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FINAL REPORT

WATER AVAILABILITY MODEL UPDATE BRAZOS RIVER BASIN

Prepared for:

Texas Commission on Environmental Quality

Contract 582-20-13329

August 31, 2021

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FINAL REPORT

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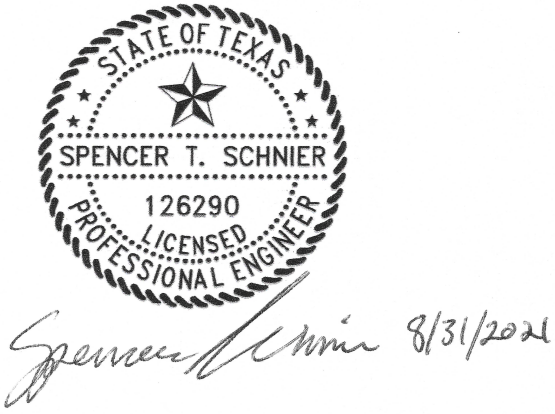

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EXECUTIVE SUMMARY

This report describes an update and extension of the naturalized flow and net evaporation datasets for the Texas Commission on Environmental Quality's (TCEQ) Brazos River Water Availability Model (Brazos River WAM). The work was authorized by TCEQ contract 582-20-13329. The update includes the period from 1940 through 2018. Previous work ended in 1997. The hydrology was extended to include the periods from 1998 through 2018 using substantially the same methodology described in the original Brazos Naturalized Streamflow Report. Where needed, the original hydrology for 1940 through 1997 was changed to correct errors and incorporate new information. The primary reasons for changes to the original hydrology include:

- Updated select fill relationships (**Chapter 3.2**).
- Used Texas Water Development Board (TWDB) updated net evaporation rates for 1994, 1999-2000, and 2012-2015 (**Chapter 2.4**).
- Updated content change and evaporation data for reservoirs that have a recalculated volumetric survey (**Table 2-2** and **Table 4-1**).
- Corrections to previous work (**Chapter 1.0**).
- Minor changes due to rounding differences and conversion factors (**Chapter 1.0**).

This report provides information regarding the update and extension. The calculations for the updated flows are provided in Excel workbooks that accompany this report. Text files with updated model code are included as well.

1.0 INTRODUCTION

In 2019, the 86th Texas Legislature authorized TCEQ to obtain or develop an updated water availability model for the Brazos River Basin by December 1, 2022. TCEQ retained the team of Freese and Nichols, Inc. (FNI) in association with HDR Engineering Inc., Rivulous LLC, and Robert J. Brandes Consulting, under Contract 582-20-13329 (Contract), as part of that obligation. This report, and the associated files delivered with it, are submitted as part of that contract. The update is primarily focused on revision and extension of hydrologic data (naturalized flows and evaporation), although modifications to the existing Brazos River WAM are included as well. For the naturalization, historical stream gage data were adjusted for water right diversions, reservoirs considered in the previous naturalization, and return flows greater than 1 million gallons per day (MGD). Naturalized flows and evaporation data were subject to revision for the entire period of record (1940 through 2018), although changes prior to 1998 are primarily to correct errors or to replace data that has since been updated.

The original hydrology for the TCEQ Brazos River Basin and San Jacinto-Brazos Coastal Basin Water Availability Model (Brazos River WAM) was developed in 2001 by HDR Engineering, Inc. in association with Freese and Nichols, Inc., Crespo Consulting Services, Inc., Densmore and DuFrain Consulting, for the Texas Natural Resources Conservation Commission, predecessor agency to TCEQ (under Contract Number 582-0-82108). The Brazos River WAM was developed pursuant to Senate Bill 1, passed by the 75th Legislature in 1997. The original contract for the Brazos River WAM includes the San Jacinto-Brazos Coastal Basin, which is also included in the current project.

The original Brazos WAM had a period of record from 1940 through 1997. This project extends the period of record through December 2018. A partial naturalization of the Brazos River Basin flows covering a period from 1998 through 2015 was conducted as part of a study that examined the impact of recent droughts on water available to the Brazos River Authority (BRA)[1,2]. The hydrology from the BRA Drought Study is referred to as partially naturalized because it only adjusted historical flows for large reservoirs (more than 10,000 acre-feet of storage), large diversions (water rights authorized for more than 1,000 acre-feet per year), and large return flows (greater than 2 million gallons per day, MGD).

[1] *Drought Study Report. June 2017. Prepared for the Brazos River Authority. Prepared by Freese and Nichols, Inc.*
[2] *Updated Natural Flow Report for the Brazos River Basin. June 2017, revised July 2017. Prepared for the Brazos River Authority. Prepared by Freese and Nichols, Inc.*

In this project, the data and naturalized flow workbooks from the BRA Drought Study were used as a starting point and are referred to in this report as the "BRA Drought Study" hydrology. The hydrology developed as part of the original model development in 2001 is referred to as the "original WAM" hydrology. At the beginning of this project, hydrology from 1940-1997 dated back to the original WAM for the most part, and partially naturalized hydrology from 1998-2015 dated back to the BRA Drought Study. As part of this project, the flows from 1940-1997 were reviewed and updated as necessary, the flows from 1998-2015 were fully naturalized, and the period of record was extended through the end of 2018. For full naturalization, historical data was adjusted for all water right diversions, major reservoirs, and return flows with permitted discharge greater than 1 MGD. The BRA Drought Study was for the Brazos River Basin, but the current flow extension includes both the Brazos River Basin and the San Jacinto-Brazos Coastal Basin.

1.1 SCOPE OF WORK

The following Scope of Work is a summary of the detailed scope of work developed in the *Final Project Management Plan*, dated August 13, 2020. A more detailed version of the scope may be found in that report.

Task 1 Project Management Plan and Work Plan

- Task 1.1. Project Management Plan
- Task 1.2 Review of Previous Flow Naturalization
- Task 1.3 Data Collection
- Task 1.4 Final Project Management Plan and Work Plan

The Final Project Management Plan and Workplan was submitted to TCEQ on August 13, 2020.

Task 2 Development of Naturalized Flow Datasets

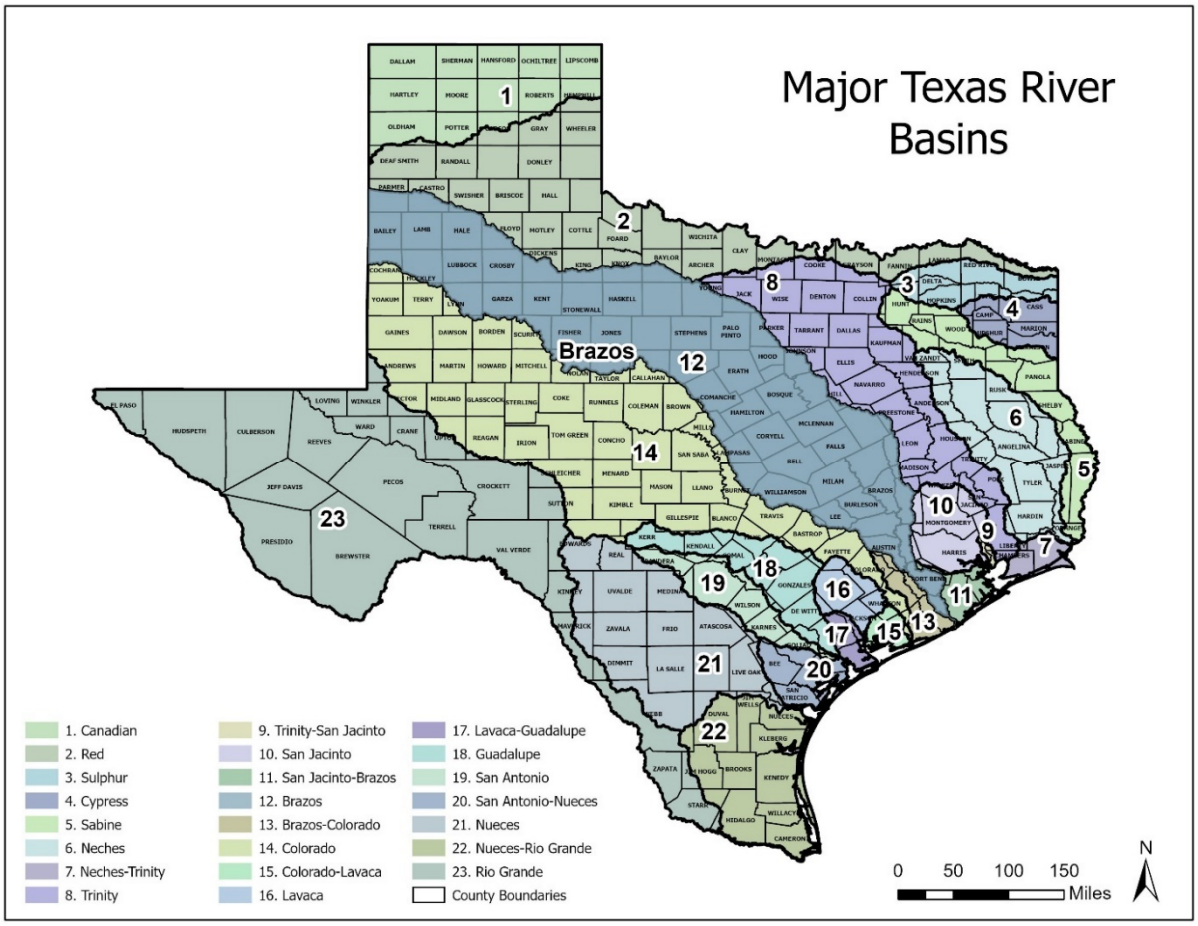
- Task 2.1 Data Review
- Task 2.2 Develop Reservoir Data
- Task 2.3 Fill in Missing Data
- Task 2.4 Develop Draft Naturalized Flows and Quality Control
- Task 2.5 Peer Review and Report
- Task 2.6 Report

1.2 DESCRIPTION OF THE BASIN

The Brazos River Basin is the second largest of the fifteen major river basins in Texas, covering a total of 45,573 square miles, of which 42,865 square miles (94 percent) are in Texas. The upper part of the basin reaches into New Mexico, but the Brazos River is formed at the confluence of Salt Fork and the Double Mountain Fork near Aspermont, Texas. The Brazos River and its tributaries then flow from the northwest towards the southeast across Texas where the river flows into the Gulf of Mexico south of Freeport, Texas (**Figure 1-1**). The surrounding basins include the Red River Basin to the north, the Trinity and San Jacinto Basins and San Jacinto-Brazos Coastal Basin to the east, and the Colorado and Brazos-Colorado Coastal Basin to the west. There are five major tributaries to Brazos River: the Clear Fork, the Bosque River, Yegua Creek, the Little River, and the Navasota River. There are over 1,000 water rights in the Brazos River Basin, with 46 existing major surface water reservoirs and one major off-channel reservoir that has a water right but has not yet been built. Most of these reservoirs are water-supply reservoirs, and nine are operated by the U.S. Army Corps of Engineers (USACE) for both water supply and flood control purposes.

There are nine main streams in the San Jacinto-Brazos Coastal Basin. Armand Bayou, Clear Creek, and Dickinson Bayou drain to Galveston Bay; Mustang Bayou, Chocolate Bayou and Austin Bayou drain to the part of Galveston Bay between the mainland and Galveston Island; Bastrop Bayou drains to Bastrop Bay southwest of Galveston Island, and Oyster Creek and the Old Brazos River Channel drain to the Gulf of Mexico. There are 64 water rights in the San Jacinto-Brazos Coastal Basin, and no reservoirs over 5,000 acre-feet. A substantial portion of the water used in the Coastal Basin is imported from the Brazos River Basin and transported via canals and small operational impoundments.

Figure 1-1: Major River Basins in Texas



1.3 ORGANIZATION OF THE REPORT

In accordance with the contract, the Final Report includes a summary of the process and updated naturalized streamflow, evaporation, and flow adjustment data for the Brazos River Basin including chapters on the following:

- **Chapter 2.0** - Data collection
- **Chapter 3.0** - Data analysis
- **Chapter 4.0** - Changes to the existing naturalized streamflow and evaporation
- **Chapter 5.0** - Corrections to the existing TCEQ water availability main input file (.DAT) and flow distribution file (.DIS) for the sole purpose of incorporating the extended naturalized streamflow and evaporation datasets
- **Chapter 6.0** - Procedure for addressing any negative incremental flow issues

- **Chapter 7.0** - Results of the independent peer review and any changes to the extended naturalized streamflow datasets resulting from the review
- **Chapter 8.0** - Final naturalized streamflow and evaporation datasets

2.0 DATA COLLECTION

Data collection was the first step in the naturalization process. This chapter describes the data collected during the project and how that data was used.

2.1 STEAMFLOW DATA

With a few exceptions, the naturalized flows used in the WAMs are based on historical streamflow records, with missing data filled in during the naturalization process using naturalized flows from nearby points. **Table 2-1** lists primary control points and the associated United States Geological Survey (USGS) streamflow gages in the Brazos River Basin and San Jacinto-Brazos Coastal Basin. Primary control points are locations where naturalized flows are input into the WAM. **Figure 2-1** is a map of the basin showing the location of primary control points and major reservoirs. The maps included in **Appendix F** also show the geographic location of primary control points but are higher resolution maps that focus on specific drainage areas within the basin.

The primary source of streamflow data was the USGS National Water Information System (https://waterdata.usgs.gov/nwis). In some cases, the USGS website did not have flow data in the previous workbooks, and we verified these data using published USGS data. The USACE Lake Proctor outflows were used for the historical flows at Leon River near Hasse, TX gage (LEHS45, USGS 08099500) from October 1991 through August 2007, when the USGS did not report flows at this location. **Appendix D** lists USGS streamflow gages in the Brazos River Basin and San Jacinto-Brazos Coastal Basin.

Gages may not have continuous flow data for various reasons. The period of missing data could be as short as a single day or last for multiple years. Missing records for short periods of time (less than 10 days) usually occur when the gage is temporarily out of service. These flows were filled in with a reasonable estimation of the daily flow so that the monthly total volume is as accurate as possible. Methods used for filling in short periods of flows included:

- Taking the average of the adjacent days,
- Taking the average of the remaining days in the month, or
- Looking at flow trends for nearby days.

The specific methods used to fill in short periods of missing data are noted in the gage flow workbooks. Methods used to estimate flows for longer periods of missing data are discussed in **Chapter 3.2**.

Daily average flow data from the USGS gages or other sources were converted from cubic feet per second to acre-feet per day and then summed up to monthly data in acre-feet per month. These flows then serve as input for the naturalization process.

The Work Plan also considered a potential primary control point at Lake Alan Henry. However, a review of the updated naturalized flows determined that a new primary control point was not necessary.

Table 2-1: Primary Control Points for the Brazos River Basin and San Jacinto-Brazos Coastal Basin

Control Point I.D.	Gage Name	USGS Number	Drainage Area (Square Miles)	Contributing Drainage Area (Square Miles)	Period of Record
Brazos River Basin					
RWPL01	Running Water Draw at Plainview	08080700	1,291	382	6/1939-9/1953, 10/1956-4/1960, 3/1961-9/1978, 10/2002-Present
WRSP02	White River Reservoir near Spur	08080910	3,069	689	4/1964-9/1976 & 2/1999-Present
DUGI03	Duck Creek near Girard	08080950	431	279	10/1964-9/1989
SFPE04	Salt Fork Brazos River near Peacock	08081000	4,619	1,985	1/1950-9/1951, 10/1964-9/1986
CRJA05	Croton Creek near Jayton	08081200	290	290	9/1959-9/1986
SFAS06	Salt Fork Brazos River near Aspermont	08082000	5,130	2,496	1/1/1924-8/1925, 7/1939-1/2020, 3/2020-Present
BSLU07	Buffalo Springs Lake near Lubbock	08079550	5,588	236	12/1966-9/1977
DMJU08	Double Mountain Fork Brazos River at Justiceburg	08079600	1,466	244	12/1961-Present
DMAS09	Double Mountain Fork Brazos River near Aspermont	08080500	8,796	1,864	1/1924-8/1934, 7/1939-Present
NCKN10	North Croton Creek near Knox City	08082180	251	251	10/1965-9/1986
BRSE11	Brazos River at Seymour	08082500	15,538	5,972	12/1923-Present
MSMN12	Millers Creek near Munday	08082700	104	104	7/1963-Present
CFRO13	Clear Fork Brazos River near Roby	08083100	228	228	1/1962-Present

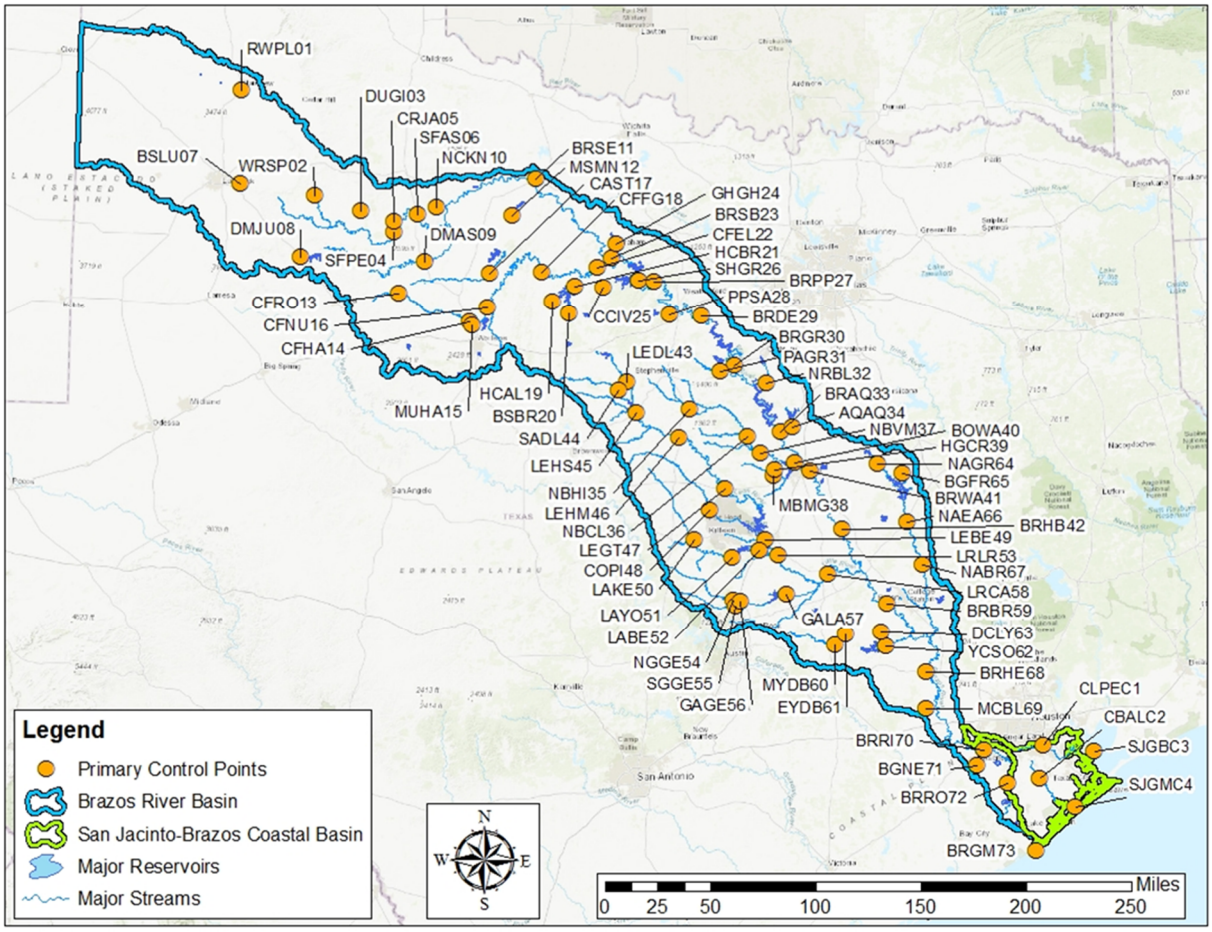
Control Point I.D.	Gage Name	USGS Number	Drainage Area (Square Miles)	Contributing Drainage Area (Square Miles)	Period of Record
CFHA14	Clear Fork Brazos River at Hwy 83 near Hawley	08083240	1,416	1,416	10/1967-9/1989, 10/2016-Present
MUHA15	Mulberry Creek near Hawley	08083245	205	205	10/1967-9/1989
CFNU16	Clear Fork Brazos River at Nugent	08084000	2,199	2,199	3/1924-Present
CAST17	California Creek near Stamford	08084800	478	478	10/1962-Present
CFFG18	Clear Fork Brazos River at Fort Griffin	08085500	4,026	4,026	2/1924-Present
HCAL19	Hubbard Creek below Albany	08086212	613	613	10/1966-Present
BSBR20	Big Sandy Creek above Breckenridge	08086290	280	280	2/1962-Present
HCBR21	Hubbard Creek near Breckenridge	08086500	1,089	1,089	5/1955-8/1986, 10/2015-Present
CFEL22	Clear Fork Brazos River at Eliasville	08087300	5,697	5,697	12/1915-4/1920, 1/1924-8/1925, 7/1928-9/1951, 10/1961-9/1982
BRSB23	Brazos River near South Bend	08088000	22,673	13,107	10/1938-Present
GHGH24	Lake Graham near Graham	08088400	221	221	3/1958-9/2000 & 10/2001-Present
CCIV25	Big Cedar Creek near Ivan	08088450	97	97	12/1964-9/1989
SHGR26	Brazos River at Morris Sheppard Dam near Graford	08088600	23,596	14,030	10/1976-9/1995
	Brazos River near Graford	08088610	23,596	14,030	10/1989-Present
BRPP27	Brazos River near Palo Pinto	08089000	23,811	14,245	2/1924-Present
PPSA28	Palo Pinto Creek near Santo	08090500	573	573	10/1924-8/1925, 5/1951-9/1976
BRDE29	Brazos River near Dennis	08090800	25,237	15,671	5/1968-Present
BRGR30	Brazos River near Glen Rose	08091000	25,818	16,252	10/1923-Present
PAGR31	Paluxy River at Glen Rose	08091500	410	410	1/1924-2/1924, 6/1924-9/1925, 6/1947-Present

Control Point I.D.	Gage Name	USGS Number	Drainage Area (Square Miles)	Contributing Drainage Area (Square Miles)	Period of Record
NRBL32	Nolan River at Blum	08092000	282	282	8/1924-9/1925, 12/1947-10/1985, 12/1985-2/1987, 10/1992-9/1996, 10/1997-12/1998, 10/2005-Present
BRAQ33	Brazos River near Aquilla	08093100	27,189	17,623	10/1938-12/1988, 2/1989-Present
AQAQ34	Aquilla Creek near Aquilla	08093500	308	308	1/1939-4/2001
	Aquilla Creek above Aquilla	08093360	255	255	10/1979-12/1991, 2/1991-9/1992, 5/2001-Present
NBHI35	North Bosque River at Hico	08094800	359	359	1/1962-9/1999, 5/2014-Present
NBCL36	North Bosque River near Clifton	08095000	968	968	10/1923-Present
NBVM37	North Bosque River at Valley Mills	08095200	1,146	1,146	8/1959-9/2005, 8/2007-Present
MBMG38	Middle Bosque River near McGregor	08095300	182	182	8/1959-9/1985, 10/2007-Present, Partial record 10/1985-9/2007
HGCR39	Hog Creek near Crawford	08095400	78.2	78.2	9/1959-9/1985, 10/2007-Present, Partial record 10/1985-9/2007
BOWA40	Bosque River near Waco	08095600	1,656	1,656	9/1959-9/1981, 3/1982-5/1982
BRWA41	Brazos River at Waco	08096500	29,559	19,993	10/1898-Present
BRHB42	Brazos River near Highbank	08098290	30,436	20,870	10/1965-Present
LEDL43	Leon River near De Leon	08099100	479	479	9/1960-9/1986, 10/1996-9/1997, 10/2007-Present
SADL44	Sabana River near De Leon	08099300	264	264	9/1960-9/1986, 10/1999-Present
LEHS45	Leon River near Hasse	08099500	1,261	1,267	1/1939-9/1991, 9/2007-Present
LEHM46	Leon River near Hamilton	08100000	1,891	1,891	1/1925-8/1931, 9/1960-12/1998, 10/2007-Present
LEGT47	Leon River at Gatesville	08100500	2,342	2,342	10/1950-Present
COPI48	Cowhouse Creek at Pidcoke	08101000	455	455	10/1950-Present

Control Point I.D.	Gage Name	USGS Number	Drainage Area (Square Miles)	Contributing Drainage Area (Square Miles)	Period of Record
LEBE49	Leon River near Belton	08102500	3,582	3,582	10/1923-Present
LAKE50	Lampasas River near Kempner	08103800	818	818	10/1962-Present
LAYO51	Lampasas River at Youngsport	08104000	1,240	1,240	3/1924-9/1980
LABE52	Lampasas River near Belton	08104100	1,321	1,321	2/1963-9/1989, 5/1999-Present
LRLR53	Little River near Little River	08104500	5,228	5,228	10/1923-4/1929, 8/1962-Present
NGGE54	North Fork San Gabriel River near Georgetown	08104700	248	248	7/1968-Present
SGGE55	South Fork San Gabriel River at Georgetown	08104900	133	133	12/1967-Present
GAGE56	San Gabriel River at Georgetown	08105000	405	405	3/1924-8/1925, 8/1934-9/1973, Partial record 11/1984-8/1986
GALA57	San Gabriel River at Laneport	08105700	738	738	8/1965-Present
LRCA58	Little River near Cameron	08106500	7,065	7,065	11/1916-Present
BRBR59	Brazos River near Bryan	08109000	39,515	29,949	8/1899-9/1993
	Brazos River at SH 21 near Bryan	08108700	39,049	29,483	8/1993-Present
MYDB60	Middle Yegua Creek near Dime Box	08109700	236	236	8/1962-Present
EYDB61	East Yegua Creek near Dime Box	08109800	244	244	8/1962-Present
YCSO62	Yegua Creek near Somerville	08110000	1,009	1,009	5/24/1924-9/1991, 10/2008-Present
DCLY63	Davidson Creek near Lyons	08110100	195	195	10/1962-Present
NAGR64	Navasota River above Groesbeck	08110325	239	239	6/1978-Present
BGFR65	Big Creek near Freestone	08110430	97.2	97.2	7/1978-Present
NAEA66	Navasota River near Easterly	08110500	968	968	3/1924-Present
NABR67	Navasota River near Bryan	08111000	1,454	1,454	1/1951-9/1994
BRHE68	Brazos River near Hempstead	08111500	43,880	34,314	10/1938-Present
MCBL69	Mill Creek near Bellville	08111700	376	376	8/1963-9/1993, 5/2000-Present
BRRI70	Brazos River at Richmond	08114000	45,107	35,541	10/1922-Present

Control Point I.D.	Gage Name	USGS Number	Drainage Area (Square Miles)	Contributing Drainage Area (Square Miles)	Period of Record
BGNE71	Big Creek near Needville	08115000	42.8	42.8	6/1947-6/1950, 4/1952-10/2016, 6/2017-Present
BRRO72	Brazos River near Rosharon	08116650	45,339	35,773	4/1967-8/1980, 5/1984-Present
BRGM73	Brazos River at Gulf of Mexico	---	45,497		None
San Jacinto-Brazos Coastal Basin					
CLPEC1	Clear Creek near Pearland	08077000	39	39	8/1944-10/1944, 3/1946-10/1946, 4/1947-12/1959, 4/1963-9/1992
CBALC2	Chocolate Bayou near Alvin	08078000	88	88	8/1944, 4/1946, 1/1947-1/1958, 3/1959-Present
SJGBC3	San Jacinto-Brazos Coastal Basin at Galveston Bay	---	1,145	1,145	None
SJGMC4	San Jacinto-Brazos Coastal Basin at the Gulf of Mexico	---	293	293	None

Figure 2-1: Primary Control Points in the Brazos River Basin and San Jacinto-Brazos Coastal Basin
(Control Point abbreviations are explained in Table 2-1)



Three primary control points are associated with multiple USGS gage numbers:

- *SHGR26* represents both the Brazos River at Morris Sheppard Dam near Graford, TX gage (08088600) and the Brazos River near Graford, TX (08088610) gage. The stream gages are at the same location. Prior to February 8, 1995, data for the Brazos River near Graford, TX (08088610) gage was published as the Brazos River at Morris Sheppard Dam near Graford, TX gage (08088600).

- *AQAQ34* is associated with both the Aquilla Creek near Aquilla, TX gage (08093500) and the Aquilla Creek above Aquilla, TX gage (08093360). In June 2001, the Aquilla Creek near Aquilla, TX gage (08093500) was discontinued and replaced with a gage upstream, the Aquilla Creek above Aquilla, TX gage (08093360). For the extended flows, the flows at the upstream 08093360 gage

were naturalized and a drainage area ratio (308 sq mi / 255 sq mi) was used to calculate the flows at the old downstream location. This fill only affects the extended flows after June 2001.

- *BRBR59* is associated with both the Brazos River near Bryan, TX gage (08109000) and the Brazos River at SH 21 near Bryan, TX gage (08108700). The Brazos River near Bryan, TX gage (08109000) was discontinued in October 1993 and replaced with a new gage, the Brazos River at SH 21 near Bryan, TX gage (08108700), a few miles upstream. In the original WAM hydrology, the missing flows at the older downstream location were filled in using a relationship with other control points. In the BRA Drought Study, the flows at the new SH 21 gage were naturalized and a drainage area ratio (29,949 sq mi / 29,483 sq mi) was applied to estimate flow at the BRBR59 location. This change affected the original flows from October 1993 through December 1997 and was updated in the official TCEQ WAM hydrology following the BRA Drought Study. This extension also uses naturalized flows at the SH 21 gage multiplied by the drainage area ratio to extend the flows through December 2018.

Appendix E includes a drainage network diagram that shows which primary control points are upstream of others, delivery factors (i.e., one minus channel loss factors), and the location of major reservoirs.

2.2 RESERVOIR STORAGE

Monthly changes in reservoir storage content and average monthly surface area are required to calculate naturalized flows. **Table 2-2** lists major reservoirs included in the flow naturalization and the methods that were used to develop the needed data. When available, we based changes in content on records from the USGS, USACE and/or records kept by others. If records were not available, content change was estimated using reservoir operational studies. Content changes for smaller reservoirs were not considered in the development of naturalized flows, which are generally reservoirs with less than 5,000 acre-feet of conservation storage.

Average surface area for each reservoir was calculated based on area-capacity-elevation curves from either the content data or historical elevation data. More information may be found in **Chapter 2.3**.

Reservoir data may not be continuous for various reasons. If the end-of-month elevation or storage was not available, the following guidelines were used to estimate reservoir storage:

- Short periods of missing data were estimated by taking the average of neighboring days, or linear interpolation.

- For longer periods of missing data, or if no reservoir data are available at all, a reservoir operation study was used to estimate reservoir storage content. These operation studies used an Excel-based mass balance model using estimated reservoir inflows, net evaporation, historical diversions, return flows, and area-capacity information to calculate reservoir storage.
- If a reservoir is used for once-through cooling or uses makeup water from an alternative source to keep the reservoir at or near full, the reservoir was assumed to be full (zero content change) and only evaporation loss was estimated.

A table showing which reservoirs are upstream of primary control points in the Brazos River Basin is included as **Appendix B**.

Table 2-2: Methods for Estimating Reservoir Content Change and Surface Area in the Brazos River Basin

Reservoir	Impoundment Date	Period	Method
White River (WRSP02)	10/1963	Before 10/1963 10/1963-3/1964 4/1964-9/1976 10/1976-6/1979 7/1979-10/1990 11/1990-12/1990 1/1991-12/1998 1/1999-12/2018	No impact **Assumed:** Even filling of reservoir **Observed:** USGS data **Simulated:** Operation study, inflows estimated from Double Mountain Fork Brazos River near Aspermont **Observed:** WRMWD Data **Assumed:** Data interpolated **Observed:** TWDB Data **Observed:** USGS data
Buffalo Springs (BSLU07)	09/1959	Before 9/1959 9/1959-12/1966 1/1967-9/1977 10/1977-12/2018	No impact **Simulated:** Operation study, inflows estimated from Double Mountain Fork Brazos River at Justiceburg, Double Mountain Fork Brazos River near Aspermont **Observed:** USGS data **Simulated:** Operation study, inflows using Double Mountain Fork Brazos River at Justiceburg
Alan Henry (DMAS09)	10/1993	Before 10/1993 10/1993-1/1995 2/1995-9/1997 10/1997-12/2018	No impact **Simulated:** Operation study, inflows using Double Mountain Fork Brazos River at Justiceburg **Observed:** BRA Elevation data **Observed:** USGS data
Davis (BRSE11)	1958	Before 1/1959 1/1959-11/1959 12/1959-9/1985	No impact **Simulated:** Operation study, inflows using Brazos River at Seymour **Simulated:** Operation study, inflows using S. Wichita near Benjamin (Red River Basin)

Reservoir	Impoundment Date	Period	Method
		10/1985-12/2018	**Simulated:** Operation study, incremental flows between S. Wichita near Benjamin and S. Wichita near Guthrie (Red River Basin)
Sweetwater (CFHA14)	1930	1/1940-9/1974	**Observed:** USGS data
		10/1974-12/1997	**Simulated:** Operation study, inflows estimated from Clear Fork Brazos River near Roby, Clear Fork near Hawley
		1/1998-3/1999	**Simulated:** Operation study, inflows estimated from Clear Fork Brazos River near Roby, Clear Fork at Nugent
		4/1999-12/2018	**Observed:** USGS elevation data with estimated year 2000 area-capacity
Abilene (CFNU16)	08/1921	1/1940-1/1964	**Simulated:** Operation study, inflows estimated from Elm Creek at Ballinger (Colorado River Basin)
		2/1964-12/1997	**Observed:** Texas Water Development Board Data
		1/1998-2/1999	**Simulated:** Operation study, inflows estimated from Elm Creek at Ballinger (Colorado River Basin)
		3/1999-3/2014	**Observed:** USGS data
		4/2014-5/2015	**Simulated:** Operation study, inflows estimated from Elm Creek at Ballinger (Colorado River Basin)
		6/2015-12/2018	**Observed:** USGS data
Kirby (CFNU16)	1928	1/1940-12/1963	**Simulated:** Operation study, inflows estimated from Elm Creek at Ballinger (Colorado River Basin)
		1/1964-12/1998	**Observed:** Texas Water Development Board Data
		1/1999-8/2011	**Simulated:** Operation study, inflows estimated from Elm Creek at Ballinger (Colorado River Basin)
		9/2011-12/2018	**Observed:** USGS data
Fort Phantom Hill (CFNU16)	10/1938	1/1940-6/1940	**Simulated:** Operation study, inflows estimated from Clear Fork Brazos River at Nugent
		7/1940-9/1986	**Observed:** USGS data
		10/1986-12/1998	**Observed:** Elevation data from Freese and Nichols, Inc. files
		1/1999-2/1999	**Assumed:** Data interpolated
		3/1999-12/2018	**Observed:** USGS data
Stamford (CFFG18)	06/1953	7/1953-9/1986	**Observed:** USGS data
		10/1986-1/1999	**Observed:** West Texas Utilities elevation data
		2/1999-9/2002	**Observed:** USGS data
		10/2002-10/2003	**Simulated:** Operation Study
		11/2003-12/2018	**Observed:** USGS data
Cisco (BSBR20)	1923	1/1940-1/1962	**Simulated:** Operation study, inflows estimated from Clear Fork Brazos River at Fort Griffin
		2/1962-1/1999	**Simulated:** Operation study, inflows estimated from Clear Fork Brazos River at Fort Griffin, Big Sandy Creek above Breckenridge
		2/1999-12/2018	**Observed:** USGS data

Reservoir	Impoundment Date	Period	Method
Hubbard (HCBR21)	12/1962	Before 9/1962 9/1962-12/2018	No impact **Observed:** USGS data
Daniel(CFEL22)	09/1948	Before 1948 9/1948-6/1949 7/1949-8/1951 9/1951-9/1961 10/1961-2/1962 3/1962-11/1964 12/1964-8/1975 9/1975-3/1976 4/1976-9/1989 10/1989-2/1999 3/1999-10/2013 11/2013-12/2018	No impact **Assumed:** Even filling of reservoir **Simulated:** Operation study, inflows estimated from Clear Fork Brazos River at Eliasville **Simulated:** Operation study, inflows estimated from Brazos River near South Bend **Simulated:** Operation study, inflows estimated from Clear Fork Brazos River at Eliasville **Simulated:** Operation study, inflows estimated from Big Sandy Creek above Breckenridge **Simulated:** Operation study, inflows estimated from Big Cedar Creek near Ivan **Simulated:** Operation study, inflows estimated from Big Sandy Creek above Breckenridge **Simulated:** Operation study, inflows estimated from Big Cedar Creek near Ivan **Simulated:** Operation study, inflows estimated from Big Sandy Creek above Breckenridge **Observed:** USGS data **Simulated:** Operation study, inflows estimated from Big Sandy Creek above Breckenridge
Millers Creek (BRSB23)	07/1974	Before 1974 7/1974-3/1977 4/1977-9/1994 10/1994-7/1998 8/1998-12/2018	No impact **Simulated:** Operation study using Millers Creek near Munday **Observed:** USGS data **Simulated:** Operation study using Millers Creek near Munday **Observed:** USGS data
Graham (GHGH24)	1929[a]	1/1940 to 12/1959 1/1960-9/2000 10/2000-10/2001 10/2001-12/2018	**Observed:** Content data from FNI files **Observed:** USGS data **Simulated:** Operation study using W Fk Trinity near Jacksboro **Observed:** USGS data
Possum Kingdom (SHGR26)	03/1941	Before 3/1941 3/1941-12/2018	No impact **Observed:** USGS data
Palo Pinto (PPSA28)	04/1964	Before 4/1964 4/1964-9/1982 10/1982-12/1990 1/1991-12/1998 1/1999-2/1999 3/1999-12/2018	No impact **Observed:** USGS data **Simulated:** Operation study, inflows estimated from Palo Pinto Creek near Santo **Observed:** Texas Water Development Board Data **Assumed:** Data interpolated **Observed:** USGS data
Mineral Wells (BRDE29)	09/1920	1/1940-12/1946	**Simulated:** Operation study, inflows estimated from Brazos River near Palo Pinto

Reservoir	Impoundment Date	Period	Method
		1/1947-12/1996	**Simulated:** Operation study, inflows estimated from West Fork Trinity River near Boyd (Trinity Basin)
		1/1997-1/1999	**Simulated:** Operation study, inflows estimated from West Fork Trinity River near Jacksboro (Trinity Basin)
		2/1999-12/2018	**Observed:** USGS data
Squaw Creek (BRGR30)	02/1977	Before 2/1977	No impact
		2/1977-12/2018	**Observed:** USGS data
Granbury (BRGR30)	10/1968	Before 10/1968	No impact
		10/1968-12/2018	**Observed:** USGS data
Pat Cleburne (NRBL32)	08/1964	Before 8/1964	No impact
		8/1964-3/1965	**Simulated:** Operation study, inflows estimated from Nolan River at Blum, Clear Fork Trintiy River near Benbrook (Trinity Basin)
		4/1965-9/1985	**Observed:** USGS data
		10/1985-12/1989	**Simulated:** Operation study, inflows estimated from Nolan River at Blum, Clear Fork Trintiy River near Benbrook (Trinity Basin)
		1/1990-6/1998	**Observed:** Texas Water Development Board Data
		7/1998-12/2018	**Observed:** USGS data
Whitney (BRAQ33)	12/1951	Before 12/1951	No impact
		12/1951-12/1997	**Observed:** USGS data
		1/1998-12/2018	**Observed:** USACE data
Aquilla (AQAQ34)	05/1983	Before 5/1983	No impact
		5/1983-12/2018	**Observed:** USGS data
Waco (BOWA40)	02/1965	1/1940-2/1965	**Simulated:** Old Lake Waco operation study inflows estimated using North Bosque near Clifton and Aquilla Creek near Aquilla
		2/1965-12/1997	**Observed:** USGS data
		1/1998-12/2018	**Observed:** USACE data
Tradinghouse (BRHB42)	07/1968	Before 7/1968	No impact
		7/1968-6/1972	**Assumed:** Even filling of reservoir
		7/1972-12/1984	**Assumed** reservoir is full, no data available
		1/1985-12/1990	**Simulated:** Operation study, inflows estimated from Aquilla Cr nr Aquilla and Hog Creek nr Crawford, and diversions estimated from Brazos River near Highbank
		1/1991-12/1991	**Assumed** reservoir is full, no data available
		1/1992-12/1999	**Observed:** TXU elevation data
		1/2000-12/2001	**Simulated:** Operation study, inflows estimated using Aquilla Cr nr Aquilla
		1/2002-3/2004	**Assumed** reservoir is full, no data available
		4/2004-12/2018	**Simulated:** Operation study, inflows estimated using Aquilla Cr nr Aquilla
Lake Creek(BRHB42)	06/1952	Before 6/1952	No impact
		6/1952-3/1953	**Assumed:** Even filling of reservoir
		4/1953-12/1984	**Assumed** reservoir is full, no data available

Reservoir	Impoundment Date	Period	Method
		1/1985-12/1990	**Simulated:** Operation study, inflows estimated from Aquilla Cr nr Aquilla and Hog Creek nr Crawford, and diversions estimated from Brazos River near Highbank
		1/1991-12/1993	**Assumed** reservoir is full, no data available
		1/1994-12/1996	**Simulated:** Operation study, inflows estimated from Aquilla Cr nr Aquilla and diversions estimated from Brazos River near Highbank
		1/1997-12/1999	**Observed:** TXU historical elevation data
		1/2000-12/2018	**Simulated:** Operation study, inflows estimated from Aquilla Cr nr Aquilla
Leon (LEDL43)	06/1954	Before 4/1954	No impact
		4/1954-12/1954	**Assumed:** Even filling of reservoir
		1/1955-9/1983	**Observed:** USGS data
		10/1983-12/1998	**Observed:** Texas Water Development Board Data
		1/1999-2/1999	**Assumed:** Data interpolated
		3/1999-12/2018	**Observed:** USGS data
Proctor (LEHS45)	09/1963	Before 2/1963	No impact
		2/1963-9/2000	**Observed:** USGS data
		10/2000-9/2001	**Observed:** USACE data
		10/2001-12/2018	**Observed:** USGS data
Belton (LEBE49)	03/1954	Before 3/1954	No impact
		3/1954-12/2018	**Observed:** USGS data
Stillhouse Hollow (LABE52)	02/1968	Before 9/1966	No impact
		9/1966-12/2018	**Observed:** USGS data
Georgetown (NGGE54)	03/1980	Before 3/1980	No impact
		3/1980-12/2018	**Observed:** USGS data
Granger (GALA57)	01/1980	Before 1/1980	No impact
		1/1980-12/2018	**Observed:** USGS data
Alcoa (EYDB61)	10/1952	Before 1953	No impact
		1/1953-12/1953	**Observed:** Alcoa Data
		1/1954-12/2018	**Assumed** reservoir is full, no data available
Somerville (YCSO62)	01/1967	Before 2/1966	No impact
		2/1966-12/2018	**Observed:** USGS data
Mexia (NAGR64)	06/1961	Before 1961	No impact
		6/1961-9/1986	**Observed:** USGS data
		10/1986-12/1998	**Observed:** Texas Water Development Board Data
		1/1999-4/1999	**Assumed:** Data interpolated
		5/1999-12/2018	**Observed:** USGS data
Limestone (NAEA66)	10/1978	Before 11/1978	No impact
		11/1978-12/2018	**Observed:** USGS data
Twin Oaks (NABR67)	1981	Before 1981	No impact
		2/1981-12/2018	**Simulated:** Operation study, inflows estimated from Big Creek near Freestone and Navasota River near Easterly
	11/1948	Before 1948	No impact

Reservoir	Impoundment Date	Period	Method
Camp Creek (NABR67)		11/1948-12/2018	**Simulated:** Operation study, inflows estimated from Navasota River near Easterly
Gibbons Creek (BRHE68)	01/1979	Before 1/1979 1/1979-12/2018	No impact **Simulated:** Operation study, inflows estimated from naturalized Bedias Cr nr Madisonville (Trinity)
Smithers (BRRO72)	10/1957	Before 1957 10/1957-12/1997 1/1998-1/2007 2/2007-12/2018	No impact **Simulated:** Operation study, inflows estimated from Big Creek near Needville **Assumed** reservoir is full **Observed:** NRG accounting plan data
William Harris (BRGM73)	10/1947		off-channel reservoir, no content or area was estimated
Brazoria (BRGM73)	05/1954		off-channel reservoir, no content or area was estimated
Galveston County Water (BRRO72)	03/1947		off-channel reservoir, no content or area was estimated
Allens Creek			permitted reservoir, not built, no content or area
Post			permitted reservoir, not built, no content or area
Paluxy			permitted reservoir, not built, no content or area

a. Lake Eddleman was completed in 1929. Lake Graham was completed in April 1958.

Lake Mexia had a surveyed storage capacity of 4,687 acre-feet in 2008 but is authorized to store 9,600 acre-feet (Certificate of Adjudication 12-5287). Although the storage in Lake Mexia is just under the 5,000 acre-feet threshold, it was included in the naturalization because the authorized storage capacity is greater than 5,000 acre-feet.

2.3 RESERVOIR AREA-CAPACITY DATA

Historical reservoir elevation data were converted to storage content and corresponding surface areas using available area-capacity-elevation data. Where multiple volumetric surveys are available, points in time were identified to change surveys that coincide with periods of high flow where there will be less of an impact on water availability. Information on specific surveys used in the naturalization process may be found in **Table 2-3**, as well as in notes in the reservoir content change workbooks included with the naturalized flow workbooks.

The average reservoir surface area each month (in acres) is multiplied by the monthly net evaporation rate (in feet) to determine the total volume of net evaporation (in acre-feet). The end of month reservoir surface area for the extension period (1998-2018) was estimated based on the reservoir's recent

volumetric surveys. The average surface area per month is taken as the average of the beginning of month (i.e., end of previous month) and the end of month surface areas.

Table 2-3: Major Reservoirs in the Brazos River Basin

Reservoir	Contributing Drainage Area (Square Miles)	Conservation Storage (Ac-Ft)			Volumetric Survey Date
		Permitted	Original	Surveyed	
White River	689 [a]	44,897	44,910	31,846	10/1992
Buffalo Springs	236	4,730	4,200 [b]	--	--
Alan Henry	395	115,937	--	96,207	8/2017
Davis	--	4,477	5,400	--	--
Sweetwater	104	10,000	11,900 [c]	--	--
Abilene	110	11,868	7,900	6,680	1980
Kirby	44	8,500	7,620 [d]	7,620	--
Fort Phantom Hill	470	73,960	74,310	70,030	11/1993
Stamford	368	59,810	57,630	51,570	8/1999
Cisco	26.7	45,000	26,000	--	--
Hubbard Creek	1,085	320,000	317,750	318,179	1/2018
Daniel	115	11,400	9,515	6,115	1980
Millers Creek	240	30,696	25,520	27,888	7/1993
Graham	221	52,389 [e]	53,680	45,302	4/1998
Possum Kingdom	14,030	724,739	724,700	538,139	12/2016
Palo Pinto	461	44,100 [f]	44,100	27,215	6/2007
Mineral Wells	63	8,140 [g]	6,760	5,461	10/2015
Squaw Creek	64	151,500	151,500	151,273	12/2007
Granbury	16,113	155,000	153,500	129,011	6/2015
Pat Cleburne	100	25,600	25,560	26,008	7/2008
Whitney	17,623	50,000	642,179	554,203	6/2005
Aquilla	255	52,400	52,400	44,566	7/2014
Waco	1,652	104,100	152,500	189,773	5/2011
Tradinghouse	39	37,814	37,814	37,800	1973
Lake Creek	17	8,500	8,400	--	--
Marlin City Lake	18	6,847	--	--	--
Leon	259	12,000	27,290	28,042	9/2015
Proctor	1,259	59,400	59,400	54,762	2/2012
Belton	3,570	457,600	457,600	432,631	10/2015
Stillhouse Hollow	1,313	235,700	235,700	229,881	12/2015
Georgetown	247	37,100	37,100	38,068	1/2016
Granger	730	65,500	65,500	51,822	3/2013
Bryan Utilities [h]	0	15,227	15,200	14,163	2/2016
Alcoa	6	14,750	14,750	14,600	1/1957
Sandow Surface Lignite Mine	--	7,529	--	--	--
Somerville	1,007	160,110	160,100	150,293	4/2012

Reservoir	Contributing Drainage Area (Square Miles)	Conservation Storage (Ac-Ft)			Volumetric Survey Date
		Permitted	Original	Surveyed	
Mexia	196	9,600	10,000	4,687	4/2008
Limestone	675	225,400	225,400	203,780	3/2012
Twin Oaks	45	30,319	30,300	--	--
Camp Creek	40	8,400	8,550	8,350	1973
Gibbons Creek	85	32,084	26,800	27,603	3/2008
Smithers	24	16,500	18,700	18,680	1973
Eagle Nest Lake & Manor Lake	13	18,000	--	--	--
William Harris	0	10,200	12,000	--	--
Brazoria	0	21,973	21,970	--	--
Galveston County Water	0	7,308	--	--	--
Allens Creek	--	138,441	--		
Post	--	57,240	--	--	--
Paluxy	--	99,674	--	--	--

a. White River reservoir design engineers report 172 square mile contributing drainage area. 689 sq. mi. is reported by USGS.
b. Capacity of Buffalo Springs Lake in 1957.
c. Capacity of Lake Sweetwater in 1948 Water Supply Report by Freese and Nichols.
d. Capacity of Kirby Lake in 1941 US SCS survey.
e. Combined permitted capacity of Lake Eddleman and Lake Graham when they were joined in 1959.
f. Lake Palo Pinto enlarged from 34,250 acre-feet in November 1965.
g. Lake Mineral Wells enlarged from 7,300 acre-feet in 1943.
h. No adjustment was made for Bryan Utilities Lake in the naturalization because the lake is maintained with groundwater.

2.4 EVAPORATION AND PRECIPITATION DATA

Precipitation and evaporation rates are monitored at several weather stations in the basin by the National Oceanic and Atmospheric Administration (NOAA) and USACE. When records are available for gages near reservoirs, the weather station data was used to estimate net reservoir evaporation rates. This means that, for some major reservoirs, the TWDB quadrangle evaporation and precipitation was used only to fill in missing data. This approach is described in the work plan and follows the method used in the original naturalization and the BRA Drought Study. The weather stations that correspond to major reservoirs are included in **Table 2-4**.

TWDB has developed monthly precipitation and evaporation rates for each one-degree quadrangle in Texas. Some of these data were revised since the original naturalization, and some were revised since the BRA Drought Study in 2017. The reported values for the gross evaporation quadrangles used in the original naturalization of the Brazos River Basin and San Jacinto-Brazos Coastal Basin flows have changed for the year 1994 (part of the original period of record from 1940-1997), 1999-2000 and 2012-2015 (part of the

BRA Drought Study extension). Compared to the BRA Drought Study, the reported monthly precipitation rates changed for the period 2012-2015. This current extension project used the latest information from TWDB for evaporation and precipitation rates, except when local weather stations were used. The TWDB quadrangles applicable to the Brazos WAM are shown in **Figure 2-2**. The equations used for estimating missing net reservoir evaporation based on TWDB quadrangle data are included in **Table 2-5**.

Adjusted net reservoir evaporation is the rate at which water is lost to evaporation from the surface of a reservoir. It represents the net impact of evaporation and of rainfall directly on the reservoir surface. The equation for adjusted net reservoir evaporation is as follows:

Adjusted Net Reservoir Evaporation = Gross Reservoir Evaporation – (Rainfall – Effective Runoff).

The sources of the data used to determine reservoir evaporation rates are as follows:

Gross Reservoir Evaporation – Gross evaporation rates have been measured for some of the study period at several of the large reservoirs, as shown in **Table 2-4**. Measurements of pan evaporation multiplied by appropriate pan factors were used to estimate gross reservoir evaporation where available. For those reservoirs that do not have pan evaporation data, or for periods when local evaporation was not available, gross evaporation rates were obtained from TWDB quadrangle data. At the time of this project, gross reservoir evaporation rates by quadrangle were available from TWDB from 1954 to 2019 (https://waterdatafortexas.org/lake-evaporation-rainfall). Evaporation data for the period from 1940 through 1953 are from older estimates of quadrangle evaporation by TWDB predecessor agencies and were retrieved from FNI files. Monthly values for a specific reservoir are derived by taking a distance-weighted average for up to four nearby quadrangles. **Table 2-5** summarizes the quadrangle factors that were used to estimate gross reservoir evaporation at specific reservoir sites when pan measurements were missing or not available.

Precipitation – Precipitation records are available throughout the basin from the National Oceanic and Atmospheric Administration and TWDB. Precipitation data by quadrangle are available from the TWDB for 1940 through 2019. When necessary, TWDB quadrangle data was used to estimate precipitation, using the same weighting factors applied to the gross evaporation (**Table 2-5**). Specific months where these data were used are noted in the net evaporation workbooks.

Effective Runoff – The amount of rainfall that falls on the reservoir surface is corrected for the portion of rainfall that would have run off and become streamflow in the absence of a reservoir. The amount of water that would have become streamflow (effective runoff) is generally obtained from flows at a nearby USGS gage or gages divided by the contributing drainage area to produce unit runoff (expressed as inches). In the Brazos River Basin and San Jacinto-Brazos Coastal Basin, estimates of effective runoff are made for each one-degree quadrangle to facilitate estimates of net evaporation using the relationships in **Table 2-5**. **Table 2-6** shows the streamflow gages that were used to estimate effective runoff for each quadrangle.

Typically, if the estimated effective runoff for a reservoir site is greater than the precipitation rate, the effective runoff is limited to the precipitation rate. However, effective runoff was not limited to precipitation in the development of the original Brazos WAM flows nor the BRA Drought Study. Effective runoff does not often exceed precipitation, and when it does, it is typically not by much. Because it was not limited in these earlier projects, effective runoff was also not limited to rainfall for this extension.

Table 2-4: Evaporation and Precipitation Stations Near Major Reservoirs

Reservoir	Evaporation Stations	Precipitation Stations
White River	None	None
Buffalo Springs	None	None
Alan Henry	None	None
Davis	None	None
Sweetwater	None	None
Abilene	None	Lake Abilene
Kirby	None	None
Fort Phantom Hill	None	None
Stamford	None	None
Cisco	None	None
Hubbard	None	None
Daniel	None	None
Millers Creek	None	None
Graham	None	None
Possum Kingdom	None	None
Palo Pinto	None	None
Mineral Wells	None	None
Squaw Creek	None	None
Granbury	None	None
Pat Cleburne	None	None
Whitney	Whitney Dam	Whitney Dam
Aquilla	None	None
Waco	Waco Dam	Waco Airport
Tradinghouse	None	None

Reservoir	Evaporation Stations	Precipitation Stations
Lake Creek	None	None
Marlin City Lake	None	None
Leon	None	None
Proctor	Proctor Reservoir	Proctor Reservoir
Belton	Belton Dam	Belton Dam
Stillhouse Hollow	Stillhouse Hollow Dam	Stillhouse Hollow Dam
Georgetown	Georgetown Lake	Georgetown Lake
Granger	Granger Dam	Granger Dam
Bryan Utilities	None	None
Alcoa	None	None
Sandow Surface Lignite Mine	None	None
Somerville	Somerville Dam	Somerville Dam
Mexia	None	None
Limestone	None	None
Twin Oaks	None	None
Camp Creek	None	None
Gibbons Creek	None	None
Smithers	Thompsons 3 WSW	Thompsons 3
Eagle Nest & Manor	None	None
William Harris	None	None
Brazoria	None	None
Galveston County Water	None	None
Allens Creek	None	None
Post	None	None
Paluxy	None	None

Figure 2-2: TWDB Quadrangles for the Brazos River Basin and San Jacinto-Brazos Coastal Basin

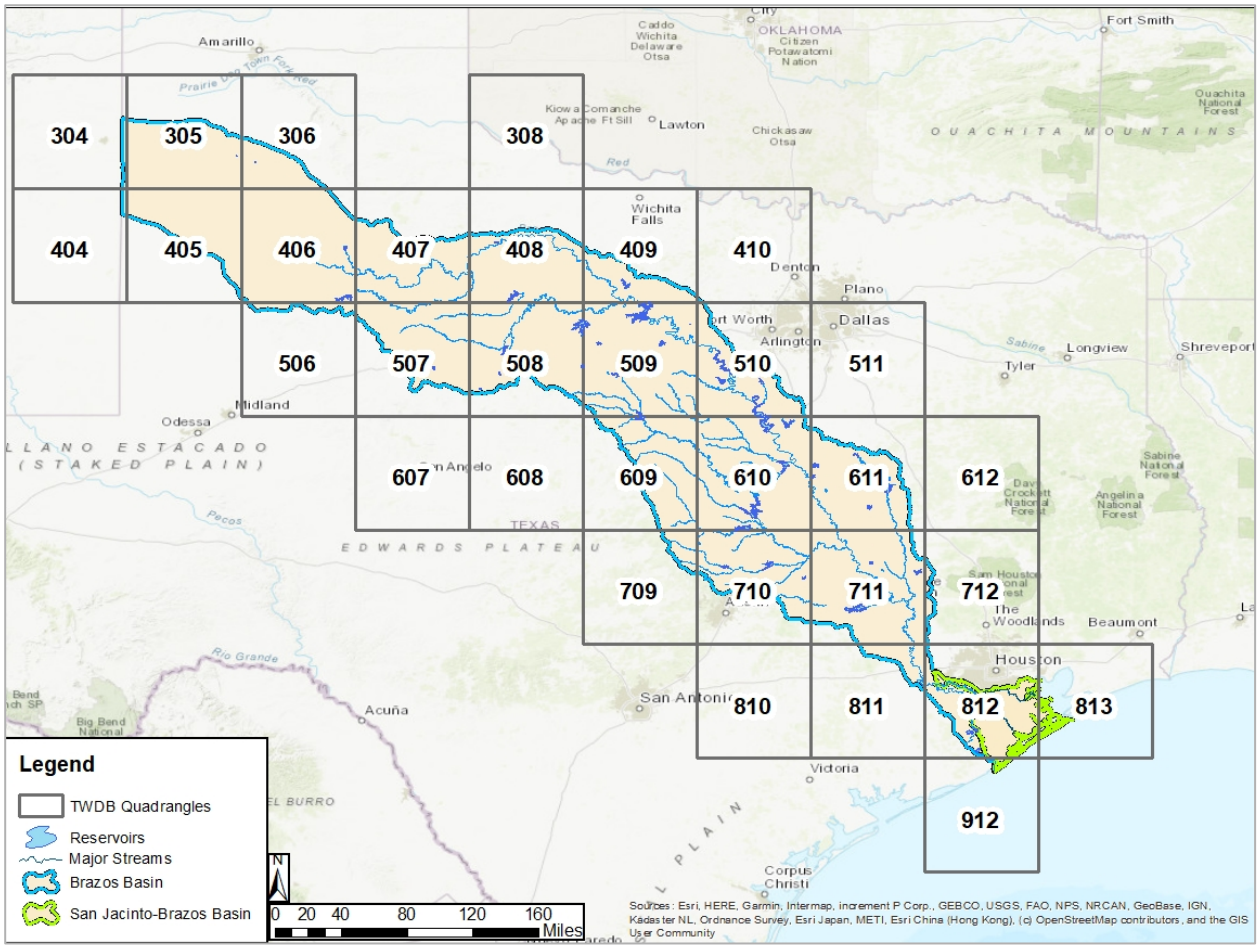


Table 2-5: Method for Estimating Net Reservoir Evaporation at Major Reservoirs based on TWDB Quadrangles

Reservoir	Quadrangle Interpolation Factor
White River	0.589 * (406) + 0.411 * (407)
Buffalo Springs	0.097 * (305) + 0.115 * (306) + 0.170 * (405) + 0.618 * (406)
Alan Henry	0.284 * (406) + 0.249 * (407) + 0.245 * (506) + 0.222 * (507)
Davis	0.267 * (407) + 0.733 * (408)
Sweetwater	0.633 * (507) + 0.158 * (508) + 0.114 * (607) + 0.094 * (608)
Abilene	0.277 * (507) + 0.364 * (508) + 0.175 * (607) + 0.184 * (608)
Kirby	0.193 * (507) + 0.550 * (508) + 0.116 * (607) + 0.141 * (608)
Fort Phantom Hill	0.103 * (407) + 0.126 * (408) + 0.168 * (507) + 0.602 * (508)
Stamford	0.188 * (407) + 0.339 * (408) + 0.176 * (507) + 0.297 * (508)
Cisco	0.345 * (508) + 0.364 * (509) + 0.146 * (608) + 0.146 * (609)
Hubbard	0.194 * (408) + 0.194 * (409) + 0.299 * (508) + 0.313 * (509)
Daniel	0.142 * (408) + 0.158 * (409) + 0.255 * (508) + 0.446 * (509)
Millers Creek	0.707 * (408) + 0.118 * (409) + 0.098 * (508) + 0.076 * (509)
Graham	0.193 * (408) + 0.410 * (409) + 0.159 * (508) + 0.237 * (509)

Reservoir	Quadrangle Interpolation Factor
Possum Kingdom	0.386 * (409) + 0.614 * (509)
Palo Pinto	0.137 * (409) + 0.108 * (410) + 0.586 * (509) + 0.170 * (510)
Mineral Wells	0.206 * (409) + 0.195 * (410) + 0.312 * (509) + 0.287 * (510)
Squaw Creek	0.218 * (509) + 0.468 * (510) + 0.142 * (609) + 0.173 * (610)
Granbury	0.199 * (509) + 0.556 * (510) + 0.112 * (609) + 0.132 * (610)
Pat Cleburne	0.577 * (510) + 0.154 * (511) + 0.157 * (610) + 0.112 * (611)
Whitney	0.296 * (510) + 0.169 * (511) + 0.355 * (610) + 0.180 * (611)
Aquilla	0.262 * (510) + 0.196 * (511) + 0.321 * (610) + 0.221 * (611)
Waco	0.138 * (510) + 0.119 * (511) + 0.528 * (610) + 0.215 * (611)
Tradinghouse	0.480 * (610) + 0.520 * (611)
Lake Creek	0.480 * (610) + 0.520 * (611)
Marlin City Lake	0.266 * (610) + 0.420 * (611) + 0.150 * (710) + 0.165 * (711)
Leon	0.177 * (508) + 0.569 * (509) + 0.113 * (608) + 0.141 * (609)
Proctor	0.511 * (509) + 0.489 * (609)
Belton	0.171 * (609) + 0.421 * (610) + 0.151 * (709) + 0.257 * (710)
Stillhouse Hollow	0.175 * (609) + 0.329 * (610) + 0.168 * (709) + 0.329 * (710)
Georgetown	0.128 * (609) + 0.158 * (610) + 0.200 * (709) + 0.514 * (710)
Granger	0.157 * (610) + 0.117 * (611) + 0.557 * (710) + 0.169 * (711)
Bryan Utilities	0.230 * (611) + 0.770 * (711)
Alcoa	0.153 * (610) + 0.146 * (611) + 0.391 * (710) + 0.309 * (711)
Sandow Surface Lignite Mine	0.153 * (610) + 0.146 * (611) + 0.391 * (710) + 0.309 * (711)
Somerville	0.798 * (711) + 0.202 * (811)
Mexia	0.064 * (510) + 0.086 * (511) + 0.094 * (610) + 0.755 * (611)
Limestone	0.655 * (611) + 0.143 * (612) + 0.113 * (711) + 0.089 * (712)
Twin Oaks	0.724 * (611) + 0.276 * (711)
Camp Creek	0.338 * (611) + 0.197 * (612) + 0.284 * (711) + 0.182 * (712)
Gibbons Creek	0.168 * (611) + 0.162 * (612) + 0.359 * (711) + 0.310 * (712)
Smithers	0.144 * (811) + 0.856 * (812)
Eagle Nest Lake	0.714 * (812) + 0.286 * (912)
William Harris	0.734 * (812) + 0.266 * (912)
Brazoria	0.565 * (812) + 0.435 * (912)
Galveston County Water	0.474 * (812) + 0.526 * (813)
Allens Creek	0.178 * (711) + 0.163 * (712) + 0.387 * (811) + 0.271 * (812)
Post	0.702 * (406) + 0.298 * (407) + 0.242 * (506) + 0.183 * (507)
Paluxy	0.259 * (509) + 0.385 * (510) + 0.166 * (609) + 0.190 * (510)

Table 2-6: Methods for Estimating Quadrangle Effective Runoff

Quadrangle	Data Source/Gage	Basin	USGS Gage Number	Drainage Area (Square Miles)	Contributing Drainage Area (Square Miles)	Period
304	Tierra Blanca Creek above Buffalo Lake near Umbarger	Red	07295500	1,968	575	1/1940-9/1954
	North Tule Draw at Reservoir near Tulia	Red	07298000	189	65	10/1954-9/1973
	Running Water Draw at Plainview	Brazos	08080700	1,291	382	10/1973-9/1978
	Prairie Dog Town Fork Red River near Wayside	Red	07297910	3,754	930	10/1978-12/2018
305	Tierra Blanca Creek above Buffalo Lake near Umbarger	Red	07295500	1,968	575	1/1940-9/1954
	North Tule Draw at Reservoir near Tulia	Red	07298000	189	65	10/1954-9/1973
	Running Water Draw at Plainview	Brazos	08080700	1,291	382	10/1973-9/1978
	Prairie Dog Town Fork Red River near Wayside	Red	07297910	3,754	930	10/1978-12/2018
306	North Tule Draw at Reservoir near Tulia	Red	07298000	189	65	1/1940-9/1973
	Running Water Draw at Plainview	Brazos	08080700	1,291	382	10/1973-9/1978
	Prairie Dog Town Fork Red River near Wayside	Red	07297910	3,754	930	10/1978-12/2018
308	Salt Fork Red River at Mangum, OK	Red	07300500	1,566	1,357	1/1940-11/1961
	Groesbeck Creek at State Highway 6 near Quanah	Red	07299670	303	303	12/1961-12/2018
404[a]	Use Runoff Developed for Quadrangle 304					
405[b]	Use Runoff Developed for Quadrangle 305					
406	Double Mountain Fork Brazos River at Lubbock	Brazos	08079500	5,300	224	1/1940-9/1949
	Double Mountain Fork Brazos River near Aspermont	Brazos	08080500	8,796	1,864	10/1949-12/2018
407	Salt Fork Brazos River near Aspermont	Brazos	08082000	5,130	2,496	1/1940-12/2018
408	Brazos River at Seymour	Brazos	08082500	15,538	5,972	1/1940-12/2018
409	Big Sandy Creek near Bridgeport	Trinity	08044000	333	333	1/1940-2/1956
	West Fork Trinity River near Jacksboro	Trinity	08042800	683	683	3/1956-12/2018

Quadrangle	Data Source/Gage	Basin	USGS Gage Number	Drainage Area (Square Miles)	Contributing Drainage Area (Square Miles)	Period
410	Big Sandy Creek near Bridgeport	Trinity	08044000	333	333	1/1940-9/1949
	Denton Creek near Justin	Trinity	08053500	400	400	10/1949-12/2018
506	Double Mountain Fork Brazos River at Lubbock	Brazos	08079500	5,300	224	1/1940-5/1946
	Colorado River at Colorado City (before Lk Thomas)	Colorado	08121000	4,082	1,585	6/1946-8/1952
	Colorado River at Colorado City (Lk Thomas not spilling)	Colorado	08121000	4,082	651	9/1952-9/1958
	Beals Creek near Westbrook	Colorado	08123800	9,902	1,988	10/1958-12/2018
507	Double Mountain Fork Brazos River near Aspermont	Brazos	08080500	8,796	1,864	1/1940-5/1946
	Colorado River at Colorado City (before Lk Thomas)	Colorado	08121000	4,082	1,585	6/1946-8/1952
	Colorado River at Colorado City (Lk Thomas not spilling)	Colorado	08121000	4,082	651	9/1952-11/1961
	Clear Fork Brazos River near Roby	Brazos	08083100	228	228	12/1961-12/2018
508	Clear Fork Brazos River at Nugent	Brazos	08084000	2,199	2,199	1/1940-9/1966
	Hubbard Creek below Albany	Brazos	08086212	613	613	10/1966-12/2018
509	Legacy WAM Naturalized Flow for Leon Reservoir	Brazos	08099000	259	259	1/1940 - 4/1951
	Palo Pinto Creek near Santo	Brazos	08090500	573	573	5/1951-2/1958
	North Bosque River at Stephenville	Brazos	08093700	96	96	3/1958-9/1979
	North Bosque River at Hico	Brazos	08094800	359	359	10/1979-12/1998
	Paluxy River at Glen Rose	Brazos	08094800	410	410	1/1999-9/1999
	Sabana River near De Leon	Brazos	08099300	264	264	10/1999-12/2018
510	Clear Fork Trinity River at Fort Worth	Trinity	08047500	518	518	1/1940 - 7/1947
	Clear Fork Trinity River near Aledo	Trinity	08046000	251	251	8/1947 - 2/1957

Quadrangle	Data Source/Gage	Basin	USGS Gage Number	Drainage Area (Square Miles)	Contributing Drainage Area (Square Miles)	Period
	Denton Creek near Justin	Trinity	08053500	400	400	3/1957 - 9/1960
	Walnut Creek near Mansfield	Trinity	08049700	62.8	62.8	10/1960-12/2018
511	Cedar Creek near Mabank	Trinity	08063000	733	733	1/1940-12/1962
	Kings Creek near Kaufman	Trinity	08062900	233	233	1/1963-9/1987
	Walnut Creek near Mansfield	Trinity	08049700	63.0	63.0	10/1987-12/2018
607	Concho River at San Angelo	Colorado	08136000	5,542	4,411	1/1940-12/2018
608	Brady Creek at Brady	Colorado	08145000	575	575	1/1940-9/1986
	Elm Creek at Ballinger	Colorado	08127000	450	450	10/1986-12/2018
609	Lampasas River at Youngsport	Brazos	08104000	1,240	1,240	1/1940-9/1950
	Cowhouse Creek at Pidcoke	Brazos	08101000	455	455	10/1950-8/1962
	Lampasas River near Kempner	Brazos	08103800	818	818	9/1962-12/2018
610	Aquilla Creek near Aquilla	Brazos	08093500	309	309	1/1940 - 8/1959
	Middle Bosque near McGregor	Brazos	08095300	182	182	9/1959-9/1985
	North Bosque River near Clifton	Brazos	08095000	968	968	10/1985-12/2018
611	Richland Creek near Richland	Trinity	08063500	734	734	1/1940 - 3/1968
	Tehuacana Creek near Streetman	Trinity	08064700	142	142	4/1968-12/2018
612	Neches Naturalized Flow Between Neches (NE_NE) and Alto (NE_AL)	Neches	08032000 - 8032500	800	800	1/1940-12/1996
	Upper Keechi Creek near Oakwood	Trinity	08065200	150	150	1/1997-12/2018
709	Pedernales River near Johnson City	Colorado	08153500	947	947	1/1940-9/1966
	Sandy Creek near Kingsland	Colorado	08152000	327	327	10/1966-9/1993
	Pedernales River near Johnson City	Colorado	08153500	901	901 [c]	10/1993-12/2018
710	San Gabriel River at Georgetown	Colorado	08105000	399	399	1/1940-7/1967
	Brushy Creek near Rockdale	Colorado	08106300	505	505	8/1967-10/1980

Quadrangle	Data Source/Gage	Basin	USGS Gage Number	Drainage Area (Square Miles)	Contributing Drainage Area (Square Miles)	Period
	Onion Creek at U.S. Highway 183 near Austin	Colorado	08159000	321	321	11/1980-12/2018
711	Yegua Creek near Somerville	Brazos	08110000	1,009	1,009	1/1940 - 9/1962
	Davidson Creek near Lyons	Brazos	08110100	195	195	10/1962-12/2018
712	East Fork San Jacinto River near Cleveland	San Jacinto	08070000	325	325	1/1940-12/2018
811	Navidad River near Ganado	Lavaca	08164500	1,062	1,062	1/1940-9/1961
	Navidad River near Hallettsville	Lavaca	08164300	332	332	10/1961-12/2018
812	Buffalo Bayou at Houston	San Jacinto	08074000	358	358	1/1940 - 9/1957
	Buffalo Bayou near Addicks	San Jacinto	08073500	293	293	10/1957-2/1959
	Chocolate Bayou near Alvin	San Jacinto - Brazos	08078000	88	88	3/1959-12/2018
813	Neches Naturalized Flow for Pine Island Bayou near Sour Lake (PI_SL)	Neches	08041700	336	336	1/1940-12/1997
	Pine Island Bayou near Sour Lake	Neches	08041700	336	336	1/1998-12/2018
912	Buffalo Bayou at Houston	San Jacinto	08074000	358	358	1/1940 - 4/1954
	San Bernard River near Boling	Brazos-Colorado	08117500	727	727	5/1954-6/1970
	Big Boggy Creek near Wadsworth	Brazos-Colorado	08117900	10	10	7/1970-9/1977
	San Bernard River near Boling	Brazos-Colorado	08117500	727	727	10/1977-12/2018

a. Quadrangle runoff was not developed for Quad 404 because this quad is not used in the relationships listed in Table 2-5.

b. Quadrangle runoff for Quad 405 uses the same runoff developed for Quad 305, consistent with the original naturalization. Quad 405 runoff is only used in the computation of evaporative losses from Buffalo Springs Lake.

c. Regarding Quad 709, the drainage area for Pedernales River near Johnson City changed from 947 sq mi to 901 sq mi.

2.5 WATER RIGHTS AND HISTORICAL WATER USE

The use of surface water in Texas is regulated through a system of water rights. TCEQ provided historical water use data from 2009 to 2018 at the beginning of this project. Earlier water use data is available from the TCEQ Water Rights and Water Use Data website (**Appendix A**). The BRA provided additional water use data. For this update, historical water use data from 1940 through 1997 were generally used from the original WAM workbooks, then water use data for water rights permitted for less than 1000 ac-ft/yr for 1998-2015 were added, and the historical water use data for all water rights in the basin were extended through the end of 2018. **Table 2-7** is a summary of authorized diversion amounts by use type by primary control point. **Appendix C** contains a detailed list of water rights in the basin for each primary control point.

The BRA through its System Order may report water use under water rights that are not at the location of the diversion, and they also make releases from reservoirs for downstream contracts that may flow past several gages before they are diverted. As a result, the TCEQ database may not reflect the actual location of diversions. As with previous naturalizations, information from the BRA on direct use from reservoirs and downstream contract releases was used in the naturalization.

Table 2-7: Authorized Diversion Amounts Between Primary Control Points by Use Type (acre-feet)

Downstream Control Point	Upstream Control Points	Municipal	Industrial	Irrigation	Others	Total
RWPL01	--	0	0	3,796	0	3,796
WRSP02	RWPL01	4,000	0	636	2,000	6,636
DUGI03	--	0	0	1,348	0	1,348
SFPE04	WRSP02 DUGI03	0	0	127	0	127
CRJA05	--	0	0	0	0	0
SFAS06	SFPE04 CRJA05	0	0	0	0	0
BSLU07	--	0	4,480	19,898	0	24,378
DMJU08	--	0	0	0	200	200
DMAS09	DMJU08	40,916	1,226	22,835	11,080	76,057
NCKN10	--	0	0	0	0	0
BRSE11	DMAS09 SFAS06 NCKN10	34	0	3,362	3,669	7,065
MSMN12	--	0	0	0	0	0
CFRO13	--	0	0	40	0	40
CFHA14	CFRO13	4,730	1,005	1,079	0	6,814

Downstream Control Point	Upstream Control Points	Municipal	Industrial	Irrigation	Others	Total
MUHA15	--	0	0	73	0	73
CFNU16	CFHA14	31,360	7,108	3,236	388	42,092
	MUHA15					
CAST17	--	842	0	205	0	1,047
CFFG18	CFNU16	13,021	0	5,473	103	18,597
	CAST17					
HCAL19	--	1,240	0	90	0	1,330
BSBR20	--	1,971	56	0	0	2,027
HCBR21	HCAL19	44,800	1,250	2,035	8,000	56,085
	BSBR20					
CFEL22	CFFG18	2,160	97	1,141	218	3,616
	HCBR21					
BRSB23	CFEL22	4,350	1,027	1,038	500	6,915
GHGH24	--	0	82	183	376	641
CCIV25	--	0	0	0	0	0
SHGR26	BRSB23	241,840	8,400	231	600	251,071
	GHGH24					
	CCIV25					
BRPP27	SHGR26	0	0	25	0	25
PPSA28	--	13,145	6,112	1,409	71	20,737
BRDE29	BRPP27	2,665	45	3,248	1,153	7,111
	PPSA28					
BRGR30	BRDE29	61,597	0	5,372	0	66,969
PAGR31	--	0	0	1,163	25	1,188
NRBL32	--	6,480	0	487	0	6,967
BRAQ33	PAGR31	13,336	23,185	8,013	157	44,691
	NRBL32					
AQAQ34	--	7,943	0	49	0	7,992
NBHI35	--	0	0	4,165	0	4,165
NBCL36	NBHI35	3,947	0	1,890	0	5,837
NBVM37	NBCL36	0	0	523	0	523
MBMG38	--	55	0	33	0	88
HGCR39	--	0	0	233	0	233
BOWA40	MBMG38	78,970	0	1,725	0	80,695
	HGCR39					
	NBVM37					
BRWA41	BRAQ33	5,600	74	2,971	1,257,530	1,266,175
	AQAQ34					
	BOWA40					
BRHB42	BRWA41	19,600	39,000	11,602	0	70,202
LEDL43	--	5,900	400	2,847	1,607	10,754
SADL44	--	0	0	783	0	783

Downstream Control Point	Upstream Control Points	Municipal	Industrial	Irrigation	Others	Total
LEHS45	LEDL43	19,658	0	7,883	0	27,541
	SADL44					
LEHM46	LEHS45	200	11	6,763	0	6,974
LEGT47	LEHM46	614	2	2,591	45	3,252
COPI48	--	0	0	518	0	518
LEBE49	LEGT47	47,804	0	1,830	0	49,634
	COPI48					
LAKE50	--	3,760	48	1,961	0	5,769
LAYO51	LAKE50	0	0	1,686	0	1,686
LABE52	LAYO51	67,768	0	103	0	67,871
LRLR53	LABE52	0	38,800	3,667	138	42,605
	LEBE49					
NGGE54	--	13,610	0	50	0	13,660
SGGE55	--	0	0	27	300	327
GAGE56	NGGE54	0	0	45	118	163
	SGGE55					
GALA57	GAGE56	19,840	203	1,017	240	21,300
LRCA58	GALA57	3,102	18,100	5,240	0	26,442
	LRLR53					
BRBR59	BRHB42	224	570	23,157	8	23,959
	LRCA58					
MYDB60	--	0	0	0	0	0
EYDB61	--	0	14,000	19	0	14,019
YCSO62	MYDB60	48,000	20	80	0	48,100
	EYDB61					
DCLY63	--	0	0	0	0	0
NAGR64	--	5,387	65	5	0	5,457
BGFR65	--	634	0	0	0	634
NAEA66	NAGR64	65,074	90	8	0	65,172
	BGFR65					
NABR67	NAEA66	0	30,319	120	0	30,439
BRHE68	BRBR59	0	17,320	20,899	319	38,538
	DCLY63					
	YCSO62					
	NABR67					
MCBL69	--	0	0	0	0	0
BRRI70	BRHE68	99,650	12,010	29,137	2,448	143,245
	MCBL69					
BGNE71	--	0	0	0	0	0
BRRO72	BRRI70	174,932	40,811	195,112	2,628	413,483
	BGNE71					
BRGM73	BRRO72	48,160	300,810	10,997	55,323	415,290

Downstream Control Point	Upstream Control Points	Municipal	Industrial	Irrigation	Others	Total
CLPEC1	--	0	0	0	11	11
CBALC2	--	0	0	2,187	0	2,187
SJGMC4	CBALC2	0	35,974	54,848	2,273	93,095
	--	30,000	0	1,575	442	32,017
SJGBC3	CLPEC1	0	142,410	1,703	291	144,404

Water use records are sometimes incomplete, or the values may be inconsistent with other water use data for a particular water right. Missing or inconsistent historical water use values were estimated using existing historical data, or by contacting water rights holders. The historical use for smaller water rights was often assumed to be zero. Historical water use is added to historical streamflows to compute naturalized flows, so assuming zero water use for smaller water rights leads to a conservatively low estimate of naturalized flow.

In the original naturalization, the diversions for Upper Leon River Municipal Water District (Upper Leon MWD) were accounted for at LEGT47. However, based on discussions with BRA, those diversions have always been taken lakeside at Lake Proctor (LEHS45). These changes are noted in **Table 4-1**.

2.6 RETURN FLOWS

Return flows, such as discharges of treated wastewater, are subtracted from measured streamflow during the naturalization process. **Table 2-8** lists municipal and industrial wastewater treatment plants (WWTPs) in the Brazos River Basin with a permitted discharge of 1 million gallons per day (MGD) or more. **Table 2-9** lists the same information for the San Jacinto-Brazos Coastal Basin. Monthly average return flows for each discharger shown in **Table 2-8** and **Table 2-9** were obtained from the EPA ECHO ICIS-NPDES database (for data from 2007-2018) and the Envirofacts Permit Compliance System database (for data prior to 2007).

In almost all cases, the return flows from the original naturalized streamflow dataset from 1940 through 1997 were used. The original WAM naturalization included return flows less than 1 MGD, however the scope of the current project only includes return flows from dischargers permitted for more than 1 MGD as of 2018. The return flow records for sub-watersheds in which all dischargers are permitted for less than 1 MGD were also extended to prevent discharges suddenly dropping to zero starting in 1998. No dischargers were identified that were operating in the 1940 to 1997 period that were permitted for less

than 1 MGD but are now permitted for more than 1 MGD that were not already included in the original naturalization.

The raw data from the EPA websites were checked for completeness and duplicate entries. If duplicates were found, they were discarded. Graphs were created to help identify erroneous entries. In most cases, erroneous entries appeared to be decimal errors, which were corrected. If they were not decimal errors, the average of adjacent months was used to estimate the values.

In most cases, the discharges permitted for more than 1 MGD had almost complete records. The Alcoa depressurization discharges available from EPA are not sufficiently accurate to use in the naturalization process. Consistent with the methodology used in the original naturalization, Alcoa return flows upstream of control point EYDB61 include an estimate of the amount of increased flow determined based on daily flow records. The correction for Alcoa depressurization decreases to zero starting in August 2008, when Alcoa's operations ceased.

The City of Post has a WWTP permitted for 0.5 MGD that disposes of treated wastewater effluent via land application upstream of control point DMAS09, a sub-watershed with no permitted discharges greater than 1 MGD. We could not verify whether the Post WWTP ever discharged to the stream. Consequently, the 1940-1997 return flows were left the same as the original naturalization, and it was assumed that zero return flows entered the stream from 1998-2018.

The City of Lubbock had significant new discharges identified in this update. Outfall 1 of the City of Lubbock's Southeast Water Reclamation Plant began discharging upstream of the control point at Buffalo Springs Lake (BSLU07) in 2003; Outfall 7 began discharging in 2016. The Northwest Water Reclamation Plant began discharging in 2018, and the Jim Bertram Lake System began adding water to the stream in 2004. The USGS gage associated with control point BSLU07 is Buffalo Springs Lake near Lubbock, TX (08079550), which is a reservoir storage gage (not a stream gage) that was discontinued in 1977. Historical streamflows at this control point were estimated using a reservoir operations model. Lubbock's new return flows were incorporated into this analysis as inflows to the reservoir to estimate the spills from Buffalo Springs Lake, which is used as the historical flow at BSLU07.

Table 2-8: Wastewater Treatment Plants in the Brazos River Basin with Permitted Discharges of 1 MGD or More

TPDES Number	NPDES Number	Facility	County	Final Permitted Flow (MGD)*	Type
WQ0010299001	TX0020443	MUSTANG CREEK WWTP	WILLIAMSON	4	MUNICIPAL
WQ0010110002	TX0021725	MARLIN, CITY OF WWTP	FALLS	2	MUNICIPAL
WQ0010205002	TX0022454	HENDERSON WWTF	LAMPASAS	1.5	MUNICIPAL
WQ0010426001	TX0022616	BURTON CREEK WWTP	BRAZOS	8	MUNICIPAL
WQ0010489002	TX0022667	SAN GABRIEL WWTP	WILLIAMSON	2.5	MUNICIPAL
WQ0010630001	TX0023108	HILLSBORO WWTP	HILL	1.81	MUNICIPAL
WQ0010585004	TX0023779	WILLOW CREEK WWTP	PALO PINTO	1.26	MUNICIPAL
WQ0010219002	TX0023914	MCGREGOR SOUTH WWTF	MCLENNAN	1.1	MUNICIPAL
WQ0010334004	TX0023973	HAMBY WWTP	TAYLOR	18	MUNICIPAL
WQ0010290001	TX0024228	STEPHENVILLE WWTP	ERATH	3	MUNICIPAL
WQ0010155001	TX0024473	CITY OF HARKER HEIGHTS WWTP	BELL	3	MUNICIPAL
WQ0010607002	TX0024490	CITY OF ROSENBERG WWTF	FORT BEND	4.5	MUNICIPAL
WQ0010351002	TX0024597	BELL COUNTY WCID 1 WWTF	BELL	18	MUNICIPAL
WQ0010487001	TX0024635	CITY OF GRAHAM	YOUNG	2.1	MUNICIPAL
WQ0010176004	TX0024953	LEON RIVER WWTP	CORYELL	1.5	MUNICIPAL
WQ0010276001	TX0025054	CITY OF SEALY STP	AUSTIN	2	MUNICIPAL
WQ0010388001	TX0025470	CITY OF BRENHAM WWTP	WASHINGTON	3.55	MUNICIPAL
WQ0011324001	TX0025577	HUTTO WWTP	WILLIAMSON	3.25	MUNICIPAL
WQ0010047001	TX0025798	CITY OF LAKE JACKSON	BRAZORIA	5.85	MUNICIPAL
WQ0010046002	TX0025879	CITY OF HEARNE WWTP 2	ROBERTSON	1.2	MUNICIPAL
WQ0010312001	TX0026182	CITY OF WEST COLUMBIA - WWTP	BRAZORIA	1.6	MUNICIPAL
WQ0011071001	TX0026506	WACO METRO AREA REGIONAL WWTPS	MCLENNAN	45	MUNICIPAL
WQ0010658001	TX0027197	CITY OF ROCKDALE WWTP	MILAM	1.25	MUNICIPAL
WQ0010882001	TX0033332	CENTRAL WWTF	BRAZORIA	2.25	MUNICIPAL
WQ0011046001	TX0035220	QUAIL VALLEY UD WWTP	FORT BEND	4	MUNICIPAL
WQ0010006001	TX0047155	CITY OF CLEBURNE WWTF	JOHNSON	7.5	MUNICIPAL
WQ0010024006	TX0047163	CARTER CREEK WWTP	LAFAYETTE	9.5	MUNICIPAL
WQ0010585001	TX0047414	POLLARD CREEK WWTP	PALO PINTO	2.35	MUNICIPAL
WQ0010537001	TX0047571	CITY OF PLAINVIEW WRP	HALE	3.3	MUNICIPAL
WQ0010470002	TX0047651	DOSHIER FARM WWTP	BELL	7.5	MUNICIPAL
WQ0010222001	TX0052990	MEXIA WWTF	LIMESTONE	2	MUNICIPAL
WQ0010004001	TX0053651	CITY OF CAMERON WWTP NO. 1	MILAM	1.25	MUNICIPAL
WQ0011655001	TX0056421	PECAN GROVE MUD WWTP	FORT BEND	1.9	MUNICIPAL
WQ0011317001	TX0058114	SUGAR LAND NORTH WWTP	FORT BEND	6	MUNICIPAL

TPDES Number	NPDES Number	Facility	County	Final Permitted Flow (MGD)*	Type
WQ0011318001	TX0058378	TEMPLE BELTON WWTP	BELL	10	MUNICIPAL
WQ0010045003	TX0067873	SOUTH PLANT WWTF	CORYELL	2.5	MUNICIPAL
WQ0010045005	TX0069841	NORTHWEST PLANT WWTP	CORYELL	4	MUNICIPAL
WQ0010045004	TX0069850	NORTHEAST WWTP	CORYELL	2.5	MUNICIPAL
WQ0010231001	TX0071790	CITY OF NAVASOTA WWTP	GRIMES	1.8	MUNICIPAL
WQ0010264001	TX0075167	BRUSHY WEST WWTP	WILLIAMSON	3	MUNICIPAL
WQ0012003001	TX0077178	FORT BEND CO MUD 25	FORT BEND	1.6	MUNICIPAL
WQ0012308001	TX0085740	CITY OF CEDAR PARK WATER RECLA	WILLIAMSON	5	MUNICIPAL
WQ0002585000	TX0090883	BRAYTON FIRE TRAINING FIELD	BRAZOS	2	MUNICIPAL
WQ0012644001	TX0092151	CITY OF LEANDER WWTF	WILLIAMSON	5.25	MUNICIPAL
WQ0010024003	TX0093262	LICK CREEK WWTP	BRAZOS	5	MUNICIPAL
WQ0012833002	TX0096881	SUGAR LAND SOUTH WWTP	FORT BEND	10	MUNICIPAL
WQ0010607003	TX0098914	ROSENBERG PLANT NO. 1A	FORT BEND	2	MUNICIPAL
WQ0010489003	TX0101281	DOVE SPRINGS WWTP	WILLIAMSON	2.5	MUNICIPAL
WQ0013355001	TX0101915	FT. BEND CO. MUD NO. 106 - WWTP	FORT BEND	1.35	MUNICIPAL
WQ0010264002	TX0101940	BRUSHY CREEK REGIONAL WWTP (E)	WILLIAMSON	25	MUNICIPAL
WQ0002889000	TX0102598	BRAZOS RIVER AUTHORITY SWATS	HOOD	2.5	MUNICIPAL
WQ0010351003	TX0102938	BELL COUNTY WCID 1 WWTP 2	BELL	6	MUNICIPAL
WQ0010178002	TX0105210	CITY OF GRANBURY WWTP	HOOD	2	MUNICIPAL
WQ0010353002	TX0106071	SOUTHEAST WATER RECLAMATION PLANT	LUBBOCK	31.5	MUNICIPAL
WQ0010426002	TX0108146	TEXAS A&M MAIN CAMPUS WWTP	BRAZOS	4	MUNICIPAL
WQ0010968003	TX0108146	TEXAS A&M MAIN CAMPUS WWTP	BRAZOS	4	MUNICIPAL
WQ0011275002	TX0111201	PRAIRIE VIEW A&M UNIV WWTF	WALLER	2	MUNICIPAL
WQ0010176002	TX0111791	STILLHOUSE BRANCH WWTP	CORYELL	2.7	MUNICIPAL
WQ0013628001	TX0111872	FORT BEND CO MUD 112	FORT BEND	6	MUNICIPAL
WQ0010489005	TX0114006	PECAN BRANCH WWTP	WILLIAMSON	3	MUNICIPAL
WQ0013873001	TX0114855	STEEP BANK FLAT BANK CREEK WWT	FORT BEND	6	MUNICIPAL
WQ0010258003	TX0115177	RICHMOND REGIONAL WWTP	FORT BEND	6	MUNICIPAL
WQ0013951001	TX0116386	FORT BEND CO MUD 118 WWTP	FORT BEND	1.2	MUNICIPAL
WQ0003466000	TX0117935	CITY OF ROBINSON WWTP	MCLENNAN	1	MUNICIPAL
WQ0010373002	TX0118346	CITY OF SWEETWATER WWTP	NOLAN	2.2	MUNICIPAL

TPDES Number	NPDES Number	Facility	County	Final Permitted Flow (MGD)*	Type
WQ0014118001	TX0119539	SEINNA PLANTATION MUD 1 (S2)	FORT BEND	1.2	MUNICIPAL
WQ0014387001	TX0125377	BELL CO WCID 1 WWTP	BELL	6	MUNICIPAL
WQ0014408001	TX0125555	FORT BEND COUNTY MUD 142 WWTP	FORT BEND	1.2	MUNICIPAL
WQ0014455001	TX0126004	FORT BEND COUNTY MUD 146 WWTP	FORT BEND	1.2	MUNICIPAL
WQ0014477001	TX0126195	LIBERTY HILL REGIONAL WWTP	WILLIAMSON	4	MUNICIPAL
WQ0014514001	TX0126624	FORT BEND COUNTY MUD 133 WWTP	FORT BEND	1.36	MUNICIPAL
WQ0014594001	TX0127698	CITY OF JARRELL DONAHOE WWTF	WILLIAMSON	4	MUNICIPAL
WQ0014612001	TX0127876	SIENNA PLANTATION MUD 1 REGIONAL WWTP	FORT BEND	3.5	MUNICIPAL
WQ0010426004	TX0128554	THOMPSONS CREEK WWTP	BRAZOS	4	MUNICIPAL
WQ0014745001	TX0129119	CROSS CREEK RANCH WWTF	FORT BEND	2.5	MUNICIPAL
WQ0014758001	TX0129216	FORT BEND COUNTY MUD 188 WWT	FORT BEND	1.5	MUNICIPAL
WQ0014889001	TX0129437	BULL HIDE CREEK WWTP	MCLENNAN	1.5	MUNICIPAL
WQ0010489007	TX0132233	NORTHLANDS WWTP	WILLIAMSON	3	MUNICIPAL
WQ0011324002	TX0132926	HUTTO SOUTH WWTP	WILLIAMSON	15.5	MUNICIPAL
WQ0005099000	TX0134953	CITY OF GRANBURY WTP	HOOD	3.75	MUNICIPAL
WQ0010353011	TX0135054	NORTHWEST WATER RECLAMATION PLANT	LUBBOCK	6	MUNICIPAL
WQ0000395000	TX0000876	ALCOA-ROCKDALE OPERATIONS	MILAM	326.28	OTHER
WQ0001267000	TX0001040	TRADINGHOUSE STEAM ELECTRIC STATION	MCLENNAN	1056	OTHER
WQ0000954000	TX0001058	LAKE CREEK SES	MCLENNAN	294	OTHER
WQ0000551000	TX0001163	TXU GRAHAM SES	YOUNG	505.4	OTHER
WQ0001176000	TX0001368	U.S. SILICA - KOSSE PLANT	LIMESTONE	2.5	OTHER
WQ0001401000	TX0001830	UNIMIN CORP - CLEBURNE PLANT	SOMERVELL	1	OTHER
WQ0001038000	TX0006394	W.A. PARISH STEAM ELECTRIC GEN. STA.	FORT BEND COUNTY	2158	OTHER
WQ0000007000	TX0006483	DOW CHEMICAL PLANT	BRAZORIA	2378.4	OTHER
WQ0001481000	TX0046400	DECORDOVA SES	HOOD	1041.48	OTHER
WQ0001903000	TX0062197	RANDLE W. MILLER SEGS - WWTP	PALO PINTO	400	OTHER
WQ0001854000	TX0065854	COMANCHE PEAK SES	SOMERVELL	3168	OTHER
WQ0001986000	TX0068021	OAK GROVE STEAM ELECTRIC STATION	ROBERTSON	1610.025	OTHER
WQ0002117000	TX0073954	ROLAND C. DANSBY SES	BRAZOS	78	OTHER

TPDES Number	NPDES Number	Facility	County	Final Permitted Flow (MGD)*	Type
WQ0002120000	TX0074438	GIBBONS CREEK SES	GRIMES	511.032	OTHER
WQ0002430000	TX0082651	LIMESTONE ELECTRIC GEN. STA.	LIMESTONE	3.597	OTHER
WQ0002443000	TX0085782	FRITO-LAY ROSENBERG	FORT BEND	1.114	OTHER
WQ0002877000	TX0101168	TWIN OAKS POWER STATTION	ROBERTSON	3	OTHER
WQ0002881000	TX0101567	CALVERT LIGNITE MINE	ROBERTSON	23.0645	OTHER
WQ0003821000	TX0113603	PROCESSING DIVISION WWTP	BRAZOS	1.678	OTHER
WQ0004167000	TX0119890	BOSQUE COUNTY POWER PLANT	BOSQUE	5.48	OTHER
WQ0004258000	TX0123510	BRAZOS VALLEY ELECTRIC ENERGY CENTER	FORT BEND	3	OTHER
WQ0004288000	TX0123820	WOLF HOLLOW I	HOOD	2.071	OTHER
WQ0004599000	TX0125679	JIM BERTRAM LAKE SYSTEM	LUBBOCK	3	OTHER
WQ0004755000	TX0127256	SANDY CREEK ENERGY STATION	MCLENNAN	2.6	OTHER
WQ0005142000	TX0135763	PETRA NOVA CAPTURE PLANT	FORT BEND	1.317	OTHER

* For permits that include interim and final permitted amounts, the amount listed is the final permitted amount shown on the TCEQ permit.

Table 2-9: Wastewater Treatment Plants in the San Jacinto-Brazos Coastal Basin with Permitted Discharges of 1 MGD or More

TPDES Number	NPDES Number	Facility	County	Final Permitted Flow (MGD)	Type
WQ0000443000	TX0003522	GALVESTON BAY REFINERY	GALVESTON	23	MUNICIPAL
WQ0000990000	TX0003697	MARATHON PETROLEUM COMPANY, LLC	GALVESTON	4.4	MUNICIPAL
WQ0001054000	TX0005380	BAYPORT FACILTIY - WWTP	HARRIS	30	MUNICIPAL
WQ0000449000	TX0006009	VALERO REFINING - TEXAS, LP	GALVESTON	4.5	MUNICIPAL
WQ0003977000	TX0008788	BASF FREEPORT SITE	BRAZORIA	7.464	MUNICIPAL
WQ0010671001	TX0022250	SEABROOK WWTP	HARRIS	2.5	MUNICIPAL
WQ0010539001	TX0022543	ROBERT T. SAVELY WATER RECLAM	HARRIS	12.16	MUNICIPAL
WQ0010206001	TX0022799	LITTLE CEDAR BAYOU WWTP	HARRIS	7.56	MUNICIPAL
WQ0010173001	TX0023655	GALVESTON COUNTY WCID 1 WWTP	GALVESTON	4.8	MUNICIPAL
WQ0010174001	TX0023671	GALVESTON COUNTY WCID 8	GALVESTON	1.5	MUNICIPAL
WQ0010526001	TX0023833	NASSAU BAY WWTF	HARRIS	1.33	MUNICIPAL
WQ0010375001	TX0023949	WALLACE R. KNOX WWTP	GALVESTON	12.4	MUNICIPAL
WQ0010005001	TX0024554	CITY OF ALVIN WWTP	BRAZORIA	5	MUNICIPAL

TPDES Number	NPDES Number	Facility	County	Final Permitted Flow (MGD)	Type
WQ0010520001	TX0024589	CITY OF WEBSTER CENTRAL WWTP	HARRIS	3.3	MUNICIPAL
WQ0010688002	TX0027791	AIRPORT WWTF	GALVESTON	4.76	MUNICIPAL
WQ0010134002	TX0032735	BARRY ROSE WWTF	BRAZORIA	4.5	MUNICIPAL
WQ0010134010	TX0032743	LONGWOOD WWTP	BRAZORIA	2.5	MUNICIPAL
WQ0010044001	TX0034436	CLUTE-RICHWOOD WWTP	BRAZORIA	4	MUNICIPAL
WQ0010495079	TX0035009	CITY OF HOUSTON	HARRIS	5.33	MUNICIPAL
WQ0010688001	TX0047309	MAIN WWTF	GALVESTON	13	MUNICIPAL
WQ0010053011	TX0134813	GOLDEN ACRES PLANT	HARRIS	10	MUNICIPAL
WQ0010548004	TX0056316	OYSTER CREEK WWTP	BRAZORIA	3.6	MUNICIPAL
WQ0001485000	TX0057843	40-ACRE FACILITYWTP	GALVESTON	15.7	MUNICIPAL
WQ0010690001	TX0062243	CITY OF HITCHCOCK - WWTP	GALVESTON	3	MUNICIPAL
WQ0010495075	TX0063070	SAGEMONT WWTP	HARRIS	6.14	MUNICIPAL
WQ0011571001	TX0069728	BLACKHAWK REGIONAL WWTP	HARRIS	9.25	MUNICIPAL
WQ0010495152	TX0069736	METRO CENTRAL WWTP	HARRIS	5	MUNICIPAL
WQ0011999001	TX0074233	FT. BEND CO. MUD 23 WWTP	FORT BEND	1.8	MUNICIPAL
WQ0010568005	TX0085618	DALLAS SALMON WWTP	GALVESTON	12	MUNICIPAL
WQ0012332001	TX0086118	BRAZORIA COUNTY MUD 3 WWTP	BRAZORIA	2.4	MUNICIPAL
WQ0012379001	TX0087271	NORTH MISSION GLEN MUD WWTP	FORT BEND	1.18	MUNICIPAL
WQ0012701001	TX0093068	MUSTANG BAYOU WWTF	FORT BEND	3	MUNICIPAL
WQ0010086002	TX0099511	FT BEND COUNTY WCID 2	FORT BEND	4	MUNICIPAL
WQ0010410003	TX0114821	WESTSIDE WWTP	GALVESTON	3	MUNICIPAL
WQ0013804001	TX0115169	TERRELL UNIT WWTP	BRAZORIA	2	MUNICIPAL
WQ0010134007	TX0116581	SOUTHWEST ENVIRONMENTAL CENTER	BRAZORIA	8	MUNICIPAL
WQ0010134008	TX0117501	FAR NORTHWEST WWTP	BRAZORIA	7	MUNICIPAL
WQ0014222001	TX0123633	BRAZORIA COUNTY MUD 21 WWTP	BRAZORIA	1.2	MUNICIPAL
WQ0010568008	TX0133043	SOUTHWEST WATER RECLAMATION FACILITY	GALVESTON	6	MUNICIPAL
WQ0000001000	TX0003875	ASCEND PERFORMANCE MATERIALS CHOCOLATE BAYOU PLANT	BRAZORIA	7.8	OTHER
WQ0001333000	TX0004821	CHOCOLATE BAYOU PLANT	BRAZORIA	8	OTHER
WQ0000575000	TX0005762	EASTMAN CHEMICAL TEXAS CITY OPERATIONS	GALVESTON	3.24	OTHER
WQ0001263000	TX0007323	ISP TECHNOLOGIES, INC.	GALVESTON	1.58	OTHER
WQ0004818000	TX0053813	SHINTECH INCORPORATED	BRAZORIA	1.11	OTHER
WQ0001961000	TX0067946	SI GROUP INC	BRAZORIA	1.6	OTHER

When discharge records are not available, the following techniques are used to estimate discharges:

- For significant municipal and industrial discharges, the entities were contacted for records.
- If records are not available, discharges were estimated as a function of water use or a per capita value.
- For industries, discharges were estimated as a function of water use and the type of industry creating the discharge.

Corrections for agricultural return flows were not included in the naturalization due to a lack of data.

Return flows for once-through cooling from reservoirs were not included in the naturalization because these return flows are recycled as part of the operation of the reservoir, and consumptive use for these facilities is defined as the forced evaporation from the reservoirs produced by these facilities. Permitted discharges of treated stormwater are also not considered since they do not reflect artificial increases to natural flows.

3.0 DATA ANALYSIS

The data described in the previous section were used to calculate the naturalized flows and net evaporation rates for input into the Brazos River WAM. The following sections describe the general procedure for calculating naturalized flows, the specific methods employed in the Brazos River WAM update, and the methods used to fill in missing naturalized flow data.

The current study reviewed the original naturalization from 1940-1997, fully naturalized the streamflow during the period of overlap with the BRA Drought Study (1998-2015) and then extended the fully naturalized flows through December 2018. As part of the BRA Drought Study, the methods used for flow naturalization in the Brazos WAM were reviewed by FNI and approved by TCEQ. The naturalized streamflow and evaporation datasets were extended using the partial update performed by the BRA as a starting point to provide consistency of methodology throughout the basin.

The naturalized streamflow and evaporation datasets for the San Jacinto-Brazos Coastal Basin were extended from January 1998 through December 2018. In the Brazos WAM, there are four primary control points in the San Jacinto-Brazos Coastal Basin. Two of those points (SJGBC3 and SJGMC4) represent points at stream outlets to Galveston Bay and the Gulf of Mexico and do not correspond to USGS stream gages (in other words, 100 percent of the data is missing). The naturalized streamflows entered in the Brazos WAM FLO file for these two control points were different than those shown in the original naturalized flow workbooks by a constant factor. The factor for SJGBC3 was 0.362, and for SJGMC4 it was 3.422. In both cases, the factor is equal to the drainage area reported for the point in the DIS file divided by the drainage areas used in the naturalized flow workbooks. The naturalized flows for these two points were extended in a manner consistent with the existing TCEQ Brazos WAM.

3.1 GENERAL PROCEDURE FOR NATURALIZATION OF FLOWS

The Water Rights Analysis Package (WRAP) is the modeling program used to run the WAMs. According to the WRAP Reference Manual, naturalized streamflows are “sequences of monthly streamflow representing natural hydrology that are developed by adjusting historical gaged streamflow data to remove the impacts of reservoir construction, water use, and other human activities.” A general equation for naturalized flow is as follows:

*Naturalized Flow = Historical Flow + Delivery Factor * (Upstream Diversions – Upstream Return Flows + Changes in Upstream Reservoir Contents + Upstream Reservoir Evaporation)*

Where:

Historical Flow – Flow recorded at USGS streamflow gages or estimated from reservoir spills and releases. Additional information on historical streamflows may be found in **Chapter 2.1**.

Upstream Diversions – Upstream diversions from historical records or as estimated when records are missing, as described in **Chapter 2.5**.

Upstream Return Flows – Upstream return flows from historical records or as estimated when records are missing, as described in **Chapter 2.6**.

Changes in Upstream Reservoir Content – Changes in content for major upstream reservoirs based on USGS records, records kept by others, or estimates of content changes if records are not available. **Table 2-2** lists the reservoirs used in the naturalization and summarizes the methods used for estimating content change for each major reservoir. Reservoirs are limited to those considered in the previous naturalization. Smaller reservoirs that are not in **Table 2-2** (generally reservoir with less than 5,000 ac-ft of storage) are not considered (**Chapter 2.2**).

Upstream Reservoir Evaporation – Evaporation from upstream reservoirs is estimated by multiplying the net reservoir evaporation rate by the reservoir surface area. Methods for determining net reservoir evaporation rates are summarized in **Table 2-5** and **Table 2-6**. Surface area is determined by taking the average of the surface area at the beginning and end of each month, as determined using the methods from **Table 2-2**. Evaporation from smaller reservoirs not included in the original naturalization is also not included in this extension. More information on evaporation data may be found in **Chapter 2.4**.

Delivery Factor (1 - channel loss factor) – applied to all upstream adjustments to determine the naturalized flow at downstream control points. The delivery factor is unique to each upstream point (**Table 3-1**). In most cases, adjustments from the local incremental watershed between the current control point and upstream control points do not have loss factors applied (the delivery factor equals 1), consistent with the original naturalization. **Table 3-1** shows the delivery factors (1 minus the channel loss factors) used for the flow extension. These are the same factors used in the original naturalization.

Table 3-1: Control points and Corresponding Delivery Factors

Upstream Control Point ID	Description	Downstream Control Point ID	Segment Delivery Factor
RWPL01	Running Water Draw at Plainview	WRSP02	0.05
WRSP02	White River Reservoir near Spur	SFPE04	0.61769
DUGI03	Duck Creek near Girard	SFPE04	0.80101
SFPE04	Salt Fork Brazos River near Peacock	SFAS06	0.84748
CRJA05	Croton Creek near Jayton	SFAS06	0.88268
SFAS06	Salt Fork Brazos River near Aspermont	BRSE11	0.53157
BSLU07	Buffalo Springs Lake near Lubbock	DMAS09	0.32574
DMJU08	Double Mountain Fork at Justiceburg	DMAS09	0.513
DMAS09	Double Mountain Fork near Aspermont	BRSE11	0.50862
NCKN10	North Croton Creek near Knox City	BRSE11	0.62723
BRSE11	Brazos River at Seymour	BRSB23	0.57884
MSMN12	Millers Creek near Munday	BRSB23	0.537792
CFRO13	Clear Fork Brazos River near Roby	CFHA14	0.6628
CFHA14	Clear Fork Brazos River at Hwy 83 near Hawley	CFNU16	0.8803
MUHA15	Mulberry Creek near Hawley	CFNU16	0.89757
CFNU16	Clear Fork Brazos River at Nugent	CFFG18	0.56482
CAST17	California Creek near Stamford	CFFG18	0.67221
CFFG18	Clear Fork Brazos River at Fort Griffin	CFEL22	0.68637
HCAL19	Hubbard Creek below Albany	HCBR21	0.86321
BSBR20	Big Sandy Creek above Breckenridge	HCBR21	0.90326
HCBR21	Hubbard Creek near Breckenridge	CFEL22	0.84488
CFEL22	Clear Fork Brazos River at Eliasville	BRSB23	0.91272
BRSB23	Brazos River near South Bend	SHGR26	0.98237
GHGH24	Lake Graham near Graham	SHGR26	0.98333
CCIV25	Big Cedar Creek near Ivan	SHGR26	0.99139
SHGR26	Brazos River at Morris Sheppard Dam near Graford	BRPP27	0.99487
BRPP27	Brazos River near Palo Pinto	BRDE29	0.98032
PPSA28	Palo Pinto Creek near Santo	BRDE29	0.95937
BRDE29	Brazos River near Dennis	BRGR30	0.98
BRGR30	Brazos River near Glen Rose	BRAQ33	0.97801
PAGR31	Paluxy River at Glen Rose	BRAQ33	0.9777
NRBL32	Nolan River at Blum	BRAQ33	0.98776
BRAQ33	Brazos River near Aquilla	BRWA41	0.98733
AQAQ34	Aquilla Creek near Aquilla	BRWA41	0.99269
NBHI35	North Bosque River at Hico	NBCL36	0.78957
NBCL36	North Bosque River near Clifton	NBVM37	0.93648
NBVM37	North Bosque River at Valley Mills	BOWA40	0.88857
MBMG38	Middle Bosque River near McGregor	BOWA40	0.94499
HGCR39	Hog Creek near Crawford	BOWA40	0.94601

Upstream Control Point ID	Description	Downstream Control Point ID	Segment Delivery Factor
BOWA40	Bosque River near Waco	BRWA41	0.9851
BRWA41	Brazos River at Waco	BRHB42	0.98619
BRHB42	Brazos River near Highbank	BRBR59	0.98035
LEDL43	Leon River near DeLeon	LEHS45	0.80254
SADL44	Sabana River near DeLeon	LEHS45	0.82774
LEHS45	Leon River near Hasse	LEHM46	0.63
LEHM46	Leon River near Hamilton	LEGT47	0.9751
LEGT47	Leon River at Gatesville	LEBE49	0.97109
COPI48	Cowhouse Creek at Pidcoke	LEBE49	0.99275
LEBE49	Leon River near Belton	LRLR53	0.9939
LAKE50	Lampasas River near Kempner	LAYO51	0.99121
LAYO51	Lampasas River at Youngsport	LABE52	0.99217
LABE52	Lampasas River near Belton	LRLR53	0.99477
LRLR53	Little River near Little River	LRCA58	0.97831
NGGE54	North Fork San Gabriel River near Georgetown	GAGE56	0.99854
SGGE55	South Fork San Gabriel River at Georgetown	GAGE56	0.99887
GAGE56	San Gabriel River at Georgetown	GALA57	0.99107
GALA57	San Gabriel River at Laneport	LRCA58	0.98762
LRCA58	Little River near Cameron	BRBR59	0.96473
BRBR59	Brazos River near Bryan	BRHE68	0.97315
MYDB60	Middle Yegua Creek near Dime Box	YCSO62	0.97764
EYDB61	East Yegua Creek near Dime Box	YCSO62	0.98052
YCSO62	Yegua Creek near Somerville	BRHE68	0.97487
DCLY63	Davidson Creek near Lyons	BRHE68	0.97181
NAGR64	Navasota River above Groesbeck	NAEA66	0.98678
BGFR65	Big Creek near Freestone	NAEA66	0.99323
NAEA66	Navasota River near Easterly	NABR67	0.99034
NABR67	Navasota River near Bryan	BRHE68	0.95909
BRHE68	Brazos River near Hempstead	BRRI70	0.97049
MCBL69	Mill Creek near Bellville	BRRI70	0.98008
BRRI70	Brazos River at Richmond	BRRO72	0.98969
BGNE71	Big Creek near Needville	BRRO72	0.99036
BRRO72	Brazos River near Rosharon	BRGM73	0.98344
BRGM73	Brazos River at Gulf of Mexico	N/A	--
CLPEC1	Clear Creek near Pearland	SJGBC3	0.98899
CBALC2	Chocolate Bayou near Alvin	SJGMC4	0.99427
SJGBC3	San Jacinto-Brazos Coastal Basin at Galveston Bay	N/A	--
SJGMC4	San Jacinto-Brazos Coastal Basin at the Gulf of Mexico	N/A	--

The computation of naturalized flows described above sometimes results in negative flows for some months. Possible reasons for this include the following:

- Timing problems created by large flows which pass different points during different months
- Errors in the estimation of hydrologic data
- Incorrect data on diversions, return flows, reservoir evaporation, or reservoir content
- Losses greater than those assumed in the naturalization process

Although negative *incremental* flows between primary control points are physically possible because they could represent actual losses of flow, negative total naturalized flows are physically impossible. Months with negative total naturalized flows were reviewed carefully to correct any data problems that could be found. Corrections to data included revisions made to diversion records based on reviewing the water use and return flow records and adjusting abnormally high or low values or adjustments to upstream reservoir releases or content change/evaporation. Remaining negative total naturalized flows were set to zero. Negative incremental flows between primary control points are discussed in **Chapter 6.0**.

3.2 ESTIMATING MISSING FLOW DATA

Chapter 2.1 discusses estimating shorter periods of missing flow data. For longer periods of missing streamflow, naturalized flow at nearby or adjacent gages were used to fill the missing data. For a given WAM primary control point, the statistical relationship is unlikely to change if the watershed still responds in a hydrologically similar way. Some relationships were updated when there was evidence of a change to the watershed's runoff characteristics since the previous evaluation.

As part of this update, all fill relationships were reevaluated and updated as necessary based on the longer period of overlapping records. The periods of available data for the primary control points are listed in **Table 2-1**. Coefficients of determination (R^2) were compared for the original period (1940-1997) and the extended data (1940-2018). For the most part, missing naturalized flow data was filled in using the same statistical relationships with other control points that were determined as part of the original Brazos WAM. **Table 3-2** summarizes the periods of missing flow data for each primary control point and the equation used to fill each gap. New fill relationships developed as part of this extension are in bold text in **Table 3-2**.

The fill relationships were computed using linear or multilinear regression with the equation forced through the origin (no constant term). The constant term, the b in y=mx+b, was set to zero so that when

flow at x is zero, the flow at y is also zero. The original naturalization also used all linear regression or multilinear regression relationships with no constant term to fill in missing data. **Appendix G** shows the fill relationships considered during the naturalization process. The periods during which each fill relationship was applied are provided in **Table 3-2**.

In 1993 the Brazos River near Bryan gage (USGS 08109000) was replaced with the Brazos River at SH 21 near Bryan gage, located a few miles upstream. The SH 21 gage was not used in the original Brazos WAM naturalization; the Highbank and Cameron gages were used to fill in the missing flows. For the BRA Drought Study, naturalized flows were also developed at the SH 21 gage and a drainage area ratio was used to translate the flows to the original Bryan gage (BRBR59). This change to the naturalized flows at BRBR59 has already been incorporated into the latest Brazos WAM.

For the primary control point CFEL22, the period of missing naturalized flow data was originally estimated using a relationship with two gages on the main stem of the Brazos River (BRSB23 and BRSE11). For the period of missing data from 1955 through 2018, this project found that a relationship based on drainage area ratios with CFFG18 and HCBR21 to fill missing data for control point CFEL22 resulted in fewer negative incremental flows. The relationship used to fill missing naturalized flows at CFEL22 was updated in this project.

Table 3-2: Relationships Used to Fill Missing Naturalized Flows
(New fill relationships developed as part of this extension are in **bold underlined** text)

Control Point	Name	Data Missing	Fill Relationship Used
RWPL01	Running Water Draw at Plainview	10/1953-9/1956 & 5/1960-2/1961	RWPL01 = 0.033 * SFAS06
		10/1978-9/2002	RWPL01 = 0.141 * WRSP02
WRSP02	White River Reservoir near Spur	1/1940-8/1963	WRSP02 = 0.207 * SFAS06
		10/1976-6/1979	Reservoir operation study outflows
DUGI03	Duck Creek near Girard	1/1940-9/1964 & 10/1989-12/2018	DUGI03 = 0.138 * SFAS06
SFPE04	Salt Fork Brazos River near Peacock	1/1940-12/1949 & 10/1951-9/1964 & 10/1986-12/2018	SFPE04 = 0.701 * SFAS06
CRJA05	Croton Creek near Jayton	1/1940-8/1959 & 10/1986-12/2018	**CRJA05 = 0.170 * SFAS06**
BSLU07	Buffalo Springs Lake near Lubbock	1/1940-8/1959	BSLU07 = 0.129 * DMAS09
		9/1959-11/1966 & 10/1977-12/2018	Reservoir operation study

Control Point	Name	Data Missing	Fill Relationship Used
DMJU08	Double Mountain Fork Brazos River at Justiceburg	1/1940-11/1961	DMJU08 = 0.201 * DMAS09
NCKN10	North Croton Creek near Knox City	1/1940-9/1965 & 10/1986-12/2018	NCKN10 = 0.154 * SFAS06
MSMN12	Millers Creek near Munday	1/1940-6/1963	MSMN12 = 0.050 * [CFFG18 - (0.56482 * CFNU16)]
CFRO13	Clear Fork Brazos River near Roby	1/1940-12/1961	CFRO13 = 0.061 * DMAS09
CFHA14	Clear Fork Brazos River at Hawley	1/1940-9/1967 & 10/1989-9/2016	CFHA14 = 0.464 * CFNU16
MUHA15	Mulberry Creek near Hawley	1/1940-9/1967 & 10/1989-12/2018	MUHA15 = 0.081 * CFNU16
CAST17	California Creek near Stamford	1/1940-9/1962	CAST17 = 0.156 * CFFG18
HCAL19	Hubbard Creek below Albany	1/1940-9/1951	HCAL19 = 0.241 * CFEL22
		10/1951-4/1955	HCAL19 = 0.179 * [BRSB23 - (0.57884 * BRSE11) - (0.62646 * CFFG18)]
		5/1955 - 9/1966	HCAL19 = 0.600 * HCBR21
BSBR20	Big Sandy Creek above Breckenridge	1/1940-9/1951	BSBR20 = 0.121 * [CFEL22 - (0.68637 * CFFG18)]
		10/1951-4/1955	BSBR20 = 0.067 * [BRSB23 - (0.57884 * BRSE11) - (0.62646 * CFFG18)]
		5/1955 - 2/1962	**BSBR20 = 0.270 * HCBR21**
HCBR21	Hubbard Creek near Breckenridge	1/1940-9/1951	HCBR21 = 0.586 * [CFEL22 - (0.68637 * CFFG18)]
		10/1951-4/1955	HCBR21 = 0.285 * [BRSB23 - (0.57884 * BRSE11) - (0.62646 * CFFG18)]
		9/1986-9/2015	Historical HCBR21 = Computed spills from Hubbard Creek Reservoir
CFEL22	Clear Fork Brazos River at Eliasville	10/1951-4/1955	CFEL22 = 0.604 * [BRSB23 - (0.57884 * BRSE11)]
		5/1955- 9/1961 & 10/1982-12/2018	**CFEL22 = 1.120 * (CFFG18 + HCBR21)**
GHGH24	Lake Graham near Graham	5/1962-9/1963, 6/1970-8/1971, 5/1973-7/1974, 8/1977-12/1978, 8/1982-9/1984, 7/1989-12/1989, 11/1996-12/1997	**GHGH24 = 0.281 * [BRPP27 - (0.97733 * BRSB23)]**
CCIV25	Big Cedar Creek near Ivan	1/1940-11/1964 & 10/1989-12/2018	CCIV25 = 0.086 * [BRPP27 - (0.97733 * BRSB23)]

Control Point	Name	Data Missing	Fill Relationship Used
SHGR26	Brazos River at Morris Sheppard Dam near Graford, Brazos River nr Graford	1/1940-9/1976	SHGR26 = 0.991 * BRPP27
PPSA28	Palo Pinto Creek near Santo	1/1940-4/1951 & 10/1976-12/2018	PPSA28 = 0.172 * [BRGR31 - (0.96071 * BRPP27)]
BRDE29	Brazos River near Dennis	1/1940-4/1968	BRDE29 = 0.904 * BRGR31
PAGR31	Paluxy River at Glen Rose	1/1940-5/1947	PAGR31 = 0.190 * [BRAQ33 - (0.97801 * BRGR31)]
NRBL32	Nolan River at Blum	1/1940-11/1947 & 11/1985 & 3/1987-9/1992 & 10/1996-9/1997 & 1/1999-9/2005	NRBL32 = 0.230 * [BRAQ33 - (0.97801 * BRGR31)]
AQAQ34	Aquilla Creek near Aquilla	6/2001-12/2018	AQAQ34 = 1.207843 * natural Aquilla abv Aquilla
NBHI35	North Bosque River at Hico	1/1940-12/1961, 10/1999-4/2014	NBHI35 = 0.250 * NBCL36
NBVM37	North Bosque River At Valley Mills	1/1940-7/1959, 10/2005-7/2007	NBVM37 = 1.186 * NBCL36
MBMG38	Middle Bosque River near McGregor	1/1940-7/1959 & Partial fill 10/1985-9/2007	MBMG38 = 0.089 * [BRWA41 - (0.98733 * BRAQ33)]
HGCR39	Hog Creek near Crawford	1/1940-8/1959 & Partial fill 10/1985-9/2007	HGCR39 = 0.045 * [BRWA41 - (0.98733 * BRAQ33)]
BOWA40	Bosque River near Waco	1/1940-8/1959 & 10/1985-9/2007	BOWA40 = 0.609 * [BRWA41 - (0.98733 * BRAQ33)]
		10/1981-2/1982 & 6/1982-9/1985 & 10/2007-12/2018	BOWA40 = 1.0324 * NBVM37 + 2.3979 * MBMG38 + 0.3561 * HGCR39
BRHB42	Brazos River near Highbank	1/1940-9/1965	BRHB42 = 0.801 * BRWA41 + 0.191 * BRBR59
LEDL43	Leon River near De Leon	1/1940-8/1960 & 10/1986-9/1996 & 10/1997-9/2007	**LEDL43 = 0.420 * LEHS45**
SADL44	Sabana River near De Leon	1/1940-8/1960 & 10/1986-9/1999	**SADL44 = 0.231 * LEHS45**
LEHS45	Leon River near Hasse	10/1991-8/2007	Historical LEHS45 = 0.93 * USACE Proctor Gated Flow
LEHM46	Leon River near Hamilton	1/1940-9/1950	LEHM46 = 1.086 * LEHS45
		10/1950-8/1960 & 1/1999 to 9/2007	**LEHM46 = 0.520 * LEHS45 + 0.427 * LEGT47**

Control Point	Name	Data Missing	Fill Relationship Used
LEGT47	Leon River at Gatesville	1/1940-9/1950	LEGT47 = 0.588 * LEHS45 + 0.357 * LEBE49
COPI48	Cowhouse Creek at Pidcoke	1/1940-9/1950	COPI48 = 0.193 * [LEBE49 - (0.59655 * LEHS45)]
LAKE50	Lampasas River near Kempner	1/1940-9/1962	LAKE50 = 0.566 * LAYO51
LAYO51	Lampasas River at Youngsport	10/1980-12/2018	LAYO51 = 1.648 * LAKE50
LABE52	Lampasas River near Belton	1/1940-1/1963	LABE52 = 1.087 * LAYO51
		10/1989-5/1999	LABE52 = 0.290 * LRLR53
LRLR53	Little River near Little River	1/1940-7/1962	LRLR53 = 1.158 * (LAYO51 + LEBE49)
NGGE54	North Fork San Gabriel River near Georgetown	1/1940-6/1968	NGGE54 = 0.565 * GAGE56
SGGE55	South Fork San Gabriel River at Georgetown	1/1940-11/1967	SGGE55 = 0.358 * GAGE56
GAGE56	San Gabriel River at Georgetown	10/1973-10/1984 & 12/1984-5/1985 & 10/1985-12/1985 & 2/1986-3/1986 & 5/1986-6/1986 & 9/1986-12/2018	GAGE56 = 1.115 * (NGGE54 + SGGE55)
GALA57	San Gabriel River at Laneport	1/1940-7/1965	**GALA57 = 1.739 * GAGE56**
BRBR59	Brazos River near Bryan	10/1993-12/2018	BRBR59 = 1.015806 * (natural Brazos at SH 21 nr Bryan)
MYDB60	Middle Yegua Creek near Dime Box	1/1940-7/1962	MYDB60 = 0.178 * YCSO62
EYDB61	East Yegua Creek near Dime Box	1/1940-7/1962	EYDB61 = 0.186 * YCSO62
YCSO62	Yegua Creek near Somerville	10/1991-9/2008	**YCSO62 = 2.424 * (MYDB60 + EYDB61)**
DCLY63	Davidson Creek near Lyons	1/1940-9/1962	DCLY63 = 0.204 * YCSO62
NAGR64	Navasota River above Groesbeck	1/1940-5/1978	NAGR64 = 0.265 * NAEA66
BGFR65	Big Creek near Freestone	1/1940-6/1978	BGFR65 = 0.099 * NAEA66
NABR67	Navasota River near Bryan	1/1940-12/1950 & 10/1994-12/2018	NABR67 = 1.228 * NAEA66
MCBL69	Mill Creek near Bellville	1/1940-7/1963	MCBL69 = 0.622 * YCSO62
		10/1993-12/1996	MCBL69 = 2.633 * CY_CY
		1/1997-4/2000	**MCBL69 = 2.377 * DCLY63**
BGNE71	Big Creek near Needville	1/1940-5/1947 & 7/1950-3/1952	BGNE71 = 0.297 * BR_HO
		11/2016-5/2017	**BGNE71 = 0.332 * CBALC2**

Control Point	Name	Data Missing	Fill Relationship Used
BRRO72	Brazos River at Rosharon	1/1940-3/1967 & 10/1980-4/1984	BRRO72 = 1.036 * BRRI70
BRGM73	Brazos River at Gulf of Mexico	1/1940-12/2018	BRGM73 = 0.9834 * BRRO72 + (DA_{BRGM73} / DA_{BGNE71}) * BGNE71 BRRO72 and BGNE71 filled data is used when historical flow is not available
CLPEC1	Clear Creek near Pearland	1/1940-7/1944 & 11/1944-2/1946 & 11/1946-3/1947 & 1/1960-3/1963 & 10/1992-12/1996	CLPEC1 = 0.299 * BR_HO
		1/1997-12/2018	**CLPEC1 = 0.323 * CBALC2**
CBALC2	Chocolate Bayou near Alvin	1/1940-12/1940	CBAL2 = 0.733 * BR_HO
		1/1941-7/1944 & 11/1944-2/1946 & 11/1946-12/1946	CBAL2 = 0.716 * Texas Rainfall / Runoff Model
		9/1944-10/1944 & 3/1946 & 5/1946-10/1946 & 2/1958-2/1959	CBAL2 = 2.478 * CLPEC1
SJGBC3	San Jacinto-Brazos Coastal Basin at Galveston Bay	1/1940-12/2018	SJGBC3 = [(DA_{SJGBC3} – DA_{CLPEC1} – DA_{CBALC2}) / (DA_{CLPEC1} + DA_{CBALC2})] * (CBALC2 + CLPEC1) + 0.98899 * CLPEC1 + 0.99427 * CBALC2 CLPEC1 and CBALC2 filled data is used when historical flow is not available.
SJGMC4	San Jacinto-Brazos Coastal Basin at Gulf of Mexico	1/1940-12/2018	SJGMC4 = [DA_{SJGMC4} / (DA_{CLPEC1} + DA_{CBALC2})] * (CLPEC1 + CBALC2) CLPEC1 and CBALC2 filled data is used when historical flow is not available.

In **Table 3-2**, there are updated fill relationships (shown in bold underlined text) for LEDL43, SADL44 and LEHM46. In each case, naturalized flow data at LEHS45 is used to fill in the missing data. These fill relationships were updated because in the original naturalization, historical streamflow data from 10/1991-12/1997 was treated as missing at LEHS45 so other relationships had to be developed to fill in the missing data during that period. However, as part of the BRA Drought Study, historical flows at LEHS45 were estimated based on releases from Lake Proctor. The filling in of historical data at LEHS45 made it possible to compute naturalized flows at LEHS45 during the period of previously missing data. Having a full period of record at LEHS45 allowed us, as part of this update, to revisit the original fill relationships

for LEDL43, SADL44 and LEHM46. The fill relationships for LEDL43, SADL44, and LEHM46 were updated as part of this extension.

4.0 CHANGES TO THE EXISTING NATURALIZED STREAMFLOW AND EVAPORATION DATASETS

During this update, the original naturalized flow and evaporation datasets used in the Brazos River WAM, as updated in the BRA Drought Study, were subject to change for the entire 1940 through 1997 period of record. Most changes are minor and make little or no difference in the resulting naturalized flows. **Appendix H** contains graphs that compare the previous naturalized flows to the updated naturalized flows.

The most common reasons for changes to the naturalized flows are:

- Rounding differences and conversion factors
- Changes in historical USGS streamflow data
- Correcting errors (leap year, transcription, or reference errors)
- Updated diversion or return flow data
- Changes in TWDB evaporation quads (only affects 1994 in the original period)
- New fill relationships (**Chapter 3.2**)
- Recalculated volumetric surveys

Of these, new fill relationships and recalculated volumetric surveys are the most consequential changes in terms of acre-feet of difference. Some of the most frequent changes, although relatively trivial, are related to slightly different conversion factors and rounding differences. USGS occasionally revised past streamflow data or changed the reported precision of historical streamflow data, which accounts for most of the changes in historical streamflow data. Changes in historical adjustments at upstream control points are passed to downstream points after accounting for channel losses, so a change at one point affects downstream points. Changes at one control can also affect points that use that control point to fill in missing data. Almost all of the above changes result in very small differences between the original naturalized flows and the updated flows. A month-by-month explanation of the changes compared to the 1940-1997 hydrology, as updated in the BRA Drought Study, is provided for each control point on the OLD_FILLED tab of the naturalized flow workbooks.

Table 4-1 is a summary of the major changes for each control point.

Table 4-1. Summary of Major Changes by Control Point

Control Point ID	Period	Differences
WRSP02	1/1994-12/1994	TWDB evaporation data changed for 1994.
CRJA05	1/1940-8/1959 10/1986-12/1997	New Fill Relationship. New Fill Relationship.
BRSE11	8/1972-12/1997	Updated Davis reservoir net evaporation using equation in the Work Plan.
CFNU16	1/1994-12/1994	TWDB evaporation data changed for 1994.
CFFG18	1/1994-12/1994	TWDB evaporation data changed for 1994.
BSBR20	5/1955-1/1962	New Fill Relationship.
HCBR21	1/1994-12/1994	TWDB evaporation data changed for 1994.
CFEL22	5/1956-9/1961 10/1982-12/1997	New Fill Relationship. New Fill Relationship.
BRSB23	1/1994-12/1994	TWDB evaporation data changed for 1994.
GHGH24	6/1962-6/1963, 6/1970-8/1971, 5/1973-7/1974, 8/1977-12/1978, 8/1982-9/1984, 7/1989-12/1989, 11/1996-12/1997	New Fill Relationship.
SHGR26	1/1988-12/1997	Began using USGS reported elevations to compute Content Change and Evap Loss data for Possum Kingdom in 1988, and a recalculated 1994 survey starting in Sept 1990. TWDB evaporation data changed for 1994.
BRGR30	11/1987-12/1997	Began using a recalculated 1993 survey for Granbury in Nov 1987.
NRBL32	1/1994-12/1994	TWDB evaporation data changed for 1994.
LEDL43	1/1940-8/1960 10/1986-9/1996 10/1997-12/1997	New Fill Relationship. New Fill Relationship. New Fill Relationship.
SADL44	1/1940-8/1960 10/1986-12/1997	New Fill Relationship. New Fill Relationship.
LEHS45	1/1988-12/1997	Change in DIVERSION data (In the Original Naturalization, Upper Leon River MWD diversions were at LEGT47 but are taken lakeside at Proctor, LEHS45). Began using a recalculated 1993 survey for Proctor in June 1990. TWDB changed the quad evaporation rates for 1994.
LEHM46	10/1950-8/1960	New Fill Relationship.
LEBE49	10/1974-12/1997	Began using a recalculated 1994 survey for Belton in Oct 1974.
LABE52	10/1988-12/1997	Began using a recalculated 1995 survey for Stillhouse in Oct 1988.
NGGE54	11/1995-12/1997	Began using a recalculated 1995 survey for Georgetown in Nov 1995.
GALA57	1/1940-7/1965	New Fill Relationship.
EYDB61	1/1994-12/1994	TWDB evaporation data changed for 1994.
YCSO62	10/1991-12/1997	New Fill Relationship.
NAGR64	1/1994-12/1994	TWDB evaporation data changed for 1994.
NAEA66	1/1994-12/1994	TWDB evaporation data changed for 1994.

Control Point ID	Period	Differences
	10/1995-12/1997	Began using a recalculated 1993 survey for Limestone in Oct 1995.
NABR67	5/1952-9/1994	Updated Camp Creek net evaporation using equation in the Work Plan.
MCBL69	1/1997-12/1997	New Fill Relationship.
CLPEC1	1/1997-12/1997	New Fill Relationship.

5.0 MODIFICATIONS TO WRAP INPUT FILES

In addition to adding the revised naturalized flows and net evaporation rates, the following modifications to the WRAP input files are required to implement the updated hydrology:

- *Modifying the JD record in the main input file (.DAT)*. Field 2 (NYRS) of the JD record (Simulation Job Control Data) was changed from 58 to 79 to include the additional 21 years of extended hydrology.
- *Modifying the JO record in the main input file (*.DAT). Field 5 (DSSRU) of the JO record (Simulation Job Options) was changed from 1 to blank so that the model would execute. In the latest version of WRAP (January 2021), fields 4 through 7 of the JO record address reading records from a DSS file, but the Brazos WAM does not use these options.
- *Extension of the HIS file*. The hydrologic index series HIS file for the Brazos WAM contains hydrologic index HI records that specify whether a given month is dry, average, or wet based on the Palmer Hydrologic Drought Index (PHDI) as part of the environmental flow standards within the WAM, as discussed in **Chapter 5.1**.

Although the following modifications are not required to incorporate the extended hydrology, they were identified during the naturalization and are suggested modifications:

- *Modifications to the DIS file.* Potential modifications to the flow distribution (DIS) include adjustments to the flow distribution (FD records) for control points on tributaries that use gages located far downstream for flow distribution, as discussed in **Chapter 5.2**. These suggested modifications have been incorporated into the DIS file provided as part of this project. The modifications to the DIS file also require modifications to field 6 of the CP record in the .DAT file.

5.1 HYDROLOGIC INDEX SERIES (HIS) INPUT FILE

The hydrologic index series (HIS) file contains hydrologic index (HI) records. The HIS file is a required input file for the Brazos WAM, so the HI records were extended through the end of 2018 as part of this update because they are needed to run the WAM for the full period covered by the extension (1940-2018). The HI records and HIS file are not part of the flow naturalization process but are used within WRAP to model environmental flow requirements specified as a function of the PHDI. The PHDI value present on the last day of the month of the preceding season, as reported by the National Weather Service (NWS), and calculated for the geographic area as described in subsection (b) of Title 30, Part 1, Chapter 298,

Subchapter G, Rule §298.470, determines the hydrologic condition for the following season. The percentages of each climatic division within each geographic area, as defined in §298.455 of Title 30 (relating to Definitions), are listed in **Table 5-1**. The PHDI criteria corresponding to specific hydrologic conditions (i.e., dry, average, or wet) for all measurement points on the Brazos River and its associated tributaries are listed in **Table 5-2**.

Table 5-1: Percentage of Climatic Division Within Each Brazos Basin Geographic Area

Climatic Division	Percentage Located in Upper Basin	Percentage Located in Middle Basin	Percentage Located in Lower Basin
High Plains	2.7%	0%	0%
Low Rolling Plains	64.7%	0%	0%
North Central	32.6%	100%	61.9%
East Texas	0%	0%	14.7%
Trans Pecos	0%	0%	0%
Edwards Plateau	0%	0%	5.7%
South Central	0%	0%	13.2%
Upper Coast	0%	0%	4.5%
TOTAL	**100%**	**100%**	**100%**

Table 5-2: The PHDI for Calculating Hydrologic Conditions for all Measurement Points on the Brazos River and Its Associated Tributaries

Geographic Area	Dry	Average	Wet
Upper Basin	Less than -1.78	-1.78 to 2.18	Greater than 2.18
Middle Basin	Less than -1.95	-1.95 to 2.39	Greater than 2.39
Lower Basin	Less than -1.73	-1.73 to 2.13	Greater than 2.13

The PHDI is reported by NWS on a monthly basis for each of the 10 climate divisions in Texas (of which 8 are listed in **Table 5-1**). The monthly PHDI data used in the development of the HIS file are included in **Appendix I**. For example, the PHDI for the Upper Basin is calculated as the PHDI for the High Plains division times 0.027 plus the PHDI for the Low Rolling Plains division times 0.647 plus the PHDI for the North Central division times 0.326. The resultant PHDI for the Upper Basin is then compared to the criteria listed in **Table 5-2** to determine the hydrologic condition of the Upper Basin: dry, average, or wet.

The HIS file is a set of zeros and ones organized in the following way: first there is a block of 79 HI records, one for every year from 1940 to 2018, that represent dry conditions in the Upper Basin (UP-DRY). Each record has twelve entries corresponding to the twelve months of the year. If the Upper Basin is in “dry” hydrologic conditions during a given month, the value is set to 1; otherwise it is set to zero. The next 79

HI records represent average conditions in the Upper Basin (UP-AVG). If the composite PHDI in the Upper Basin is between -1.78 and 2.18 for a given month, then the value for that month in the UP-AVG HI record is set to 1, otherwise it is zero. HI records for UP-WET conditions are calculated in a similar manner. Because the Upper Basin can be in only one of the three hydrologic conditions during any given timestep, the sum of HI entries for any given month among UP-DRY, UP-AVG, and UP-WET must equal one. The same procedure is repeated for the Middle and Lower Basins for a total of (79 * 3 * 3 =) 711 HI records in the final HIS file.

The HIS file developed for the Drought Study uses data developed by the Brazos Basin and Bay Area Stakeholder Committed (BBASC) data through February 2013. For the remainder of the period, PHDI data were obtained from the NOAA website for Historical Palmer Drought Indices (**Appendix A**).

5.2 FLOW DISTRIBUTION (DIS) INPUT FILE

The flow distribution (DIS) file contains the set of all FD/FC records followed by the set of all WP records. These records are used to distribute the naturalized flow from the primary gaged control points, where naturalized flow is input directly in the FLO file, to secondary ungaged control points, where the flow is unknown. Within the Brazos WAM, the watershed drainage areas entered in the WP records of the DIS file are also used to adjust net evaporation-precipitation volumes for reservoir site runoff. The WP records were developed under another contract specifically for the Brazos WAM so, although the watershed drainage area in the WP records do not always match the contributing drainage areas reported by the USGS, no changes to the WP records were identified.

Naturalized flows are distributed more accurately to the Lake Alan Henry control point using only naturalized flows from the Double Mountain Fork of the Brazos River at Justiceburg gage (DMJU08 rather than DMAS09) translated downstream to the Lake Alan Henry control point using a drainage area ratio. The control point for Lake Alan Henry is 4146P1, and the proposed change to the FD record is below.

The old FD Record for 4146P1 is:

```
FD4146P1   DMAS09        1   DMJU08   BSLU07
```

The proposed new FD Record for 4146P1 is:

```
FD4146P1   DMJU08       -1
```

There are three other ungaged control points on the same reach (downstream of DMJU08 and upstream of DMAS09) that would benefit from a similar change to maintain consistency. These changes have been incorporated into the datasets submitted with this project.

The old FD Records are:

```
FDCON160  DMAS09       1  DMJU08  BSLU07
FDCON008  DMAS09       1  DMJU08  BSLU07
FDW12411  DMAS09       1  DMJU08  BSLU07
```

The proposed new FD Records are:

```
FDCON160  DMJU08      -1
FDCON008  DMJU08      -1
FDW12411  DMJU08      -1
```

The modifications to the DIS file described above also require modifications to field 6 of the corresponding CP records in the .DAT file. The modifications are required because field 6 of the CP records for CON160, CON008, 4146P1, and W12411 specifies Option 6 (channel loss coefficient with drainage area ratio method) for distributing the flows from gaged control points to ungaged control points. However, Option 6 is only applicable when the ungaged control point is upstream of the gaged control. Since CON160, CON008, 4146P1, and W12411 are downstream of DMJU08, Option 7 (traditional drainage area ratio method) is used instead.

6.0 PROCEDURE FOR NEGATIVE INCREMENTAL FLOWS

As discussed in **Chapter 3.1**, negative total naturalized flows are impossible and were set to zero. No adjustments were made to naturalized flows calculated in adjacent months to offset the adjustments made to correct the negative total naturalized flows. This methodology is consistent with the methodology used in the development of the original Brazos WAM naturalized flows.

There are many times where the computation of naturalized flows results in negative incremental flows for some months (i.e., the naturalized flows at a downstream primary control point is less than the sum of the naturalized flows at the upstream primary control points after accounting for channel losses). Although this is physically possible, it has implications for the distribution of available water by WRAP. Possible reasons for negative incremental naturalized flows include:

- Timing problems, in which the flow from upstream control point arrives at the downstream control point in a different month;
- Incorrect historical data (inaccurate gage data, streamflows too low, return flows too high, diversions too low, change in reservoir contents too low, evaporation too low); and
- Losses different from those assumed in the naturalization process, including losses to side or bank storage.

Most of the negative incremental flows are relatively small, but larger values do occur downstream of major reservoirs. One example is the main stem of the Brazos River below Lake Whitney, where negative incremental naturalized flows can occur during periods of flood control releases. WRAP has several built-in options for dealing with negative incremental flows. Option 5, described below, was the assumption used in the original naturalization and is the most frequently applied option in other TCEQ WAMs. Based on our experience, Option 5 provides a reasonable and stable way to handle negative incremental flows in the Brazos River Basin. The Independent Peer Reviewer did not express concern with using this option, however there are several other options within WRAP (Field 9 of the JD Record) for choosing how to handle negative incremental flows which allows exploration of various options.

In contrast to Options 2, 3 and 4, Option 5 in Field 9 of the JD record does not compute an adjustment for negative incremental flows. Instead, the simulation is modified as follows:

1. The amount of available streamflow is taken to be the minimum of the flow at the control point of the water right and the flow at the same time step at downstream control points at which

senior water rights are located. Any control points with zero flow or control points downstream of a control point with zero flow are not considered.

2. After determining the streamflow depletion and other quantities for the water right, an adjustment to the downstream water rights is applied. With Option 5 active, this adjustment is limited to the minimum regulated flow at any intermediate control point between the water right and any downstream senior rights. These adjustments end if a control point with zero regulated flow is encountered.

7.0 INDEPENDENT PEER REVIEW

Dr. Robert Brandes from Robert J. Brandes Consulting is the Independent Peer Reviewer for the update of the Brazos WAM hydrology. The Independent Peer Reviewer provided an overall review of the technical side of the project, including formal comments on the Work Plan, Draft Final Naturalized Flows and Draft Final Report. The Peer Reviewer was also available for consultation regarding technical issues throughout the project.

The comments provided by the reviewer and the changes to address those comments are found in **Appendix J**.

8.0 FINAL NATURALIZED FLOWS AND NET EVAPORATION RATES

Appendix K contains tables of the final naturalized flow and net evaporation datasets. In addition to this final written report, electronic files have been provided as part of the deliverables, including the naturalized flow and data workbooks used in this project. **Table 8-1** is a summary of the types of Excel workbooks included with the project. Two sets of naturalized flow workbooks were provided, one with links to other workbooks and one with the linked data converted to values. The linked workbooks contain a macro that can be used to update links as needed. **Appendix L** describes the procedure for updating links within the naturalized flow workbooks. The comments provided by the TCEQ on the Draft Final Naturalized Flows and the Draft Final Report, as well as the changes to address those comments are found in **Appendix M**.

Table 8-2 shows the recommended order in which the naturalized flow workbooks can be opened to propagate changes properly (alternatively, the workbooks could be opened in upstream to downstream order twice). If no changes are being made, the order in which the files are opened does not matter.

Other support files have been provided in electronic format as well. These include gage flow workbooks, reservoir content change and evaporation calculations, and other supporting material. Text files with the updated WAM input files have been included as well.

Table 8-1. Naturalized Flow Workbooks

Type	Description	File Name
Naturalized Flow	Calculation of naturalized flows from gage flows, including adjustments for diversions, return flows, reservoirs, and other adjustments, as well as fills for missing data.	*20Nat_XXXX##*
Water Use	Historical water use data by water right holder	*20WU_XXXX##*
Return Flows	Historical return flows for more than 1 MGD of permitted discharge	*20RF_XXXX##*
Content Change	Calculation of content change and evaporative loss for major reservoirs (more than 5,000 ac-ft of storage)	*RESNAME_Acecalc_Extended*
Evaporation	Calculation of net evaporation rates for major reservoirs	*RESNAME_EVAP_Extended*

Notes: *XXXX* is a four-letter code associated with each naturalized flow location; *##* are numbers that refer to the river order; *RESNAME* is the name of the reservoir

Table 8-2. Order In Which to Open Naturalized Flow Workbooks

Control Point ID	Control Points Used in Fill Relationships	Control Points Immediately Upstream	Open in this Order
RWPL01	SFAS06, WRSP02		1
WRSP02	SFAS06	RWPL01	1
DUGI03	SFAS06		1
SFPE04	SFAS06	WRSP02, DUGI03	1
CRJA05	SFAS06		1
SFAS06		SFPE04, CRJA05	1
BSLU07	DMAS09		2
DMJU08	DMAS09		2
DMAS09		BSLU07, DMJU08	2
NCKN10	SFAS06		3
BRSE11		SFAS06, DMAS09, NCKN10	4
MSMN12	CFNU16, CFFG18		5
CFRO13	DMAS09		5
CFHA14	CFNU16	CFRO13	5
MUHA15	CFNU16		5
CFNU16		CFHA14, MUHA15	5
CAST17	CFFG18		5
CFFG18		CFNU16, CAST17	5
HCAL19	BRSE11, CFFG18, HCBR21, CFEL22, BRSB23		6
BSBR20	BRSE11, CFFG18, HCBR21, CFEL22, BRSB23		6
HCBR21	BRSE11, CFFG18, CFEL22, BRSB23	HCAL19, BSBR20	6
CFEL22	BRSE11, CFFG18, HCBR21, BRSB23, CFFG18	HCBR21	6
BRSB23		BRSE11, MSMN12, CFEL22	6
GHGH24	BRSB23, BRPP27		7
CCIV25	BRSB23, BRPP27		7
SHGR26	BRPP27	BRSB23, GHGH24, CCIV25	7
BRPP27		SHGR26	7
PPSA28	BRPP27, BRGR30		8
BRDE29	BRGR30	BRPP27, PPSA28	8
BRGR30		BRDE29	8
PAGR31	BRGR30, BRAQ33		9
NRBL32	BRGR30, BRAQ33		9
BRAQ33		BRGR30, PAGR31, NRBL32	9
AQAQ34			10
NBHI35	NBCL36		11

Control Point ID	Control Points Used in Fill Relationships	Control Points Immediately Upstream	Open in this Order
NBCL36		NBHI35	11
NBVM37	NBCL36	NBCL36	12
MBMG38	BRAQ33, BRWA41		13
HGCR39	BRAQ33, BRWA41		13
BOWA40	BRAQ33, NBVM37, MBMG38, HGCR39, BRWA41	NBVM37, MBMG38, HGCR39	13
BRWA41		BRAQ33, AQAQ34, BOWA40	13
BRHB42	BRWA41, BRBR59	BRWA41	14
LEDL43	LEHS45		14
SADL44	LEHS45		14
LEHS45		LEDL43, SADL44	14
LEHM46	LEHS45, LEGT47	LEHS45	14
LEGT47	LEHS45, LEBE49	LEHM46	14
COPI48	LEHS45, LEBE49		14
LEBE49		LEGT47, COPI48	14
LAKE50	LAYO51		14
LAYO51	LAKE50	LAKE50	14
LABE52	LAYO51, LRLR53	LAYO51	14
LRLR53	LEBE49, LAYO51	LEBE49, LABE52	14
NGGE54	GAGE56		14
SGGE55	GAGE56		14
GAGE56	NGGE54, SGGE55	NGGE54, SGGE55	14
GALA57	GAGE56	GAGE56	14
LRCA58		LRLR53, GALA57	14
BRBR59	BR_SH21	BRHB42, LRCA58	14
BR_SH21		BRHB42, LRCA58	14
MYDB60	YCSO62		15
EYDB61	YCSO62		15
YCSO62	MYDB60, EYDB61	MYDB60, EYDB61	15
DCLY63	YCSO62		16
NAGR64	NAEA66		17
BGFR65	NAEA66		17
NAEA66		NAGR64, BGFR65	17
NABR67	NAEA66	NAEA66	18
BRHE68		BRBR59, YCSO62, DCLY63, NABR67	19
MCBL69	YCSO62, CY_CY (San Jacinto Basin), DCLY63		20
BRRI70		BRHE68, MCBL69	21
BGNE71	BR_HO (San Jacinto Basin), CBALC2		22

Control Point ID	Control Points Used in Fill Relationships	Control Points Immediately Upstream	Open in this Order
BRRO72	BRRI70	BRRI70, BGNE71	22
BRGM73	BGNE71, BRRO72		22
CLPEC1	BR_HO (San Jacinto Basin), CBALC2		22
CBALC2	BR_HO (San Jacinto Basin), TxRR, CLPEC1		22
SJGMC4	CLPEC1, CBALC2		23
SJGBC3	CLPEC1, CBALC2		24