels under proposed LCRA water management policies. Model results also indicate that using modified naturalized flows causes the 1945-1957 modeled drought period to become the "drought of record" for the Highland Lakes watershed, rather than the modeled 2008-2016 period currently endorsed by LCRA and TCEQ.

Using LCRA's firm yield model with the original naturalized flows, the study reproduced a baseline firm yield within one percent of LCRA's reported estimate of approximately 414,000 acre-ft per year. The small difference reflects reservoir capacities that exclude LCRA's 2032 sedimentation adjustments. Measured against that baseline, all 14 adjusted model runs produced lower firm yields, with reductions of 9.0 to 21.2 percent (approximately 37,500 to 88,300 acre-ft per year). Adjustment Method #4, the most comprehensive approach, produced the largest reduction. In the 2032 WMP simulations, the minimum combined storage of Lakes Buchanan and Travis fell below the 600,000 acre-foot threshold the proposed plan was designed to maintain under Method #2 (548,256 acre-ft) and Method #4 (532,372 acre-ft), compared with a minimum of 615,440 acre-ft in the original model. In the remaining 12 adjusted runs, minimum storage stayed above the threshold.

Would Central Texas have sufficient water supplies if
current rainfall patterns equaled those from
the 1950s Texas Drought?

While the causes of declining capture rates and inflows to the Highland Lakes are not explicitly addressed in this report, the theoretical influence of small ponds is detailed herein.

Recommended future studies include the development of rainfall-runoff models for the Highland Lakes watershed and potentially shifting the flow naturalization process to involve both rainfall and streamflow calculations.

Note: Modeled drought periods are those indicated from WAM simulations, whereas historical drought periods are defined based on the actual combined storage contents of Lakes Buchanan and Travis. Modeled drought periods are often defined as the period from when the lakes were full to when they have emptied and are therefore of shorter duration than observed drought periods.

1. Introduction and Purpose

The Colorado River Basin of Texas extends from the New Mexico border southeastward through central Texas to the Gulf of Mexico. Its namesake Colorado River provides the majority of the water supply for the City of Austin and surrounding region, and also supplies water for industry, power production, agricultural irrigation, and freshwater flows for sustaining aquatic habitat within the Colorado River and Matagorda Bay. In addition, it can provide a significant water supply for the City of Corpus Christi, which transports the diverted river water outside of the basin over to Nueces County via the Mary Rhodes pipeline. The basin has historically experienced both periods of intense drought and flooding, often within the same calendar years. Both drought and flood events are managed through the Highland Lakes system, which is a series of on-channel reservoirs upstream from the City of Austin. The Lower Colorado River Authority (LCRA) was created in part to manage the watershed and the Highland Lakes system (Figure 1) to protect inhabitants and preserve long-term water supplies for the region. For this analysis, the Highland Lakes watershed is defined as the land area downstream from OH Ivie Lake which drains to the outlet of Lake Travis.

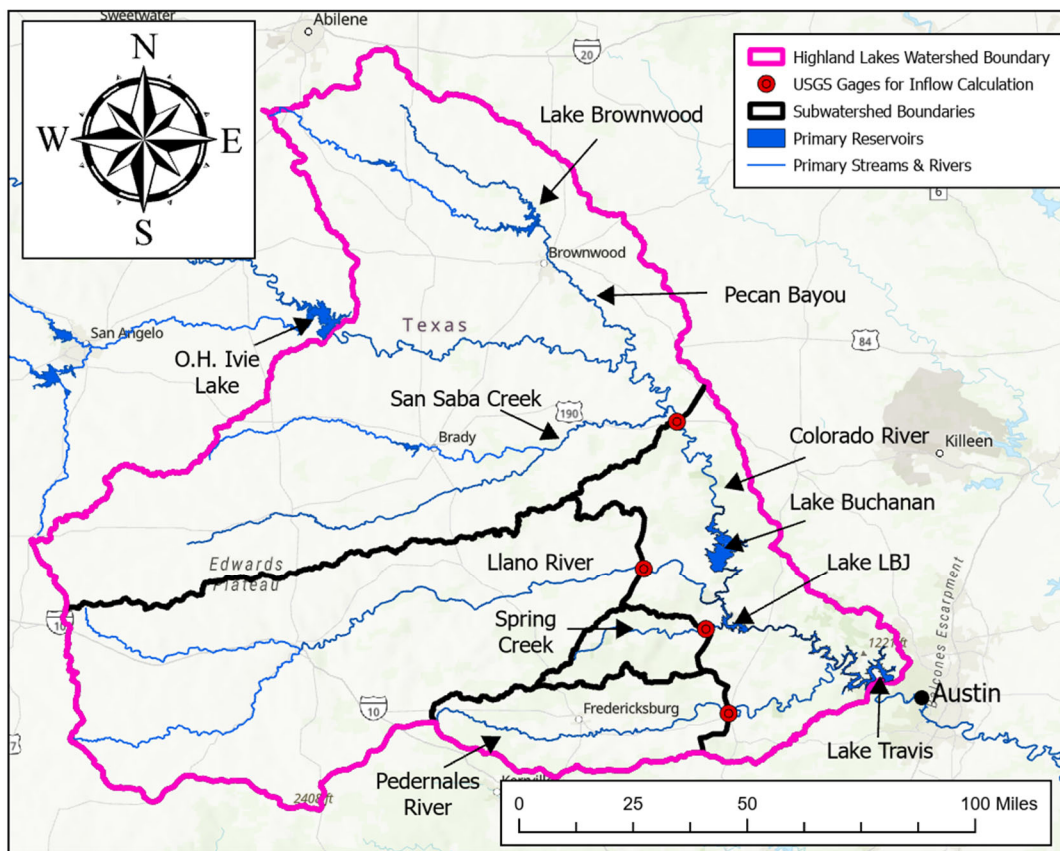


Figure 1 – Map of the Highland Lakes system and contributing watershed between OH Ivie Lake and Lake Travis.

To support its water supply and flood protection mission, the LCRA is continuously monitoring and studying the Highland Lakes watershed, assessing how weather patterns may affect long-term water availability, short-term drought conditions, and flooding concerns. LCRA actively

participates within the Region K Regional Water Planning process to help ensure local water supplies are sufficient to meet needs while working within the established State of Texas water planning framework. LCRA also performs detailed hydrologic analyses to develop its Texas Commission on Environmental Quality (TCEQ)-approved “Water Management Plan (WMP),” which serves as a blueprint for how the LCRA will manage water supplies in the immediate future. The Central Texas Water Coalition (CTWC), a nonprofit organization, commissioned this study to consider whether a new scientific approach is needed to adequately protect the Lower Colorado River water supply and the millions of Texans dependent upon it.

LCRA, with support from the TCEQ, has defined the hydrologic period of record for the Highland Lakes watershed to be from 1940 to Present, as data available over this time is considered sufficiently reliable, abundant, and accurate. LCRA has also defined periods of drought to be times when the combined storage of Lakes Buchanan and Travis are below 98% of the managed conservation pool storage (approximately 1.956 million acre-ft; LCRA, 2020). During this period of record, there have been three significant drought events with the drought duration exceeding four years: 1) the 1945-1954 drought, 2) the 2008-2016 drought, and 3) the 2019-2026 drought which recently ended as the result of back-to-back years with catastrophic July flooding events. The 2008-2016 drought is currently considered the “drought of record” for the watershed, making it a more severe drought than the previous drought of record (which was the 1945-1954) drought. The 2019-2026 drought may have become more severe than the drought of record, had July 2025 rains not changed the watershed’s hydrologic condition. LCRA defines the drought of record based on results of water accounting simulations performed using official State of Texas Water Availability Models (WAMs). These models utilize streamflow as their primary input and main driver of water availability throughout the basin. Streamflows serve as inflows to the Highland Lake system, and both inflows and lake levels have become part of the public consciousness as measures of the region’s water supply prosperity.

Inflows to the Highland Lakes system have declined markedly, with nine of the ten lowest annual inflow volumes on record occurring since 2006. This is despite the fact that only three of the lowest annual rainfall totals were measured over this same period. This sustained pattern of lower annual inflows with generally average rainfall strongly suggests there has been a systemic shift in hydrologic behavior of the watershed. While reduced precipitation contributes to this low inflow trend, a more significant concern is the disproportionate decline in runoff reaching the lakes, signaling a measurable reduction in watershed productivity. Conceptually, we define “watershed productivity” as the ability of the watershed (or subwatershed) to produce water flow at its defined outlet. The productivity is reflective of both surface water and groundwater contributions to streamflow, and is defined over a certain timeframe (days, months, or years).

The Highland Lakes are managed using LCRA’s Water Management Plan (“WMP”; LCRA 2020), which relies heavily on outputs from the WAM for the Colorado River Basin. The LCRA developed a “WMP 2032” WAM for the purposes of preparing its most recent updates to its WMP, and this WAM was based on the official Colorado River Basin and Brazos-Colorado Coastal Basin Full Authorization WAM available from the TCEQ (TCEQ, 2026). WAMs use historical hydrology to simulate “What if....” scenarios for water management, essentially

demonstrating how the watershed system would have behaved hydrologically in the past using proposed conditions (diversions, reservoirs, and water management policies). Using the historical hydrology in the WAM to make future water availability assessments requires the assumption of hydrologic stationarity—that historical streamflow patterns, once adjusted through naturalization, remain representative of future conditions. However, increasing evidence suggests that this stationarity assumption may no longer be valid for developed areas like the Highland Lakes watershed (Milly et al., 2008; Matalas, 2011; Wang and Yang, 2024; Twinomuhangia et al., 2025).

Naturalized flows used in the WAM are derived by adjusting gaged streamflow records to remove the effects of large reservoirs, diversions, and return flows. Naturalized flows are therefore the flows that would have occurred without human intervention or water resources development in the watershed. This approach has long been used for water planning and it presumes that watershed responses to precipitation remain consistent over time. In recent decades, this presumption has become increasingly questionable due to changes within the watershed, including the prevalence of small ponds (LCRA, 2024). Such ponds are typically small (< 200 acre-ft capacity), privately owned waterbodies that have collectively greatly increased the storage capacity of the Highland Lakes watershed.

Multiple factors have altered the watershed's productivity, reflected in its efficiency at translating rainfall into runoff that reaches the Highland Lakes. Extended drought periods, rising temperatures, and increased evaporation have reduced effective runoff into the Highland Lakes (Furnans et al., 2019). Changes in rainfall intensity over time may also affect runoff production, as has been documented for numerous watersheds across the US (Mamo, 2015; Hu et al., 2020) and the world (Di et al., 2023; Bilodeau et al., 2025; Tamer et al., 2025). Additionally, a 2001 change in Texas law enabled the construction of unregistered ponds for fishing and wildlife purposes, whereas previous construction was only enabled if the pond were for domestic and livestock use (TWC, 2001). This addition of possible pond uses effectively increased the ease with which homeowners could construct a pond and justify its existence on their property. Since the 2001 law change, thousands of these impoundments have been constructed throughout the watershed. These features intercept and store runoff that would have historically contributed to downstream flows, thus reducing the volume and altering the timing of inflows to the Highland Lakes. Figure 2 presents the proliferation of ponds within the San Saba River watershed as quantified under a study contracted by the Texas Water Development Board ("TWDB"; Furnans et al., 2019). The data confirm an increase in ponds after 2001, although dates of this increase reflect the limited historical aerial photos available on Google Earth used to identify dates of pond construction. LCRA presented its own data for the Highland Lakes watershed, reporting only 3,943 ponds in the San Saba watershed in 2023, yet showing an increase from 3,265 ponds in 2015 (LCRA, 2024). While LCRA's pond counts are less than half of those reported by TWDB, both quantification efforts showed pond numbers increasing in recent years. Both studies acknowledged how this proliferation of ponds is an important factor in effectively decreasing streamflow, further diminishing downstream inflows (LCRA, 2024; Furnans et al., 2019) and altering the relationship between precipitation and Highland Lakes inflow. Conclusions from the TWDB report suggested that ponds could

Would Central Texas have sufficient water supplies if current rainfall patterns equaled those from the 1950s Texas Drought?

decrease downstream streamflow by up to 8%, yet the authors admitted their modeling assumptions needed further scrutiny to increase the accuracy of that streamflow reduction quantity (Furnans et al., 2019). Neither the LCRA nor TWDB studies fully quantified the impacts and proliferation of small ponds across the entire Highland Lakes watershed over a time period spanning both the 1947-1957 and 2008-2016 modeled drought periods.

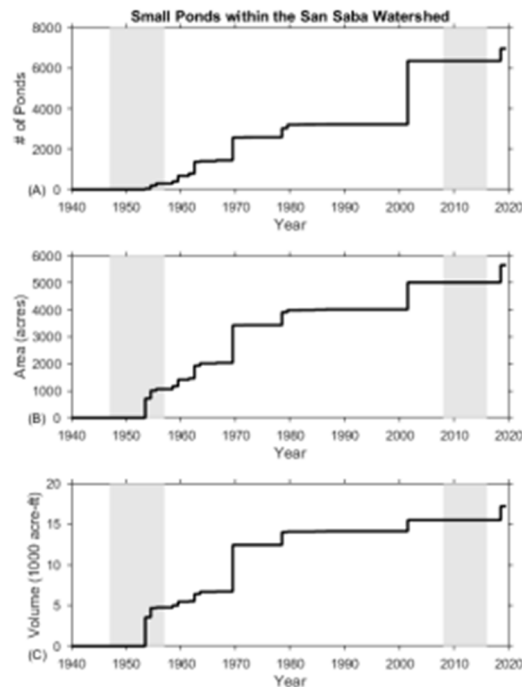


Figure 2 - Small pond time-series data for the San Saba watershed – (A) Number of ponds, (B) total surface area of ponds (when full), and (C) total volume of ponds (when full). Grey areas denote the 1947-1957 and 2008-2016 critical drought periods. Copied from Furnans et al., (2019).

Reservoir operations themselves also influence runoff dynamics. As upstream impoundments increase (in number and/or size), a larger portion of runoff is retained, evaporated, or otherwise consumed before reaching the Highland Lakes. These cumulative effects are not fully reflected in the traditional flow naturalization methods utilized in Texas, which focus on streamflow rather than rainfall and runoff. As a result, official Texas WAMs, including those developed by TCEQ and modified by LCRA, may overestimate available streamflow generated from historical storms with current watershed conditions.

CTWC is concerned that the water availability assumptions and water supply management practices in Central Texas are too reliant on hydrologic inputs that do not adequately account for these evolving conditions, including declining watershed productivity and the non-stationarity of climatic behavior. In particular, the concern arose that current water availability modeling underestimates the severity and frequency of prolonged low-inflow periods and may not sufficiently predict and incorporate the hydrologic characteristics of the 1945-1954 drought—potentially the most severe drought of record in Texas from a low rainfall perspective. Under present-day watershed and population conditions, a recurrence of a repeated low-rainfall sequence of years of similar magnitude to that of the 1945-1954 period could pose substantially

greater risks to the regional water supply than those anticipated by current planning models (which focus on the 2008-2016 controlling drought period).

To evaluate these concerns, CTWC engaged Dr. Jordan Furnans, PE, PG (Windward Water's Principal Engineer & University of Texas at Austin Lecturer in Hydrology and Hydraulics) to assess trends in watershed productivity, the validity of stationarity assumptions embedded in WAM results interpretation, and the implications of current naturalized flow methodologies for long-term water supply planning in the Highland Lakes system.

This analysis focuses on investigating and answering three primary questions:

1. Given the increasing frequency of low-inflow years, how can watershed productivity be determined and evaluated, and how has watershed productivity changed over time?
2. Do existing naturalized flow methodologies and WAM assumptions accurately represent present and expected future hydrologic conditions, given changes in productivity, storage, and evaporation across the watershed?
3. Should the drought of the 1950s be recognized as the controlling drought of record for water supply planning under current basin conditions? If yes, what would be the expected outcomes on Firm Yield and Minimum Combined Storage from a repeat of the 1945-1954 rainfall under current watershed conditions and when applying the parameters from the proposed LCRA 2032 WMP?

The third question may be adequately rephrased as:

Would Central Texas have sufficient water supplies if current rainfall patterns equaled those from the 1950s Texas Drought?

The remainder of this report details an approach toward addressing these questions using readily available data (streamflows and rainfall) along with accepted WAMs. CTWC hopes this research will lead to water management policies that are more protective of the Highland Lakes and the regional water supplies.

2. Rainfall on the Highland Lakes Watershed

Ultimately, rainfall is the source of all water flowing into the Highland Lakes, and rainfall totals are commonly reported statistics presented by LCRA and news agencies when detailing the status of the region's water supply. Yet in the current regional water planning and permitting processes undertaken in Central Texas, rainfall analyses are often skipped in favor of streamflow analyses, thereby ignoring the importance of watershed productivity in water planning. To understand the productivity of the Highland Lakes watershed and how efficiently inflows are created from rain events, it is necessary to assess and quantify the magnitudes and properties of historical rain events based on available regional rainfall data. In this section, an analysis is presented of historical rainfall totals (depths in a specified time period) and spatial distributions for the Highland Lakes watershed. Section 3 provides a similarly focused analysis of Highland Lakes inflows, and Section 4 combines rainfall and inflows to assess watershed productivity. Currently the water planning process, including LCRA's process for developing its WMP, focuses only on historical streamflow and includes minimal rainfall analyses.

Rainfall over the Highland Lakes watershed was quantified in two ways: 1) using quadrangle-based estimates published by the TWDB, and 2) using published gridded data for the conterminous United States as available within the PRISM dataset. Data from both sources are derived from rain gage records, which are then interpolated or modeled for areas located between rain gages. PRISM data incorporates rainfall observations from TWDB's and LCRA's sensor network (PRISM, 2026) as well as from other local stations that meet acceptable standards for data quality. Older rainfall estimates are likely based on data from fewer rainfall gages and may be less accurate.

Rainfall records from the TWDB have been historically considered as "the gold standard" and best available data for use in Texas' hydrological analyses. The data are published as monthly totals currently from January 1940 through December of 2025, and are available (as of June 15, 2026) from

<https://waterdatafortexas.org/lake-evaporation-rainfall>

as specified over 1° by 1° quadrangles for the entire state of Texas. Figure 3 presents the Highland Lakes watershed between OH Ivie Lake (upstream) and Lake Travis (downstream), with the TWDB-defined quadrangles overlain. The quadrangles are denoted by black rectangles with red numerical labels. As shown, portions of the watershed are found within portions of ten (10) quadrangles, and none of the quadrangles are entirely within the watershed. Table 1 presents the ten (10) quadrangles within which portions of the Highland Lakes watershed are found, as well as the acreage within each quadrangle that lies within the Highland Lakes watershed. The percentage field in Table 1 relates the acreage from each quadrangle to the acreage of the entire Highland Lakes watershed (9,347,213 acres as computed for this analysis based on official Hydrologic Unit Code (HUC) boundaries excluding the area upstream of the outlet of OH Ivie Lake).

Changing Hydrology and Impacts on Water Planning
in the Highland Lakes Watershed, Central Texas

Table 1 - Acreage of Highland Lakes Watershed within Each TWDB Quadrangle:

Quadrangle	Watershed Acreage	Percentage
508	528,987	5.66%
509	16,708	0.18%
607	78,472	0.84%
608	2,010,600	21.51%
609	1,155,000	12.36%
707	1,196,089	12.80%
708	2,288,502	24.48%
709	1,985,764	21.24%
710	84,478	0.90%
808	2,612	0.03%

To compute annual average rainfall totals for the Highland Lakes watershed, a weighted-average total was computed by month, using the area-percentages shown in [Table 1](#). Annual totals were then computed as the sum of the monthly totals for

Would Central Texas have sufficient water supplies if
current rainfall patterns equaled those from
the 1950s Texas Drought?

each calendar year.

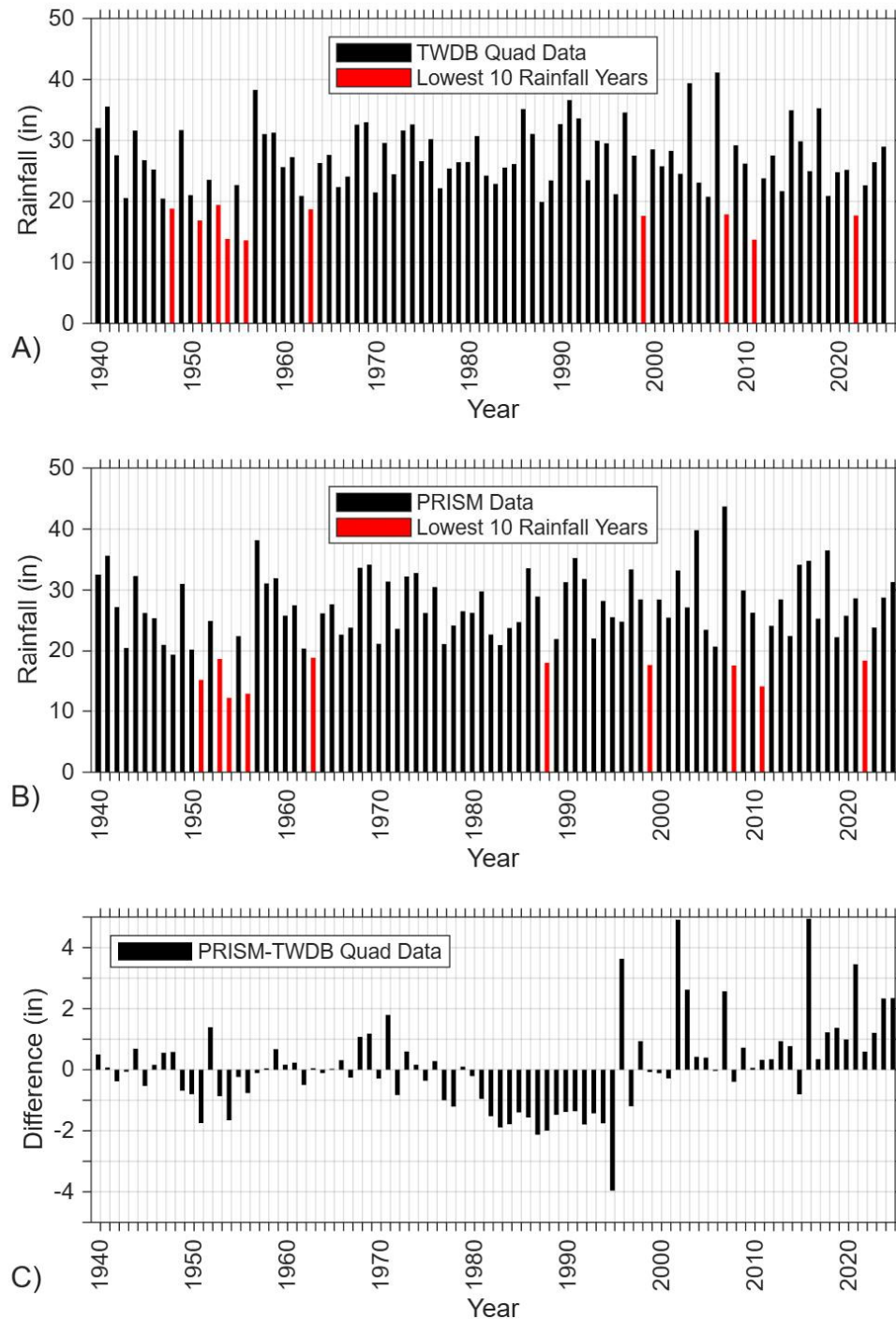


Figure 4A presents the annual rainfall totals for the Highland Lakes using the TWDB quadrangle data. As shown, totals ranged from 13.6 inches (1956) to 41.1 inches (2007). Six of the lowest

ten rainfall years occurred prior to 1963, with the other four lowest rainfall years occurring after 1999.

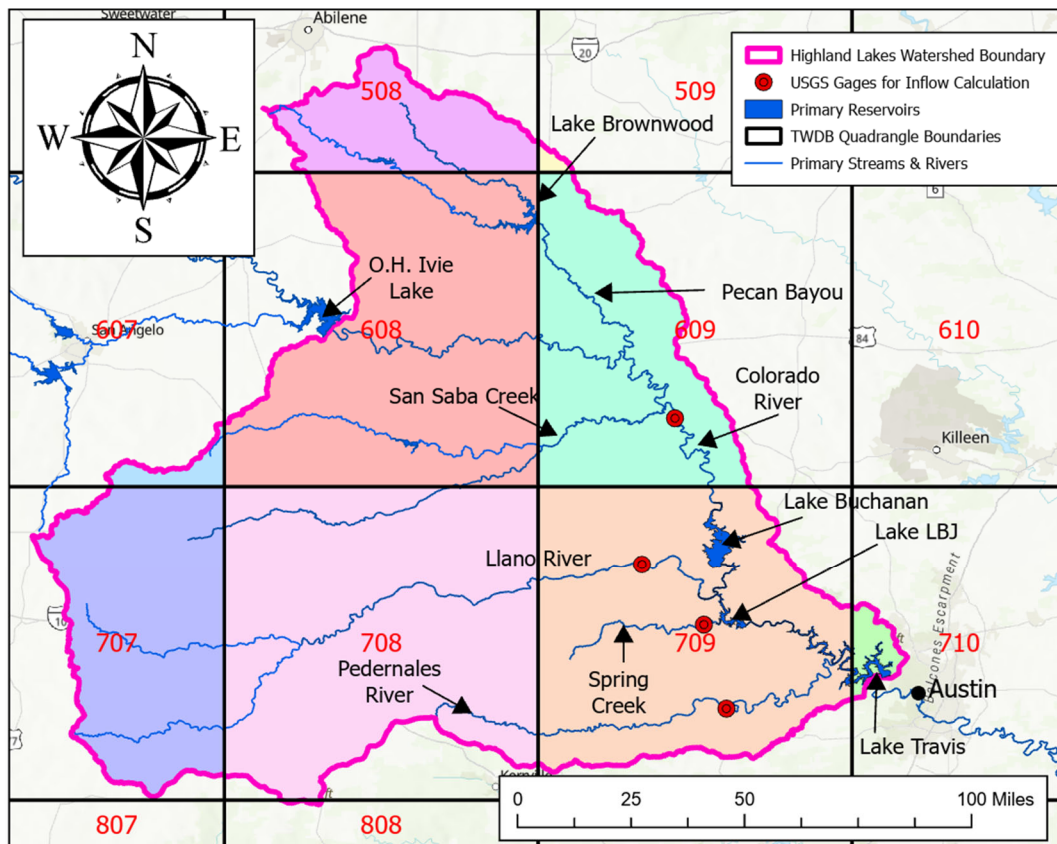


Figure 3 – TWDB Quadrangles (black rectangles with red numerical labels) overlain on the Highland Lakes watershed (Pink outline and colored areas).

Would Central Texas have sufficient water supplies if
current rainfall patterns equaled those from
the 1950s Texas Drought?

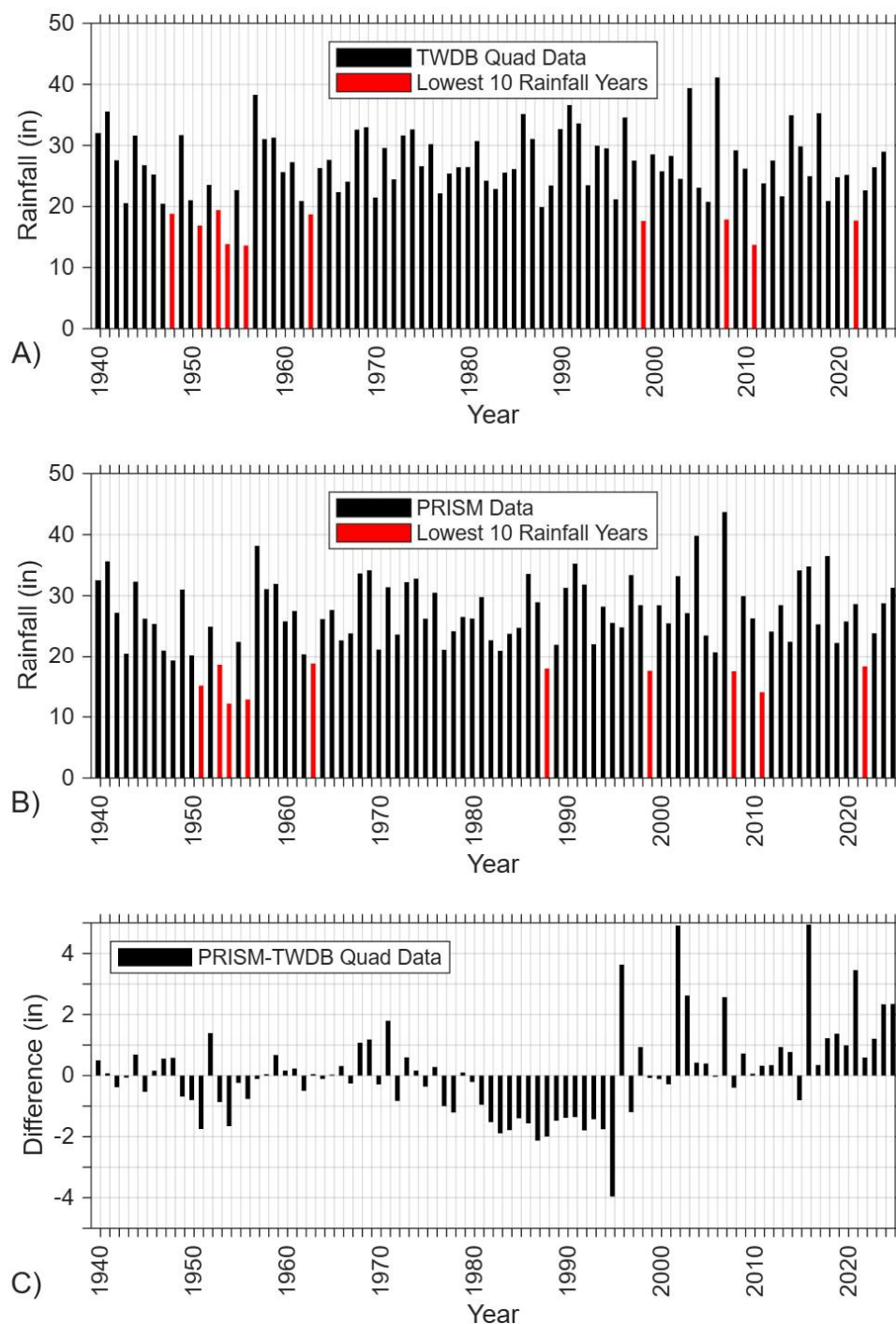


Figure 4 – Annual Rainfall totals for the Highland Lakes watershed, 1940-2025. Red bars denote the ten lowest rainfall totals out of the 86-year period of record of available data from TWDB. A) TWDB Quadrangle data, B) PRISM data, C) differences between PRISM and TWDB Quadrangle data.

PRISM rainfall data are available as a 4km x 4km (approximately 2.5 mile x 2.5 mile) gridded dataset for the conterminous United States, providing nearly 580 rainfall values inside each TWDB rainfall quadrangle. The gridded datasets are based on measured values from available sensors, with values between sensors interpolated and/or modeled using terrain analysis and statistical techniques (Daly et al., 1994; Daly et al., 2002; Daly et al., 2008; Daly et al., 2021). PRISM data are downloadable from:

<https://prism.oregonstate.edu/data/>

The data are available in monthly and annual totals from 1895-1980, and in daily, monthly, and annual totals for 1981-Present. Data were downloaded monthly from 1895-1980, and as daily datasets from 1981-present. Each downloaded grid was clipped to the extent of the Highland Lakes watershed, and annual totals were computed as the average precipitation depth across the entire watershed or subwatershed. Data was processed within ArcGIS and using customized MATLAB scripts

Would Central Texas have sufficient water supplies if
current rainfall patterns equaled those from
the 1950s Texas Drought?

for raster processing and computing spatially-averaged total rainfall values.

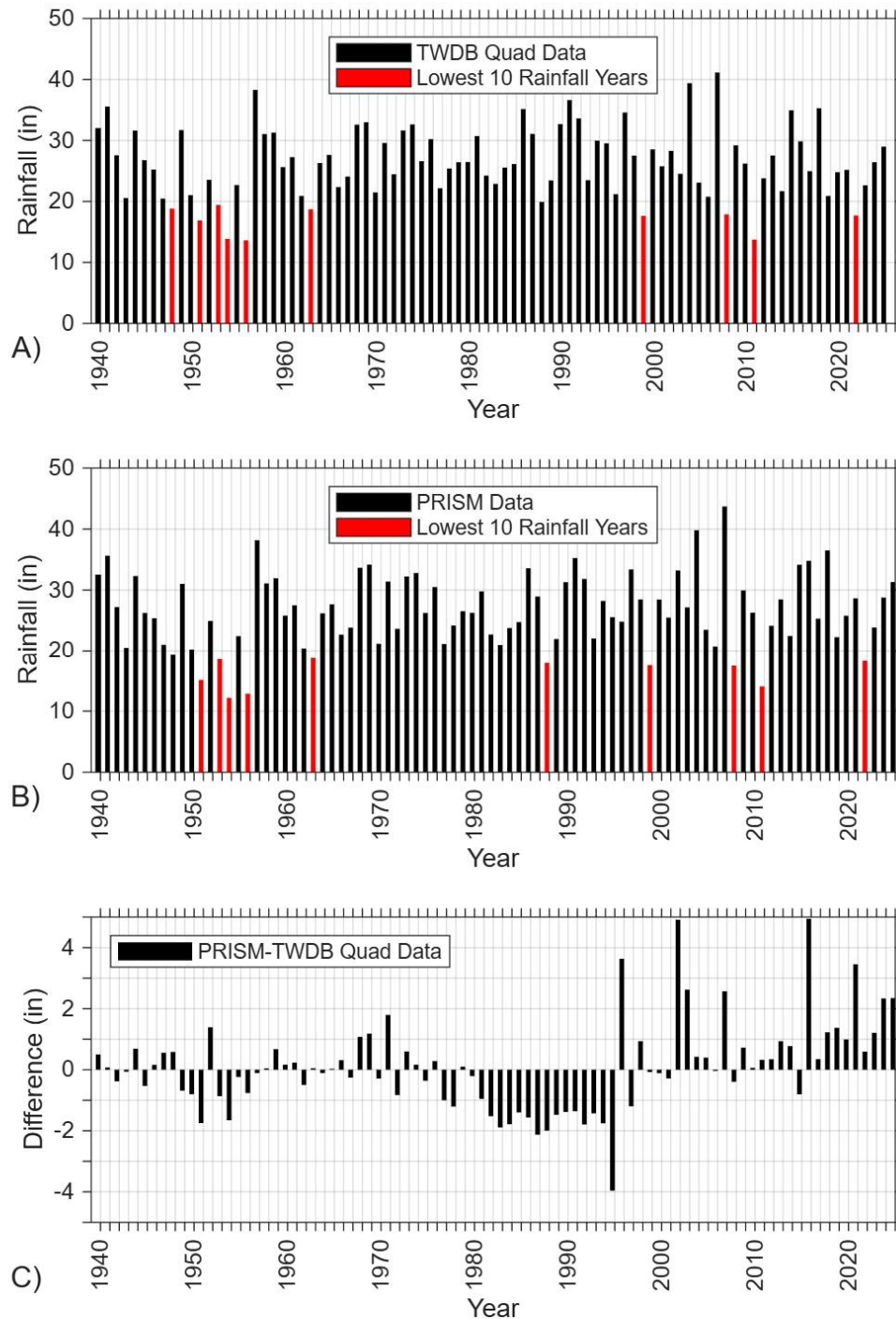
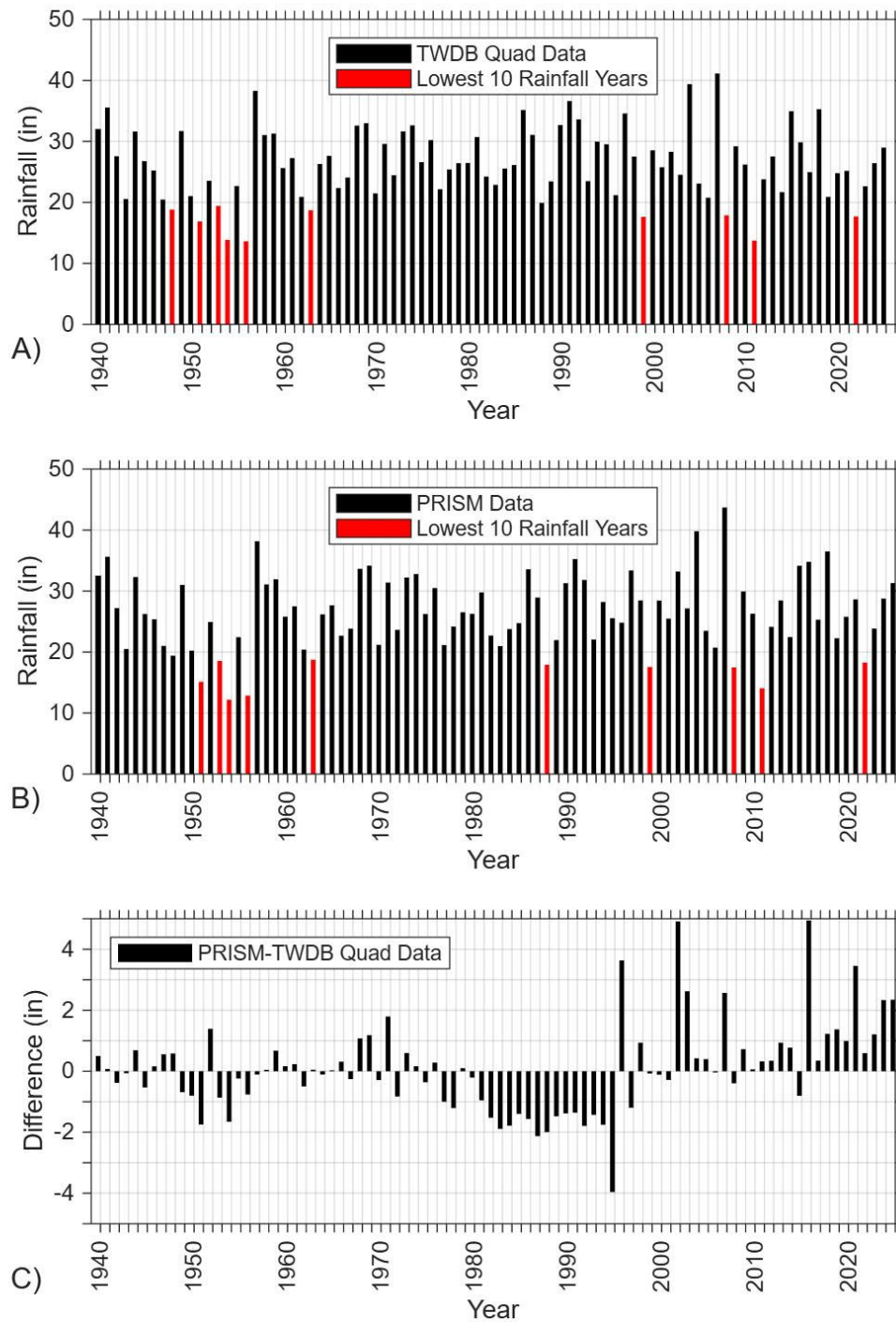


Figure 4B presents the PRISM rainfall totals for 1940-2024, with the ten (10) lowest rainfall years shown in red. As indicated, five (5) of the lowest rainfall years occurred prior to 1963, and

five (5) occurred from 1988 to present. The lowest rainfall total from the PRISM dataset was 12.2 in (1954) and the highest total was 43.7 in (2007).



Would Central Texas have sufficient water supplies if
current rainfall patterns equaled those from
the 1950s Texas Drought?

Figure 4C presents the difference in annual rainfall totals from the PRISM and TWDB quadrangle datasets. The differences in the datasets did not exhibit any consistent pattern, yet larger differences (positive and negative) were calculated for later years of the period of record common to each dataset. Figure 5 presents both the PRISM (BLUE) and TWDB Quadrangle (GREEN) rainfall data on a normalized scale, showing that PRISM rainfall data are consistently higher than TWDB Quadrangle rainfall data after 1997, yet on average the datasets are comparable.

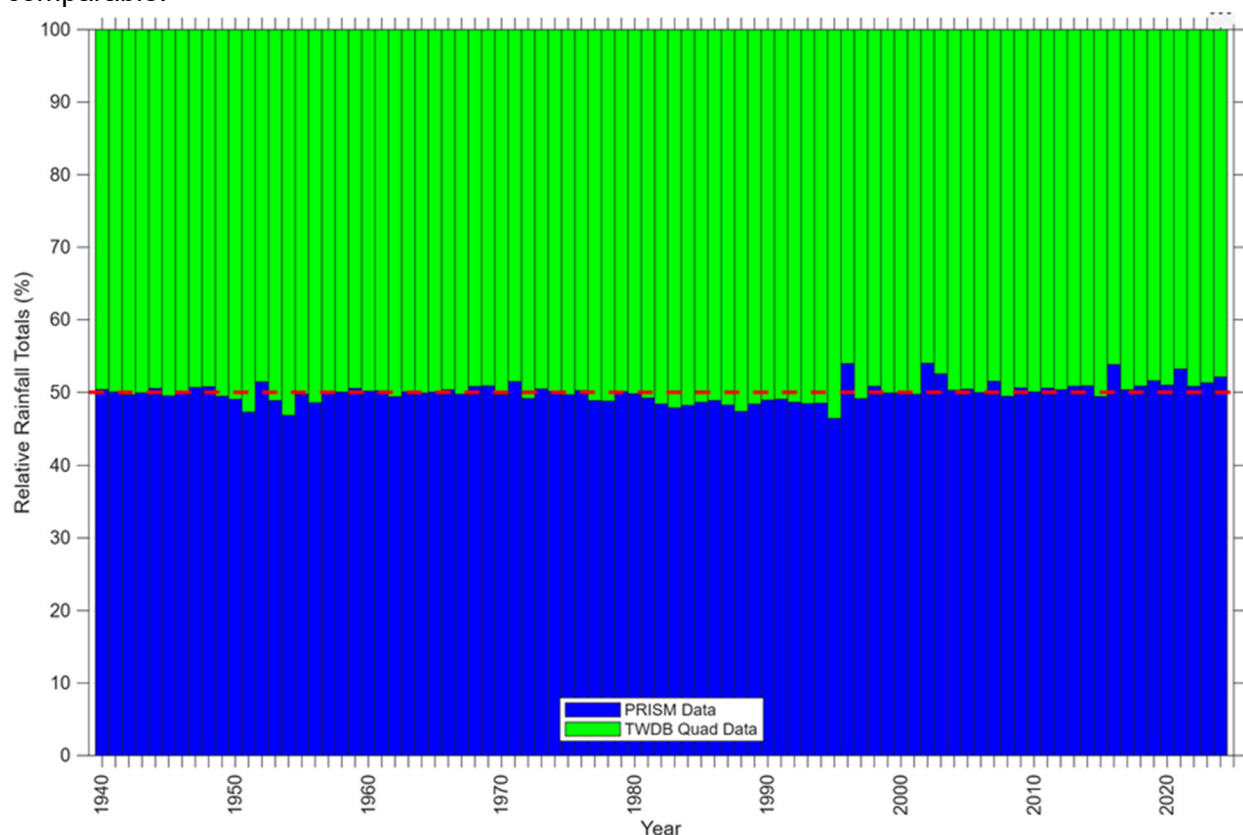
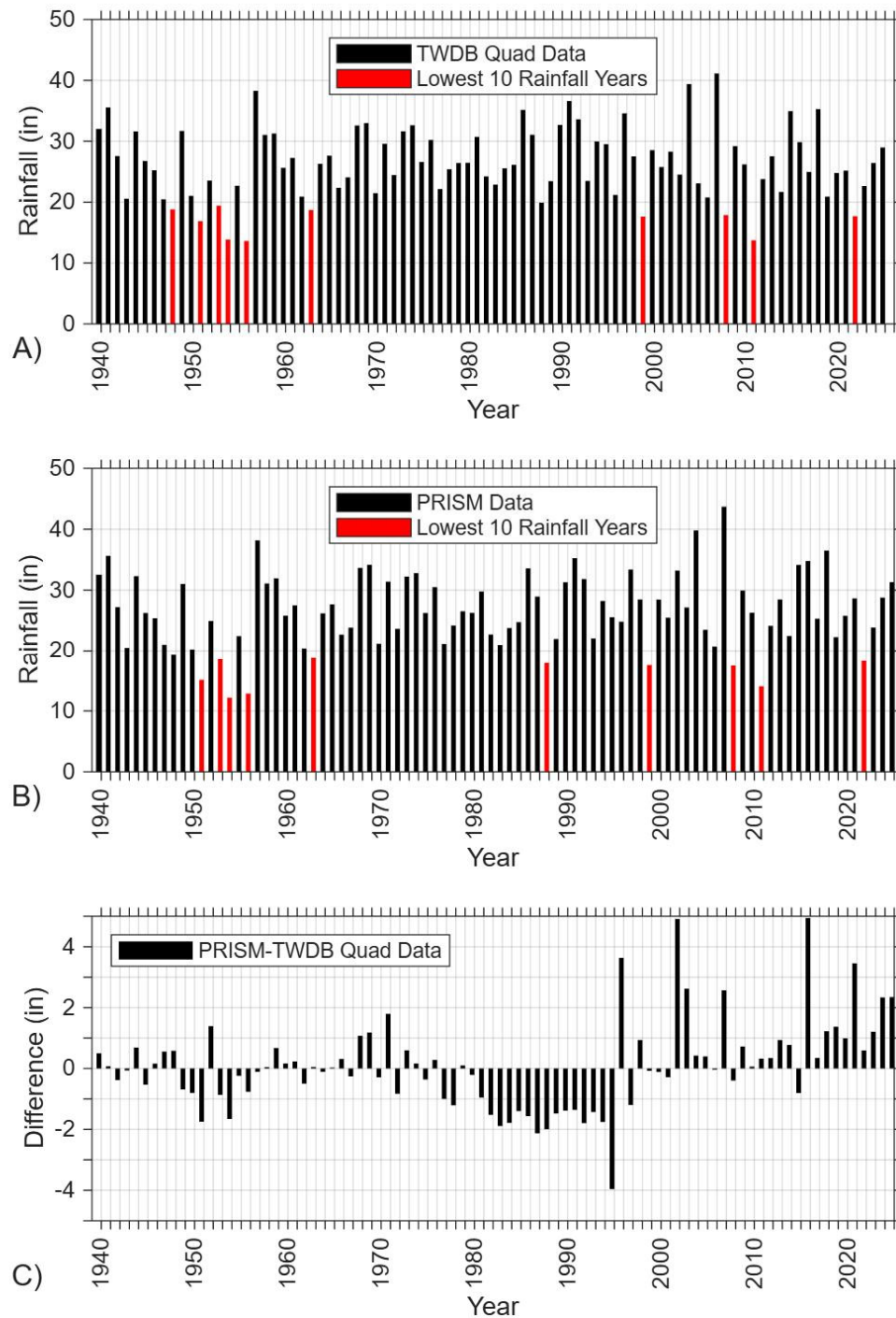


Figure 5 – PRISM & TWDB Quadrangle Rainfall data on a normalized scale



As shown in

Figure 4 and Figure 5, the PRISM rainfall data tends to indicate larger precipitation averages over the Highland Lakes watershed than the TWDB Quadrangle data. The correlation between

the two datasets is high, with an R^2 value of 0.94 (Figure 6). Year to year trends in annual rainfall totals are also largely consistent within each dataset, further suggesting reasonable comparability. Within Figure 6, data are grouped into four 21-year periods, with the 1940-1960 period and the 2003-2023 period exhibiting wider ranges of rainfall totals. These 21-year periods were used to group the available data into time-categories to be used in water availability modeling. Data suggests that PRISM values in the 2003-2023 period are consistently higher than in the TWDB Quadrangle dataset, whereas the opposite appears to occur in the 1982-2002 data. Differences in the PRISM and TWDB quadrangle datasets likely stem, at least in part, from the data averaging process used in creating each dataset.

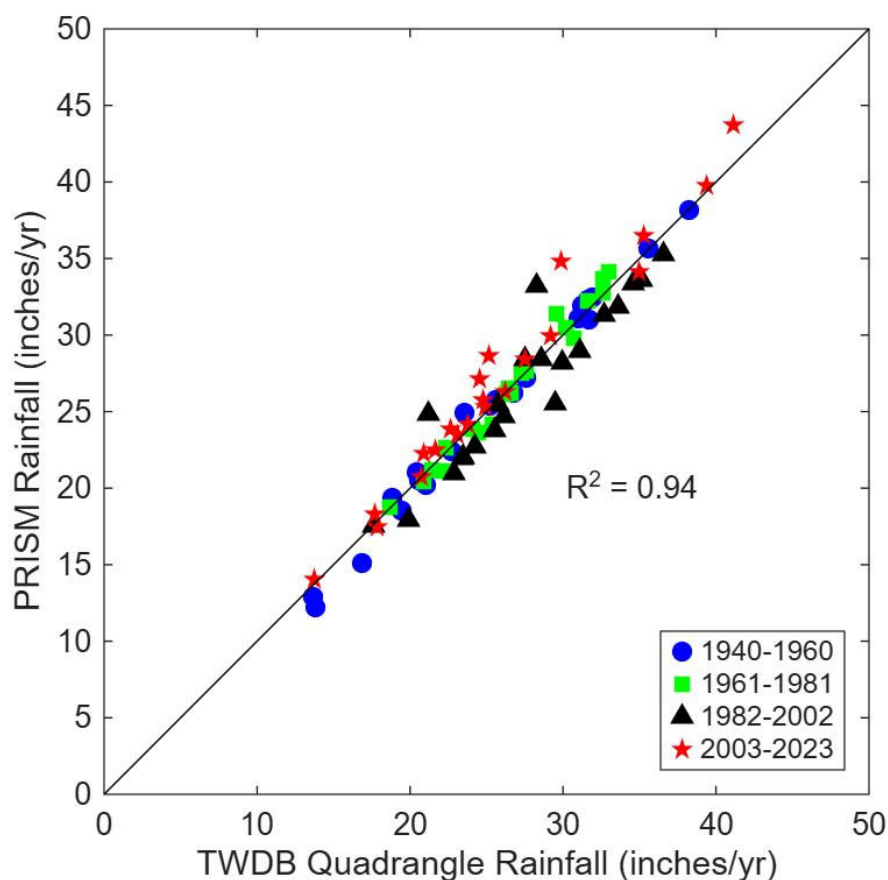


Figure 6 – Comparison of Rainfall datasets, showing annual totals with significant correlation yet PRISM data trending higher than TWDB Quadrangle based data.

Figure 7A presents the rainfall totals (in inches) for the Highland Lakes watershed as defined by the TWDB Quadrangle dataset for September of 1952 (when a large rain event occurred within the watershed). The highest rainfall occurred within Quadrangle 709, suggesting that 11.13 inches of rain fell uniformly across the entire quadrangle, contributing rainfall and runoff to Lake Buchanan, Lake LBJ, and the upper portion of Lake Travis. In contrast, the PRISM data for this same month and year (Figure 7B) indicates that there was spatial variability in the rainfall, with 16.8 inches of rain falling on the Pedernales River watershed near the Gillespie County-Blanco County border, and with only 9.0 inches falling on the watershed immediately around Lake Buchanan. The PRISM dataset, given its greater spatial discretization compared to the TWDB

dataset, allows for better relative assessments of rainfall and inflow patterns. Using the PRISM data, for example, it becomes evident why the September 1952 rain event resulted in significant flooding on the Pedernales River and large inflows into Lake Travis, whereas less inflows entered Lake Buchanan. Such conclusions cannot be reached from the TWDB Quadrangle data as it is averaged over a larger area.

Would Central Texas have sufficient water supplies if current rainfall patterns equaled those from the 1950s Texas Drought?

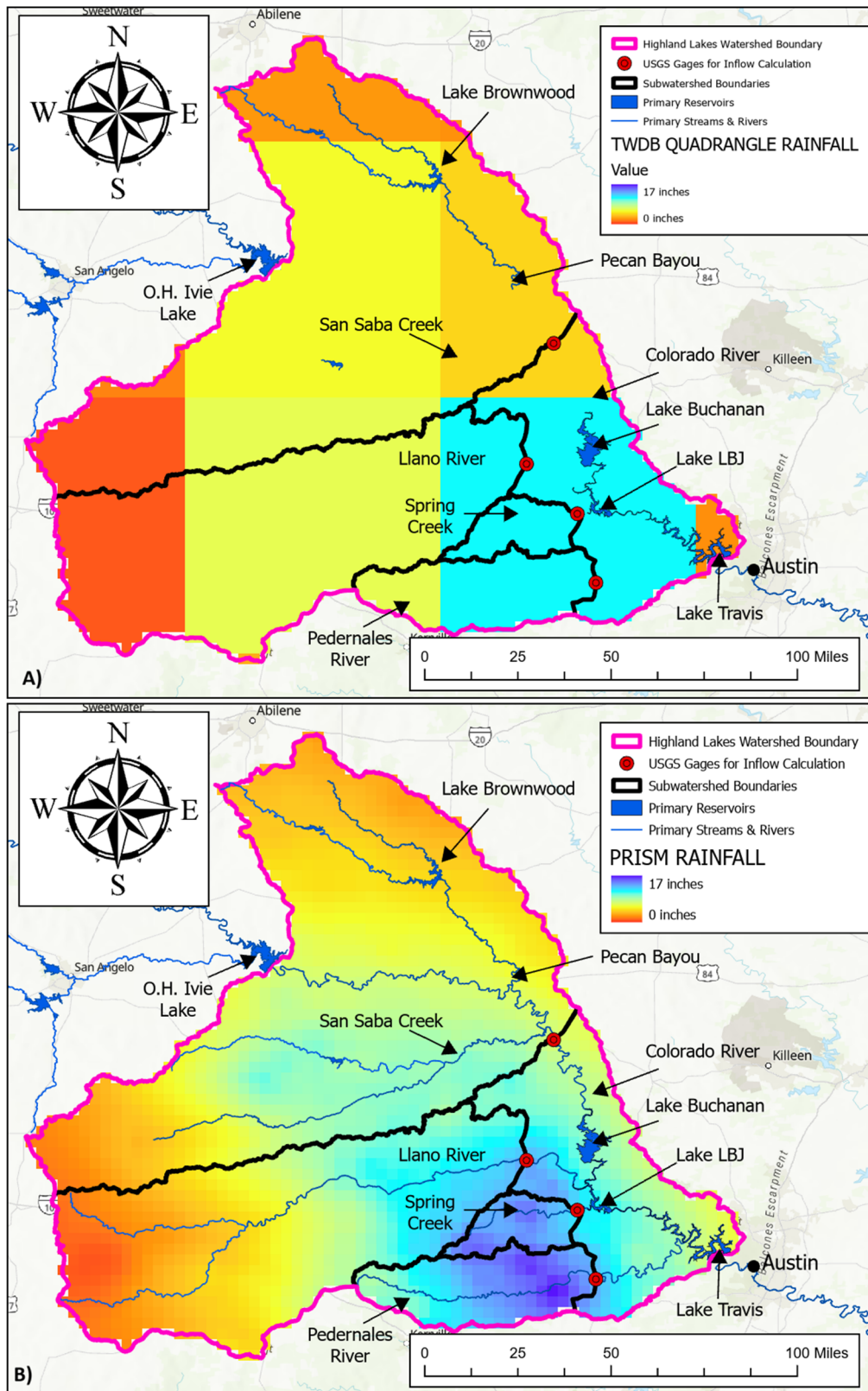


Figure 7– September 1952 Monthly Rainfall Totals as derived from: A) the TWDB Quadrangle Dataset, B) the PRISM dataset.

The effect of spatial averaging on the TWDB Quadrangle data is also evident when considering Quadrangle 609, of which approximately half is included within the Highland Lakes watershed. Rainfall totals for this quadrangle were 4.2 inches in September 1952 and reflected the fact that the large storm event did not extend northeastward to the rest of the quadrangle. This resulted in a lower average rainfall depth within the TWDB Quadrangle dataset, compared to the PRISM dataset. Similar averaging effects apply to all quadrangles, including the western quadrangles, which will likely have lower rainfall totals due to the generally decreasing rainfall patterns occurring in the westward direction across Texas.

Given the greater spatial resolution of the PRISM rainfall data, it is a superior product for assessing the rainfall-to-runoff relationships within the Highland Lakes watershed. It is also beneficial that the PRISM dataset covers a longer period of record (1895-Present) than the TWDB Quadrangle dataset (1940-2025), yet this benefit is limited in assessing watershed productivity (for which streamflow data becomes more limiting). The improved temporal resolution of the PRISM data (daily records from 1981-Present) also presents the opportunity for assessing rainfall-runoff responses while considering antecedent moisture conditions; such assessments are not possible using monthly data such as the TWDB Quadrangle data. The comparison of datasets is detailed here to demonstrate the superiority of the relatively new PRISM dataset, and to initiate the transition away from only using the spatially and temporally averaged TWDB Quadrangle datasets in assessing hydrologic conditions within Texas.

PRISM Data Analysis

One component of watershed productivity with respect to Highland Lakes inflows is the total precipitation that falls on the watershed within a given time. Trends in precipitation records, if any exist, might suggest trends in watershed productivity, and may therefore be important in assessing trends in inflows to the Highland Lakes. As the current water supply planning process focuses almost entirely on inflows, linking inflow trends to precipitation trends could prove important.

Figure 8 presents the extended historical annual precipitation totals over the entire Highland Lakes watershed from 1895-2025, using the PRISM data. As shown, three of the lowest rainfall years occurred prior to 1940, with the lowest total (12.0 in) occurring in 1917. Mann-Kendall statistical analyses indicate that there is neither a significant increasing nor decreasing trend in the PRISM annual total rainfall data over the 1895-present period. Annual rainfall totals have therefore been statistically stable over this 131-year period of record. The mean rainfall over this period of record is 26.1 inches, and the rainfall distribution follows an approximately normal distribution with a standard deviation of 6.2 inches. As shown in Figure 8, the lowest and highest rainfall years were outside of two standard deviations from the mean, indicating less than a 2.3% likelihood of occurrence. There were not any years where rainfall totals were outside of three standard deviations from the mean, indicating that more extreme outlier years were not experienced over this period of record.

Would Central Texas have sufficient water supplies if current rainfall patterns equaled those from the 1950s Texas Drought?

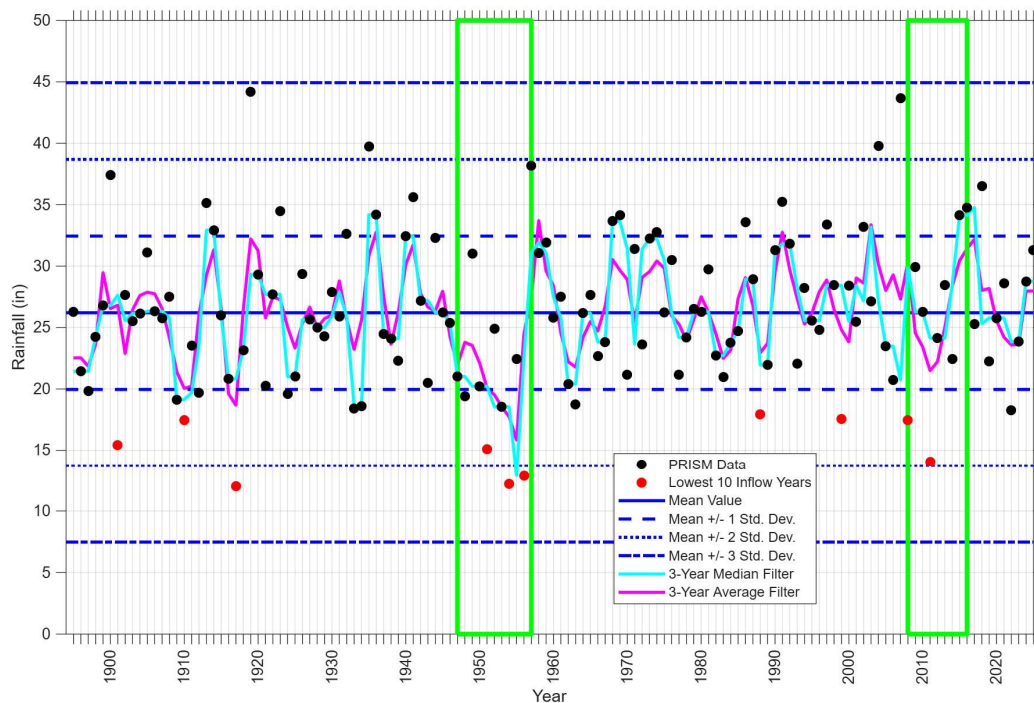


Figure 8 – Historical rainfall totals over the Highland Lakes Watershed – 1895-2025, using the PRISM dataset. Green Boxes show the 1947-1957 and 2008-2016 drought periods.

Figure 8 also highlights the differences in rainfall patterns during the 1947-1957 drought period and that from the 2008-2016 drought of record for the Colorado River Basin. As shown, three of the lowest rainfall years occurred during the 1947-1957s drought period, and in that time not one of the 10 years of rainfall totals exceeded one standard deviation above the mean (not until 1957 when the drought ended). In contrast, the 2008-2016 drought of record period contained two lower than average rainfall years and had generally higher rainfall years than during the 1947-1957 drought. The 2008-2016 drought was “broken” by two consecutive years (2015 and 2016) of rainfall exceeding one standard deviation above the mean.

The lower rainfall during the 1947-1957 drought period is also evident from the 3-year median filtered trendline (light blue line in Figure 8). This line shows trends in year-to-year rainfall without being influenced mathematically by the magnitude of the rainfall events. As shown, the 3-year median filtered trendline is always below the -1 standard deviation line during the 1950s drought, whereas during the 2008-2016 drought it is only slightly below the mean. Similarly, the 3-year average filtered trendline (purple line in Figure 8) is nearly always higher during the 2008-2016 drought than during the 1947-1957 drought. The lower rainfall during the 1947-1957 drought is also evident in Figure 9, where cumulative rainfall totals over each drought period diverge after 5 years from drought commencement. By the end of the 9-year drought of record (2008-2016), the watershed had received almost 50 inches more rainfall than it had during the first 9 years of the 1947-1957 drought period. This amounts to nearly 2-years of average rainfall totals (26.1 inches) for the Highland Lakes watershed.

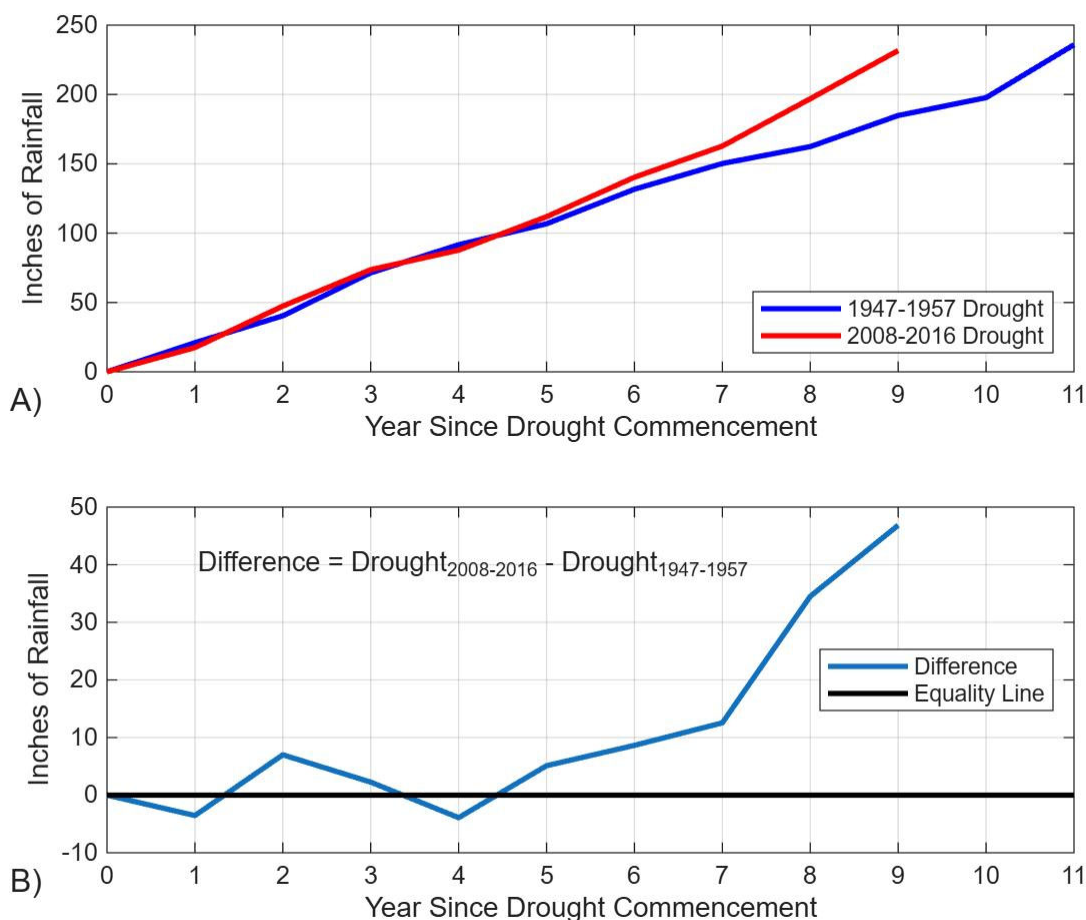


Figure 9 – Rainfall totals (inches) during the 1947-1957 and 2008-2016 droughts in the Highland Lakes Watershed – A) cumulative totals, B) difference in rainfall totals by year since drought commencement.

These facts combined demonstrate that rainfall totals for the Highland Lakes watershed during the 1947-1957 drought were lower than those of the more recently designated drought of record (2008-2016). In Texas, droughts of record are determined based on the naturalized streamflows, and streamflows were lower during the 2008-2016 period than they were during the 1950s drought period. This raises the question: **Why did the 1947-1957 period's lower rainfall amounts not produce correspondingly lower streamflow and inflows into the Highland Lakes?**

3. Analysis of Inflow Data

As watershed productivity is defined based on a measured outflow from a watershed, it is necessary to consider how watershed outflows are calculated. For this analysis, the outflow of water from the Highland Lakes watershed is taken as inflows to the lakes themselves. The LCRA has developed two methods for computing inflows to the Highland Lakes, and both methods are used by LCRA within the WMP (for operations) and long-term planning efforts (LCRA, 2026). Inflow method #1 is used to perform day-to-day operations and management of the river system according to WMP rules. With this method, inflows are computed as the sum of four gaged streamflows at locations within the Highland Lakes watershed, with each gaged streamflow first multiplied by a “runoff factor.” The runoff factors were determined based on drainage area ratios upstream and downstream of the gages (Leonard Oliver, LCRA, Personal Communication, 2025), yet documentation of how the runoff factors were calculated has not been found during the preparation of this report. Table 2 provides the gages and respective runoff factors used in calculating inflows to the Highland Lakes.

Table 2 – USGS Gages & LCRA Runoff Factors used in computing inflows to the Highland Lakes.

USGS Gage Description	USGS Gage Number	LCRA Runoff Factor
Colorado River Nr. San Saba	08147000	1.035
Llano River @ Llano	08151500	1.000
Sandy Creek Nr. Kingsland	08152000	2.367
Pedernales River Nr. Johnson City	08153500	2.030

Inflow method #2 is the State of Texas defined practice of computing naturalized flows. Naturalized flows are calculated streamflows that would have occurred without man-made alterations (such as major reservoirs, water diversions, and return flow discharges). According to this method, naturalized flows are calculated only on monthly timesteps and are defined at certain “primary control points” within the Highland Lakes watershed. Inflows to the Highland Lakes, as defined in this analysis, are considered as the naturalized flows computed at Mansfield Dam on Lake Travis (WAM control point I20000). Incremental naturalized flows for the Highland Lakes watershed, however, are defined as the naturalized flows at Mansfield Dam on Lake Travis MINUS the naturalized flows for the location downstream of OH Ivie Lake (WAM control point D20000). The incremental naturalized flows are flows that result only from the Highland Lakes watershed. Note that inflow method #2 does not consider the priority dates by which LCRA is authorized to store water within the Highland Lakes and only focuses on quantifying the water from the watershed that would reach the outlet of Lake Travis without human intervention.

Figure 10 presents annual Highland Lake inflows derived from Inflow method #1 for the period from 1942-2025, and the inflows derived from Inflow method #2 for the period from 1940-2023. Streamflow gage data from Sandy Creek near Kingsland are only available from 1966 onward, and LCRA has developed methods for approximating its flow for the 1942-1965 period. Naturalized flow data are available from 1940-2023.

Changing Hydrology and Impacts on Water Planning in the Highland Lakes Watershed, Central Texas

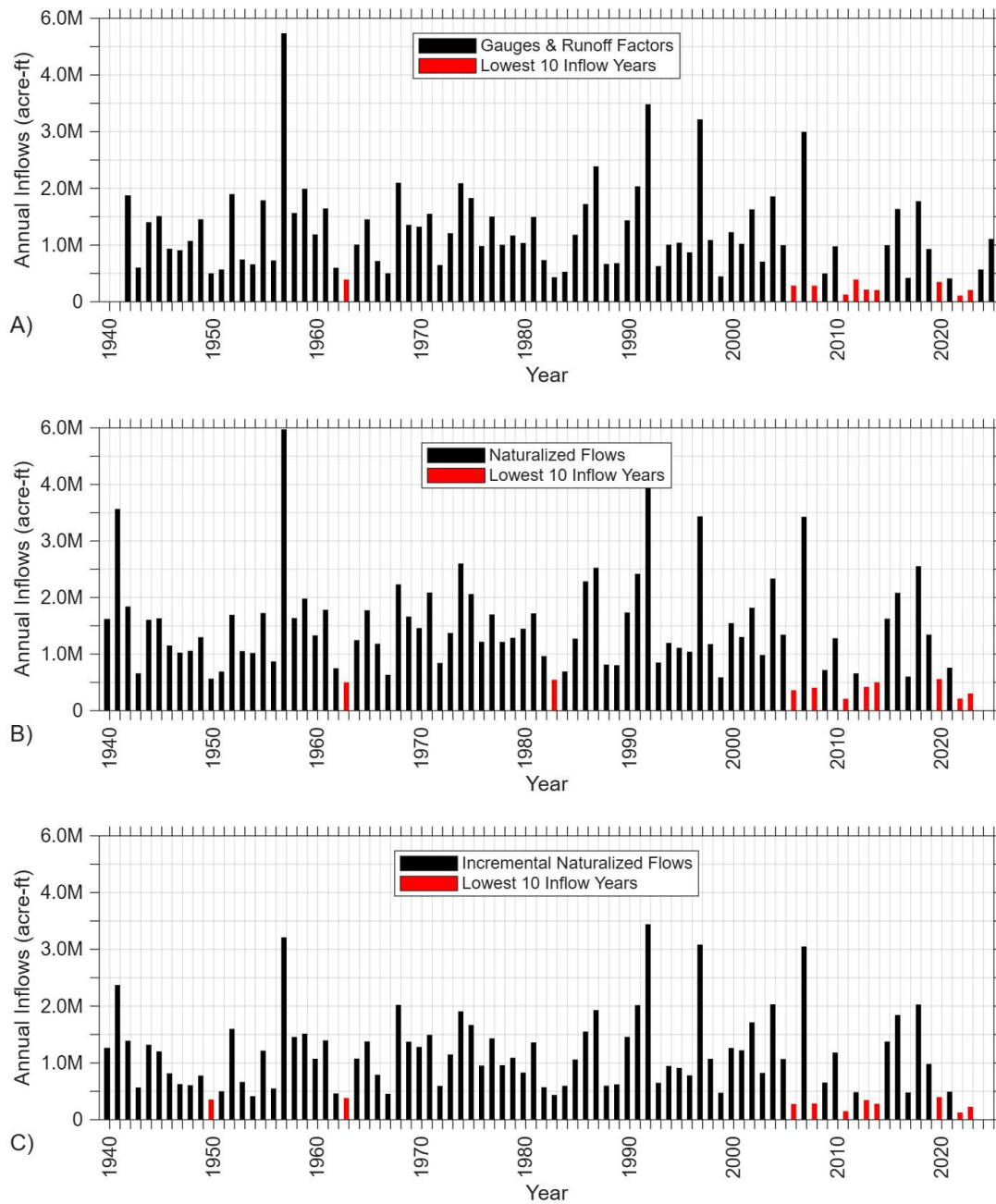


Figure 10– Inflows to the Highland Lakes – A) Gage Flows & Runoff factors, B) Naturalized Flows, C) Incremental Naturalized Flows from the Highland Lakes watershed (excluding releases from OH Ivie Lake).

As shown in Figure 10, inflows from each method are generally consistent in their temporal pattern with naturalized flow values exceeding values from gages and runoff factors in each year from 1961 to 2023. Median inflows based on naturalized flows equal approximately 1.18

million acre-ft/year, and median inflows based on gages and runoff factors equal approximately 1.01 million acre-ft/year. It is logical that inflows based on naturalized flows exceed those based on gages and runoff factors, as the gaged data is not corrected for any physical upstream water diversions that occur within the watershed. It is notable in Figure 10 that, irrespective of the method used to quantify inflows, the majority of the years with the lowest inflows have occurred after 2003. This is true for both the total naturalized flows dataset (Figure 10B) and the incremental naturalized flows dataset (Figure 10C), which signifies that the construction of OH Ivie Lake and the resulting reduction in Colorado River flows downstream of the lake is not responsible for the observed lower inflows after 2003.

4. Watershed Productivity – Capture Rate Analysis

To assess how the current watershed may enhance or limit water availability, it is necessary to link watershed productivity to rainfall and streamflow. As previously defined, watershed productivity is the ability of the watershed to produce streamflow. This can be quantified through calculation of a “Capture Rate” defined as the volume from the watershed divided by the volume of rainfall falling on the watershed (over a defined period of time). Thus the capture rate is given by the formula:

$$\text{Capture Rate} = \frac{\text{Watershed Outflow Volume} - \text{Watershed Inflow Volume}}{\text{Watershed Rainfall Volume}} \cdot 100\%$$

Where the capture rate is expressed as a percentage and all volumes are defined over the same time period. As applied to the Highland Lakes watershed, the inflow volume would be the volume of water entering the watershed as streamflow released from OH Ivie Lake. The outflow volume would be equivalent to the inflows to the Highland Lakes, as defined using inflow method #1 or method #2. For subwatersheds without inflows, the “watershed inflow volume” is zero. Simply stated, the capture rate is the portion of rainfall over the watershed that is conveyed downstream of the watershed as stream runoff. Capture rate values incorporate any water infiltration, evapotranspiration, storage, or groundwater flux within the hydrologic control volume incorporating the watershed.

Capture rates must be quantified over a specific period (day, month, or year), and the outflows and rainfall volumes must be quantified over the same period. This may be problematic as there may be a time delay between the occurrence of the rainfall event and the outflow of that rain event through the watershed. For example, quantifying capture rates on a monthly timestep may lead to the scenario when there is a runoff-inducing rain event at the end of the month, yet that runoff does not flow out of the watershed (as streamflow) until sometime during the next month. This “travel time” effect is less important when capture rates are determined over longer periods.

Capture rates also reflect the different timescales over which the hydrologic cycle acts on a watershed. For example, if a watershed had experienced prolonged drought, it is likely that streamflow would be low, derived mostly from groundwater contributions through the stream

bed. During a rain event over this initially dry watershed, much of the precipitation would initially infiltrate into the ground, replenishing the aquifer system. The remainder of the precipitation that is not lost to evapotranspiration, trapped in puddles, or otherwise intercepted would become runoff and would enter the stream network as overland flow. This runoff would increase the outflows from the watershed on a relatively short timescale. In contrast, the replenished aquifer system would likely increase streamflow over a longer timescale, as the infiltrated rainwater may flow as groundwater into the stream over longer periods. Thus, capture rates computed over a longer timescale would more readily reflect the longer-term influence of rainfall events on watershed hydrology. As such, it is recommended to quantify capture rates on the annual or monthly timescale, rather than on daily schedules. Daily capture rates, however, may prove insightful in quantifying the rapidity of rainfall-runoff responses and groundwater flux through watersheds, especially if the analysis focuses on smaller subwatersheds within the larger Highland Lakes system. For this analysis, focus was first set to defining annual capture rates for the entire Highland Lakes watershed, and then both monthly and annual rates were determined for assessing patterns of behavior within subwatersheds. Capture rates were also statistically aggregated over multi-year periods to better assess long-term watershed behavior.

To define a capture rate, it is necessary to quantify both rainfall and outflows for a given watershed. With both the TWDB Quadrangle and PRISM datasets, it is relatively easy to quantify rainfall over any watershed or subwatershed. However, to quantify outflows, it is necessary to define watersheds as having outlets corresponding to stream gage locations. For example, it would be possible to quantify different capture rates for each of the subwatersheds draining to the four gages used by LCRA in quantifying inflows (See Figure 1 or Table 2). It is also possible to quantify outflows from other watersheds for which gages exist at their outlets, or for which TCEQ or LCRA has defined naturalized flows (which are also typically defined at gaged locations). For the Highland Lakes, four possible capture rate computational approaches were analyzed (Table 3):

Table 3 – Capture Rate Data Combinations

		Outflow	
		Gaged Flow & Runoff factors	Naturalized Flows
Rainfall	TWDB Quadrangle	#1	#2
	PRISM	#3	#4

Plotted in Figure 11 are the annual capture rates computed for each of the four possible rainfall and flow combinations for the Highland Lakes watershed between OH Ivie Lake and Mansfield Dam on Lake Travis. As shown, there are common trends evident in all capture rate datasets, and namely low and high relative capture rate values are consistent across each dataset. This suggests that each data source is consistent compared to the other sources, and that all data may be used in assessing trends across time for the entire watershed. There are also other general trends consistent with those observed in the individual rainfall and flow data. For example, the PRISM data consistently suggested greater rainfall over the watershed than the TWDB quadrangle data; this greater rainfall would result in lower capture rates, as evident in the

Would Central Texas have sufficient water supplies if current rainfall patterns equaled those from the 1950s Texas Drought?

green and black lines/symbols in Figure 11. It was also noted that the flows computed from the Gaged and Runoff Factors data were often larger than the naturalized flows prior to 1961; this is evident with higher pre-1961 capture rates for the blue datapoints compared to the red datapoints.

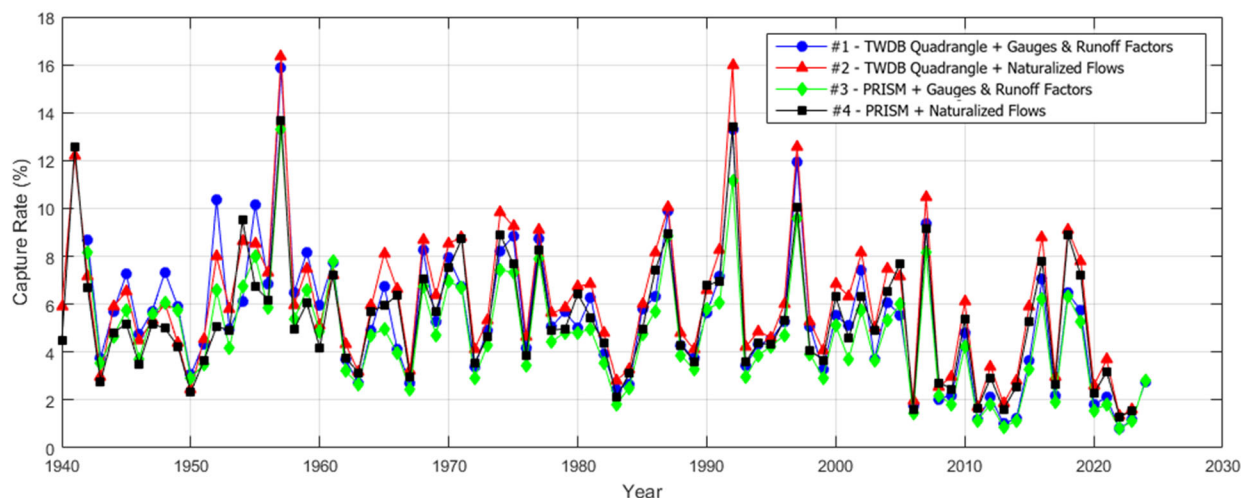


Figure 11 – Annual Capture Rates for the entire Highland Lakes Watershed between the outlets of OH Ivie Lake and Lake Travis.

Figure 12 presents the same capture rate data as in Figure 11, yet showing trends toward lower capture rates in more recent years for each dataset. Thus, irrespective of the rainfall or flow data sources, the resulting **capture rates are lowest for more recent years**. This is indicated by the red columns in Figure 12, which denote the ten-lowest capture rates calculated from each set of rainfall and flow data sources. For both capture rates calculated from Gages and Runoff factors, all of the lowest ten capture-rate years occurred after 2003 (Figure 12A, Figure 12C). For capture rates calculated using naturalized flows, eight of the ten lowest capture-rate years occurred after 2003. These results suggest that watershed conditions affecting the generation of runoff into the Highland Lakes have changed over time, with less of the rainfall contributing to streamflow and thus available to refill the Highland Lakes.

Table 4 and Figure 13 present rainfall and capture rate data for the Highland Lakes watershed aggregated over four 21-year periods: 1940-1960, 1961-1981, 1982-2002, and 2003-2023. Data are presented as “Median,” “Mean,” and “Total” values over the 21-year periods where “Median” and “Mean” have their standard definitions and “Total” as it pertains to capture rates reflects the total inflows over the 21-years divided by the total rainfall over the same 21-years. Total rainfall and Mean rainfall have identical values.

As indicated, rainfall Median, Mean, and Total quantities demonstrate relatively little differences between each of the four 21-year periods, with higher values in the middle two periods. Median rainfall in 2003-2023 is lower than Median Rainfall in 1940-1960, yet Mean rainfall is slightly higher in the 2003-2023 period. Capture rates from the 2003-2023 period are consistently lower than all other periods, with the Median value less by 51% compared to the 1940-1960 period. Lesser declines are seen in the Mean and Total capture rates, demonstrating that calculation methods can produce different results yet with similar implications for watershed productivity.

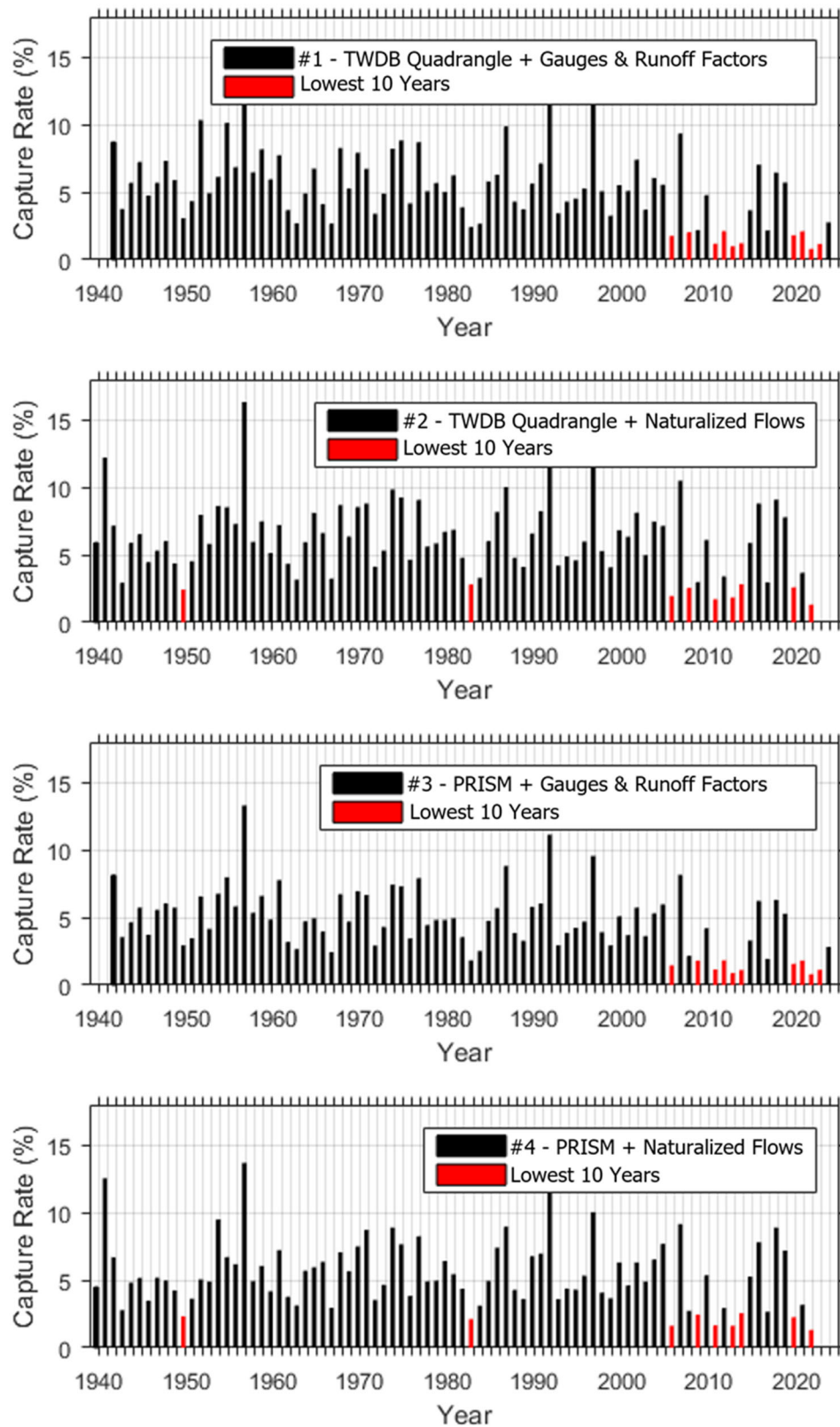


Figure 12 –Annual Capture Rates for the Highland Lakes Watershed, with various rainfall and flow combinations.

Would Central Texas have sufficient water supplies if
current rainfall patterns equaled those from
the 1950s Texas Drought?

Table 4 – Median, Mean, and Total Rainfall and Capture Rates for the Highland Lakes Watershed, computed over 4x21-year periods making up the WAM period of Record (1940-2023).

Median Values over Entire Highland Lakes Watershed			
Period	Rainfall (in/yr)	Capture Rate (%)	Change
1940-1960	25.17	5.3	N/A
1961-1981	26.50	5.3	0%
1982-2002	27.44	5.0	-6%
2003-2023	24.74	2.6	-51%
Mean Values over Entire Highland Lakes Watershed			
Period	Rainfall (in/yr)	Capture Rate (%)	Change
1940-1960	25.08	5.4	N/A
1961-1981	26.65	5.4	0%
1982-2002	27.48	5.5	+2%
2003-2023	25.94	3.9	-28%
Total Values over Entire Highland Lakes Watershed			
Period	Rainfall (in/yr)	Capture Rate (%)	Change
1940-1960	25.08	5.7%	NA
1961-1981	26.65	5.5%	-4%
1982-2002	27.48	5.8%	+6%
2003-2023	25.94	4.3%	-25%

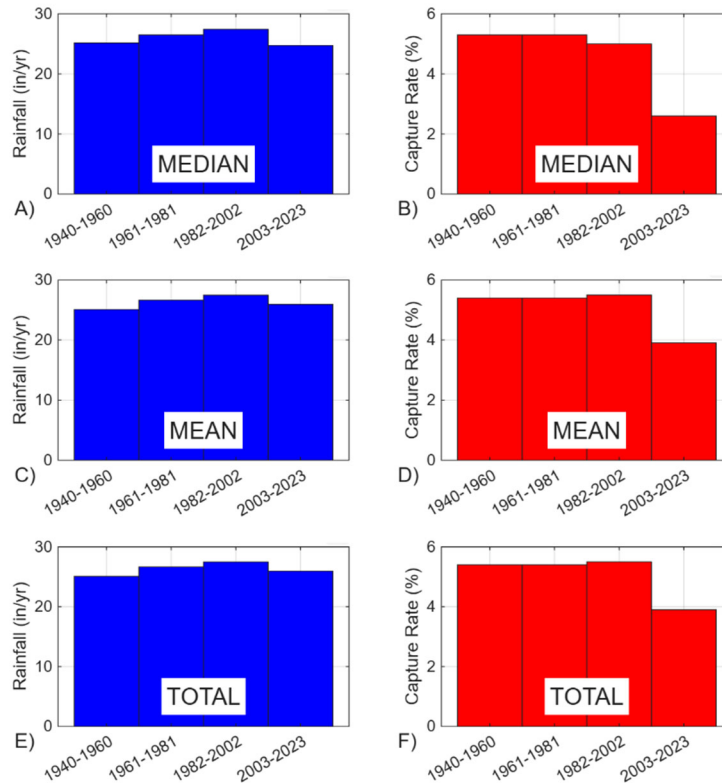


Figure 13 – Highland Lakes watershed data aggregated over 4x21-year periods making up the WAM period of record (1940-2023), A) median rainfall, B) median capture rates, C) mean rainfall, D) mean capture rates, E) total rainfall, F) total capture rate. **Note "Total" is defined for the entire 21 year period, and total rainfall is equal to mean rainfall on a yearly basis.

Causes of observed capture rate declines may be discerned through consideration of the hydrologic cycle as applied to the Highland Lakes watershed, and such assessments are beyond the scope of this current study. Some of the potential causes are listed below, and relative contributions of each potential cause to the overall watershed productivity have yet to be determined for the Highland Lakes. The TWDB has completed two studies investigating each of these potential causes (Kennedy, 2017; Furnans et al., 2019) yet has not derived any definitive conclusions regarding the combined or relative impact of each cause on watershed productivity. The net effect of all of these potential causes is observed within the capture rate data presented in Figure 12. The potential causes of declines in watershed productivity include:

- Changes in rainfall patterns and intensities
 - Changes in the frequency of large and small rain events
 - Changes in the duration of dry periods between rain events
- Changes in gross evaporation and transpiration rates
- Changes in groundwater tables for surficial aquifers
- Changes in land use/land cover within the watershed
- Changes in human/animal capture/consumption of rainfall (including within small ponds)

In general, water falling on a watershed will either soak into the ground, will run overland into the stream drainage network, or will return to the atmosphere through evapotranspiration. However, a fourth possibility is that the water will be intercepted and used directly by animals, including humans. Increases in land surface temperatures (during both day and night hours) tend to increase evaporation rates, and such temperature increases have been noted across the Highland Lakes watershed (Furnans et al., 2019). Transpiration has also increased, as mesquite and other higher water-consuming vegetation have replaced native flora across Texas (McLendon et al., 2012; Asquith and Bumgarner, 2014). Lowering of groundwater tables, through increased transpiration and/or increased groundwater usage will contribute to lowering the baseflow of streams and may even cause some streams in certain locations to transition from gaining streams (those which increase in flow due to groundwater influx) to losing streams (those which lose flow to infiltration into the underlying aquifers). Increases in groundwater development throughout the Highland Lakes region, both in outcrop aquifers and deeper confined aquifers, have lowered the artesian pressures in the groundwater systems (Deeds, 2024), and thus may have lowered the contributions of groundwater to streamflows. The lowering of groundwater tables also may result in greater infiltration of rainfall into the ground, resulting in less surficial runoff reaching streams. This is also related to changes in the land use/land cover patterns historically observed across the watershed, including the general increase in development and related impervious cover amounts across the watershed. Impervious cover changes, for example, may result in increased runoff to streams, with less overall infiltration across the watershed. The infiltration that does occur may also be focused on certain drainage areas only (through detention basins and via managed aquifer recharge). This geospatial alteration of recharge locations may affect subwatershed capture rates, causing either increases or decreases. cursory analyses of the subwatersheds within the study area, however, suggest that increases in impervious cover are minimal, and the watershed remains largely undeveloped.

Rainfall intensities and frequencies may also play a large part in altering watershed capture rates over time. In general, more intense rainfall will result in a greater volume of runoff entering the stream drainage network and will thus result in higher capture rates. In addition, if storms occur more frequently, successive storms will generate more runoff as infiltration into the groundwater system generally decreases. In contrast, if there is greater time between runoff-generating storm events, the overall streamflows will likely decrease, as the groundwater system will “dry out” more between the storms, resulting in greater groundwater infiltration potential for the successive storm events. There has been some evidence that Highland Lakes rainfall has been increasing in recent years, but this is caused by more frequent, lower intensity storms (Furnans et al., 2019). Such events would likely result in lower streamflows compared to the same number of higher intensity storms because a greater percentage of the rainfall volume is returned to the atmosphere (via evapotranspiration) or infiltrated into the ground.

Capture rates can also decrease over time if consumption of rainfall by humans and animals increases. This has been a concern for states such as Colorado, which initially banned household rainwater harvesting systems under the theory that such systems would result in a noticeable reduction in runoff and streamflow. Similarly, increases in local storage of streamflow, in stock or amenity ponds, would result in the reduction of runoff reaching streams and downstream water supply reservoirs. TWDB and LCRA have both performed studies on the impacts of such small ponds on water supplies yet have not produced peer-reviewed published conclusions regarding pond impacts on water availability (Furnans et al., 2019; LCRA, 2024). Slade (2020) presents the only peer reviewed report of streamflow depletion due to “minor reservoir” proliferation within the Highland Lakes watershed, where it was demonstrated that reduced inflows to Lake Buchanan could be linked to the increased storage from the ponds.

In theory, the construction of small ponds within a watershed would result in the capture of surface water runoff in the ponds; thus, preventing the runoff from reaching the watershed outlet. Streamflow from the watershed would be reduced, until all small ponds on the drainage network were full and unable to capture additional runoff. Evaporation from the watershed also increases with increases in the prevalence of small ponds, as there is greater water surface area from which water is lost through evaporation. LCRA (2024) and TWDB studies (Furnans et al., 2019) have demonstrated that the combined surface area of small ponds within the Highland Lakes watershed is comparable to the surface areas of Lakes Buchanan and Travis. Hence evaporative losses from these ponds can be an important factor in the water balance of the watershed, making less water available as runoff and inflows to the Highland Lakes.

5. Naturalized Flows, Rainfall, and Small Ponds

To answer the primary questions driving this research, it is necessary to consider how the current watershed conditions (including the existing small ponds) would respond to historical rainfall events to produce runoff and streamflow. Current practice in Texas is to use streamflow records to make water availability decisions. However as streamflow is dependent upon watershed productivity and rainfall patterns, it is important to consider whether water availability decisions may need to be adjusted if the factors that generate streamflow have changed within the watershed. This section provides an analysis of how the existence of small ponds within a watershed may alter the streamflow to be expected from historically observed rainfall events. This will lead to the assessment in the following sections regarding adjusting historical streamflow within LCRA's WAMs to account for changes in watershed conditions (including small ponds and other potential factors altering the rainfall-runoff response).

The TCEQ and LCRA utilize monthly naturalized flows to make water availability decisions throughout the Colorado River Basin. Naturalized flows are conceptual, non-verifiable streamflow values that are representative of the streamflows that would have occurred historically without the influence of humans. Human influence generally reduces streamflows through diversions yet may increase streamflow in certain locations due to return flow discharges. Streamflow is also generally reduced through the impoundment of water within upstream reservoirs. These reservoirs will receive inflows and capture the water behind the reservoir dam, subjecting the water to evaporation. Hence the existence of a reservoir has two impacts on streamflow: 1) downstream streamflow is altered as water is routed through the reservoir with reservoir inflows not necessarily equal to reservoir outflows, and 2) downstream streamflow is reduced because water is lost from the reservoir surface due to evaporation. In general, the naturalized flow (on a per unit time basis) downstream from a reservoir may be computed as:

$$Q_{natural} = Q_{observed,downstream} + A_{reservoir} \cdot E_{net} + D + \Delta S_{reservoir}$$

Where "Q" is the streamflow (acre-ft), "A" is the surface area of the reservoir (acres), "E_{net}" is the net evaporative loss rate of water from the reservoir (ft), "D" is the volume of water diverted from the reservoir (acre-ft), and "ΔS" is the change in storage within the reservoir (acre-ft). This is a simplified version of the flow naturalization equation used by TCEQ as it does not explicitly consider instream channel losses or return flows, yet is still illustrative of the naturalized flow concept as applied to this analysis.

As an example of the flow naturalization process, consider a reservoir that is 100 acres in size, experiences a net evaporation rate of 0.1 inch per day, experiences a 10 acre-ft increase in storage on the given day, and has a 3 acre-ft/day diversion. If the downstream stream gage registered 10 acre-ft on a given day, the naturalized streamflow at this location would be calculated as:

Would Central Texas have sufficient water supplies if
current rainfall patterns equaled those from
the 1950s Texas Drought?

$$Q_{natural} = 10 \text{ acre-ft} + (100 \text{ acres}) \cdot \left(\frac{0.1}{12} \text{ ft}\right) + 3 \text{ acre-ft} + 10 \text{ acre-ft}$$
$$Q_{natural} = 23.83 \text{ acre-ft}$$

In this example, if the reservoir were not present (and had the diversion not taken place), the measured streamflow of 10 acre-ft/day would have been over 2x higher at 23.83 acre-ft/day.

Water availability models used by TCEQ, LCRA, and regional water planning groups use the naturalized flows along with the planned or known diversions, existing (and planned) reservoirs, and measured evaporation rates to demonstrate how hydrologic systems could be operated under planned conditions using historical hydrology. One drawback of the calculation process, however, is that it requires significant amounts of data to make accurate naturalized flow computations. Ideally, every reservoir, pond, or impoundment within a watershed would be incorporated into the naturalized flows calculation process. This is necessary because every structure that retains water in the watershed will affect the downstream measured streamflow, and this effect is not “captured” by the flow naturalization process unless the structure is included within the process. This is irrespective of whether the structure is linked to a water right simulated in the WAM, as small ponds (without water rights) could be simulated as senior-most water rights with priority access to water. The effects of small ponds could also be addressed through changes to the Flow Adjustments (FAD) file used in some WAM simulations.

Traditionally, TCEQ and LCRA have only included within the flow naturalization process impoundments with storage capacities exceeding 5,000 acre-ft. The process has excluded the over 43,000 small ponds that now exist in the Highland Lakes watershed (Figure 14; Furnans et al., 2019; LCRA, 2024). Based on LCRA’s data, approximately 750 ponds were constructed each year between late 2015 and mid-2023, and no published studies exist that identify if additional ponds have been created in the three years since the end of LCRA’s study. All of these ponds capture streamflow or surface runoff that would otherwise eventually reach a stream network and be measured at a stream gage. These small ponds reduce the amount of streamflow measured at a stream gage, and this reduction is not accounted for in the flow naturalization process. The reduction in streamflow resulting from the small ponds yields lower naturalized flows for the region than those which would have resulted had the ponds not been constructed. The impacts of small ponds are therefore included in naturalized flow data developed after pond construction. However, for the period prior to pond construction, naturalized flows for the region would not reflect the existence of the ponds, even though the WAMs are designed to simulate current (or proposed) watershed conditions (which includes ponds) under past hydrology (which excluded the ponds). **As a result, the naturalized flows resulting from a rainfall event would be lower now than those naturalized flows resulting from the same rainfall event occurring at a time before the small ponds were constructed.** Specifically, a repeat of the low rainfall years during the 1947-1957 period would now result in lower streamflows due to the increased abundance of the small ponds within the current watershed. The current flow naturalization process does not take this into account as it focuses only on historical streamflow, not on historical rainfall and the watershed’s ability to convert rainfall into runoff and streamflow.

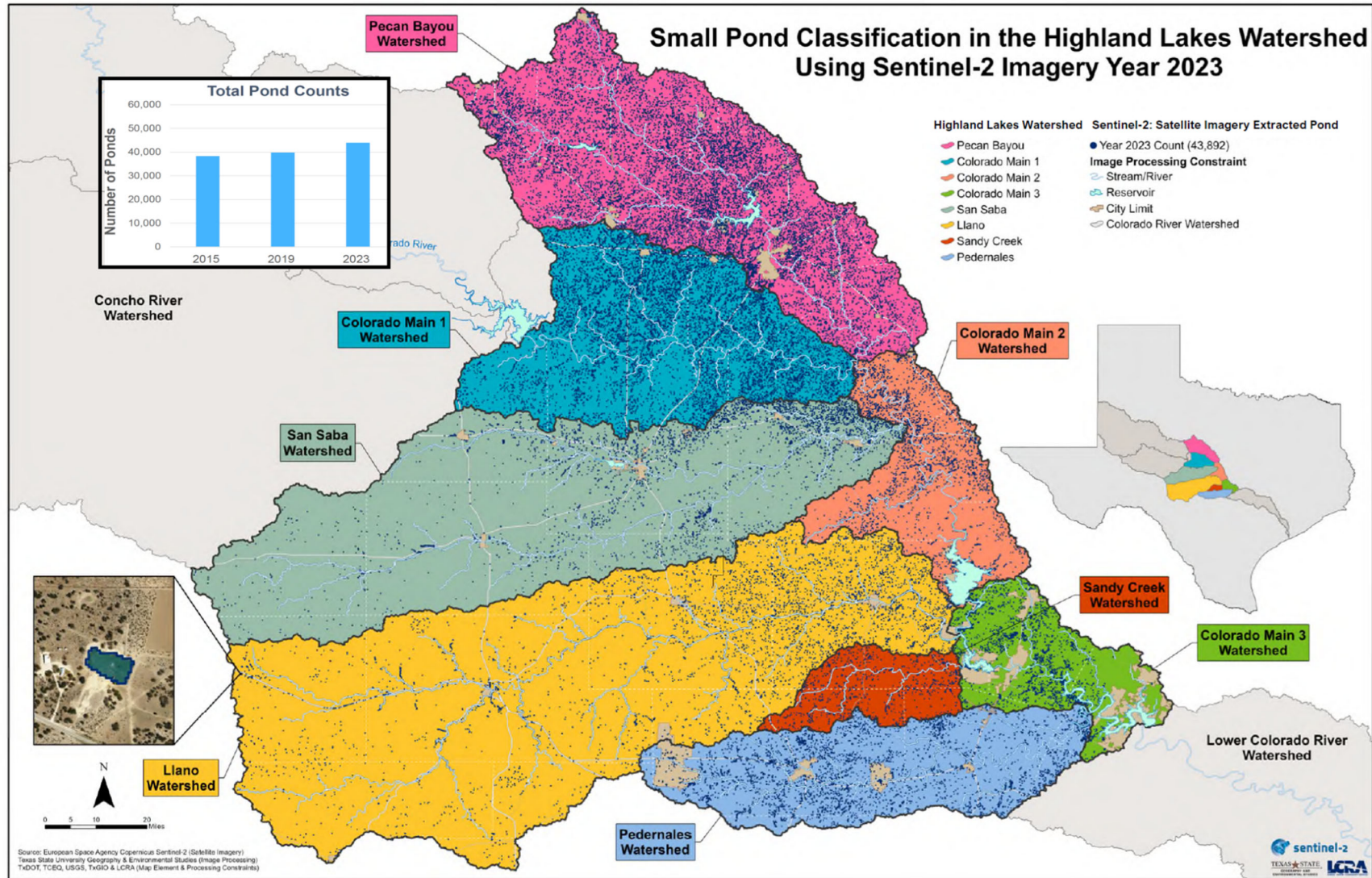


Figure 14 – LCRA & Texas State University small ponds study results, reproduced from LCRA (2024), showing ponds identified in the year 2023, and total pond counts increasing by approximately 750 per year from 2015 to 2023.

To further demonstrate the impact of small ponds, reservoirs, and impoundments on a watershed, consider another hypothetical example linking rainfall totals to runoff and inflows using the standard Soil Conservation Service (“SCS”) curve number method (Andrews, 1954; USDA, 1964). This method is a standard hydrologic method used to calculate runoff from rainfall events and has been used in thousands of applications worldwide (Mishra and Singh, 2003). The method may ultimately prove too simplistic for full application to the Highland Lakes watershed (Sreejith et al., 2024), yet it is sufficiently illustrative of the rainfall-runoff concept for use in explaining small pond impacts on streamflow.

Under the SCS Method, a given land surface is assigned a “curve number” based on its land use type, antecedent moisture condition, and soil group. Curve numbers run from 30 to 100, with 100 representing 100% of the rainfall will become runoff, and lower numbers representing less runoff and greater water infiltration into the soil. According to the SCS Method, during any initial rain event, rainfall will first infiltrate the soil, and only after sufficient infiltration will runoff begin to be generated. Formulas (using US units) for the runoff depth (P_e), initial abstraction (I_A) depth, and continuing extraction depth (F_A) are based on the curve number (CN):

$$\begin{aligned} S &= \frac{1000}{CN} - 10 \\ I_A &= 0.2S \\ P_e &= \frac{(P - I_A)^2}{P - I_A + S} \\ F_A &= P - I_A - P_e \end{aligned}$$

Consider now an example 100-acre watershed within the Highland Lakes watershed with a curve number of 85, a stream gage at the watershed outlet, and two ponds constructed on the stream in 2001. In this example with a 3” rainfall event the initial abstractions (I_A) would equal 0.35” of rain, signifying that runoff would not start until this depth of rain had fallen. The total volume of runoff would be given by the runoff depth (P_e , computed as 1.59”) multiplied by the watershed area, or 13.25 acre-ft. For the time before 2001 when the ponds were not present in the watershed (as in the 1947-1957 drought period), the entire 13.25 acre-ft of runoff would become measured streamflow and would have therefore been included in any flow naturalization process. However, for the time since pond construction in 2001, some portion of that runoff would be needed to fill the ponds before the runoff would continue downstream and become measured streamflow. This situation is shown in Figure 15, where the original stream receives flow Q at all locations, yet the original stream with ponds only produces downstream flow at the stream gage location if Pond A and Pond B are full. In this scenario with the ponds, if the combined volume deficit (defined as the volume of water needed to fill the ponds) of Pond A and Pond B is greater than 13.25 acre-ft, then all of the runoff from this example storm event will be captured within the ponds and will not contribute to streamflow at the downstream gaging station. As such, with the ponds, none of the example runoff will become measured streamflow at the gage and therefore none will be included in any flow naturalization process for the stream/watershed.

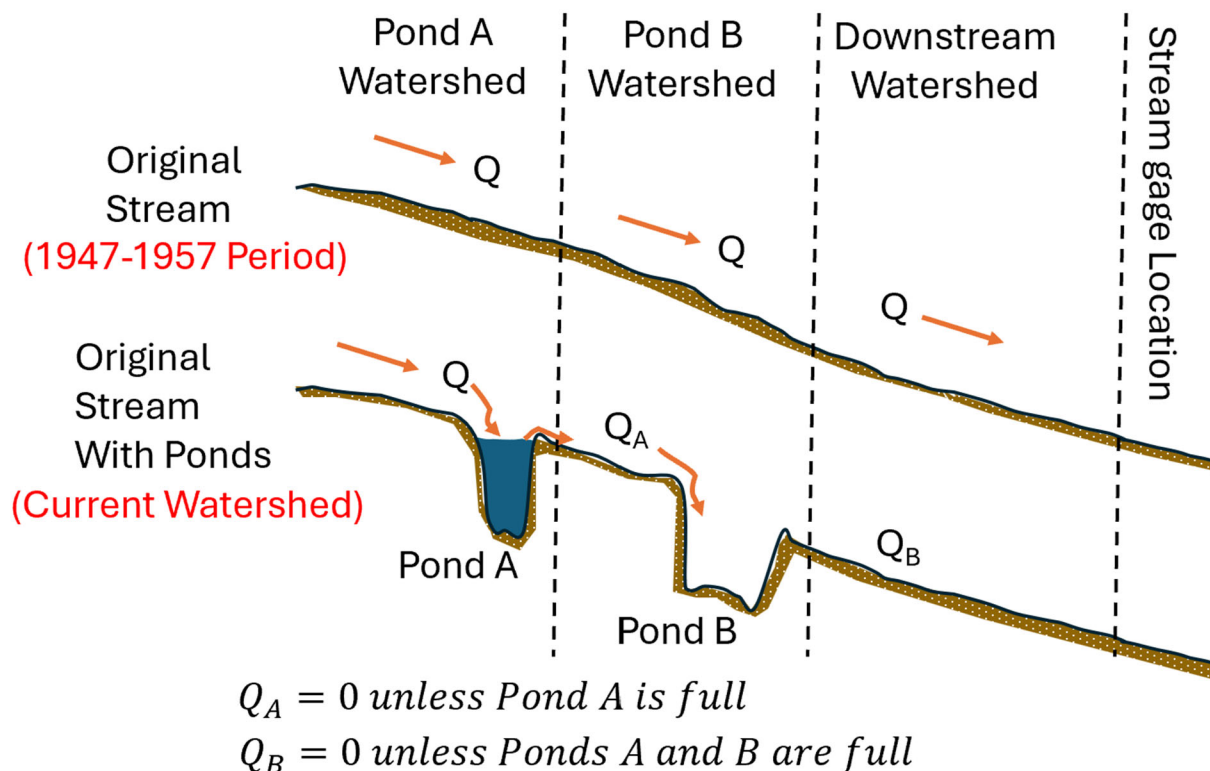


Figure 15 – Streamflow (Q) reductions as ponds capture runoff before flows reach the stream gage location. Flow progresses from left to right, and flow will pass the ponds only when ponds are full.

Continuing with this above example, if ponds A and B are initially empty and have a combined storage of 10 acre-ft, then the available runoff of 13.25 acre-ft would fill up the ponds. This would result in 3.25 acre-ft of water flowing out of Pond B, which would be measured at the downstream gaging station and would become part of the current flow naturalization process. In this instance, the ponds would reduce the productivity (i.e. runoff) from this watershed by approximately 75%. Similarly, for a current storm event to produce the same 13.25 acre-ft of runoff downstream of Ponds A and B (after first filling both ponds), the runoff depth would need to be 2.79" (using the SCS method equations), and thus the total rainfall depth would need to be 4.37". Therefore to produce the same amount of runoff after the pond construction, rainfall would need to be 45.6% greater than it would have needed to be historically, before pond construction.

The above example regarding streamflow and ponds illustrates the impact that ponds can have on downstream gaged streamflow resulting from a given rainfall event. In Section 2 it was demonstrated that annual rainfall totals for the Highland Lakes have not exhibited any statistically significant trends over the past 131 years. As such, it is probable that historical rainfall totals will be observed into the future, and that the Highland Lakes watershed will again experience low rainfall totals as observed during the 1947-1957 drought. However, if the current watershed were to receive that same rainfall, it would produce less runoff and less streamflow, because of the existence of small ponds now which did not exist during the 1947-1957 drought (as conceptually illustrated in the above example). This scenario could possibly result in a

drought worse than the current 2008-2016 drought of record. The current watershed is different than the historical watershed, and it would produce less streamflow in part because of the proliferation of the small ponds, and in total because the watershed productivity has decreased (likely due to multiple causes, including the proliferation of ponds). **Thus to address the question of water availability now if historically low rainfall totals were to occur, it is necessary to include watershed productivity within a modified flow naturalization process.**

One approach to addressing changing watershed productivity within the flow naturalization process would be to expand the process focus from only streamflow to also including rainfall. This would require the development of detailed rainfall-runoff models to predict available streamflow that would have resulted from historical rainfall patterns falling on the current watershed (including all of its ponds). The predicted available streamflow would become the naturalized flow data input into the WAMs. The complexities of such an effort were beyond the scope of this current project, yet the approach warrants further consideration for implementation within LCRA's WAM models for the region.

As an alternative approach to conducting a large-scale rainfall-runoff analysis, in this current project historically calculated naturalized flows were adjusted based on the capture rate and watershed productivity concepts. These adjustments effectively account for all the possible processes that lower a watershed's efficiency at producing runoff, including, but not limited to, the effects of small ponds. The next sections detail how naturalized flows were modified according to a comparative capture rate-based analysis and demonstrate the effect of these modifications on the firm yield of the Highland Lakes as well as on LCRA's proposed 2032 WMP.

6. Water Availability Modeling & Capture Rate Adjustments

As observed in previous sections, the lowest rainfall totals for the Highland Lakes most often occurred during the 1945-1957 drought period, and the lowest capture rates occurred primarily during more recent years. The “Drought of Record” for the Highland Lakes watershed has been defined as the drought that occurred from 2008-2016, as this was the period with the lowest cumulative inflows to the Highland Lakes. However, rainfall totals during the 2008-2016 period were generally larger than the rainfall totals that occurred during the 1950s drought. Inflows during the 1945-1957 drought period were higher than those during the 2008-2016 drought period. From this observation, it is possible to conclude that the Highland Lakes watershed was more productive at translating rainfall into runoff during the 1950s than during current times. This raises the question:

“Would a repeat of the rainfall from the 1950s drought period, combined with the lower watershed productivity of recent years, result in conditions worse than the current drought of record?”

If so, then the firm yield from the Highland Lakes system would be lower than currently reported. LCRA defines the firm yield as the maximum amount of water that may be diverted annually from the Highland Lakes system. The firm yield is effectively established during a modeled drought period and is defined when the WAM-modeled combined storage of Lakes Travis and Buchanan are driven to zero inventory for a single month. LCRA can commit firm water only up to the firm yield, because firm supply must be met with 100% reliability within the WAM. Given that LCRA has already issued water contracts for a majority of its estimated firm yield (LCRA, 2026A), having a lower than reported actual firm yield could mean that LCRA’s Highland Lakes supplies could be insufficient to meet all firm customer needs. To address this question as part of this study, adjustments were made to the naturalized flows within the LCRA-developed WAMs used to compute firm yield and assess WMP conditions for the Highland Lakes watershed during the ongoing 2032 WMP revision process. The naturalized flows adjustments were based on recent and historical capture rates.

Application of Naturalized Flow Adjustments

WAM simulations are based on naturalized flows, and these flows are specified as model inputs at defined locations called “control points.” The model input files define the drainage network within a watershed (or subwatershed) based on the control points, with each control point linked to the next downstream control point to which it contributes flow. Water rights and reservoirs must be defined at control point locations, as modeled water allocations to water rights occur only at defined control points. Within the WAM, “primary” control points are those for which naturalized flows are specified as model input. “Secondary” control points are intermediate

Would Central Texas have sufficient water supplies if
current rainfall patterns equaled those from
the 1950s Texas Drought?

points within the modeled drainage network, and the WAM calculates flows at those locations based on nearby primary control point flows and user-defined drainage area ratios.

Within the Highland Lakes watershed, there are 19 primary control points, from which 18 subwatersheds may be defined (Figure 16). The most downstream primary control point is I20000 and corresponds with the outlet location on Lake Travis. The most upstream primary control point on the Colorado River is D20000 and is located downstream of OH Ivie Lake. Each subwatershed is defined as the area draining to a primary control point and is either limited on the upstream end by a watershed divide or an upstream primary control point. Figure 16 shows a small subwatershed between point D20000 and the outlet of OH Ivie Lake; this subwatershed is excluded from this analysis so that control point D20000 can be considered the upstream limit of the Highland Lakes watershed.



Figure 16 – Primary Control Points and associated subwatersheds within the Highland Lakes Watershed.

Figure 17 is a schematic representation of the primary control points and corresponding subwatersheds in the Highland Lakes System and also shows the primary control points on the Colorado River between the Lake Travis outlet and the Gulf of Mexico. Adjustments to naturalized flows specified for any given control point must be propagated downstream to ensure mathematical continuity within WAM simulations. For example, if the flows specified at control point E40000 were reduced from 200 acre-ft/month to 100 acre-ft/month, the flows at all primary control points directly downstream of point E40000 must also be reduced by 100 acre-ft/month. In this example, reductions are required at points E30000, E10000, F10000, I40000, I20000, and at all points on the Colorado River downstream from Lake Travis. It would not be necessary, however, to reduce the flows at point E20000 as this point is not directly downstream of control point E40000. As currently implemented, channel losses (or gains) between control points are not considered within this alteration effort. Yet using this scheme, channel losses are still included as specified within the WAM (via the model input *.DAT file).

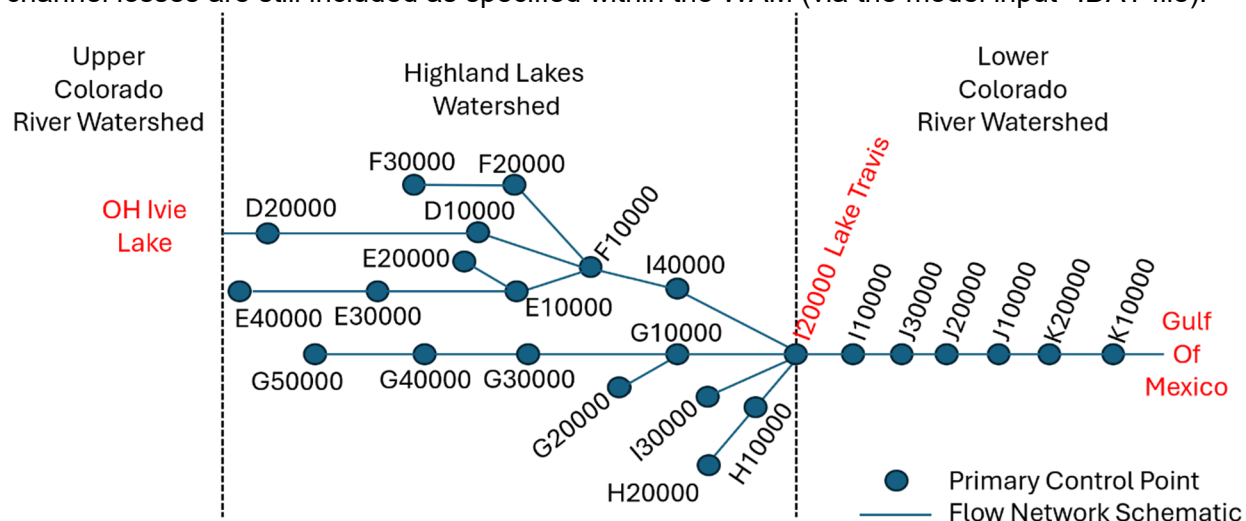


Figure 17 – Schematic illustrating the primary control point connectivity in Colorado River Basin WAM.

Using the WAM-specified naturalized flows for each control point as well as the PRISM rainfall data summed over each subwatershed area, monthly and annual capture rates were computed. For subwatersheds defined based on upstream and downstream control points, the watershed outflow volume was computed as the difference between the flows at the downstream and upstream control points. This “incremental flow” for the subwatershed was then compared to the subwatershed rainfall volume to estimate the capture rate. Monthly and annual capture rates for each subwatershed (and for the Highland Lakes watershed in total) are provided in the “HighlandLakes_CaptureRate_Calculations_09072026” spreadsheet available from CTWC upon request (directed via email to Info@CentralTexasWaterCoalition.org).

Based on these capture rates, adjustments to naturalized flows were computed using one of four proposed methods. The objective of the adjustments was to assess the impact of receiving historically recorded rainfall on the current watershed, noting that the current watershed is generally less efficient in transferring rainfall into inflows to the Highland Lakes. Changes resulting from each adjustment method were applied separately to each of the 18 subwatersheds. Adjustments were then propagated downstream, resulting in changes to the

naturalized flows simulated at all primary control points shown in Figure 17. No adjustments were made to other primary control points within the Colorado Basin WAM and not shown in Figure 17, including all primary control points upstream of OH Ivie Lake (upstream of point D20000).

Within the WAM, naturalized flows are specified as monthly values, allowing the WAM user to effectively ignore water's travel-time between points within the modeled flow network. In this analysis, however, each of the four methods for assessing adjustment rates was derived based on annual rainfall and capture rate data. This was intentional, as making adjustments based on annual values lessens the impact of the timing of rainfall events on capture rates. For example, if a large rain event were to occur at the end of a month, the corresponding inflow (or runoff) may not be included in the values computed for that month; the natural time-lag of the rainfall-runoff process may cause the inflows to be measured and included in totals for the next month. This would lower the capture rate for the month when the rainfall occurred and increase the capture rate for the following month. Capture rates based on an annual calendar will not reflect this potential timing-based inaccuracy (unless the rainfall occurs in late December), and so may be more representative of true watershed rainfall response behavior. Adjustment rates were calculated annually and were applied to monthly sets of naturalized flow data, with the same rate initially applied uniformly to each month of the calendar year. Assessing the "time of concentration" of runoff within each subwatershed could yield insight into the appropriateness of monthly versus annual adjustment rates; this task is reserved for future study.

Initial WAM simulations using this approach suggested the need for further alterations to how adjustment rates were applied to monthly naturalized flow datasets. For example, in September 1952 there was a large storm event that generated intense flooding on the Pedernales River and caused significant inflows into the Highland Lakes (See Figure 7B). The intensity of that rain event would have also been likely to generate significant runoff (and inflows) under current watershed conditions. This suggested that adjustment rates should not be applied during months when large volumes of runoff (or inflows) were generated. To set a threshold defining when adjustment rates should be applied, the 75th percentile capture rate by subwatershed for the 1940-1960 period was used. For any month where the computed monthly capture rate exceeds the 75th percentile monthly capture rate for the subwatershed, naturalized flow adjustments were not applied. This preserved naturalized flows resulting from more intense storm events, including the September 1952 flooding event on the Pedernales River. Utilizing a different percentile threshold (either higher or lower) would also potentially alter when capture rate adjustments were applied, which could also alter the overall modeling results presented herein.

Each of the four proposed methods of defining naturalized flow adjustments based on the comparison of capture rates have pros and cons with respect to their application. Each method is also partially based upon classifications of the calendar year being either "Wet," "Dry," or "Average" based on the annual rainfall total. Specifically, "Wet" years are those with an annual total rainfall exceeding the 75th percentile rainfall total for the period of record (1895-2025 for the

PRISM dataset). Similarly, “Dry” years had a rainfall total less than the 25th percentile rainfall total. Average years had rainfall totals in between the 25th and 75th percentiles.

Table 5 provides the number of years falling into each rainfall category (as defined for the Highland Lakes watershed), over the 84-year WAM period of record as split into 21-year sections (as in Figure 13 and Table 4). As shown, the 1940-1960 period contained the largest number of “Dry” years as well as the largest number of “Wet” years, compared to the other 21-year periods. This 1940-1960 period fully encompasses the historic 1945-1957 drought period which was the drought of record for the Colorado River Basin until the 2008-2016 drought period. The 2003-2023 period, which includes both the 2008-2016 current drought of record and most of the 2019-2026 drought period exhibits basically the same distribution of Dry, Average, and Wet years as occurred over the two prior 21-year periods (which did not experience significant droughts). This suggests the current droughts are not as influenced by the lack of rainfall as was the historic 1945-1957 drought period.

Table 5 – Frequency of Wet, Average, and Dry Years by 21-year portions of the WAM period of record, for the entire Highland Lakes Watershed.

Time Period	Number of Years By Rainfall Category		
	Dry	Average	Wet
1940-1960	8	6	7
1961-1981	4	12	5
1982-2002	4	11	6
2003-2023	4	12	5

Each of the four proposed methods for defining naturalized flow adjustments uses data from the 2003-2023 period in comparison to data from the 1940-1960 period. When applying each method, adjustments are made only to the monthly naturalized flows specified for the 1940-1960 period. **These adjustments attempt to reflect how the current watershed would produce different (and likely lower) streamflows under the historically observed rainfall conditions.** Each method also accounts (to varying degrees) for the fact that spatial and temporal averaging will tend to reduce the impact of local intense rain events and inflow-inducing flooding. Flow adjustments were not made for either the 1961-1981 or 1982-2002 periods because neither period contained a drought period likely to become a drought of record (even with modified naturalized flows). The following sections detail each of the four methods used in creating systematic adjustments to naturalized flows. The methods become progressively more complex and rigorous in an effort to better capture the spatial and temporal variability of rainfall patterns across the Highland Lakes watershed.

Method #1 – Simple Reduction in Dry Years

Under this purposefully and overly simplistic method, naturalized flow adjustments are computed separately based on the classification of the year with respect to rainfall. The process is applied identically to each subwatershed, yet designations of “Wet,” “Average,” and “Dry” years are based on analyses of rainfall totals over the individual subwatershed (from 1895-2025). As such, it is possible for a given year to be considered “Wet” for one subwatershed, yet to be considered “Dry” for a different subwatershed. For the “Dry” years from 1940-1960, this method reduces the monthly capture rate (and the monthly naturalized flow) by 50%. For example, if the originally computed capture rate for May 1950 (a dry year) was 5% and rainfall volume for that month amounted to 5,000 acre-ft, then the original naturalized flow from this watershed would have been 250 acre-ft/month. With the 50% adjustment, the modified naturalized flow would become 125 acre-ft/month. This reduction of 125 acre-ft/month would then propagate downstream as an equal adjustment to all downstream primary control points. The 50% reduction rate is generally representative of the reduction in capture rates as computed for the entire Highland Lakes watershed in 2022 (0.90%, rounded up to 1%) compared with the capture rate computed in 1950 (2.28%, rounded down to 2%).

This method is intentionally simplistic and unscientific in its approach to adjusting naturalized streamflows. It largely ignores spatial and temporal variability in capture rates and rainfall patterns. Results from this method are presented for the purposes of discussion, to help demonstrate the effects of naturalized flows reductions on computed water availability in the Colorado River Basin. Under this method, naturalized flows for “Average” and “Wet” years were unaltered. This method may, however, be a reasonable estimate of the broad decline in watershed productivity observed when comparing current and historical dry years.

Method #2 – Direct Year to Year Comparison

Under this method, annual adjustments are made by direct comparison between years with similar rainfall totals. This method requires professional judgement of the hydrologist implementing the adjustments. Results are therefore subject to interpretation and debate, as different hydrologists may make different adjustments based on each’s analysis of the presented data. The adjustment steps are as follows:

- Classify each year as a “Wet,” “Average,” or “Dry” for a given subwatershed, following the approach described under Method #1
- Compare 1940-1960 and 2003-2023 periods separately for each year classification
 - Make adjustments to the 1940-1960 period naturalized flows based on observed trends or comparisons between the 1940-1960 and 2003-2023 period annual rainfall totals and capture rates.

To illustrate the adjustment rate calculation process and its reliance on professional judgement, an analysis is presented using data from subwatershed #1 for dry years (Table 6). As shown, there were 8 dry years in the 1940-1960 period, with rainfall totals ranging from 10.9 inches to

23.9 inches. In contrast, for the 2003-2023 period there were only 5 dry years, with rainfall totals ranging from 14.9 inches to 23.8 inches. In both 2005 and 2019, relatively large rain events occurred within the year, resulting in large flooding events and large inflows, which resulted in the high captures rates. As the rainfall was concentrated in 1-2 events in those years, and not more evenly distributed across the calendar year, these anomalous years were excluded from the adjustment analysis. The remaining recent dry years (2008, 2011, and 2022) had very low capture rates, with 2022 not resulting in any additional naturalized flows derived from rainfall on the subwatershed. In general, median capture rates from the 2003-2023 period were significantly lower than those from the 1940-1960 period, suggesting that naturalized flow reductions should also be significant.

Table 6 – Sample Adjustment Rate Calculations for Subwatershed #1, Dry years

Subwatershed #1								
1940-1960 Dry Years						2003-2023 Dry Years		
Year	Rainfall (in)	Capture Rate		Adjustment Rate	Adjusted Capture Rate		Capture Rate	Rainfall (in) Year
1943	22.6	4.18%		50%	2.09%		11.80%	20.5 2005
1947	21.9	6.71%		100%	6.71%		0.24%	15.4 2008
1948	21.7	2.71%		50%	1.36%		0.56%	14.9 2011
1950	19.8	2.27%		50%	1.14%		10.81%	23.8 2019
1951	19.7	1.29%		50%	0.65%		0.00%	17.5 2022
1953	23.9	3.32%		50%	1.66%			
1954	10.9	1.83%		33%	0.61%			
1956	13.9	0.83%		33%	0.28%			

Note: the 0.00% capture rate for Subwatershed #1 in 2022 is correct, indicating that the watershed did not produce any inflows for this year.

In making the adjustment rates for each year, comparisons of annual rainfall totals and capture rates were made and evaluated. For example, rainfall totals in 1954 were low (10.9 inches), yet the capture rate was 1.83%, a relatively high capture rate compared to those from 2008, 2011, and 2022. The adjustment rate for 1954 was set to 33%, as this is roughly the ratio of the capture rate from 2011 compared to the capture rate from 1954. The adjustment rate for 1947, however, was set to 100% which means that the naturalized flows for that year were not adjusted. This is because 1947 showed a relatively high capture rate, and likely indicates it was influenced by 1-2 intense storm events which would generate a large amount of inflow in a short period. Such large, intense storm events would likely still produce a large amount of inflow under current watershed conditions, so the naturalized flows for 1947 were not adjusted. Adjustment rates for other years were selected based on ratios of capture rates, with a floor-value adjustment of 33%.

Adjustment rates derived under Method #2 are subjective and time-intensive to develop, relying on professional judgement of the hydrologist reviewing the data. They can, however, be based on other factors known to the hydrologist but not inherent in the annual rainfall data and capture rates. This method does provide some flexibility of interpretation regarding appropriate adjustment rate values.

Method #3 – Random Adjustments within a Defined Range

Within this method, naturalized flow adjustments are made randomly according to the rules presented below, with the adjustments limited to a range of values indicated by the annual capture rates computed for the 1940-1960 and 2003-2023 periods. The adjustment creation steps are as follows:

- Classify each year as a “Wet,” “Average,” or “Dry” year for a given subwatershed, following the approach described under Method #1.
- Compute annual capture rates for the given subwatershed.
- For all Dry years within the 1940-1960 period, determine the minimum and maximum capture rate.
- For all Dry years within the 2003-2023 period, determine the minimum and maximum capture rate.
- Compute the change in the minimum capture rate between the 2003-2023 and 1940-1960 periods, as a percentage of the 1940-1960 period’s capture rate. This becomes the lower-bound of the capture rate adjustment range.
- Compute the change in the maximum capture rate between the 2003-2023 and 1940-1960 periods, as a percentage of the 1940-1960 period’s capture rate. This becomes the upper-bound of the capture rate adjustment range.
- Compute the adjustment factor by multiplying a random number (between 0 and 1) to the capture rate adjustment range and adding the result to the lower bound. As performed in Microsoft Excel, the random numbers have a uniform distribution so that any value within the distribution range is equally likely to occur.
- Repeat the steps for all “Average” and “Wet” years.

Consider the following example to illustrate the process of adjusting naturalized flows under Method #3, using the data from Table 6. A subwatershed had minimum and maximum capture rates (in Dry years) of 0.83% and 6.71% in the 1940-1960 period, and of 0.00% and 11.80% in the 2003-2023 period. In comparing the minimum capture rates, the 2003-2023 minimum is a 100.0% **reduction** of the minimum from the 1940-1960 period (i.e., it decreased from 0.83% to 0.00%). In contrast, the maximum 2003-2023 capture rate is a 75.9% **increase** compared to the maximum from the 1940-1960 period (i.e., it increased from 6.71% to 11.80%). The resulting adjustment range is therefore -100.0% to +75.9%. If the assigned random number (derived from a random number generator) is 0.345, then the computed adjustment factor would be:

$$Adjustment = ([75.9\%] - [-100.0\%]) * 0.345 + (-100.0\%) = -39.3\%$$

If the original naturalized flow value was 50 acre-ft/month, then the adjusted naturalized flow would be 50 acre-ft/month * (100%-39.3%) = 30.4 acre-ft/month.

This method allows for naturalized flows to be adjusted downward or upward based on the range of capture rate values observed over the two periods. As it utilizes a random number generator, this method will result in different adjustments every time the method is implemented. It utilizes different random numbers for each subwatershed, year, and rainfall category. Multiple

invocations of this method could be used to assess the variations in WAM results that may be expected given uncertainty in input data and modification assumptions. Assessing the range in firm yields and reservoir storage levels resulting from invocations of Method #3 is demonstrated in Section 7.

Method #4 – Median Capture Rates by Rainfall Category

This fourth method of determining adjustment rates was derived in order to avoid subjective interpretations yet still maintain spatial and temporal variability. In this method, naturalized flows from 1940-1960 are adjusted based on the relative values of median capture rates for dry, average, and wet years. The adjustment rate creation steps are applied to individual subwatersheds as follows:

- Classify each year as a “Wet,” “Average,” or “Dry” year for a given subwatershed following the approach described under Method #1
- Determine the median capture rate for years in each rainfall classification category
- Set the adjustment rate as the ratio of the 2003-2023 median capture rate to the 1940-1960 median capture rate for the given category.

Using the dry year data for subwatershed #1 (Table 6), the median capture rate for the 2003-2023 period is 0.56%. The median capture rate for the 1940-1960 period is 2.49%. The adjustment rate is calculated as the ratio of these two medians:

$$adjustment\ rate = \frac{0.56\%}{2.49\%} = 22.5\%$$

According to Method 4, naturalized flows in subwatershed #1 will be reduced to 22.5% of their original value for dry years within the 1940-1960 period. Differing adjustment rates will be calculated and applied for average and wet years, and there is nothing limiting the adjustments so as to only reduce naturalized flows; naturalized flows could increase as a result of this method's application.

The benefit of adjustment rates calculated from Method #4 is that the adjustments are based on median values calculated over a 21-year period. This limits extreme occurrences (droughts or floods) from influencing the adjustment amount, and it takes into account longer-term changes in the watershed's efficiency in converting rainfall to runoff and inflows. Specifically, it looks at all the years per rainfall category within each 21-year period and utilizes a “middle of the road” approach to estimating watershed efficiency changes between the two periods.

7. WAM Modeling Results

The effect of the adjustment of the naturalized flows was assessed for two different scenarios following the processes developed by LCRA in its 2032 WMP revision. In each scenario, WAM runs were undertaken using the modified 1940-1960 naturalized flows, combined with the unmodified 1961-2023 naturalized flows.

The first set of model runs used the “firm yield model,” as developed by LCRA for the 2032 WMP revision process, yet without the 2032 sedimentation rates included. In this case, the WAM used was the LCRA’s firm yield WAM from June 2025, which was made public prior to LCRA’s adjustments of the reservoir stage-area-capacity relationships. This June 2025 WAM was updated in July 2026 after LCRA revised its official naturalized flows dataset, so the model used in this effort differs from LCRA’s “final” firm yield model only by the simulated reservoir storage capacities (affected by sedimentation rates). LCRA uses its firm yield WAM to calculate the firm yield of the Highland Lakes system based on potentially allowing both Lakes Buchanan and Travis to empty completely during the drought of record. The calculated firm yield represents the maximum amount of firm water LCRA can sell to firm contract holders capable of receiving water from the Highland Lakes system.

The second set of model runs used the LCRA 2032 WMP WAM, which simulates expected 2032 demands and sedimentation conditions with water management requirements related to instream and environmental flows, as well as interruptible releases for irrigation (LCRA, 2026). The version used was also from June 2025, and it also did not include LCRA’s 2032 sedimentation rates (but did incorporate LCRA’s revised naturalized flows from July 2026). The LCRA 2032 WMP WAM was developed through LCRA’s WMP revision process and is used to assess impacts of water management policies LCRA intends to enforce through 2032 (when a subsequent WMP revision may be developing). The water management policies included within the LCRA 2032 WMP WAM were designed so that water would be available to meet expected firm customer needs and to provide some defined quantities of interruptible water for use by downstream irrigation operations and for satisfying environmental flow requirements. The policies were also developed so that the modeled minimum combined storage of Lakes Travis and Buchanan would not drop below 600,000 acre-ft at any time. This threshold reflects a priority of LCRA stakeholders and TCEQ, and was heavily debated by stakeholders during the WMP revision process. Per LCRA’s WMP rules/guidelines (LCRA, 2020), combined storage levels below the 600,000 acre-ft threshold should cause the declaration of a drought worse than the drought of record (DWDR; LCRA, 2020), resulting possibly in firm water use curtailment, loss of water supply for some firm customers, and water rationing.

Firm Yield Modeling

For the first set of runs using the firm yield model, all water rights are simulated to their full, permitted capacity. Fifteen model runs were conducted, with the first utilizing the LCRA original unmodified naturalized flow dataset, and with runs 2-5 using the modified naturalized flows datasets derived from the applications of Methods #1-#4, respectively. Runs #6-15 were

repeated simulations using the Method #3 modifications, which vary for each instance. For each simulation, the WRAP program was set using the “FY” code, forcing the model to iterate demands on the water right “61405482001C” until the modeled combined storage just reached zero (or near zero) acre-ft for one simulated month. After the FY simulations were conducted, the water right 61405482001C was modified to simulate the annual target from the FY simulations, and model results for the FY scenario were produced. Firm yield quantities were calculated according to the procedures outlined by LCRA in Technical Paper A-5, available in “draft” form on LCRA’s website and dated January 2026 (LCRA, 2026).

Figure 18 presents the modeled combined storage of Lakes Buchanan and Travis resulting from simulations using LCRA’s original naturalized flow dataset and modified according to Method #4. Plots of modeled combined storage resulting from applications using Methods #1-#3 look visually indistinguishable from that presented in Figure 18 and were excluded for clarity purposes. The firm yields and critical periods for each scenario are provided in Table 7, with the critical period defined as the modeled time (month and year) from when the lakes were empty backward to the modeled time when the lakes were last full.

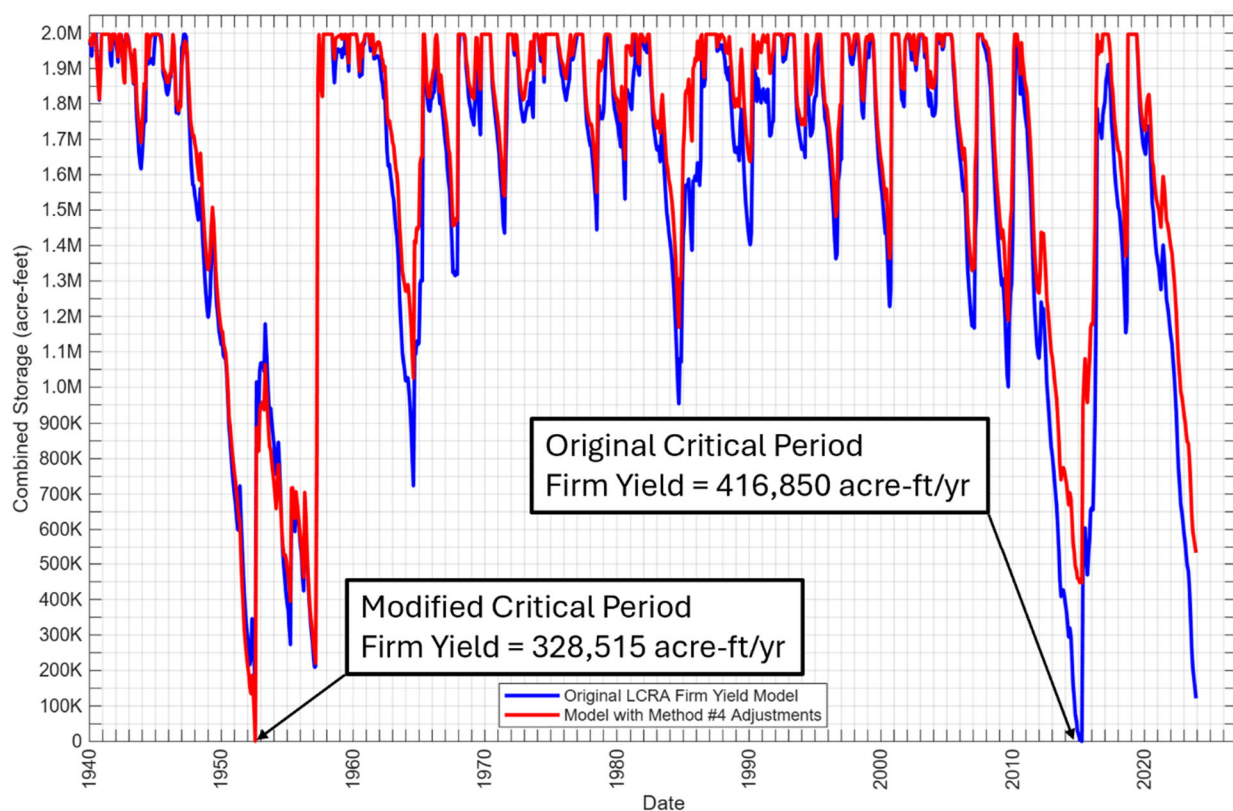


Figure 18 – Firm Yield WAM results – comparing the modeled combined storage of Lakes Travis and Buchanan using the original and modified naturalized flow datasets.

Table 7 – WAM Modeled Firm Yields and Critical Periods

Model Run	Modeled Scenario	Firm Yield	Reduction		Critical Period
		Acre-ft/year	Acre-ft/year	Percentage	
1	LCRA Original Flows	416,850	NA	NA	10/2007-4/2015
2	Method #1	373,244	43,606	10.5%	6/1946-8/1952
3	Method #2	344,704	72,146	17.3%	6/1946-8/1952
4	Method #3, Run 1	364,407	52,443	12.6%	5/1947-8/1952
5	Method #4	328,515	88,335	21.2%	6/1946-8/1952
Method #3 Runs					
4	Method #3, Run 1	364,407	52,443	12.6%	5/1947-8/1952
6	Method #3, Run 2	345,551	71,299	17.1%	6/1946-8/1952
7	Method #3, Run 3	351,826	65,024	15.6%	6/1946-8/1952
8	Method #3, Run 4	350,359	66,491	16.0%	6/1946-8/1952
9	Method #3, Run 5	354,776	62,074	14.9%	6/1946-8/1952
10	Method #3, Run 6	368,819	48,031	11.5%	6/1947-8/1952
11	Method #3, Run 7	345,584	71,266	17.1%	6/1946-8/1952
12	Method #3, Run 8	363,091	53,759	12.9%	6/1947-8/1952
13	Method #3, Run 9	367,948	48,902	11.7%	5/1947-8/1952
14	Method #3, Run 10	379,326	37,524	9.0%	6/1947-8/1952
15	Method #3, Run 11	371,442	45,408	10.9%	6/1947-8/1952

As shown in Table 7, by modifying the naturalized flows from the 1940-1960 period, the firm yield of the Highland Lakes dropped by 37,524-88,335 acre-ft/year, or 9.0%-21.2% of the firm yield resulting from the original naturalized flows dataset. The largest decrease in firm yield resulted from the application of the Method #4 modifications (Model Run #5 in Table 7), and the lowest decrease occurred in one of the iterations of Method #3 (Model Run #14 in Table 7). Firm yields resulting from applications of the Method #3 modifications ranged from 345,551 acre-ft/year to 379,326 acre-ft/yr over the 11 model runs simulated. For all model runs, the modeled critical period also shifted from the 2007-2015 period to a modeled critical period ending in August 1952. Under the modified flow scenarios, the lakes emptied in 1952, partially refilled as a result of the September 1952 flood on the Pedernales River, and then remained at relatively low storage levels until the 1957 drought-ending flood events (Figure 18). In contrast, the LCRA WAM with original naturalized flows resulted in the lakes emptying in 2015, at a time when the modified flow WAMs had approximately 450,000 acre-ft of water remaining within the lakes. It is also notable that the 2019-2023 drought resulted in approximately 125,000 acre-ft of remaining combined storage under the LCRA WAM with original naturalized flows yet resulted in 550,000 acre-ft of remaining storage under the modified naturalized flows scenario (Figure 18). The increase in reservoir storage during the 2007-2015 and 2019-2023 modeled drought periods is an expected result, as the modeled diversions (firm yields) are significantly lower within the modified flow WAMs. It is notable that the critical periods in the modified flow scenarios started in either 6/1946, 5/1947, or 6/1947, which changes the modeled drought duration as well as the resulting firm yield.

LCRA 2032 WMP Modeling

Figure 19 presents the comparison of modeled combined storage resulting from the 2032 WMP WAM using original and modified naturalized flow datasets. Over the entire modeled period of record (1940-2023), the only differences in model results are obtained during the 1940-1960 period. As shown in Figure 19, the minimum combined storage from LCRA's original model was 615,440 acre-ft, which occurred in December 2014. This minimum value exceeded the 600,000 acre-ft storage threshold, allowing LCRA to consider the WMP plan as acceptable.

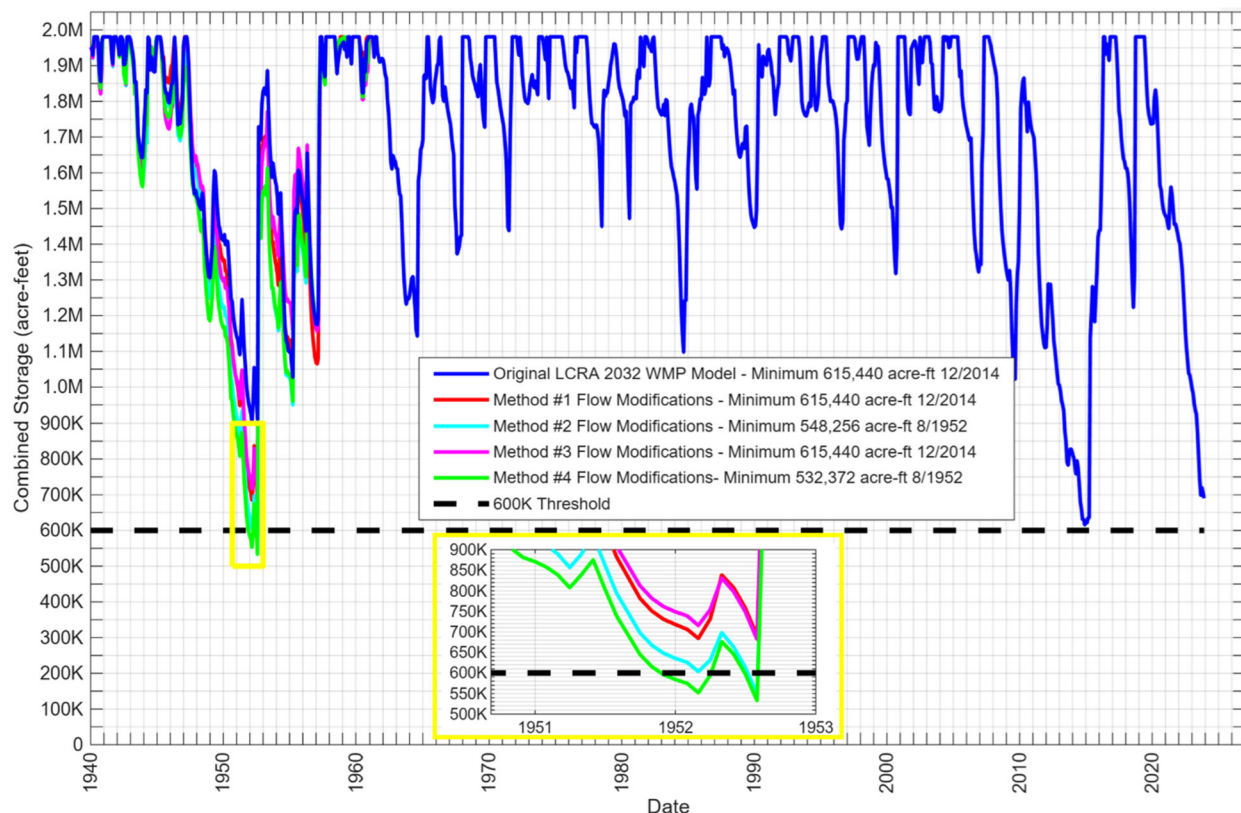


Figure 19 – LCRA 2032 WMP Modeling with original and modified naturalized flows (Model Runs 1-5)

When running the LCRA 2032 WMP WAM using modified naturalized flows, however, the resulting combined storage during the 1940-1960 period was lower than that from the original model for some simulations. With modifications using Method #2 and Method #4, combined storage values dropped below the 600,000 acre-ft threshold in modeled year 1952. Specifically, modeled combined storage dropped to 548,256 acre-ft and 532,372 acre-ft under Method #2 and Method #4, respectively. For model runs under Method #1 and 10 of the 11 different model runs using Method #3 modifications, the minimum combined storage occurred during the modeled 2008-2015 critical period. In these instances, the naturalized flows modifications were not large enough to shift the modeled lowest storage period from the 2008-2015 period to the 1946-1952 period. Based on these results, the 2032 WMP may not be sufficiently protective of basin water resources under a repeat of the 1946-1957 low rainfall period, depending upon which approach is used to adjust naturalized flows.

8. Conclusions & Implications

This study was undertaken to answer three fundamental questions regarding the long-term reliability of the Highland Lakes water supply system and the assumptions used to manage one of Texas' most important water resources.

Question 1: Has watershed productivity changed over time and how can it be measured?

This analysis demonstrated that watershed productivity can be effectively measured through a capture rate analysis, which evaluates the relationship between rainfall and resulting inflows to the Highland Lakes. The results indicate that watershed productivity has noticeably declined over time. While long-term rainfall records show no statistically significant reduction in precipitation, inflows to the Highland Lakes and watershed capture rates have declined substantially, with most of the lowest inflow and lowest capture-rate years occurring in the modern era (within the last 20 years).

These findings indicate that a smaller percentage of rainfall is reaching the Highland Lakes as usable runoff than occurred historically. Simply stated, the watershed is now producing less water than it would have in the past for similar rainfall events. This report only demonstrates this effect and does not definitively identify the cause or causes of the reduced productivity.

Question 2: Do existing naturalized flow methodologies and Water Availability Model assumptions adequately represent present and future watershed conditions?

This analysis indicated that current methodologies may not fully represent the hydrologic realities of today's watershed because they rely upon historical relationships between rainfall, runoff, storage, and streamflow that may have changed over time. Changes in watershed productivity, increased evaporation, groundwater influences, land-use changes, and the cumulative impacts of thousands of small ponds and impoundments have altered the relationship between rainfall and runoff.

Historical streamflow patterns may not be representative of future streamflow patterns. However, the assumption of a repeat of historical hydrology guides applications of the WAM in Texas water planning and permitting. The findings of this report demonstrate that the reliance on this assumption of stationarity limits our ability to effectively plan for water development and protect citizens and the environment from water scarcity. Stationarity appears to have been violated based on observed trends in capture rates for the Highland Lakes watershed as a whole.

While naturalized flows and WAMs remain valuable planning and permitting tools, they are fundamentally dependent upon assumptions regarding watershed behavior. The evidence presented in this report suggests those assumptions should be reevaluated considering observed declines in capture rates and inflows without discernible declines in rainfall. As

watershed conditions continue to evolve, reliance on historical streamflow patterns alone will likely overstate future water availability and system reliability.

Question 3: Should the drought of the 1950s be recognized as the controlling drought for water supply planning under current watershed conditions? If yes, what would be the expected outcomes on Firm Yield and Minimum Combined Storage from a repeat of the Drought of the 1950s rainfall under current watershed conditions and when applying the parameters from the proposed LCRA 2032 WMP?

The analysis supports recognition of the drought of the 1950s as the controlling drought with respect to firm yield, therefore making it more appropriate for planning purposes under present-day watershed conditions. Although the 2008–2016 drought produced the lowest naturalized inflows on record, the drought of the 1950s was characterized by more severe and sustained rainfall deficits (from normal totals) across the watershed. As shown in Figure 9, the Highland Lakes Watershed received nearly 50 inches less total rainfall during the 1950s drought compared to an equally long period during the 2008-2016 drought. These repeated years of lower rainfall in the 1950s would have likely produced lower inflows with today's watershed conditions and therefore would have likely produced the lowest modeled combined storage of the Highland Lakes within the LCRA's WAMs.

Modeling performed in this study using current watershed conditions and the rainfall characteristics of the 1950s demonstrates that a recurrence of that drought today would result in more severe impacts to water supply reliability than are reflected in current planning assumptions. The results as presented herein indicate lower system yield, reduced minimum combined storage, and greater risks to water supply reliability than previously reported within regional and state water planning documents, including current plans.

Through capture rate analyses and comparisons of the recent period to the 1940-1960 period, this report demonstrated the potential impact on water supplies if the current less-productive watershed received the lower rainfall observed historically. The result, as calculated based on TCEQ and LCRA approved WAMs with modified input hydrology, is that the calculated firm yield from the Highland Lakes drops between 9% and 21%, with the most comprehensive analysis approach (Method #4) indicating the largest decline. In addition, when running the LCRA 2032 WMP WAM using the modified naturalized flows, the resulting combined storage during the 1940-1960 period was lower than that from the original model under the more comprehensive modeling scenarios. With modifications using both Method 2 and Method 4, combined storage values dropped below the 600,000 acre-ft threshold in modeled year 1952, falling to approximately 548,000 and 532,000 acre-ft combined storage, respectively. Based on these results, the proposed 2032 WMP would not be sufficiently protective of basin water resources if the Method #2 or Method #4 naturalized flow modifications were considered. Dropping below the 600,000 acre-ft combined storage threshold should trigger the declaration of a new drought of record, firm water user curtailment, loss of water supply for some Firm Customers, and water rationing.

Collectively, these findings indicate that the amount of water the Highland Lakes system can reliably produce under current watershed conditions may be materially different from the amount resulting from current planning assumptions in LCRA's proposed 2032 WMP.

Implications for Water Management

The findings of this study suggest that the Highland Lakes watershed is producing inflows differently than it did historically and that current planning and permitting assumptions may not fully reflect present-day conditions.

A recurring theme throughout this analysis is that total annual rainfall has remained relatively stable while inflows and watershed productivity have declined. This divergence suggests that water availability can no longer be evaluated solely through historical streamflow records. Understanding how today's watershed responds to rainfall is now as important as understanding how much rainfall occurs. Determining the actual yield of the Highland Lakes system under current conditions should therefore be considered a critical planning priority.

Most importantly, the study demonstrates that inflows alone are not the primary driver of current water supply concerns. Rather, the ability of the watershed to convert rainfall into runoff has declined. As a result, the actual water available to refill the Highland Lakes may be materially different from that suggested by historical assumptions, especially if those assumptions are in regard only to streamflow and ignore rainfall.

This has potentially profound implications for how we manage our water and protect firm customers. Water management decisions, water supply commitments, firm yield calculations, drought contingency planning, and long-term water supply strategies are all dependent upon an accurate understanding of how much water the watershed can reliably produce. If watershed productivity has declined, then the actual yield of the Highland Lakes system would likely be lower than currently assumed and reported in LCRA's proposed 2032 WMP.

The findings of this study do not suggest that water planning should cease. Rather, they demonstrate the need for a more complete understanding of the watershed, using all components of the hydrologic cycle rather than only streamflow. This holistic understanding of the watershed is needed before additional long-term water supply commitments are made, as historical assumptions may no longer be valid.

The prudent course is not to maximize theoretical water availability, but to ensure reliable water supplies under the full range of conditions that may reasonably occur in the future. Until a comprehensive watershed productivity analysis and updated yield assessment are completed, water management decisions should prioritize reliability, resilience, and protection of existing firm customers over expansion of water commitments based solely on historical assumptions. Where observed watershed conditions differ from planning assumptions, management decisions should favor reliability, prudent reserve capacity, and protection of existing water

supplies. Determining the actual yield of the Highland Lakes system under current watershed conditions should be considered a necessary next step in ensuring the long-term sustainability of this critical water resource. Until this step is taken, the Highland Lakes system should be operated and managed under a “safe yield” condition such that the combined storage of the Highland Lakes remains above at least 1-2 years of expected annual demands. These annual demands must include those for firm customers, evaporative losses, environmental flows, and interruptible irrigation operations.

CTWC and Windward Water jointly urge LCRA, TCEQ, TWDB, and the State of Texas to consider changes to the water planning and management process, so that Texans may be more prepared for future low rainfall periods.

9. Recommended “Next Steps”

There are numerous avenues of research that must be undertaken to properly and fully assess whether the water supplies of the Lower Colorado River watershed are adequately protected and secure. The proposed studies listed below will build upon the watershed productivity concepts developed and described in this report. Each study is merely introduced with suggested avenues of exploration, and the full scope of each effort should be developed by project stakeholders including the TWDB, TCEQ, and LCRA. Each of these studies can be conducted simultaneously and has been partially initiated by CTWC and Windward Water. Completing each study would ensure that TWDB, TCEQ, and LCRA are truly using the “Best Available Science” in performing water planning and management activities in the Colorado River Basin. Studies are listed in priority order of importance.

Recommended Study #1 – Highland Lakes Safe Yield Analysis

As detailed in this report, the LCRA currently determines water availability from the Highland Lakes using a firm yield analysis. This analysis determines the maximum amount of water available to a set of LCRA customers as determined based on the ability to draw the combined storage of Lakes Buchanan and Travis down to zero inventory. Yet this resulting firm yield may be overstated, depending upon whether the modeling includes accounting for lower watershed productivity than historically observed. Therefore, to be more protective of Highland Lakes water supplies, it is prudent to quantify a 1-2 year safe yield for the system, and to limit water usage to safe yield levels. Many regional water planning groups in Texas use safe yields when performing long-term water supply planning efforts. Currently LCRA and the Region K water planning group do not use a safe yield approach.

While the WRAP software has means to calculate the safe yield of the Highland Lakes system, the LCRA Firm Yield WAM is not currently set up to properly make such computations. As detailed in Technical Paper A-5 (LCRA, 2026), LCRA calculates the firm yield as the sum of

modeled water provided to numerous simulated water right holders averaged over the modeled critical period. To calculate a safe yield for the Highland Lakes, all of the water rights with access to water in storage within the lakes would need to be removed from the WAM and collectively replaced with a single water right. Model iterations could then be made, modifying the diversion target for the single water right until desired minimum storage levels are achieved for the Highland Lakes. Such exercises are more in line with the approved definition of firm yield as stated by the TWDB (Zhu et al., 2025), as modified as needed to also apply to safe yield computations.

A simple desktop study should be performed to calculate the safe yield of the Highland Lakes at 0-year, 1-year, 2-year and potentially other time intervals. Results of the study should be documented and available for review by entities other than LCRA and Region K. It would also be interesting to compare the computed 0-year safe yield to LCRA's published firm yield as detailed in Technical Paper A-5 (LCRA, 2026). Both yields should be identical as both would allow modeled storage in the Highland Lakes to drop to zero. However, due to differences in the calculation methodologies, it is likely that LCRA's published firm yield would be slightly higher.

Recommended Study #2 – Rainfall-Runoff Analysis to assess small pond affects

This report emphasized the prevalence of small ponds as potentially being a significant driver of reduced inflows to the Highland Lakes. This significance was partially demonstrated by Slade (2020) and Furnans et al., (2019), yet additional work is needed to truly verify the impacts thousands of small ponds may have on downstream streamflow.

Recommended study #2 is to perform a rainfall-runoff analysis on the Highland Lakes watershed under conditions with and without small ponds. The approach would follow the SCS Curve number example provided in Section 5, and could initially focus on small subwatersheds defined based on individual small ponds or a series of small ponds on a stream network. The objective of the study would be to determine any reductions in downstream flow that would result from rain events falling on the subwatershed including small ponds, relative to the subwatershed if all small ponds were removed. This analysis could be performed on any and all subwatersheds within the Highland Lakes system and could yield insight into whether pond management and/or additional legislation related to pond construction may or may not be warranted. The rainfall-runoff analysis could eventually be expanded to serve as a means to potentially compute water availability based on both historical rainfall and streamflow, rather than the current practice of basing availability only upon historical streamflow. The approach could also be used to assess the effects of land use/land cover changes (urbanization) and brush control on Highland Lakes water management.

Recommended Study #3 – Rainfall Intensity Analysis

While small ponds are one factor that may result in lower current inflows to the Highland Lakes, another factor worth further investigation is rainfall intensity. PRISM data indicate that total

annual rainfall for the Highland Lakes watershed has been stable and does not indicate increasing or decreasing trends (Figure 8). Yet complete studies have not been conducted to determine whether rainfall is occurring more or less often, and whether storms that are occurring are generally more or less intense than previously observed. As incorporated into the SCS curve number method, more intense rain events will generate greater runoff. Therefore it is possible to have two years of equal rainfall totals, but with one year generating more runoff due to it having less frequent yet more intense rain events. This possibility was studied by TWDB for selected watersheds in the Colorado River Basin (Furnans et al., 2019), yet not for the entire Highland Lakes watershed.

Unfortunately, neither the PRISM rainfall dataset nor the TWDB Quadrangle rainfall dataset have sufficient temporal resolution to properly assess rainfall intensity changes between the 1947-1957 and 2008-2016 drought periods for the Highland Lakes watershed. For this recommended study, it will be necessary to obtain rainfall records that span this entire historical period and are available as hourly or daily totals (rather than monthly totals). Windward Water has conducted a preliminary analysis of rainfall data (daily) from a NOAA station in Brady, TX that is available over this entire period. This station is also located in close proximity to a stream gage which has recorded streamflow records over this same period. Analyses of these datasets are ongoing, yet preliminary results do not indicate statistically significant changes in the number of rainy days per year, the number of days per year when storms would produce runoff, or the total runoff depths per year. Changes in streamflow data have also yet to be determined and identified. Efforts are underway to identify additional daily rainfall and streamflow datasets within the Colorado River Basin which may be suitable for assessing changes over the 1940-Present time period.

Recommended Study #4 – Evaporation Rate Change Analysis

Evaporation of water from reservoirs is incorporated into the WAMs and affects water availability computations. It is also part of the flow naturalization process (See Section 5), and thus changes in evaporation rates could result in changes to computed naturalized flows. In 2024, LCRA staff (Ron Anderson) and collaborators published a study detailing the creation of a daily lake evaporation model and its application to reservoirs within Texas (Zhao et al., 2024). This new model produces different evaporation rates than those currently included within the WAMs. Preliminary modeling was performed by Windward Water incorporating these revised evaporation totals into the LCRA Firm Yield WAM (as both part of the modeled evaporation rates and as rates used in the flow naturalization process). Results suggest that the new evaporation rates cause changes in computed firm yield as much as those resulting from LCRA's application of new sedimentation rates (approximately a 2,500 acre-ft/yr yield reduction).

Studies must be conducted to assess which evaporation rates are more accurate for use in water planning. If the new evaporation rates are more accurate, then the WAMs for all of Texas should be updated, and planning models (by LCRA and others) should be refined. It would also be beneficial to assess trends in computed evaporation rates over time, possibly linked to

Would Central Texas have sufficient water supplies if
current rainfall patterns equaled those from
the 1950s Texas Drought?

minimum and maximum temperature data (available from PRISM). TWDB began such an analysis for select watersheds in the Colorado Basin (Furnans et al., 2019), yet few published efforts have been undertaken since that time.

10. References

Andrews, R.G. (1954), 'The use of relative infiltration indices for computing runoff (unpublished),' Soil Conservation Service, Fort Worth, Texas, 6 p

Asquith, W.H., and Bumgarner, J.R., 2014, Linkage of the Soil and Water Assessment Tool and the Texas Water Availability Model to simulate the effects of brush management on monthly storage of Canyon Lake, southcentral Texas, 1995–2010: U.S. Geological Survey Scientific Investigations Report 2013–5239, 25 p., <http://dx.doi.org/10.3133/sir20135239>.

Bilodeau, E., J. Martel, R. Arsenault, and F. Brissette., 2025. "Evaluation of the Impact of Rainfall Increases on Runoff in Urban Watersheds." *Journal of Water Management Modeling* 33: C559. <https://doi.org/10.14796/JWMM.C559>

Daly, C., R.P. Neilson, and D.L. Phillips. 1994. [A statistical-topographic model for mapping climatological precipitation over mountainous terrain](#). *Journal of Applied Meteorology* 33(2): 140-158. [doi:10.1175/1520-0450\(1994\)033<0140:ASTMFM>2.0.CO;2](https://doi.org/10.1175/1520-0450(1994)033<0140:ASTMFM>2.0.CO;2)

Daly, C., W.P. Gibson, G.H. Taylor, G.L. Johnson, and P. Pasteris. 2002. [A knowledge-based approach to the statistical mapping of climate](#). *Climate Research* 22(2): 99-113. [doi:10.3354/cr022099](https://doi.org/10.3354/cr022099)

Daly, C., M. Halbleib, J.I. Smith, W.P. Gibson, M.K. Doggett, G.H. Taylor, J. Curtis, and P.A. Pasteris. 2008. [Physiographically-sensitive mapping of temperature and precipitation across the conterminous United States](#). *International Journal of Climatology* 28(15): 2031-2064. [doi:10.1002/joc.1688](https://doi.org/10.1002/joc.1688)

Daly, C., M.K. Doggett, J.I. Smith, K.V. Olson, M.D. Halbleib, Z. Dimcovic, D. Keon, R.A. Loiselle, B. Steinberg, A.D. Ryan, C.M. Pancake, and E.M. Kaspar. 2021. [Challenges in observation-based mapping of daily precipitation across the conterminous United States](#). *Journal of Atmospheric and Oceanic Technology* 38(11): 1979-1992. [doi:10.1175/JTECH-D-21-0054.1](https://doi.org/10.1175/JTECH-D-21-0054.1)

Deeds, N. (2024) Groundwater Resources of Burnet County, TX. Report to the Central Texas Groundwater Conservation District. Available as of 9.6.2026 at: <https://centraltexasgcd.org/data-and-services/studies-and-reports/>

Di Chang, Shuo Li, Zhengqing Lai (2023) "Effects of extreme precipitation intensity and duration on the runoff and nutrient yields" *Journal of Hydrology*, Volume 626, Part A, 130281, ISSN 0022-1694, <https://doi.org/10.1016/j.jhydrol.2023.130281>

Furnans, J., Keester, M., and Kennedy, K. (2019) "Final Report: Evaluation of Rainfall-Runoff Trends in the Upper Colorado River Basin (Phase Two). Texas Water Development Board

Contract Report #1800012283, available as of 8.23.2026 at:
https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1800012283.pdf

Hu , Huancui, L. Ruby Leung, and Zhe Feng.,2020. "Understanding The Distinct Impacts Of MCS And Non-MCS Rainfall On The Surface Water Balance In The Central United States Using A Numerical Water-Tagging Technique". Journal Of Hydrometeorology 21: 2343-2357.
doi:10.1175/jhm-d-20-0081.1

Kennedy, K, (2017) "Evaluation of Rainfall/Runoff Patterns in the Upper Colorado River Basin. TWDB Contract No. 1600012011, available as of 8.23.2026 at:
https://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600012011_Kennedy.pdf

LCRA, 2020. "Water Management Plan and Drought Contingency Plan". Lower Colorado River Authority, available as of 8.23.2026 at: <https://www.lcra.org/water/water-supply-planning/water-management-plan-for-lower-colorado-river-basin/>

LCRA, 2024. "Small Pond Identification in the Highland Lakes Watershed Using Satellite Imagery." PowerPoint presentation included as part of the meeting packet for the Region K Regional Water Planning meeting held October 16, 2024, available as of 8.23.2026 at:
https://www.regionk.org/s/20241016_RegionK_Packet.pdf

LCRA, 2026. "Technical Paper A-5 Development of Combined Firm Yield of Lakes Buchanan and Travis." Lower Colorado River Authority, January. Available as of 8.23.2026 at:
<https://www.lcra.org/download/wmp-draft-tp-a-5/?wpdmdl=40684>

LCRA, 2026A. "Firm Contracts List". Lower Colorado River Authority, October. Available as of 10.02.2026 at: <https://www.lcra.org/water/permits-contracts/water-supply-contracts/firm-water-use/>

Mamo, T (2015) Evaluation of the Potential Impact of Rainfall Intensity Variation due to Climate Change on Existing Drainage Infrastructure. Journal of Irrigation and Drainage Engineering. Volume 141, Issue 10.

Matalas, Nicholas C. (2011) "Note on the Assumption of Hydrologic Stationarity," Journal of Contemporary Water Research and Education: Vol. 112: Iss. 1, Article 11. Available at:
<https://opensiuc.lib.siu.edu/jcwre/vol112/iss1/11>

McLendon, T., Pappas, C., Coldren, C., Fish, E., Beierle, M., Hernandez, A., Rainwater, K., Zartman, R. (2012) Application of the EDYS Decision Tool for Modeling of Target Sites In Gonzales County for Water Yield Enhancement Through Brush Control." Report to the Texas State Soil and Water Conservation Board.

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer (2008). Stationarity is dead: Whither water management? *Science* – 319(5863), 573-574.

Mishra, S.K., Singh, V.P. (2003). SCS-CN Method. In: Soil Conservation Service Curve Number (SCS-CN) Methodology. Water Science and Technology Library, vol 42. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-0147-1_2

PRISM, 2026 - https://prism.oregonstate.edu/documents/PRISM_datasets.pdf

Slade RM Jr. 2020. Runoff inflow volumes to the Highland Lakes in Central Texas: temporal trends in volumes and relations between volumes and selected climatic indices. *Texas Water Journal*. 11(1):32-60. Available from: <https://doi.org/10.21423/twj.v11i1.7025>.

Sreejith, K. S., Kumar, G. P., and Dwarakish, G. S., “A Critical Review of the Soil Conservation Services – Curve Number Method in Hydrological Modelling”, *Wetlands*, vol. 44, no. 8, Art. no. 117, Springer, 2024. doi:10.1007/s13157-024-01873-w.

Tamer, M., Adego, E. & Abiyu, A. (2025) Understanding rainfall runoff dynamics across various land uses and landscape positions in North Western Ethiopia. *Sci Rep* 15, 15287 . <https://doi.org/10.1038/s41598-025-98437-7>

TCEQ (2026) – Colorado River Basin and Brazos – Colorado Coastal Basin WRAP Input files, available as of 8.23.2026 at: <https://tceq.com/downloads/permitting/water-rights/wams/colorado-brazos/colorado-full.zip>

TWC (2001) – Texas Water Code Sect. 11.142(b), available as of 8.23.2026 at: <https://statutes.capitol.texas.gov/?tab=1&code=WA&chapter=WA.11&artSec=>

Twinomuhangia, M., Bamutazea, Y., Kabengeb, I., Wanyamab, J., Kizzac, M., Gabirid, G., and Egli, P., (2025) Analysis of stationary and non-stationary hydrological extremes under a changing environment: A systematic review. *HydroResearch* 8 (2025) 332–350

USDA Soil Conservation Service. (1964). *National Engineering Handbook, Section 4: Hydrology*. U.S. Department of Agriculture, Washington, D.C.

Wang, Z., & Yang, Y. (2024). Stationarity of high- and low-flows under climate change and human interventions across global catchments. *Earth and Space Science*, 11, e2023EA003456.

Zhao, B., Huntington, J., Pearson, C., Zhao, G., Ott, T., Zhu, J., et al. (2024). Developing a general Daily Lake Evaporation Model and demonstrating its application in the state of Texas. *Water Resources Research*, 60,e2023WR036181.

Would Central Texas have sufficient water supplies if
current rainfall patterns equaled those from
the 1950s Texas Drought?

Zhu J, Fernando DN, Holmquist H, Leber N, Guthrie CG. 2025. Projected Reservoir Rating
Curves and Their Utility for Water Planning in Texas. Texas Water Journal. 16(1):40-56.
Available from: <https://doi.org/10.21423/twj.v16i1.7179>

JORDAN E. FURNANS, PHD, PE, PG

Principal Engineer, Project Hydrogeologist, Business Developer



EDUCATION

PhD, Civil Engineering, The University of Texas at Austin, 2005

M.S. Engineering, Environmental & Water Resources Engineering, The University of Texas at Austin, 2001

B.S. Engineering, Civil/Geological Engineering, Princeton University, 1999

US Fulbright Fellowship, Centre for Water Research, The University of Western Australia, 2002-2003

REGISTRATIONS

Professional Engineer
TX (2006) No. 97316
CO (2010) No. 44217
OK (2012) No. 26095
AZ (2015) No. 61061
KS (2019) No. 26856
NV (2024) No. 32843
NE (2024) No. 20780
HI (2024) No. 21134

Professional Geoscientist
TX (2011) No. 11002

TCEQ Class D Water Operator
#WO 0054936 (2025)

Dr. Jordan Furnans is a passionate water resources engineer and geologist dedicated to providing reliable water supplies for fellow Texans. His 25 years of professional experience encompasses both field hydrologic data collection and analysis of data through the development and application of numerical models. He specializes in hydrodynamic modeling, surface water analyses & accounting, groundwater development (including wellfield design, construction oversight, and permitting), field investigations, flooding assessments, water availability modeling (groundwater and surface water), hydrology & hydraulics, and water supply planning/evaluation. Jordan also regularly serves as an expert witness on water supply disputes in Texas.

EMPLOYMENT & GENERAL EXPERIENCE

PRINCIPAL ENGINEER, OWNER | Woodward Water Resources Engineering & Geoscience, PLLC – 2026-Present, Round Rock, TX

Offering groundwater and surface water development consulting services throughout Texas, as a sole proprietor.

PRINCIPAL ENGINEER, SENIOR PROJECT MANAGER | Spheros Environmental / LRE Water, 2015 – 2026, Round Rock, TX

Opened the TX office of LRE Water in 2015 and grew the business to include 10 hydrogeologists and engineers working to develop and manage water supplies throughout Texas and Oklahoma. Developed and procured multiple years of \$2.5M project revenue, overseeing project development, scope negotiation, contracting, work completion and reporting. Conducted and supervised water resource investigations, including floodplain analyses, watershed hydrology, groundwater & surface water availability modeling, and water rights accounting. LRE Water joined Spheros Environmental in 2023.

ADJUNCT FACULTY/LECTURER | The University of Texas at Austin, Department of Civil, Architectural, and Environmental Engineering 2016 – Present, Austin, TX.

Teaching CE 356 – Fundamentals of Hydraulic Engineering
Teaching CE 374 – Hydrology

SENIOR WATER RESOURCES ENGINEER & TEAM MANAGER | INTERA, Inc., 2009 – 2015, Austin, TX

Provided water availability modeling (WAM) services for various clients in the Brazos River, Concho River, Colorado River and Guadalupe River Basins in Texas.

ENGINEER | Texas Water Development Board, Surface Water Resources Division, 2003 – 2009, Austin, TX