Hydrology and Hydraulics Appendix C
Integrated Planning and Design Analysis and Environmental Assessment
Waco Metropolitan Area Regional Sewerage System Treatment Plant
Waco and McLennan County, Texas
Brazos River
Section 14 Emergency Streambank and Shoreline Protection

May 2021

US Army Corps
of Engineers®
Fort Worth District

Section 1 – General Information

1.0 Study Area. The study area consists of the Brazos River adjacent to the Waco Metropolitan Area Regional Sewerage System (WMARSS) Central Wastewater Treatment Plant in Waco, Texas and within McLennan County. The WMARSS Central Wastewater Treatment Plant is located about 1.2 miles downstream of SH 6. Figure 1-1 shows the location of the study area.

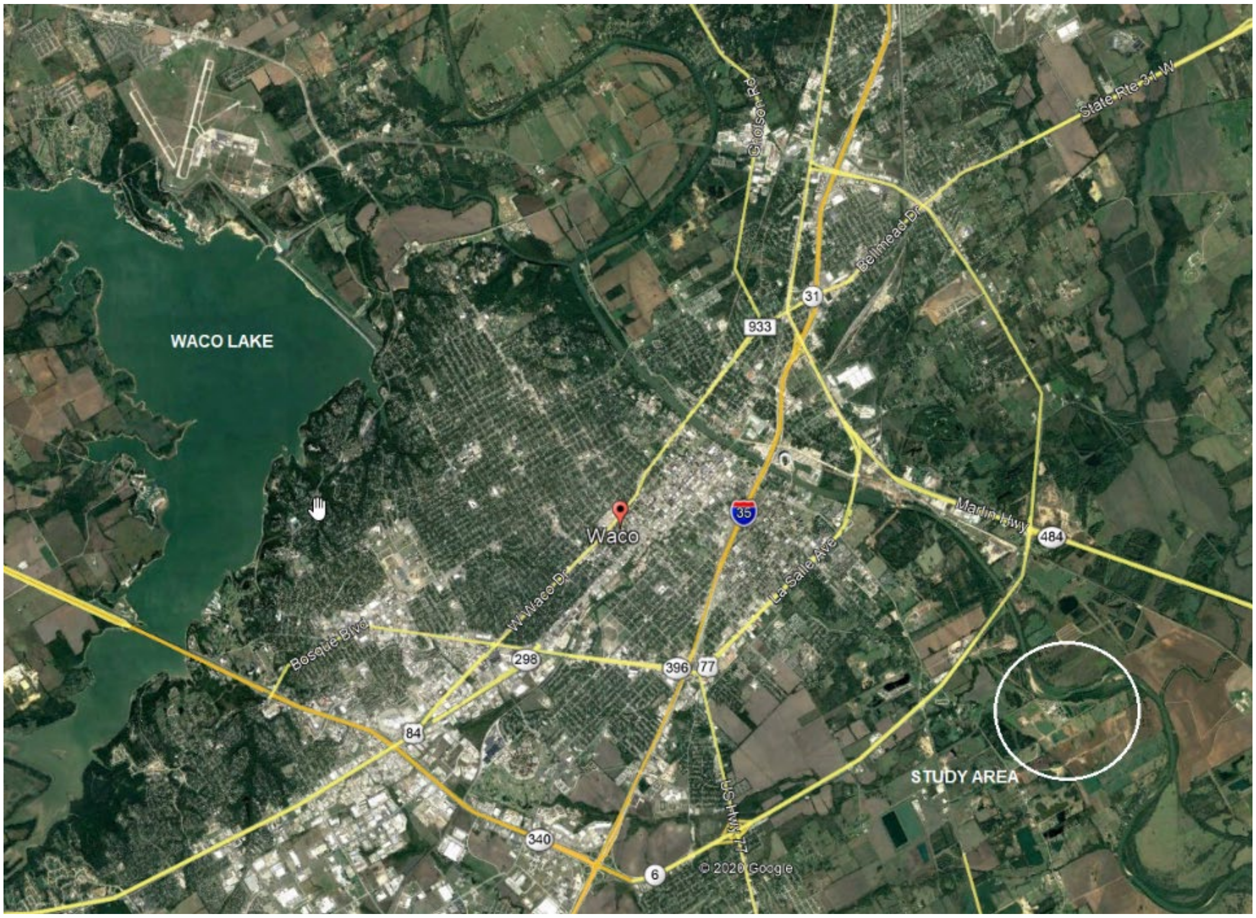

Figure 1-1. Study Area

1.1 Problem Identification. The right bank of the Brazos River, adjacent to the WMARSS Central Wastewater Treatment Plant, has been steadily eroding during the past several years. The erosion, if allowed to continue, will impact three critical infrastructure facilities: WMARSS Central Wastewater Treatment Plant, city of Robinson water intake (located about 1,000 feet upstream), and the Sandy Creek power plant intake structure (located within the WMARSS Central Wastewater Treatment Plant facility). A chronological display of the erosion from 1995 – 2019 is shown in Figure 1-2. A ground view of the erosion is shown in Figure 1-3.

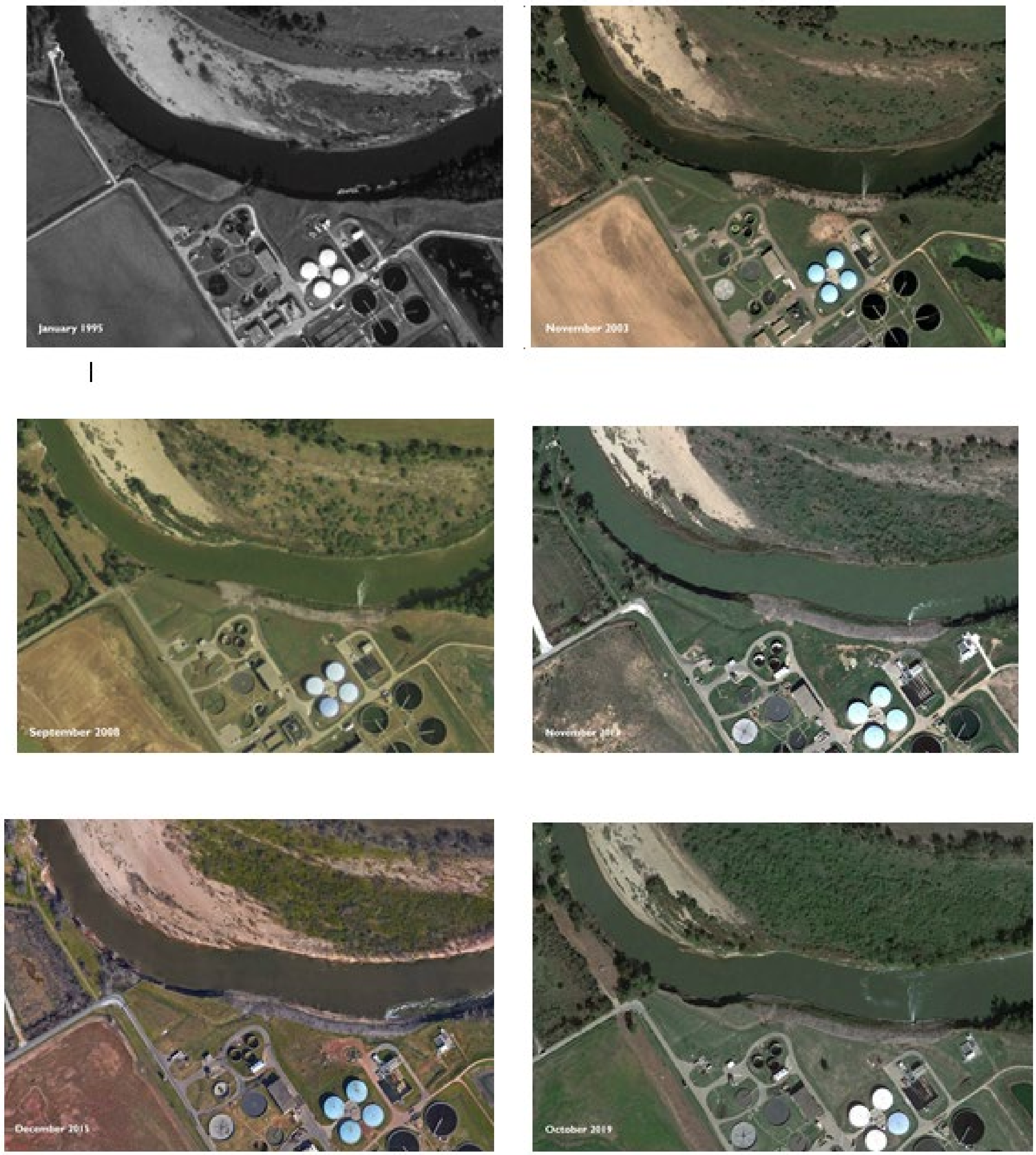

Figure 1-2. Study Area Erosion 1995 - 2019

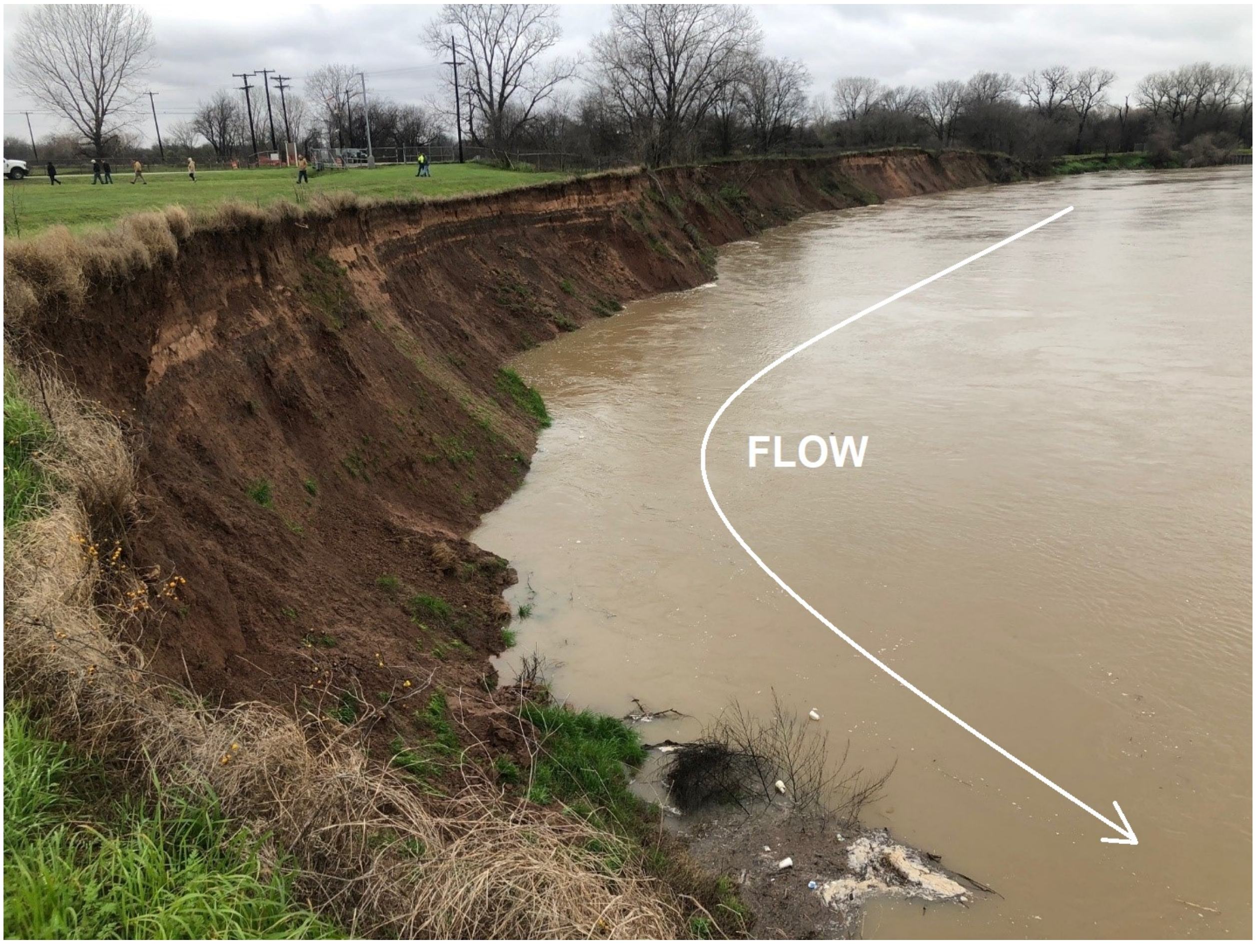

Figure 1-3. Study Area Erosion (February 2020)

1.1.1 Rate of Erosion. The rate of erosion of the Brazos River right bank was estimated by the Civil Design Section using aerial photographs over a 24-year time period and by measuring the distance from the riverbank to the corner point of the WMARSS Central Wastewater Treatment Plant access road. Table 1-1 shows the results of the measurements. Figure 1-4 shows a typical measurement point.

Table 1-1. Riverbank Erosion Rates

Date	Distance from Road to Riverbank (ft)	Distance Eroded (ft)	Cumulative Years
January 1995	216	0	0
November 2003	162	54	9
October 2005	159	57	11
October 2008	162	54	14
March 2009	155	61	14
December 2009	153	63	15
November 2011	150	66	17
December 2012	145	71	18
February 2015	145	71	20
August 2015	130	86	20.5
December 2015	122	94	21
January 2017	122	94	22
January 2018	122	94	23
August 2018	114	102	23.5
February 2019	95	121	24
Erosion Rate			
Initial 10 years	average rate = 6 ft/year		
Second 10 years	average rate = 4 ft/year		
Last 4 years	average rate = 7 ft/year		

Figure 1-4. Erosion Measurement Point

1.3 Existing Improvement. There is an existing U. S. Army Corps of Engineers Section 14 civil works project located at the WMARSS Central Wastewater Treatment Plant. The project consists of about 900 feet of streambank protection (24-inches of stone riprap over 9-inches of bedding). The project was completed in 2002. The project was constructed to repair erosion along the right bank of the Brazos River. The project is annually inspected by the Fort Worth District. The city of Waco is the Local Sponsor and is responsible for maintenance. Figures 1-5 to 1-7 show the existing project.

Figure 1-5. Existing Streambank Protection Project

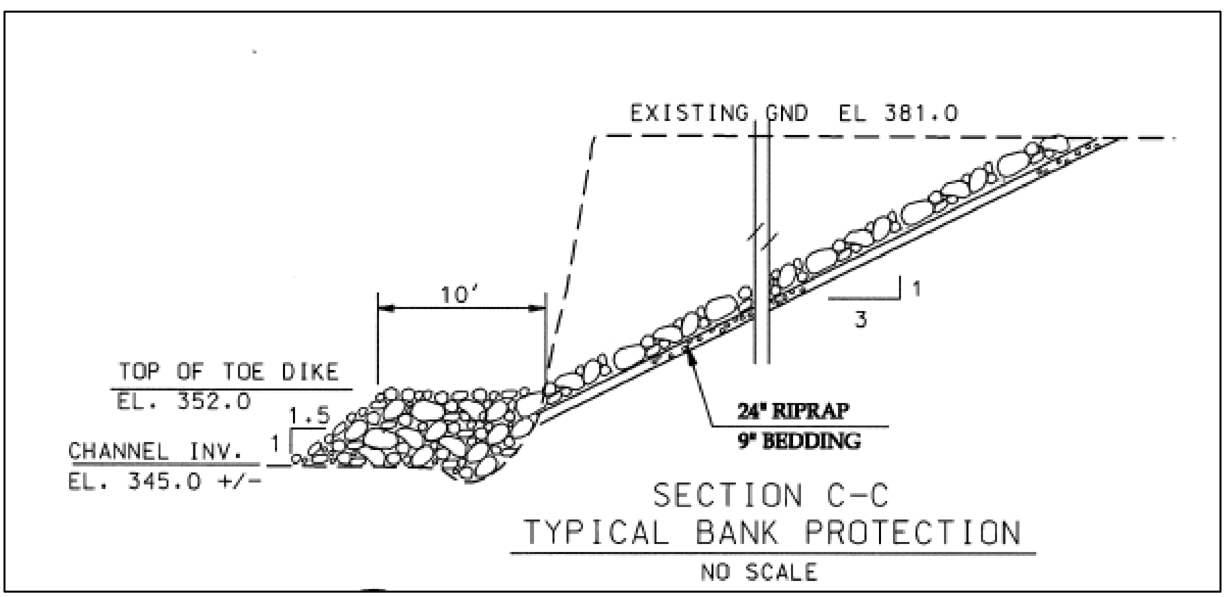

Figure 1-6. Existing Streambank Protection Project Typical Cross-section

Figure 1-7. Existing Streambank Protection Project

Section II - Hydrology

2.0 Watershed. The Brazos River flows in a generally southeast direction through the study area. Descending from the broad smooth plateau of the High Plains, the Brazos River traverses a wide area of strongly rolling and deeply dissected North Central Plains to the Balcones Fault Zone near Waco. Formations near the Balcones fault Zone are upper Cretaceous limestones, shales, and marls. McLennan County and portions of Bosque County and Hill County are located in the Gulf Coastal Plains region. This region changes from rolling hills of post oak and short grass in the west to a flat plain of dense grass as the river nears the Gulf of Mexico.

There are three USACE lakes located upstream of the study area (Aquilla Lake, Waco Lake, and Whitney Lake). The three major tributaries of the Brazos River within the study area are Aquilla Creek, Bosque River, and Tehuacana Creek. Aquilla Dam regulates discharges on Aquilla Creek. The total drainage area above Aquilla Dam is 255 square miles. The drainage area of the Aquilla Creek watershed downstream of Aquilla Dam is 152.3 square miles. The Bosque River watershed, located northwest of Waco, is rectangular in shape and about 89 miles long, and averages about 19 miles in width. Waco Dam regulates discharges on the Bosque River. The total drainage area above Waco Dam is 1,652 square miles. The drainage area of the Bosque River watershed downstream of Waco Dam is 6.9 square miles. The drainage area of the Tehuacana Creek watershed is about 300 square miles. The uncontrolled area above the Brazos River at the Brazos River at Waco Gage (SH 6) is 463 square miles. The plan of regulation for these three projects allows for a combined flow at the Brazos River at Waco gage of 60,000 cfs.

2.1 Soils. McLennan County is in the Grand Prairie and Texas Blackland Prairie Major Land Resource Areas. Most of the soils formed under prairie vegetation and are dark colored clays, silty clays, or clay loams – these soils are naturally slow draining and lie wet for long periods. In some areas on terraces along the Brazos River, the soils formed under post oak-savannah vegetation. These soils are mostly light-colored sandy loams or loamy fine and tend to drain quickly after rain or watering. Infiltration is the term applied to the process of water entry into the soil, generally by downward flow through all or part of the soil surface. Loss rates within the soils are highly variable and dependent on antecedent conditions.

2.2 Groundwater. The study area is located within the South Trinity Groundwater Conservation District. The District has within its boundaries the Trinity, the Woodbine, and the Brazos River Alluvium aquifers. The Brazos River Alluvium Aquifer consists of water bearing alluvial sediments that occur in floodplain and terrace deposits proximate to the Brazos River as it flows through McLennan County. The Brazos River Alluvium Aquifer is an unconfined aquifer that receives recharge primarily from direct precipitation on the floodplain surface but may also be recharged from overbank flows during flood events and from lateral flow from adjacent formations. The aquifer discharges through springs and seeps into the Brazos River and streams within the outcrop of the alluvium.[1] The aquifer is up to seven miles wide and 350 miles long and is one of the 21 minor aquifers that can be found in the state of Texas.

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[1] Southern Trinity Groundwater Conservation District, Groundwater Management Plan - 2015

2.3 Climatology. The climate of Waco is humid subtropical with hot summers. It is a continental type climate characterized by extreme variations in temperature. At the Waco Regional Airport, the highest recorded temperature was 112 degrees on 11 August 1969. The lowest recorded temperature was -5 degrees on 31 January 1949. Tropical maritime air masses predominate throughout the late spring, summer and early fall months, while Polar air masses frequent the area in winter. In an average year, April and May are the wettest months, while the July-August period is the driest. Most warm season rainfall occurs from thunderstorm activity. Consequently, considerable spatial variation in amounts occurs. Winters are mild. Cold fronts moving down from the High Plains often are accompanied by strong, gusty, northerly winds and sharp drops in temperature. Cold spells are of short duration, rarely lasting longer than 2 or 3 days before a rapid warming occurs. Winter precipitation is closely associated with frontal activity, and may fall as rain, freezing rain, sleet, or snow. During most years, snowfall is of little or no consequence. Daytime temperatures are hot in summer, particularly in July and August. Cloudiness and showers are more frequent in the spring than in the fall. The average first occurrence of 32°F is late November and the average last occurrence is in mid-March.[2] The Waco/McLennan County area has historically experienced droughts (in the 1950s and in 2017-2018). However, potential for extreme storm events and flooding still exists.

2.4 Precipitation. The maximum annual precipitation at Waco, from the Waco Regional Airport, is 59.48 inches, occurring in 2004. The minimum annual precipitation was 14.92 inches occurring in 1954. The average annual precipitation is 34.7 inches. Waco and McLennan County are located in a region that is subject to extreme variations in precipitation including drought conditions and extreme flooding conditions. The annual precipitation of the Waco area from 1960 to 2018 is presented in Figure 2-1.

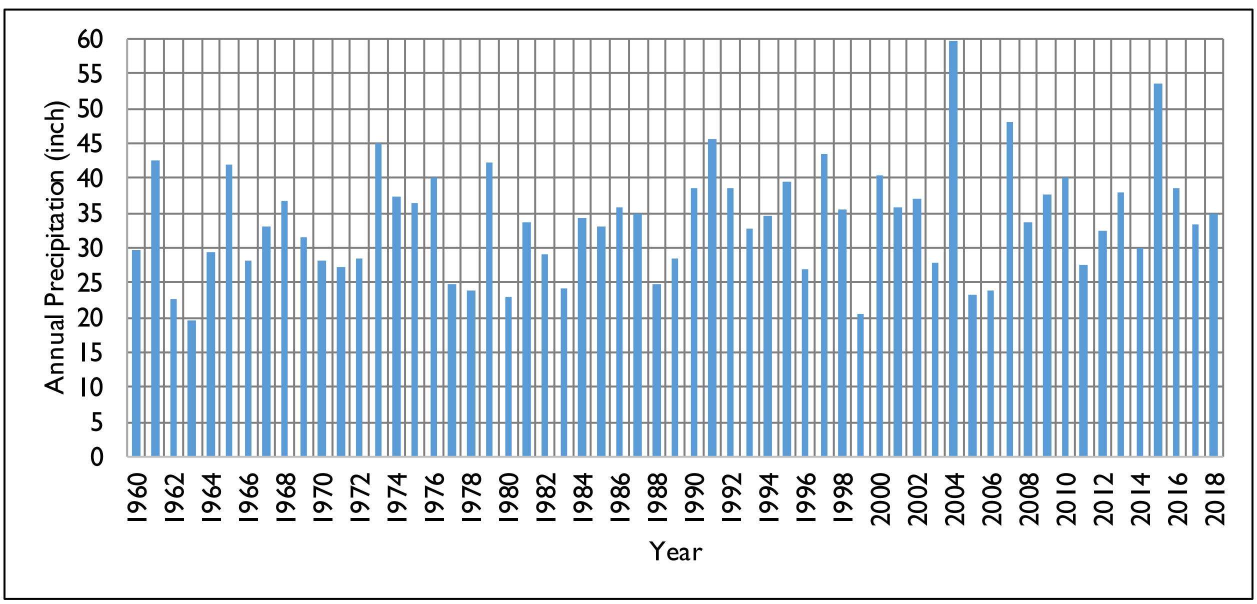

Figure 2-1. Annual Precipitation From 1960 - 2018

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[2] National Weather Service

2.5 Historical Flooding. The largest flows recorded at the Brazos River at Waco gage since 1990 are listed in Table 2-1.

Table 2-1. Largest Recorded Flow at Brazos River at Waco Gage Since 1990

Date	Peak Gage Height (ft)	Peak Flow (cfs)
1990 May 12	24.35	40,800
1991 December 21	26.50	50,000
1997 March 10	23.45	38,000
2007 March 30	26.46	39,900
2015 October 24	25.22	37,000

Figure 2-2 shows the October 2015 hydrograph at the Brazos River at Waco Gage and the peak flow of 37,000 cfs. The hydrograph shows the flow peaked and receded quickly. Later in the year smaller flow peaks occurred in November and December. Quickly rising and falling river levels will impact the condition of the riverbanks as well as smaller, longer duration flows.

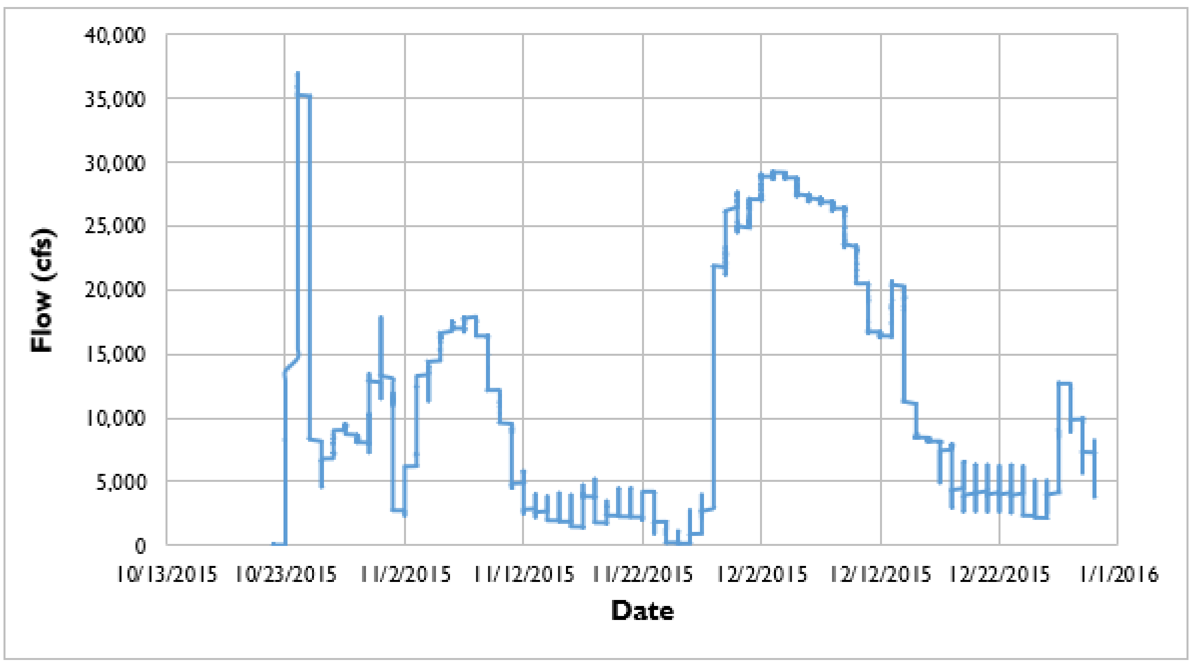

Figure 2-2. October - December 2015 Hydrograph at Brazos River at Waco Gage

2.6 Hydrology Model Development. The U. S. Army Corps of Engineers - Fort Worth District Water Resources Branch completed a Water Resource Investigation for the city of Waco and McLennan County in March 2019. The results of the study were presented to the city of Waco and McLennan County 7 March 2019. The study consisted of the development of new hydrologic and hydraulic models for the Waco and McLennan County area downstream of the three USACE lakes. The study analysis included updated Brazos River and Bosque River hydrologic and hydraulic models, recommended Federal Emergency Management Agency (FEMA) Brazos River 100-year Base Flood Elevations, flood inundation models along with flood inundation mapping for a range of flows on the Brazos River, and products for update of current FEMA Flood Insurance Rate Maps, through the Letter of Map Revision (LOMR) process.

A watershed-runoff model for the area was developed utilizing the United States Army Corps of Engineers (USACE) computer program HEC-HMS (Hydrologic Modeling System). The watershed was delineated using Arc-GIS and HEC-GeoHMS software. The drainage area was divided into 53 sub-areas to obtain flood hydrographs at all major points of interest. These points included the confluence of Brazos River with all major tributaries, Brazos River near Aquilla gage (FM 2114), Lake Brazos Dam, Brazos River at Waco gage (SH 6/Loop 340), and SH 7. A fifteen-minute computation time interval was used in the model to provide detail (shaping) of the unit hydrograph applied at the smaller sub-areas in the analysis. The measurable parameters of drainage area, stream length, length to centroid, and slope were determined from the topographic data using Arc-GIS and HEC-GeoHMS software. Urbanization and imperviousness values were determined to represent development of the watershed. Figure 2-3 shows the study area drainage area map with sub-areas used in the HEC-HMS model.

Whitney Dam. Aquilla Dam, and Waco Dam are three of the nine USACE multi-purpose projects in the Brazos River basin. The projects are operated by the USACE Water Resources Branch – Water Management Section. Whitney Dam and Waco Dam have tainter gates, while Aquilla Dam has an uncontrolled spillway. Releases from Whitney Dam, Aquilla Dam, and Waco Dam are made at a rate, when combined with runoff from downstream areas, not to exceed the discharges at the Brazos River at Waco Gage of 60,000 cfs.

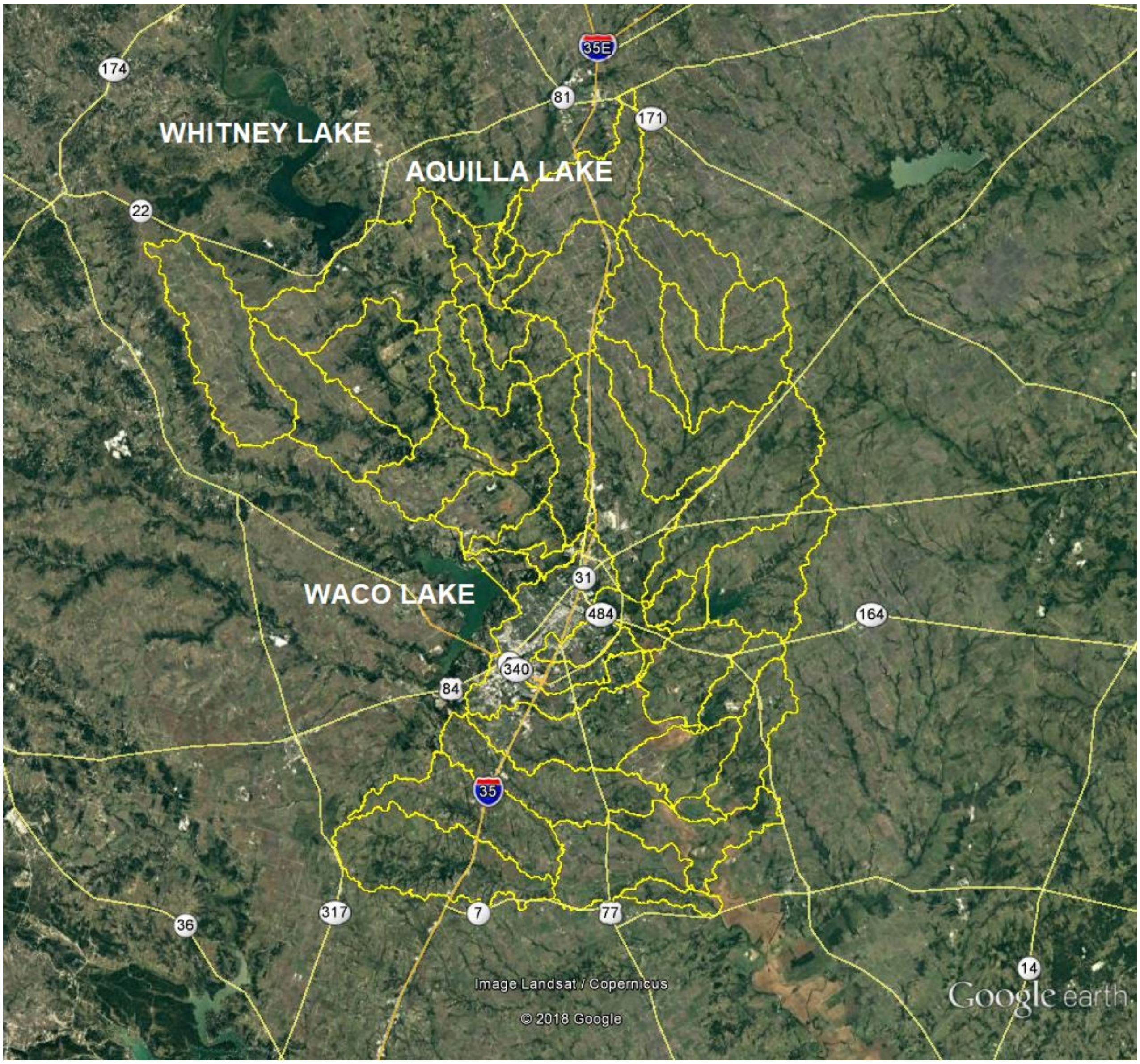

Figure 2-3. Brazos River Drainage Area

2.7 Model Rainfall. The hypothetical precipitation for the 2-, 5-, 10-, 25-, 50-, 100-, 250-, and 500-year frequency storms used for the study to produce flood frequency flows and water surface profiles is based on "NOAA Atlas 14, Precipitation-Frequency Atlas of the United States, Volume 11 Version 2.0: Texas." NOAA Atlas 14 is the product of a study used to analyze historical rainfall data to update statistical hypothetical rainfall events in Texas. This precipitation data was published on 27 September 2018.

2.8 USGS Stream Gage. There is a USGS stream gage located at SH 6. Pertinent data is as follows:

USGS 08096500 Brazos River at Waco, Texas
Hydrologic Unit Code 12060202
Latitude 31°32'09", Longitude 97°04'23" NAD27
Drainage area 29,559 square miles
Contributing drainage area 19,993 square miles
Gage datum 349.34 feet above NGVD29

The gage is located about 0.75 miles upstream of the WMARSS Central Wastewater Treatment Plant.

2.9 Peak Flood Frequency Flows. The 2-, 5-, 10-, 25-, 50-, 100-, 250-, and 500-year peak flows, at the study area location, for the uncontrolled drainage area downstream of Whitney Dam, Aquilla Dam, and Waco Dam, for the Brazos River are presented in Table 2-2.

Table 2-2. Brazos River Peak Flows at the Study Area

2-Year (cfs)	5-Year (cfs)	10-Year (cfs)	25-Year (cfs)	50-Year (cfs)	100-Year (cfs)	250-Year (cfs)	500-Year (cfs)
21,400	34,500	43,400	59,700	75,700	99,400	126,000	200,000

Section III – Hydraulics

3.0. Hydraulic Model Development. The hydraulic analysis developed for the Water Resource Investigation for the city of Waco and McLennan County in March 2019 consisted of the development of HEC-RAS models for the computation of frequency flood profiles and inundation mapping products for the Brazos River and Bosque River. The U.S. Army Corps of Engineers River Analysis System (HEC-RAS) program, version 5.0.3, was used in this study. HEC-RAS was developed by the Hydrologic Engineering Center in Davis, California. HEC-RAS is an integrated system of software comprised of a graphical users interface (GUI), analysis components, data storage and management capabilities, and graphics and reporting facilities. HEC-RAS designed to perform one-dimensional and two-dimensional calculations for a full network of natural and constructed channels and overbank/floodplain areas and is considered the industry standard for modeling river hydraulics. The HEC-RAS models for the study were generated in steady flow. Channel and floodplain information required by the HEC-RAS model was extracted from the DEM using HEC-GeoRAS. HEC-GeoRAS is a set of procedures, tools, and utilities for processing geospatial data in ArcGIS using a graphical user interface (GUI). The interface allows the preparation of geometric data for import into HEC-RAS and processes simulation results exported from HEC-RAS.

The Brazos River is modeled from a point within Falls County (RM 387.95), through McLennan County, to downstream of Whitney Dam (RM 462.70) in Bosque County. The total length is 74.75 miles. The WMARSS Central Wastewater Treatment Plant is located at Brazos River approximate river mile 417.8.

3.0.1 Data Collection. The data used in the development of HEC-RAS models was collected from several sources. These sources are as follows:

- Terrain. TNRIS provided 1-meter hydro-enforced DEMs developed from 2011 50-cm point cloud LiDAR (Light Detection and Ranging) data covering the southern portion of the study area. This data was used in the development of the HEC-RAS cross-sections.

- Bathymetry. The DEM did not include bathymetry data. Bathymetric information for the lower Brazos River mile from river mile 415.25 to the downstream end of the study was developed utilizing Brazos River channel data from SH 6/Loop 340 and SH 7 bridge plans. The bathymetry between these two bridge locations was interpolated.

- Manning n values. Manning n values were assigned for each type of land use defined by the land use polygons generated in HEC-GeoRAS. The n values were generally assigned based on aerial photography. Field site vists were used for verification of these values. Adjustments to these values for the main channel were made during the model calibration process. Channel n values were estimated for the channel as a whole, rather than separate values for the channel bottom and the channel banks. Overbank n values were assigned using aerial photography as well. The range of n values used in the Brazos River HEC-RAS model are as follows: channel (0.030 – 0.033) and overbanks (0.030 – 0.10).

3.0.2. Result of Analysis. The Brazos River HEC-RAS model cross-section in the vicinity of the WMARSS Central Wastewater Treatment Plant is shown in Figure 3-1. The flood event water surface elevations are shown in Table 3-1.

Figure 3-1. HEC-RAS Cross-sections at the WMARSS Central Wastewater Treatment Plant

Table 3-1. Water Surface Elevations

Flood Event	Q Total (cfs)	W.S. Elev. (ft)	Depth (ft)
2-year	21,400	369.3	24
5-year	34,500	372.8	28
10-year	43,400	374.4	29
25-year	59,700	377.2	32
50-year	75,700	379.5	35
100-year	99,400	381.8	37
250-year	126,000	383.5	38
500-year	200,000	385.1	40

3.1. Brazos River Conditions. The Brazos River in the study reach is undergoing aggradation and degradation. Aggradation and degradation are the fluvial processes mostly associated with a river and its differentiating parameters. Aggradation and degradation are generally influenced by river discharge, sediment load, morphological characteristics of river channel, and human interventions. If the river water is unable to transfer the bed load or the channel material, then the same is deposited within the channel and channel height increases, i.e. aggradation occurs. This also leads to changes in the river morphology and hydraulic geometry. Degradation is the process which is responsible for the lowering of riverbed and shifting of the river channel banks.

Meandering river channels are asymmetrical. The deepest part of the channel is on the outside of each bend. The water flows faster in these deeper sections and erodes material from the riverbank. The water flows more slowly in the shallow areas near the inside of each bend. The slower water cannot carry as much sediment and deposits its load on a series of point bars.

- As a river goes around a bend, most of the water is pushed towards the outside. This causes increased speed and therefore increased erosion (through hydraulic action and abrasion).
- The lateral erosion on the outside bend causes undercutting of the bank to form a river cliff.
- Water on the inner bend is slower, causing the water to slow down and deposit the eroded material, creating a gentle slope of sand and shingle.
- The build-up of deposited sediment is known as a slip-off slope (or sometimes river beach).

Figures 3-1 and 3-2 show the aggradation and degradation process for a river system.

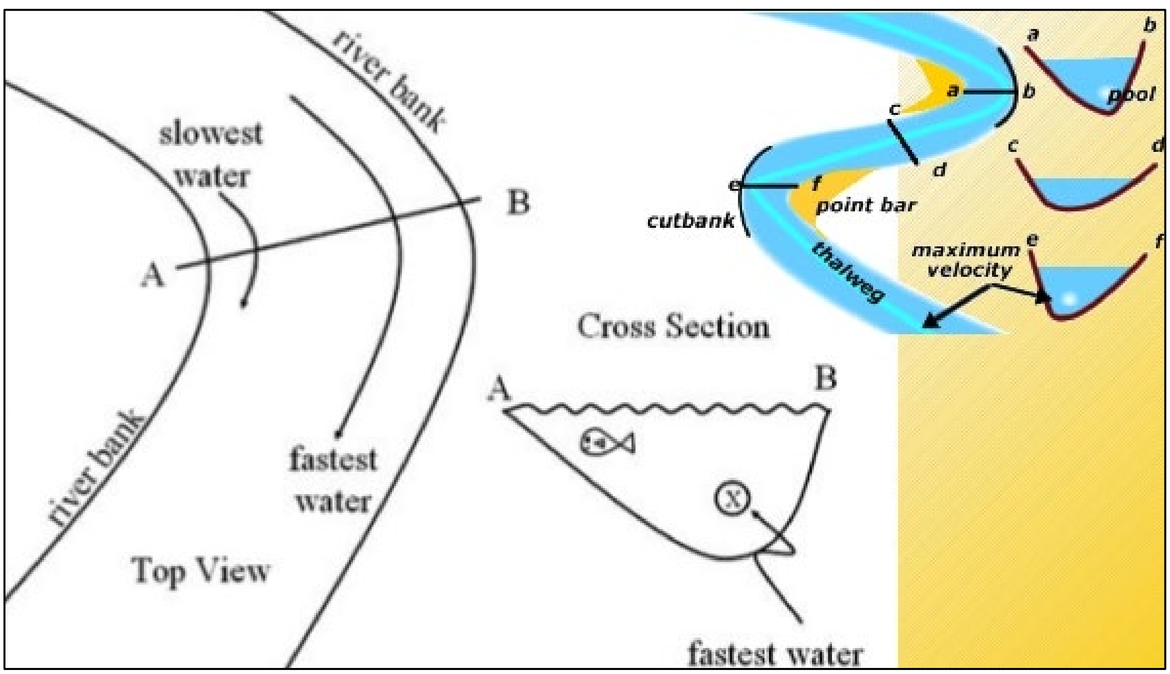

Figure 3-1. Aggradation and Degradation Process

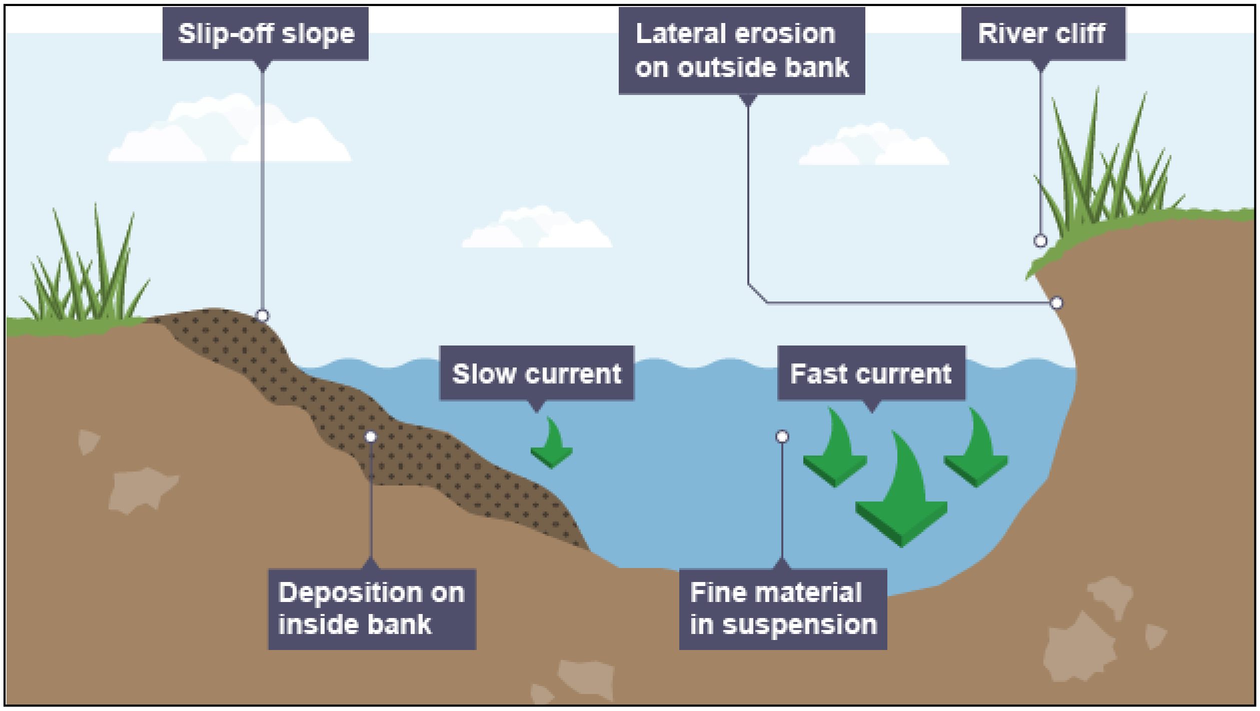

Figure 3-2. Aggradation and Degradation Process

There are three ways for streambanks to erode: 1. Hydraulic. Water carries away bed and/or bank material because the shear stress of the flowing water is stronger than the shear strength or cohesiveness of the bank. (Fischenich 1989) "...Hydraulic failure is usually characterized by a lack of vegetation, high boundary velocities [swift high water], and no mass wasting at the toe of the bank." (King 1993). This generally occurs in noncohesive soils; glacial till is a good example. 2. Geotechnical. Gravity exerts a stronger force on the bank than the materials can withstand, and they slide. Its shear strength is compromised. In many cases, excess moisture retention is the cause of mass wasting (landslide) at the toe of the bank. 3. Hydraulic and Geotechnical. Bank failure caused by this combination is more likely to occur than either one alone. Examples include bed degradation and erosion, which lowers the bed so much that the banks become overly steep and fail(slide) and mass wasted material lying at the toe of a slope is washed away. (Fischenich 1989) (King 1993)[3]

The Brazos River flows in a straight alignment for about 0.75 miles from the upstream SH 6 bridge before it bends as it approaches the WMARSS Central Wastewater Treatment Plant. The major part of the Brazos River right bank erosion in the study area is located at this bend in the river (approximate radius of 1,000 feet). The erosion adjacent to the WMARSS Central Wastewater Treatment Plant is occurring at the outside bend of the river, while sediment deposition is occurring on the opposite inside bend of the river. The flow of the Brazos River is directed towards the outer bank. Over time, this outer bank has continued to erode. It is likely that the river thalweg (the deepest part of the river channel) is located adjacent to the right bank. Figure 3-3 shows the Brazos River alignment in the study area. The hydraulic forces on the right bank appear to be the predominant cause of the erosion.

[3] A Soil Bioengineering Guide, USDA Forest Service

The Brazos River channel geometry from HEC-RAS model at cross-section 417.81 is an approximation based on known channel geometry from upstream and downstream bridges. The channel geometry is shown in Figure 3-4. The river channel velocities as computed from the Brazos River HEC-RAS model are shown in Figure 3-5.

Figure 3-3. Brazos River Alignment in the Study Area

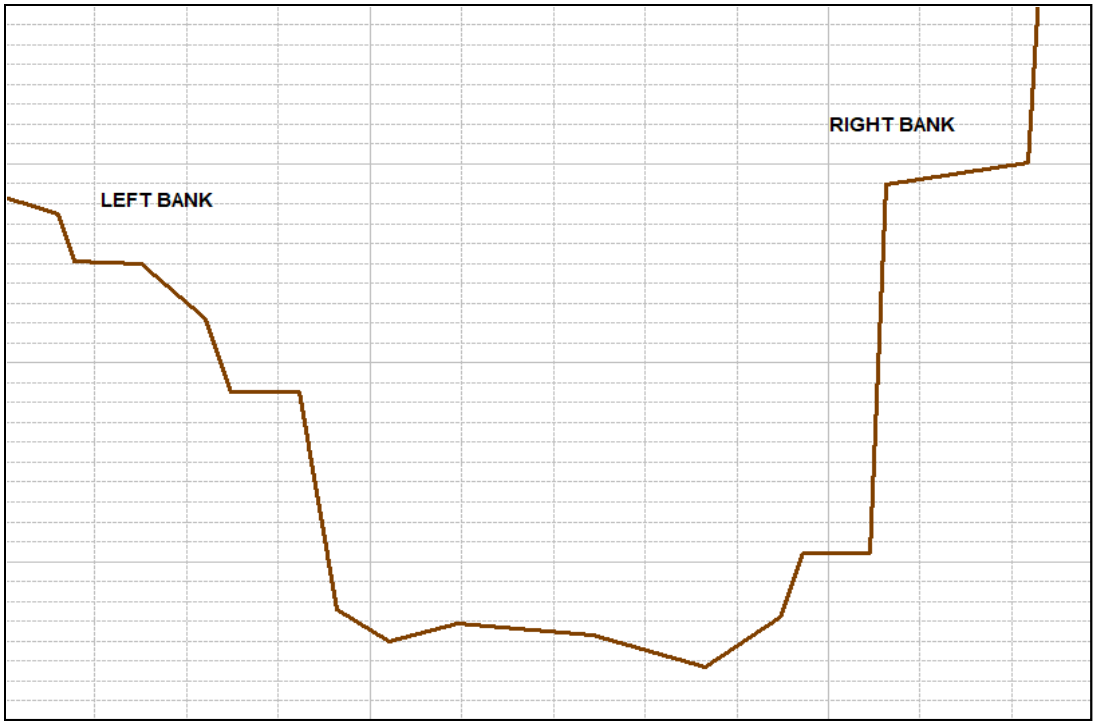

Figure 3-4. Brazos River Channel Geometry Cross-section 417.81

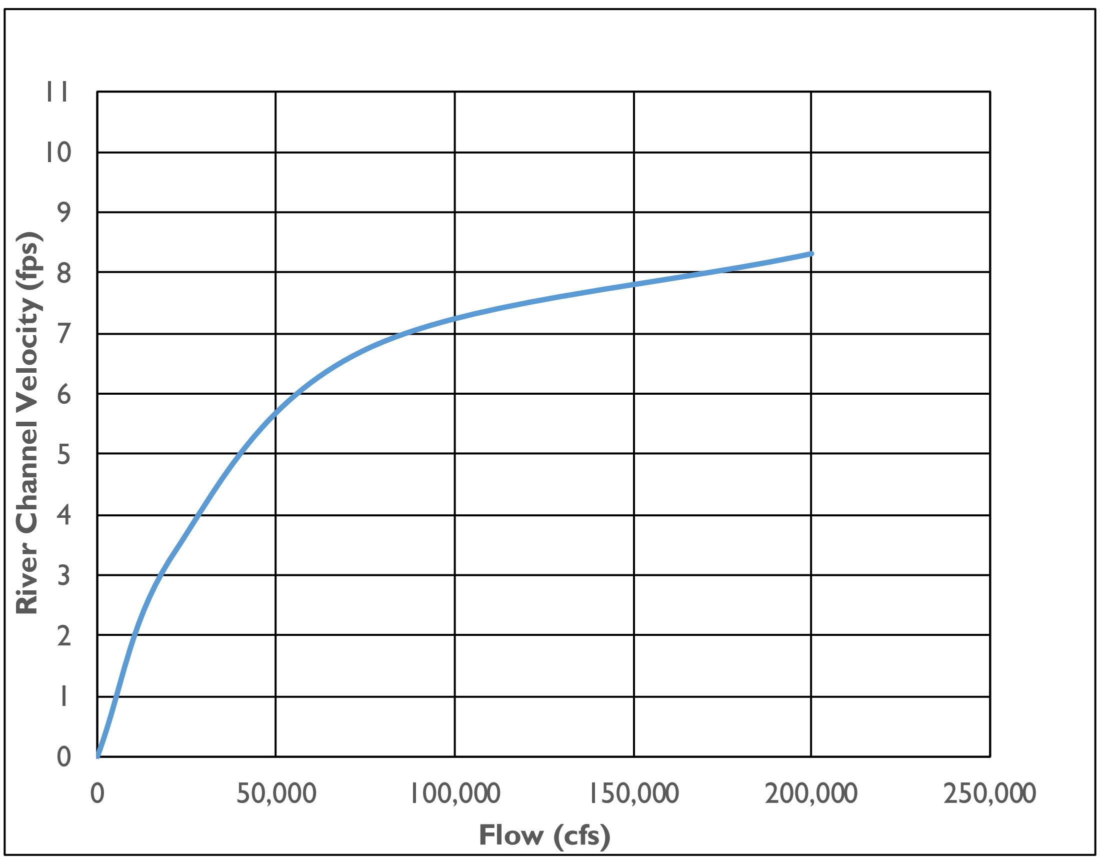

Figure 3-5. Brazos River Channel Velocity

Section IV – Future Without Conditions

The erosion along the right bank of the Brazos River will continue to erode without a structural plan of improvement. The alignment of the Brazos River will continue to direct flow towards the river outer (right) bank. Over time, this outer bank erosion will expand and likely impact the WMARSS Central Wastewater Treatment Plant, the city of Robinson water intake structure, and the Sandy Creek power plant intake structure facilities and operations.

Section V – Alternatives

5.0 Description of Alternatives. Three structural alternatives were evaluated to address the study area erosion issues. These alternatives are described below. Full descriptions of each alternative are included in the Civil Design portion of this report.

Alternative 1 - Longitudinal Peaked Stone Dike and Tie Back. Alternative 1 consists of a longitudinal peaked stone toe dike placed at the toe along a 1,300-feet section upstream of exiting riprap bank protection and 300 feet section downstream of existing riprap on the right bank of the Brazos River. The upstream reach of the stone toe dike would begin at station 0+00 (north of the City of Robinson intake structure). The downstream reach of the stone dike would run adjacent to the Sandy Creek intake structure. The longitudinal stone toe dike would have a triangular cross section with an approximate height of 8 feet, a base width of about 48 feet, and 3H:1V side slopes. The entire 1,600-foot reach of the longitudinal stone toe dike would have stone tie-back dikes extending out perpendicularly from the crest of the longitudinal stone dike to the bank and would be spaced every 100-feet along the longitudinal stone dike. The crest height of the tie-back dikes would match the crest height of the longitudinal stone dike at the juncture of the two and would slope up toward the bank on a slope of 5H:1V.

Alternative 2 - Stone Riprap Toe Protection. Alternative 2 consists of stone riprap placed on the slope from the toe to the top of bank along approximately 1,300-feet upstream of existing riprap bank protection and 300 feet downstream of existing riprap on the right bank of the Brazos River. The upstream reach of the riprap would begin at station 0+00 (north of the city of Robinson intake structure). The downstream reach of the riprap would run adjacent to the Sandy Creek intake structure. An 18-inch thick stone riprap layer will be placed along the slope of the dressed-up bank and extend to the top of bank to provide erosion protection. The existing earth slope would be reshaped, and the riprap would be placed at a 2:1 1 (horizontal to vertical) slope to improve slope stability. The riprap would be keyed into the riverbed (and anchored at the top of the slope) as an additional mitigation measure to reduce the potential for toe erosion.

Alternative 3 - Longitudinal Peaked Stone Toe Protection with Bendway Weirs. Alternative 3 consists of bendway weirs constructed of stone in combination with a longitudinal peaked stone toe dike placed at the toe along approximately 1,300-feet section upstream of exiting riprap bank protection and 300 feet section downstream of existing riprap on the right bank of the Brazos River. The upstream reach of the stone toe dike would begin at station 0+00 (north of the City of Robinson intake structure). The downstream reach of the stone dike would run adjacent to the Sandy Creek intake structure. The weirs have a trapezoidal cross-section about 4 feet in height, a 5-foot crest width, 2H:1V side slopes and would slope downward toward the center of the riverbed on a 20H:1V slope. The weirs would be spaced every 100 feet and extend out toward the centerline of the riverbed 15 feet from the longitudinal stone toe dike. The weirs are angled upstream approximately 10 to 15 degrees from the radius of the bend to direct flow away from the bank toward the center of the riverbed.

5.1 Design Characteristics. The design channel velocity used in the sizing of the stone riprap is 10 fps.

5.2 Selected Plan Justification. The Selected Plan design is similar in design to the existing U. S. Army Corps of Engineers Section 14 civil works project located at the WMARSS Central Wastewater Treatment Plant. The project consists of about 900 feet of streambank protection (24-inches of stone riprap over 9-inches of bedding). The project was completed in 2002. This project has been functioning as designed for 18 years. The Selected Plan will extend the stone riprap of similar size for 1,300 feet upstream and 300 feet downstream of the existing stone riprap, thereby creating a long (+2,500 feet), armored bank protection system. The length of the protection system will solve the current erosion issue, i.e., protect the existing infrastructure along the Brazos River, at a cost that is the least of the three alternatives considered. The length of the protected section of the riverbank at 1,300 feet also envelopes the curvature of the riverbank, which is one of the contributory factors to the erosion potential. The Selected Plan will be maintained by the city of Waco, as they have been doing for the existing Section 14 project and will not present new or unique maintenance challenges for the city.