ABSTRACT

Effluent-Impacted Groundwater-Surface Water Interactions in the Brazos River Alluvium Aquifer: A Study on Bullhide Creek

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The primary recharge source to the Brazos River Alluvium Aquifer (BRAA), a water table aquifer in central Texas, is through direct precipitation on the floodplain. However, recharge provided by other sources, such as Brazos River tributaries crossing the alluvium is not well known. To quantify potential recharge from tributaries hydraulically connected to the BRAA and understand spatiotemporal interactions with the aquifer, Bullhide Creek was chosen due to its constant effluent discharge from a wastewater treatment plant and a 3-mile reach that interacts with the BRAA. Based on ionic and isotopic compositions, nutrient densities, and changes in flow measured throughout the studied reach, Bullhide Creek exhibits perennial streamflow after the wastewater contribution and gains flow from the BRAA during baseflow conditions. However, the creek may provide measurable recharge to the aquifer during periods of high flow through seepage to aquifer sediments adjacent to the channel and banks.

Effluent-Impacted Groundwater-Surface Water Interactions in the Brazos River Alluvium Aquifer: A Study on Bullhide Creek

by

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LIST OF ABBREVIATIONS

BHC – Bullhide Creek

BRAA – Brazos River Alluvium Aquifer

CBOD – Carbonaceous biochemical oxygen demand

CRASR – Center for Reservoir and Aquatic Systems Research

CWWUS – Waco Water Utilities Services

DO – Dissolved oxygen

DSS – Decision support tools

GNIP – Global Network of Isotopes in Precipitation

HAWQS – Hydrologic and Water Quality System

HRU – Hydrologic response unit

IAEA – International Atomic Energy Agency

IC – Ion chromatography

ICPMS – Inductivity coupled plasma mass spectrometer

LMWL – Local Meteoric Water Line

MGD – Million gallons per day

NCEI – National Centers for Environmental Information

NCEP – National Centers for Environmental Prediction

NED – National Elevation Database

NLCD – USGS National Elevation Data

NOAA – National Oceanic and Atmospheric Administration

NWS – National Weather Service

RFC – River Forecast Center

STATSGO – USDA State Soil Geographic

SWAT – Soil and Water Assessment Tool

TCEQ – Texas Commission on Environmental Quality

TDS – Total dissolved solids

TN – total nitrogen

TP – Total phosphorus

TPDS – Texas Pollutant Discharge Elimination System

TSS – Total suspended solids

VSMOW – Vienna Standard Mean Ocean Water

WMARSS – Waco Metropolitan Area Regional Sewerage System

WSR-88D – Weather Surveillance Rada – 88 Doppler

WWTP – Wastewater treatment plant

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DEDICATION

To my parents Craig and Sherri, siblings Lindsey, Corbin and Chase, and to my soon-to-be husband, Shane. I could not have accomplished all that I have without you.

CHAPTER ONE

Introduction

Background

Water availability limitations imposed by population growth, increased urbanization, climate change, and surface water quality impairments are forcing communities facing water challenges to seek additional freshwater resources. Groundwater represents the most reliable source of freshwater globally (Oelkers and others, 2011, Trenberth and others, 2007) and municipal water reuse offers the potential to significantly increase the nation's available water resources through artificial recharge to groundwater basins (National Academy of Sciences, 2007). Understanding the processes controlling groundwater-surface water interactions is essential for resource management and protecting sensitive environments, particularly in effluent dominated streams. Consequently, the hyporheic zone underlying streams is frequently investigated as the physical, chemical, and biotic processes from active mixing of groundwater and surface water can alter the constituents present in the two water systems (Krause, 2009). However, impacts from effluent-impacted streams to shallow aquifers beyond the hyporheic zone is often overlooked and understudied.

The flow systems between large rivers and their hydrologically connected groundwater reservoirs are often studied, however small tributaries are typically ungauged and their interactions with groundwater are not well known. Stream channels are a preferential flow path between groundwater and surface water as channels often consist of coarse alluvial sediments that may be more permeable than the surrounding floodplain (Woessner 1998). Streams that interact with shallow groundwater systems are generally considered gaining if perennial and losing if ephemeral (Figure 1.1). Gaining streams receive baseflow from groundwater systems whose altitude of the hydrologically connected water table is higher than the altitude of the stream-water surface. Conversely, losing streams lose water by outflow to groundwater systems and the altitude of the connected water table is lower than the altitude of the stream surface. The flow directions between surface water and groundwater can vary spatially and temporally and when streams are ungauged or understudied it can be difficult to identify and quantify the interactions between the two, restricting the understanding of the streams and aquifers involved (Winter and others, 1998).

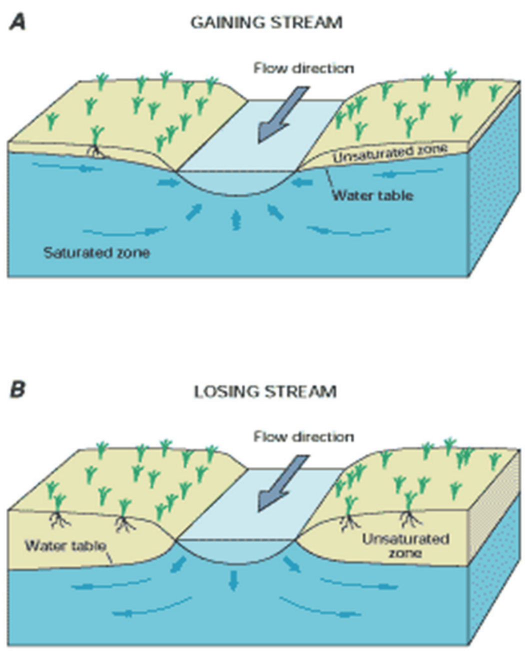

Figure 1.1. Diagram showing the interaction of streams and groundwater (Adapted from Winter and others, 1998). Gaining streams (A) receive water from groundwater whereas losing streams (B) lose water from their channel to groundwater.

The Brazos River Alluvium Aquifer (BRAA) is a minor aquifer in east-central Texas (Figure 1.2) that consists of the alluvial floodplain and terrace deposits of the Brazos River from Whitney Dam to Fort Bend County (Ewing and others, 2016). Groundwater production is primarily used for irrigation and rural livestock purposes. Municipal use of this resource is limited due to high levels of salinity, with most of the groundwater exceeding the Environmental Protection Agency's (EPA) secondary drinking level standards of 500 mg/L for total dissolved solids and 250 mg/L for chloride and sulfate (United States Environmental Protection Agency, 2018). Recharge to the aquifer is primarily through precipitation on the floodplain surface and varies from under two inches to more than five inches per year (Cronin and Wilson, 1967), however little has been done to quantify the recharge potential of Brazos River tributaries and the BRAA. Due to the numerous tributaries interacting with the alluvium, a significant quantity of water may be exchanged between the reservoirs and act as recharge sources or sinks depending on gaining and losing sections.

Nearly 100 tributaries flow across the BRAA to the Brazos River in the northern segment of the aquifer in Bosque, Hill, McLennan, and Falls counties. Whereas the northern segment of the BRAA accounts for 226 square miles, the total watershed area of the tributaries in the northern segment is 913.3 square miles with individual watersheds ranging from about 16-68 square miles (Figure 1.3). These numerous tributaries transport large amounts of water to the Brazos River and flow across the BRAA. Because the interactions between the tributaries and the BRAA are not known, eight tributaries were investigated in the northern segment from June through November 2020. Mini-piezometers were placed along the streams in the alluvium to spatially and temporally

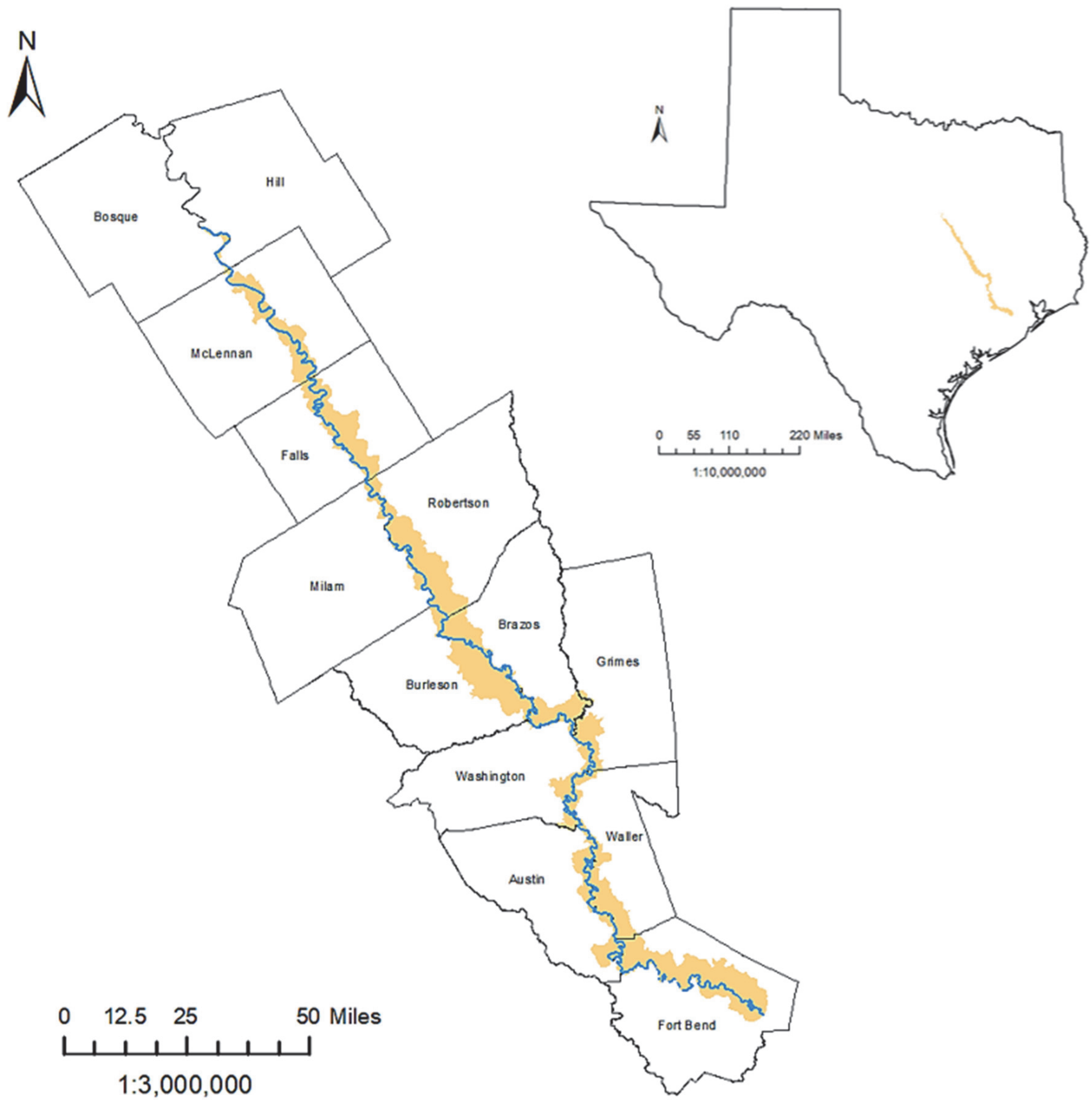

Figure 1.2. Map of the extent of the Brazos River Alluvium Aquifer, beginning at the Lake Whitney Dam to northeastern Fort Bend County.

determine stream segments that gain and lose along the aquifer. Of the eight tributaries, three were losing at some time during observation where stream behavior varied upon season, rain events, and was site specific. Detailed observations from this portion of study can be found in appendix A. To characterize and measure the interactions tributary streams may have with an alluvial aquifer, Bullhide Creek was chosen for detailed study due to a wastewater treatment plant providing a constant discharge into the creek and because it can be considered a representative stream for the tributaries in this study area due to its drainage pattern (urban-fringe bedrock to rural alluvium) and watershed size of 36 square miles (median watershed area of 37 square miles in the northern segment).

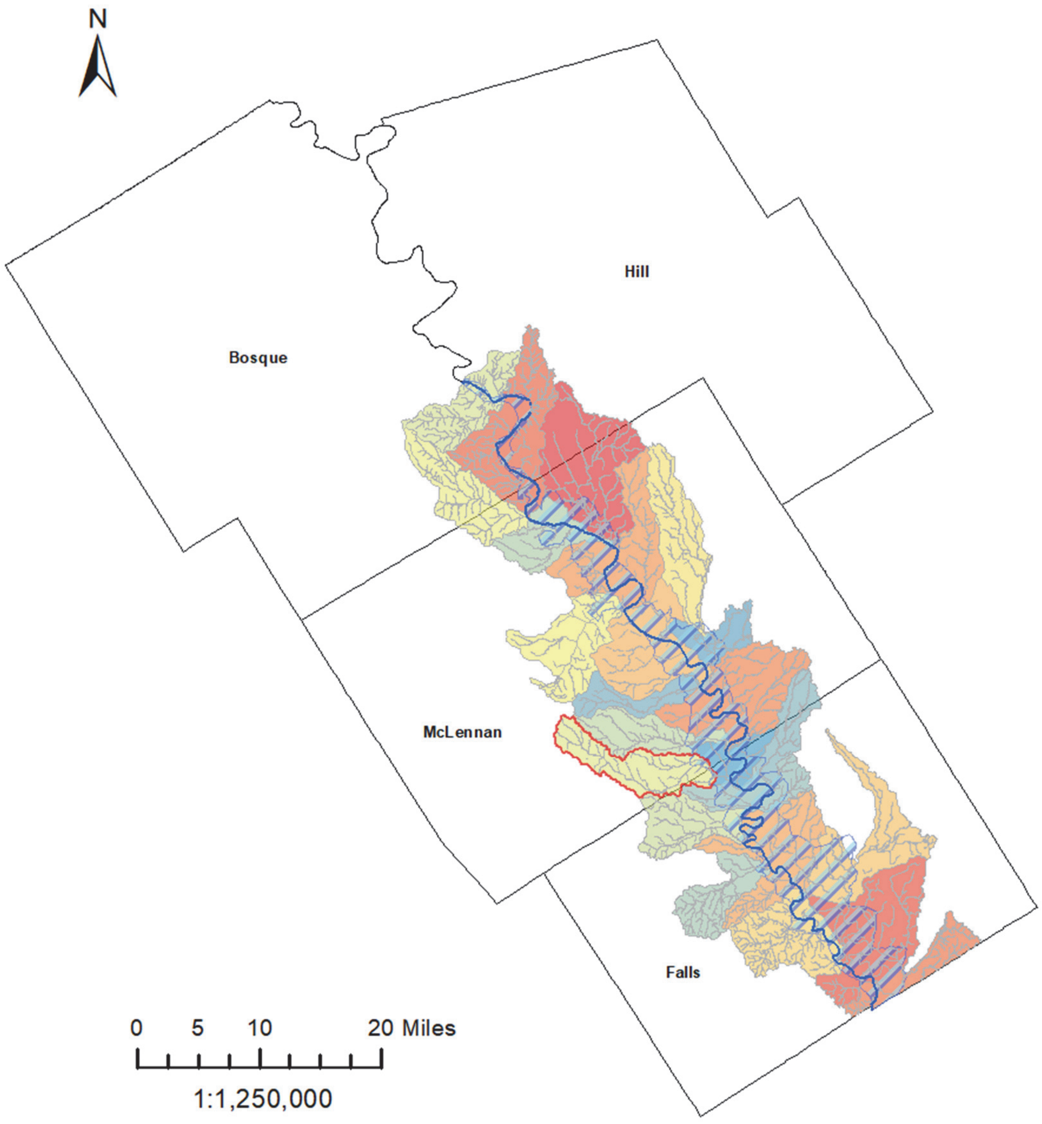

Figure 1.3. Map of the Brazos River tributaries (gray) and their watersheds in the northern segment and their proximity to the BRAA (blue hatch). Size of the watersheds is by color, where blue is the smallest category and red is the largest. The Bullhide Creek watershed is outlined in red.

Purpose and Objectives

The purpose of this study is to gain a better understanding of interactions between a tributary stream and the Brazos River Alluvium Aquifer. Although precipitation onto floodplain and alluvial terrace deposits is considered the primary source of recharge to the BRAA (Cronin and Wilson, 1967), contributions made by ungauged Brazos River tributaries have not yet been studied and may be significant. Bullhide Creek interacts with the Brazos River Alluvium Aquifer and receives constant flow from the Waco Metropolitan Area Regional Sewerage System Bullhide Creek Wastewater Treatment Plant (WMARSS BHC WWTP). Wastewater treatment systems that discharge into streams may affect the flow system and chemistry of the stream which can then affect hydrologically connected aquifers. Alluvial aquifers are especially sensitive to effluent-impacted systems due to their proximity to in-stream hydrologic conditions where wastewater derived constituents can easily be exchanged.

To improve the understanding of the baseflow dynamics of effluent-influenced Bullhide Creek and the Brazos River Alluvium Aquifer, three specific objectives were created for this project:

Objective 1: Investigate the point source contribution from the WMARSS Bullhide Creek Wastewater Treatment Plant to Bullhide Creek in quantity and quality. The flow augmentation of Bullhide Creek by effluent discharge modifies both the physical and chemical hydrologic characteristics. Coupled with the point source contribution of the WMARSS Bullhide Creek Plant and the downstream attenuation of its signature, the impact of the effluent on Bullhide Creek in baseflow conditions can be investigated.

Objective 2: Examine the interactions between Bullhide Creek and the Brazos River Alluvium Aquifer during baseflow conditions with emphasis on the bedrock-aquifer boundary. The movement of water between groundwater and surface water provides major pathways for chemical transfers; therefore, along with physical flow impacts from point source contributions to the stream, chemical constituents can be also used as tracers (Winter and others, 1998). Therefore, the interaction between Bullhide Creek and the BRAA was investigated in terms of physical and chemical exchanges between the two reservoirs to investigate the spatial and temporal interactions and the subsequent chemical exchanges.

Objective 3: Perform a spatially based precipitation-recharge analysis comparing direct infiltration into the floodplain versus peak flow events using a *Hydrologic and Water Quality System (HAWQS) Model and ArcGIS.* To quantify the potential recharge offered by tributary streams in comparison to direct inflitration on the floodplain alluvium, a HAWQS model will be created to simulate peak flows of Bullhide Creek where water may rise in the channel and lose to the adjacent aquifer sediments. Peak stream flows will be related to large precipitation events, where Weather Surveillance Radar – 88 Doppler (WSR-88D) data will be used to investigate four precipitation events from 2018 and the four related peak streamflow events simulated by HAWQS will be used to compare potential recharge from Bullhide Creek to that of direct floodplain infiltration.

CHAPTER TWO

Location and Setting

The focus of this study is the Bullhide Creek watershed and the connected portion of the Brazos River Alluvium Aquifer in McLennan and Falls Counties (Figures 1.3 and 2.1). The aquifer boundary within the Bullhide Creek watershed has not been well defined but is considered to be approximately 16 river miles downstream from its inception before FM 434. The BRAA is considered one of the 21 minor aquifers in Texas and covers approximately 216 square miles within McLennan and Falls Counties.

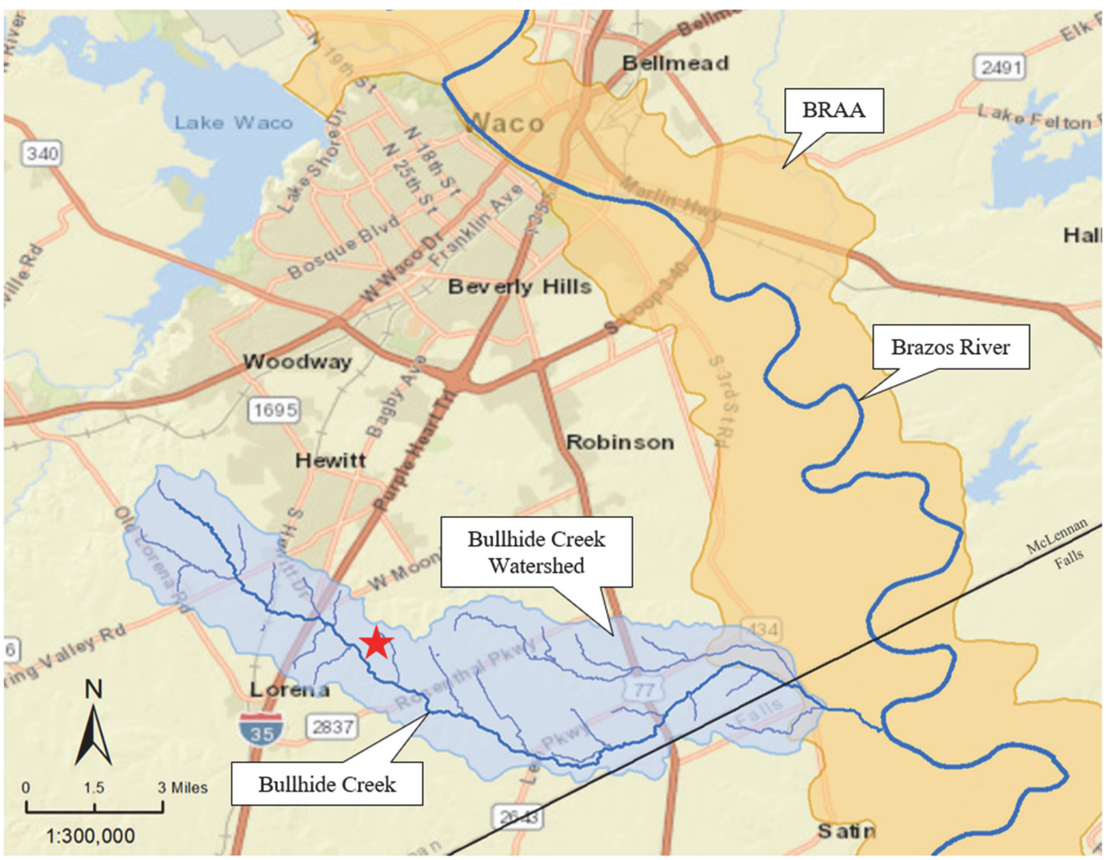

Figure 2.1. Map of the Bullhide Creek watershed (blue) and its proximity to the surrounding municipalities, BRAA (orange) and the Brazos River. The red star details the location of the WMARSS BHC WWTP.

Climate

Because Bullhide Creek is a lotic system and the Brazos River Alluvium Aquifer is a shallow water table aquifer, both systems are physically and chemically sensitive to weather and climate variations. McLennan and Falls counties lie within the subtropical-humid climate region, and the northernmost portion of McLennan county lies within the transitional zone between the subtropical subhumid and subtropical humid climates. Predominant onshore flow of tropical maritime air from the Gulf of Mexico causes the study area to be generally characterized by hot summers and dry winters (Larkin and Bomar, 1983).

Tropical maritime air masses dominate the study area from late spring to early fall and Polar air masses frequent the region in the winter. These systems cause extreme variations in temperature. The warmest month is August with a mean high of 96°F and the coldest month on average in January with a mean low of 35°F. Average annual precipitation is 36.4 inches in Waco, Texas from the period of record of 1991-2020 from the National Oceanic and Atmospheric Administration (NOAA) weather station at the Waco Regional Airport. The study area experiences seasonal variation in monthly rainfall. Spatial variation in precipitation also occurs due to most warm season rainfall occurring mostly during stratiform events and most winter precipitation being a result of frontal activity. On average, May is the wettest month and the period between July and August is considered the driest. Average rainfall totals for the months of May and July are approximately 5 inches and 2 inches, respectively (National Oceanic and Atmospheric Administration, 2021).

Geologic Setting

The geology of the study area includes three primary components: Cretaceous bedrock, terrace alluvium deposited by the paleo-Brazos River, and floodplain alluvium deposited by the modern Brazos River. Geologic maps, cross sections, and a stratigraphic column are located in Figures 2.2, 2.3, and 2.4 and Table 2.1.

Bedrock

The bedrock strata underlying the BRAA and Bullhide Creek watershed in this study include two Cretaceous-age bedrock units: the Austin Chalk and the Taylor Group (Figures 2.2 and 2.3). The Austin Chalk is comprised of interbedded massive chalk and thin-bedded marl with micro and macro fossils, primarily minor Foraminifera tests and Inoceramids (Stephenson, 1937). Thickness of the unit varies comparatively to changes in relative sea level throughout time and with lateral distance from the San Marcos Platform (Podell and others, 1993). The Taylor Group unconformably overlies the Austin Chalk is consisted of a blue-gray marly shale that locally contains sandy marl and some chalk (Barnes, 1970). Fossils were not observed in the Taylor Group in the study area, however the unit is known to contain ammonoids and Inoceramids in some areas (Beall, 1964). The Austin Chalk and Taylor Group trend northeast to southwest and dip gently southeast towards the Gulf of Mexico (Shah and others, 2007). They are highly fractured and faults present in the area are normal tension faults associated with the Balcones Fault Zone. Fractures allow water movement through the units where small quantities of water can contribute to streams and the BRAA in the study area (Figure 2.4).

Terrace Alluvium

The terrace alluvium consists of older Brazos River alluvial deposits that occur above the current floodplain elevation of the Brazos River. The terraces generally consist of a fining upward sequence of gravel, sand, silt, and clay that can be somewhat cemented in places (Cronin and Wilson, 1967). Thickness of the terraces can be as much as 75 feet but is generally thinnest in the northern section, and thickness decreases with depositional age (Epps, 1973). Older terrace deposits are often found as isolated bodies on hilltops or river-cut benches on the current floodplain and are typically laterally and hydraulically separate from the younger terrace deposits and floodplain alluvium (Ewing and others, 2016). Although these older terrace deposits can provide local amounts of water, their separation from the floodplain by outcropping bedrock or differential erosion keeps them from being considered part of the BRAA (Harlan, 1985). Younger terraces that are less dissected are, in places, laterally and hydraulically connected to the floodplain alluvium and may contribute small amounts of water through lateral flow (Cronin and Wilson, 1967; Pinkus, 1987). These terraces can be considered part of the aquifer, are relatively undissected by tributaries, have a better developed soil profile, and grade into the floodplain without a distinct scarp (Epps, 1973).

Floodplain Alluvium

The floodplain alluvium represents the water-bearing unit within the Brazos River Valley and refers to the alluvial deposits deposited by the ancestral Brazos River (Ewing and others, 2016). The alluvium is flanked by bedrock and older terrace deposits of the Brazos River and ranges in width from one mile to eight miles, causing the width and depth of the floodplain to be bedrock controlled (Figure 2.5). The northern section of the study area is considerably narrow as the aquifer primarily overlays carbonates, however moving southeast of Waco the width of the aquifer increases as the deposits overlay shales and marls (Rupp 1976). In general, the thickness of the BRAA increases towards the Gulf Coast (Shah and others, 2007).

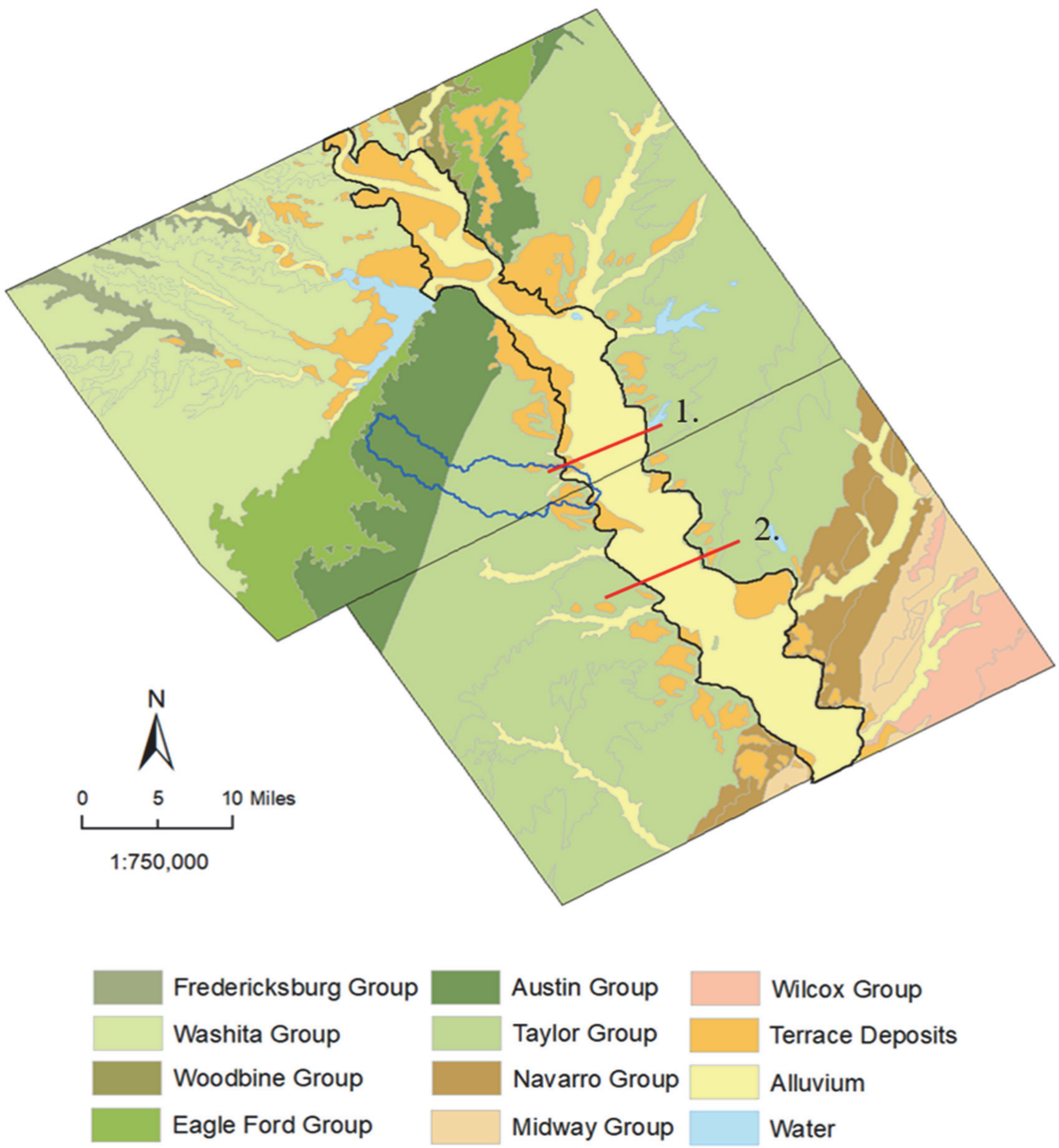

Figure 2.2. Map of surface geology of the northern segment. Bullhide Creek's watershed (blue outline) and the BRAA (black outline) are shown. Red lines (1. And 2.) indicate approximate location of cross sections in Figure 2.5.

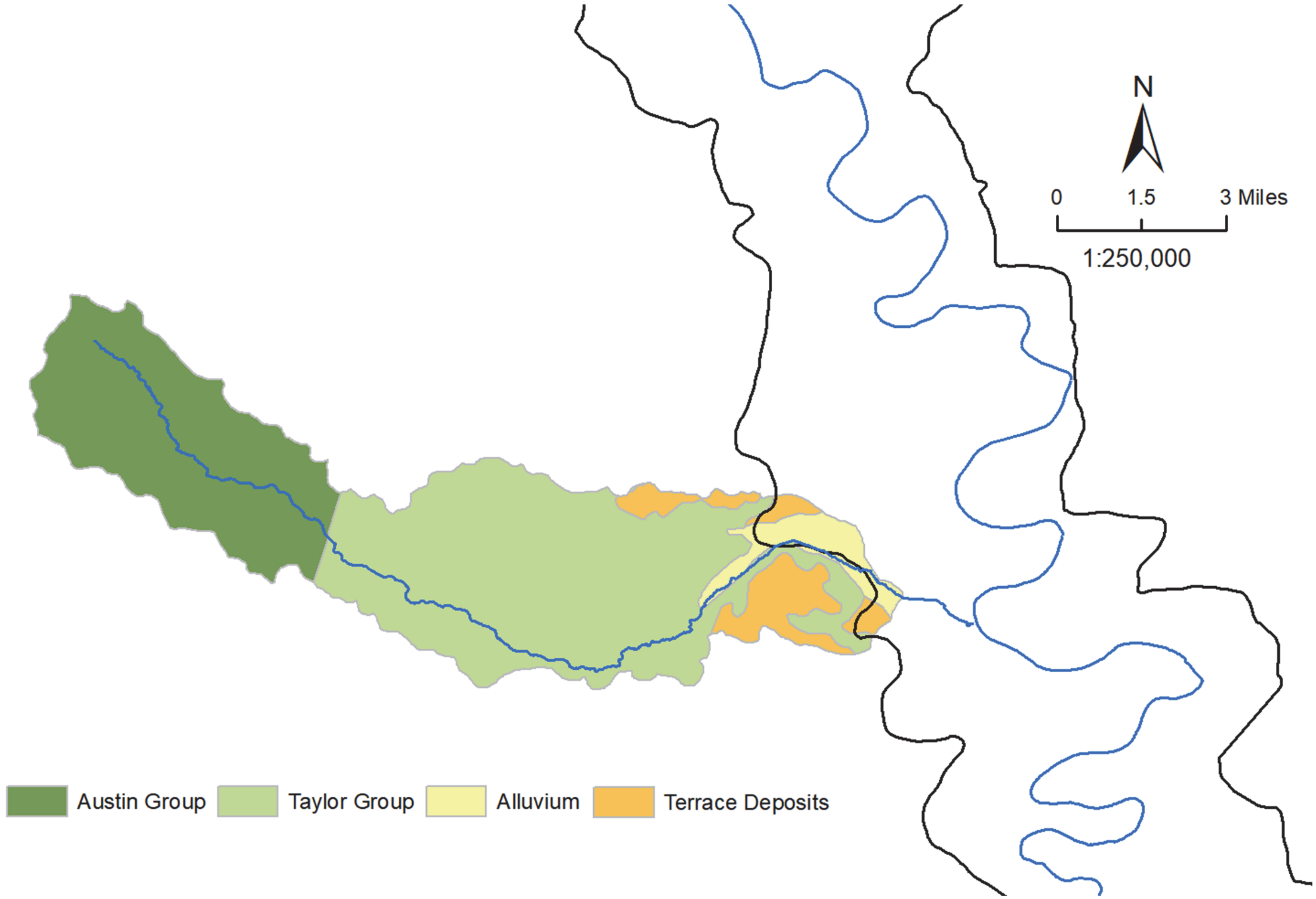

Figure 2.3. Surface geology map of the Bullhide Creek watershed and its proximity to the BRAA (black outline).

System	Series	Geologic Unit	Geologic Description [1]
Quaternary	Holocene	Alluvium	Floodplain and tributary alluvium, clay, sand, silt and gravel. Yields small to large quantities of water
	Pleistocene	Terrace Deposits	Clay, silt, sand, and gravel, somewhat cemented in places. Locally yields small quantities of water.
Tertiary	Eocene	Wilcox	Sand, clay, silt, and lignite. Yields small to large quantities of water.
	Paleocene	Midway	Glauconitic clay, silt, sandy clay, and sand. Yields small quantities of water
Cretaceous	Gulfian	Navarro	Sandy marl, clay, and some sand. Yields small quantities of water
		Taylor	Marl, clay, chalk, and sand. Locally yields small quantities of water.
		Austin	Chalky and marly limestone. Yields small quantities of water.
		Eagle Ford	Shale, sandy shale, and thin beds of sandstone and limestone. Not known to yield water to wells in study area.
		Woodbine	Sand, clay, silt. Yields small to large quantities of water. [2]
	Comanchean	Washita	Marl, clay, and limestone. Yields small quantities of water
		Fredericksburg	Limestone, marl, and clay. Yields small quantities of water.

[1] from Cronin and Wilson (1967) unless noted otherwise; small quantities of water refer to less than 100 gallons per minute, moderate quantities of water refer to 100 to 1,000 gallons per minute, and large quantities of water refers to greater than 1,000 gallons per minute.
[2] from Plummer and others (1931)

Figure 2.4. Stratigraphic column for the study area. Units within the Bullhide Creek watershed are outlined. (Modified from Ewing and others, 2016).

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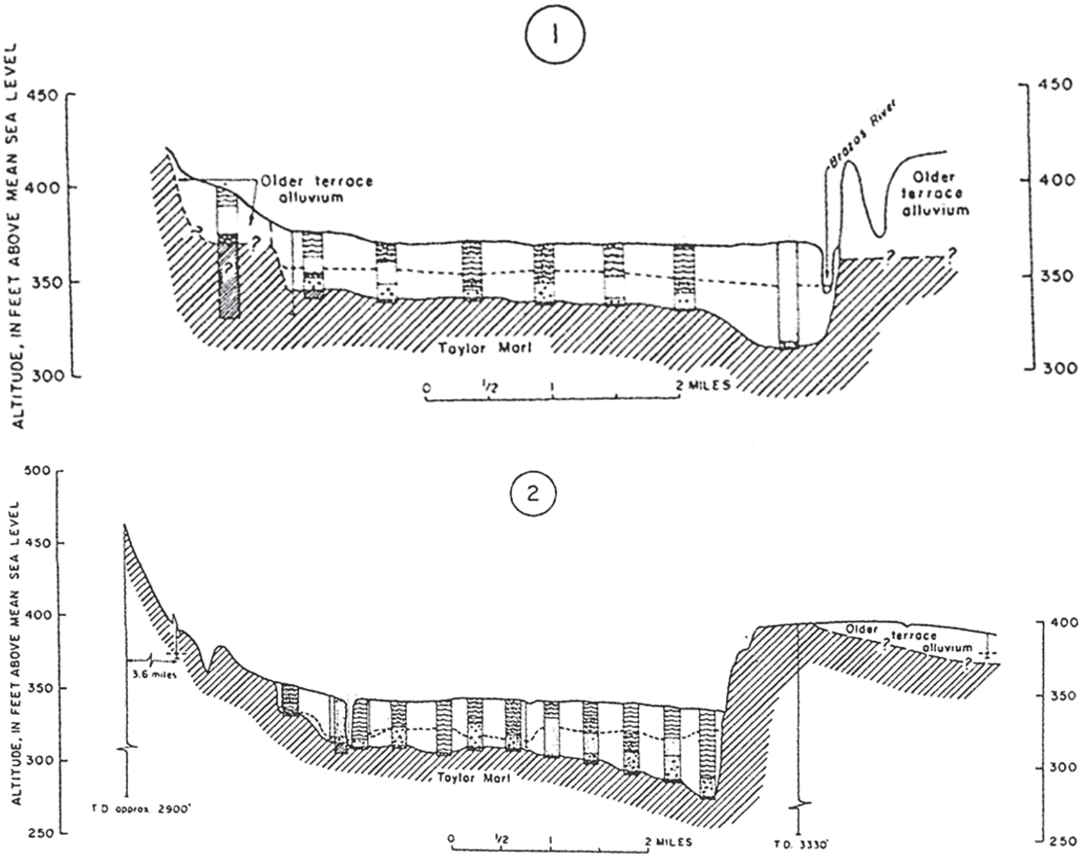


Figure 2.5. Cross sections of BRAA in McLennan County (1) and Falls County (2) (Adapted from Cronin and Wilson, 1967). Locations are given in Figure 2.2.

Early stages of alluvium deposition occurred due to a more competent Brazos River, where large amounts of gravels and sands were deposited, creating the most hydraulically conductive portion of the aquifer (Epps, 1973). Deposition of buff to red siliceous gravels, sandy silts, and clays occurred in the late Pleistocene uncomfortably over bedrock and are comprised of several stacked fluvial sequences (Waters and Nordt, 1995). Due to the fluvial nature of the sediments, they can be extremely heterogeneous both laterally and vertically with individual beds or lenses of sand and gravel truncating into finer or coarser material, though a general fining upwards trend is observed throughout the aquifer (Cronin and Wilson 1967). Gravels were deposited in association with in-stream processes of the river and finer sediments were lain during periods of overbank flow. Clay is common in the upper portion of the aquifer and can create local confining conditions (Shah and others, 2007). Clay lenses can be found to be approximately 12 to 16 feet below the surface and are followed by very fine sand and then silt.

Hydrogeologic Setting

The BRAA is classified as one of the 22 minor aquifers in the State of Texas. It lies in central Texas under water table conditions although locally confined, artesian conditions may exist in areas where clay lenses overlie lenses of sand or gravel (Ewing and others, 2016). Hydrogeologic characteristics such as recharge, hydraulic conductivity, transmissivity, groundwater flow, and discharge vary spatially due to the heterogeneity of aquifer material. Cronin and Wilson (1967) described the aquifer material as poorly sorted by exhibiting a general fining-upwards sequence with existing lenses of clay and silt. The capacity of the aquifer to yield water for appreciable use depends upon the coefficients of permeability, transmissivity, and storage. Table 2.1 highlights the variability in aquifer properties of the BRAA from field and laboratory experiments.

Groundwater flow in the BRAA is primarily influenced by the elevation of the Brazos River but may also be influenced by the topography of the underlying bedrock surface. The Brazos River acts as a discharge point through seepage and springs. Groundwater flow is generally towards the river and slightly down-valley (Harlan, 1985). Pinkus (1987) also found that high stream stage of the Brazos River, tributary dissection,

Table 2.1. Hydrogeologic characteristics of the BRAA. Cronin and Wilson (1967) data were determined by several laboratory methods. Shah and others (2007) data were determined by seven wells (Modified from Ju, 2014).

Aquifer Properties	Cronin and Wilson, 1967	Shah and others, 2007
Hydraulic Conductivity (cm/s)	4.7×10^{-8} - 8.5×10^{-2}	6.3x10-2 - 1.6×10^{-1}
Specific Capacity ([gal/min]/ft)	6 - 134	2.14 - 134
Transmissivity (ft^2/day)	6,684 - 40,104	289 - 27,800
Porosity (%)	24.7 - 59.5	-

or low permeability obstructions such as clay liners or low transmissivity zones may cause deviations in flow paths within the aquifer. Jarvis (2019) found groundwater flow paths in the northern segment to also be constrained through compartmentalized discrete flow systems due to bedrock and river boundaries.

Groundwater is discharged from the aquifer through wells, evapotranspiration and gravel pits that intersect the water table (Cronin and Wilson, 1967; Ashworth and Hopkins, 1995). Cronin and Wilson (1967) found that in a 56.4-mile study area of the Brazos River between the Falls-Robertson county line and Bryan, Texas, the aquifer was estimated to provide about 0.3 cfs per mile to streamflow. Records of streamflow suggest it might be greater between Waco and Bryan, roughly 0.56 cfs per mile during December of 1951 to January 1952.These values presumably not only reflect contributions from the BRAA, but also from effluent from sewage treatment plants and ungauged tributary inflow (Cronin and Wilson, 1967).

Primary recharge to the BRAA is through direct precipitation over the Brazos River floodplain. Recharge rates to the aquifer are affected by the magnitude of precipitation, superimposing soil type and antecedent moisture, and land use. On average, 10% of annual precipitation infiltrates and provides recharge (Cronin and Wilson, 1967).

Other potential sources of recharge consist of natural or induced infiltration from streams, underflow from terraces, vertical and lateral from adjoining bedrock, infiltration from surface irrigation, and inundation of the floodplain by flood waters. These potential sources are local and limited to small areas; therefore, the recharge potential from these sources has not been widely estimated.

Hydrologic Setting

The location of this study is primarily within Bullhide Creek's watershed. Bullhide Creek is a third order perennial stream at its confluence with the Brazos River and has a watershed of approximately 36 square miles. Bullhide Creek begins about three miles south of Woodway, Texas in McLennan County and flows southeast for 19 miles to its mouth on the Brazos River in Falls County (Figure 2.1). The creek crosses three major geologic units, the Austin Chalk, Taylor Group, and Brazos River Alluvium (Figure 2.3). It is a generally gaining stream due to fracture flow discharges from the bedrock into the channel. Little is known regarding Bullhide Creek's interactions with the BRAA; however, a previous mini-piezometer study completed in the fall of 2020 indicated that Bullhide Creek primarily gains from the BRAA but may lose water to the aquifer in times of high flow events or during very dry periods (Appendix A).

Bullhide Creek has a slope of approximately 0.004 with a headwater elevation of 710 feet above sea level to 350 feet at the Brazos River. The creek crosses flat to rolling prairie with locally steep slopes and is flanked by Blackland Prairie soils typically comprised of dark-colored alkaline clays that are interspersed with gray sandy loams (Texas Park and Wildlife, 2010). Juniper, oak, mesquite and grasses are supported by the rich soil in the upper and middle reaches and hardwoods and conifers are present in the lower reach (Texas State Historical Association, 1999). Bullhide Creek is an urban-fringe stream where about 9% of its watershed area is covered by urban development. The other 91% is comprised of agricultural fields and rangeland that are supported by the alluvium as well as the Blackland Prairie (Figure 2.6).

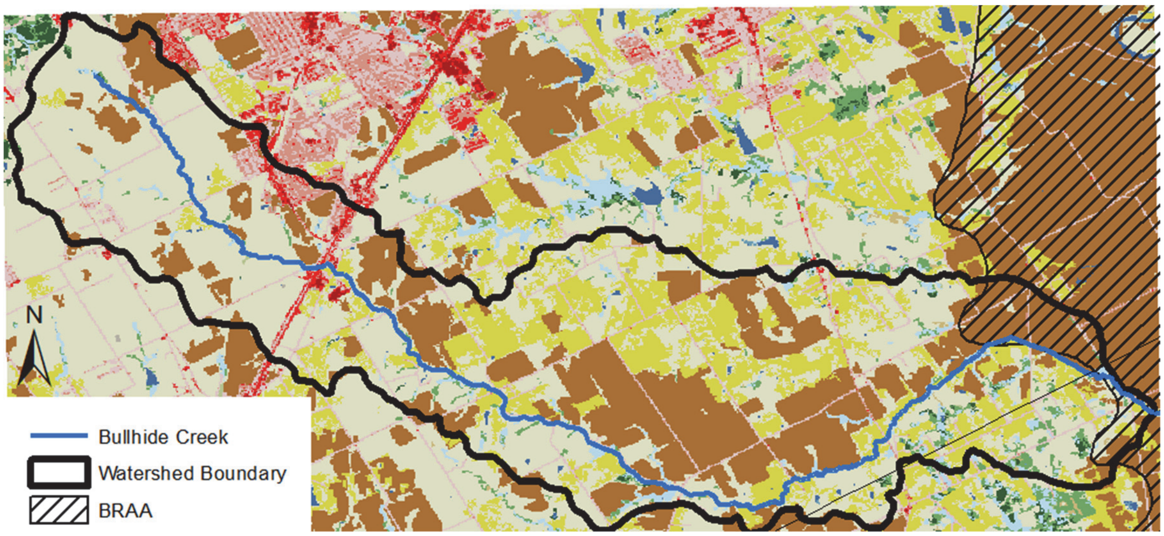


Figure 2.6. Map of land cover in the Bullhide Creek watershed (black outline), where red colors indicate developed land and yellow to brown colors indicate crop and rangeland. The BRAA is represented by the crosshatching; note the agricultural use present within the boundary.

Approximately six miles from Bullhide Creek's start, the Waco Metropolitan Area Regional Sewerage System Bullhide Creek Wastewater Treatment Plant (WMARSS BHC WWTP) in Lorena, Texas, discharges wetland-filtered effluent into the stream (Figure 2.7). The wastewater treatment plant began operation in 2012 after the cities of Lorena and Hewitt, Texas, experienced rapid growth. In effort to conserve developable land, reduce costs, outsource management, and expand treatment capacity, the cities joined a wastewater consortium established by the City of Waco known as WMARSS (Kultgen, 2013). The facility treats an average of 1.5 million gallons per day (MGD). Sewage is broken down by bacteria, and ultraviolet light is used to disinfect the effluent before it is discharged into the 7-acre wetland and pond feature. Sludge is not treated at the facility and is transported to the main WMARSS treatment plant on the Brazos River. The plant's current Texas Pollutant Discharge Elimination system (TPDS) effluent discharge permit issued by the Texas Commission on Environmental Quality (TCEQ) contains a daily average phosphorus limit of 1.0 mg/L and CBOD/TSS/NH_3N limits of 7/15/3 mg/L, respectively. Further limits and operation requirements are described in Appendix B.

From the wetland feature, eight effluent outflows were present during this study (Figure 2.8). As effluent is discharged into the wetlands, water is stored and then discharged to Bullhide Creek through channels that traverse a field before reaching the northern edge of the Bullhide Creek floodplain escarpment. Some of the outflows discharge considerable flow and have eroded into the bedrock on the northern escarpment, and others are characterized by immeasurable small flows. A beaver pond is present between the wetland and the creek, where the ponded outflows may undergo further nutrient absorption and reduction. Small springs are present in an approximate 10-foot section in the cut bank opposite from the effluent outflows (Figure 2.9). The groundwater appears to flow through fractures in the Taylor Group and contributes a small amount of flow to the creek at this location.

Ten miles downstream from the WMARSS BHC WWTP, Bullhide Creek interacts with the BRAA until its union with the Brazos River two miles farther. Bullhide Creek is considered a gaining stream where groundwater baseflow is provided by

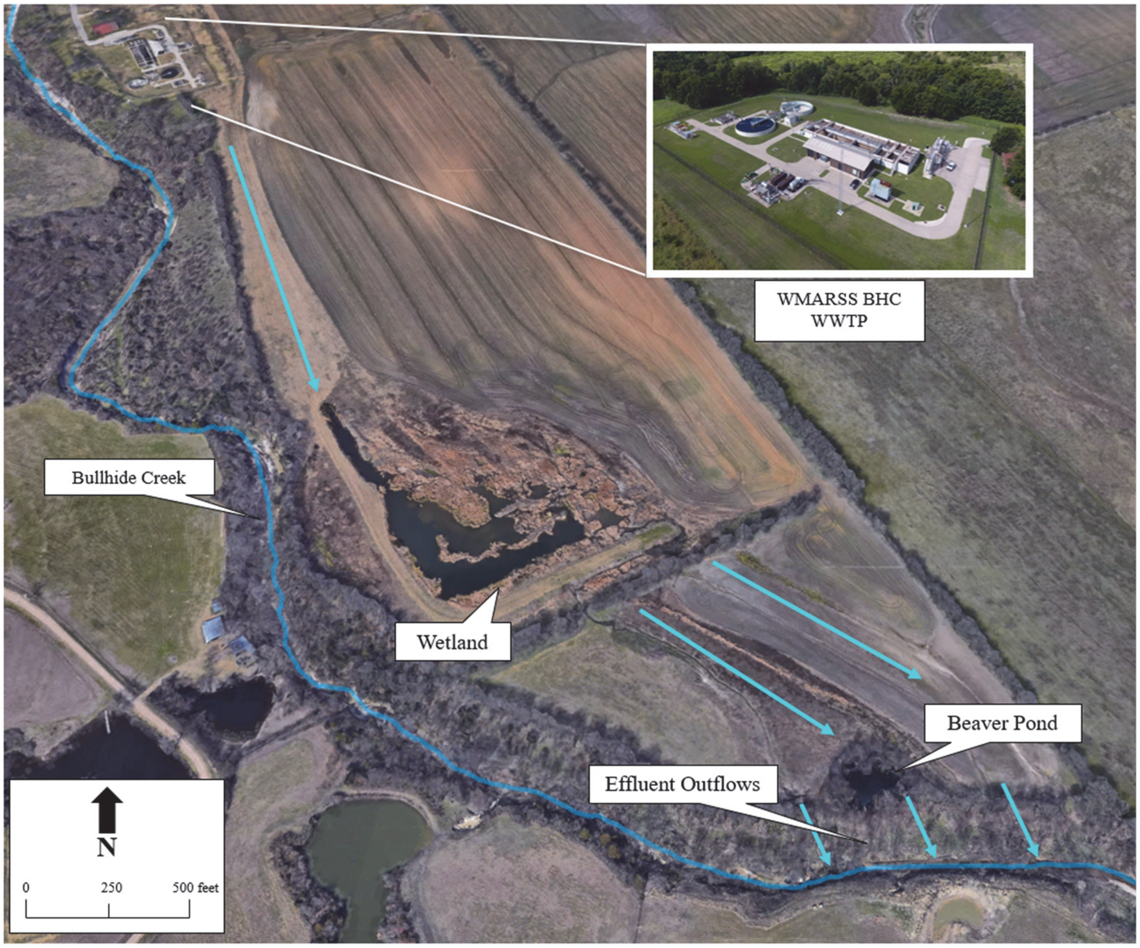


Figure 2.7. Aerial image of the WMARSS BHC WWTP and its proximity to Bullhide Creek, the wetland, and a beaver pond created by dammed effluent outflows. Blue arrows indicate flow direction. Image of WWTP adapted from WMARSS, 2013.

discharge from bedrock units upstream, however the interactions between the creek and BRAA have not been studied. Mini-piezometers were placed at two locations in the stream, the first in close proximity to the bedrock-aquifer boundary at FM 434 and the second was placed between the boundary and the Brazos River at the Arcosa Property. The mini-piezometers were measured from June 2020 to November 2020. They indicated Bullhide Creek consistently gained from the BRAA except on 10/20/2020 and 11/20/2020, where losing conditions were indicated by the piezometers (Figure 2.10). Seasonal trends may affect behavior, however gaining conditions observed during this period appeared to be well correlated with large precipitation events (>1 inch), where precipitation may infiltrate into the aquifer, raise the water table, and discharge into the creek.

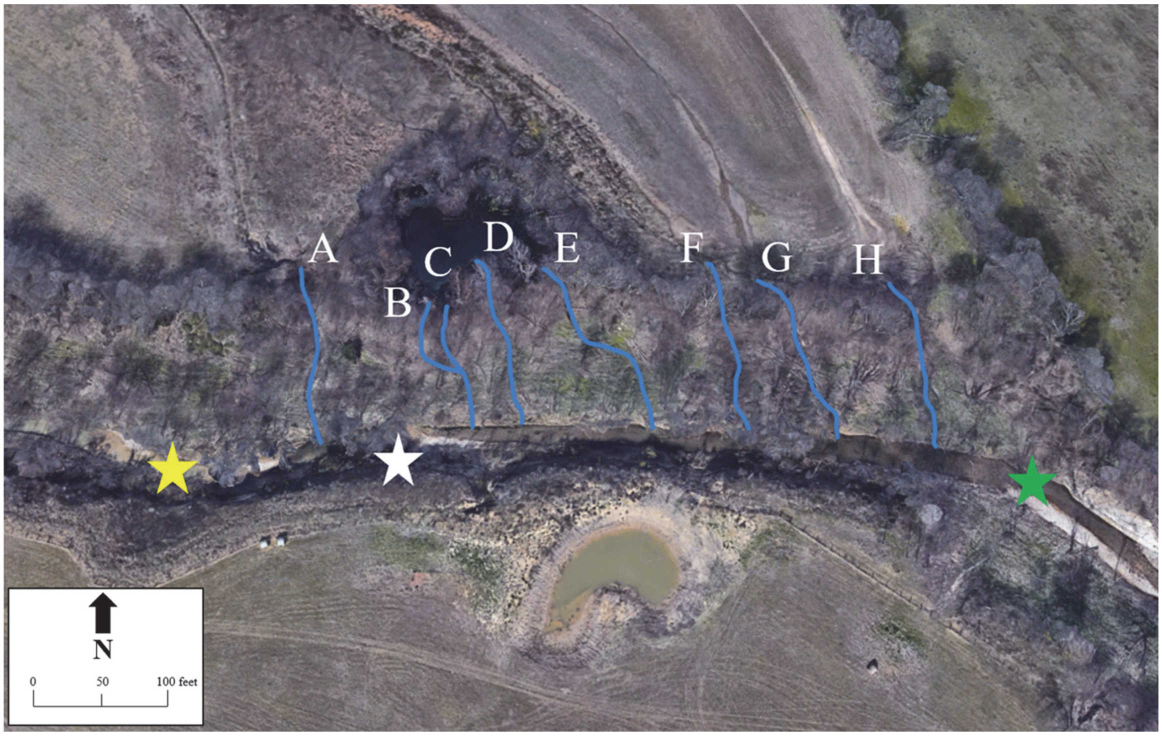


Figure 2.8. Aerial image of the approximate locations of the effluent outflows from the WMARSS BHC WWTP wetland. Outflows B-E fill and then flow out of a beaver pond that has dammed the flows. Adjacent upstream (yellow star) and downstream (green star) areas of the creek from the outflows are shown along with springs that discharge from bedrock outcrop on the opposite bank from outflows (white star).

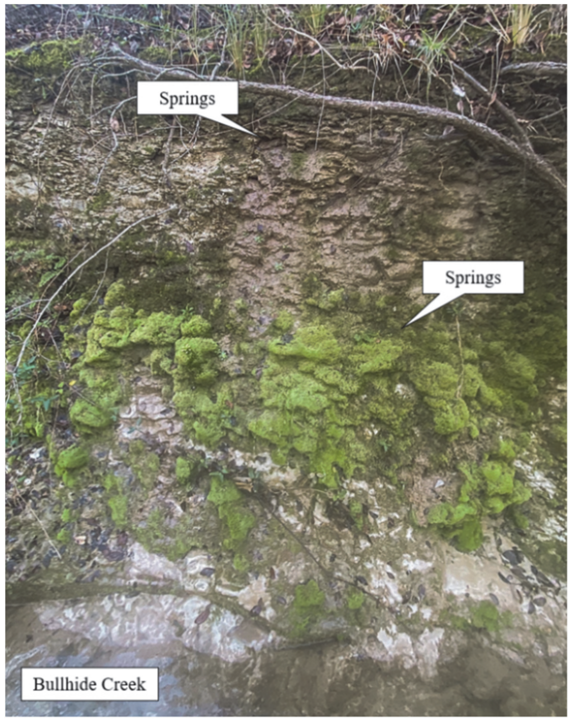


Figure 2.9. Image of springs flowing out of the Taylor Group on the southern bank of Bullhide Creek, opposite from the effluent outflows.

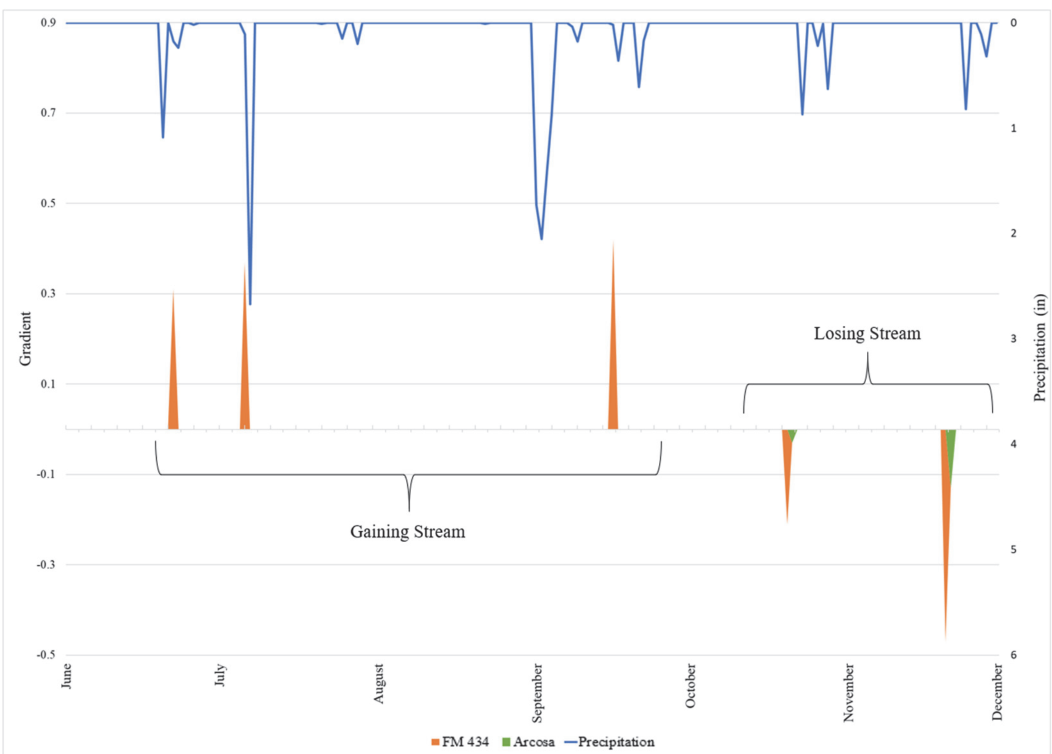


Figure 2.10. Graph of groundwater gradient provided by mini-piezometers at Bullhide Creek in relation to local daily precipitation from June 2020 to December 2020.

CHAPTER THREE

Methods

The following methods were employed to characterize the effects of the constant effluent discharge to Bullhide Creek and determine the spatial and temporal interactions between the creek and the Brazos River Alluvium Aquifer under baseflow conditions: 1) measuring streamflow variations in Bullhide Creek, 2) chemical analysis of water samples collected from points along Bullhide Creek for common ions, nutrients, and isotopes, 3) physical modeling using a HAWQS model to simulate streamflow and target high flow events, 4) precipitation and streamflow recharge analysis for high flow events using WSR-88D data and ArcGIS.

For this study, seven locations along the creek were included (Figure 3.1). Cooksey Lane was used as the upstream "control" location as this is the only site at which neither the BRAA nor the WMARSS BHC WWTP influence the stream. The Reyna site was accessed when permitted to investigate the effects of the WMARSS BHC WWTP, where the effluent outflows were measured and compared to the immediately adjacent upstream and downstream locations (Figure 2.8). Rosenthal Parkway, Levi Parkway, and Highway 77 were used to observe the downstream effects of the WWTP. The FM 434 site was chosen to observe the interactions between Bullhide Creek and the BRAA at the bedrock-alluvium boundary and the Arcosa property, accessed through permission with Arcosa, Inc in Falls County, Texas, was utilized to observe the downstream behavior between the creek and aquifer.

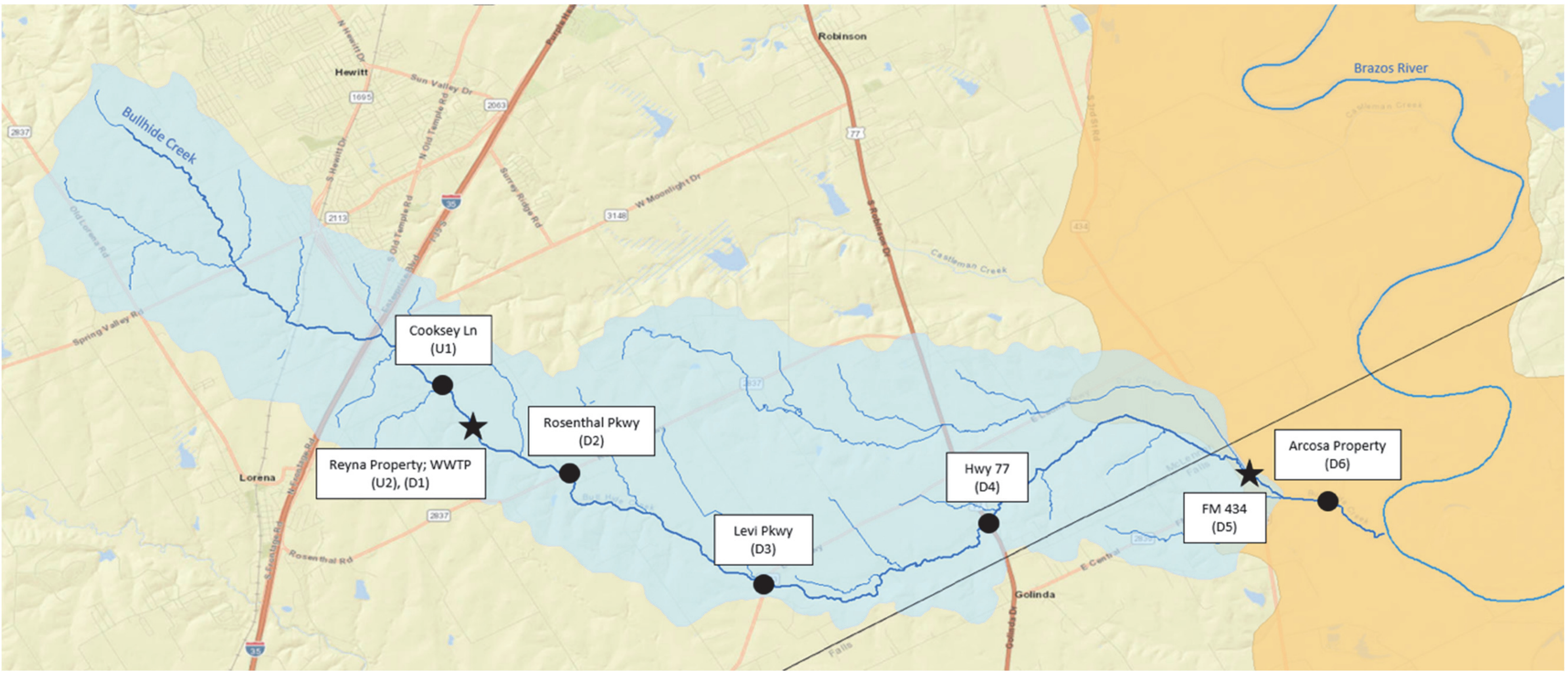


Figure 3.1. Map of the seven sample points along Bullhide Creek used for this study. Locations of particular interest (WWTP, BRAA) are shown as stars. For this study, Cooksey to Rosenthal is considered the "upper reach," Rosenthal to Hwy 77 is the "middle reach" and Hwy 77 to the river is referenced as the "lower reach."

Measuring Channel Flow of Bullhide Creek

The first step in this study was to define baseflow conditions of Bullhide Creek and its main point source contributors, the WMARSS BHC WWTP and the BRAA. The OTT MF Pro (OTT HydroMet) flow meter was used to calculate in-stream velocities at each sample point. It uses electromagnetic current through an inductive probe which is well suited for shallow channels and turbulent conditions, common in Bullhide Creek. Velocity measurements were taken at 1-foot intervals and approximately 0.6 depth along a cross section at each sample point. The measurements were then multiplied by the respective depth of the streambed and width of the measurement section and then totaled to calculate overall streamflow at each of the locations. Detailed measurement procedures can be found in appendix C.

Streamflow measurements at the seven Bullhide Creek locations and at two of the effluent outflows were taken on 1/28/21. Two streamflow measurements were taken at the Reyna location surrounding the outflows to gain better insight on the contribution they provide. Because of errors in measurements, the seeps were remeasured on 3/5/21. Each of the eight outflows and subsequent upstream and downstream stream sections were measured using the OTT MF Pro. The outflows were measured once in each channel because many of the channels were a foot or less in diameter and usually just a few inches deep with relatively steep slopes.

Bullhide Creek Water Analysis

To characterize the spatial variabilities of the chemical characteristics of Bullhide Creek resulting from different inputs, water samples were collected at each of the seven sample points along the creek and at one of the effluent outflows. Two sets of samples were collected, one on 1/28/21 and the other on 3/21/21 by filling sterile, unopened vials with water. Duplicate samples, trip blanks, and field blanks were utilized to check lab precision and ensure contamination of the samples during collection did not occur. Detailed sampling procedures can be found in appendix D.

Water samples from both dates were sent to the Center for Reservoir and Aquatic Systems Research (CRASR) laboratory at Baylor University to be analyzed for dissolved nitrogen (cadmium reduction-sulfanilamide method), phosphorus (ascorbic acid-molybdate method) and ammonia (phenolate method). The samples from both dates were also sent to the Baylor University Department of Geoscience's Stable Isotope Lab to be analyzed for deuterium and oxygen-18 isotopes. The samples were analyzed using a gas source isotope ratio mass spectrometer and all values were reported as per mil difference from the Vienna Standard Mean Ocean Water (VSMOW).

Samples collected on 3/21/21 were also sent to the BIO CHEM Lab in West, Texas, to be analyzed for major dissolved cations and anions. Samples to be analyzed for cations were acidized with nitric acid and were analyzed using an inductivity coupled plasma mass spectrometer (ICPMS). Water samples to be measured for anions were not acidized and were analyzed using ion chromatography (IC). Titrations using sulfuric acid were also performed on the samples in the Baylor Hydrogeology Lab after sampling to determine the bicarbonate concentrations in the water. Detailed lab procedures can be found in appendix D.

Specific conductance, temperature, dissolved oxygen (DO), and pH were measured in the field using the YSI Pro DSS on two dates, 3/5/21 with focus on the WWTP outflows and on 3/21/21, where each sample point along Bullhide Creek was measured except for the effluent outflows and creek at the Reyna property because access to the property was not available. Each of the eight outflows were able to be investigated except for outflow “E” because the negligible flow was unable to be analyzed by the meter. Temporal and seasonal differences are not captured in these data sets due to access limitations, however spatial variabilities along the reach are able to be observed and should generally pertain to Bullhide Creek under baseflow conditions.

Framework of HAWQS and Watershed Modeling

To gain insight on streamflow conditions in Bullhide Creek with a particular interest in stormflow events, a HAWQS model was created to simulate streamflow (Figure 3.2). HAWQS is a web-based modeling interface that utilizes the physics-based Soil and Water Assessment Tool (SWAT) 2012 rev. 636 model to predict hydrologic responses to changes in climate, land use, and land management practices (HAWQS, 2020; Neitsch and others, 2011). Inputs are pre-compiled by the HAWQS interface from open-source national databases: National Elevation Data (NED), USDA State Soil Geographic (STATSGO), and the USGS National Landcover Database (NLCD). Weather data such as precipitation, temperature, and wind speed are compiled from the National Centers for Environmental Information (NCEI) NOAA database collected from stations in the target area. Because the HAWQS interface compiles updated, dynamic inputs to the model, a preliminarily calibrated SWAT model is automatically generated through the web-based decision support tools (DSS) (Yen and others, 2016).

The Bullhide Creek watershed is a HUC12 watershed. It is encompassed by one subbasin that was divided into 20 hydrologic response units (HRUs) with a total area of 0.38 square miles (93.49 km^2). HRUs with an area less than 1.0% of the total subbasin were eliminated and the subsequent land use distributions are shown in Figure 3.3. After thresholds were applied, five soil types are present in the watershed: Austin (51%), Houston Black (45%), Ships (3%), and Silawa (1%) and the entire watershed falls in the 0-1 slope class (0%-8% slope). Detailed HRU classifications can be found in appendix E.

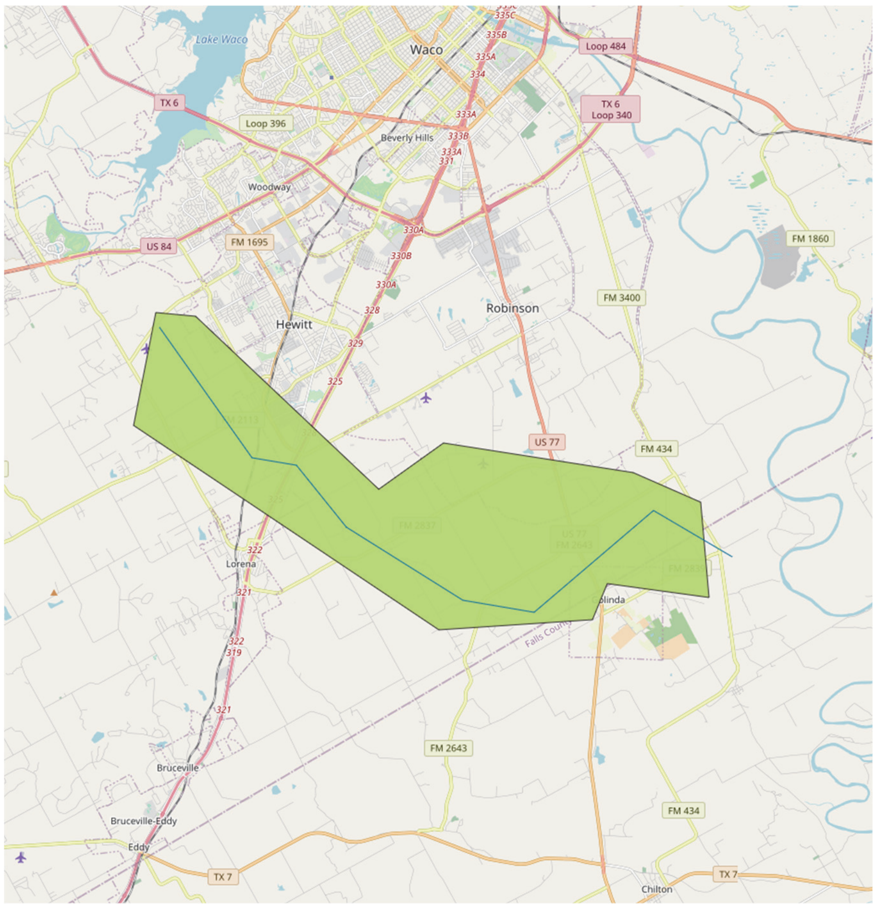


Figure 3.2. The HUC-12 Bullhide Creek watershed simulated by HAWQS.

The simulated period was 1/1/2012 to 12/31/2018 with a warmup period of two years (2012-2014). This period was chosen to simulate the watershed in current conditions and given that the discharge provided by the WMARSS BHC WWTP originated in 2012. A daily time step was chosen for the model to receive the best resolution to investigate peak streamflow from high precipitation events. Effluent discharge rates were added to the model so that the simulated system better represents

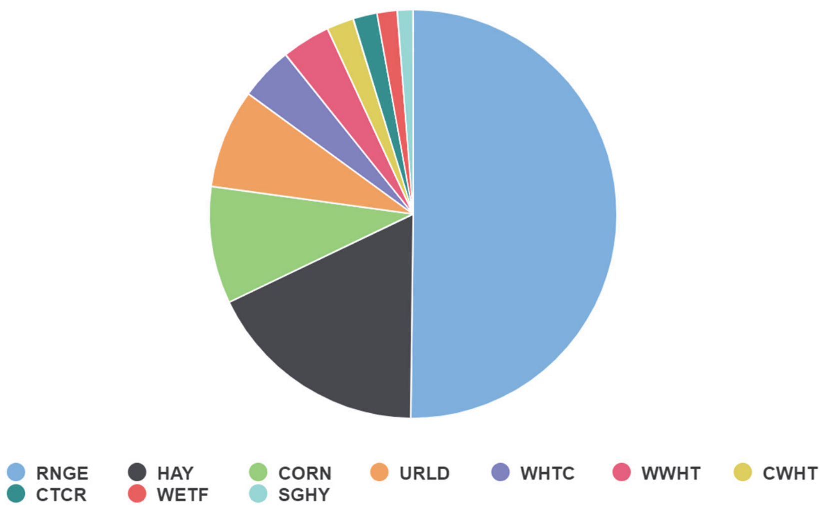


Figure 3.3. Land use distribution (by percent area) of the Bullhide Creek watershed with thresholds applied. Land use code explanation can be found in appendix F.

total flow in Bullhide Creek. Data were provided in monthly averages by the City of Waco Water Utilities Services (CWWUS) for the 2014-2018 period. Monthly effluent discharges used as a point source to the model can be found in appendix G.

The model created for this study was not manually calibrated. As Bullhide Creek is an ungauged tributary, there were no streamflow data to use for calibration. SWAT is known to provide satisfactory predictions on hydrologic budgets, especially baseflow, without calibration because of the dynamic input datasets and process-based, mass balance approach it utilizes (Moriasi and others, 2007; Srinivasan and others, 2010). Several studies conducted by Fuka and others (2013) and Tram and others (2014) determined that HAWQS simulated ungauged streams and received satisfactory simulated flows for the watersheds. Last, an uncertainty analysis, such as PEST, was not performed on the model as the web-based interface would require an incredibly complex source code and because only an average annual number of peak flow events was desired, it was not necessary for this study.

Spatial Precipitation Analysis

To gain an understanding of the recharge potential of Bullhide Creek to the Brazos River Alluvium Aquifer and compare it to aerial recharge, peak streamflow events simulated by SWAT were chosen to compare recharge through the channel to the precipitation that induced the peak flows and may have recharged the adjacent floodplain. First, ArcGIS was used to determine the aerial recharge provided to the BRAA. Precipitation data for the events were obtained from the National Weather Service (NWS) River Forecast Centers (RFCs). These data are quality-controlled, multi-sensor (radar and rain gauge) precipitation estimates that are mosaicked by the National Centers for Environmental Prediction (NCEP). Raster images containing precipitation values were downloaded for each day that provided precipitation to the peak streamflow events. They were then clipped to the counties surrounding McLennan and Falls counties to have a wide extent for further analysis (Figure 3.4). The clipped raster images were mosaicking using the “sum” function to add the daily precipitation value in each overlapping cell to a new raster that would represent the total precipitation that occurred for each event. Next, the raster values were extracted to point data using the WSR-88D grid points assigned in each cell. The precipitation values of each point were used to interpolate a smooth raster image that represented the total precipitation using spline functions, in which points with known values are connected by smooth lines that pass exactly through known point values. Spline was chosen because the data were distributed at equal distances from each other and an interpolation method was not desired for interpolating unknown surfaces away from the study data.

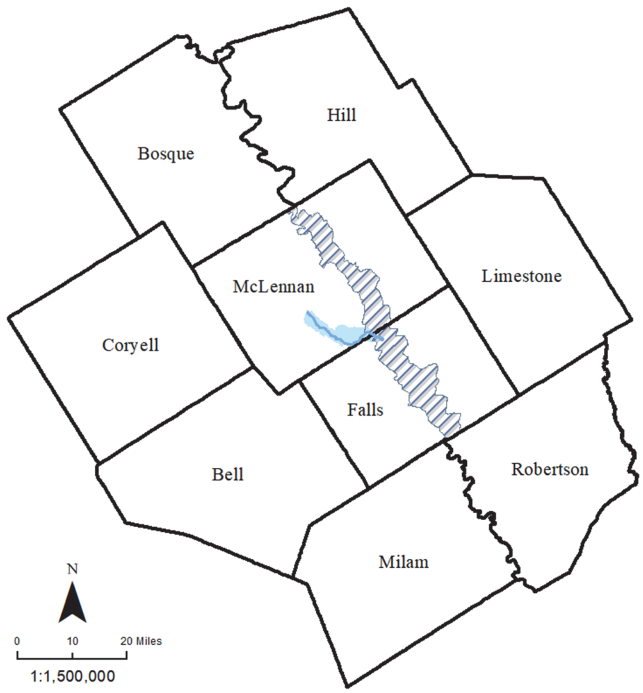


Figure 3.4. Map of counties used for the ArcGIS precipitation analysis in relation to the BRAA (cross hatches) and Bullhide Creek Watershed (blue).

The recharge to the floodplain alluvium offered by the individual precipitation events was calculated according to recharge estimates by Chowder and others (2010) and Cronin and Wilson (1967). Recharge estimates for the BRAA have not been widely studied and heterogeneity of aquifer sediments makes extrapolation of recharge estimations difficult. Cronin and Wilson (1967) first estimated recharge in the BRAA using the method described by Keech and Dreeszen (1959) where differences in estimated flow in upstream and downstream sections of the aquifer was attributed to recharge. Using this method, they determined recharge to the aquifer to be about 10% of annual precipitation. However, using multiple digital base flow separations and chloride mass balance techniques, Chowdhury and others (2010) determined the average recharge (inches per year) of the BRAA to be approximately 2% of the total precipitation. For this study, both the 2% and 10% recharge estimates were used to compare to Bullhide Creek potential recharge.

Although Bullhide Creek primarily gains from the BRAA under baseflow conditions, water in the channels of streams may rise or even inundate the surrounding sediments during periods of high flow. When this happens, surface water may seep into the adjacent alluvial aquifer and provide recharge. To estimate the recharge offered by Bullhide Creek during periods of high flow, the Darcy equation is used to determine possible infiltration of surface water into the surrounding sediments. It is thought that the channel does not frequently inundate the topsoil and stays in its channel, so for these calculations the seepage through the channel bank and bed during losing conditions was investigated. The area of Bullhide Creek that could lose into the aquifer is divided into two sections: the bank and the channel bed. The area of the bed was calculated using the average width of the channel and total stream length of Bullhide Creek from the aquifer boundary to the Brazos River. The area of the bank was found by multiplying the length of the stream by the water elevation during high flow events. This was estimated to be approximately 3 feet based on observations taken during several high flow events at Bullhide Creek and understanding the depth varied throughout the event. The area of the channel bed and banks of Bullhide Creek were calculated to be 79,200ft^2 and 31,680ft^2, respectively.

The hydraulic conductivity of the sediments within Bullhide Creek was based on measurements taken in Sandy Creek in Falls County. The channel sediments in Sandy

Creek are comparatively similar to that in Bullhide Creek, where coarser gravels are present on the surface and smaller gravels, coarse sand, and some silt make up the sediment below the channel (Figure 3.5). The hydraulic conductivity of the sediments was measured on 8/20/2020 using the Guelph Permeameter and produced a 35.2 feet per day hydraulic conductivity value to being used for these calculations. The gradient of the water infiltrating the sediments during high flow events is 0.3 for this study. This value was obtained by considering the mini-piezometer study concluded in the fall of 2020, where the gradient of the gaining sections was typically about 0.15 and given the rapid rise in water and head in the opposite direction, a gradient of 0.3 was estimated. The gradient, hydraulic conductivity, and areas were then summed to estimate the recharge potential of Bullhide Creek under high flow storm conditions.

Figure 3.5. Image of channel sediments at Sandy Creek analyzed by the Guelph Permeameter. Sediments in this creek are consistent with channel and bank sediments found along Bullhide Creek after the alluvium boundary.

CHAPTER FOUR

Results and Discussion

Channel Flow of Bullhide Creek

The first step to understanding the baseflow conditions of Bullhide Creek is to characterize stream flow and its contributors in these settings. The seven sample locations were measured on 1/28/21 along with two of the effluent outflows. Bullhide Creek had a baseflow velocity of approximately eight cubic feet per second (cfs) that was provided by fracture flow discharge from the Austin Chalk and had a final velocity of roughly 16 cfs at Arcosa, near the Brazos River (Table 4.1). A 112% increase in total streamflow was observed in the studied portion of Bullhide Creek from Cooksey Lane to Arcosa.

Table 4.1. Streamflow measurements taken on 1/28/2021 with the OTT MF Pro velocity meter.

ID	Location	flow (cfs)
U1	Cooksey	7.8
U2	Reyna, upstream	8.2
G	"small" outflow	0.4
A	"large" outflow	1.6
D1	Reyna, downstream	10.9
D2	Rosenthal	11.1
D3	Levi Pkwy	14.6
D4	Hwy 77	14.8
D5	FM 434	18.9
D6	Arcosa	16.5

Contribution from the WMARSS BHC WWTP to Streamflow

Of the eight effluent outflows, only the large ("A") and small ("G") outflows were measured due to time and access restrictions. Their combined flow is approximately 2.0 cfs and to further investigate the WWTP contribution, each of the eight outflows and the direct upstream and downstream locations were again measured on 3/5/21 (Table 4.2). Outflow "A" had the largest measured flow and contains 90% of the total effluent contribution. The substantial flow within its channel has eroded through the topsoil and cut into the local bedrock (Figure 4.1). In the creek, the upstream and downstream measurements provided more accurate results when compared to the total outflow contribution than in the previous sample period. The total effluent was measured to be approximately 3.0 cfs and the difference between the downstream and upstream locations bordering the outflows was also roughly 3.0 cfs. In total, the WWTP effluent outflows contributed to approximately 33% of streamflow to Bullhide Creek on 3/5/21. A discharge this substantial likely enhances Bullhide Creek's perennial nature and could sustain flow year-round.

Monthly discharged effluent was provided by CWWUS for the period of January 2020 to February 2021 (Table 4.3). Flow was measured using a totalizing meter at the WWTP and reported continuously. Effluent totals provided by the organization were divided by the number of days for each month to receive an approximate average daily flow. The treated sewage is continuously sent through pipes to the 7-acre wetland and from the data provided, the average daily discharge to the wetland is 1.5 cfs (0.97 MGD). The plant is permitted to treat 1.5 MGD of influent and according to their data, the WWTP is discharging less than the allotted amount. Compared to the outflows measured on 3/5/21, the approximate 3.0 cfs entering the creek is substantially higher than the average recorded effluent entering the wetland. The wetlands may be gaining water from groundwater in the Taylor Group or from local runoff stored in the wetland, however further studies are required to confirm this.

Table 4.2. Measured outflow velocities at each of the outflow channels on 3/21/21. Outflows "D" and "E" were immeasurable due to very shallow flow. Attributing outflow locations can be found in Figure 2.8.

Location	Flow (cfs)
outflow A	2.86
outflow B	0.03
outflow C	0.096
outflow D	unmeasurable
outflow E	unmeasurable
outflow F	0.07
outflow G	0.12
outflow H	0.008
total outflows	3.18
upstream	8.25
downstream	10.93

The increase in streamflow observed at Levi Pkwy was attributed to two significant tributaries that discharge into the creek before this location or due to groundwater baseflow, neither of which were documented. Streamflow measurements taken further downstream at Hwy 77 indicate flow similar to Levi Pkwy, though measurements taken at this location may not accurately describe the volumetric flow of the creek at this location due to the presence of a beaver dam. Streamflow measurements were taken below the dam where sticks and boulders are present within the channel and may decrease the accuracy of the streamflow measurement; however, “plateaus” displayed by the velocity meter were obtained at each sample point, indicating a consistent reading from the meter (Figures 4.2 and 4.3).

Figure 4.1. Image looking upstream at Outflow “A,” the largest effluent flow exiting the WWTP wetland. High flow velocities have caused the channel to incise through the soils and into bedrock.

Table 4.3. Total effluent discharged from the WMARSS BHC WWTP from January 2020 to February 2021. Provided by CWWUS on 3/26/2021.

Month	Monthly Total Effluent (MGD)	Average Daily Effluent (cfs)
Jan-20	24.08	1.2
Feb-20	32.05	1.7
Mar-20	37.43	1.9
Apr-20	38.76	2.0
May-20	32.78	1.6
Jun-20	26.19	1.4
Jul-20	23.85	1.2
Aug-20	22.73	1.1
Sep-20	33.69	1.7
Oct-20	24.48	1.2
Nov-20	23.40	1.2
Dec-20	25.87	1.3
Jan-21	38.22	1.9
Feb-21	29.49	1.6

Figure 4.2. Image of the beaver dam present in Bullhide Creek at Highway 77. The streamflow measurements taken with the OTT MF Pro were below the yellow measurement tape.

Figure 4.3. Image of the OTT MF Pro measuring a consistent stream velocity at Hwy 77, indicated by the flat line. Inconsistent or varying readings are displayed by peaks or disjointed lines.

Contribution from the Brazos River Alluvium Aquifer to Streamflow in Bullhide Creek

The BRAA boundary is located between Hwy 77 and FM 434 with close proximity to FM 434. Streamflow measurements taken in January near FM 434 indicated Bullhide Creek gained 27% of total streamflow from the aquifer near the boundary. Approximately 3,000 feet downstream, streamflow at Arcosa was less than that observed at FM 434. Bullhide Creek appeared to be gaining near the bedrock-alluvium boundary and may begin to lose into the aquifer as it flows further downstream. Little is known about the interactions between Bullhide Creek and the BRAA in the 6,000 feet reach between Arcosa and the Brazos River.

It was determined that hydraulic conductivity of streambed sediments can be well correlated with gaining and losing conditions, as Chen and others (2013) found that losing sections of a stream were often characterized by streambeds with lower hydraulic conductivity than those of gaining sections. The downward movement of water minimizes pore spaces by orienting fine particles into an otherwise coarse sediment matrix. In gaining reaches, upward winnowing of finer particles increases pore spaces between sediments, which, in turn, increases the hydraulic conductivity. Coarse alluvial sediments make up the channel bed at each of the locations, however finer sediments are present in the channel and banks at Arcosa (Figure 4.4a). In contrast, coarse gravels are present at the FM 434 site and springs consistently discharged from the banks into Bullhide Creek throughout the study period.

Water Quality Parameters of Bullhide Creek

Parameters in the Upper Reach and of the WMARS BHC WWTP

Analyses of the specific conductance of Bullhide Creek and the effluent outflows show that the effluent outflows have noticeably different water quality parameters than Bullhide Creek (Tables 4.4, 4.5, and 4.6). The outflows exhibited much higher average specific conductance than the waters of Bullhide Creek (Figure 4.5). The effluent input produced a 22% increase in specific conductance at the Reyna property and measurements taken on 3/21/21 indicated a 30% increase between Cooksey and Rosenthal. On 3/5/21 the effluent had an average specific conductance of 961 µS/cm with

Figure 4.4. Images of channel sediments present at the FM 434 and Arcosa locations. a) Looking downstream at the FM 434 location with consistently coarse-grained streambed sediments and exposed bedrock in places. Springs are present at this location on the northern bank. b) Looking upstream at the Arcosa site, where streambed sediments are finer than observed at FM 434 and the banks are clay filled and mostly disconnected from coarse alluvial sediments.

site “A” having the lowest conductance (901 μS/cm) and site “B” having the highest (1015 μS/cm). Site “A” likely displays the lowest conductance due to the channel incision that has occurred, where the effluent flows primarily over Taylor Group bedrock before reaching Bullhide Creek. Suspended clay particles from bedrock erosion in this effluent outflow likely act as an insulator.

In total, the outflows elevate the specific conductance of the Bullhide Creek; however, upstream creek flow is much greater than the effluent contribution and acts as a buffer, minimizing the effluent signature in the creek (Figure 4.6). When calculating a weighted average of the specific conductance of Bullhide Creek combining the upstream flow (450 μS/cm) and the effluent outflows (average of 950 μS/cm), the total specific conductance was calculated to be 575 μS/cm in the creek water. This value is similar to the one measured in Bullhide Creek after the effluent outflow contribution at the Reyna property (568 μS/cm).

The downstream portion of Bullhide Creek at the Reyna property was nearly 2°C warmer than the upstream portion of the creek. The effluent outflows exhibit fairly consistent temperatures with outflow B being the coolest as it flows from the beaver pond and H being the warmest due to it having shallow flow and the longest path to the creek. As outflow “A” contributes 90% of the total effluent to the creek, it likely has the largest effect on the temperature change of the creek. A dense tree canopy primarily shelters the outflows while the downstream measurement was taken in an unobstructed portion of the creek, likely attributing to the observed temperature difference. The dissolved oxygen concentration in Bullhide Creek was also elevated after the effluent contribution and this is likely due to the distance they travel from the wetland and the turbulent nature of some

Table 4.4. Water quality parameters of the effluent, groundwater, and creek water present at the Reyna property on 3/5/2021. Outflow "E" was not able to be measured due to very low flow.

Parameter	Effluent Outflow Sites								Bullhide Creek		Spring
	A	B	C	D	E	F	G	H	Upstream	Downstream	
T (°C)	17.9	15.4	17	17	-	17.4	16.5	18.1	17	18.7	16.9
DO (mg/L)	9.37	9.7	9.38	10.15	-	9.91	9.82	9.26	10.06	11.08	8.78
SpC (µS/cm)	901	1015	968	958	-	966	968	952	465.7	568	554
pH	8.13	8.18	8.28	8.46	-	8.41	8.35	8.41	8.04	8.2	7.52

Table 4.5. Water quality parameters for Bullhide Creek on 3/21/2021. The Reyna property (U2-D1) was not measured due to access limitations.

Parameter	Cooksey U1	Rosenthal D2	Levi Pkwy D3	Hwy 77 D4	FM 434 D5	Arcosa D6
T (°C)	19.1	14.4	15.1	14.8	16.9	18.3
DO (mg/L)	10.93	11.31	11.86	9.86	11.32	10.48
SpC (µS/cm)	453	589	619	588	674	712
pH	8.07	8.21	8.19	8.07	7.93	7.96

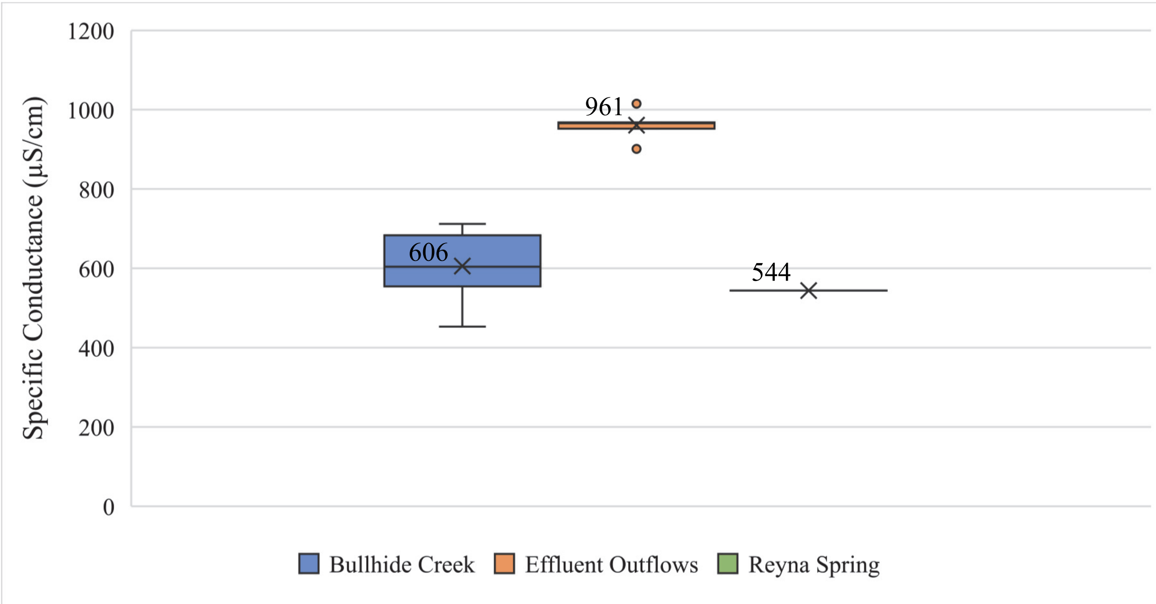


Figure 4.5. Box and whisker plot of the specific conductance of the effluent outflows and spring at the Reyna property (3/5/2021) in relation to the entire study reach of Bullhide Creek (3/21/2021).

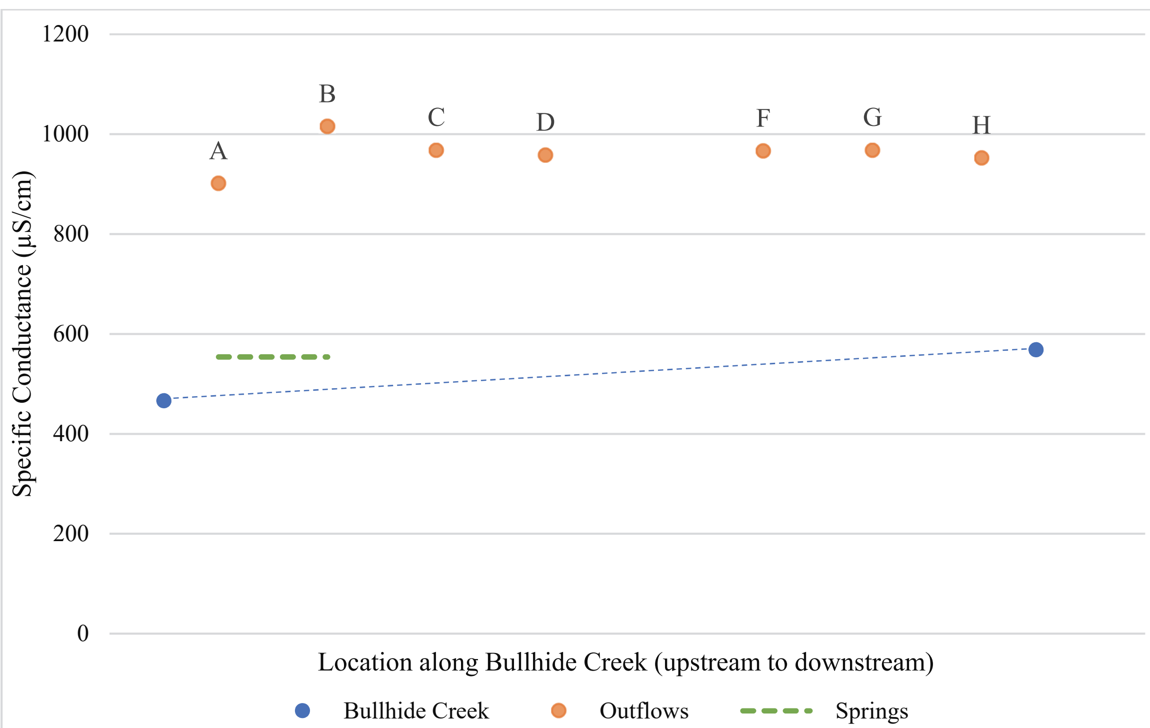


Figure 4.6. Chart of the specific conductance of the effluent, groundwater, and creek water present at the Reyna property from the upstream and downstream measurement sites.

of the outflows, specifically “A” and “D”. According to the WWTP permit, the plant is unable to discharge effluent with a DO concentration less than 5.0 mg/L. Each of the outflows exhibit a concentration around two times greater than the limit, therefore the effluent may be gaining DO as it flows out of the wetland and/or it flows relatively quickly through the wetland since they are generally known to be low-oxygen environments.

The pH of Bullhide Creek rose from 8.04 to 8.20 from the upstream and downstream locations at Reyna. The effluent outflows, with a collective average of 8.14, expectedly contributed to the observed increase. Each of the outflows indicated the effluent was between the limits of 6.0 and 9.0 detailed by the permit.

The contribution of the springs at the Reyna property, though minimal, provides insight into the local groundwater that provides baseflow to Bullhide Creek. The groundwater had a specific conductance more than 400 µS/cm less than the outflows but was greater than the upstream portion of Bullhide Creek. The springs had a temperature similar to the outflows and upstream segment but a much lower DO concentration and pH than the other two waters. The springs at this location likely do little to minimize the effluent signature in the creek, however the groundwater that provides baseflow to Bullhide Creek overall minimizes the effluent signatures in the creek by providing the baseflow that dilutes it.

Parameters in the Middle Reach

The middle reach of Bullhide Creek between Rosenthal Pkwy and Hwy 77 is of significant interest to this study because this section allows the fate of the effluent signature in Bullhide Creek to be studied as it flows farther from the WMARSS BHC

WWTP and interacts with the natural system. Changes in water chemistry that occur in this reach will affect the water quality of the potential recharge to the BRAA and to the Brazos River further downstream, in the lower reach.

In-situ measurements taken on 3/21/21 indicate changes in each parameter as Bullhide Creek flows downstream (Table 4.5). The temperature of the waters increased from Rosenthal to Levi by 0.7 °C and the dissolved oxygen concentration stayed consistent. The DO then decreased by almost 17% between Levi Pkwy and Hwy 77. The specific conductance of the waters increased by 5% between Rosenthal and Levi Pkwy but then regressed at Hwy 77 to a concentration similar to that observed at Rosenthal.

Parameters observed at Levi Pkwy result from an influx of water to Bullhide Creek. The tributaries intersecting the creek between Rosenthal and Levi Pkwy are the likely source of the increase in temperature and specific conductance of Bullhide Creek. Because these tributaries flow over agricultural fields before reaching the creek, the shallower flows experience rapid warming from solar radiation and transport considerable amounts of dissolved constituents from the soil.

Water quality parameters measured at Hwy 77 are primarily influenced by physical stream characteristics at this location. Bullhide Creek at Rosenthal and Levi Pkwy is characterized by a thin channel with shallow, turbulent flow and a streambed primarily comprised of channel alluvium (Figure 4.7a). In contrast, the stream channel at Hwy 77 is nearly two times wider and several feet deeper than each of the upstream sites. A beaver dam downstream from the bridge at this location has created a wider and deeper channel where large amounts of silt have been deposited over the streambed due to the pooled water (Figure 4.7b). Downstream from the beaver dam Bullhide Creek continues to exhibit a wider, deeper channel than the upstream locations. These conditions generally increase the temperature and decrease the DO available in the stream as the slower flows and larger exposed surface area is warmed from increased exposure to solar radiation.

Parameters in the Lower Reach of Bullhide Creek and of the Brazos River Alluvium Aquifer

Changes in water quality parameters along sections of a stream that may be hydraulically connected to other reservoirs may offer insight into spatial and temporal variations in the interactions that can occur. The highest observed specific conductance along Bullhide Creek was after the aquifer boundary. A 14% increase in specific conductance was observed between Hwy 77 and FM 434, an increase equivalent to that observed after the WWTP on the same day. The highest total specific conductance measured for the entire reach was at Arcosa, a total increase of 57% from Cooksey. Temperature of the lower reach increased with distance for a final temperature of 18.3°C. Dissolved oxygen in Bullhide Creek saw an overall increase and was highest at FM 434. The riffles and cascades present above the FM 434 sample point likely enhance the measured DO when compared to Arcosa, which is characterized by runs and deeper pools.

Water Quality parameters measured in the lower reach indicate that Bullhide Creek was gaining from the BRAA due to increases in specific conductance and temperature. Noonan (2019) found that of 32 wells sampled in the BRAA during the spring and summer of 2018, temperatures of the groundwater ranged from 20.0 to 29.2

Figure 4.7. Images of channel sediments present at Rosenthal Parkway and Highway 77. a) Looking upstream at Rosenthal Pkwy, channel sediments consist of coarse channel alluvium. b) Looking upstream at Hwy 77 where Bullhide Creek is characterized by a wider channel that is more than three feet deep in some areas. Several inches of silt have been deposited over the coarser bed material.

°C. The notable increase in temperature at FM 434 and Arcosa is likely attributed to the addition of groundwater to Bullhide Creek because groundwater in the region is typically warmer than surface water during this season. To compare specific conductivity gained in the creek to that of the aquifer, the FM 434 and Arcosa measurements were converted to TDS using the standard conversion of 0.65 for comparison to groundwater in nearby wells. This indicated groundwater in and around the Bullhide Creek watershed contains TDS concentrations between 500 to 1,000 mg/L with one well having TDS in the 1,000 to 3,000 mg/L range (Figure 4.8). Bullhide Creek before the aquifer's influence had a TDS of 372 mg/L and after the aquifer boundary the TDS increased to 431 mg/L at FM

434 and 455 mg/L at Arcosa. Groundwater with comparatively much higher TDS infiltrates Bullhide Creek and subsequently increases the concentration observed in the stream.

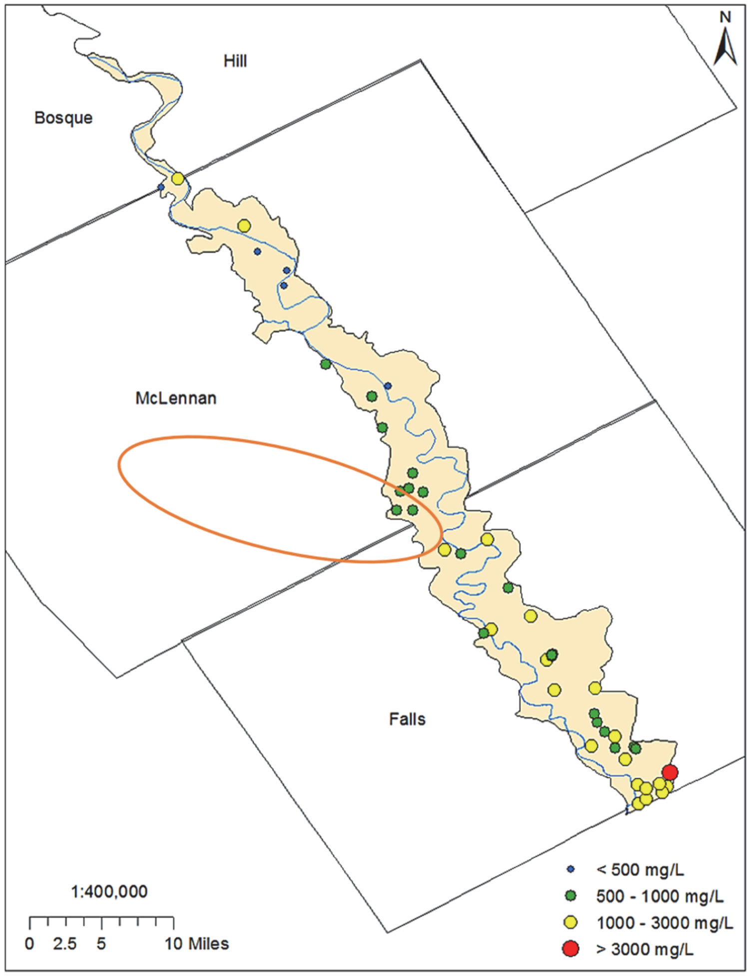


Figure 4.8. Map of TDS in the Brazos River Alluvium Aquifer related to the proximity of the Bullhide Creek watershed (orange) (Modified from Noonan, 2019).

Nutrient Loading to Bullhide Creek

The spatial variability and sources of nutrient loading to Bullhide Creek were characterized by collecting water samples on 1/28/21 and 3/21/21 for nitrogen and phosphorus analyses. The effluent outflows and Reyna property were not measured on 3/21/21 due to access restrictions, however the nutrients can be examined downstream and compared to 1/28/21 to infer trends. The WMARSS BHC WWTP monitors the constituents present in the effluent to enter the wetlands, however no effort has been made to investigate the effluent entering the stream or its subsequent downstream fate. In addition, no work has been done to investigate the interactions between Bullhide Creek and the BRAA where periods of hydraulic connectivity may be indicated by nutrient loading.

Nutrient Loading in the Upper Reach and of the WMARSS BHC WWTP

Analyses of nutrients in upstream waters at Cooksey show the lowest concentration of total nitrogen (TN) and total phosphorus (TP) observed in this study (Figures 4.9 and 4.10). Total nitrogen measured at Cooksey was higher in January than in March with a maximum concentration of 0.56 mg/L and tables 4.6 and 4.7 show that the nitrogen measured on 1/28/21 is primarily in the form of nitrate, as nitrite quickly changes into nitrate and practically no ammonia was detected in the stream. The TP concentration was slightly higher in March than in January and was dominated by phosphates on both dates (Figures 4.11 and 4.12).

The effluent measured at the Reyna location had TN and TP concentrations higher than observed anywhere else in the study area. Phosphates made up 40% of TP in outflow "G" and TN was measured as 4.9 mg/L. According to outflow "G," the wetlands are efficient in removing nitrogen and phosphorus in the effluent as the reported monthly average for TN and TP were decreased by 67% and 39% respectively in January 2021 when compared to effluent discharge reported by the WWTP. Total nitrogen measured in the wetland outflow to Bullhide Creek was less than that of the nitrogen reported in the discharged effluent for the January 2020 to February 2021 period (Figure 4.13). Detailed

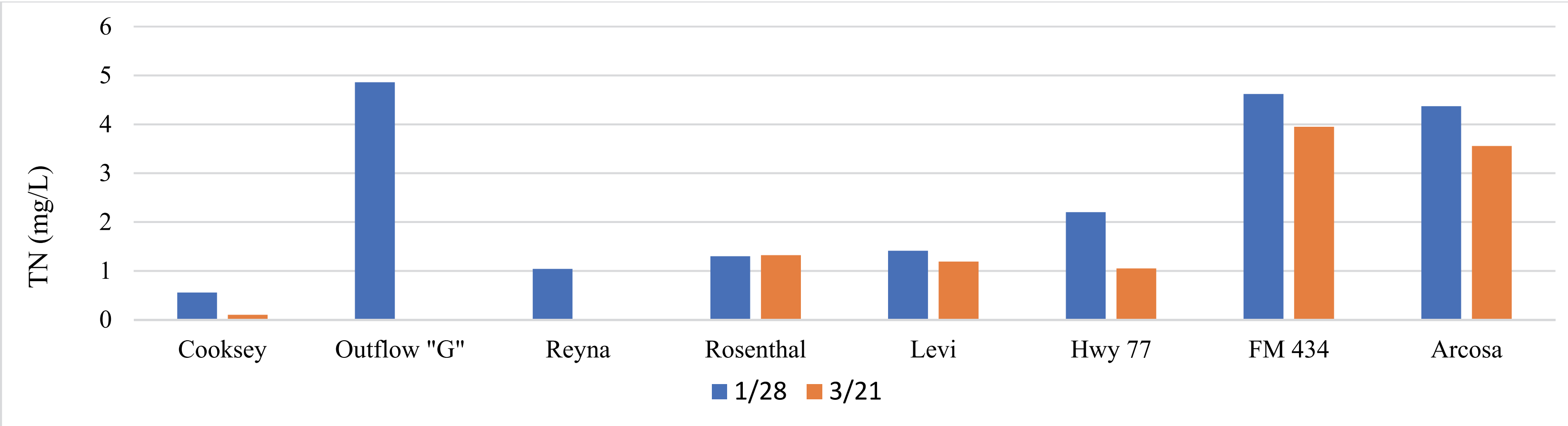


Figure 4.9. Bar chart depicting total nitrogen concentrations present in Bullhide Creek and in Outflow “G” measured on 1/28/2021 and 3/21/2021.

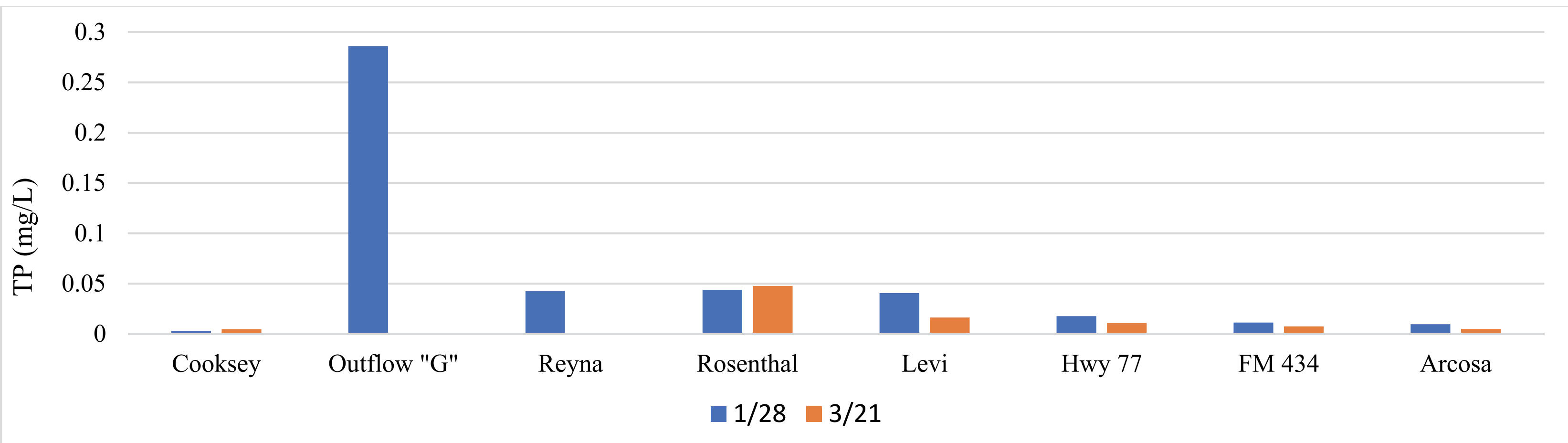


Figure 4.10. Bar chart depicting total phosphorus concentrations present in Bullhide Creek and in Outflow “G” measured on 1/28/2021 and 3/21/2021.

Table 4.6. Nutrient concentrations in mg/L measured in Bullhide Creek and Outflow "G" on 1/28/2021.

Sample ID	TP	PO_4	TN	NO_3/NO_2	NH_3
Cooksey	0.00291	0.00401	0.556	0.448	0
Outflow "G"	0.286	0.19	4.86	4.72	0
Reyna	0.0423	0.00547	1.04	0.791	0.01
Rosenthal	0.0438	0.00531	1.3	1.18	0
Levi Pkwy	0.0406	0.0127	1.41	1.17	0
Hwy 77	0.0177	0.00327	2.2	1.45	0
FM 434	0.0112	0.00435	4.62	4.39	0
Arcosa	0.00957	0.00519	4.37	4.25	0

Table 4.7. Nutrient concentrations in mg/L measured in Bullhide Creek on 3/21/2021. The Reyna property was not measured due to access limitations.

Sample ID	TP	PO_4	TN	NO_3/NO_2	NH_3
Cooksey	0.0047	0.004	0.102	0.0611	0.001
Rosenthal	0.0477	0.0203	1.32	1.175	0.02
Levi Pkwy	0.0163	0.0101	1.19	1.17	0.01
Hwy 77	0.0108	0.0025	1.05	0.696	0.02
FM 434	0.00752	0.0033	3.95	2.71	0.01
Arcosa	0.00481	0.0049	3.555	3.42	0.01

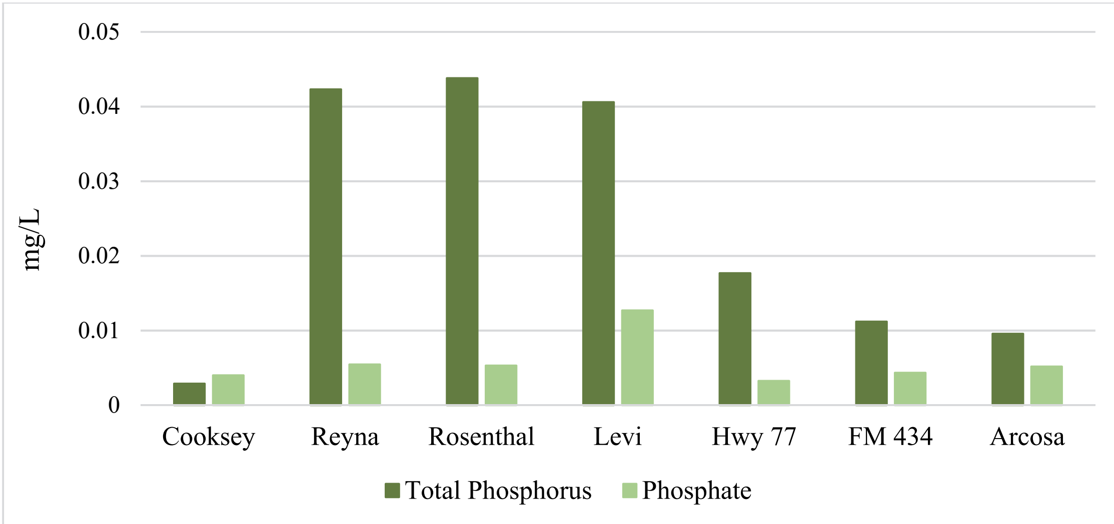


Figure 4.11. Bar chart depicting the total phosphorus and phosphate present within Bullhide Creek on 1/28/2021.

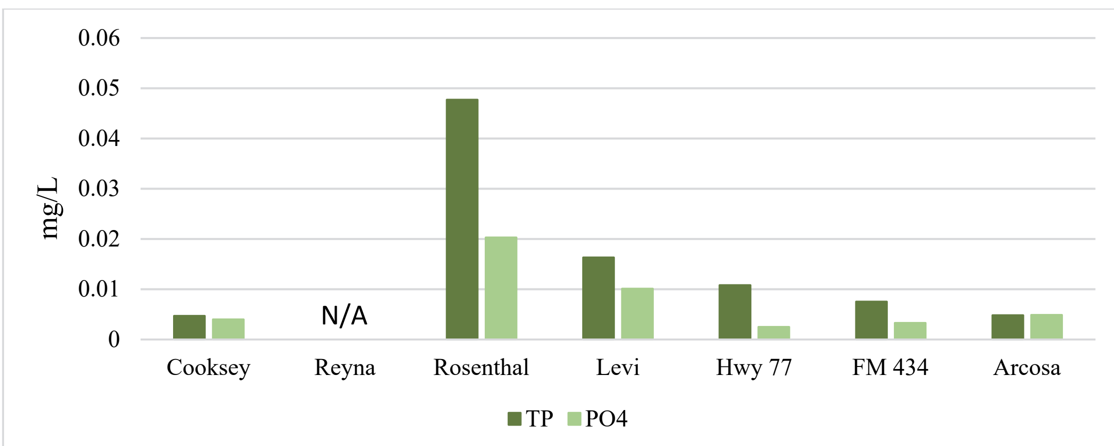


Figure 4.12. Bar chart depicting the total phosphorus and phosphate present within Bullhide Creek on 3/21/2021.

nutrient concentrations within the effluent reported by CWUSS can be found in appendix. H. Figure 4.14 shows that the measured wetland outflow to Bullhide Creek has a TP concentration lower than the median of the effluent discharged from the plant into the wetlands and is within the interquartile range of the measured discharges. In addition to the wetlands effectively reducing TP and TN concentrations, ammonia and nitrates were also significantly decreased before reaching the creek.

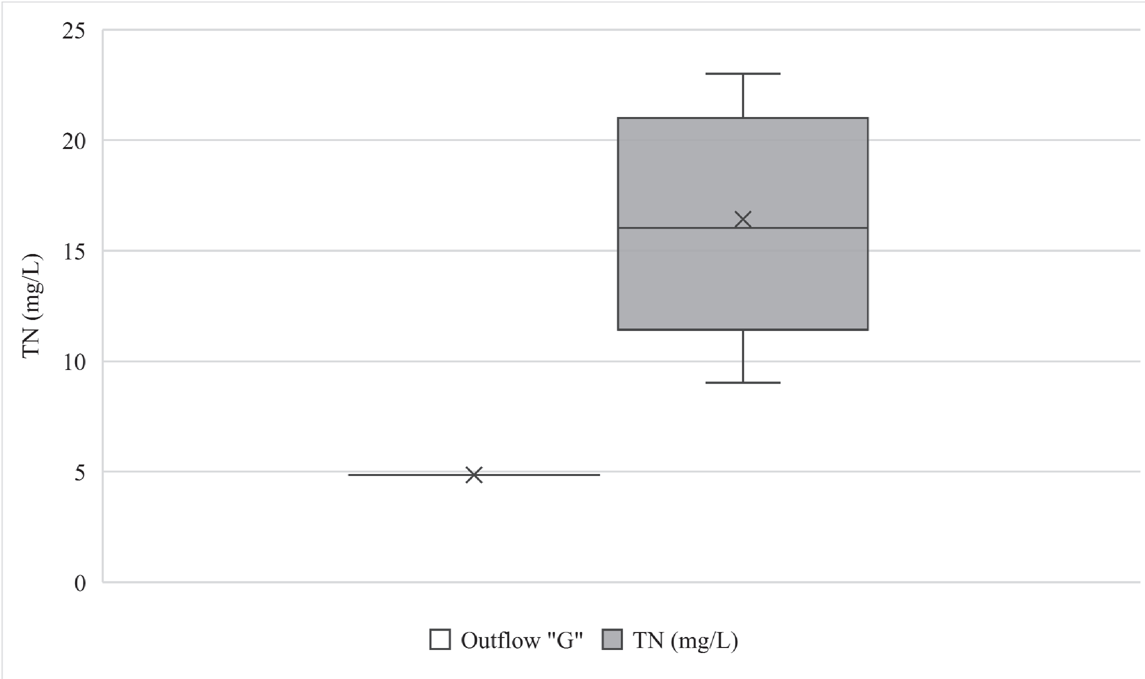


Figure 4.13. Box and whisker plot of recorded TN in the WMARSS BHC WWTP effluent from January 2020 to February 2021 and the effluent outflow "G" measured on 1/28/2021.

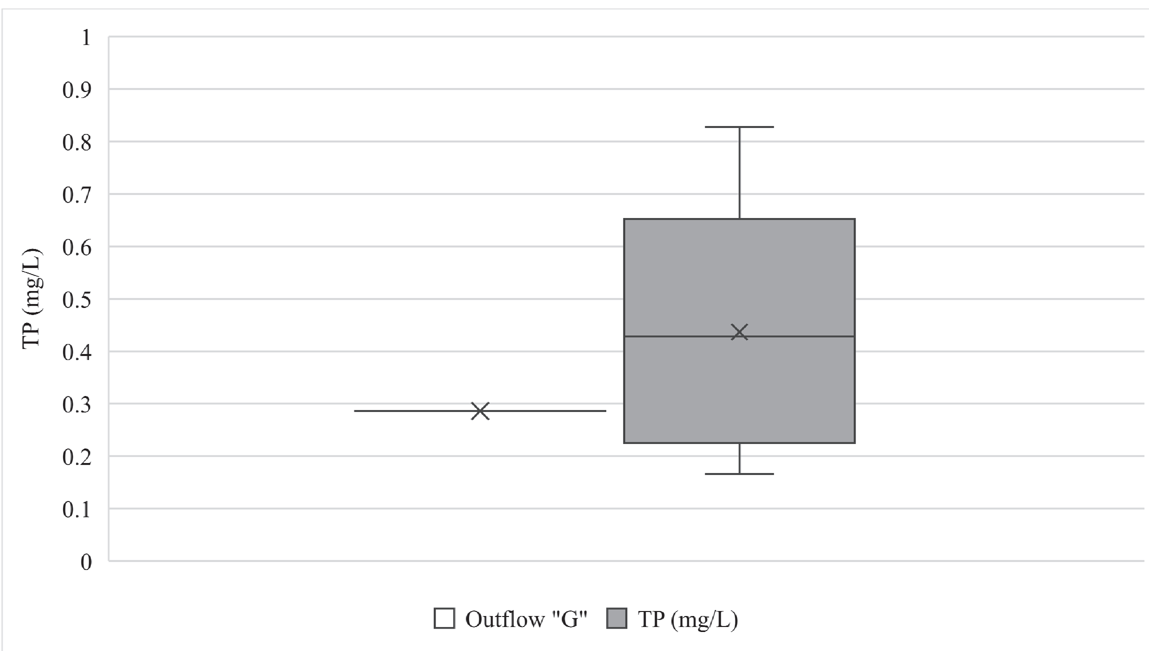


Figure 4.14. Box and whisker plot of recorded TP in the WMARSS BHC WWTP effluent from January 2020 to February 2021 and the effluent outflow "G" measured on 1/28/2021.

Subsequent to the effluent contribution to Bullhide Creek, Reyna and Rosenthal have TN and TP concentrations higher than observed at Cooksey but lower than the effluent outflows. On 1/28/21 TP increased by 1,400% between Cooksey and Reyna, though only a 40% increase in phosphates was observed. In addition, total nitrogen increased by 87% with most of the nitrogen being in the form of nitrates.

Nutrient Loading in the Middle Reach

Nutrient loading and fate in the middle reach appeared significantly different between the first and second sample dates. The January dataset showed nitrogen concentrations in the creek increased with distance from Rosenthal to Hwy 77 and were higher at each sample point than observed immediately after the effluent outflows. Total phosphorus concentrations remained elevated in the stream between Rosenthal and Levi Pkwy and did not decrease as quickly as expected. In contrast, samples taken on 3/21/21 show that TN concentrations decrease with distance and the reduction in TP is rapid.

It is likely that tributary flow contributed to Bullhide Creek and affected the nutrient concentrations in the stream on 1/28/21. Figure 4.15 shows the local precipitation events that occurred in the months before sampling. The 1/28/21 collection dates were preceded by several significant precipitation events in the weeks before sampling, however no significant rains occurred in more than two months before samples were taken on 3/21/21. Precipitation-enhanced tributary flow to Bullhide Creek in January may have transported nutrients from the upland agricultural fields in the form of nitrates and phosphates, primarily before the Levi Pkwy sample point. During the drier period sampled in March, tributaries were not adding noticeable flow to the creek, allowing the nutrient concentrations in the stream to decrease with distance.

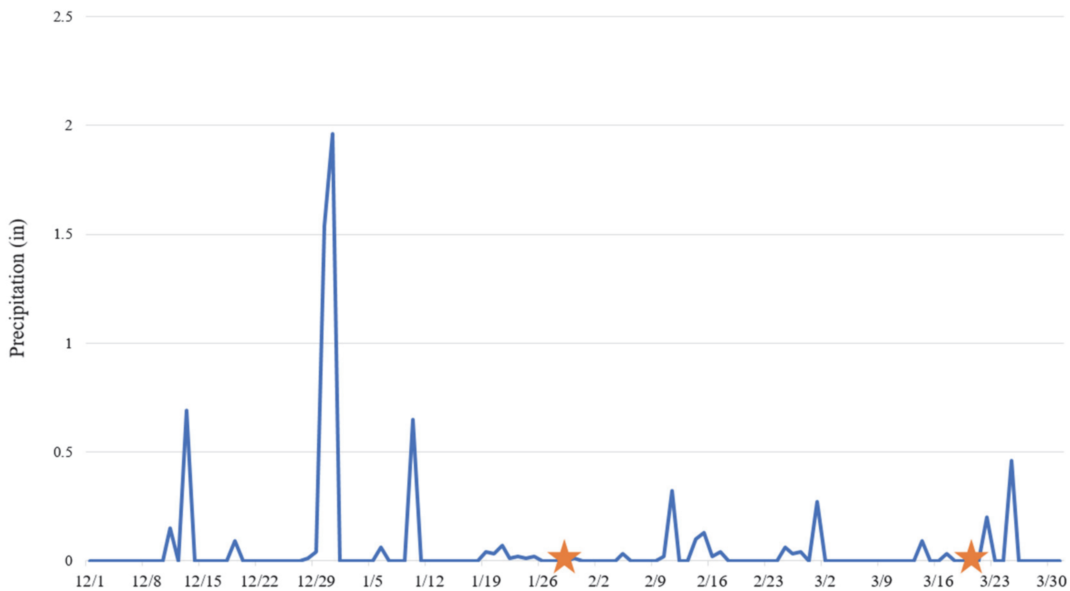


Figure 4.15. Line graph depicting local precipitation measured at the Waco Regional Airport collected from NOAA NCDC for the period between December 1, 2020 to March 31, 2021. Sample dates 1/28/21 and 3/21/21 are shown by the orange stars.

Nutrient Loading in the Lower reach and of the Brazos River Alluvium Aquifer

Patterns observed in the nutrient concentrations of the lower reach were consistent on both sample dates where a large increase in nutrients was observed at FM 434 and reduced before Arcosa. A substantial increase in TN was observed between Hwy 77 and FM 434 with a 110% and 276% increase measured on 1/28 and 3/5, respectively. Total phosphorus measured in the stream did not increase in Bullhide Creek along the alluvium. However, the phosphate to TP ratio increased down the reach and was greater than one at Arcosa on 3/5/21, similar to the concentration and ratio observed at Cooksey on the same day. The nutrient concentrations present in Bullhide Creek in this reach are unknown during losing conditions as each date sampled during this study suggests gaining conditions through added nutrients observed in the stream.

Some streams are known to have nitrate and other pollutants reduce in gaining reaches but because of extensive agricultural practices that affect water quality and nutrient concentrations in the BRAA, the water quality of Bullhide Creek is affected by the influx of groundwater (Jimenez Fernandez and others, 2020). Chowdhury and others (2010) examined chemical compositions of groundwater in the BRAA and found the highest nitrate concentrations to be adjacent to the study area (Figure 4.16). Long term, widespread use of agricultural fertilizers has elevated the nutrients present in the groundwater; Noonan (2019) observed maximum nitrate concentrations of 11.4 and 6.8 mg/L in the BRAA within McLennan and Falls counties, respectively.

Ionic Chemistry of Bullhide Creek

The major ions present in Bullhide Creek during baseflow conditions were analyzed on 3/21/21 (Table 4.8). Analyses during baseflow conditions best illustrate the common streamflow contributions to the creek because high flow events are typically caused by excess runoff that transports solutes from larger areas and therefore does not reflect most flow conditions (Rose, 2002). Piper diagrams were used to display the hydrochemical facies of the waters and two water types were indicated (Figure 4.17). Bullhide Creek at Cooksey is representative of calcium bicarbonate water indicative of baseflow produced from the Austin Chalk. The downstream waters consist of a bicarbonate type water with a slight calcium dominance and a mixed bicarbonate type with no dominant cation (Levi Pkwy).

Dissolved solute concentrations in Bullhide Creek vary primarily in response to the two large streamflow contributors: the WWTP and BRAA. The ions present downstream from the WWTP are affected by the influx of nutrients and ions present in the effluent discharge, with most being sodium and chloride. Figure 4.18 illustrates the large increase in sodium from 20.8 mg/L to 51.6 mg/L at Rosenthal after the effluent

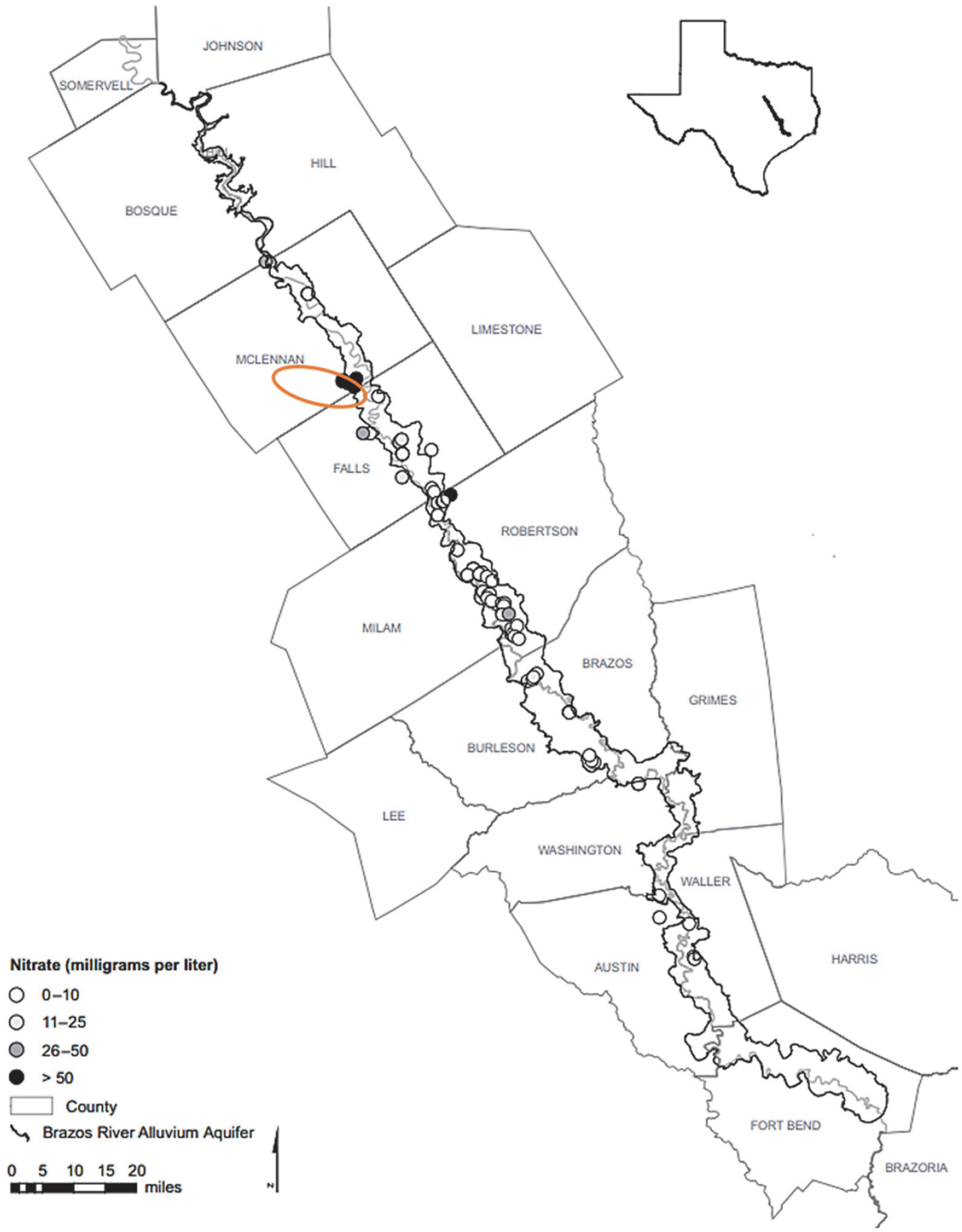


Figure 4.16. Nitrate concentrations in the BRAA within the extent of the aquifer (Modified from Chowdhury and others, 2010). Note that the highest concentrations observed in the aquifer are adjacent to the Bullhide Creek watershed.

Table 4.8. Concentrations of common ions of Bullhide Creek measured on 3/21/2021.

Sample ID	Cooksey	Rosenthal	Levi Pkwy	Hwy 77	FM 434	Arcosa
Chloride (mg/L)	20.40	33.00	35.10	34.80	32.70	33.40
Sulfate (mg/L)	33.10	43.60	49.40	55.00	61.60	73.40
Calcium (mg/L)	80.20	77.70	75.10	69.50	81.20	84.60
Magnesium (mg/L)	1.91	2.71	3.29	3.51	4.52	5.10
Potassium (mg/L)	2.10	2.63	2.94	2.85	2.63	2.66
Sodium (mg/L)	20.80	51.60	84.60	60.40	67.60	72.20
Bicarbonate (mg/L)	224.48	244.00	241.56	222.04	263.52	258.64

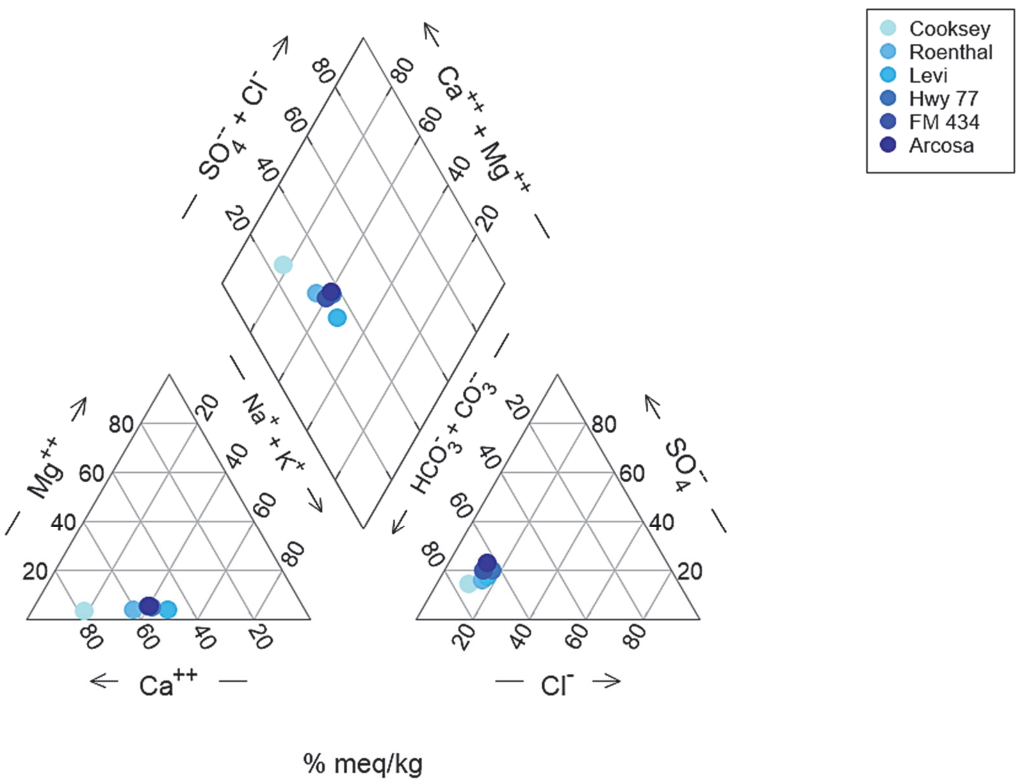


Figure 4.17. Piper diagram illustrating the hydrochemical facies of Bullhide Creek waters on 3/21.

discharge to Bullhide Creek. Elevations in chloride (62% increase), sulfate (32% increase), and bicarbonate (9% increase) were also observed and are consistent with the major ions concentrated in sewage effluent (Verbanck, 1989).

Chloride and potassium stayed generally consistent throughout the creek after the WWTP whereas magnesium and sulfate concentrations increased with distance. The highest concentration of sodium observed in this study was at Levi Pkwy with a concentration of 84.6 mg/L. The high sodium concentration along with increasing chloride and sulfate concentrations suggests streamflow of Bullhide Creek at this location may be dominated by effluent during baseflow conditions or evaporation has concentrated the ions compared to upstream waters, particularly as these samples were collected during a dry period. A decrease in calcium and bicarbonate in the waters were observed at Levi Pkwy and a significant decrease in sodium was observed downstream at Hwy 77. In addition, each of the analyzed ions decreased in concentration at Hwy 77 except for magnesium and sulfate. The pooled channel resulting from the beaver dam at this location likely influences the dissolved ions present in the water.

The BRAA contributed a significant amount of sodium and bicarbonate to Bullhide Creek at FM 434 and Arcosa. The highest concentrations of bicarbonate, magnesium, and sulfate in Bullhide Creek are observed along this section. Irrigation may be a source of the salinity in this region of the aquifer as cultivated cropland dominate the surface of the BRAA. Review papers by Foster and others (2018) and Wichelns and Manzoor (2015) demonstrate many cases world-wide where irrigation has increased the salinity in soils, rivers, and aquifers. Evaporation and transpiration increase the salinity of irrigated return flow, causing a buildup of salts in the soils that eventually leach into the

BRAA. Noonan (2019) found that sediment size largely contributes to the variability of salinity within the BRAA and had a larger effect on salinity than irrigation. In the aquifer, finer sediments such as clay contain larger amounts of salinity as the increased residence time of the groundwater allows more salt to accumulate and the low permeability can limit flushing. Casteel (2020) determined aquifer sediments adjacent to Bullhide Creek are comprised mostly of clay near the surface and large amounts of sand and gravel near the base of the core, more than 8 meters below the surface (figures 4.19 and 4.20). The clay that comprises the upper portion of the aquifer increases evaporation and concentrates salinity seen in the groundwater input to Bullhide Creek at this location. The ionic balance of the dissolved solutes in Bullhide Creek indicate the cations (meq/kg) are slightly larger than the anions after the addition of the sewage effluent (Figure 4.21). The ions at Cooksey had a balance of 1.0 and all other sample points had a balance of 1.1 except for Levi Pkwy and Arcosa, of which had ionic balances of 1.3 and 1.2, respectively. The unbalanced ions may be an underestimation of bicarbonate or from inconsistent analyses. Two samples were taken at each location, one for bicarbonate titration completed in the Baylor Hydrogeology Lab and the other was sent to the BIO CHEM lab a day later for the complete ion analysis. The samples were kept on ice and bicarbonate concentrations were analyzed soon after all the samples were collected. However, an underestimation in bicarbonate is likely not the cause of the unbalanced anions in all samples because the Cooksey sample was collected first and therefore the longest time occurred between sampling and analysis. Because this sample produced well-balanced ions, it is assumed the bicarbonate was not underestimated due to changes in temperature or carbonate precipitation in these data.

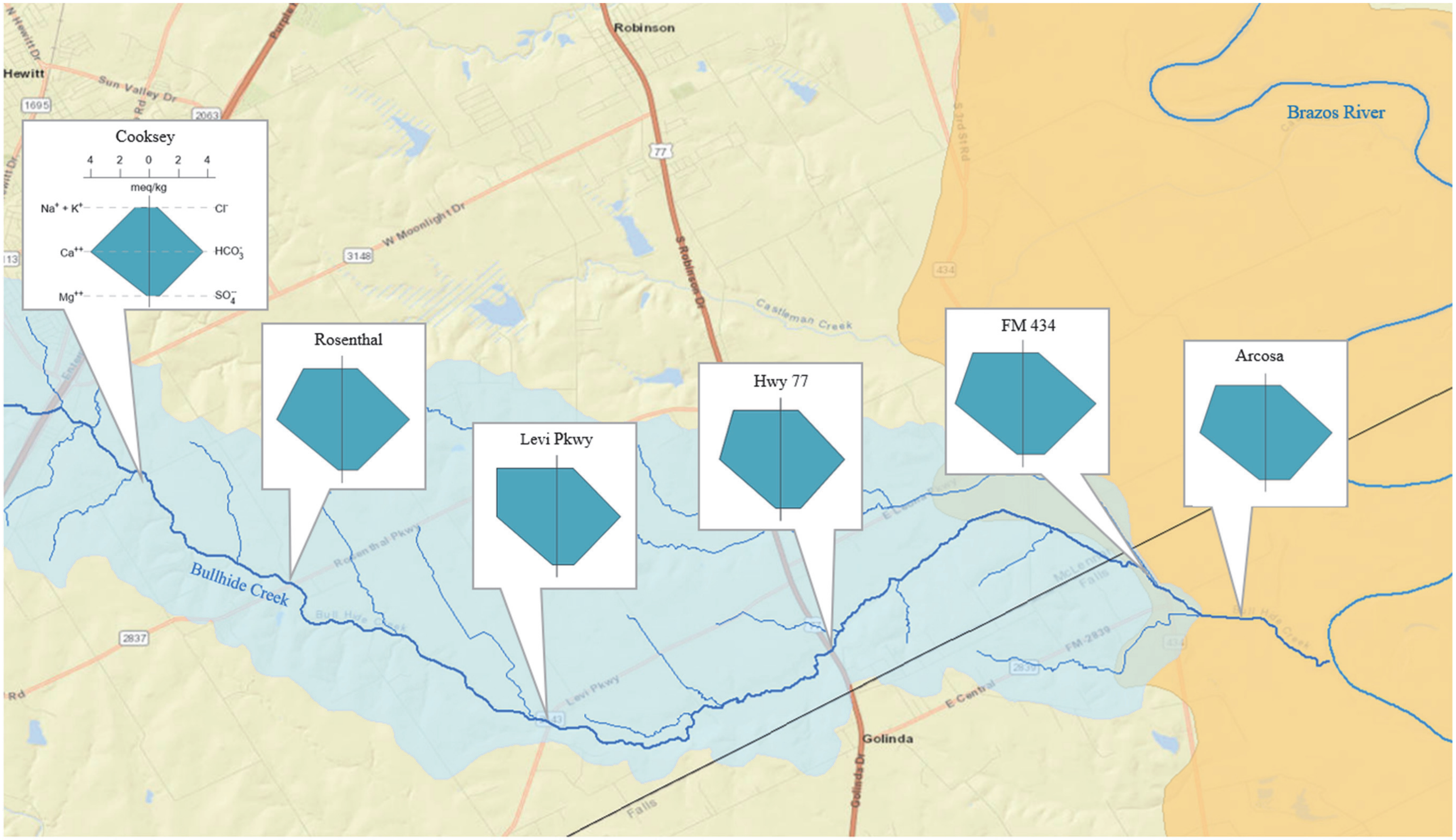


Figure 4.18. Stiff diagrams displaying the ionic compositions of water along Bullhide Creek on 3/21/2021.

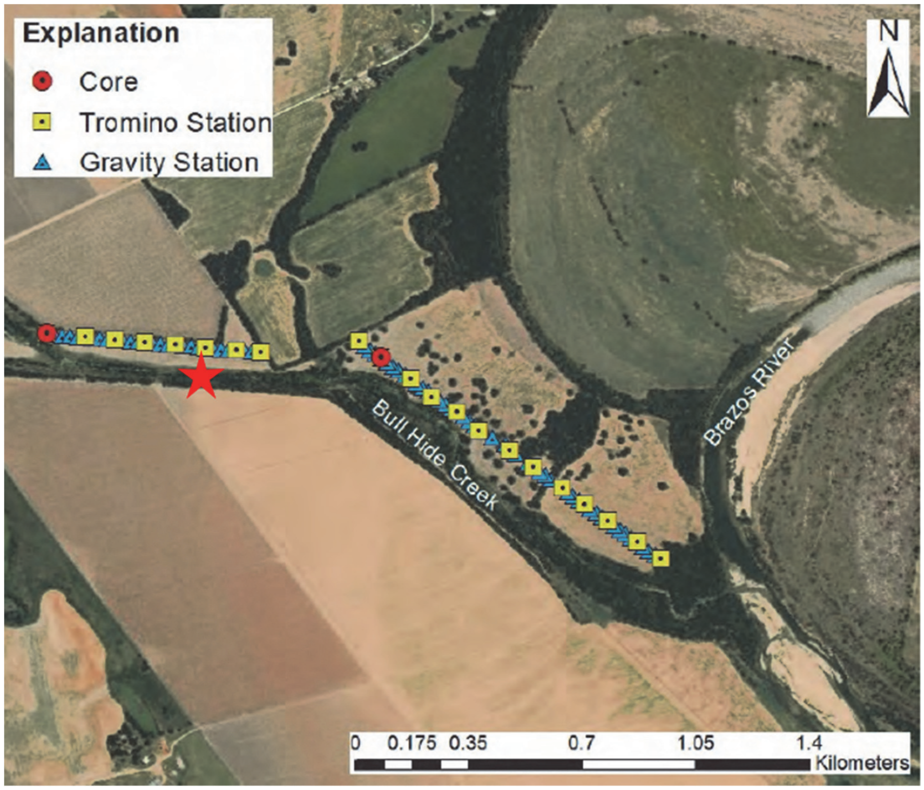


Figure 4.19. Map of transects completed at Arcosa using gravity stations, passive seismic (Tromino) stations, and core locations (modified from Casteel, 2020). Red star indicates location of "Arcosa" streamflow measurement.

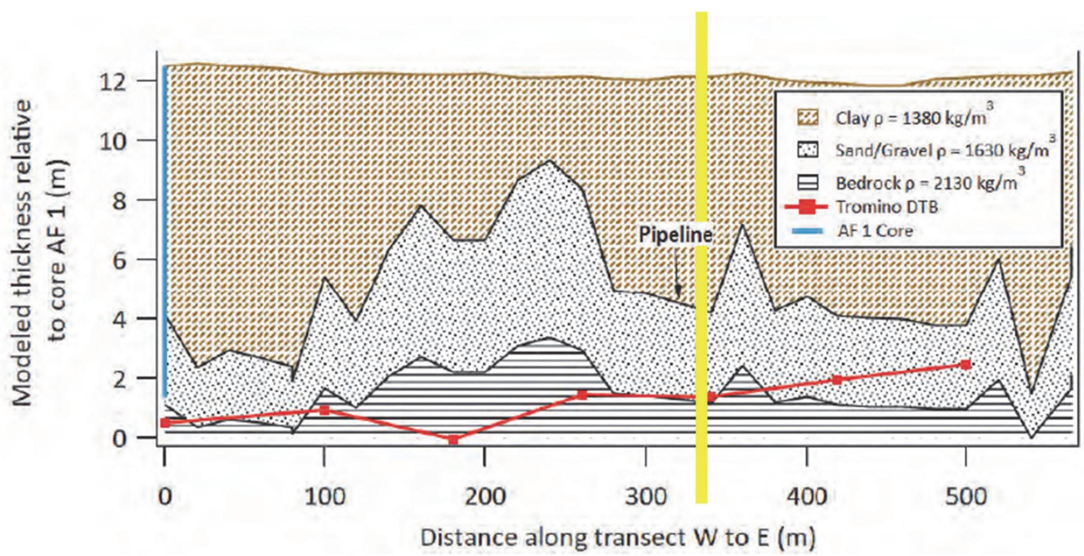
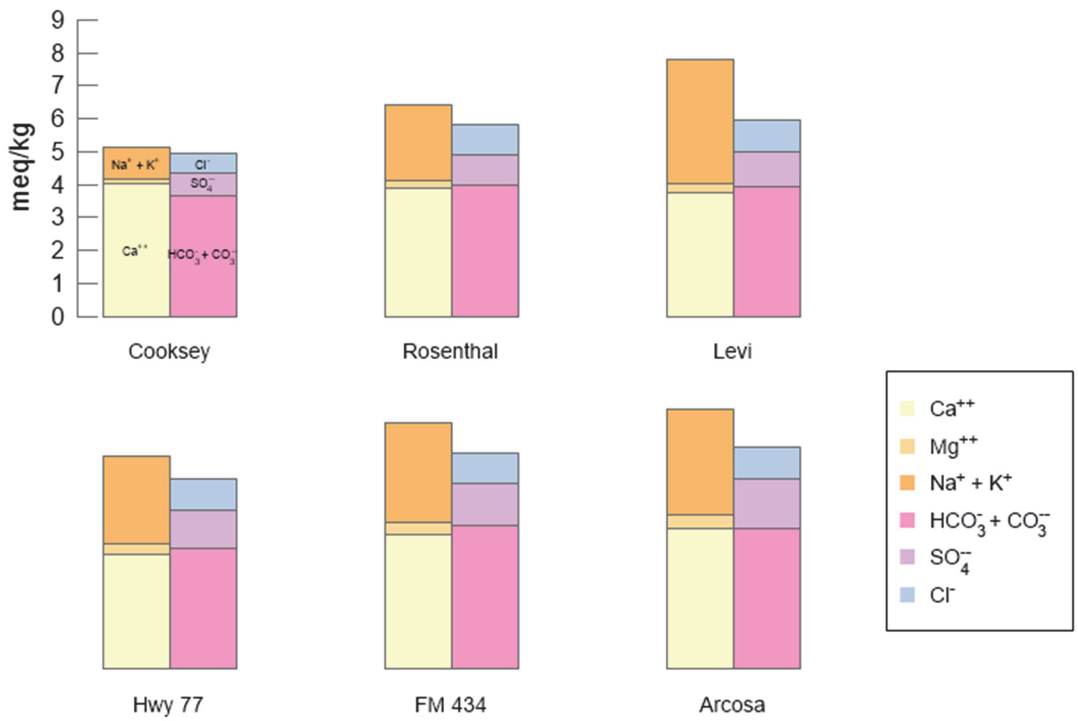


Figure 4.20. Modeled results of bedrock elevation and alluvium material and thickness at the Arcosa property in relation to the Bullhide Creek streamflow measurement location (yellow line) (modified from Casteel, 2020). Pipeline shown upstream in Figure 4.1b.

Fluoride is an anion that is often analyzed in water due to its occurrence in drinking water and as health concerns, such as skeletal fluorosis, can occur if concentrations exceed 4-8 mg/L (Kundu, 2001). Fertilizers and leaching from rocks or enriched soils containing fluoride can cause it to enter groundwater, however Ju (2014) performed a complete ion analysis on the BRAA and found no detectible fluoride. It is possible that the absent anions may be attributed to nitrate and phosphorus concentrations in the creek that were observed and not represented with the common ions. The concentrations of nitrate were highest at FM 434, and the Rosenthal had the ighest concentration of phosphate, however the ion balance of these locations is both 1.1. Because the absence of these anions cannot be determined as the cause of the unbalanced ions at some locations, the unbalance may be attributed to the large increases in sodium observed, particularly at Levi Pkwy and Arcosa, or the dataset may have obtained error during collection or lab analysis.

Isotopic Composition of Bullhide Creek

Naturally occurring hydrogen and oxygen isotopes (^{1}H, ^{2}H, ^{16}O, ^{18}O) are commonly used in hydrologic studies because they can act as tracers to understand processes such as precipitation, groundwater and surface water interactions, and discharge sources. The common driver of isotope variations in water is fractionation between isotopologs through physical processes such as evaporation, condensation and precipitation (Gat and others, 2000). Therefore, as water is transported, mixed, and undergoes phase changes in the hydrologic cycle, the water is typically accompanied by



4.21. Bar chart of the charge balances of major ions within Bullhide Creek.

the transferring of isotopic signatures and can be used to trace the movement of water between reservoirs and study processes affecting water such as seasonality and climatic changes (Durowoju and others, 2019; Leketa and Abiye, 2020). Xia and others (2021) applied the distribution of oxygen and hydrogen isotopes to investigate the source of stream water in a mountainous region in China used them as tracers to pinpoint sources of agricultural and effluent pollution to the stream. Because Bullhide Creek receives flow contribution from several sources, hydrogen and oxygen isotopes were used to indicate streamflow contributions during baseflow conditions.

Samples collected from Bullhide Creek on 1/28/21 included the entire study reach, Outflow G, and the Reyna property. Samples collected on this day represent Bullhide Creek under baseflow conditions during a "wet" period, where precipitation events occurred in the weeks before sampling (Figure 4.15). The second set of water samples for isotopic analysis were taken on 3/21/21 along Bullhide Creek, not including Reyna and Outflow G. Drier conditions were observed with these data as significant precipitation did not occur in more than 2 months before sampling. Variations within isotopic compositions of the samples are minimal and range a total of 0.56‰ $\delta^{18}O$ VSMOW with an average of -3.55 ± 0.29 and 5.14‰ δD VSMOW with an average of 21.28 ± 1.42‰. The isotopic compositions of all samples can be found in appendix I.

Bivariate plots of the oxygen and hydrogen isotope samples are in relation to the local meteoric water line (LMWL), which represents the variability in the annual isotopic composition of precipitation in Riesel, Texas (14 miles south of Waco, Texas). These data were obtained from the International Atomic Energy Agency (IAEA) Global Network of Isotopes in Precipitation (GNIP) data set. Precipitation data for the LMWL were collected in the 1960s and 1970s and a strong positive correlation was observed between δD and $\delta^{18}O$. The average oxygen isotopic composition of precipitation in Waco, Texas, is -4.03‰ $\delta^{18}O$ VSMOW and -22.87‰ δD VSMOW (IAEA/WMO, 2017). Variability within isotopic compositions of annual precipitation is primarily due to seasonality, the source of the water vapor, and the distance it has traveled (interiority effect).

Figure 4.22 shows the oxygen isotopic composition of waters measured at Bullhide Creek on 1/28/21. The samples had a relatively consistent $\delta^{18}O_{VSMOW}$ compositions that ranged from -3.83‰ to -3.55‰. Alternatively, $\delta^{2}H_{VSMOW}$ compositions had a wider range of compositions from -23.43‰ to -20.05‰ and allow spatial trends within the waters to be examined. The upstream sample at Cooksey is the lightest sample of the set and falls off the LMWL considerably. The baseflow dominated streamflow at this location was likely affected by runoff from previous precipitation events and anthropogenic inputs from upstream urban areas may have affected the isotopic composition. Outflow G represents the heaviest $\delta^{18}O$ sample in the dataset, which is indicative of the greater amount of evaporation that can affect water in wetlands versus streams that are dominated by precipitation and groundwater flow. The addition of effluent in Bullhide Creek at Reyna causes the creek water to be heavier than Cooksey but lighter in comparison to water directly from the outflows. Isotopic compositions of Rosenthal and Hwy 77 occur closer to the LMWL and may be affected by streamflow contributions that have not undergone as much evaporation or groundwater seepage. Levi Pkwy is even lighter and is likely result of the tributary contributions near this location that add streamflow from precipitation enhanced tributaries.

Isotopic signatures of Bullhide Creek on 1/28/21 after intersecting the BRAA boundary display two distinct isotopic signatures. Waters at FM 434 fall closely on the LMWL whereas, at Arcosa, the isotopic composition of the creek is heavier and falls away from the LMWL. As the BRAA is a water table aquifer that is thought to be dominantly recharged by precipitation, the isotopic composition of the groundwater should reflect the mixing of annual rainfall recharge compositions for the region.

Noonan (2019) measured the isotopic composition of the BRAA through 34 samples in McLennan and Falls counties and found the average isotopic composition of the aquifer to be -4.22‰ $\delta^{18}O$ VSMOW and -23.30‰ δD VSMOW in the spring/summer of 2018. The hydrogen and oxygen isotopic signatures indicate evaporation effects the recharge sources of the BRAA throughout the northern segment and caused the samples to fall off the LMWL. In contrast to the results found in that stud, the isotopic signatures

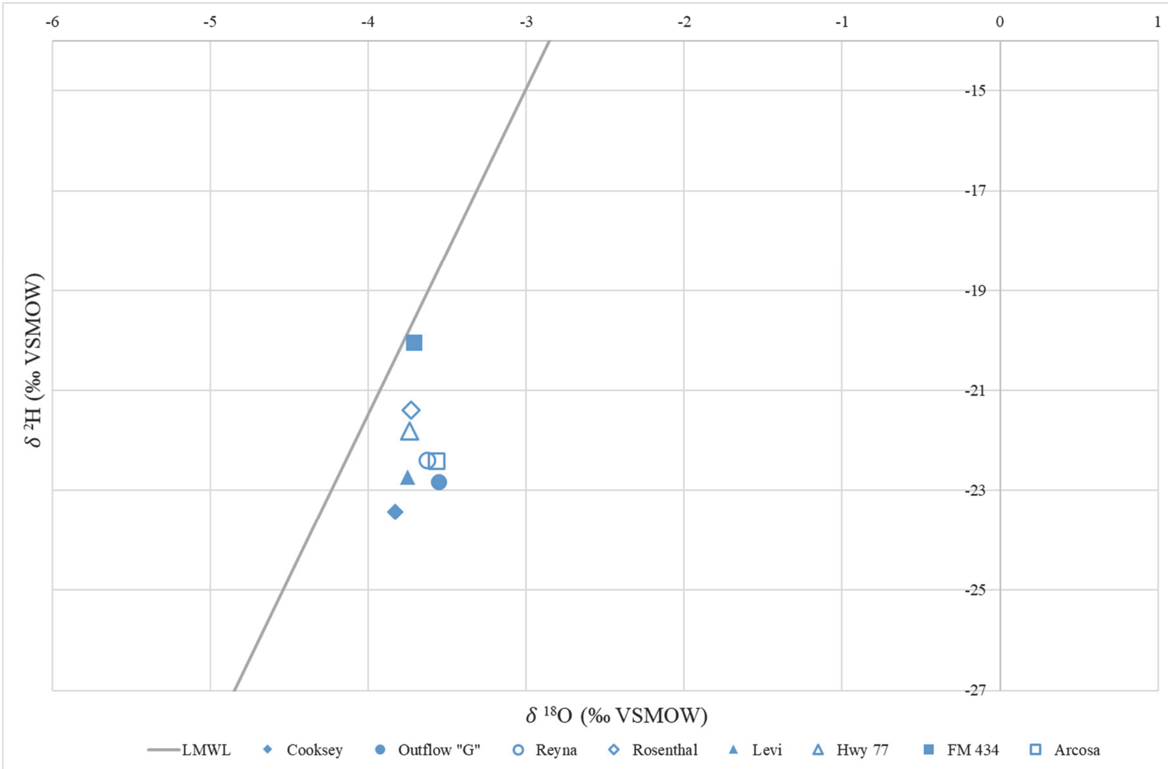


Figure 4.22. Bivariate plot of hydrogen versus oxygen isotopic composition Bullhide Creek and effluent outflow G, on 1/28/2021. The LMWL has an equation of $\delta D = 6.51\delta 18O + 4.58$ and a regression coefficient of 0.91.

of Bullhide Creek at FM 434 occurred near the LMWL because precipitation that occurred in the weeks before sampling could have temporarily perched on top of the water table and discharged into Bullhide Creek before mixing with the aquifer (Figure 4.23). This stratification may have caused the isotopic compositions of the creek at this location to closer reflect recent precipitation more closely than typical groundwater from the BRAA in the region.

In contrast, isotopic compositions of the creek measured at Arcosa indicate isotopically lighter hydrogen and slightly heavier oxygen isotopes than the FM 434 location. Evaporation in the creek water between FM 434 and Arcosa presumably did not result in the heavier composition at this location because the magnitude of evaporation needed to fractionate δD and $\delta^{18}O$ isotopes to this extent is unlikely to occur in stream waters at this distance. Irrigation return flow and clay layers within the upper portion of the aquifer may cause the isotopic signatures in the groundwater to be heavy. Because a significant amount of clay is present within the upper portion of the aquifer near this location, groundwater flows slower and has a longer residence time than in sandier locations and may undergo further fractionation due to the prolonged proximity to the surface.

Figure 4.24 shows a bivariate plot of δD and $\delta^{18}O$ isotopic compositions from Bullhide Creek taken on 3/21/21 and does not include Reyna and Outflow G. The $\delta^{18}O_{VSMOW}$ values for the samples range from -3.52‰ to -3.26‰ and the $\delta^{2}H_{VSMOW}$ values from -21.41‰ to -18.29‰. The isotopic composition of Cooksey is similar to groundwater in Austin chalk at Upper Proctor Spring at Cameron Park in Waco, Texas measured in early March of 2020. The spring flows through fractures in the Austin chalk and had an isotopic composition of -3.67‰ $\delta^{18}O$ VSMOW and -23.40‰ δD VSMOW. Slight differences may originate from anthropogenic inputs to the Bullhide Creek watershed or to the urban-influenced Proctor Springs springshed. Downstream, Rosenthal is similar to Cooksey but shows evidence of evaporation. Levi Pkwy indicates slightly less evaporation than Rosenthal, where small contributions to streamflow before this sample may dilute the isotopic signatures of the effluent that are dominated by

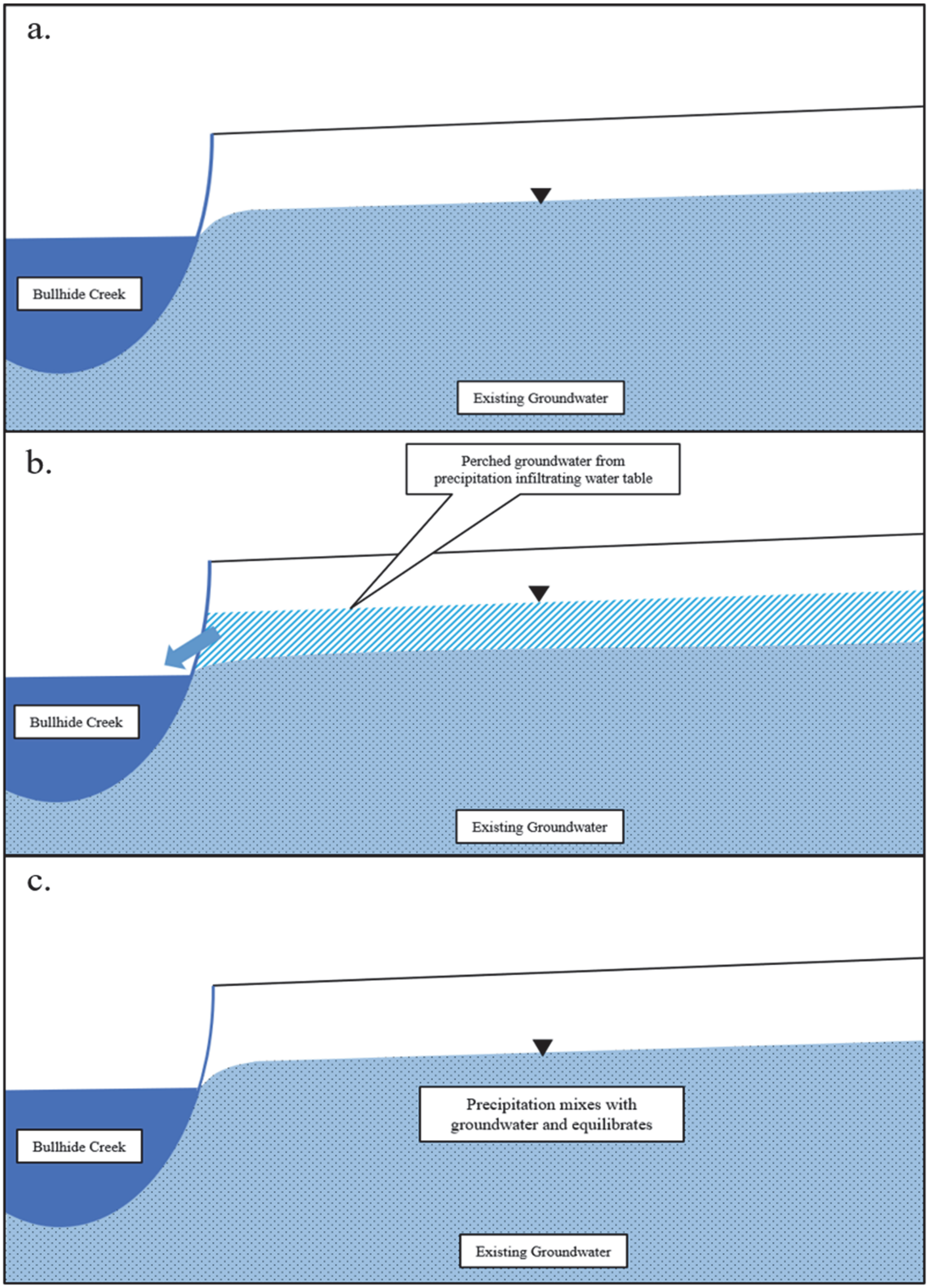


Figure 4.23. Diagram of groundwater stratification that may have caused the isotopic compositions of Bullhide Creek at FM 434 on 1/28/2021. a.) Bullhide Creek under general gaining conditions. b) Perched groundwater on the water table from recent precipitation events that have not wholly infiltrated the aquifer. C) Stratification is no longer present as groundwaters mix over time.

evaporation. Hwy 77 indicates the heaviest isotopic signature measured on both sample dates and is likely the result of the beaver dam ponding the streamflow at this location, allowing evaporation to impact the surface water.

Deuterium isotopic compositions at FM 434 and Arcosa are lighter in comparison to the water in the upstream portions of Bullhide Creek but are slightly heavier than the isotopes of this location taken in January. It is apparent that groundwater from the BRAA is present in these samples because the groundwater that is recharged through precipitation does not undergo as much evaporation as surface waters. In addition, if groundwater was absent in this section the isotopic compositions of FM 434 and Arcosa would likely be heavier than the sample taken at Hwy 77 as evaporation continuously occurs with distance.

Trends in the isotopic compositions of Bullhide Creek are distinctly different from 1/28/21 to 3/21/21 and are shown in Figure 4.25. An overall shift was observed due to general warmer temperatures in March than in January (seasonality). The isotopic compositions of Bullhide Creek downstream also indicate a larger influence of evaporation in the stream in March than observed in January. The isotopic composition of FM 434 varies greatly between the two sample dates. Whereas in January the creek was gaining a significant amount of groundwater due to an elevation in the water table onset by precipitation, the isotopic composition of FM 434 in March indicates that stratification in the aquifer was no longer occurring and Bullhide Creek gained groundwater with typical BRAA compositions for the region. Last, Bullhide Creek at Arcosa has an isotopic composition that indicates more evaporation present in the stream in March than in January and is likely due to the contribution of normal groundwater at FM 434 and warmer temperatures increasing the evaporation that occurs with distance.

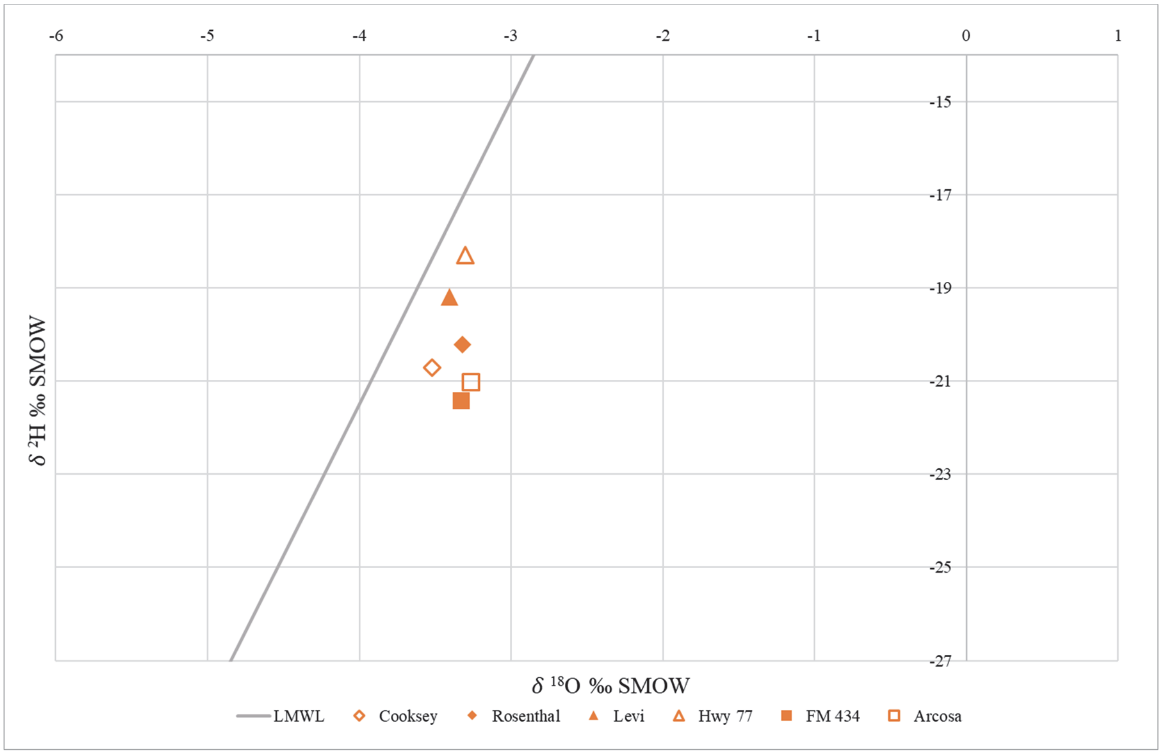


Figure 4.24. Bivariate plot of hydrogen versus oxygen isotopic composition of water samples from Bullhide Creek on 3/21/2021.

Precipitation Spatial Analysis: Floodplain Alluvium and Bullhide Creek

Bullhide Creek HAWQS Model

Streamflow of the Bullhide Creek watershed was simulated using the physics-based SWAT model through HAWQS for the period of 2014 through 2018 (Figure 4.26). Average streamflow was observed to be 35.50 cfs with a minimum flow of 0.00 cfs and maximum of 3.09 x 10^3 cfs on 10/31/2015. Due to baseflow contributions to Bullhide Creek classifying it as a perennial stream prior to the WMARSS BHC WWTP contribution, it is recognized that Bullhide Creek sustains flow year-round. SWAT generally lacks groundwater baseflow knowledge and is often coupled with groundwater models such as MODFLOW to account for groundwater contributions when they are well known This study followed Fant and others (2017) and used an added point source to the

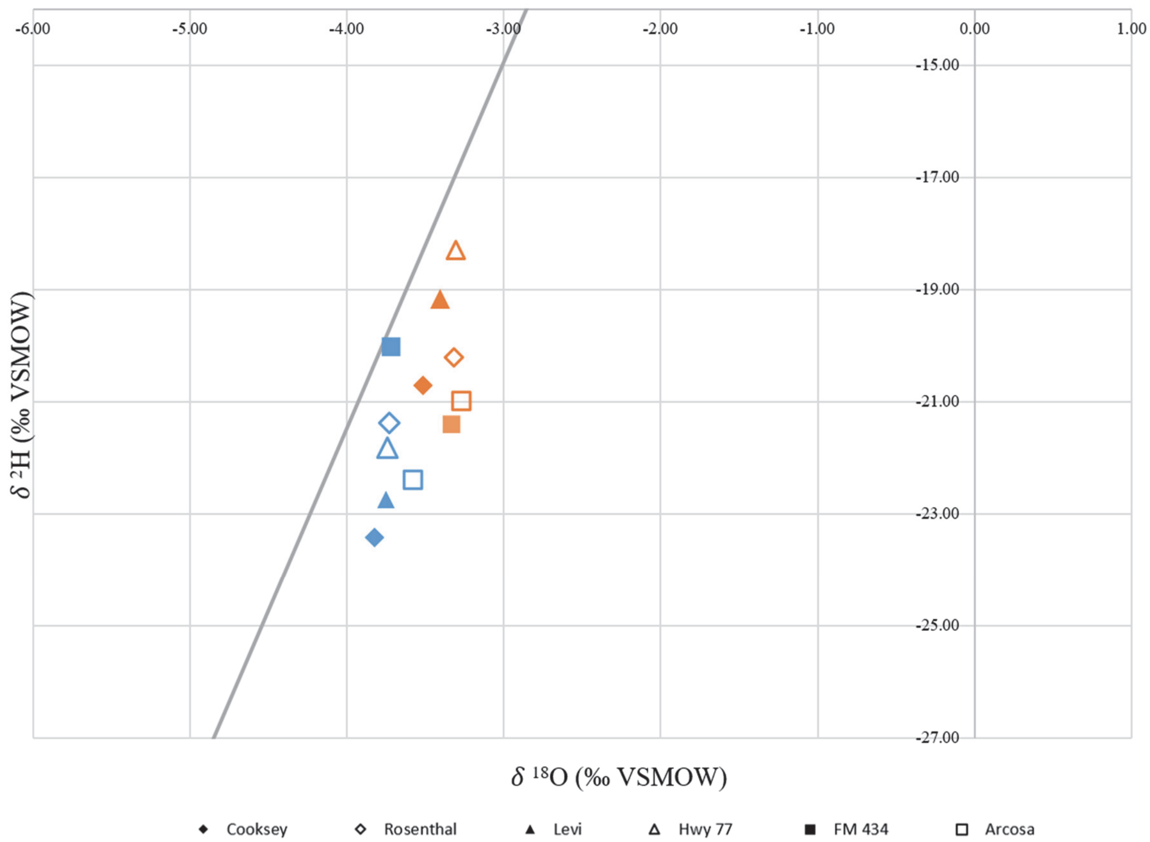


Figure 4.25. Bivariate plot of hydrogen versus oxygen isotopic composition of water samples from Bullhide Creek on 1/28/2021 (blue) and 3/21/20201 (orange).

upper reach instead of coupling SWAT with a groundwater model. As Bullhide Creek at Cooksey is dominated by groundwater contributions, a point source contribution to the reach of 7 cfs was added to the model based on flow measurements taken on 1/28/21 to determine if the magnitude of peak flow events was modified. There was no observed increase in streamflow or in magnitude of storm flow events, therefore the model is assumed adequate for simulating the number of peak flows because it uses recorded precipitation and updated land use, soils, and topographic characteristics.

Seasonal effects of flow in Bullhide Creek were well represented by the model. The wettest months in Waco, Texas, according to the 30-year normal observed by the

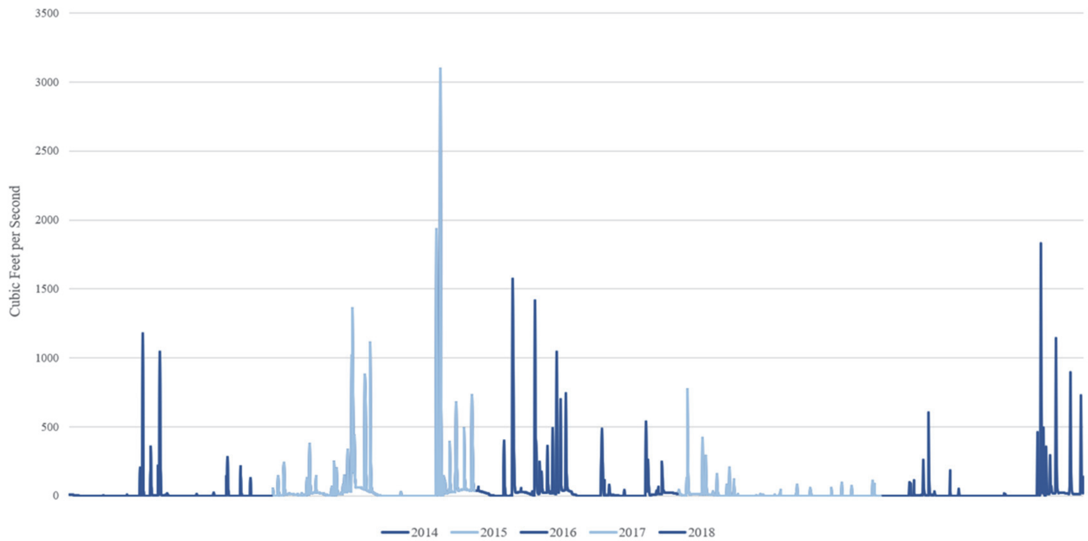


Figure 4.26. Graph of HAWQS simulated streamflow for the period of 2014-2018.

NOAA are May and October with an average monthly precipitation of 4.44 inches and 4.41 inches, respectively. HAWQS simulated 14 peak flow events for the period studied where 6 of them occurred during May and October and another five occurring in the subsequent months (June and November) due to saturation of the soil profile (Figure 4.27).

Events were considered peak flow events if the flow was larger than 725 cfs. According to the simulated stream flows between 2014 and 2018 there are, on average, 3.5 peak stormflow events. HAWQS indicated that 2015 saw the largest number of stormflow events with seven individual peak flows greater than 725 cfs and 2017 saw the fewest events with only one occurring above the threshold. Daily streamflow simulations for the 2014 to 2018 period can be found in appendix J. For the precipitation analysis, 2018 was chosen as it observed four peak events, similar to the average number, and each of the four events lasted several days and were at different magnitudes. The events to be studied are between the months of October and December.

ArcGIS Precipitation Recharge Analysis

Figure 4.28 shows the events used for this precipitation analysis. The simulated peak flows were well correlated with high precipitation events due to the model using observed data. Four high flow events between October to December 2020 were chosen due to their high peaks of ranging magnitudes. The high flow event on October 15 to 19 lasted three days and observed the largest streamflow of the events. November 11 through 13, December 7 to 9, and December 26 to 28 were of decreasing magnitudes and high flow in the stream lasted two days.

Precipitation totals for the four events ranged from 0.5 inches to upwards of five inches. The highest precipitation over the alluvium study area was between three and four inches during the first event. Figure 4.29 shows the precipitation totals for the four events. Because the designated Bullhide Creek watershed boundary overlies only a small portion of the BRAA, it was extended towards the Brazos River to determine aerial recharge provided to the aquifer adjacent to Bullhide Creek. The total area of the section of the aquifer studied was 7 mi^2, or 1.95×10^8. Table 4.9 gives the total precipitation that fell over the study area of the BRAA for each of the events and the estimated recharge that occurred. The largest rain event consisted of 6.50×10^7 ft^3 of water that fell over the study area and the smallest precipitation event consisted of a volume of 4.5×10^7 ft^3.

With the variables provided to the Darcy Equation, Bullhide Creek showed the potential to recharge the BRAA by 2,338,459 ft^3/day. For the 2- and 3-day events, total potential recharge provided ranges from 4,676,918 ft^3 to 7,015,378 ft^3, respectively.

When compared to aerial recharge, these estimates are much larger than the 2% estimate of recharge through the precipitation events and are comparable to the 10% estimate. Recharge values calculated for Bullhide Creek may be an overestimate because the gradient is not a known value and the hydraulic conductivity of the sediments may vary, however, aquifer material has both higher and lower conductivity values than that used for calculations as coarse gravels and silty sands are both present. In total, Bullhide Creek may provide significant recharge to the adjacent aquifer sediments in comparison to precipitation recharge, which is considered the aquifer’s primary source. Once the water levels in the creek decline, groundwater may reverse direction and discharge back into Bullhide Creek, potentially minimizing the recharge stored.

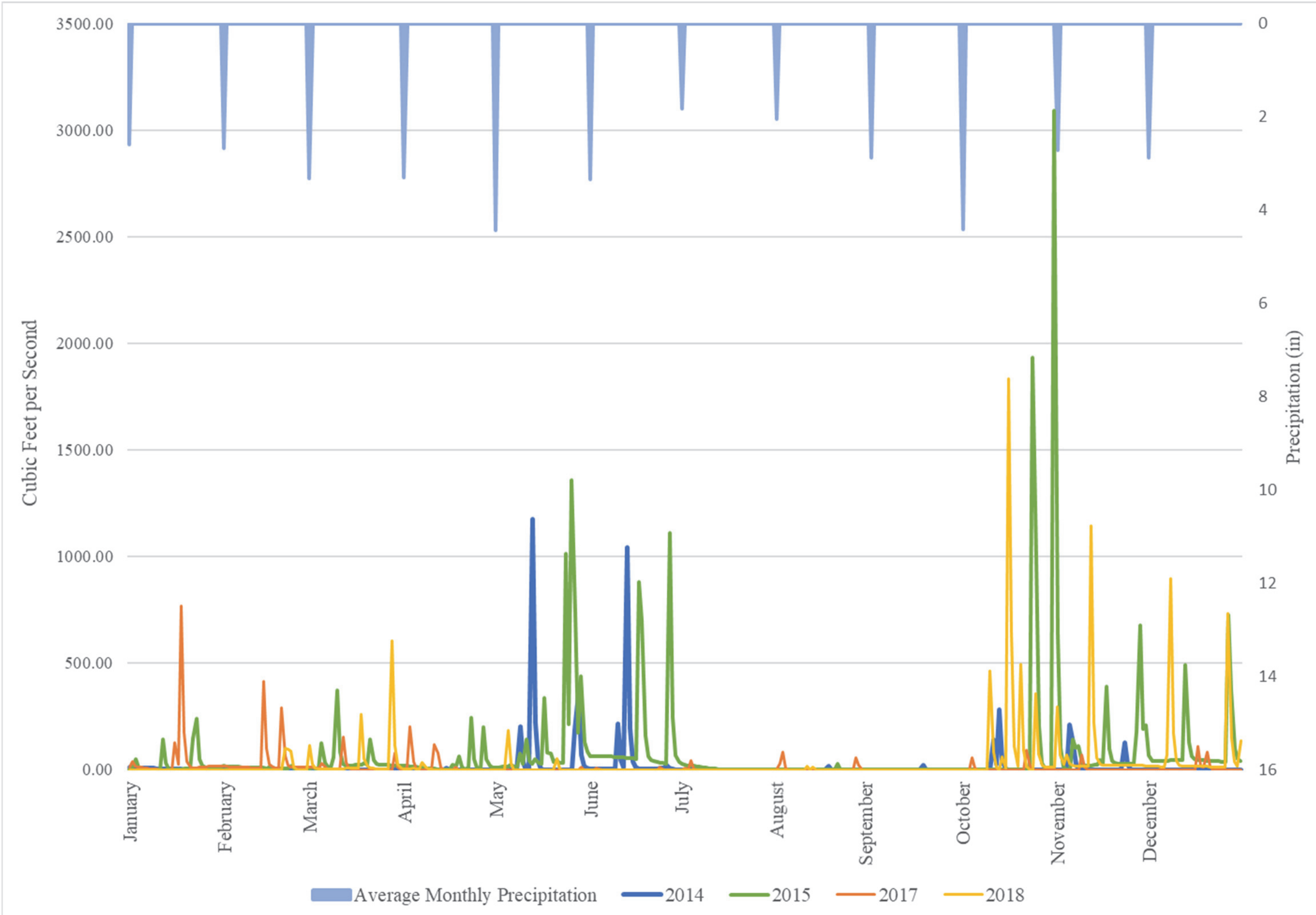


Figure 4.27. Line graph of HAWQS simulated annual streamflow in Bullhide Creek for the 2014-2018 period in comparison to the NOAA 30-year normal monthly precipitation from 1990-2020

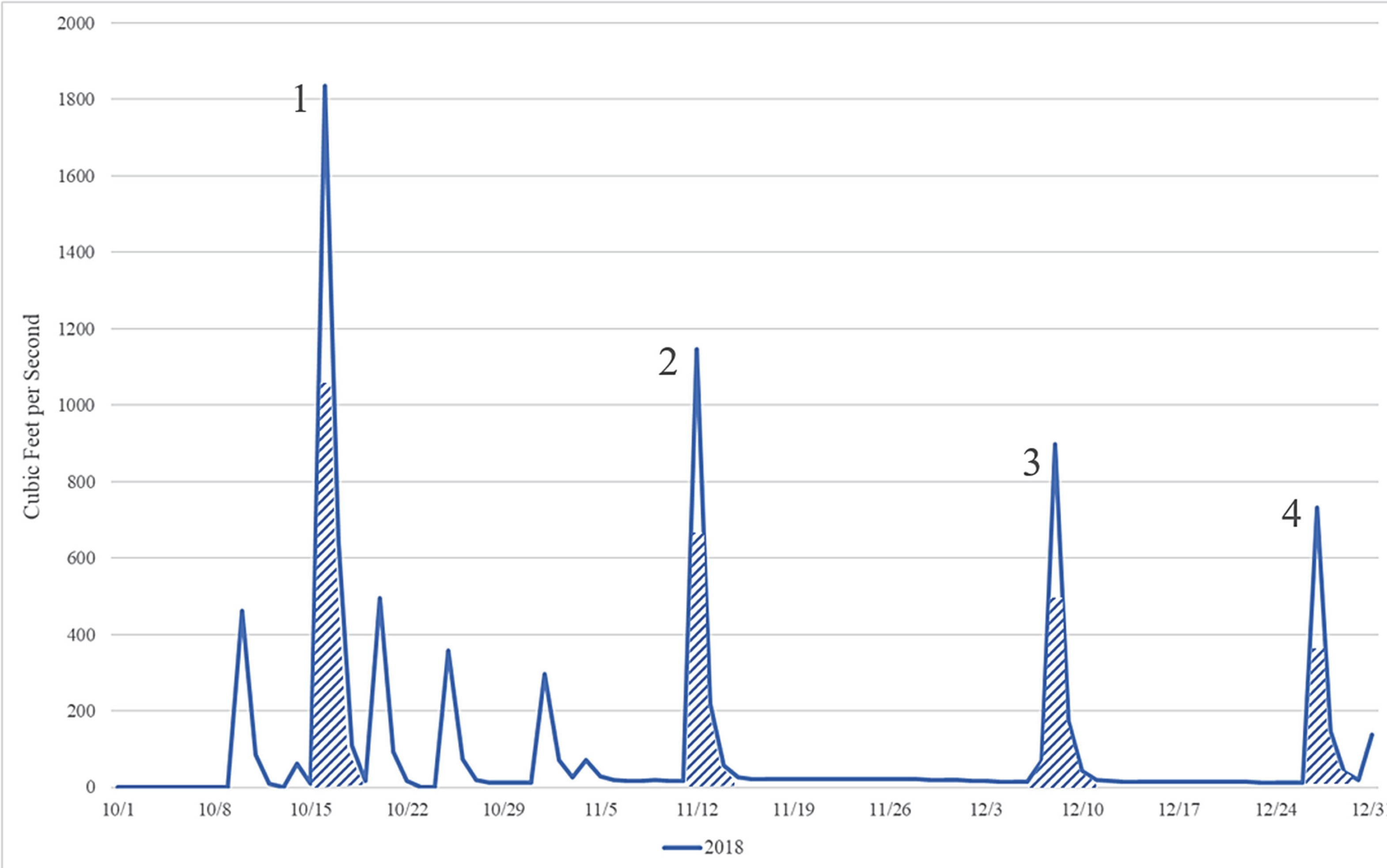


Figure 4.28. Line graph of HAWQS simulated streamflow in Bullhide Creek for the 2018 period. Cross hatches indicate the periods of high flow within the stream, where the peaks are very short events.

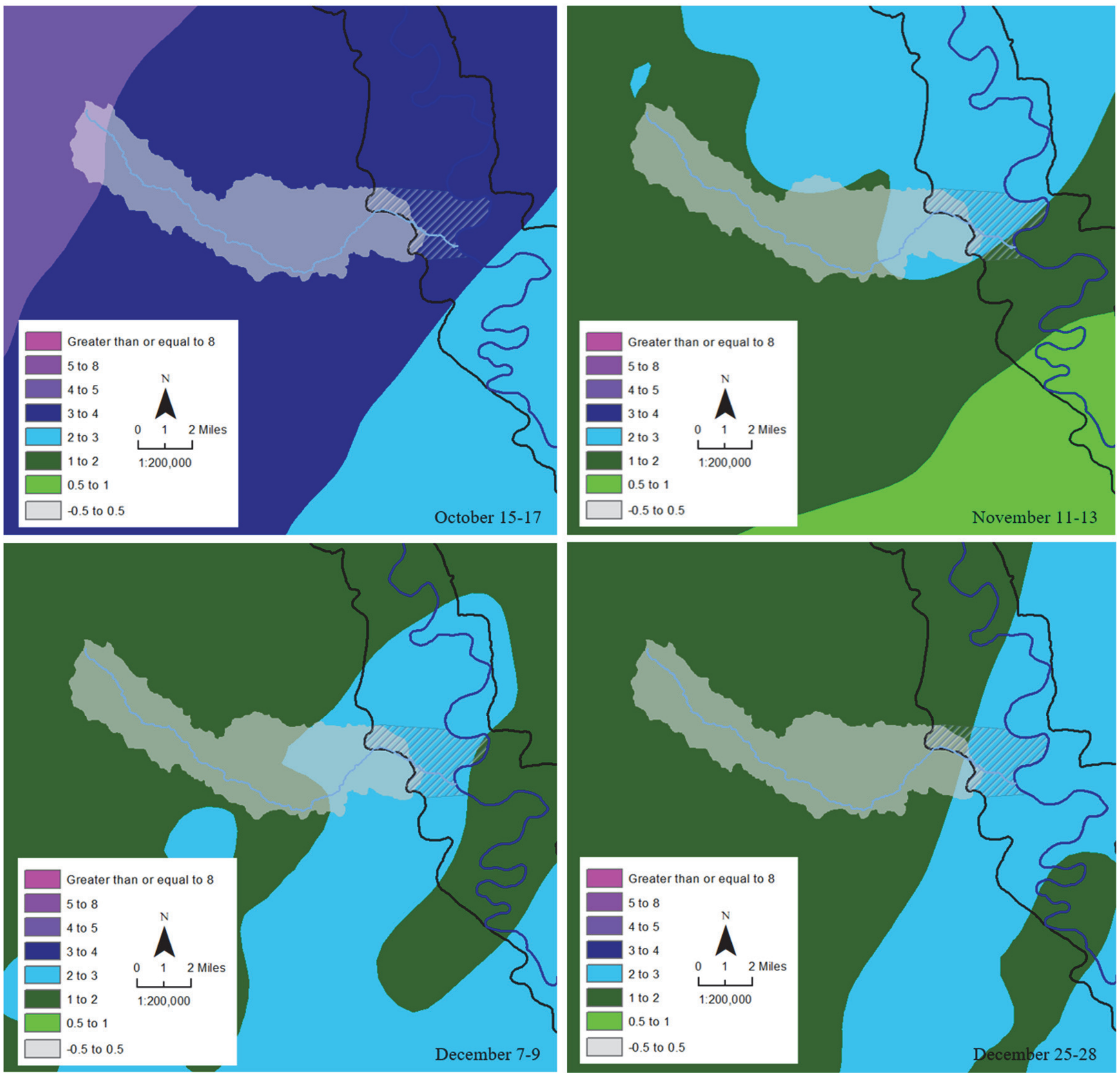


Figure 4.29. Maps of total precipitation over the study area for the simulated peak streamflow events. The Bullhide Creek watershed is in gray and the crosshatching over the aquifer boundary is the study area over the BRAA, determined by extending the watershed boundaries to the Brazos River

Table 4.9. Recharge estimates comparing aerial recharge to the BRAA adjacent to Bullhide Creek in comparison to that from Bullhide Creek during high flow events.

Event	1	2	3	4
Total Precipitation (ft^3)	6.50×10^7	4.62×10^7	4.81×10^7	4.53×10^7
Aerial Recharge (ft^3)				
2% (1)	1.30×10^6	9.25×10^5	9.62×10^5	9.06×10^5
10% (2)	6.50×10^6	4.62×10^6	4.81×10^6	4.53×10^6
Tributary Recharge (ft^3)				
Duration of High Flow Event (days)	3	2	2	2
Seepage into BRAA (ft^3/day)	2.34×10^6	2.34×10^6	2.34×10^6	2.34×10^6
Total Recharge from Bullhide Creek (ft^3)	7.02×10^6	4.68×10^6	4.68×10^6	4.68×10^6

(1) from Chowdery and others (2010) where 2% of annual precipitation is estimated as recharge to the BRAA
(2) from Cronin and Wilson (1967) where 10% of annual precipitation is estimated as recharge to the BRAA.

CHAPTER FIVE

Summary and Conclusions

1. Bullhide Creek receives flow contributions from the WMARSS BHC WWTP and the Brazos River Alluvium Aquifer, with about a 30% increase in streamflow measured for each contributor. However, Bullhide Creek likely loses flow to the aquifer downstream from the aquifer boundary. Tributary contribution also provides measurable streamflow to the middle reach in the weeks prior to precipitation events, however in drier periods effluent has a larger presence in Bullhide Creek.
2. Specific conductance for the entire reach increased by 57% with primary origin from the Brazos River Alluvium Aquifer. High salinity levels in the aquifer discharge large amounts of TDS into Bullhide Creek during gaining periods characteristic of baseflow. The effluent outflows and tributary contribution near Levi Pkwy also increased salinity levels in the stream, however low TDS in the upstream flow minimized the impact of the salinity influxes.
3. Primary nutrient loads to Bullhide Creek under baseflow conditions are from the WMARSS BHC WWTP and the Brazos River Alluvium Aquifer. The wetlands efficiently reduced nitrogen and phosphorus concentrations in the effluent by 79% and 66% respectively. Tributary streams transport nutrients from the uplands to the creek, and the BRAA caused an increase in nitrogen of 110% and phosphorus of 276% within Bullhide Creek perhaps due to ubiquitous agricultural practices on the alluvium surface.

4. The ionic chemistry of the waters of Bullhide Creek indicate mostly calcium bicarbonate type waters with a mixed type near Levi Pkwy. The effluent adds large amounts of chloride, sulfate, and sodium to the creek and the aquifer further increases the concentrations of sulfate, calcium, magnesium, and sodium. Longer residence times of groundwater allow the increase in dissolved ions; however, Levi Pkwy observed the largest increase and total concentration in sodium for the entire reach at 84.6 mg/L from effluent concentrated flow.
5. The $\delta^{18}O$ and δD isotopic compositions of waters within Bullhide Creek indicate seasonal warming trends between the two sample dates. March samples indicated higher levels of evaporation in Bullhide Creek during dry baseflow conditions. Isotopic compositions of the effluent indicated large amounts of evaporation that increased heavy signatures observed in the creek. Tributary streams brought lighter isotope due to precipitation induced flow on 1/28/21, however without the influx of tributary contribution upstream, Hwy 77 on 3/21/21 was the heaviest location due to extensive evaporation resulting from the beaver dam. Bullhide Creek near the BRAA boundary on 1/28/21 indicated increased groundwater discharge due to previous precipitation events, however on 3/21/21, the water table receded and groundwater signatures indicate significant levels of evaporation.
6. Physical modeling of the Bullhide Creek watershed through HAWQS produced, on average, 3.5 annual storm flow events that may recharge the aquifer. Peak flow events were well correlated with the two wettest months of the year according to

the 30-year climate normal in Waco, Texas, where 11 out of 14 peak flow events occurred in during these months and one month after.

7. The capability of Bullhide Creek to recharge the BRAA during periods of heightened stream flow is comparable to the recharge provided by precipitation on the adjacent floodplain, given the estimates made. Although recharge may by localized and a smaller percentage of the water entering the aquifer during these events may be stored, the potential for tributary streams to provide recharge the BRAA during periods of high flow warrants further studies.

Summary

1. Overall, under baseflow conditions, Bullhide Creek receives point source discharges that substantially affect the quantity and quality of the stream. The creek primarily gains from the Brazos River Alluvium Aquifer near the bedrock/alluvium boundary; however, Bullhide Creek may provide significant and measurable recharge to the adjacent portion of the Brazos River Alluvium Aquifer in periods of increased streamflow. The presence of effluent and cropland runoff in the creek may affect recharge quality to the aquifer, potentially diluting elevated levels of nutrients and salinity present within the groundwater.

CHAPTER SIX

Recommendations

1. This study worked to characterize a tributary stream under baseflow conditions and the investigate the potential to provide significant recharge to the Brazos River Alluvium Aquifer. Tributaries have not been widely considered potential recharge sources, however given the potential detailed in this study, more work should be performed to understand the interactions between tributary streams and the BRAA.
2. If tributary streams are to be investigated as recharge sources, they need to be discretely studied on an individual basis due to extremely varying characteristics. Spatial and temporal trends vary between streams and portions of the aquifer and will need individual examination.
3. Preexisting data were not available for this study as most Brazos River tributaries are ungauged. Increasing the number of gauged tributaries would help to constrain the spatial and temporal interactions between them and the Brazos River Alluvium Aquifer and help further studies to determine the widespread significance of recharge offered from this source. Stream gauges would also allow model calibration to be performed on SWAT/HAWQS models, which would improve the understanding and management of these tributaries.
4. Bullhide Creek was primarily investigated under baseflow conditions to receive a foundational understanding of the stream and its dynamics, however more work is needed to gain a full understanding of the physical and chemical components of

the stream. Storm flow events may alter the dissolved constituents and conductance of the creek, affecting the quality of potential recharge to the aquifer during these events.

5. Oxygen and hydrogen isotopes were utilized in this study to investigate sources of streamflow contributors to Bullhide Creek. Many sources and trends were observed, and the addition of nitrogen isotope analyses may be able to constrain sources and concentrations of nutrient additions to the creek.

APPENDICES

APPENDIX A

Table A.1. Mini-Piezometer Study Results from Fall 2020

Location	DoM	Behavior	Gradient
Cedar Creek	6/9/20	G	0.020
Dry Creek	6/20/20	L	0.240
Cottonwood Creek	7/6/20	G	0.025
Giles Branch	7/6/20	G	0.96
McKenzie Branch	7/6/20	G	0.85
Bullhide Creek			
434	6/22/20	G	0.14
434	7/6/20	G	0.15
434	9/16/20	G	0.11
434	10/20/20	L	0.21
434	11/20/20	L	0.38
Arcosa	10/20/20	G	0.03
Arcosa	11/20/20	L	0.13
Flat Creek			
bridge	6/17/20	G	0.186
bridge	6/22/20	G	0.187
bridge	7/6/20	G	0.012
bridge	8/22/20	dry stream	-
bridge	9/7/20	washed out	-
bridge	11/9/20	G	1.360
Sandy Creek			
bridge-old	6/22/20	G	0.019
bridge-old	8/20/20	L	0.005
middle	8/20/20	L	0.095
bridge-new	9/10/20	G	0.031
downstream	9/10/20	G	0.182
bridge-new	9/23/20	G	0.013
downstream	9/23/20	G	0.172
bridge-new	11/9/20	L	0.014
downstream	11/9/20	G	0.066

APPENDIX B

Effluent Limitations and Monitoring Rudiments per the WMARSS BHC WWTP Permit

City of Waco, City of Woodway, City of Bellmead, City of Lacy Lakeview, City of Robinson, City of Hewitt and City of Lorena

TPDES Permit No. WQ0014889001

EFFLUENT LIMITATIONS AND MONITORING REQUIREMENTS

Outfall Number 001

1. During the period beginning upon the date of issuance and lasting through the date of expiration the permittee is authorized to discharge subject to the following effluent limitations:

   The annual average flow of effluent shall not exceed 1.5 million gallons per day (MGD); nor shall the average discharge during any two-hour period (2-hour peak) exceed 4,167 gallons per minute (gpm).

Effluent Characteristic	Discharge Limitations				Minimum Self-Monitoring Requirements	
	Daily Avg	7-day Avg	Daily Max	Single Grab	Report Daily Avg. & Daily Max.	
	mg/l(lbs/day)	mg/l	mg/l	mg/l	Measurement Frequency	Sample Type
Flow, MGD	Report	N/A	Report	N/A	Continuous	Totalizing Meter
Carbonaceous Biochemical Oxygen Demand (5-day)	7 (88)	12	22	32	Two/week	Composite
Total Suspended Solids	15 (188)	25	40	60	Two/week	Composite
Ammonia Nitrogen	3 (38)	6	10	15	Two/week	Composite
Total Phosphorus	1.0 (13)	2	4	6	Two/week	Composite
Total Nitrogen	Report (Report)	N/A	Report	N/A	Two/week	Composite
E. coli Bacteria colonies per 100 ml	126	N/A	394	N/A	One/day	Grab

2. The permittee shall utilize an Ultraviolet Light (UV) system for disinfection purposes. An equivalent method of disinfection may be substituted only with prior approval of the Executive Director.
3. The pH shall not be less than 6.0 standard units nor greater than 9.0 standard units and shall be monitored once per week by grab sample.
4. There shall be no discharge of floating solids or visible foam in other than trace amounts and no discharge of visible oil.
5. Effluent monitoring samples shall be taken at the following location(s): Following the final treatment unit and prior to entering the Bonus Feature.*
6. The effluent shall contain a minimum dissolved oxygen of 5.0 mg/l and shall be monitored twice per week by grab sample.
7. The annual average flow and maximum 2-hour peak flow shall be reported monthly.

* (See Other Requirements Number 10 on page 24)

APPENDIX C

Streamflow Measurement Procedures

Before all field measurements, the OTT MF Pro velocity meter was charged and calibrated by faculty in the Environmental Sciences Department at Baylor University. Location of streamflow measurements were chosen at each sample point based on characteristics of the stream. Obstructions of flow were avoided as much as possible and uniform sections were chosen over those with large pools or shallow ripples.

A measurement tape was placed from one side of the bank to the other and the width of the channel was recorded. Measurements were taken at one-foot increments across the creek and the depth of the channel at each location was recorded. When measuring the velocity, the measurement was not recorded until the display indicated a consist reading. This was indicated by the "plateauing" of the line, where a stable measurement indicated a consistent velocity being measured by the meter. Inconsistent or varying readings are indicated by peaks and valleys or disjointed lines and were allowed to stabilize until the velocity was recorded. Measurements could take between 30 seconds and over a minute before plateaus were reached and were consisted representative of channel velocity.

APPENDIX D

Water Sampling Procedures

Before all water sampling, a chain of custody was attained for each sample set to be filled out after each sample collection in the field. Trip blanks for each sample set were performed in the lab to check against possible contamination from the lab, procedures, or DI water. A field blank of DI water was collected at a random site on each sampling trip during this study to check against possible contamination from the field sites, procedures, or DI water. In addition, a field duplicate was collected to check the precision of the laboratory. All blanks and duplicates were prepared according the sampling guidelines below.

Water samples collected from Bullhide Creek for nutrient and dissolved ion analysis were collected using a syringe that was triple rinsed in the creek at each specific location and then filtered using a 0.45 μm syringe filter. In addition, the first few drops of sample discharged through each new filter were discarded and filters were changed at each location. Filtered water was collected into sterile sample tubes that were then labeled and put on ice. All sampling equipment was triple rinsed with DI water between samples and then rinsed in situ with creek water to prevent dilution of measurements or contamination from previous sites. CRASR sampling procedures included filling 40 mL of sample in a 50 mL sample bottle whereas BIO CHEM sampling procedures involved filling a 250 mL sample bottle with at least 100 mL of sample. The cations were acidized with nitric acid and anions were not acidized. All samples were placed on ice prior to sampling and then refrigerated until analysis.

The Department of Geosciences Stable Isotope Lab sampling procedures required leaving no head space in the sample bottle and taping the lid of the sample bottle with electrical tape to prevent isotope fractionation due to evaporation from occurring after collection. All samples were refrigerated until analysis.

Water samples for titrations were collected in a sterile 250 mL bottle and placed on ice. Once in the lab, 50 mL of water sample was placed in a 200 mL glass beaker and a burette with a stopcock was willed with 0.0200 N sulfuric acid. The initial pH and temperature of the sample were recorded. The initial volume of acid in the burette was recorded and sulfuric acid was slowly added to the sample, stirring the solution and recording the pH of the solution and acid volume in the burette after each addition. Sulfuric acid was added until a pH of 2.9 was reached. Them, the pH of the solution was plotted against milliliters of acid used to determine the inflection point, which represent the amount of acid to neutralize all of the bicarbonate in solution. The concentration of the bicarbonate in the sample was then calculated using the volume of water sample, volume of sulfuric acid, and normality of the sulfuric acid.

Before all conductivity sampling, the YSI Pro DSS was calibrated using a 1,413 µS/cm conductivity standard. Tap water was always in the probe cap during storage and between measurements so that the probe did not dry and skew calibration efforts. In the field, the measurement probe was triple rinsed in the creek before placed in the channel for water measurement.

APPENDIX E

Table E.1. HRU Classifications for the Bullhide Creek Basin

SWAT_ID	Print_ID	Subbasin	Soil	Area	Slope	Fraction	Land_Use	OV_N	Slope_Length	Slope_Class	CN2	HRU
10001	1	1.21E+11	TX514	1.10696	0.01739	0.01184	CORN	0.14	121.9512	0-1	87	120701010101TX514CORN1
10002	2	1.21E+11	TX235	3.286664	0.03218	0.035153	URLD	0.1	91.46341	0-1	79	120701010101TX235URLD1
10003	3	1.21E+11	TX235	9.540986	0.03146	0.102048	HAY	0.3	91.46341	0-1	79	120701010101TX235HAY1
10004	4	1.21E+11	TX235	7.557515	0.02934	0.080833	CORN	0.14	91.46341	0-1	87	120701010101TX235CORN1
10005	5	1.21E+11	TX515	1.090858	0.03174	0.011668	RNGE	0.15	91.46341	0-1	69	120701010101TX515RNGE1
10006	6	1.21E+11	TX514	2.02473	0.03193	0.021656	RNGE	0.15	91.46341	0-1	84	120701010101TX514RNGE1
10007	7	1.21E+11	TX034	12.82262	0.03333	0.137148	RNGE	0.15	91.46341	0-1	79	120701010101TX034RNGE1
10008	8	1.21E+11	TX235	1.790289	0.02778	0.019149	CTCR	0.14	91.46341	0-1	87	120701010101TX235CTCR1
10009	9	1.21E+11	TX235	1.152244	0.02396	0.012324	SGHY	0.143	91.46341	0-1	87	120701010101TX235SGHY1
10010	10	1.21E+11	TX035	17.67412	0.03205	0.189038	RNGE	0.15	91.46341	0-1	79	120701010101TX035RNGE1
10011	11	1.21E+11	TX035	1.973407	0.02939	0.021107	WWHT	0.15	91.46341	0-1	81	120701010101TX035WWHT1
10012	12	1.21E+11	TX235	1.502446	0.03375	0.01607	WETF	0.05	91.46341	0-1	84	120701010101TX235WETF1
10013	13	1.21E+11	TX034	2.237065	0.03254	0.023927	URLD	0.1	91.46341	0-1	72	120701010101TX034URLD1
10014	14	1.21E+11	TX035	1.809376	0.03181	0.019353	URLD	0.1	91.46341	0-1	72	120701010101TX035URLD1
10015	15	1.21E+11	TX034	1.963344	0.03137	0.020999	WHTC	0.14	91.46341	0-1	81	120701010101TX034WHTC1
10016	16	1.21E+11	TX034	7.020137	0.03203	0.075086	HAY	0.3	91.46341	0-1	72	120701010101TX034HAY1
10017	17	1.21E+11	TX235	13.31572	0.03251	0.142422	RNGE	0.15	91.46341	0-1	84	120701010101TX235RNGE1
10018	18	1.21E+11	TX235	2.008629	0.01928	0.021484	CWHT	0.14	121.9512	0-1	87	120701010101TX235CWHT1
10019	19	1.21E+11	TX235	1.987496	0.02861	0.021258	WHTC	0.14	91.46341	0-1	84	120701010101TX235WHTC1
10020	20	1.21E+11	TX034	1.63025	0.02988	0.017437	WWHT	0.145	91.46341	0-1	81	120701010101TX034WWHT1

APPENDIX F

Table F.1. HAWQS HRU Land Use Explanations

Land Use	Explanation	% of Total Area
RNGE	Range-Grasses	50.19
HAY	Hay	17.71
CORN	Corn	9.27
URLD	Urban- Low Density	7.84
WWHT	Winter Wheat	3.85
WHTC	Winter Wheat-Corn Rotation	4.23
CWHT	Corn-Winter Wheat Rotation	2.15
WETF	Wetlands-Forested	1.61
CTCR	Upland Cotton/Corn	1.91
SGHY	Sorghum Hay	1.23

APPENDIX G

Table G.1. Average Monthly Effluent Recorded by the WMARSS BHC WWTP for HAWQS Input

Month	Average Monthly Effluent (MGD)	Average Daily Effluent (cfs)
Jan-12	0.808	1.51
Feb-12	0.737	1.37
Mar-12	0.872	1.62
Apr-12	0.818	1.52
May-12	0.972	1.81
Jun-12	0.952	1.77
Jul-12	0.643	1.20
Aug-12	0.674	1.26
Sep-12	0.642	1.20
Oct-12	0.783	1.46
Nov-12	0.950	1.77
Dec-12	0.965	1.80
Jan-13	0.808	1.51
Feb-13	0.737	1.37
Mar-13	0.872	1.62
Apr-13	0.818	1.52
May-13	0.972	1.81
Jun-13	0.952	1.77
Jul-13	0.643	1.20
Aug-13	0.674	1.26
Sep-13	0.642	1.20
Oct-13	0.783	1.46
Nov-13	0.950	1.77
Dec-13	0.965	1.80
Jan-14	0.732	1.36
Feb-14	0.653	1.22
Mar-14	0.604	1.13
Apr-14	0.600	1.12
May-14	0.782	1.46
Jun-14	0.957	1.78
Jul-14	0.615	1.15
Aug-14	0.582	1.08
Sep-14	0.596	1.11

Average Monthly Effluent Recorded by the WMARSS BHC WWTP for HAWQS Input, continued.

Month	Average Monthly Effluent (MGD)	Average Daily Effluent (m^3/d)
Oct-14	0.620	1.15
Nov-14	0.677	1.26
Dec-14	0.623	1.16
Jan-15	0.768	1.43
Feb-15	0.680	1.27
Mar-15	0.979	1.82
Apr-15	0.824	1.54
May-15	1.519	2.83
Jun-15	1.199	2.23
Jul-15	0.668	1.24
Aug-15	0.567	1.06
Sep-15	0.563	1.05
Oct-15	0.834	1.55
Nov-15	1.595	2.97
Dec-15	1.533	2.86
Jan-16	1.102	2.05
Feb-16	0.834	1.55
Mar-16	1.272	2.37
Apr-16	1.110	2.07
May-16	1.170	2.18
Jun-16	1.291	2.41
Jul-16	0.675	1.26
Aug-16	0.827	1.54
Sep-16	0.653	1.22
Oct-16	0.599	1.12
Nov-16	0.634	1.18
Dec-16	0.691	1.29
Jan-17	0.784	1.46
Feb-17	0.833	1.55
Mar-17	0.742	1.38
Apr-17	0.848	1.58
May-17	0.666	1.24
Jun-17	0.651	1.21
Jul-17	0.612	1.14
Aug-17	0.685	1.28
Sep-17	0.643	1.20
Oct-17	0.623	1.16
Nov-17	0.617	1.15
Dec-17	0.663	1.24
Jan-18	0.655	1.22
Feb-18	0.688	1.28

Average Monthly Effluent Recorded by the WMARSS BHC WWTP for HAWQS Input, continued.

Month	Average Monthly Effluent (MGD)	Average Daily Effluent (m^3/d)
Mar-18	0.762	1.42
Apr-18	0.709	1.32
May-18	0.722	1.35
Jun-18	0.662	1.23
Jul-18	0.648	1.21
Aug-18	0.706	1.32
Sep-18	0.754	1.40
Oct-18	1.238	2.31
Nov-18	1.223	2.28
Dec-18	1.312	2.45

APPENDIX H

Table H.1. Monthly Average Effluent Nutrients from the WMARSS BHC WWTP as Reported by CWUSS

	NO2	**NO3**	**TKN**	**TN**	**NH3**	**TP**
Jan-20	0.11	13.19	1.23	14.54	0.15	0.17
Feb-20	0.16	9.90	1.49	11.54	0.25	0.22
Mar-20	0.11	9.44	1.51	11.06	0.27	0.65
Apr-20	0.10	8.95	1.34	10.39	0.17	0.17
May-20	0.13	6.84	2.05	9.02	0.74	0.23
Jun-20	0.19	13.19	2.17	15.56	0.30	0.67
Jul-20	0.31	19.24	1.58	21.13	0.25	0.24
Aug-20	0.51	17.64	1.95	20.10	0.61	0.83
Sep-20	0.36	20.79	1.86	23.01	0.48	0.42
Oct-20	0.38	17.21	2.21	19.80	0.30	0.51
Nov-20	0.38	18.61	1.97	20.96	0.21	0.29
Dec-20	0.43	18.50	2.59	21.52	0.26	0.81
Jan-21	0.46	12.28	2.10	14.84	0.36	0.47
Feb-21	0.41	14.31	1.78	16.51	0.39	0.43

APPENDIX I

In Depth Isotopic Analyses of Bullhide Creek

Table I.1. Isotopic compositions and analyses of Bullhide Creek and Outflow "G" sampled on 1/28/2021.

Sample ID	$\delta^{18}O$ VSMOW	δD VSMOW	Standard	$\delta^{18}O$ VSMOW	Lab value	δD VSMOW	Lab value
u1	-3.83	-23.43	ICE REF3	-33.44	**-33.78±0.14‰**	-268.75	**-267.14±1.64‰**
out	-3.55	-22.83	ICE REF3	-33.62		-266.74	
d1	-3.63	-22.41	**Avg:**	**-33.53**		**-267.75**	
d2	-3.73	-21.39	**STDEV:**	**0.13**		**1.42**	
d3	-3.75	-22.73					
d4	-3.74	-21.81					
d5	-3.71	-20.05					
d6	-3.57	-22.42					
Total: 16 analyses							

Table 1.2. Isotopic compositions and analyses of Bullhide Creek sampled on 3/21/2021.

Sample ID	$\delta^{18}O$ VSMOW	δD VSMOW	Standard	$\delta^{18}O$ VSMOW	Lab value	δD VSMOW	Lab value
u1	-3.52	-20.71	ICE REF3	-33.54	**-33.77±0.15‰**	-266.36	**-267.15±1.60‰**
d2	-3.32	-20.22	ICE REF3	-33.58		-267.46	
d3	-3.40	-19.18	**Avg:**	**-33.56**		**-266.91**	
d4	-3.30	-18.29	**STDEV:**	**0.03**		**0.78**	
d5	-3.33	-21.41					
d6	-3.26	-21.02					
Total: 12 analyses							

Appendix J

Table J.1. HAWQS Simulated Streamflow in Bullhide Creek

Day	2014	2015	2016	2017	2018
1	10.23	0.00	37.79	13.00	0.00
2	9.25	4.73	36.73	40.26	0.00
3	8.83	50.85	36.73	16.85	0.00
4	8.40	8.72	36.73	11.69	0.00
5	7.84	0.00	36.37	10.24	0.00
6	7.38	0.00	35.67	8.58	0.00
7	6.96	0.00	65.33	7.88	0.00
8	6.46	0.00	41.32	5.09	0.00
9	5.97	0.00	35.67	4.34	0.00
10	5.44	0.00	33.69	2.94	0.00
11	4.91	0.00	32.74	1.16	0.00
12	4.87	140.55	31.68	0.90	0.00
13	3.64	30.44	30.62	0.91	0.00
14	3.16	7.20	30.12	0.48	0.00
15	2.78	2.52	28.32	0.19	0.00
16	2.31	2.25	27.44	125.72	0.00
17	1.90	2.62	26.31	23.66	0.00
18	1.52	2.88	25.14	769.86	0.00
19	1.04	3.39	23.94	176.57	0.00
20	0.64	3.64	23.24	38.14	0.00
21	0.22	3.78	21.47	13.28	0.00
22	0.34	148.32	20.24	9.85	0.00
23	0.00	238.02	18.96	9.82	0.00
24	0.00	49.79	17.55	11.72	0.00
25	0.00	16.67	16.24	12.96	0.00
26	0.00	11.23	11.72	14.06	0.00
27	0.00	10.95	10.21	14.83	0.00
28	0.00	11.87	9.29	15.36	0.00
29	0.00	12.54	5.90	15.68	0.00
30	0.00	13.07	5.90	15.72	0.00
31	0.00	13.56	5.72	15.79	0.00
32	0.00	19.28	4.03	14.87	0.00
33	0.00	15.04	1.63	14.48	0.00
34	0.00	13.38	1.66	14.02	0.00

HAWQS Simulated Streamflow in Bullhide Creek, continued.

Day	2014	2015	2016	2017	2018
35	0.00	13.03	1.70	13.74	0.00
36	0.00	12.82	0.00	13.24	0.00
37	0.00	12.61	0.00	12.40	0.00
38	0.00	11.97	0.00	11.72	0.00
39	0.00	11.41	0.00	11.12	0.00
40	0.00	10.88	0.00	10.42	0.00
41	0.00	10.42	0.00	9.92	0.00
42	0.00	9.71	0.00	9.53	0.00
43	0.00	9.15	0.00	7.13	0.00
44	0.00	9.29	0.00	6.75	0.00
45	0.00	8.12	0.00	416.71	0.00
46	0.00	7.42	0.00	99.94	0.00
47	0.00	13.70	0.00	25.00	0.00
48	0.00	9.78	0.00	10.28	0.00
49	0.00	6.18	0.00	7.59	0.00
50	0.00	5.16	0.00	6.75	0.00
51	0.00	4.52	0.00	288.87	0.00
52	0.00	3.92	0.00	64.27	100.29
53	0.00	4.10	208.36	20.38	96.06
54	0.00	20.27	399.06	11.80	87.93
55	0.00	7.10	72.40	10.21	14.13
56	0.00	3.33	11.80	10.21	0.00
57	0.00	10.28	0.29	10.42	0.00
58	0.00	4.73	0.00	10.63	0.00
59	0.00	3.60	0.00	10.28	0.00
60	0.00	3.88	0.00	10.17	111.95
61	0.00	8.97	0.12	10.17	24.68
62	3.14	5.69	0.05	9.89	6.07
63	0.00	5.76	1.09	9.22	3.22
64	0.00	126.07	1.30	30.69	3.23
65	0.00	33.65	1.55	14.55	3.92
66	0.00	13.98	1.22	5.51	4.77
67	0.00	10.06	0.99	3.31	4.63
68	0.00	58.98	1.32	2.63	5.51
69	0.00	374.34	1575.03	1.29	5.54
70	0.00	83.34	942.90	0.00	5.51
71	0.00	29.81	209.42	155.74	5.37
72	0.00	20.31	317.13	33.44	5.90
73	0.00	19.88	74.51	7.73	6.22
74	0.00	20.69	28.43	1.81	6.43
75	0.00	21.58	21.12	0.21	6.50
76	0.00	22.00	21.29	0.16	6.25

HAWQS Simulated Streamflow in Bullhide Creek, continued.

Day	2014	2015	2016	2017	2018
77	0.00	22.71	23.13	0.00	259.92
78	0.00	30.16	23.84	0.00	52.62
79	0.00	23.63	26.17	0.00	15.86
80	0.00	141.26	27.44	0.00	7.70
81	0.00	45.91	28.25	0.00	5.76
82	0.00	27.23	28.64	0.00	5.19
83	0.00	23.13	28.82	0.00	5.01
84	0.00	23.27	58.62	0.00	4.52
85	0.00	22.39	36.02	0.00	4.48
86	0.00	21.61	29.98	0.00	1.43
87	0.00	20.77	28.11	0.00	603.88
88	0.00	20.27	27.40	79.46	114.77
89	0.00	19.53	26.59	13.00	24.26
90	0.00	18.79	25.64	0.00	7.73
91	0.00	18.05	25.25	0.00	4.27
92	0.00	16.70	24.65	14.20	3.13
93	0.00	15.93	27.05	202.71	3.12
94	0.00	13.24	22.99	38.49	9.25
95	0.00	14.20	21.93	3.99	4.87
96	0.00	10.49	19.85	0.00	2.77
97	0.00	7.88	18.82	0.00	33.23
98	0.00	6.04	17.87	0.00	10.17
99	0.00	5.58	16.39	0.00	4.77
100	0.00	6.53	15.29	0.00	1.77
101	0.00	4.98	11.16	117.24	0.52
102	0.00	1.73	10.10	78.05	0.19
103	0.00	2.03	9.96	14.27	0.00
104	0.00	0.00	32.84	0.60	0.00
105	7.31	0.00	10.24	0.00	0.00
106	0.00	0.00	4.63	0.00	0.00
107	0.00	21.15	1.01	0.00	0.00
108	0.00	20.31	0.29	14.30	0.00
109	0.00	63.57	1416.12	1.14	0.00
110	0.00	13.60	254.27	0.00	0.00
111	0.00	1.71	413.18	0.00	0.00
112	0.00	7.98	356.68	0.00	0.00
113	0.00	245.08	77.69	0.00	0.00
114	0.00	49.44	25.29	0.00	0.00
115	0.00	11.90	15.64	0.00	0.00
116	0.00	4.63	15.01	0.00	0.00
117	0.00	200.23	16.03	0.00	0.00
118	0.00	47.67	248.26	0.00	0.00

HAWQS Simulated Streamflow in Bullhide Creek, continued.

Day	2014	2015	2016	2017	2018
119	0.00	18.22	66.74	0.00	0.00
120	0.00	12.04	30.41	0.00	0.00
121	0.00	11.16	175.16	0.00	0.00
122	0.00	11.87	55.44	0.00	0.00
123	0.00	12.96	29.98	0.00	0.00
124	0.00	13.56	25.25	0.00	0.00
125	0.00	13.88	24.97	0.00	186.46
126	0.00	23.45	25.07	0.00	32.03
127	0.00	16.60	25.04	0.00	0.40
128	0.00	15.04	24.61	0.00	0.00
129	202.00	78.40	23.94	0.00	0.00
130	35.17	28.00	23.94	0.00	0.00
131	1.06	144.79	22.85	0.00	0.00
132	0.00	42.73	363.74	0.00	0.00
133	1175.98	27.65	88.29	0.00	0.00
134	221.78	50.15	30.51	0.00	0.00
135	38.49	32.00	22.07	0.00	0.00
136	4.84	29.10	18.19	0.00	0.00
137	0.00	335.14	34.89	0.00	0.00
138	0.00	82.28	20.69	0.00	0.00
139	0.00	78.40	16.28	0.00	0.00
140	0.00	37.79	18.40	0.16	0.00
141	0.00	47.32	490.87	0.00	53.68
142	0.00	33.73	107.00	4.34	5.54
143	0.00	32.38	32.77	0.00	0.00
144	0.00	1013.53	18.72	0.00	0.00
145	0.00	212.95	16.00	0.00	0.00
146	1.23	1359.61	14.87	0.00	0.00
147	188.58	741.61	15.72	0.00	0.00
148	356.68	173.04	1041.78	0.00	0.00
149	71.34	437.90	335.49	11.51	0.00
150	15.61	129.25	78.05	0.00	0.00
151	5.62	84.76	39.20	0.00	0.00
152	3.81	64.27	25.11	0.00	0.00
153	3.34	61.09	65.33	0.00	0.00
154	3.00	61.80	74.87	9.96	0.00
155	3.32	62.86	699.23	2.68	0.00
156	3.09	63.21	239.43	0.00	0.00
157	3.20	63.21	73.81	0.00	0.00
158	3.05	62.51	42.73	0.00	0.00
159	2.74	61.80	38.49	0.00	0.00
160	4.87	60.74	38.14	0.00	0.00

HAWQS Simulated Streamflow in Bullhide Creek, continued.

Day	2014	2015	2016	2017	2018
161	216.48	59.33	38.49	0.00	0.00
162	45.91	57.92	39.91	0.00	0.00
163	10.03	56.86	40.26	0.00	0.00
164	1041.78	54.03	40.26	0.00	0.00
165	191.76	52.62	741.61	0.00	0.00
166	38.49	56.15	167.39	0.00	0.00
167	11.12	48.73	63.57	0.00	0.00
168	5.09	879.34	43.79	0.00	0.00
169	4.31	699.23	38.49	0.00	0.00
170	3.67	161.39	37.79	0.00	0.00
171	3.41	63.57	35.17	0.00	0.00
172	2.89	44.14	32.95	0.00	0.00
173	3.85	39.55	32.03	0.00	0.00
174	4.73	35.67	30.19	0.00	0.00
175	7.31	32.70	26.24	10.74	0.00
176	6.11	30.72	18.43	0.00	0.00
177	18.86	29.42	15.29	0.00	0.00
178	6.78	1108.88	12.68	0.00	0.00
179	2.54	243.32	9.64	0.00	0.00
180	1.04	67.45	8.19	0.00	0.00
181	0.33	36.02	8.58	0.00	0.00
182	0.01	29.24	7.59	0.00	0.00
183	0.00	22.50	6.32	9.75	0.00
184	0.00	20.20	3.25	0.00	0.00
185	0.00	18.15	0.00	42.73	0.00
186	0.00	17.20	0.64	2.94	0.00
187	0.00	13.10	0.00	0.00	0.00
188	0.00	12.22	0.34	0.00	0.00
189	0.00	9.22	0.00	0.00	0.00
190	0.00	8.48	0.00	0.00	0.00
191	0.00	7.49	0.00	0.00	0.00
192	0.00	5.19	0.00	0.00	0.00
193	0.00	4.41	0.00	0.00	0.00
194	0.00	2.01	0.00	0.00	0.00
195	0.00	2.09	0.00	0.00	0.00
196	0.00	0.85	0.00	0.00	0.00
197	0.00	0.00	0.00	0.00	0.00
198	0.00	0.00	0.00	0.00	0.00
199	0.00	0.00	0.00	0.00	0.00
200	0.00	0.00	0.00	0.00	0.00
201	0.00	0.00	0.00	0.00	0.00
202	0.00	0.00	0.00	0.00	0.00

HAWQS Simulated Streamflow in Bullhide Creek, continued.

Day	2014	2015	2016	2017	2018
203	0.00	0.00	0.00	0.00	0.00
204	0.00	0.00	0.00	0.00	0.00
205	0.00	0.00	0.00	0.00	0.00
206	0.00	0.00	0.00	0.00	0.00
207	0.00	0.00	0.00	0.00	0.00
208	0.00	0.00	0.00	0.00	0.00
209	0.00	0.00	0.00	0.00	0.00
210	0.00	0.00	0.00	0.00	0.00
211	0.00	0.00	0.00	0.00	0.00
212	0.00	0.00	0.00	0.00	0.00
213	0.00	0.00	0.00	0.00	0.00
214	0.00	0.00	0.00	27.86	0.00
215	0.00	0.00	0.00	80.87	0.00
216	0.00	0.00	0.00	9.01	0.00
217	0.00	0.00	0.00	0.00	0.00
218	0.00	0.00	0.00	0.00	0.00
219	0.00	0.00	0.00	0.00	0.00
220	0.00	0.00	0.00	0.00	0.00
221	0.00	0.00	0.00	0.00	0.00
222	0.00	0.00	0.00	0.00	0.00
223	0.00	0.00	0.00	0.00	15.96
224	0.00	0.00	0.00	0.00	0.00
225	0.00	0.00	0.00	0.00	13.88
226	0.00	0.00	0.00	0.00	0.00
227	0.00	0.00	0.00	0.00	0.00
228	0.00	0.00	0.00	0.00	0.00
229	0.00	0.00	286.40	0.00	0.00
230	14.73	0.00	487.34	0.00	0.00
231	0.00	0.00	253.91	0.00	0.00
232	0.00	0.00	53.68	0.00	0.00
233	0.00	25.67	4.48	0.00	0.00
234	0.00	0.22	113.36	0.00	0.00
235	0.00	0.00	20.91	0.00	0.00
236	0.00	0.00	0.07	0.00	0.00
237	0.00	0.00	0.00	0.00	0.00
238	0.00	0.00	0.00	0.00	0.00
239	0.00	0.00	0.00	55.44	0.00
240	0.00	0.00	7.42	23.03	0.00
241	0.00	0.00	2.82	0.00	0.00
242	0.00	0.00	2.26	0.00	0.00
243	0.00	0.00	80.87	0.00	0.00
244	0.00	0.00	21.58	0.00	0.00

HAWQS Simulated Streamflow in Bullhide Creek, continued.

Day	2014	2015	2016	2017	2018
245	0.00	0.00	8.09	0.00	0.00
246	0.00	0.00	5.97	0.00	0.00
247	0.00	0.00	6.04	0.00	0.00
248	0.00	0.00	6.07	0.00	0.00
249	0.00	0.00	5.86	0.00	0.00
250	0.00	0.00	7.20	0.00	0.00
251	0.00	0.00	6.22	0.00	0.00
252	0.00	0.00	5.51	0.00	0.00
253	0.00	0.00	5.01	0.00	0.00
254	0.00	0.00	4.84	0.00	0.00
255	0.00	0.00	4.63	0.00	0.00
256	0.00	0.00	4.38	0.00	0.00
257	0.00	0.00	3.28	0.00	0.00
258	0.00	0.00	2.57	0.00	0.00
259	0.00	0.00	2.06	0.00	0.00
260	0.00	0.00	0.51	0.00	0.00
261	23.20	0.00	0.00	0.00	0.00
262	0.25	0.00	0.00	0.00	0.00
263	0.00	0.00	0.00	0.00	0.00
264	0.00	0.00	0.00	0.00	0.00
265	0.00	0.00	0.00	0.00	0.00
266	0.00	0.00	0.00	0.00	0.00
267	0.00	0.00	0.00	0.00	0.00
268	0.00	0.00	0.00	0.00	0.00
269	0.00	0.00	0.00	0.00	0.00
270	0.00	0.00	40.26	0.00	0.00
271	0.00	0.00	5.37	0.00	0.00
272	0.00	0.00	0.00	0.97	0.00
273	0.00	0.00	0.00	0.00	0.00
274	0.00	0.00	0.00	0.00	0.00
275	0.00	0.00	0.00	0.00	0.00
276	0.00	0.00	0.00	0.00	0.00
277	0.00	0.00	0.00	56.86	0.00
278	0.00	0.00	0.00	8.33	0.00
279	0.00	0.00	0.00	0.00	0.00
280	0.00	0.00	0.00	0.00	0.00
281	0.00	0.00	0.00	0.00	0.00
282	0.00	0.00	0.00	0.00	0.00
283	0.00	0.00	0.00	0.00	462.62
284	142.32	0.00	0.00	0.00	84.40
285	23.41	0.00	0.00	0.00	10.10
286	280.40	0.00	0.00	0.00	0.00

HAWQS Simulated Streamflow in Bullhide Creek, continued.

Day	2014	2015	2016	2017	2018
287	48.73	0.00	0.00	0.00	61.09
288	4.31	0.00	0.00	0.00	9.15
289	0.00	0.00	0.00	0.00	1832.83
290	0.00	0.00	0.00	0.00	646.26
291	0.00	0.00	0.00	0.00	108.06
292	0.00	0.00	0.00	0.00	16.32
293	0.00	0.00	0.00	0.00	494.41
294	0.00	0.00	0.00	0.00	91.82
295	0.00	0.00	0.00	92.88	15.50
296	0.00	0.00	0.00	15.64	0.00
297	0.00	1931.71	0.00	0.00	0.00
298	0.00	995.87	0.00	0.00	356.68
299	0.00	203.77	0.00	0.00	74.51
300	0.00	32.95	0.00	0.00	20.16
301	0.00	1.64	0.00	0.00	11.41
302	0.00	0.00	0.00	0.00	11.12
303	0.00	0.00	0.00	0.00	12.11
304	0.00	3093.56	0.00	0.00	13.00
305	0.00	632.13	0.00	0.00	296.64
306	0.00	101.71	0.00	0.00	70.63
307	0.00	16.60	0.00	0.00	26.84
308	0.00	0.49	0.00	0.00	70.28
309	211.89	0.00	536.78	0.00	29.52
310	145.50	140.91	245.44	0.00	19.18
311	24.47	102.41	41.32	0.00	17.37
312	0.00	110.53	31.92	0.00	17.37
313	0.00	32.95	263.80	68.86	18.19
314	0.00	18.96	81.93	10.91	17.20
315	0.00	17.98	16.67	0.00	16.67
316	0.00	20.16	4.80	0.00	1144.20
317	0.00	21.68	4.70	0.00	218.95
318	0.00	23.06	5.16	0.00	55.80
319	0.00	45.56	7.17	0.00	26.20
320	0.00	29.31	8.19	0.00	21.40
321	0.00	391.99	9.15	0.00	20.34
322	0.00	100.29	9.53	0.00	20.91
323	0.00	41.67	10.03	0.00	21.61
324	0.00	31.01	10.45	0.00	21.97
325	0.00	29.81	10.24	0.00	21.97
326	0.00	29.24	10.14	0.00	22.35
327	128.90	29.21	9.85	0.00	22.39
328	26.38	28.89	37.43	0.00	22.25

HAWQS Simulated Streamflow in Bullhide Creek, continued.

Day	2014	2015	2016	2017	2018
329	3.33	28.08	15.64	0.00	21.82
330	0.00	27.33	33.90	0.00	21.58
331	0.00	179.75	63.92	0.00	21.08
332	0.00	678.04	21.82	0.00	20.38
333	0.00	192.82	12.93	0.00	19.53
334	0.00	207.65	11.55	0.00	18.68
335	0.00	68.16	11.72	0.00	18.01
336	0.00	42.73	12.08	0.00	16.88
337	0.00	38.85	12.36	0.00	16.67
338	0.00	39.91	245.79	0.00	15.08
339	0.00	41.32	149.38	0.00	14.13
340	0.00	42.38	40.97	0.00	13.21
341	0.00	43.08	39.20	0.00	69.57
342	0.00	43.79	24.01	0.00	896.99
343	0.00	44.50	21.19	0.00	171.98
344	0.00	44.85	21.33	0.00	43.44
345	0.00	44.85	22.21	0.00	19.71
346	0.00	44.50	22.95	0.00	15.50
347	0.00	490.87	23.55	0.00	14.58
348	0.00	129.60	23.17	0.00	14.80
349	0.00	61.09	23.98	0.00	14.97
350	0.00	47.67	23.91	0.00	14.94
351	0.00	45.20	23.84	111.24	14.90
352	0.00	44.14	23.27	18.68	14.69
353	0.00	43.79	23.10	11.48	14.48
354	0.00	42.73	23.55	84.05	14.69
355	0.00	42.02	22.53	14.69	13.91
356	0.00	40.61	21.86	0.00	13.35
357	0.00	39.55	21.19	0.00	12.82
358	0.00	38.85	20.66	0.00	12.36
359	0.00	36.73	19.92	0.00	11.87
360	0.00	35.24	18.93	0.00	11.19
361	0.00	727.48	18.01	0.00	731.01
362	0.00	374.34	17.27	0.00	147.26
363	0.00	99.59	16.14	0.00	39.20
364	0.00	47.67	16.03	0.00	18.36
365	0.00	38.85	14.44	0.00	137.73

BIBLIOGRAPHY

Ashworth, J.B., and Hopkins, J., 1995. Aquifers of Texas: TWDB, Report 345.

Barnes, V.E., 1970. Geologic atlas of Texas, Waco sheet: University of Texas-Austin, Bureau of Economic Geology Geologic Atlas of Texas, 1 sheet, [9 p.], scale 1:250,000.

Beall A. O., Jr., 1964. Stratigraphy of the Taylor Formation (Upper Cretaceous) East-Central Texas. Baylor Geological Studies, Bulletin NO. 6.

Casteel, C. M. III., 2020. Using Microgravity and Passive Seismic Methods Jointly to Explore the Brazos River Alluvium Aquifer: Baylor University, unpublished Master thesis, p. 1-91.

Chen, X., Dong, W., Ou, G., Wang, Z., & Liu, C., 2013. Gaining and losing stream reaches have opposite hydraulic conductivity distribution patterns. *Hydrology and Earth System Sciences*, *17*(7), 2569-2579.

Chowdhury, A.H., Osting, T., Furnans, J., and Mathews, R., 2010. Groundwater-surface water interaction in the Brazos River Basin: evidence from lake connection history and chemical and isotopic compositions: TWDB, Report 375. Corbett, K., et al. (1987). "Fracture Development and Mechanical Stratigraphy of Austin Chalk, Texas1." *AAPG Bulletin* **71**(1): 17-28.

Cronin, J., and Wilson, C., 1967. Ground water in the flood plain alluvium of the Brazos River, Whitney Dam to the vicinity of Richmond, Texas: Texas Water Development Board Report 41, p. 1-78.

Durowoju, O. S., Ekosse, G. I. E., & Odiyo, J. O., 2019. Determination of isotopic composition of rainwater to generate local meteoric water line in Thohoyandou, Limpopo Province, South Africa. *Water SA*, *45*(2), 183-189.

Epps, L. W., 1973. “A Geologic History of the Brazos River.” *Baylor Geological Studies Bull*, no. 24: 44.

Ewing, J. E., Harding, J. J., and Jones, T. L., 2016. Final Conceptual Model Report for the Brazos River Alluvium Aquifer Groundwater Availability Model, Texas Water Development Board, p. 1-514.

Fant, C., Srinivasan, R., Boehlert, B., Rennels, L., Chapra, S.C., Strzepek, K.M., Corona, J., Allen, A. and Martinich, J., 2017. "Climate Change Impacts on US Water Quality Using Two Models: HAWQS and US Basins." *Water* 9(2): 118.

Foster, S., Pulido-Bosch, A., Vallejos, Á., Molina, L., Llop, A., & MacDonald, A. M., 2018. Impact of irrigated agriculture on groundwater-recharge salinity: a major sustainability concern in semi-arid regions. *Hydrogeology Journal*, *26*(8), 2781-2791.

Fuka, D. R., Collick, A. S., Kleinman, P. J., Auerbach, D. A., Harmel, R. D., & Easton, Z. M., 2016. Improving the spatial representation of soil properties and hydrology using topographically derived initialization processes in the SWAT model. *Hydrological Processes*, *30*(24), 4633-4643.

Gat, J. R., Mook, W. G., Meijer, H. A. J., 2000. Environmental Isotopes in the Hydrological Cycle – Principles and Applications: Atmospheric Water. UNESCO/IAEA Series on Environmental Isotopes in the Hydrological Cycle: Principles and Applications, II. Centre Isotope Research, Groningen, The Netherlands.

Harlan, S. K., 1985. Hydrogeological Assessment of the Brazos River Alluvial Aquifer Waco-Marlin, Texas. Baylor University, unpublished Bachelor thesis.

HAWQS, 2020, "HAWQS System and Data to model the lower 48 conterminous U.S using the SWAT model", doi.org/10.18738/T8/XN3TE0, Texas Data Repository Dataverse, V1, Texas Data Repository Dataverse, V1

IAEA/WMO, 2017. Global Network of Isotopes in Precipitation, The GNIP Database, Station: Waco, Texas, Accessible at: http://www.iaea.org/water.

Jarvis, J. C., 2019. Compartmentalization in the Northern Segment of the Brazos River Alluvium Aquifer: Baylor University, unpublished Master thesis.

Jimenez Fernandez, O., Osenbrück, K., Wang, Z., Fleckenstein, J., Schmidt, C., Lüders, T., and Schwientek, M., 2020. How alternating gaining and losing conditions along a low order agricultural stream govern the behavior of nitrogen species. EGU General Assembly Conference Abstracts.

Ju, D. H., 2014. Aquifer Framework Restoration (AFR) in an Alluvial Aquifer, Central Texas: Baylor University, unpublished Master thesis.

Keech, C. F., and Dreeszen, V. H., 1959. Geology and ground-water resources of Clay County, Nebraska: United States Geological Survey, Water -Supply Paper 1468.

Krause, S., Hannah, D. M., and Fleckenstein, J.H., 2009. Hyporheic hydrology: interactions at the groundwater-surface water interface. Hydrol. Process., 23: 2103-2107.

Kultgen, P. M., 2013. Perceived Risk and the Siting of a Controversial Wastewater Treatment Plant in Central Texas. Doctoral dissertation, Texas A & M University.

Kundu, N., Panigrahi, M., Tripathy, S., Munshi, S., Powell, M., & Hart, B., 2001. "Geochemical appraisal of fluoride contamination of groundwater in the Nayagarh District of Orissa, India." Environmental Geology **41**(3-4): 451-460.

Larkin, T. J., & Bomar, G. W., 1983. *Climatic atlas of Texas*. Texas Department of Water Resources.

Leketa, K., & Abiye, T., 2020. Investigating stable isotope effects and moisture trajectories for rainfall events in Johannesburg, South Africa. *Water SA*, *46*(3), 429-437.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L., 2007. "Model evaluation guidelines for systematic quantification of accuracy in watershed simulations." Transactions of the ASABE **50**(3): 885-900.

National Oceanic and Atmospheric Administration, 2021. U.S. Climate Normals, Annual/Seasonal Station USW00013959 Waco Regional Airport, Texas, 5/1/18-1/1/19.

National Academy of Sciences, USA, 2007. Ground water recharge using waters of impaired quality. Executive Summary.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R., 2011. Soil and water assessment tool theoretical documentation version 2009, Texas Water Resources Institute.

Noonan, E. P., 2019. Salinity in the northern segment of the Brazos River Alluvium Aquifer: a hydro-forensic approach: Baylor University, unpublished Master thesis, p. 1-103.

Oelkers, E. H., Hering J. G., and Zhu, C., 2011. "Water: is there a global crisis?" *Elements* **7**(3): 157-162.

Pinkus, J. R., 1987. Hydrogeologic Assessment of Three Solid Waste Disposal Sites in the Brazos River Alluvial Deposits: Baylor University, unpublished Master thesis, p. 1-156.

Plummer, F. B., and Sargent E. C., 1931. Underground waters and subsurface temperatures of the Woodbine sand in northeast Texas. University of Texas at Austin.

Podell, M., Kyle L., and Krystinik L. F., 1993. The Origin of the Austin Chalk "Waco Channel" in the Greater Giddings Field Area. AAPG Search and Discovery Article #90994. Union Pacific Resources Company, Ft. Worth, Texas.

Rose, S., 2002. "Comparative major ion geochemistry of Piedmont streams in the Atlanta, Georgia region: possible effects of urbanization." *Environmental Geology* **42**(1): 102-113.

Rupp, S., 1976. Urban Geology of Greater Waco Part III: Water Subsurface Waters of Waco: Baylor University, unpublished Bachelor thesis.

Shah, S.D., Houston, N.A., and Braun, C.L., 2007, Hydrogeologic characterization of the Brazos River alluvium aquifer, Bosque County to Fort Bend County, Texas: U.S. Geological Survey, Scientific Investigations Map 2989, 5 sheets.

Srinivasan, R., Zhang, X., & Arnold, J., 2010. "SWAT ungauged: hydrological budget and crop yield predictions in the Upper Mississippi River Basin." *Transactions of the ASABE* **53**(5): 1533-1546.

Stephenson, L. W., 1937. Stratigraphic Relations of the Austin, Taylor, and Equivalent Formations in Texas. United States Department on the Interior Geological Survey, Professional Paper 186-G, pages 133-146.

Texas Park and Wildlife, 2010. Texas Ecoregions, Hunter Education Chapter 9: Wildlife Conservation. Austin, Texas.

Texas State Historical Association, 1999. Bull Hide creek. *The Handbook of Texas Online*, 1.

Tram, V. N. Q., Liem, N. D., & Loi, N. K., 2014. "Assessing water availability in PoKo catchment using SWAT model." Khon Kaen Agric. J 42(Suppl. 2): 73-84.

Trenberth K. E., Smith L., Qian T., Dai A., Fasullo J., .2007. Estimates of the global water budget and its annual cycle using observational and model data. Journal of Hydrometeorology – Special Section 8: 758–769

United States Environmental Protection Agency, 2018. Drinking Water Standards and Health Advisories Tables, Office of Water United States Environmental Protection Agency, p. 1-12.

Verbanck, M., Vanderborght, J. P., & Wollast, R., 1989. "Major ion content of urban wastewater: assessment of per capita loading." Research Journal of the Water Pollution Control Federation **61**(11/12): 1722-1728.

Waters, M.R. and Nordt, L.C., 1995. Late Quaternary Floodplain History of the Brazos River in East-Central Texas. *Quaternary Research* 43, 311-319.

Wichelns, Dennis, and Qadir, Manzoor, 2015. Achieving Sustainable Irrigation Requires Effective Management of Salts, Soil Salinity, and Shallow Groundwater: *Agricultural Water Management* 157, p. 31-38.

Winter, T.C., Harvey, J.W., Franke, O.L., and Alley, W.M., 1998. Ground water and surface water-- A single resource: U.S. Geological Survey Circular 1139, 79 p.

WMARSS, 2013. Aerial of Bull Hide Creek WWTP. Vol. 1.8 mb. Waco, Texas.: City of Waco Water Utility Services.

Woessner, W., 1998. Changing views of stream-groundwater interaction. Proceedings of American Institute of Hydrology/International Association of Hydrologists XXVIII Congress: Gambling with Groundwater, Physical, Chemical and Biological Aspects of Aquifer-Stream Relationships St. Paul, MN.

Xia, C., Liu, G., Wang, Z., Meng, Y., Chen, K., Song, H., & Mei, J., 2021. "Distribution of hydrogen and oxygen stable isotopes and pollution indicators in water during a monsoon transitional period in Min River Basin." *Science of The Total Environment* **782**: 146780.

Yen, H., Daggupati, P., White, M. J., Srinivasan, R., Gossel, A., Wells, D., & Arnold, J. G., 2016. "Application of Large-Scale, Multi-Resolution Watershed Modeling Framework Using the Hydrologic and Water Quality System (HAWQS)." *Water* **8**(4): 164.