ABSTRACT

Compartmentalization in the Northern Segment of the Brazos River Alluvium Aquifer

Jacob C. Jarvis, M.S.

Mentor: Joe C. Yelderman, Jr., Ph.D.

Alluvial aquifers such as the Brazos River Alluvium aquifer in central Texas can contain locally significant amounts of groundwater that may be used for irrigation, domestic supply, or to mitigate stress applied to other groundwater and surface water resources. Alluvial aquifers occur within the alluvial valley of major rivers and are intrinsically connected to the stream. In order to properly manage groundwater uses in the Brazos River Alluvium aquifer, the dynamic relationship between the aquifer and the Brazos River needs to be understood. For the Brazos River Alluvium, the Brazos River is a gaining stream and influences groundwater flow through affecting the elevation of the water table and interacting with lateral and underlying bedrock boundaries. This study utilizes spatial analysis, sediment core, and field observations to characterize how the relationship between the Brazos River and bedrock boundaries of the aquifer may compartmentalize groundwater flow within the Brazos River Alluvium aquifer.

Compartmentalization in the Northern Segment of the Brazos River Alluvium Aquifer

by

Jacob C. Jarvis B.S.

A Thesis

Approved by the Department of Geosciences

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Stacy Atchley, Ph.D., Chairperson

Submitted to the Graduate Faculty of
Baylor University in Partial Fulfillment of the
Requirements for the Degree
of

Master of Science

Approved by the Thesis Committee

____
Joe Yelderman, Jr., Ph.D., Chairperson

____
Steve Dworkin, Ph.D.

____
Wade C. Rowatt, Ph.D.

Accepted by the Graduate School
May 2019

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J. Larry Lyon, Ph.D., Dean

Page bearing signatures is kept on file in the Graduate School.

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ACKNOWLEDGMENTS

To my professors and mentors: Dr. Joe, Wayne, and Scooter, without your wisdom and guidance this would not have been possible. Your availability for conversation, no matter the time, topic, or importance has made this process much more enjoyable. Thank you to my committee Dr. Dworkin and Dr. Rowatt for taking time from their busy schedule to provide feedback and insight to my project.

To the Southern Trinity Groundwater Conservation District, Clearwater Underground Water Conservation District and Baylor University: Thank you for supplying the funding needed to conduct and complete this project.

Special thanks to the land owners that allowed me to access their property in order to conduct my research: Mark Jackson of Waco Dairy, Lewis Hirsch of Hirsch Dairy, Dannis Russell of Russell’s Pecans, and Glen and Mary Maurcek of G&M Farms.

To my colleagues: Thank you for the comradery, support and help anytime I needed it. Special thanks to Erin Noonan, Rebecca Taormina, Will Brewer, Stephanie Wong, and Wynne Casteel for their contributions to my field efforts and collaboration.

To my parents: It is only because of you that I reached the finish line.

To my family: India, thank you for inspiring me everyday to do my best and be the best husband and father I can be. Jaxson, watching you grow and learn everyday has given my life true meaning. I promise to work every day to be the best role model I can for you. I love you both immensely.

CHAPTER ONE

Introduction

Background

Alluvial aquifers commonly occur along major streams and can contain locally significant amounts of water. This water that may be used to mitigate stress applied to deep confined aquifers and surface water bodies. The scope of this study contains the groundwater stressed region of Central Texas that includes Bosque, Hill, McLennan and Falls Counties. Within this area the Brazos River Alluvium aquifer (BRAA) is a potential source for alternative water that could reduce pumping from the rapidly declining Trinity aquifer and could moderate the expense of surface waters such as Lake Waco in McLennan County.

Historically, the groundwater needs of the region have been supplied from the Trinity aquifer. The Trinity Group consists of southeasterly (gulfward) dipping Cretaceous-aged formations that extend through the central portion of Texas from the Red River in North Texas to the Hill Country in South- Central Texas (Ashworth and Hopkins 1995). The formations that comprise the aquifer are the Paluxy, Glen Rose, and Twin Mountains-Travis Peak. The Travis Peak formation includes eight units the most productive being the Hensell and Hosston. These units are the most extensively developed portions of the Trinity Aquifer within McLennan County and the greater Waco Area (Ashworth and Hopkins 1995). By 1970 cones of depression had formed in both units beneath Waco and has caused the Trinity aquifer to experience water level declines in excess of 400 feet, (Figure 1) (Cronin and Wilson 1967, Bene et. al. 2004, Diehl 2012). In 1997, Texas Water Code Chapter 35 called for the Texas Commission on Environmental Quality (TCEQ) to designate and report upon Priority Groundwater Management Areas (PGMA). An area qualifies as a PGMA if it is experiencing or expects to experience critical groundwater problems within 25 years. Figure 2 shows the areas of McLennan, Coryell, Bosque, Hill and Somervell Counties that were deemed a PGMA in 2005. Though current urban water supply in Waco is sourced from the surface reservoir, Lake Waco, surrounding communities still source water from the Trinity aquifer. Continued rapid development along the I-35 corridor suggests that the aquifer will experience increased pumping stresses that will cause continued drawdown (Bene et. al. 2004). With regional groundwater shortages a possibility in the future, there is need for future characterization and improved management of other available groundwater resources such as the Brazos River Alluvium aquifer.

Typically, techniques utilized to increase or maximize longevity of groundwater resources include conservation practices, augmenting and/or increasing water storage, or sourcing previously under or unused water resources. Recently, the favored method for groundwater management in Texas has been through the creation of Groundwater Conservation Districts (GCDs). A GCD or underground water conservation district (UWCD) is an entity created under Texas Constitution, Article III, Section 52 or Article XVI, Section 59. There are currently 98 GCDs operating in Texas and approximately 72% of major and minor aquifers are overlain by a GCD (TWDB 2016). The explicit duties of GCDs are to monitor and manage withdrawal of groundwater resources, permit new water wells and draft and implement Desired Future Conditions (DFC) (TWDB 2016).

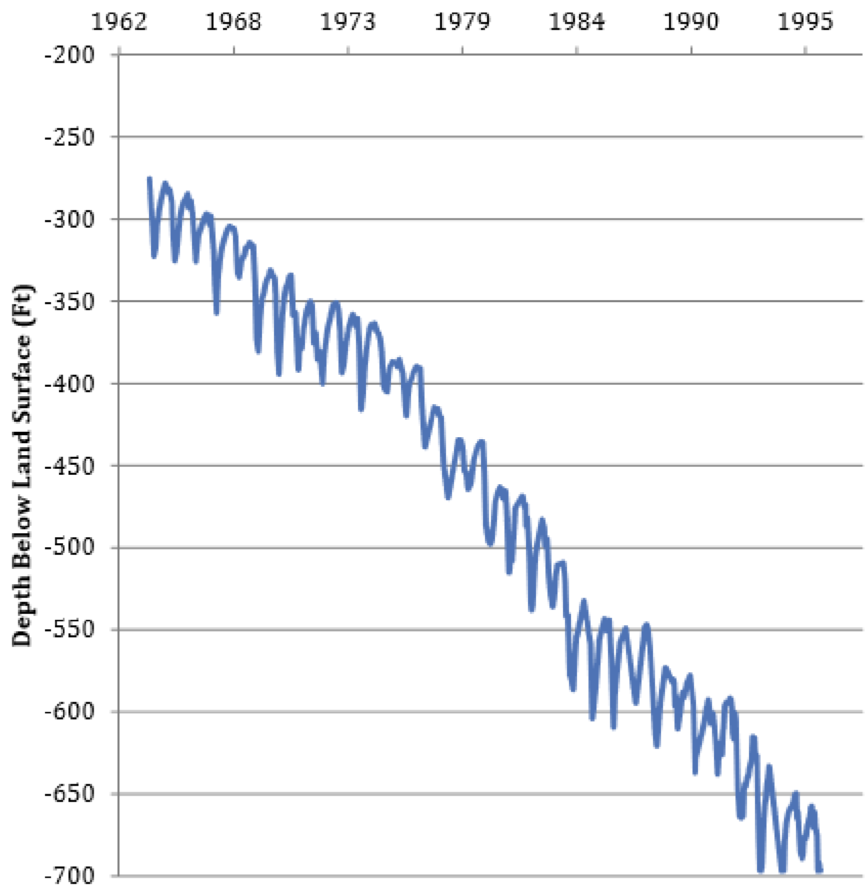


Figure 1. Hydrograph of Hosston well #4031802 in the Waco area. The average annual decline is over 10 feet per year with more than 420 feet of decline from 1962 to 1995. (from Diehl, 2012).

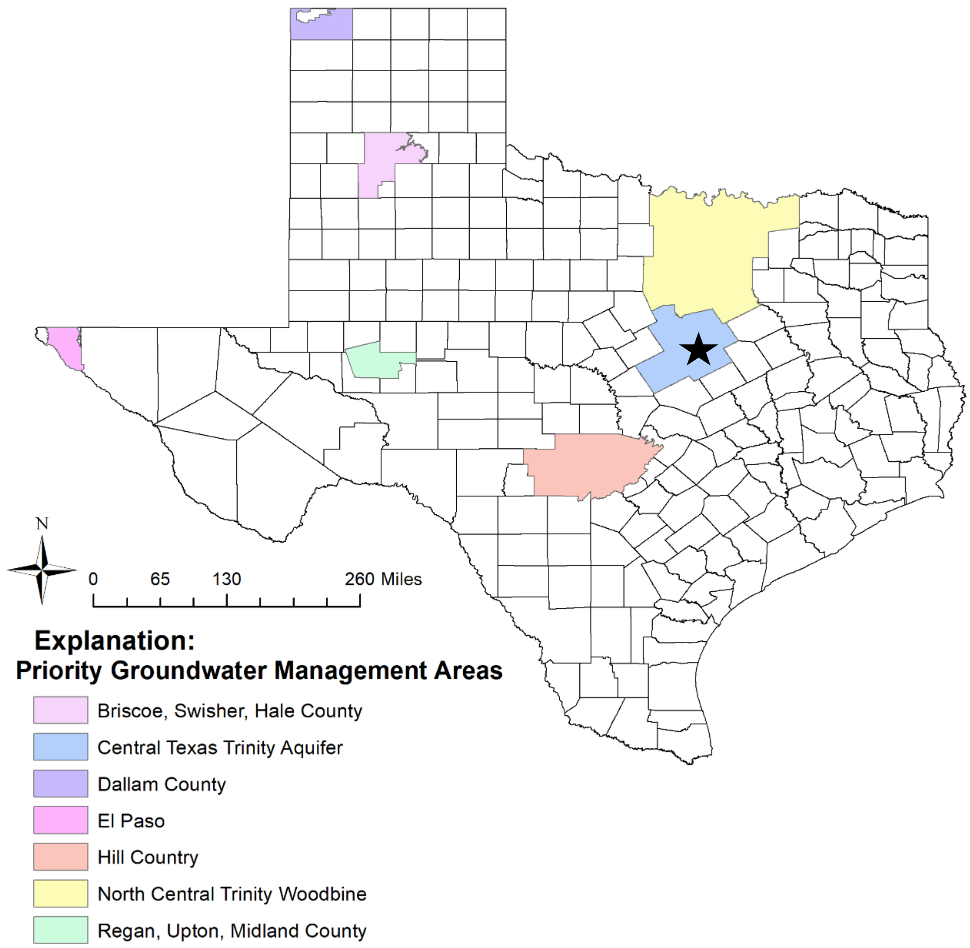


Figure 2. Map of Priority Groundwater Management areas in Texas. The PGMA that includes the Central Texas Trinity Aquifer is labeled in blue with the black star and includes 3 out of 4 counties in the northern segment.

In the study area the Brazos River Alluvium aquifer is located within four counties in which three GCDs operate: Prairielands GCD within Hill County, Middle Trinity GCD within Bosque County and Southern Trinity GCD within McLennan County. Falls County does not currently have a GCD (Figure 3). Of the three GCDs in the study area, Southern Trinity GCD is the only entity that includes the BRAA within their current management plan.

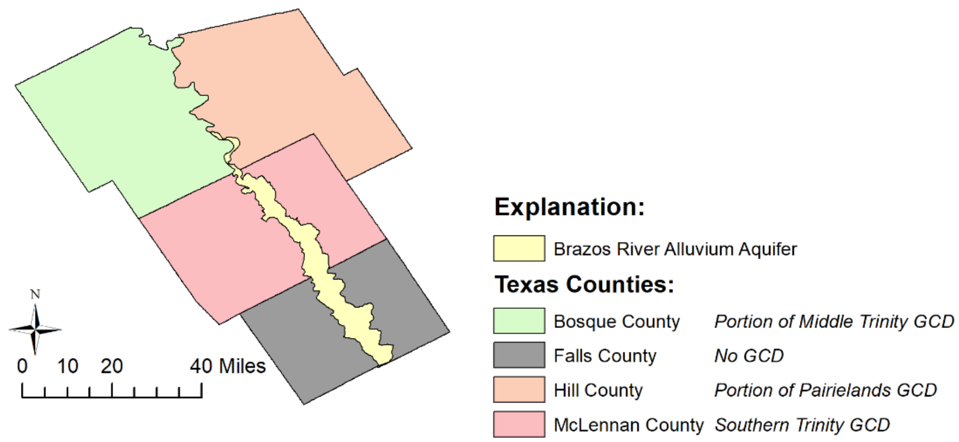


Figure 3. Map of groundwater conservation districts in the study area.

Southern Trinity GCD manages water withdrawal from the BRAA by issuing permits to groundwater users. Permitting groundwater users allows Southern Trinity GCD to monitor and manage groundwater use by establishing limits to groundwater withdrawal, requiring monthly pumping reports and insuring that water wells are properly spaced. Southern Trinity GCD has historically issued three types of permits: Exempt Well Pumping Permits, Historical Use Pumping Permits (HUPP), and Non-Historical Use Pumping Permits (NHUPP). For a well to qualify for an Exempt Well Pumping Permit in the Brazos River Alluvium Aquifer, it must be completed and capable of withdrawing water solely from the BRAA, only for domestic or livestock use, and must be incapable of producing more than 25,000 gallons per day. Additionally, if the tract of land the well is completed on is between 2-5 acres the well cannot be capable of producing more than 5,000 gallons per day, for 5-7 acres the well cannot be capable of producing more than 12,000 gallons per day, for 7-10 acres no more than 17,000 gallons per day and for tracts of land greater than 10 acres the well cannot produce greater than 25,000 gallons per day.

The Southern Trinity GCD has registered a total of 29 exempt wells since 2011, but more wells may be undocumented within county. For a well to qualify for a Historical Use Pumping Permit, the well must have been completed and operational prior to January 1, 2010, capable of producing more than 25,000 gallons per day, and the owner of the well was required to submit an application prior to May 1, 2010. In order to apply for a Non-Historical Use Pumping Permit, Southern Trinity GCD must determine that there is sufficient groundwater available for the district to issue a permit. Then the district board must issue a written order authorizing the filing and processing of NHUPP applications. Once the applications have been received the district must review and approve them to insure that an appropriate volume of groundwater is permitted to the user. The Southern Trinity GCD currently has 19 non-exempt HUPP and NHUPP issued in the BRAA that total 3,077 acre-feet of permitted pumping annually.

According to the current Groundwater Availability Model published by Texas Water Development Board, the BRAA has a modeled available groundwater (MAG) volume of 15,023 acre-feet per year in McLennan County which is based on preserving 82% of the aquifer's saturated thickness through 2050. This is a significant volume when compared to the MAG for the Trinity aquifer within McLennan County which is 20,690 acre-feet per year.

Location

The Brazos River Alluvium aquifer begins below Whitney Dam in Bosque and Hill counties and continues to Fort Bend county near Houston, TX for a total of 350 river miles, about double the airline distance. It has the capability to supply water for irrigation, domestic, stock, and commercial use (Shah and others 2007). The BRAA is a shallow unconfined aquifer that occurs immediately adjacent to the Brazos River and is confined to its alluvial valley. The aquifer saturates packages of heterogeneous fluvial sediments whose hydrologic properties range over wide limits (Cronin and Wilson 1967). The sediments typically fine upward from gravels to sands, silts, and clays, however sediment packages are discontinuous in both the vertical and horizontal direction. It is common for coarse grained material to truncate laterally with clays and silts. Groundwater flow in the BRAA is influenced by the Brazos River and groundwater flow is generally toward the river and slightly downstream. Currently the BRAA is managed as one continuous aquifer whose flow system is not interrupted by the Brazos River. With increased demand for alluvial water for irrigation, and municipal purposes it is prudent to better understand the relationship between the Brazos River and the aquifer.

The specific study area is the northern segment of the aquifer which is defined to be the portion from Whitney Dam to the southern end of Falls county (Figure 4). The southern boundary of the northern segment marks the transition from Cretaceous-aged bedrock into Tertiary-aged bedrock. Within the northern segment the Cretaceous bedrock consists of shales and limestones that act as confining layers with no known significant cross-formational flow or groundwater influence. The Tertiary units to the south of the study area are not confining and contain other aquifers that may contribute significant cross-formational flow, so dividing the aquifer into segments may be beneficial for management practices. Within the study area sediment cores were taken in transects in five localities to help characterize boundary relationships and sediment geometry. These transects occurred at: Waco Dairy within Steinbeck Bend, Hirsch Dairy southeast of Baylor University, G&M Farms near Downsville, TX, Russell’s Pecans in Gholson, TX and along CR-417 in Falls County, near Moonlight Ranch. At these locations permission to core was granted by the land owner, if on private property, and cleared by DigTest when coring along public roadways.

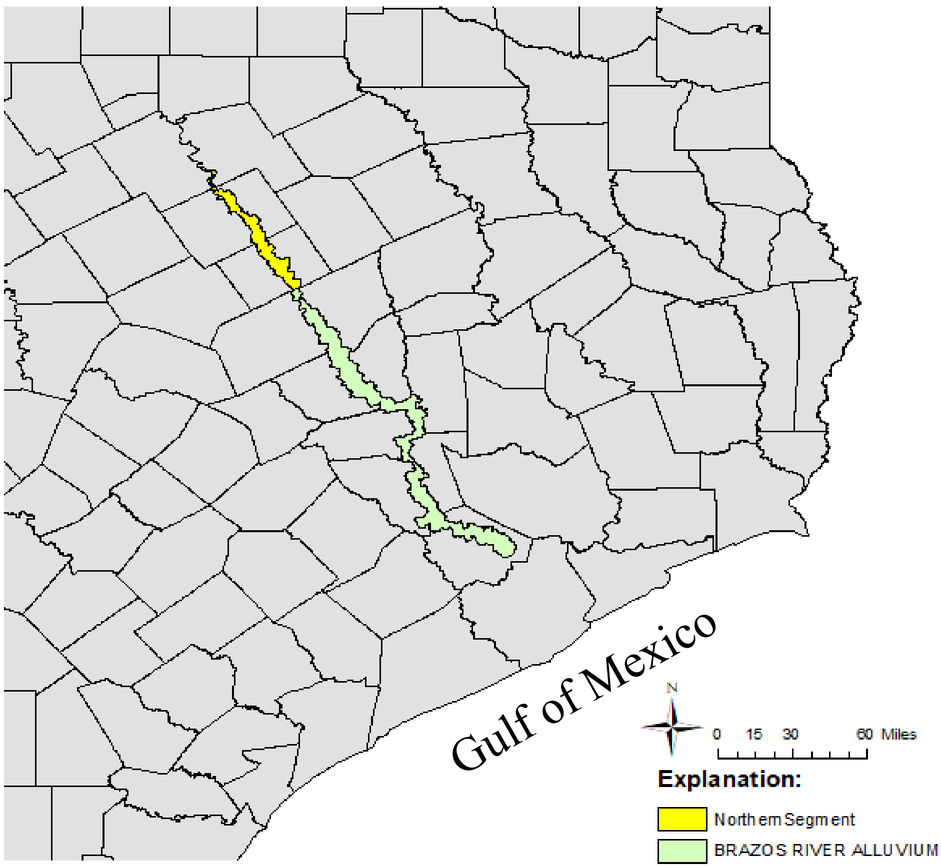


Figure 4. The state boundary of the Brazos River Alluvium Aquifer. The aquifer trends southeasterly following the present-day Brazos River and is confined to its alluvial valley. The Northern Segment is highlighted in the northern-most portion of the aquifer.

Purpose

The purpose of this study is to examine the possibility of a compartmentalized aquifer. Spatial characterization of aquifer thickness, sediment distribution, aquifer-stream relationships, and aquifer-bedrock relationships show that discreet flow systems may be present in isolated packages of sediment. In the BRAA the Brazos River is the low point of the water table and groundwater preferentially flows toward the river from either side then discharges into it, forming a hydrologic boundary. In most locations the present-day Brazos River Channel penetrates nearly the entire thickness of the alluvium, (Larkin and Sharp, 1992), and in some cases the river has incised through the entire alluvium section and is flowing on bedrock. When the Brazos River intersects the lateral bedrock boundaries of the aquifer it forms compartments where groundwater flow systems may be isolated. Figure 5 shows a conceptual diagram, a satellite image of the BRAA and the boundary conditions needed to form a compartment.

To better characterize aquifer-stream relationships, sediment distribution and how the Brazos River compartments may be delineated, three research objectives have been created:

Objective 1: Create a spatial dataset from available published water well and boring data and use spatial analysis tools within ArcGIS to generate surfaces that model groundwater flow systems between the Brazos River and bedrock boundaries. By improving understanding of the relationship between the aquifer, the Brazos River and bedrock boundaries, groundwater flow segmentation can be better delineated.

Objective 2: Record changes in bank material along a segment of the Brazos River in the northern segment, to document bank material and connectivity to the aquifer.

Objective 3: Core and describe sediment in transects perpendicular to the Brazos River and bedrock boundaries and draft cross sections that show boundary conditions and sediment distribution within individual compartments.

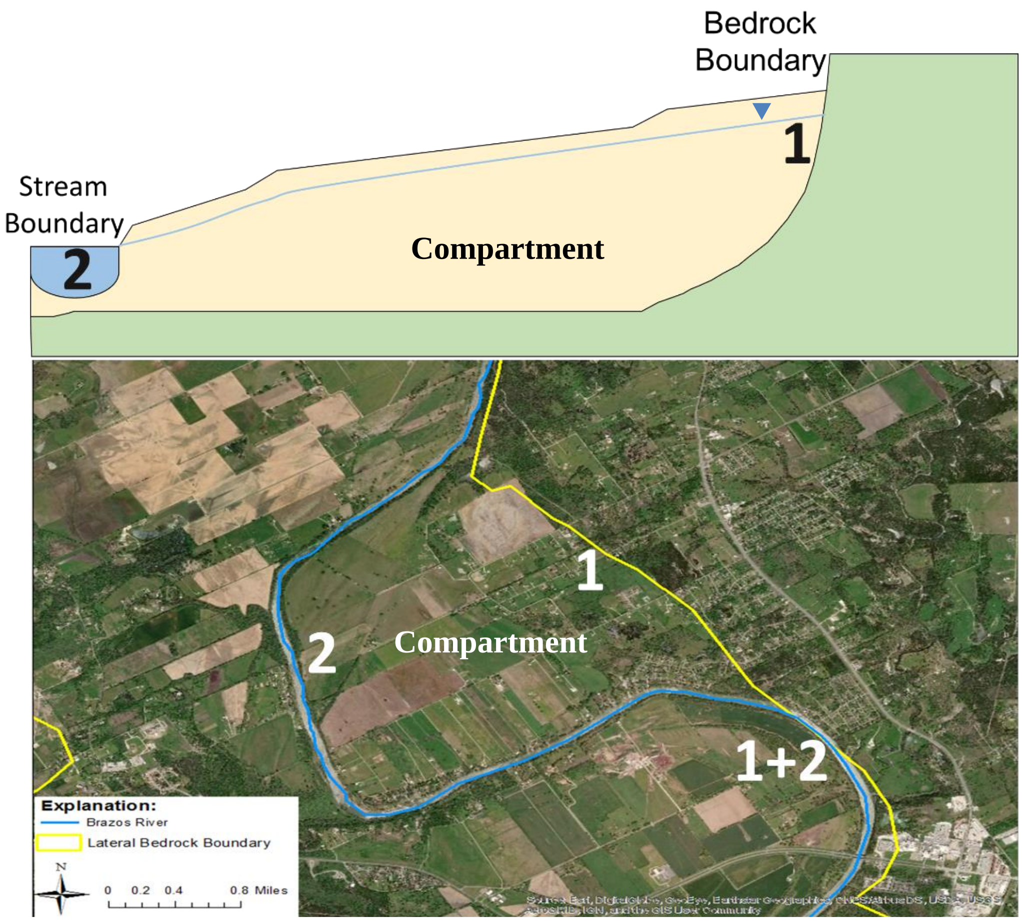


Figure 5. Conceptual diagram and satellite image of boundary conditions that cause compartmentalization.

Previous Works

There have been several studies focused in the BRAA that describe aquifer characteristics, paleo-stream conditions, alluviation history, groundwater availability, and land-use impact. However, the aquifer has not been assessed with emphasis on the relationship between the Brazos River and the aquifer flow systems.

Cronin and Wilson (1967) conducted a hydrogeologic assessment of the Brazos River Alluvium Aquifer from Whitney Dam to Richmond, TX. This was the first comprehensive study of the aquifer and the hydrologic properties reported in this study are the baseline values used in studies of the aquifer today.

Epps (1973), a Baylor Geological Studies Bulletin, utilized flow records, field data and observations, and topography to assess the history and composition of terrace and floodplain sediments associated with the Brazos River. Epps (1973) concluded that historically the Brazos River had a sustained discharge that was 5 to 9 times greater than present day and had an approximate width of 2600ft at bankfull stage.

Harlan (1985) assessed the Brazos River Alluvium Aquifer between the low-water dam in Waco to Falls on the Brazos Park below , Marlin, TX. Harlan (1985) drafted cross sections showing topography, bedrock, and water table depth both laterally and longitudinally to the alluvial valley and concluded that groundwater flow is primarily toward the stream.

Birdwell (1986) investigated a portion of terrace alluvium adjacent to Cow Bayou creek in Falls County for its potential as an alternative groundwater resource to Cow Bayou Farms. Birdwell (1986) concluded that due to a thin saturated zone and the proximity of discharge points at Post Oak Creek and the terrace - bedrock contact that the terrace is unsuitable as an alternative source of groundwater for the local farming community.

Pinkus (1987) assessed three solid waste disposal sites located in the Brazos River alluvium by comparing groundwater chemistry from piezometers both up and down gradient from the sites. Pinkus (1987) found that the three sites each exhibited contamination trends and that all waste disposal within the alluvium has potential for groundwater contamination.

Ward (1989) studied the potential for groundwater pollution through abandoned gravel pits within the Brazos River alluvium. Ward (1989) specifically focused on gravel pits along the urban fringe because the gravel pits in that area are the most likely to be affected by pollution. The study incorporated water-level data and chemical analysis at three abandoned gravel pits and found that the gravel pits were not currently transporting contaminates but are flow-through dominated and could become contaminated at any time.

Harlan (1990) followed up Harlan (1985) that assessed the hydrogeologic properties of the BRAA by conducting a hydro-chemical assessment of the aquifer from Waco to Marlin, TX. Harlan (1990) concluded that the groundwater is primarily a calcium bicarbonate type. Within the study area there was significant variation in groundwater chemistry and mappable groundwater facies could not be identified.

Waters and Nordt (1995) assessed a 75-km segment of the Brazos River floodplain between Hearne and Navasota, TX. They constructed a detailed climatic reconstruction of central Texas as well as described the late Quaternary sequence of changes on the floodplain in order to delineate factors responsible for changing the regime of the Brazos River, the mode and timing of deposition and the processes responsible for the timing and degree of soil formation.

Shah and Houston (2007) compiled and organized data from driller and borehole geophysical logs in the Brazos River Alluvium aquifer. Shah and Houston (2007) generated a geodatabase from these data to be implanted in the groundwater availability model for the aquifer.

Wong (2012) utilized geospatial techniques to analyze and compile datasets to model aquifer thickness and available water in the northern reach of the Brazos River Alluvium aquifer. Wong (2012) concluded that geospatial techniques and tools were useful for defining and quantifying change in the Brazos River alluvium, specifically when characterizing areal and volumetric impact of sand and gravel mining within the aquifer.

Ju (2014) studied the effects of native and foreign materials used to fill open mine pits in the BRAA, to restore the aquifer. Ju (2014) characterized the fill materials by identifying their physical and chemical properties and how they affect the aquifer. Results showed that native fill materials are the least hydraulically conductive while foreign materials were the most hydraulically conductive. Foreign materials showed the largest range in K values, likely due to poor sorting, and a large range in particle size. Chemically, pits filled with native materials had little effect on the ionic chemistry of waters. Construction debris, the most common material found in foreign fill elevated sulfate concentrations when freshly filled but decreased over time to ion concentrations that are observed naturally in the BRAA. Overall, foreign materials showed the greatest potential for fill material and aquifer restoration.

Ewing and others (2016) prepared the current groundwater water availability model (GAM) for the BRAA. The GAM correlates a compilation of studies that describe the aquifer’s stratigraphy, measured water levels, groundwater flow, recharge and discharge dynamics, and water quality. Ewing and others (2016) list groundwater availability for the BRAA on a per county basis and describe a total aquifer recharge calculation pre and post 1950.

In light of these studies there is need for a study that focuses on aquifer-stream relationships and how the Brazos River affects groundwater flow in the BRAA. This is especially true for the northern segment of the aquifer where the alluvium is the thinnest, the Brazos River has the highest penetration percentage, and the BRAA does not interact with any other significant bedrock aquifers. With increased population and increased water withdrawal from the BRAA in the study area, the importance of proper aquifer management facilitates a need for better understanding the aquifer flow systems.

CHAPTER TWO

Aquifer Setting

Geology

The geology in the study area ranges from Cretaceous bedrock to Pleistocene terraces deposited by the paleo-Brazos River and Quaternary alluvium deposited by the present-day Brazos River. The BRAA is underlain by the Cretaceous bedrock and can be bordered by either bedrock or terrace alluvium.

The Cretaceous bedrock underlying and bordering the BRAA in the study area consists of shales and limestones deposited unconformably above a Pennsylvanian section of considerable thickness (Adkins 1923). The bedrock dips and thickens to the southeast toward the Gulf of Mexico. The units are subdivided, from oldest to youngest into the Edwards, Georgetown, Del Rio, Buda, Woodbine, Eagle Ford, Austin and Ozan, Wofle City, and Pecan Gap formations (Figure 6). These units act as underlying and lateral confining units to the BRAA and are not known to contribute a significant source of groundwater to the aquifer (Cronin and Wilson 1967). The incision of the Brazos River Valley into the bedrock and its subsequent alluviation occurred through a sequence of degradational and aggradational events that were driven by glaciation during the Pleistocene (Epps, 1973).

The terraces within the study area mark the position of the paleo-Brazos River above the modern floodplain. Cronin and Wilson (1967) described three major terraces based on elevation above mean low water level of the Brazos River: the lower terrace, 20 to 50ft above mean low water; the middle terrace, 50 to 75ft above mean low water; the upper terrace, 75 to 125ft above mean low water. There is a fourth level composed of alluvial material higher than 125ft above mean low water, but it is minor (Rupp, 1976). The terrace material rests uncomfortably on the Cretaceous bedrock and consists mainly of clay, silt, sand, and gravel. It can be somewhat cemented in places and be as thick as 75 feet across the whole BRAA, but is generally much thinner (Cronin and Wilson, 1967).

Age	Formation	
Recent	Floodplain soil, sand and gravel etc.	
Pleistocene	Lower Terrace Middle Terrace Upper Terrace	Unconformity
Upper Cretaceous	Pecan Gap Wolfe City Ozan Austin Eagleford Woodbine	Disconformity
Lower Cretaceous	Buda Del Rio Georgetown Edwards	

Figure 6. Stratigraphy in the study area.

The higher, older terraces have been dissected and eroded more than the lower, younger terraces. Higher terraces can be found on hilltops, or cap river-cut benches. From erosion and dissection, the higher terraces have been isolated both geologically and hydrologically from the lower terraces and modern floodplain (Cronin and Wilson, 1967). The lower terraces nearest the modern floodplain have opportunities for hydraulic connection to the BRAA. Where terrace alluvium is hydraulically connected to the floodplain alluvium, water is contributed directly through lateral flow. The amount of groundwater moving from terraces into the floodplain depends on the saturated thickness of the terrace alluvium, gradient of the water table, and permeability of the saturated material (Cronin and Wilson, 1967). The location and amounts are not known at this time.

The floodplain alluvium represents the major water-bearing unit within the Brazos River Valley. The composition of the floodplain alluvium varies from place to place with individual beds or lenses of sand and gravel truncating laterally and vertically into finer or coarser material (Cronin and Wilson, 1967). Typically, a stratigraphic profile of floodplain sediments displays a fining upwards sequence, where coarse sands and gravels are in the lower portion topped with finer clays and silts. In the BRAA the lower portion of the alluvial sediments are saturated and form the aquifer.

The width of the floodplain is bedrock controlled. Where the Brazos River flows over the more resistant units such as chalk and limestone the floodplain is narrow and restricted and where the Brazos River flows over the less resistant units such as shales and marls the floodplain is considerably wider (Rupp, 1976). The Brazos River in the portion of the floodplain located north of the Taylor Group is within a system of incised meanders. These incised meanders may be further classified as ingrown meanders where lateral planation combined with downcutting has formed asymmetric cross channel profiles with well-developed slip-off slopes on the inside of the meander and steep cutbank walls on the outside of the meander (Stricklin, 1961). Beginning at the Taylor formation the floodplain widens, and the Brazos River channel is no longer fixed by bedrock slopes and begins typical floodplain meandering where the channel migrates freely. Figure 7 shows the northern segment and the transition from incised meandering channel to typical floodplain meandering channel at the Austin- Taylor boundary. For the purposes of this study the portion of the aquifer north of the boundary will be referred to as the incised portion while the portion and the aquifer south of the boundary will be referred to as the meandering portion.

Hydrogeology

In general, the groundwater in the BRAA is under water table conditions and hydrogeologic characteristics including recharge, groundwater flow, transmissivity, hydraulic conductivity, and discharge are spatially variable due to heterogeneity of aquifer material. Groundwater occurs in the pore spaces of the unconsolidated sand, gravel, silt, and clay of the floodplain alluvium and due to near surface permeability variations locally artesian conditions can occur (Cronin and Wilson, 1967, Larkin and Sharp, 1992).

The capacity of an aquifer to yield water to wells depends upon the coefficients of permeability, transmissivity, and storage which may be measured in the field or by laboratory methods (Cronin and Wilson, 1967). In the BRAA these aquifer properties are highly variable because the sediments that comprise the aquifer are heterogeneous and the distribution of coarse-grained material is spatially variable. In Table 1, studies by Cronin and Wilson, (1967) and Shah and others, (2007) highlight these aquifer properties of the BRAA from field and laboratory experiments. Groundwater flow in the BRAA is influenced by topography and the elevation of the Brazos River, flow direction is generally toward the stream and slightly down-valley (Cronin and Wilson, 1967). This baseflow dominated trend is due to the high incision percentage of

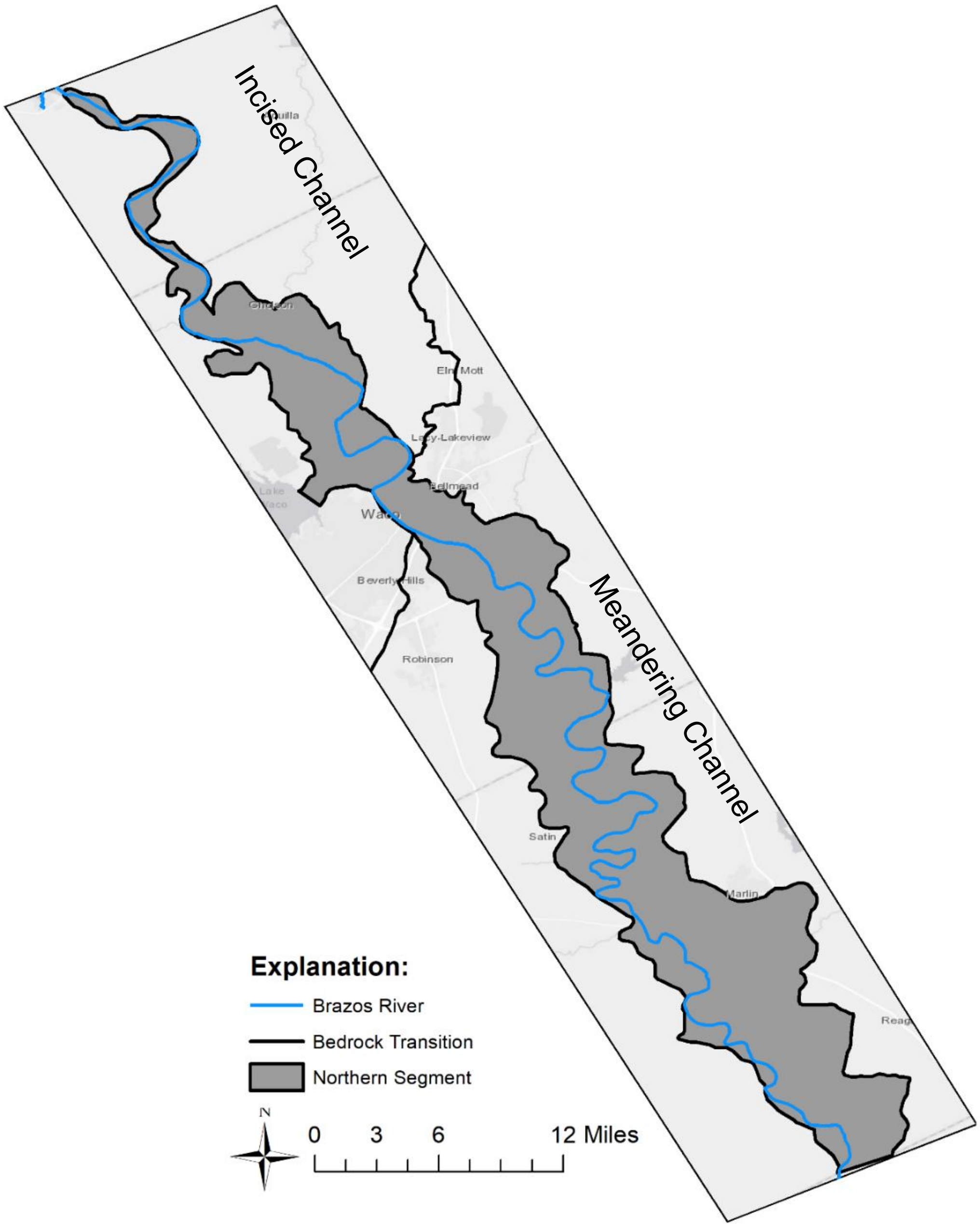


Figure 7. The transition from incised meandering to typical floodplain meandering at the contact between the Austin and Taylor Formations.

the Brazos River and the low ratio of gulf-ward to stream-ward slope of the alluvial valley (Larkin and Sharp, 1992).

Table 1. Hydrogeologic data of the BRAA found in the literature (Modified from Ju, 2014)

Aquifer Properties	Cronin and Wilson 1967	Shah and others 2007
Hydraulic Conductivity (cm/s)	$4.7x10^{-8}$ - $8.5x10^{-2}$	$6.3x10^{-2}$ - $1.6x10^{-1}$
Specific Capacity ([gal/min]/ft)	6 - 134	1.44 - 134
Transmissivity (ft^2/day)	6,684 - 40,104	289 - 27,800
Porosity (%)	24.7 - 59.5	-

Toth (1963) and Freeze and Witherspoon (1967) state that baseflow- controlled groundwater flow is expected where longitudinal valley slope is insignificant compared to the lateral valley slope. Larkin and Sharp (1992) found that baseflow conditions dominate in the BRAA where the lateral valley slope can be anywhere from 2.8 to 12.7 times the channel slope. Larkin and Sharp (1992) concluded that when the penetration of the river or the depth to which the bottom of the streambed cuts through the material present on the valley floor is greater than 20 percent baseflow-controlled groundwater flow dominates. Larkin and Sharp (1992) found the penetration percentage of the Brazos River to be 80% or greater (Figure 8). Figure 9 modified from (Larkin and Sharp 1992) shows groundwater baseflow dominated groundwater flow in the BRAA near Sugarland, Texas where groundwater flow is generally towards the Brazos River.

The influence the Brazos River has on water levels in the aquifer is function of proximity to the river; the closer to the stream the greater the impact (Pinkus, 1987). Pinkus (1987) noted that at around 2,200 feet from the river, aquifer response to changing river levels became negligible. Figure 10 shows water level changes in a monitoring well

635 feet from the river compared to changes in river level from 5-2-2016 through 7-9-2016. The monitor well was equipped with a pressure transducer and water levels were reported every hour. The river level data are from the Brazos River Stream Gage #08096500. Note the magnitude of change in river level is more than the recorded level in the aquifer, however the general trend of Brazos River stage is observed in the monitor well.

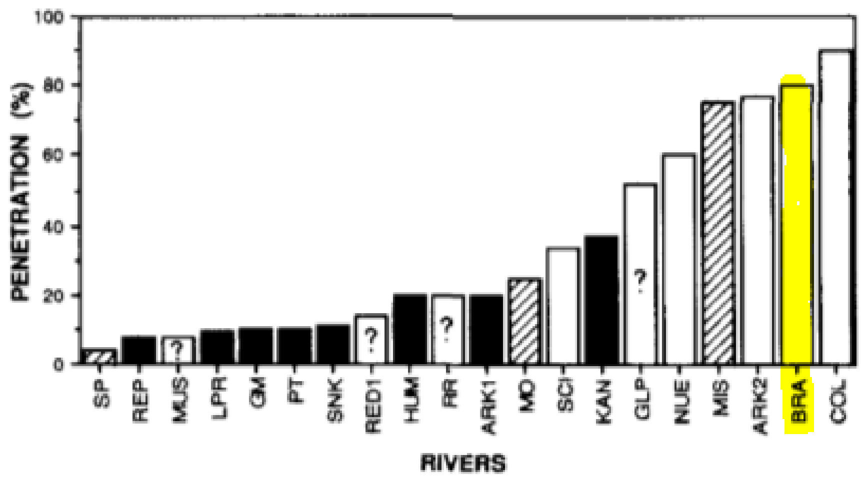


Figure 8. River penetration percentages into alluvial section from Larkin and Sharp 1992. The Brazos River is highlighted. Solid bars indicate underflow dominated systems, hatched bars represent mixed flow systems, and open bars represent baseflow dominated systems.

Recharge to the aquifer is primarily through direct precipitation over the Brazos Alluvium, but is augmented some by runoff from adjacent upland, occasional floodwaters from the Brazos River and other tributaries, and perhaps lateral flow from bedrock. The amount of precipitation that infiltrates into the aquifer is affected by rain magnitude, antecedent soil moisture, soil type, and land use. Cronin and Wilson (1967) estimated recharge by determining differences in groundwater flow between upstream and

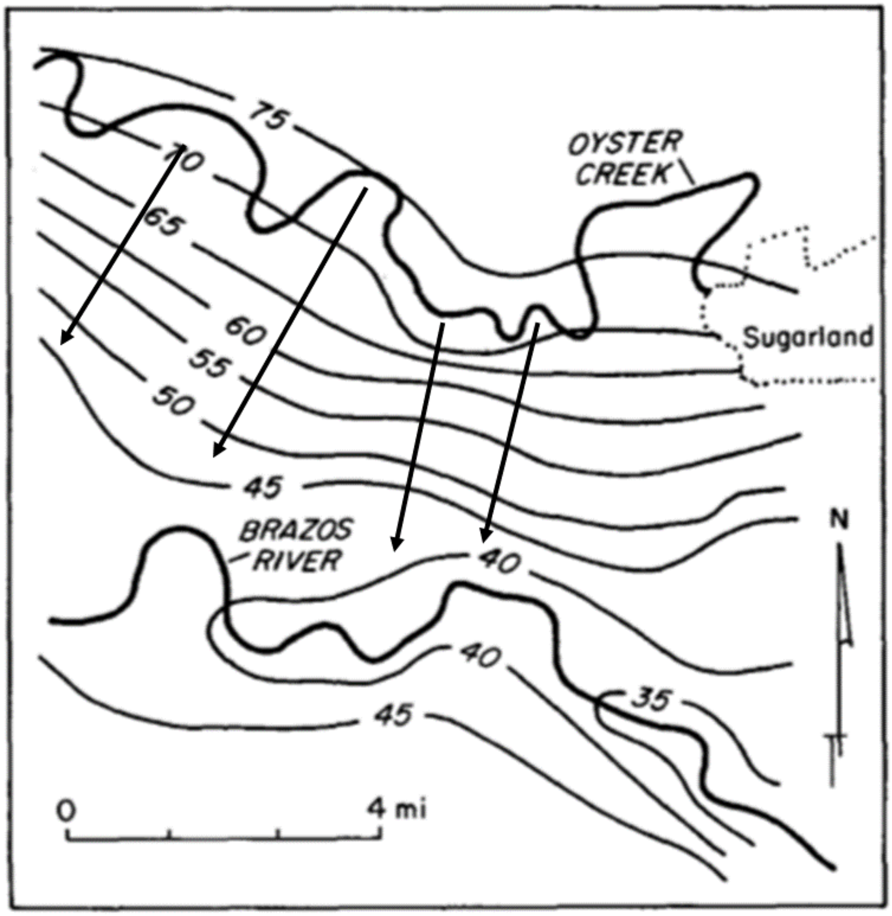
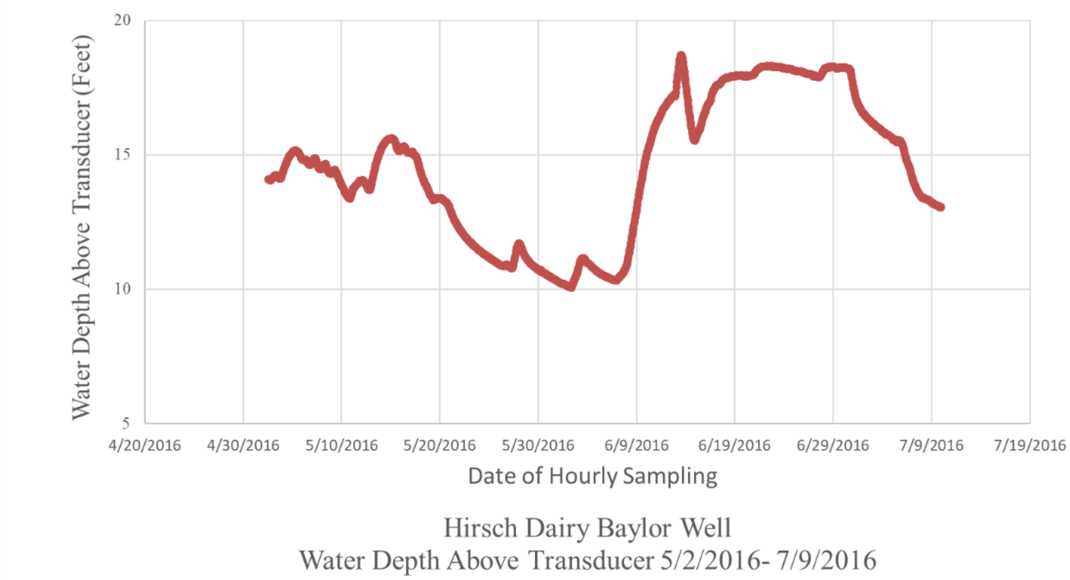


Figure 9. Map showing groundwater flow in a portion of the BRAA near Sugarland, Texas. Black arrows indicate flow direction. (Modified from Larkin and Sharp 1992)



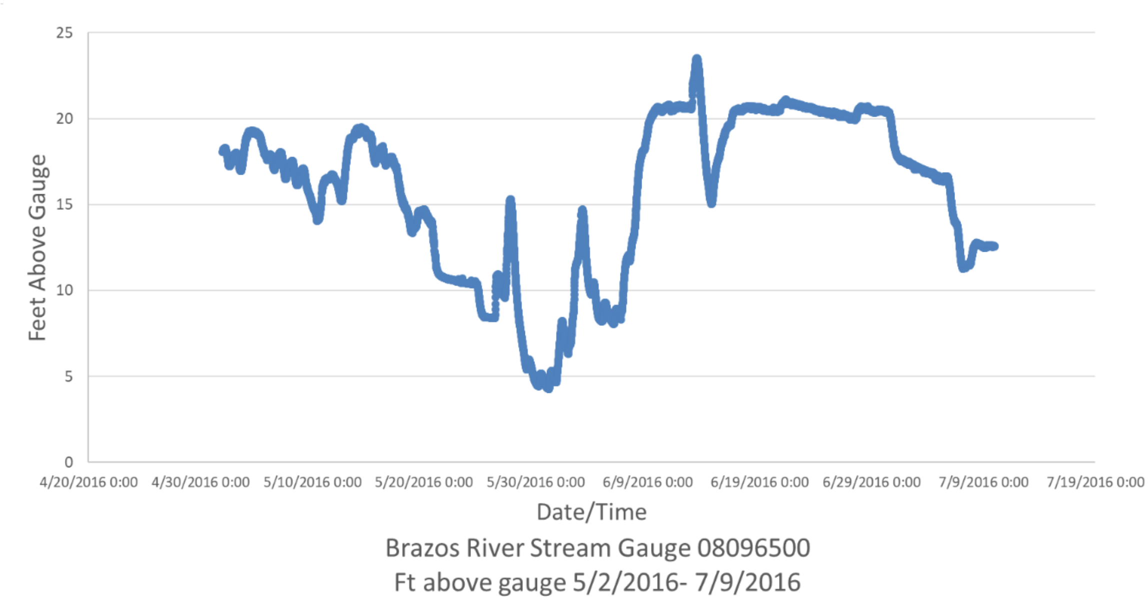


Figure 10. Hydrograph of BRAA monitor well compared to changes in Brazos River water level.

downstream sections of the saturated alluvium between two successive flow lines, which they assumed equal to the infiltration from precipitation and found recharge to vary from 2 to 5 inches annually across the BRAA with an average of 3 inches annually. Groundwater flow modeling studies report much lower recharge rates of 0.3 to 0.4 inches per year (Chowdhury, and others 2010, Dutton and others, 2003). Chowdhury and others (2010), also estimated recharge using digital hydrograph separation and chloride mass balance methods in a portion of the BRAA south of the study area. The digital hydrograph separation method estimates baseflow by calculating stream flow differences at two gages on the Brazos River using an automatic digital filter (Arnold and others, 1995). The difference in the baseflow values from upstream to downstream is considered to equal recharge from precipitation for the drainage areas associated with the gage sites. Their analysis yielded an average annual recharge of 0.74 and 0.95 inches. The chloride mass balance approach estimates recharge by multiplying the mass of chloride added to the system from precipitation with the concentration of chloride in precipitation balanced by the mass drained from the system multiplied by chloride concentration in the drainage water in the unsaturated zone (Chowdhury and others, 2010). This method yielded recharge estimates ranging from 0.11 to 3.39 inches per year with an average of 0.33 inches annually.

Discharge from the alluvium is primarily from seeps and springs, baseflow into the Brazos River, evapotranspiration, and pumping from wells. Other discharge occurs through dewatering in mining activities, and from evaporation from open water bodies in gravel pits. Discharge from water wells in the BRAA is primarily for irrigation. In McLennan County prior to the 1950's little or no water was used for irrigation and the number of irrigation wells in existence was limited (Rupp 1976). By 1963 irrigating with groundwater from the floodplain increased considerably with an estimated total of 150 acre-feet per year in the Waco area (Cronin and Wilson, 1967, Rupp, 1976). The Southern Trinity GCD reported a total of 137 acre-feet of groundwater withdrawal in

McLennan across all of the HUPP and NHUPP groundwater users in 2017, this value does not include exempt wells.

In the northern segment the BRAA is contained within Cretaceous-aged bedrock with varying influences on channel morphology and aquifer characteristics. Groundwater flow in the BRAA is baseflow dominated due to high ratio of lateral-valley slope to longitudinal slope and the high penetration percentage of the Brazos River. This study investigates further how the interaction of the Brazos River with the bedrock boundaries isolates the baseflow dominated groundwater flow systems.

CHAPTER THREE

Methodology

Published aquifer data were compiled and analyzed using geospatial tools in ArcGIS. The data collected include groundwater elevations, used to characterize how groundwater flow is compartmentalized by boundary conditions, and well tests used to calculate specific capacity. A portion of the Brazos River alluvium was observed from the channel by boat during base-flow conditions to inspect and document bank material and potential connections to the river. Sediments were cored in transects perpendicular to stream and bedrock boundaries at 5 locations to better constrain boundary conditions, and to characterize sediment distribution within compartments.

Geospatial Analysis

Published aquifer data for the BRAA were collected from the Texas Water Development Board. The TWDB has compiled data for nearly 140,000 water wells across the state and have made the records available within the TWDB Groundwater Database (GWDB) downloadable through the website (TWDB 2019). The GWDB contains well information including location, depth, well type, owner, driller, construction and completion data, aquifer, water-level and water quality data (TWDB 2019). The TWDB has also made available for download the Texas Department of Licensing and Regulation's (TDLR) Submitted Driller's Report Database (SDR). The database comprises records from 2001 to present and contains well location, construction and completion data, and lithologic logs. The data from the GWDB and the SDR range in quality and completeness. These water wells and borings were completed over several decades by numerous people and all attributes such as water level and well depth are not always recorded, therefore not every report is useful, and the dataset must be edited. Figure 11 shows the raw data source in the TWDB's groundwater data viewer. The BRAA is outlined in orange, the purple points are the GWDB and the orange points are SDRs. Data from the GWDB can be exported in comma separated values based on county and aquifer then imported directly into an Excel workbook. Within Excel, the data were edited and organized to include only the State Well Number, Latitude and Longitude coordinates, the surface elevation of the well, well depth, water table elevation, well bottom elevation, and saturated thickness. Data within the GWDB do not typically include lithologic descriptions or reports of bedrock depth, therefore for this study well depth is used as a proxy to the total thickness of the Brazos Alluvium. Wong (2012) found that using well depth as a proxy to aquifer thickness was an acceptable method by showing that the difference in interpolated thickness using proxy depths compared to lithologic data yields a difference of 10 feet or less between the two interpolations, within McLennan County. After editing and finalizing the data there are a total of 261 data points from the GWDB located within the Northern Segment.

The SDR are not easily exported, to extract the data each report must be read and recorded individually. The data extracted from the SDRs include State Identification Number, Latitude and Longitude locations, depth to water, depth to bedrock, saturated thickness and any pumping data available. In order to calculate specific capacity, the pumping data must include the amount of time the well was pumped, the amount of water that was pumped, and the total drawdown that occurred. The majority of the SDR do not include the surface elevation of the well or boring, to convert depth below land surface to elevations the surface elevation had to be interpolated. To find the elevation of each point, the dataset was imported into Google Earth Pro which uses Digital Elevation Model and topography map data to

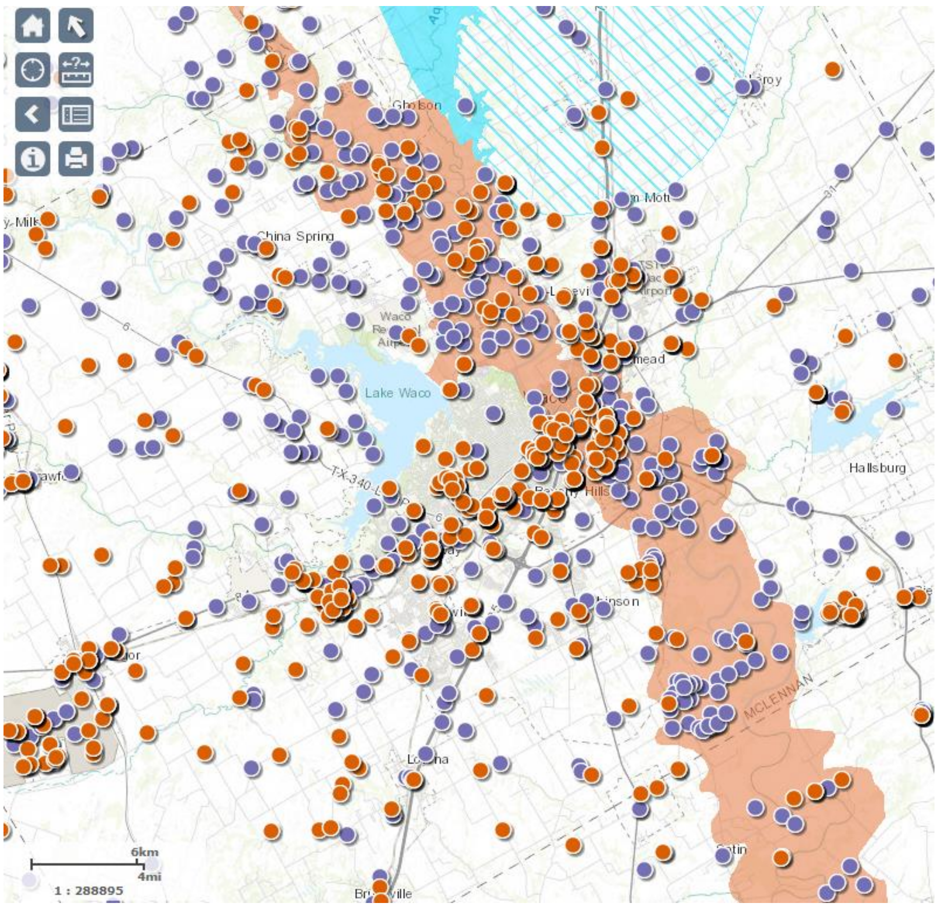


Figure 11. All available raw data in the TWDBs groundwater data viewer. The BRAA is outlined in orange, the purple points are the GWDB and the orange points are the SDR.

interpolate land surface elevation. The elevations recorded in Google Earth were compared against topographic maps in ArcGIS to insure agreeance. After land surface elevation measurements were completed for each data point, bedrock depth and water depth were converted to elevations. There is a total of 58 useable groundwater elevation points and a total of 53 useable specific capacity points from SDRs, within the Northern Segment of the BRAA.

For the purposes of this study, and to achieve the best data coverage, data from the GWDB and the SDR were combined into one composite dataset. The combination of the two datasets yields a total of 314 data points (Figure 12). Data points include, State Well Number, Latitude and Longitude locations, well depth, surface elevation, water table elevation, aquifer bottom elevation, saturated thickness and aquifer thickness. Under baseflow conditions the Brazos River is a gaining stream, making the river the low point of the water table, in order to generate an accurate groundwater flow map the elevation of the Brazos River must be considered and included into the dataset. Elevations were assigned along the location of the present-day Brazos River by adding closely-spaced point-source elevations along the course of the river. Elevation interpretations were made of the Brazos River bank from topographic map data and digital elevation model data, where available. The river elevation data points were then merged with the composite GWDB and SDR dataset and used to generate a raster surface of groundwater elevation. Figure 13 is the composite GWDB and SDR dataset merged with Brazos River elevations.

Inverse Distance Weighting (IDW) was the spatial interpolation method used to generate surfaces in ArcGIS. IDW assigns the value of an unsampled point to be the weighted average of known values near the point, and the weights are inversely related to the distance between the unsampled location and the sampled location (Lu and Wong

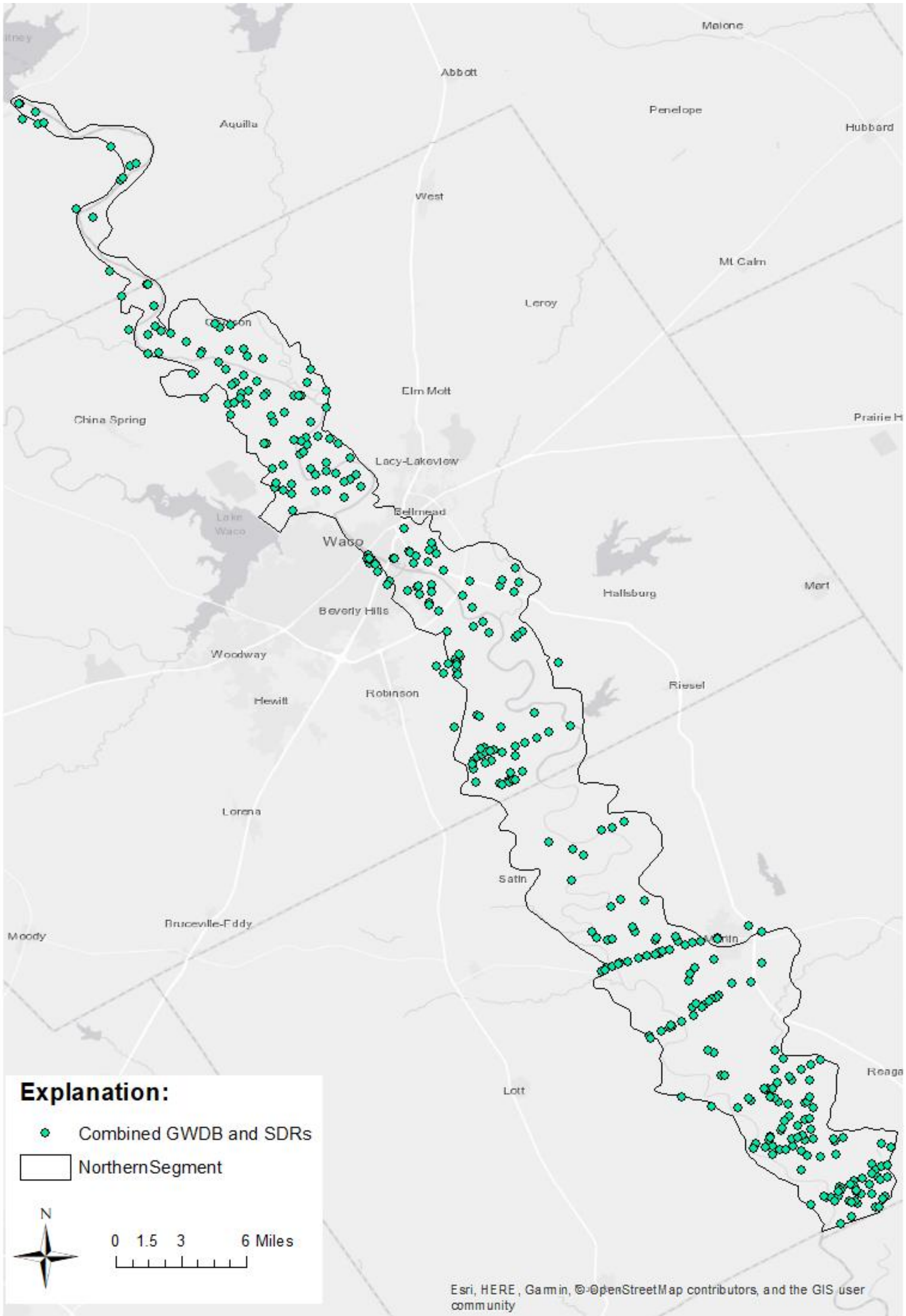


Figure 12. Combined GWDB and SDR in the Northern Segment. n = 319

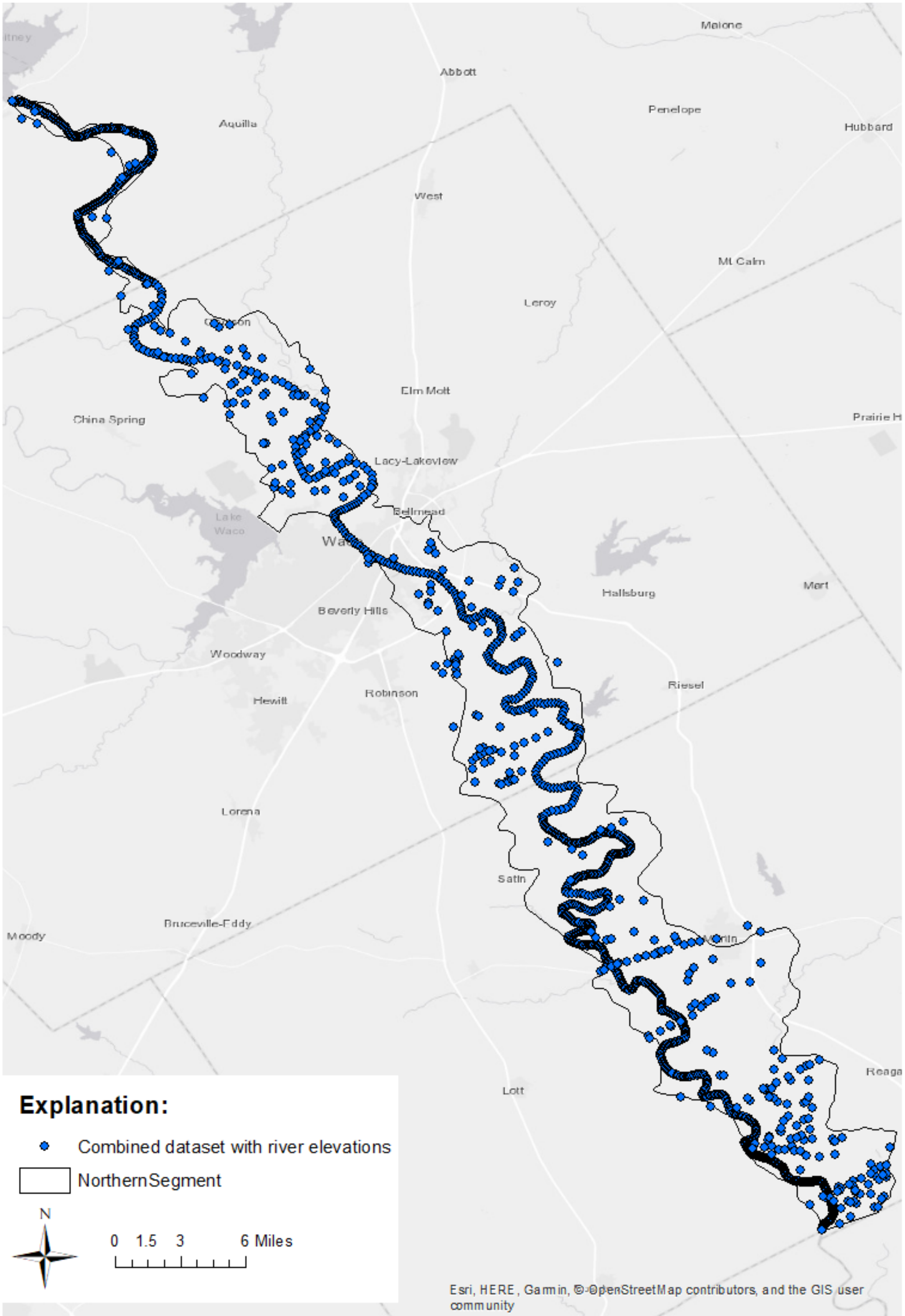


Figure 13. Combined GWDB and SDR dataset with Brazos River elevations.

2008). Predictions made through IDW honor the range of the known dataset (Wong 2012).

River Bank Analysis

In the study area the Brazos River is a boundary to groundwater flow both as a hydrologic boundary and absolute boundary (Figure 14). In hydrologic boundary conditions the Brazos River is incised through some portion of the alluvium but is perched a distance above the bedrock bottom of the aquifer, in an absolute boundary condition the river has incised through the entire alluvium section and is flowing on bedrock. This causes a physical divide in alluvium on either side of the river. In order to field check and document the Brazos River as hydrologic boundary and absolute boundary, in the floodplain meandering section of the study area, a river float trip was conducted from the Highway 7 river crossing to the end of Falls on the Brazos Park in Falls County, during baseflow conditions. Along this reach, changes in bank material were recorded using a hand-held GPS system then analyzed in the lab to further document the Brazos River as a hydrologic and absolute boundary.

Sediment Cores and Cross Sections

In order to further investigate the boundaries present in the BRAA that cause compartmentalization and to better understand sediment distribution within compartments, series of continuous sediment cores were drilled in transects perpendicular to the Brazos River and perpendicular to lateral bedrock boundaries. The cores were analyzed and described in the lab with an emphasis on grain size and sorting. From the core data, cross sections were drafted to visually delineate boundaries and represent possible sediment geometry.

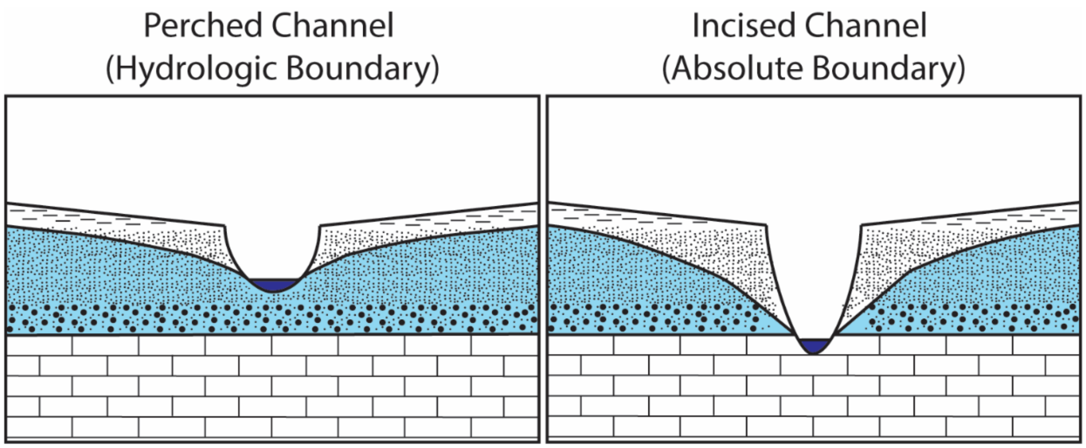


Figure 14. Conceptual diagram of stream as a hydrologic boundary where the channel is perched a distance above the bedrock bottom of the aquifer and an absolute boundary where the stream has incised through the alluvial material and is flowing on bedrock, physically dividing the aquifer.

A total of 21 cores were taken along 6 transects, 3 transects are in the incised portion of the study area and 3 are in the floodplain meandering section. In the incised meandering section 2 of the transects are perpendicular to both stream and bedrock boundaries and 1 is perpendicular to a stream boundary, in the floodplain meandering section 2 transects are perpendicular to a stream boundary and 1 is perpendicular to a bedrock boundary.

When possible, continuous core was taken from land surface to the bedrock contact in order to capture in detail the entire alluvium section, however in some cases it was not possible to core the complete section due to limits of time, machinery, and feasibility. In circumstances when a full core was not achieved flight augers were utilized to drill to the bedrock contact to record the total alluvium thickness at that location.

Coring and augering were conducted with use of the Baylor Geosciences Geoprobe 6620DT, a track-driven mobile drill rig that can hydraulically hammer when coring and rotary drill when augering. Cores were captured using MC5 dual-tube technology that allows for capture of continuous undisturbed 2.25-inch diameter sediment core within a 4- foot core barrel. Figure 15 shows steps involved when extracting core: unloading and moving the rig to position, aligning the rig derrick and push rod to insure a straight hole, and extracting core.

Once a core was extracted it was immediately sealed on top and bottom with tape, to help keep the sediments inside the core tube. Water levels were estimated in the field based on the depth that the sediment was saturated within the core tube, when returned to surface. In the lab, cores were stored sealed until they could be described. In general, core description occurred within 24 hours of extraction. Sediments were described based on the National Groundwater Association "Guide for Using the Hydrogeologic Classification System for Logging Water Well Boreholes" Hanna (2006). Tools utilized in the lab include; hand lens, ruler, grain size template, color chart, and sediment classification chart from (Hanna 2006).

Figure 15. Field photos showing Geoprobe operation. A) Unloading and moving Geoprobe to coring/augering location. B) Leveling rig derrick and MC5 pipe for proper core extraction. C) MC5 core that has been extracted, sealed on top and bottom and labeled with core name and depth. D) Full cores that have been returned to lab, ready to be opened and described.

CHAPTER FOUR

Results and Discussion

Groundwater Flow and Compartments

In ArcGIS a raster surface of water table elevations was generated from Figure 13. The groundwater elevation raster surface contoured with a 10-foot interval is shown in Figure 16. A general trend of groundwater flow toward the stream occurs throughout most of the northern segment. Groundwater contour lines are parallel to the Brazos River so that flow is directly to the stream. In the area of Figure 16 outlined in the rectangle the contour lines cross more perpendicular to the Brazos River, possibly due to the river entering a series of wide meanders across the floodplain causing down-valley groundwater flow to dominate or due to poor data constraint.

Figure 17 is a water table contour map with a 10-foot contour interval focusing on with the incised portion of the study area. Considering the idea put forth in Figure 5 everywhere the Brazos River intersects the lateral bedrock boundary of the aquifer then the groundwater flow systems should be isolated, and a compartment formed. In Figure 17 the black arrows show the direction of groundwater flow, flowing from aquifer toward the river and terminating, not crossing. Where the river intersects the lateral bedrock boundaries of the aquifer the flow systems break and become separate from the flow systems across the stream. In Figure 17, 3 compartments are easily identified: the Aquilla compartment, the Steinbeck Bend compartment, and the Horseshoe Bend compartment. Figure 18 is the water table raster with 5-foot contour interval focusing on the portion of the aquifer immediately south of Waco within the floodplain meandering portion of the study area. At this point the bedrock transitions from resistant chalk and limestone units to shale, the floodplain becomes considerably wider, the alluvium thickens, and the Brazos River channel is migrating freely through the floodplain. In this portion flow lines indicate that groundwater flow is still toward the river and typically to do not cross the river. However, the flow lines within the black rectangle cross the river and the general flow direction in down-valley rather across valley. In this part of the floodplain there are fewer data points and the Brazos River begins a series of broad cross-valley meanders such that the dominate direction of flow in the river appears to be cross-valley rather than down-valley. Therefore, the flow lines that cross perpendicular to the river are still influenced by the river, and the current path of the river may cause the groundwater to flow more down-valley rather than cross-valley.

In Figure 18 the Brazos River intersects the lateral boundaries of the aquifer in three places and the groundwater elevation contours and flow lines show two large compartments: South Waco Compartment 1 in gray and South Waco Compartment 2 in black. The compartments are not as cleanly outlined by the contours in this portion of the aquifer because there is less relief in elevation of the water table than in the incised meandering portion of the study area and the cross-valley meandering of the Brazos River along the southern boundary of the compartments alters the typical cross-valley groundwater flow. Figure 19 is the contoured water table surface in the southernmost portion of the study area, within Falls county. In this area, the Brazos River transitions from broad cross-valley meanders, shown in the black rectangle, to small meanders positioned on the western boundary of the aquifer. The direction of groundwater again transitions with the Brazos River from down-valley flow back to cross-valley flow, toward the river.

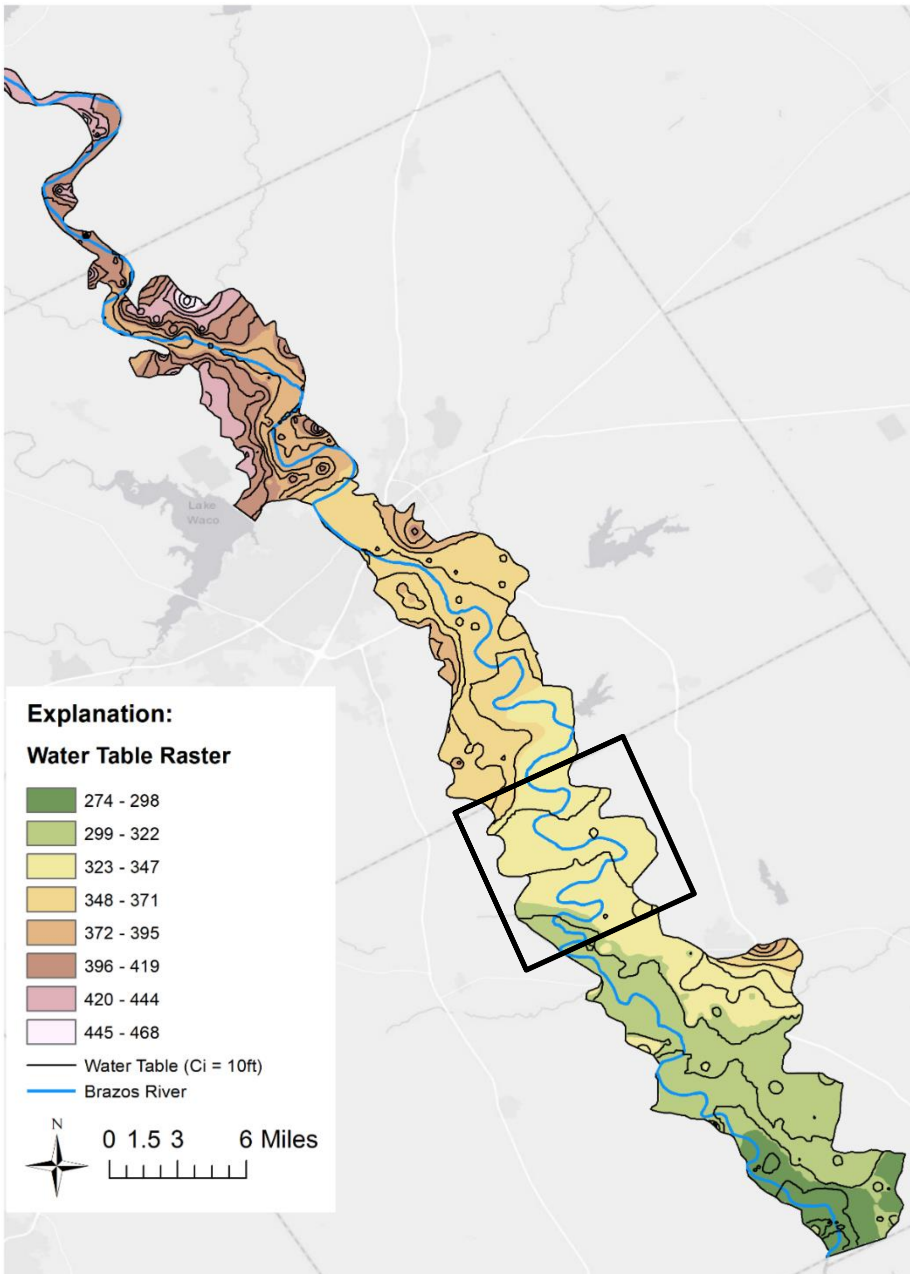


Figure 16. Contoured water table surface in the Northern Segment. The box highlights the area where the Brazos River enters a series of broad cross-valley meanders that may cause the dominate groundwater flow direction to change.

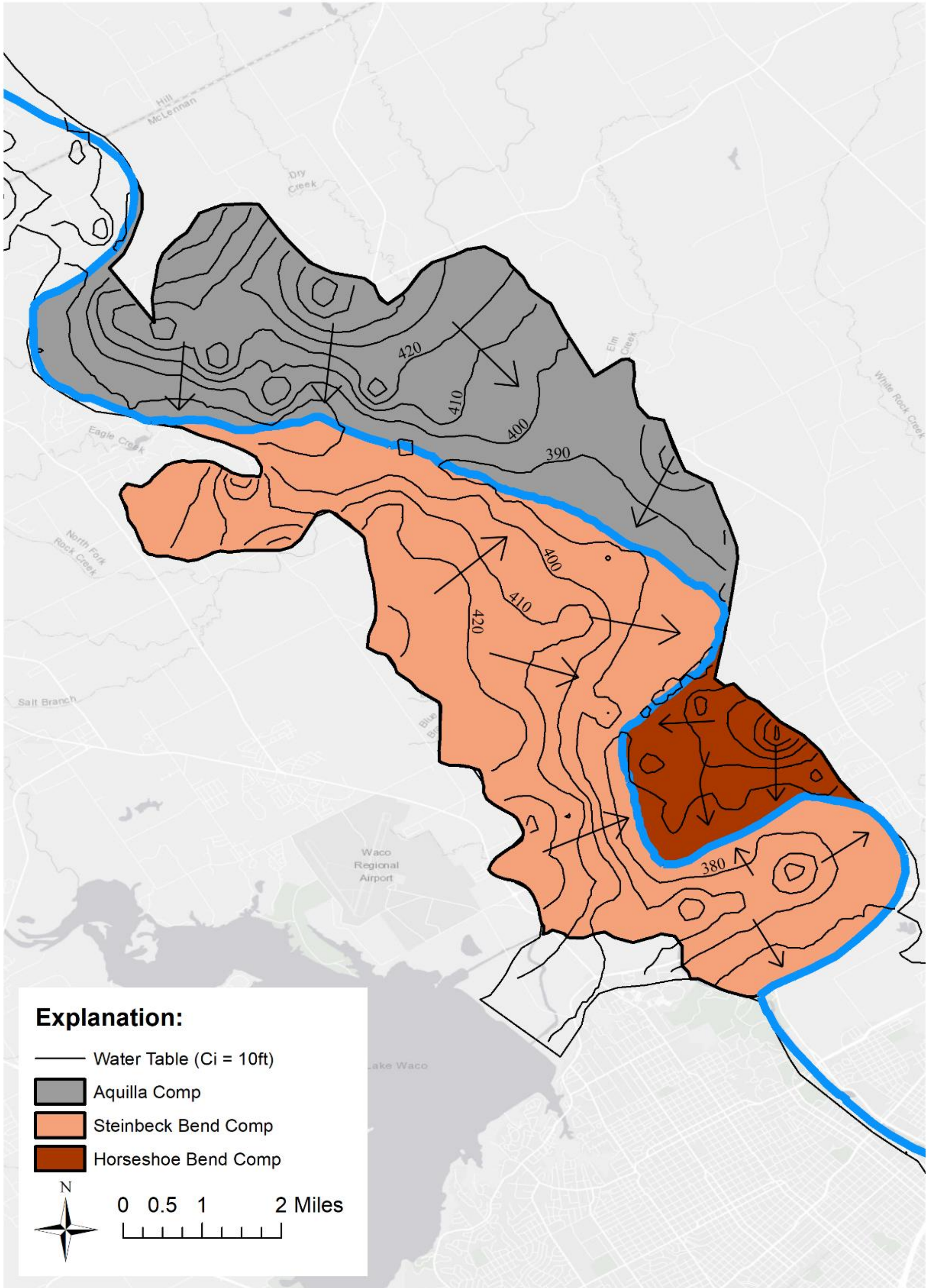


Figure 17. Contoured water table surface in the incised meandering portion of the study area. The arrows show direction of groundwater flow. There are three distinct compartments with isolated flow systems.

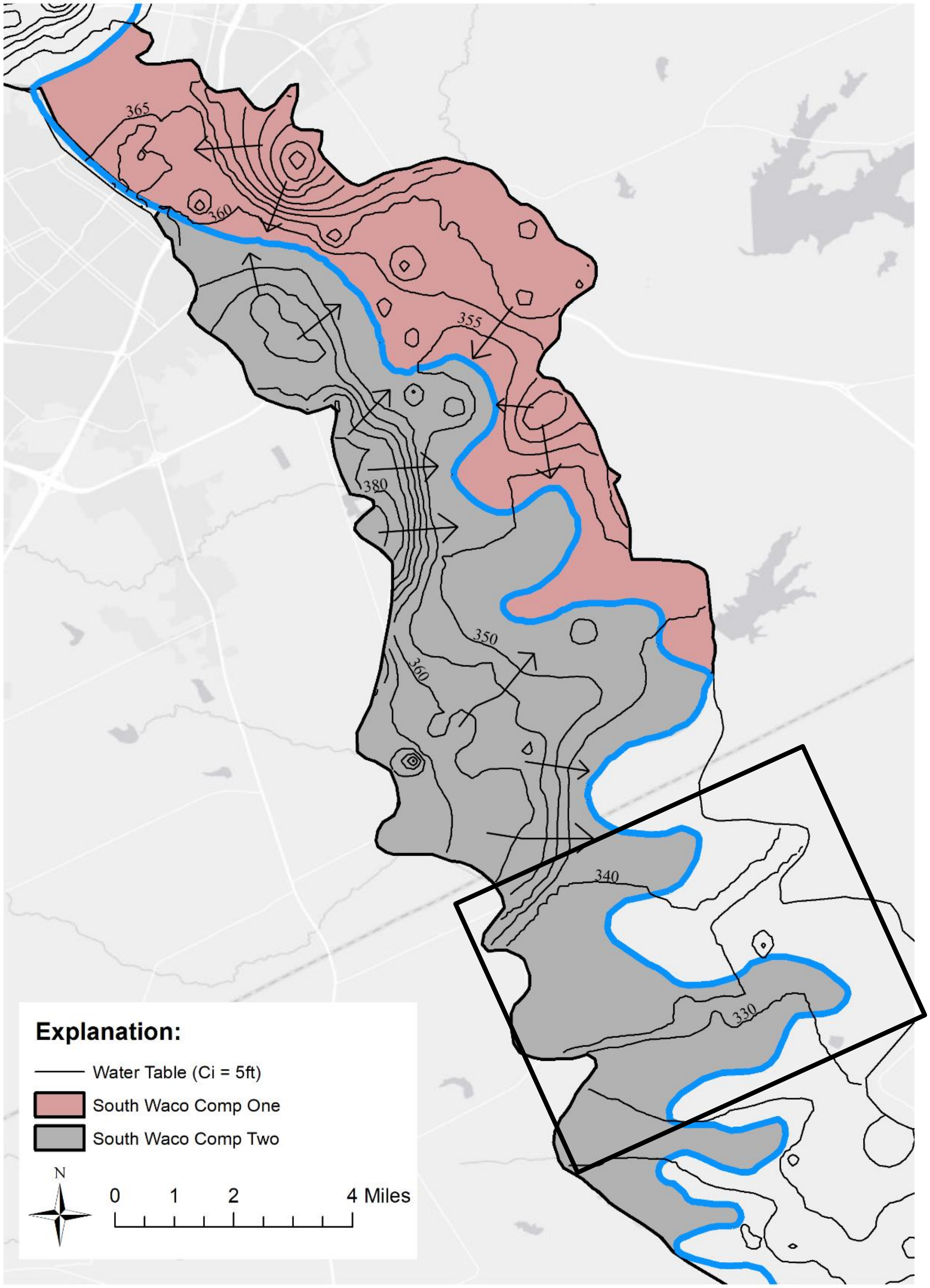


Figure 18. Contoured water table surface in the portion of the study area immediately south of Waco in the floodplain meandering portion of the study area. The arrows show direction of groundwater flow. There are two large compartments comprising the remaining aquifer in McLennan County.

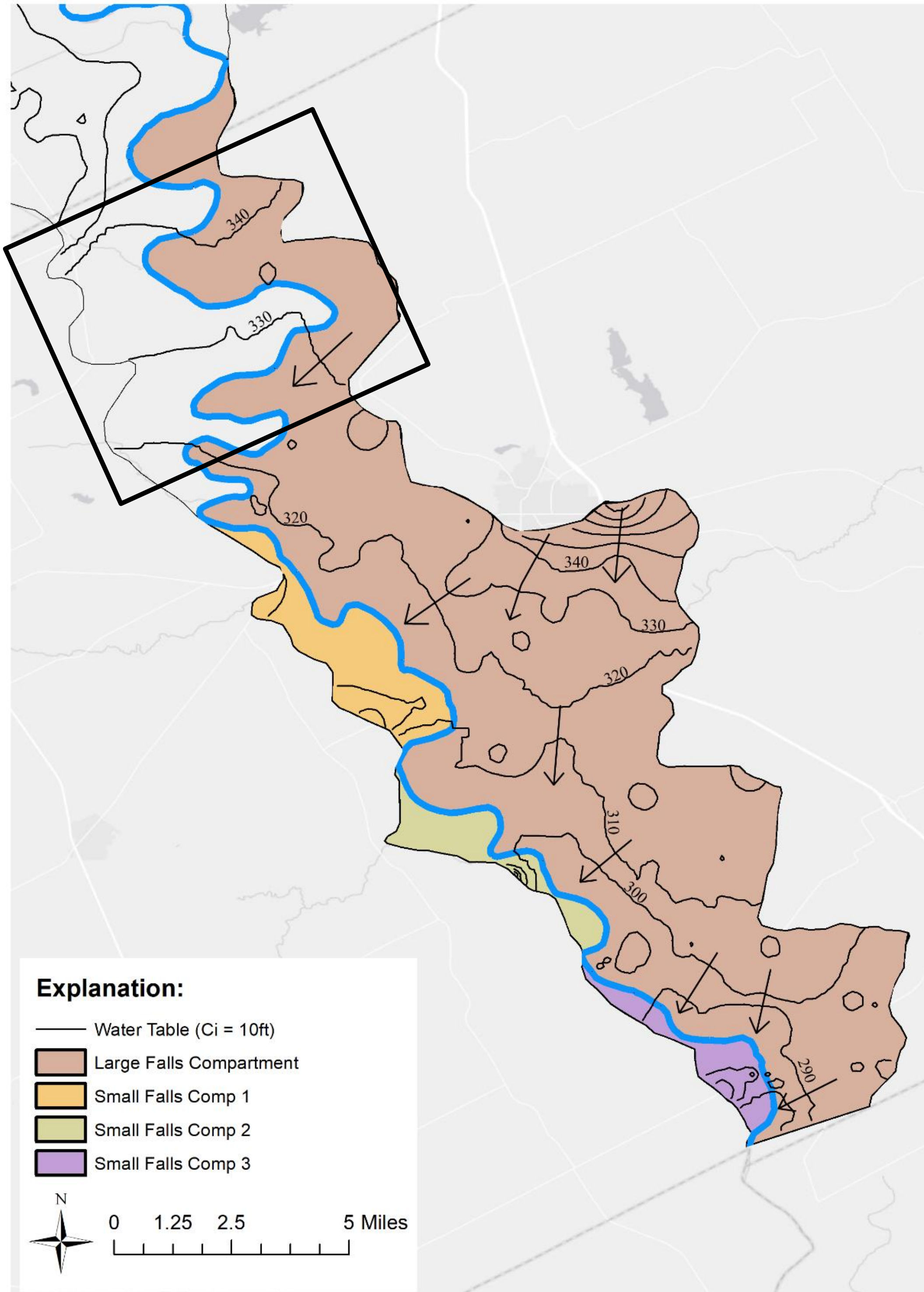


Figure 19. Contoured water table surface in Falls county. Arrows show the direction of groundwater flow. There is one large compartment in Falls county, with three smaller compartments formed where the Brazos River intersects the lateral bedrock boundaries.

In Falls county the Brazos River contacts the lateral bedrock boundary of the aquifer in 4 places along the western boundary, forming one large compartment occupying most of the aquifer in the county and 3 subsequent small compartments in the remaining aquifer on the west of the river.

The groundwater spatial analysis shows that the Brazos River influences groundwater flow in the Northern Segment. The river is as much as 80 feet lower than the highest point of the water table in the incised meandering portion of the study area, in the Aquilla Compartment, and as much as 90 feet lower than the highest point of the water table in the meandering portion, in the Large Falls compartment.

Where the Brazos River intersects the lateral boundary of the aquifer the groundwater flow is segmented and forms compartments. By segmenting the aquifer in all locations that the river contacts the lateral bedrock boundary, the extent of compartmentalization in the Northern Segment is shown (Figure 20). There are 13 compartments that range in size from 1,563 to 75,000 acres. The largest compartment is the Large Falls Compartment which makes up 39.02% of the Northern Segment. Table 2 lists the compartments, their size in acres and what percent of the Northern Segment they occupy. Compartments increase in size in the southern direction. In the floodplain meandering portion of the study area the floodplain is wider than in the incised meandering portion and the Brazos River does not contact the lateral boundaries of the aquifer as frequently. The average compartment size in the floodplain meandering section is 24,831 acres while the average compartment size in the incised section is 6,175 acres. Larger compartment size in the floodplain meandering section means that

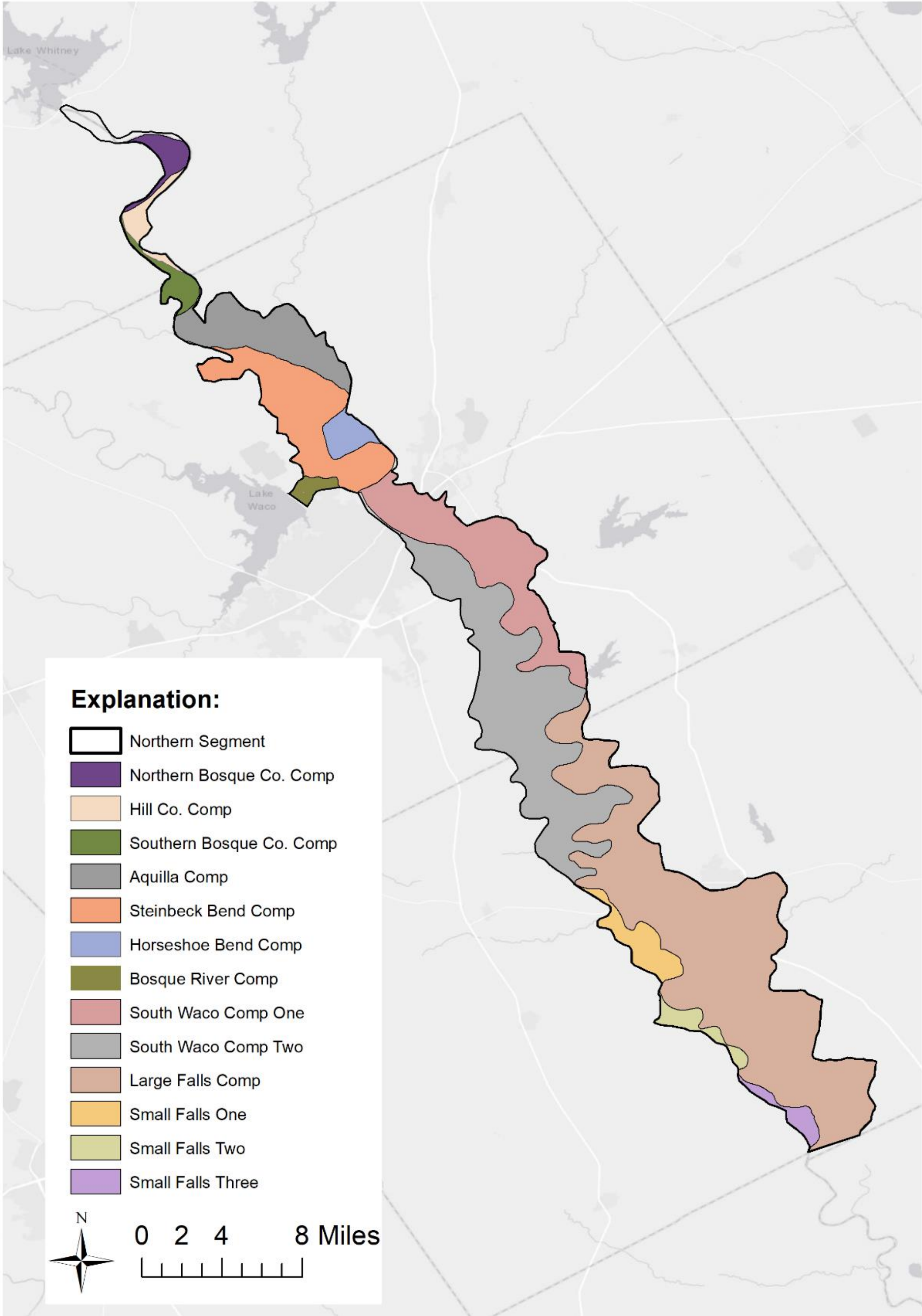


Figure 20. Compartments within the Northern Segment, n = 13.

compartmentalization may not affect groundwater users as much as groundwater users in the incised meandering section. Groundwater users located within smaller compartments have access to less groundwater volume than those located in large compartments, therefore the aquifer will be more sensitive to groundwater withdrawal in those areas.

Table 2. Compartments in the Northern Segment, their size and percent of the aquifer they occupy.

	Compartment Name	Compartment Number	Area (acres)	% of Northern Segment
Incised	Northern Bosque	1	2973	1.55
	Hill County Comp	2	2589	1.35
	Southern Bosque	3	2864	1.49
	Aquilla Comp	4	11059	5.75
	Steinbeck Bend	5	19072	9.92
	Horseshoe Bend	6	3105	1.62
	Bosque Comp	7	1563	0.81
Meandering	Swaco Comp One	8	21736	11.31
	Swaco Comp two	9	41715	21.70
	Large Falls Comp	10	75000	39.02
	Small Falls One	11	5298	2.76
	Small Falls Two	12	2873	1.49
	Small Falls Three	13	2364	1.23

River Bank Analysis

To further analyze how the Brazos River influences and is a boundary to groundwater flow, the river bank analysis was conducted. Figure 21 shows the reach of the Brazos River that was floated from Highway 7 to the Falls on the Brazos Park in Falls County. The Brazos River bank material transitioned 4 times through this reach from fine grained bank material, to coarse grained bank material, to occasional bedrock in the bank, to bedrock banks. When the Brazos River has fine grained bank material the river is poorly to moderately connected to the aquifer and may not exchange significant amounts of water with the aquifer. In portions where the river has coarse grained bank material it

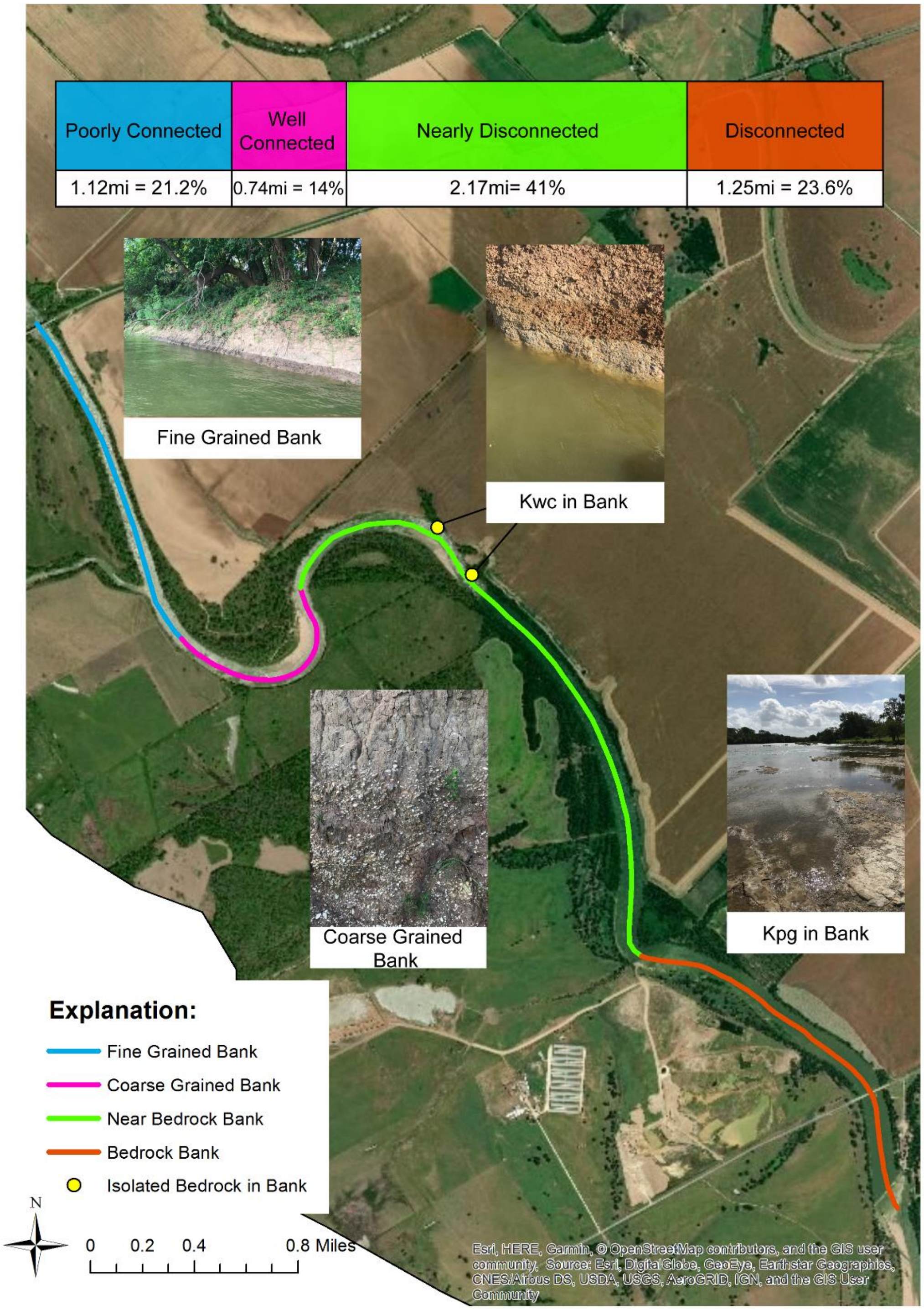


Figure 21. Analysis of river bank material along observed reach.

is likely well connected to the aquifer and easily exchanges water with the aquifer. In the portion when the river has bedrock occasionally cropping out in the channel to having complete bedrock banks then the river has incised nearly through or completely through the alluvial section and is a physical boundary between the aquifer on either side. The total river length in the recorded section is 5.28 miles, of which 1.12 miles, 21.2% was fined grained bank material, 0.74 miles, 14% was coarse grained bank material, 2.17 miles, 41% was occasional bedrock bank material, and 1.25 miles, 23.6% was bedrock banks. Therefore, of the 5.28-mile reach that was recorded 3.42 miles of the river bank were near bedrock or consisted of bedrock making 64.6% of the aquifer in this area physically divided by the Brazos River on either side.

Cores, Cross Sections and Implications

Cross sections A-F were drafted from detailed sediment core data taken throughout the northern segment. The cross sections show boundary conditions and sediment distribution. In order to best represent the heterogeneity of the alluvial sediments in detail, the vertical scale has been exaggerated.

Cross section lines A-A’ and B-B’ are along core transects in the incised meandering portion of the study area, in the Steinbeck Bend Compartment (Figure 22). The cores that make up A-A’ pass through Steinbeck Bend in a general N-S direction and the cores that make up B-B’ are in a general W-E direction and form a tied set. The cross sections show the Brazos River boundary, Austin Chalk lateral bedrock boundary, the alluviated slip-off slope and sediment distribution across the meander, (Figures 23 and 24).

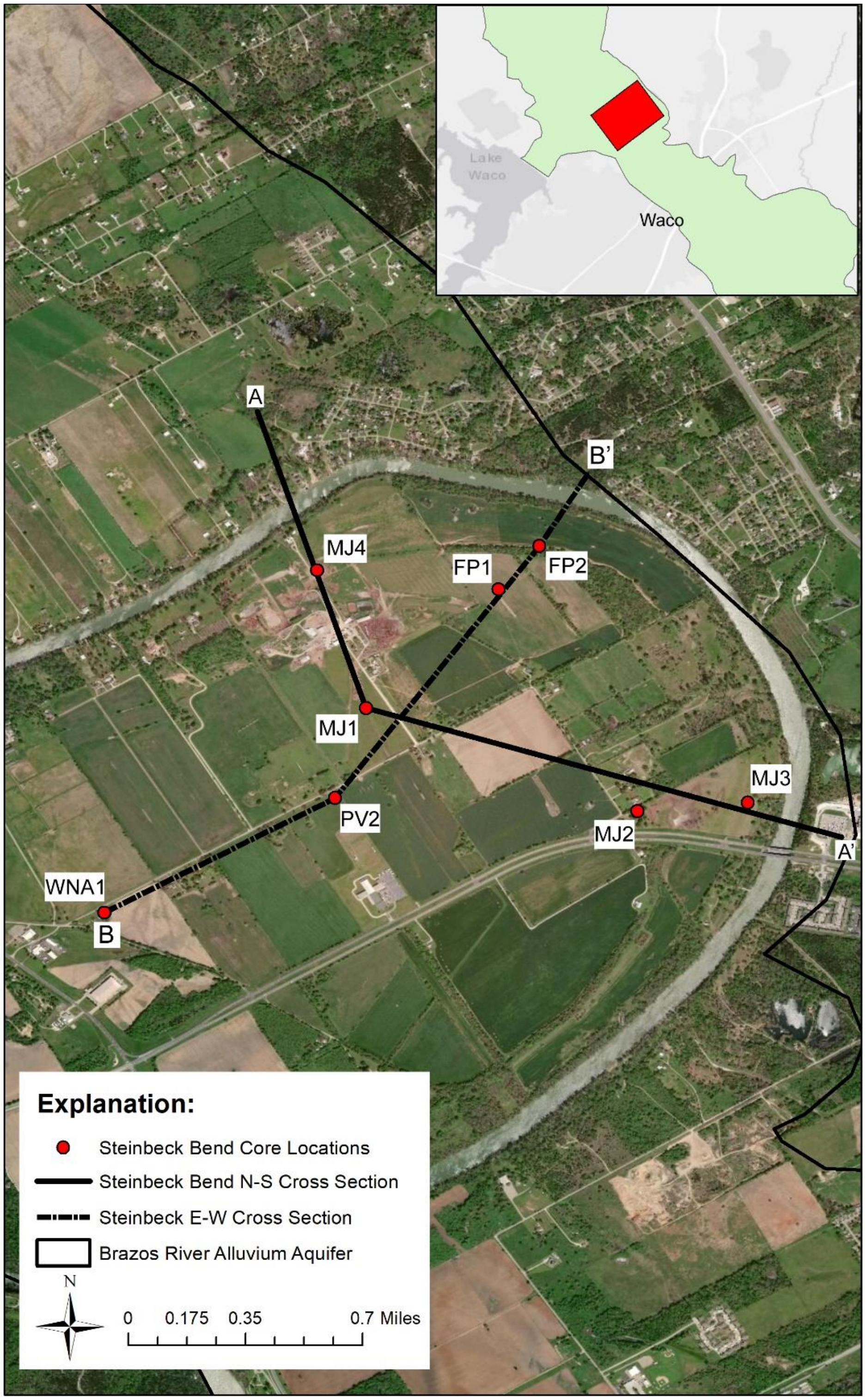


Figure 22. Location map of cores and cross sections A-A’ and B-B’ within Steinbeck Bend.

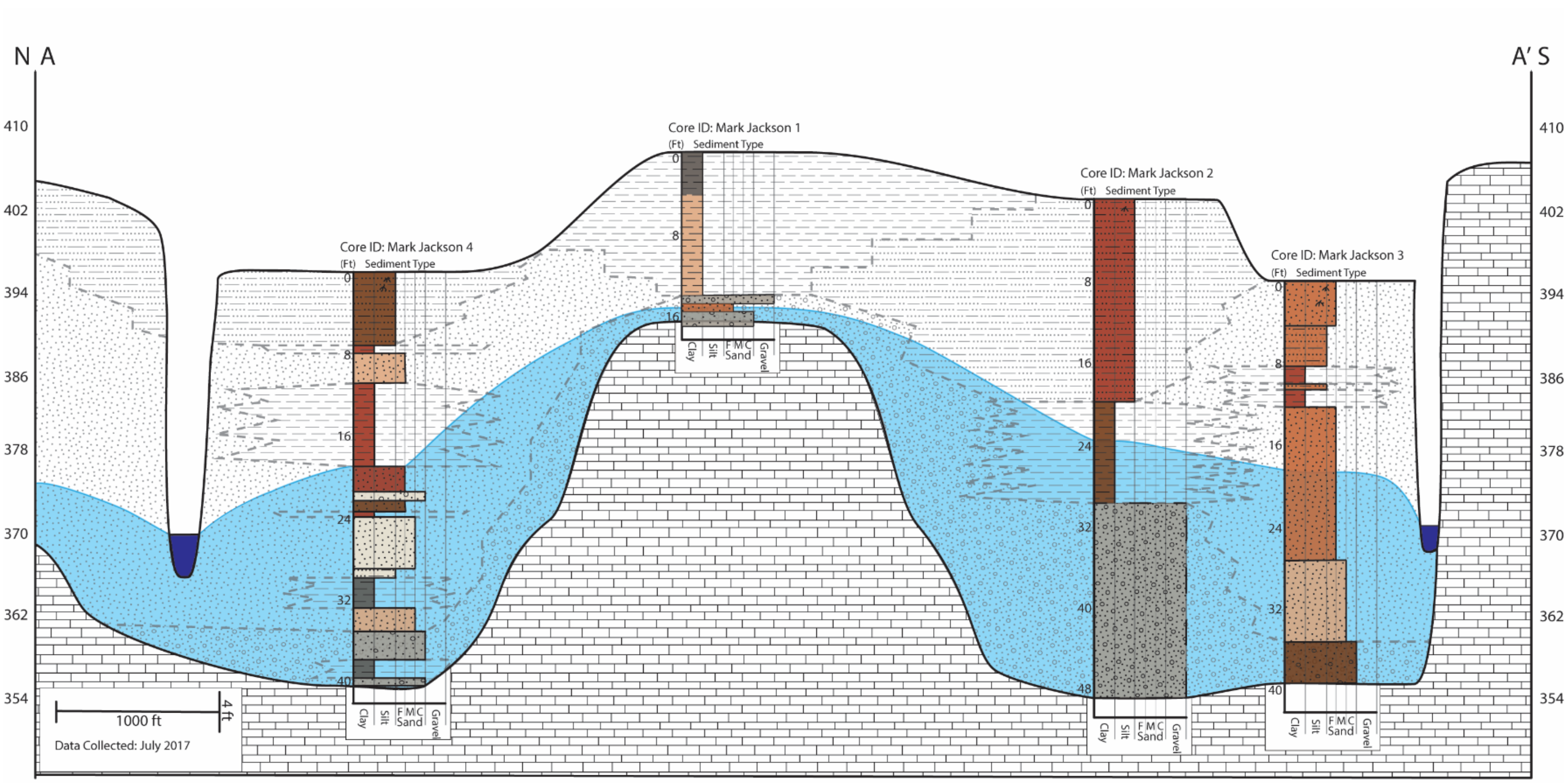


Figure 23. Cross section A-A' that is N-S through Steinbeck Bend.

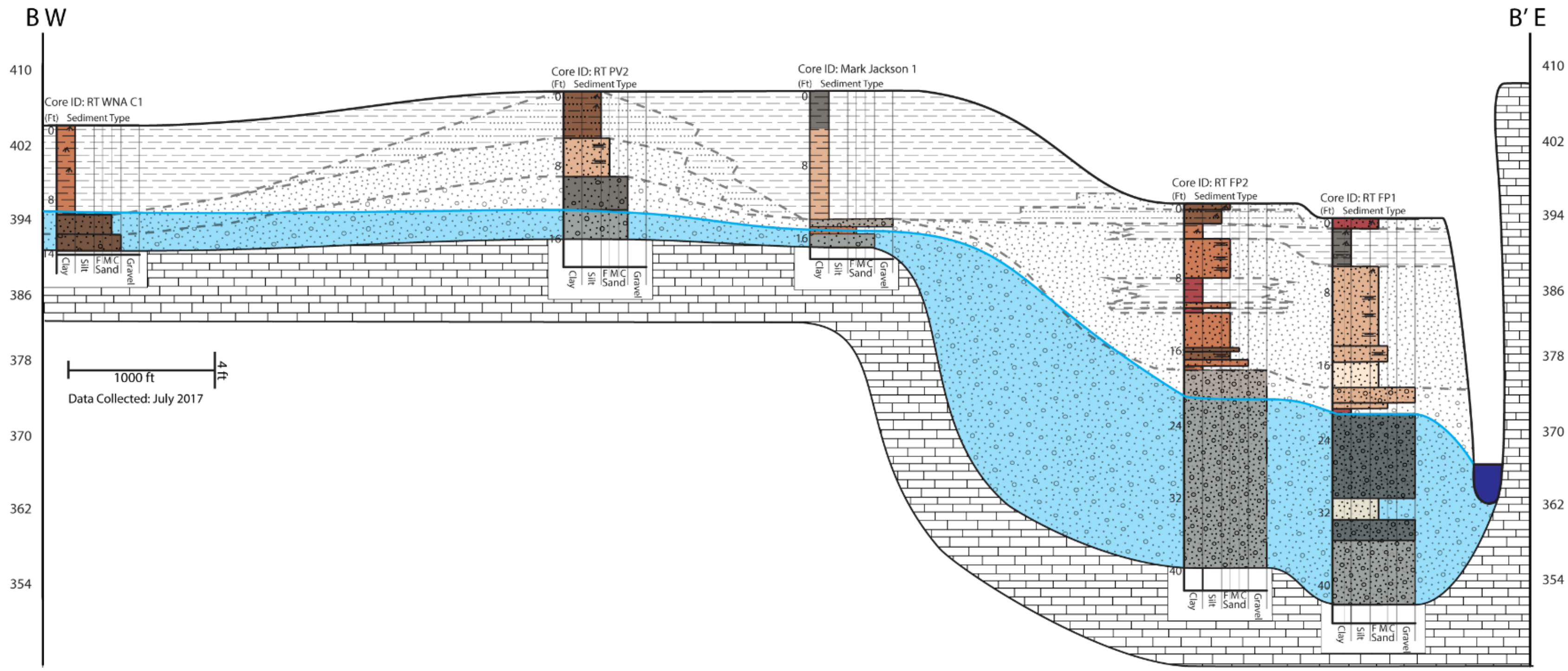


Figure 24. Cross section B-B' that is W-E through Steinbeck Bend.

Cross section A-A’ consists of four cores, MJ1, MJ2, MJ3, and MJ4, begins north of the Brazos River within the Horseshoe Bend compartment and passes through the Brazos River and Steinbeck bend, crosses the Brazos River again and ends in the Austin Chalk bedrock boundary (Figure 23). MJ1 is in the center of the meander, on top of the buried bedrock ridge that defines the slip-off slope. The alluvium thickness at MJ1 is 17 feet and had one foot of saturated thickness on 7-17-17. The MJ1 core consists of 14.9 feet of clay, 1.8 feet of sand and 0.3 feet of gravel, within one major fining upward sequence. MJ2 is southeast of MJ1, the core is not fully penetrating, bedrock contact was made with flight augers. The total alluvium thickness at MJ2 is 49.0 feet with 20.0 feet of saturated thickness on 7-17-17. The total core depth of MJ2 is 30.0 feet consisting of silt that has varying amounts of clay from 0-20 feet underlain with 10 feet of clay, the total clay thickness is unknown. The augers returned no sediment from 30 feet to bedrock, when the augers were brought to surface they were coated with saturated sand and gravel in the bottom 15 feet. MJ3 is east of MJ2 directly toward the river, in the lowest part of the floodplain. MJ3 is core from surface to bedrock, is 39.5 feet thick with a saturated thickness of 25.5 feet on 7-20-17. The MJ3 core consists of one major fining upward sequence that contains 27 feet of sand that fines upward to 4.5 feet of clay, the sand in the lower 4.5 feet is coarse and has gravel throughout. The fining upward sequence terminates eight feet below land surface and is overlain with silt and sand that coarsen upward. MJ4 is north of MJ1 in the lowest part of the floodplain with core from surface to bedrock. MJ4 is 40.0 feet thick with a saturated section of 21.5 feet on 7-24-17. The core consists of five fining upward sequences of sand that transition to clay beds of considerable thickness. MJ4 is the most complex and heterogeneous core within the A-A’ cross section and contains the most fine-grained material with clay and silt making up 55% of the total alluvium section, a detailed core diagram is shown in Figure 25. The sediment in MJ4 is saturated immediately beneath an eight feet thick clay layer, suggesting that the water table may be locally confined. There are three more clay beds within the saturated section that could cause vertical isolation of groundwater flow systems.

In the A-A' cross section, alluvium thickness and saturated thickness varies considerably. Alluvium thickness averages 36.4 feet with a range of 23.0 feet and saturated thickness averages 17.0 feet with a range of 24.5 feet. Both alluvium thickness and saturated thickness are affected mainly by the large bedrock ridge in the axis of Steinbeck Bend. Overall, alluvium thickness and saturated thickness increases with proximity to the Brazos River. Table 3 lists the A-A' cores, depth to bedrock, saturated thickness, grain size percent of the total core, and number of major fining upward sequences.

Cross section B-B' is along the W-E core transect through the axis of the Steinbeck Bend meander and contains cores, WNA1, PV2, FP1, and FP2, tied with MJ1. WNA 1 is the western most core, is 13.5 feet thick and had a saturated section of 3.7 feet on 6-15-17. The core consists of one major fining upward sequence that is 3.7 feet of sand overlain by 9.8 feet of clay. PV2 is east of WNA 1, is 16 feet thick and had 7.0 feet of saturated section on 6-26-17. The core has one incomplete fining upward sequence that is 11 feet of sand overlain by five feet of silt. FP1 is east of MJ1 and does not include the entire alluvial section. The alluvium thickness at FP1 is 39.5 feet with 24.5 feet of saturated thickness on 7-13-17 of which only 18 feet was cored. The core contains 3 sand to clay fining upward sequences overlain by two feet of silt and sand. FP2 core does not

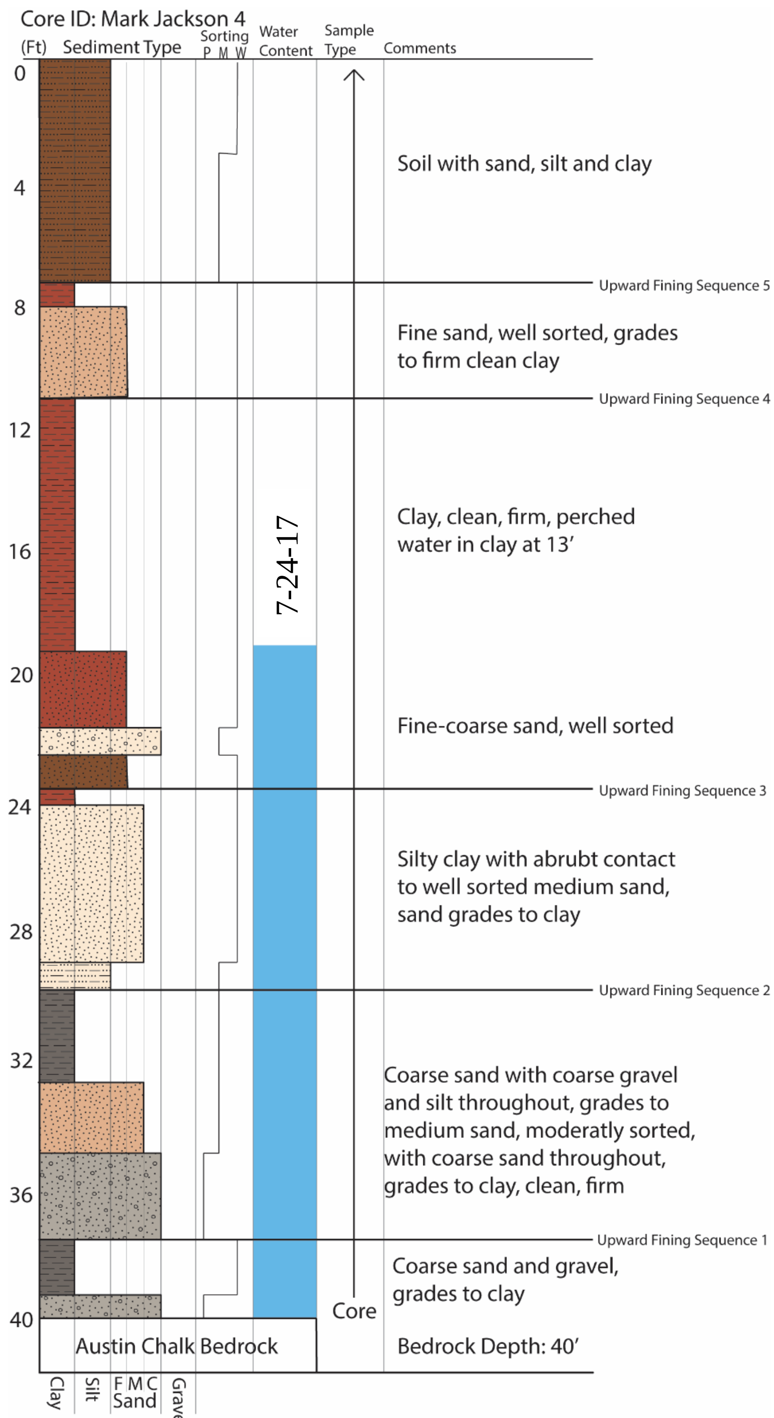


Figure 25. Detailed core diagram of MJ4 core showing grain size distribution, sediment color, sorting, water content, sample type, description and fining upward sequences.

include the entire alluvium section. The alluvium thickness at FP2 is 42.0 feet with 27.0 feet of saturated section on 7-14-17, of which 34 feet were cored. The FP2 core has three fining upward sequences. The first fining upward sequence is fine sand overlain with gravel, this is mostly likely an erosional surface where the top of the sequence one was removed and coarse-grained deposition began again. Fining upward sequences two and three are sand to clay sequences.

Table 3. Cores along A-A' cross section, bedrock (BR) depth, saturated thickness (SAT T), grain size percentages, and number of fining upward sequences (# F/U SEQ).

Core Name	BR Depth (ft)	SAT T (ft)	Fines (%)	Sand (%)	Gravel (%)	# F/U SEQ
MJ1	17	1	85.3	10.4	1.5	1
MJ2	49	20	100.0	0.0	0.0	0
MJ3	39.5	25.5	21.5	78.5	0.0	1
MJ4	40	21.5	55.0	45.0	0.0	5

Alluvium thickness and saturated section again varies considerably in B-B'. Alluvium thickness averages 27.8 feet with a range of 28.5 feet. Saturated section averages 15.6 feet with a range of 23.3 feet. These variations are due to the placement of the cores relative to the bedrock topography. WNA1 and PV2 are positioned on top of the bedrock ridge where the alluvial section and saturated thickness is thinned considerably and FP1 and FP2 are positioned east of the bedrock ridge in the portion of the floodplain where the paleo-Brazos River removed the bedrock during lateral planation and incision (Stricklin 1961). Table 4 lists the cores along B-B', their depth, saturated thickness, grain size percent of whole core, and number of fining upward sequences.

Considering the paths of A-A' and B-B' the bedrock ridge and its influence on groundwater flow and sediment distribution can be understood. The shape of the alluviated slip-off slope mimics topography and the shape of the Steinbeck Bend meander and causes groundwater flow to do the same. The cross sections and Tables 3 and 4 show that coarse grained material was deposited primarily along the outside of the meander, away from the slip-off slope where the alluvial section is thickest. Along the top of the slip-off slope where the alluvium is thinnest there is a larger fraction of fine-grained material and the saturated section is much thinner.

Table 4. Cores along B-B' cross section, bedrock (BR) depth, saturated thickness (SAT T), grain size percentages, and number of fining upward sequences (# F/U SEQ).

Core Name	BR Depth (ft)	SAT T (ft)	Fines (%)	Sand (%)	Gravel (%)	# F/U SEQ
RT WNA 1	13.5	3.7	72.6	27.4	0.0	1
RT PV3	16.0	7.0	31.3	68.8	0.0	1
RT FP1	39.5	24.5	41.7	58.3	0.0	3
RT FP2	42.0	27.0	11.8	52.9	35.3	3

Looking at the flow map in Figure 17 the groundwater flow reflects the shape of the slip-off slope with groundwater flowing radially away from the center of the meander toward the stream in all directions. This relationship is shown again throughout the incised meandering portion of the study area, specifically within the Horseshoe Bend compartment where there may be another similar bedrock feature influencing aquifer properties.

Figure 26 shows cross section line C-C' within the Aquilla Compartment in the incised meandering portion of the study area. Cross section C-C' crosses the Brazos River boundary, shows the relief of the bedrock and sediment distribution (Figure 27). The cross section includes cores RP1, RP2, RP3 and RP4. RP1 is the northern most core,

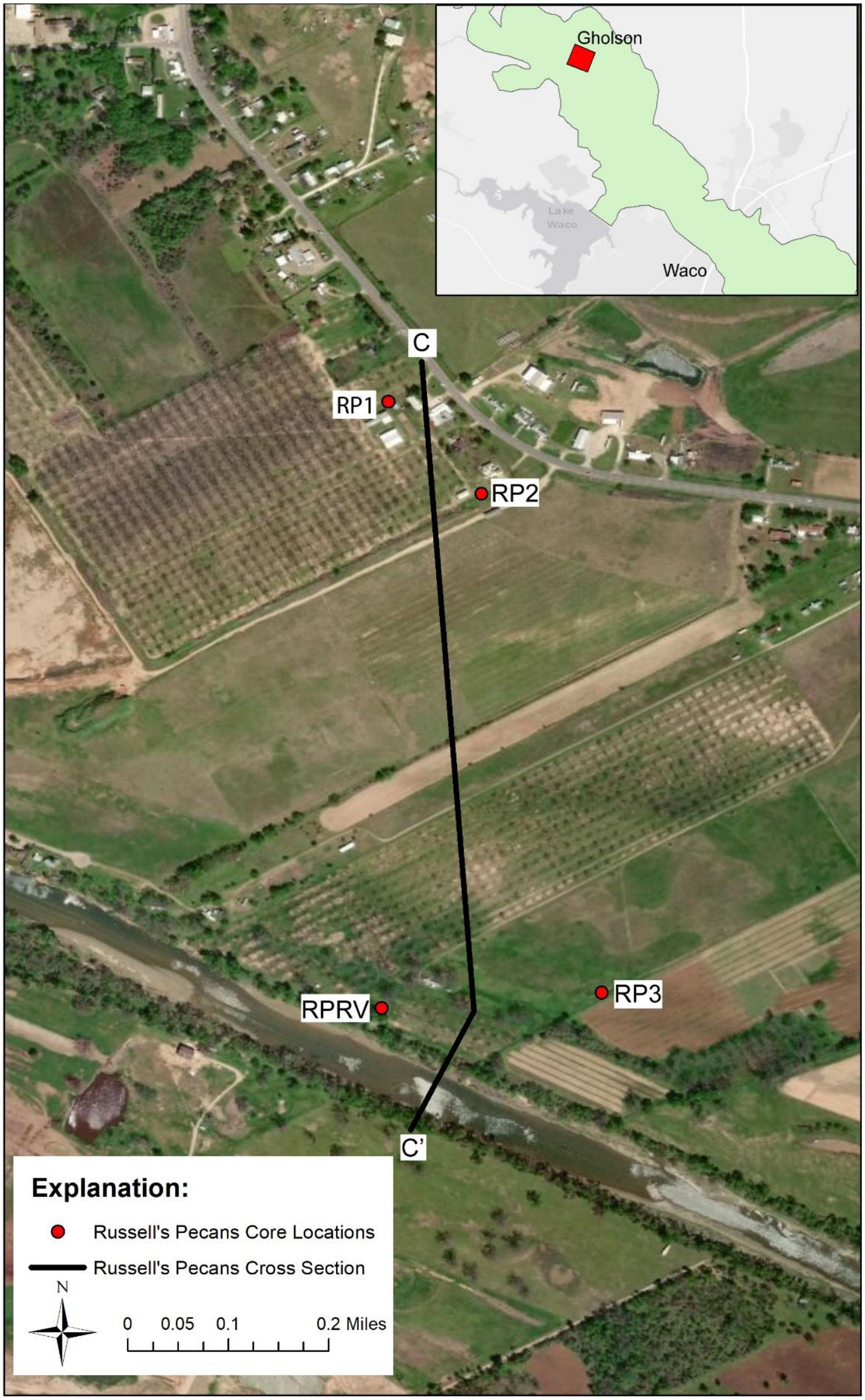


Figure 26. Location map of cores and cross section line C-C'.

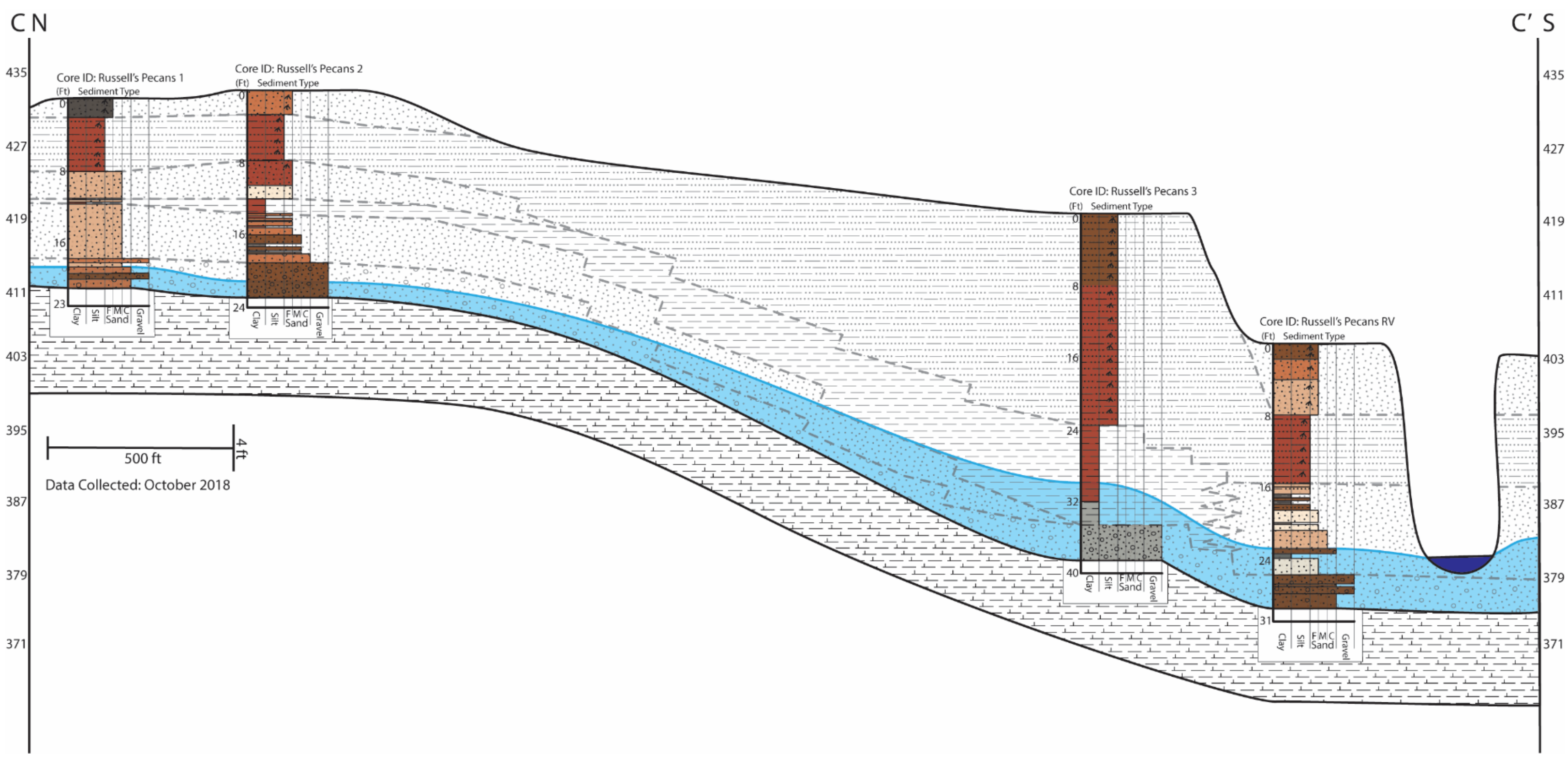


Figure 27. Cross section C-C'.

is 21.0 feet deep and had 2.0 feet of saturated section on 10-2-2018. The sediment consists of gravel, sand and silt within 1 major fining upward sequence. RP2 is southeast of RP1, is 23 feet thick and had 1.5 feet of saturated section on 10-2-2018. There are two major fining upward sequences. Sequence 1 is gravel that grades to sand that has cm scale clay lenses throughout, topped with a two feet thick clay bed. Sequence 2 is sand that grades to silt. RP3 is southwest of RP2, closer to the Brazos River. The alluvium section is thicker in this location and the core is not fully penetrating. The alluvium section at RP3 is 38.5 feet thick with a saturated section of 8.5 feet on 10-4-2017. The RP3 core is 36 feet and consists entirely of silt in the upper 23.5 feet that underlain by clay in the bottom 8.5 feet. RPRV is nearest the river, in the lowest part of the floodplain and includes the entire alluvial section. Bedrock at RPRV is at 29.5 feet, with a saturated section of 5.8 feet on 10-3-2017. There are three fining upward sequences, sequences one and two are gravel to clay, sequence 3 is sand to silt. Sequence 3 is overlain by eight feet of sand that is an erosional boundary.

Alluvium thickness, saturated section and sediment composition differ in each core and with changes in proximity to the Brazos River. Table 5 lists the cores in the transect along C-C’, their depth, saturated thickness, grain size percentage, and number of fining upward sequences.

In each of the cores along C-C’ there is a silt layer that is very hard and oxidized dark red that is terrace material, the silt layer is correlated across the transect. In RP1, RP2, and RP3 there is a clay layer correlated that thickens toward the stream, forming a localized confining layer. The saturated sand and gravel are also correlated across the transect, thinning between RP2 and RP3, then thickening considerably between RP3 and RPRV.

The relief of the bedrock bottom of the aquifer is similar to cross sections A-A' and B-B', thickening toward the Brazos River. The bedrock along C-C' drops about 37 feet in elevation from RP1 to RPRV. The Brazos River is the lowest point of the water table in cross section C-C', with around five feet of alluvium present beneath the river. The slope and relief of the bedrock bottom of the aquifer and the position of the Brazos River cause the saturated section to be increasingly thin with increased distance from the river. It is common for well drillers to drill through the alluvium and in to the bedrock in order to add storage to water wells completed in this area because of the thin saturated section.

Table 5. Cores along C-C' cross section, bedrock (BR) depth, saturated thickness (SAT T), grain size percentages, and number of fining upward sequences (# F/U SEQ).

Core Name	BR Depth (ft)	SAT T (ft)	Fines (%)	Sand (%)	Gravel (%)	# F/U SEQ
RP1	21.0	2.0	28.6	66.3	5.2	1
RP2	23.0	1.5	32.6	50.4	17.0	2
RP3	38.5	8.5	100.0	0.0	0.0	0
RPRV	29.5	5.8	33.2	60.3	6.4	3

Cross section D-D' is the first cross section south of Waco in the floodplain meandering portion of the study area in South Waco Compartment 2. Figure 28 shows the cross section line D-D'. Figure 29 is the cross section that includes three of the four cores taken in the area, Upper Hirsch, Middle Hirsch, Lowest Hirsch. Upper Hirsch is positioned highest in the floodplain the furthest away from the present-day Brazos River.

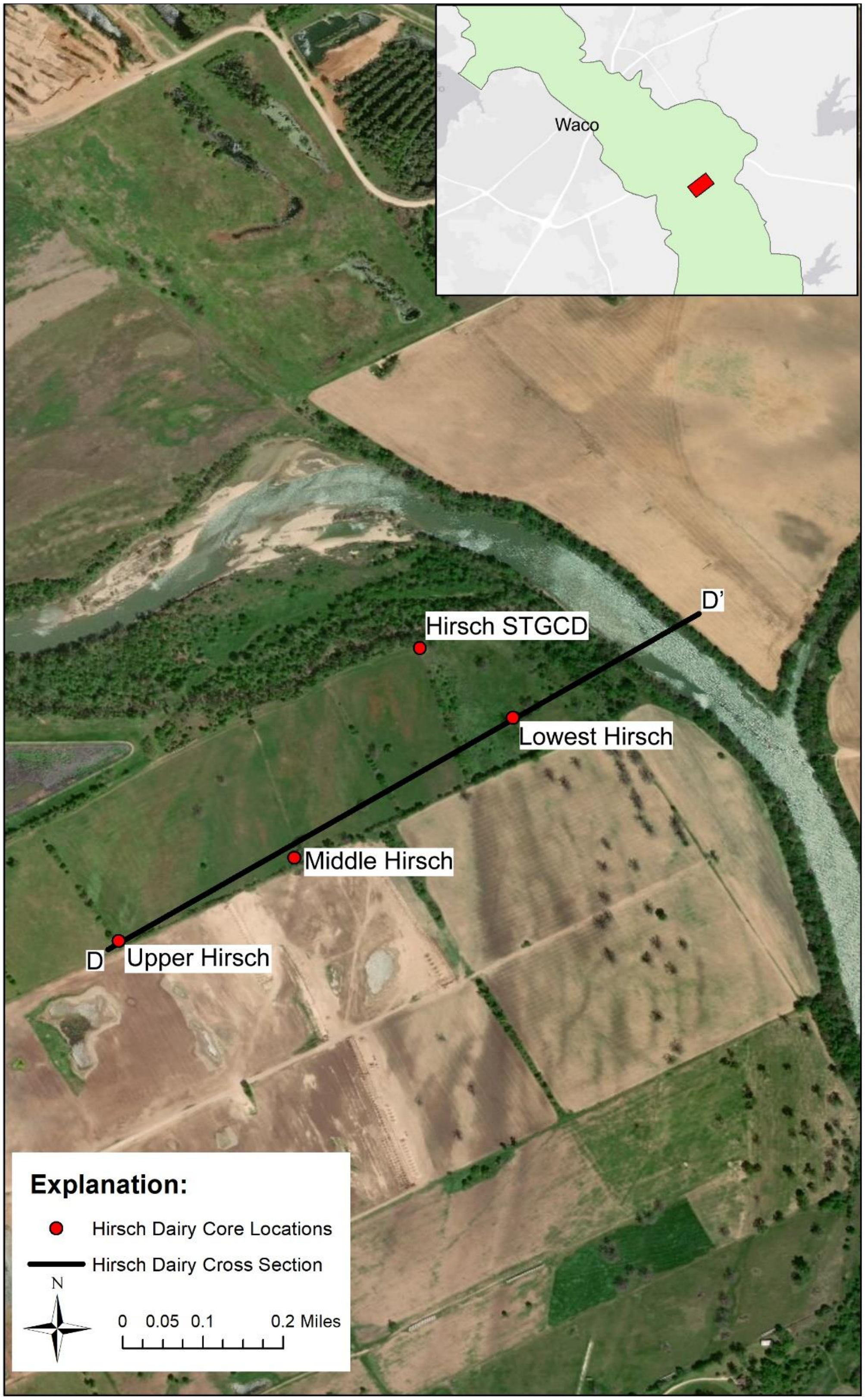


Figure 28. Location map of cores and cross section line D-D'.

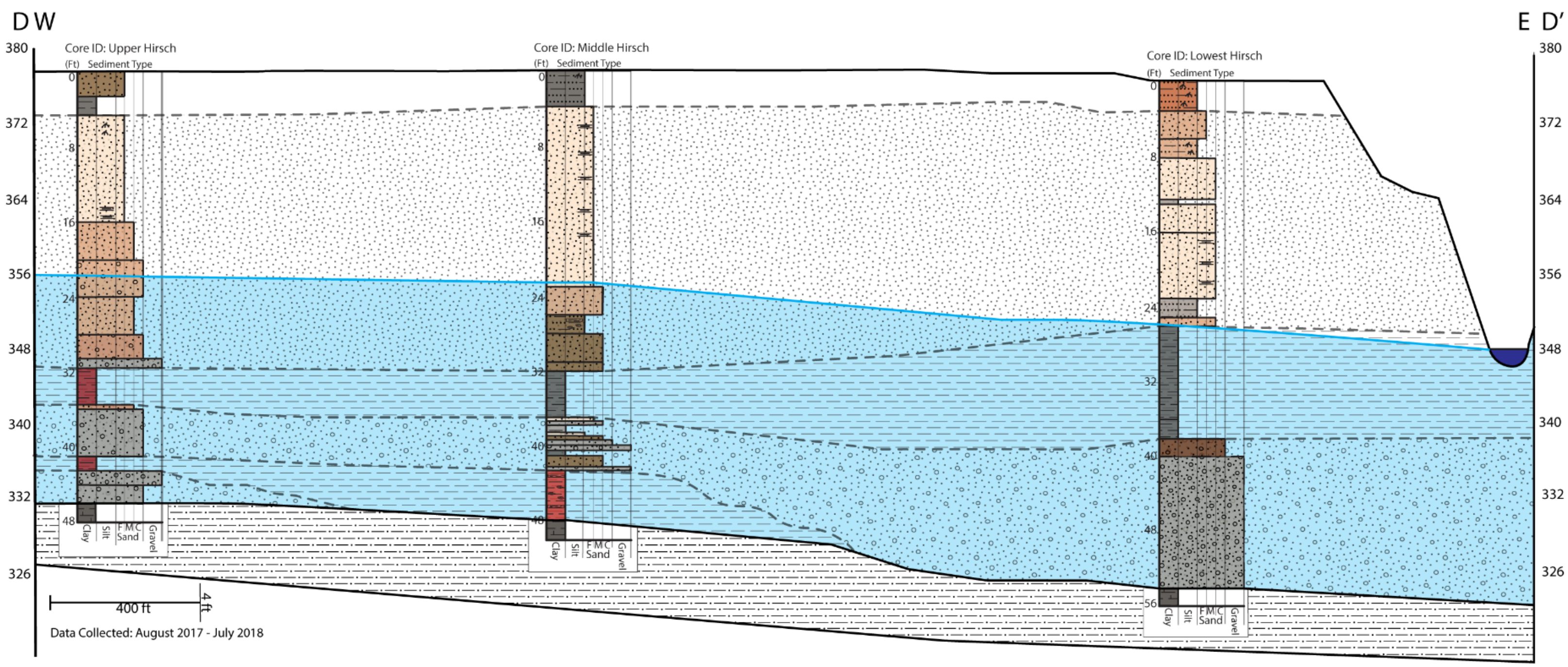


Figure 29. Cross section D-D'.

The alluvium thickness at Upper Hirsch is 46 feet with a saturated thickness of 30.0 feet on 8-9-17. There are 3 fining upward sequences that are gravel to clay and sand to clay. There are two clay beds within the saturated section that could cause localized confining and vertical isolation of groundwater flow systems. Middle Hirsch is east of Upper Hirsch toward the Brazos River. The alluvium thickness at Middle Hirsch is 48 feet and had 25 feet of saturated thickness on 4-16-18. There are five fining upward sequences that grade from gravel to sand to clay and from sand to silt. Coarse-grained material in the saturated section is very discontinuous with 48% being clay. Figure 30 is a detailed core diagram of Middle Hirsch that shows the rapidly fining upward gravel, sand, and clay sequences that overlain and underlain by thick clay beds. Lowest Hirsch is east of Middle Hirsch, nearest the Brazos River and is in the lowest part of the floodplain. The alluvium thickness at this location is 54 feet, the thickest found in McLennan County during this study, and had 26 feet of saturated section on 4-17-18. The Lowest Hirsch core is 40 feet and has four fining upward sequences that grade from sand to clay, and sand to silt. The sediment becomes saturated beneath a clay layer that is 10 feet thick that could cause localized confining.

In the cores along the C-C' cross section there is a clay layer that correlates across the section and forms a localized confined groundwater flow system, there are saturated sediment above the clay layer that are under water table conditions, it is likely that these two flow systems are isolated from one another by the clay layer.

The expression of the bedrock bottom of the aquifer is subdued compared to the incised meandering section with only eight feet of bedrock elevation change from Upper Hirsch to Lower Hirsch. The saturated thickness is thicker and more consistent in cross section D-D' compared to the cross sections in the incised portion, with an average thickness of 26.8 feet and a range of only five feet. Table 6 shows the cores in the D-D'

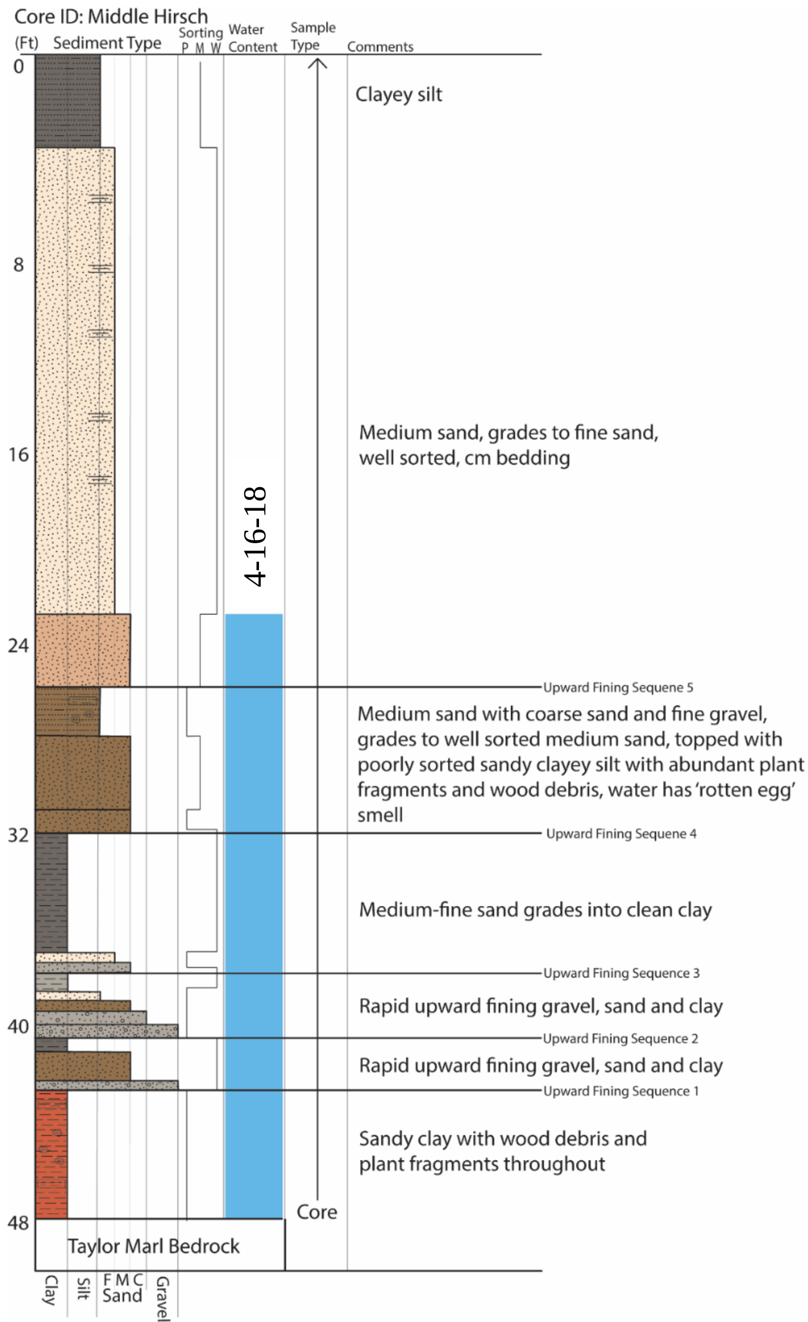


Figure 30. Detailed core diagram of Middle Hirsch core showing grain size distribution, sediment color, sorting, water content, sample type, description and fining upward sequences.

cross section with bedrock depth, saturated thickness, grain size percentages, and number of fining upward sequences.

The Brazos River is the lowest point of the water table at this location and will form a hydrologic boundary, but it does not depress the water table as much as shown in the incised meandering section and there is a significant portion of the alluvium left beneath the river. However, for the aquifer to communicate beneath the Brazos River then the water table would have to be lowered to the point that the Brazos River became a losing stream and flow ceased in the channel. While there is flow in the Brazos River channel, in a losing stream situation, the aquifer would receive water from the river and groundwater flow would not cross the channel.

Table 6. Cores along D-D' cross section, bedrock (BR) depth, saturated thickness (SAT T), grain size percentages, and number of fining upward sequences (# F/U SEQ).

Core Name	BR Depth (ft)	SAT T (ft)	Fines (%)	Sand (%)	Gravel (%)	# F/U SEQ
Upper Hirsch	46.0	30.0	16.3	78.3	5.4	3
Middle Hirsch	48.0	25.0	37.5	59.4	3.1	5
Lowest Hirsch	54.0	26.0	50.0	50.0	0.0	4

Figure 31 shows the cross section line E-E', located south of cross section D-D' still within South Waco Compartment 2. The cross section line crosses the Brazos River Boundary and the minor tributary Castleman Creek. Figure 32 is the cross section E-E' that shows the Brazos River boundary, the losing stream Castleman Creek and contains cores GM9, GM4, and GMRV. GM9 is the southern-most core the furthest away from

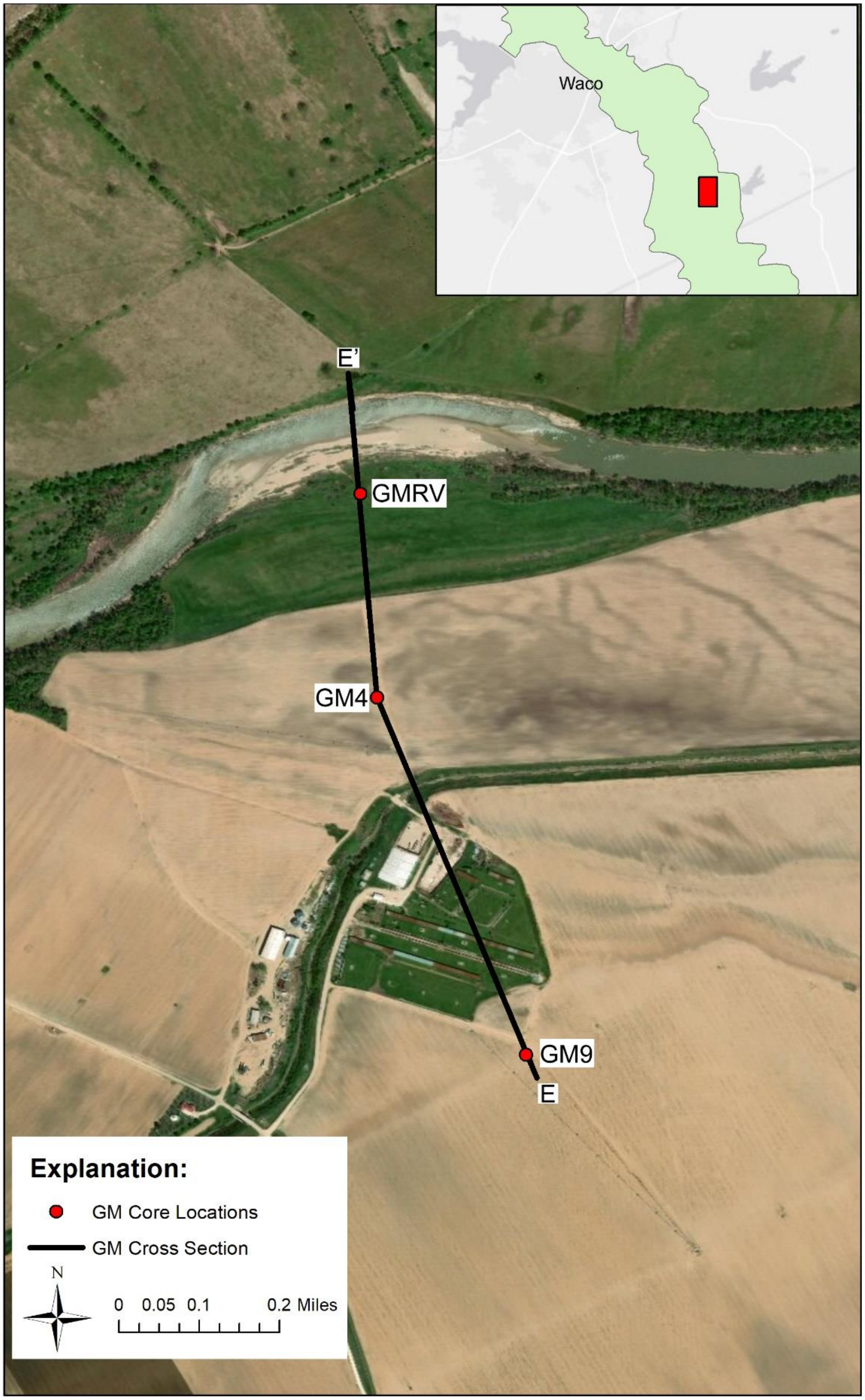


Figure 31. Location map of cores and cross section line E-E'.

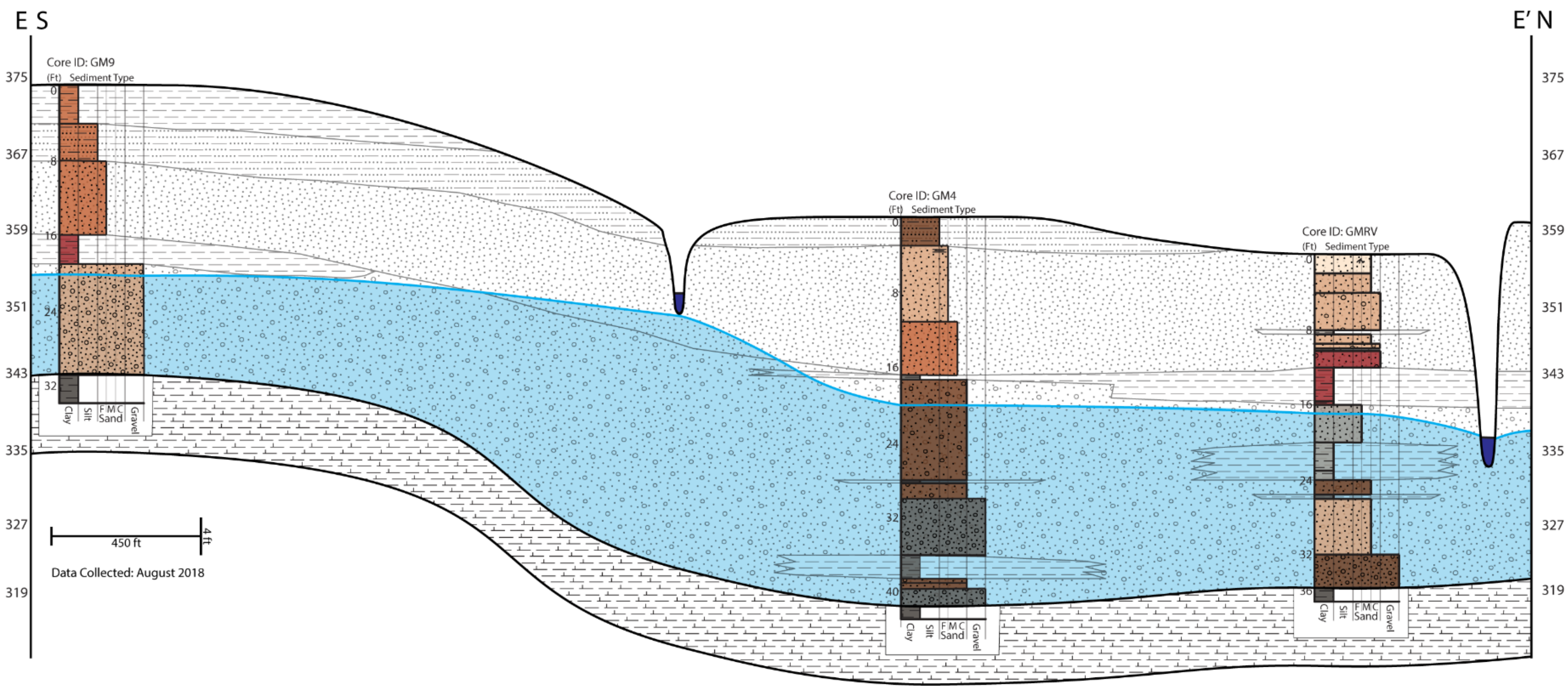


Figure 32. Cross section E-E'.

the Brazos River. The alluvium thickness at GM9 is 31.0 feet with 11 feet of saturated thickness on 8-27-18. The sediments are in two fining upward sequences. Sequence 1 grades gravel to clay, and sequence 2 grades sand, silt to clay. GM4 is north of GM9 closer to the Brazos River. The alluvium thickness at GM4 is 41.5 feet with 18.5 feet of saturated thickness on 8-30-18. There are two complete fining upward sequences that grade gravel, sand to clay and are overlain by 16.5 feet of sand that grades to silt. GMRV is north of GM4 nearest to the Brazos River and is within a modern point bar deposit. The alluvium thickness at GMRV is 36.0 feet with 16.0 feet of saturated thickness on 8-29-18. There are five fining upward sequences. Sequence 1 grades from gravel, sand to silt, sequences 2-5 grade from sand to clay.

There is more bedrock relief in cross section E-E' than in D-D' with about 24 feet of elevation change from GM9 to GMRV. The Brazos River also depresses the water table more along E-E' than D-D' and only has about 12 feet of alluvium remaining beneath the river. Due to the increased relief of the bedrock bottom and higher penetration rate of the Brazos River the saturated thickness is more variable along E-E' with an average of 15.2 and a range of 7.5 feet. Though the general trend of the aquifer is thickening toward the Gulf of Mexico, alluvium thickness along cross section D-D' is averages 14.3 feet thicker than along E-E'. Table 7 lists the cores along E-E', bedrock depth, saturated thickness, grain size percentages, and number of fining upward sequences.

Cross section D-D' and E-E' are in the same compartment but have different sediment distributions, in cross section D-D' there is a significant clay bed that correlates across the cores may vertically isolate flow systems or form locally confined groundwater flow. In D-D' the distribution of coarse-grained material is discontinuous with fine grained material making up most of the saturated section in areas. Along E-E' the distribution of coarse-grained material is much more continuous, and areas of confinement are less prevalent. The differences in alluvium thickness, saturated thickness, and sediment distribution between D-D' and E-E' show that within large compartments aquifer characteristics can be drastically different. Where in smaller compartments aquifer characteristics and sediment distribution may be more similar across the area of the compartment.

Table 7. Cores along E-E' cross section, bedrock (BR) depth, saturated thickness (SAT T), grain size percentages, and number of fining upward sequences (# F/U SEQ).

Core Name	BR Depth (ft)	SAT T (ft)	Fines (%)	Sand (%)	Gravel (%)	# F/U SEQ
GM9	31.0	11.0	35.5	64.5	0.0	2
GM4	41.5	18.5	14.5	66.3	19.3	2
GMRV	36.0	16.0	25.0	65.3	9.7	5

Figure 33 shows cross section line F-F' in Falls county near Moonlight Ranch. The cross section crosses the lateral bedrock boundary with three cores. Moonlight 1 was cored 720 feet outside of the aquifer boundary, Moonlight 2 was cored directly on top of the aquifer boundary and Moonlight 3 was cored 918 feet inside the aquifer boundary. The purpose of this cross section was to test the placement of the lateral bedrock boundary, the type of boundary (i.e. no flow boundary) and to examine the thickness of the alluvium at its boundaries in Falls County.

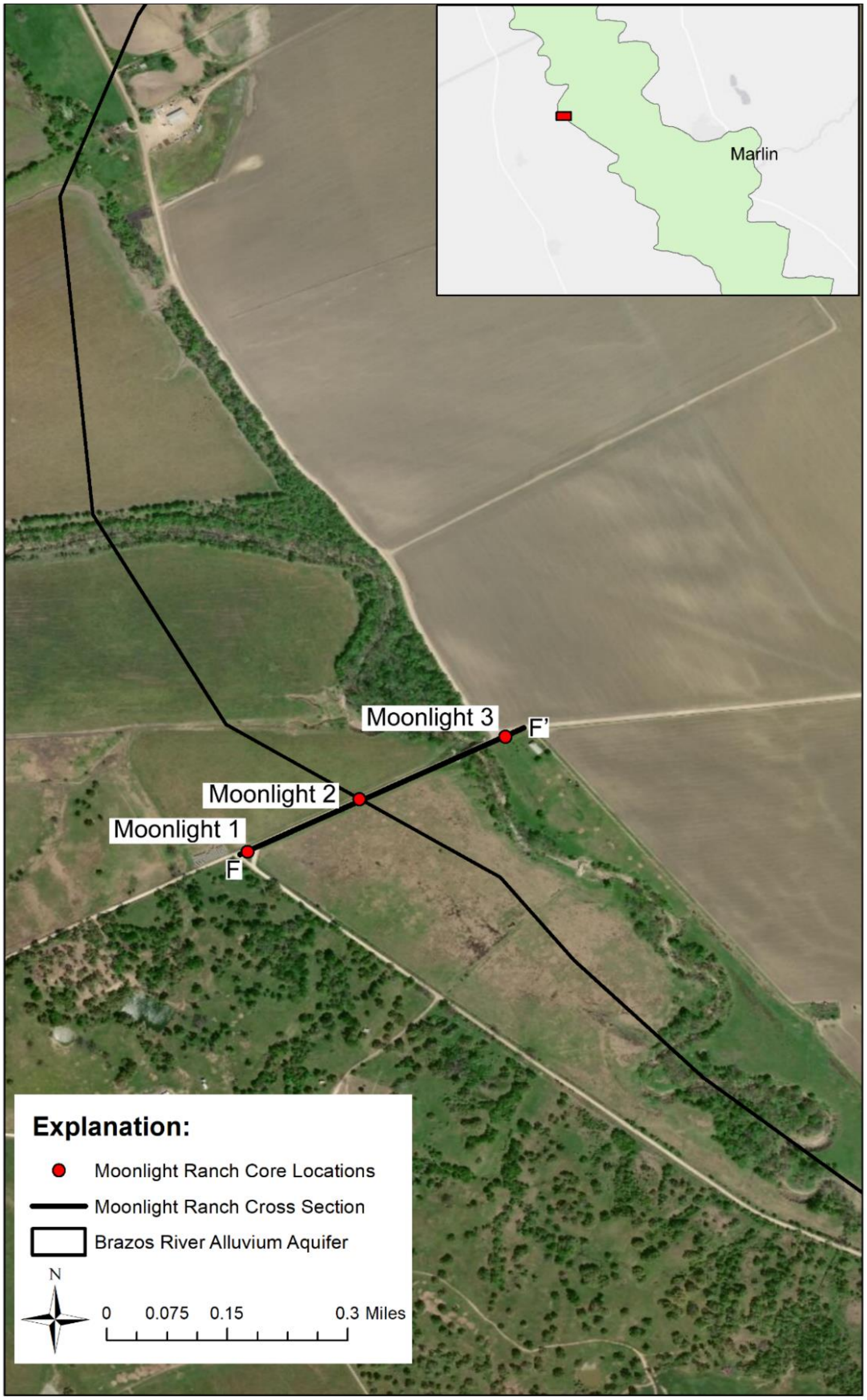


Figure 33. Location map of cores and cross section line F-F'.

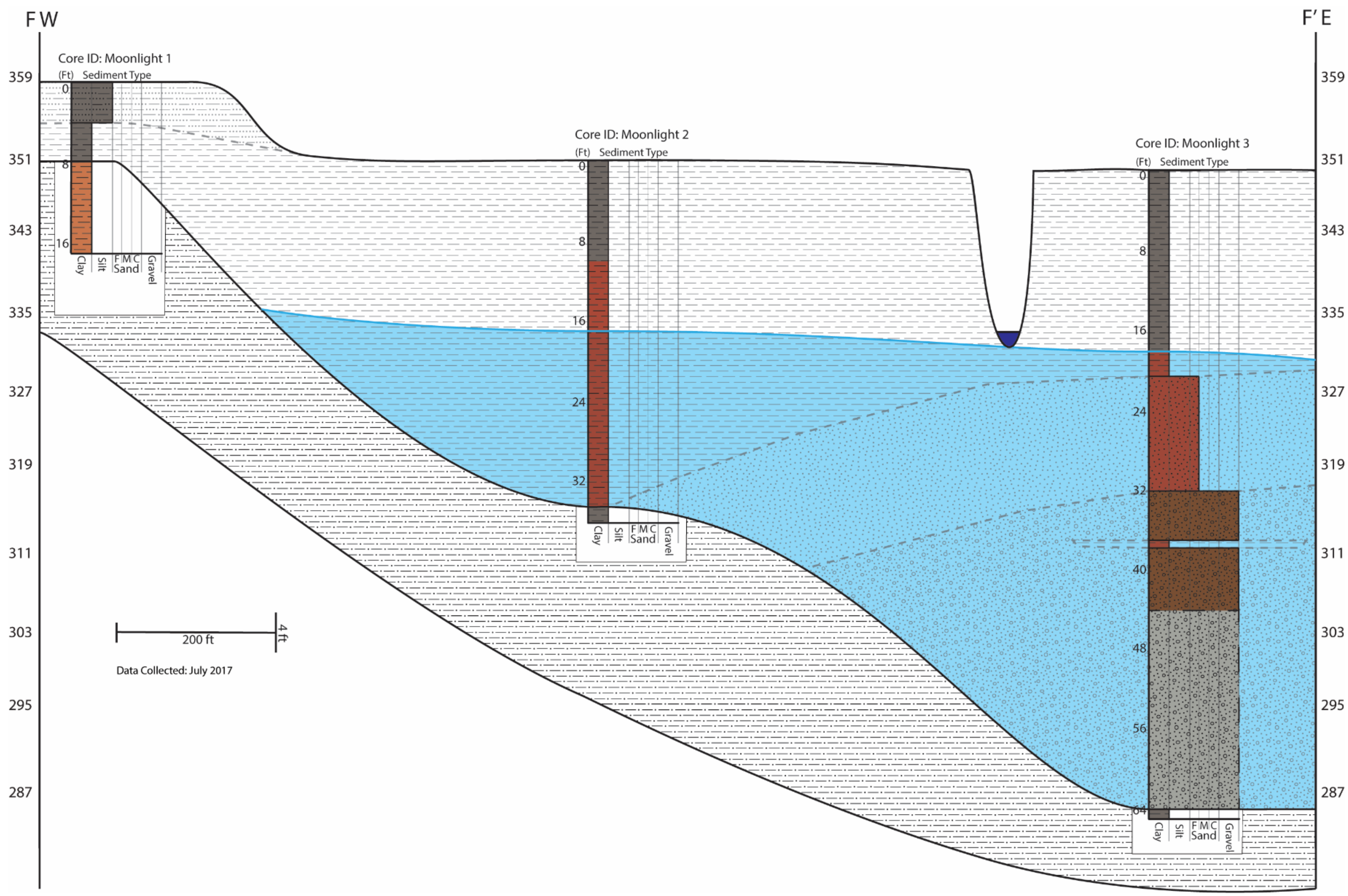


Figure 34. Cross Section F-F'.

The Moonlight 1 core consists of weathered upland silt and clay soils that contact clay bedrock eight feet below land surface. The clay bedrock was much harder than the upland material and had bedding. Moonlight 2, directly on the state boundary of the alluvium had 34.5 feet of alluvial clay before contacting the Wolf City bedrock. At this location there is no productive aquifer material however there is 34.5 feet of alluvium present. Moonlight 3 located within the state boundary of the aquifer was 64 feet thick and had 44 feet of saturated thickness on 7-27-17, the thickest recorded in the study. The moonlight 3 core is 44’ and had one large fining upward sequence that is gravel to clay.

Figure 33 shows the shape of the alluvial valley incision along the cross section. With bedrock being eight feet from the surface at Moonlight 1 to 64 feet below the surface at Moonlight 3. The location of the state boundary of the aquifer is an area where there is no aquifer material but there is considerable alluvial material. The Moonlight 1 core shows that the alluvium likely pinches out near that location and that it is outside of the saturated alluvium section.

The accumulation of the cores taken throughout the northern segment show significant changes in, alluvium thickness, saturated thickness and sediment distribution. In the incised meandering portion of the study area there are alluviated slip-off slopes that greatly affect the aquifer thickness and distribution of coarse grained sediments. The relief of the bedrock in relation to the incision percentage of the Brazos River causes the saturated thickness to thin with increased distance from the river. Figure 35 shows specific capacity measurements within McLennan County. The lowest values are located in the incised meandering portion where the bedrock topography combined with the incision percentage of the Brazos River causes a thin saturated section. Within the incised meandering portion, the average range in alluvium thickness recorded in the cores is 23.0 feet while the average range in the meandering portion is 9.3 feet. Consequently, the range in saturated thickness in the incised portion is much more than in the meandering

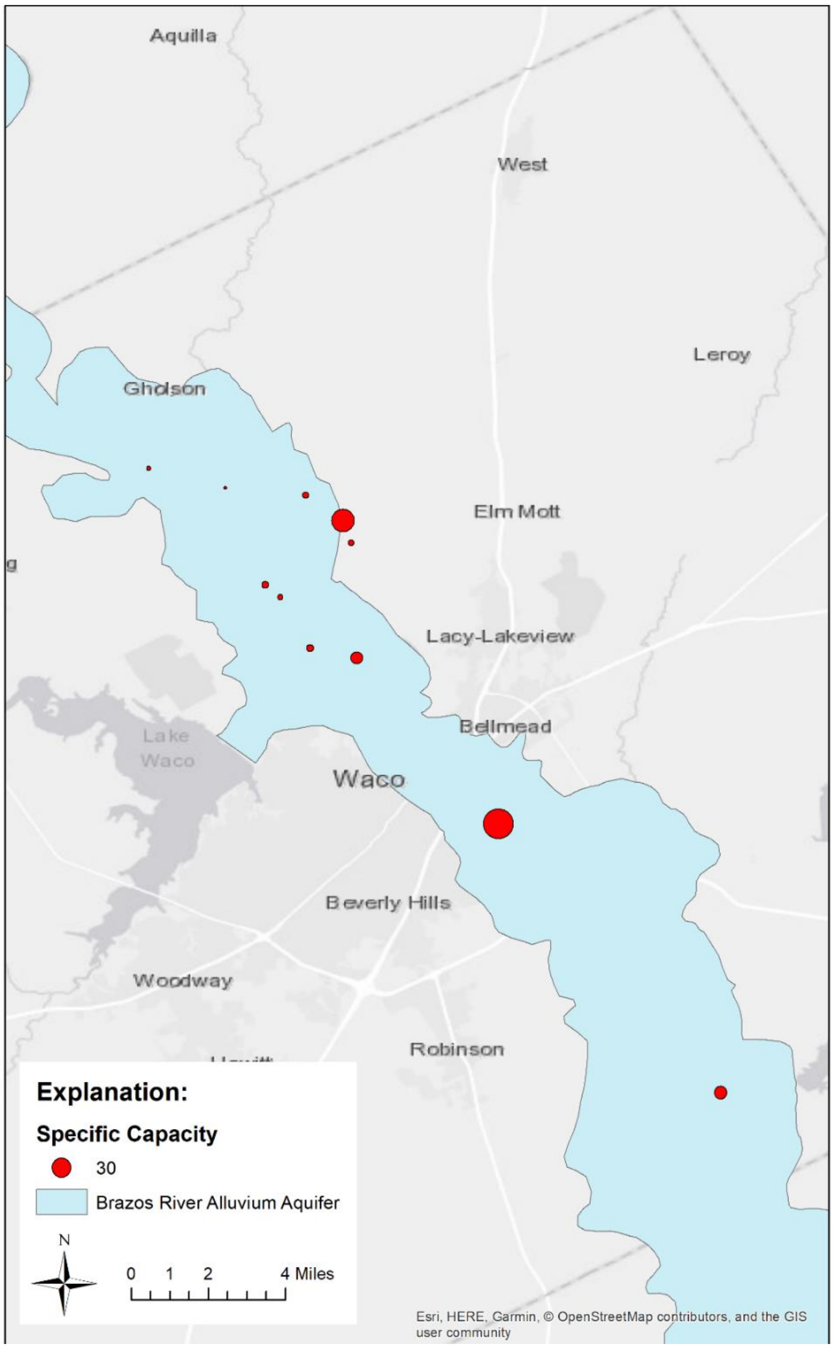


Figure 35. Specific capacities of BRAA wells in McLennan County. The size of the points represents magnitude of the value.

portion averaging 18.3 feet and 6.3 feet respectively. Figured 36 shows specific capacity measurements within Falls county in the meandering portion, the values are larger than in the incised meandering portion due to the increased alluvium thickness, saturated thickness, and subdued bedrock topography.

Sediment distribution varies considerably from transect to transect with some areas having clay beds that may cause locally confined groundwater flow and vertically segmented groundwater flow systems, as shown in cross section C-C' and D-D'. It is likely that groundwater flow within compartments is further segmented by the distribution of fined grained material throughout the alluvial section. In some cases, the presence of coarse-grained material is minimal as shown in the Middle Hirsch Core (Figure 30) or the distribution of coarse-grained material is vertically segmented by clay beds as shown in MJ4 (Figure 25). However, in most cases sand makes up the majority of the alluvium with portions of gravel and clay varying from location to location.

The cross sections show that the Brazos River is the lowest point of the water table in the BRAA and in all cases has incised through more than 50% of the alluvial section and in all but the Hirsch Dairy D-D' cross section has less than 20 feet of alluvium present beneath the channel. In the incised portion of the study area buried bedrock features such as slip –off slopes further aid in the division of groundwater flow systems across the Brazos River channel. In the floodplain meandering portion, though the river does not depress the water table as drastically as in the incised meandering portion, however the Brazos River is still a gaining stream and will serve as a hydrologic boundary as long as there is flow in the channel.

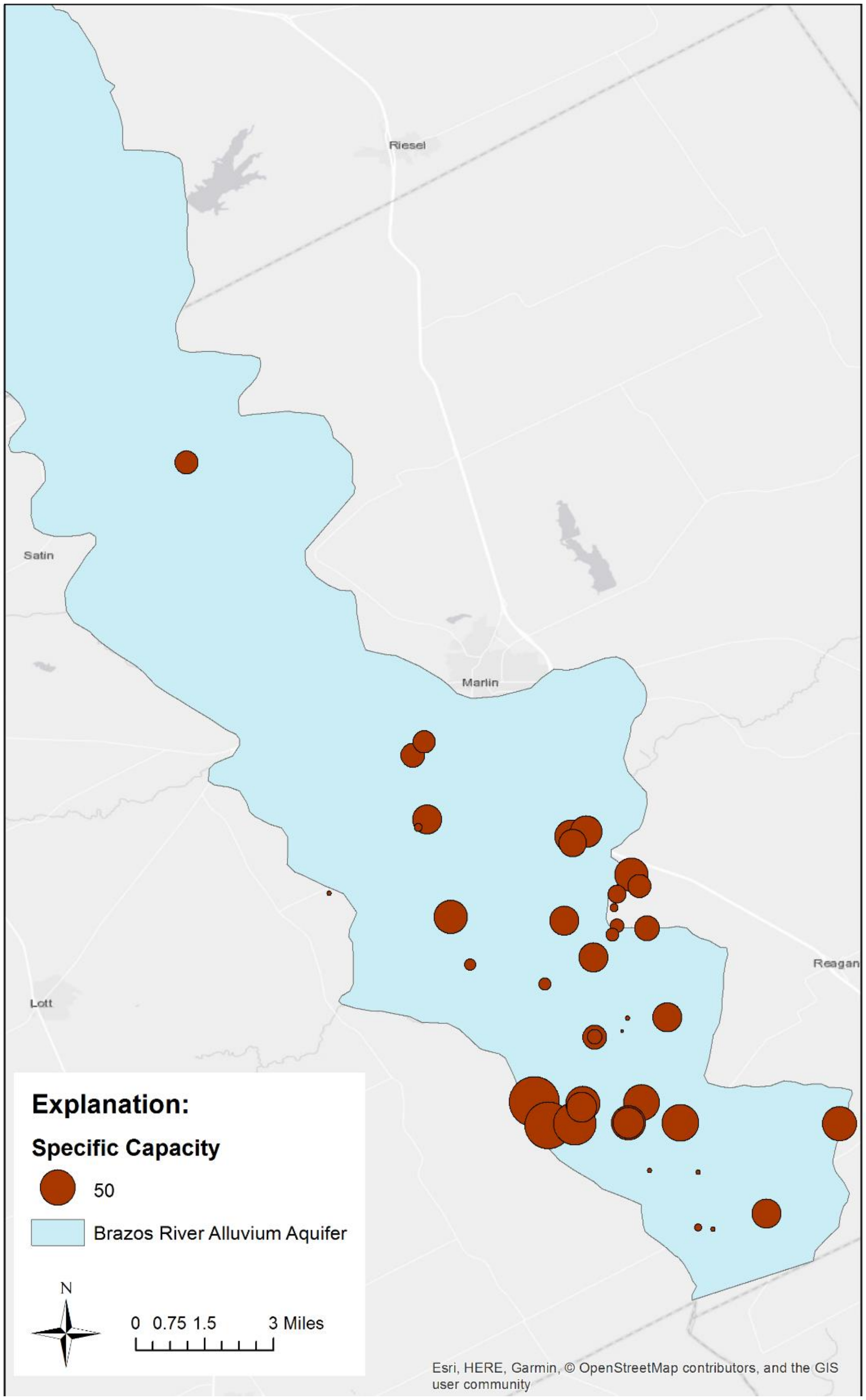


Figure 36. Specific capacities of BRAA wells in Falls County. The size of the points represents magnitude of the value.

CHAPTER FIVE

Conclusions

1. The Brazos River is a discharge site and groundwater contours show flow toward the river in most places.
2. Geospatial Analysis shows that the Brazos River influences groundwater flow in the BRAA by acting as a hydrologic boundary. The BRAA on one side of the Brazos River appears to function as an independent flow system from the BRAA on the other side of the river.
3. The Brazos River is a boundary to groundwater flow in 2 ways in the study area, as a hydrologic boundary and an absolute boundary. As a hydrologic boundary the Brazos River has incised through most of the alluvial section but is perched a distance above the bedrock bottom of the aquifer. As an absolute boundary the Brazos River has incised through the entire alluvial section and is flowing on bedrock, forming a physical divide in the aquifer on either side of the channel.
4. Interactions between the Brazos River and lateral bedrock boundaries form isolated compartments where discreet flow systems are present.
5. Within the northern segment the BRAA could further be divided into 2 segments. The incised meandering portion and the floodplain meandering portion. Within the incised meandering portion, the Brazos River channel is bounded by buried slip-off slopes that mimic the shape of the incised meander. These bedrock features influence aquifer properties and the distribution of coarse-grained material.

6. In the incised meandering portion alluvium thickness operates as a function of distance from the Brazos River, becoming thicker with proximity to the river where lateral planation and incision have removed the resistant bedrock. In the floodplain meandering portion the alluvium thickness is not dependent on the location of the Brazos River because the river has removed the less resistant bedrock and migrates freely throughout the floodplain.
7. Compartment size varies throughout the study area. Compartments are larger in the floodplain meandering portion because the floodplain is considerably wider and the Brazos River does not contact the lateral bedrock boundaries of the aquifer as frequently. The effect compartmentalization has on groundwater users will largely depend on compartment size and pumping within compartments. Smaller compartments are more likely to be affected by groundwater withdrawal than larger compartments.
8. Sediment distribution varies considerably from compartment to compartment and within compartments. There are areas where continuous clay layers may vertically isolate groundwater and may cause locally confined groundwater flow and areas that have few discontinuous clays where the aquifer may not be vertically isolated.

CHAPTER SIX

Recommendations

1. Currently the Brazos River is managed as a single aquifer with continuous uninterrupted flow systems. In the future, groundwater management may need to be adjusted to management on a compartment to compartment basis. This would be especially important in smaller compartments.
2. Due to the fluctuation in recharge, discharge and aquifer volume throughout compartments it will be necessary to conduct further investigations that quantify recharge, discharge and groundwater availability throughout compartments.
3. In the area of the aquifer where the Brazos River begins broad cross-valley meanders and the dominate direction of groundwater flow changes from cross-valley to down-valley, further characterization of the river boundary and groundwater flow may be necessary to better understand how the river is influencing groundwater flow in the area.
4. In order to further delineate compartmentalization, a groundwater chemistry dataset could be built on a compartment to compartment basis in order to see if individual compartments can have individual chemical signatures.
5. There are major tributaries in the study area such as the Bosque River, Aquilla creek, and Tehuacana creek. These tributaries may have significant alluvial deposits that contribute groundwater or be incised enough into the Brazos River alluvium to influence groundwater flow in the BRAA. Further investigations to characterize this relationship should be completed.

APPENDICES

APPENDIX A

Groundwater Database Used in Flow Map (n = 261)

State Well Number	Latitude	Longitude	Water Table Elevation (ft)
4031304	31.613056	-97.145	391
4023409	31.671111	-97.217778	418
4031202	31.620278	-97.196667	433
4023807	31.636945	-97.201112	423
4023408	31.668055	-97.242222	445
4023102	31.716389	-97.224722	445
4031204	31.605834	-97.189445	418
4023406	31.677778	-97.221667	422
4032505	31.552501	-97.082222	376
4032704	31.536111	-97.098334	375
4023405	31.683055	-97.216112	395
4031206	31.607778	-97.195	424
4022601	31.698056	-97.2725	393
4040511	31.448056	-97.075	385
4031207	31.610556	-97.194167	428
4032904	31.511667	-97.029444	369
4023407	31.676667	-97.224167	426
4023704	31.656112	-97.225	438
4031205	31.603334	-97.184167	391
4022306	31.729167	-97.276111	426
4032503	31.542222	-97.044722	365
4031302	31.606112	-97.160556	393
4031203	31.622778	-97.19	422
4023401	31.699167	-97.243889	424
4032804	31.511667	-97.080278	382
4022604	31.683889	-97.250556	441
4022305	31.710834	-97.265001	437
4032706	31.530833	-97.092222	370
4023501	31.670555	-97.200834	408
4023703	31.663889	-97.226667	427
4031305	31.616112	-97.140556	372
4022303	31.712778	-97.271667	429
4022304	31.715556	-97.275	423
4031209	31.605278	-97.168055	409
4022301	31.743334	-97.281111	409
4040605	31.417778	-97.029444	354
4023702	31.664167	-97.222778	428
4032602	31.554167	-97.034722	371
4032407	31.568055	-97.09	400
4022202	31.713334	-97.293056	450
4031306	31.608612	-97.1375	370

4022602	31.705556	-97.254723	440
4032504	31.546111	-97.043056	365
4031208	31.609723	-97.184445	411
4032401	31.563889	-97.0875	383
4023101	31.714723	-97.232222	450
4022201	31.735278	-97.298056	446
4023505	31.668889	-97.178055	400
4031307	31.601389	-97.148611	376
4040512	31.425	-97.062501	386
4023801	31.6516667	-97.171111	387
4023602	31.6725	-97.160834	402
4032707	31.529444	-97.0925	373
4023502	31.669444	-97.202501	409
4040901	31.411667	-97.039445	360
4040802	31.410278	-97.045	364
4040902	31.410834	-97.038611	360
4040602	31.4175	-97.038056	363
4032601	31.544167	-97.031944	365
4023901	31.6402778	-97.158888	404
4040603	31.4175	-97.038056	363
4023403	31.699722	-97.225833	439
4023503	31.693889	-97.203334	411
4032903	31.538056	-97.035556	372
4032902	31.508056	-97.034445	368
4040606	31.434722	-97.034167	352
4040903	31.412223	-97.035834	361
4023902	31.642222	-97.166667	408
4040904	31.412778	-97.034445	361
4032901	31.509445	-97.033055	369
4032406	31.566389	-97.091945	395
4032408	31.571111	-97.090834	405
4040609	31.444445	-97.011945	349
4040803	31.409167	-97.043334	364
4032409	31.5425	-97.090556	362
4040515	31.425	-97.050278	357
4040513	31.432222	-97.056667	357
4023404	31.700556	-97.216389	418
4040506	31.428055	-97.059723	361
4040608	31.440556	-97.020278	353
4032807	31.518055	-97.056112	356
4032806	31.515278	-97.062501	366
4040507	31.433889	-97.055278	359
4040607	31.437222	-97.028055	355

4023804	31.636389	-97.173889	384
4040516	31.430833	-97.043611	356
4040201	31.494722	-97.071111	377
4040505	31.429444	-97.056945	361
4032802	31.535556	-97.069722	353
4040504	31.430833	-97.054167	362
4040601	31.428333	-97.034445	361
4040202	31.493056	-97.074722	378
4032705	31.538056	-97.090556	365
4040502	31.432778	-97.048889	361
4040503	31.431944	-97.051389	362
4040508	31.433611	-97.058056	360
4023805	31.641111	-97.174444	388
4023803	31.629722	-97.178333	385
4040801	31.410556	-97.061112	370
4040203	31.496389	-97.071944	379
4040301	31.491111	-97.006112	389
4023802	31.638611	-97.1775	384
4032805	31.511112	-97.051945	365
4040604	31.456945	-97.021389	343
4040501	31.423889	-97.054167	362
4032801	31.527778	-97.063056	364
3933401	31.448334	-96.997778	338
4040509	31.4475	-97.044445	356
4040510	31.455556	-97.060278	355
4032703	31.525	-97.085834	372
4040514	31.42	-97.062223	367
4031308	31.619167	-97.160556	379
4023808	31.636945	-97.202501	428
3933701	31.380555	-96.969444	335
3941101	31.366389	-96.996389	332
3941102	31.362223	-96.988611	327
3941401	31.305556	-96.972778	325
3941402	31.306667	-96.980278	322
3941403	31.311112	-96.983055	325
3941404	31.327778	-96.970555	335
3941405	31.332778	-96.964167	329
3941501	31.305556	-96.940556	327
3941502	31.310834	-96.954167	326
3941503	31.331944	-96.948056	333
3941504	31.304167	-96.925833	323
3941505	31.307778	-96.927222	327
3941507	31.296667	-96.9375	316

3941509	31.297222	-96.938889	318
3941510	31.294722	-96.946389	319
3941511	31.296111	-96.940556	319
3941512	31.297778	-96.936111	325
3941513	31.299167	-96.931111	323
3941514	31.302223	-96.920555	324
3941515	31.293056	-96.952501	323
3941601	31.2925	-96.901945	330
3941605	31.303612	-96.916112	319
3941606	31.304445	-96.910556	324
3941701	31.2866667	-96.973333	325
3941702	31.290278	-96.965278	319
3941703	31.284167	-96.976667	336
3941707	31.285278	-96.974167	324
3941708	31.287778	-96.97	317
3941709	31.289167	-96.965834	316
3941710	31.290834	-96.959445	324
3941801	31.278055	-96.918333	320
3941802	31.251112	-96.923333	318
3941901	31.277222	-96.876667	321
3941902	31.262223	-96.907778	318
3941903	31.260278	-96.909723	316
3941904	31.276389	-96.889445	333
3941906	31.266944	-96.900278	316
3941907	31.254723	-96.915001	316
3941908	31.2658333	-96.903333	325
3949202	31.248056	-96.929444	323
3949203	31.248334	-96.930555	322
3949204	31.244722	-96.937222	330
3949205	31.241389	-96.944722	334
3949301	31.2297222	-96.9016667	313
3949302	31.215001	-96.896667	310
3949303	31.215001	-96.894167	305
3949602	31.197778	-96.876944	299
3949604	31.194167	-96.903334	383
3949605	31.199722	-96.878611	300
3949606	31.193056	-96.885834	299
3950101	31.231389	-96.860834	312
3950102	31.211389	-96.838056	314
3950103	31.211945	-96.849445	311
3950105	31.221389	-96.839167	312
3950106	31.221944	-96.836667	312

3950107	31.219167	-96.843056	311
3950108	31.214445	-96.851389	313
3950109	31.209723	-96.859723	311
3950205	31.225555	-96.830555	307
3950401	31.205834	-96.866112	314
3950402	31.206112	-96.862223	315
3950403	31.205556	-96.866944	314
3950404	31.196667	-96.841111	316
3950405	31.1975	-96.839722	317
3950406	31.185278	-96.840834	311
3950407	31.186389	-96.8375	309
3950408	31.178333	-96.856667	299
3950409	31.176944	-96.855834	298
3950410	31.173889	-96.864445	290
3950411	31.167778	-96.862778	291
3950412	31.167778	-96.849167	299
3950413	31.171667	-96.840556	301
3950414	31.169722	-96.873333	287
3950415	31.18	-96.856389	300
3950416	31.178889	-96.837222	308
3950417	31.193056	-96.835	313
3950418	31.174722	-96.842778	303
3950419	31.1725	-96.849722	304
3950420	31.181389	-96.845834	303
3950421	31.1875	-96.851112	312
3950422	31.184722	-96.854167	308
3950423	31.196945	-96.858889	307
3950424	31.199722	-96.860834	311
3950425	31.200834	-96.864445	310
3950427	31.206112	-96.868333	311
3950428	31.172222	-96.835	303
3950501	31.171111	-96.820555	317
3950502	31.172222	-96.821944	315
3950503	31.173333	-96.815001	303
3950504	31.170555	-96.82	297
3950701	31.162223	-96.862778	291
3950702	31.165278	-96.857778	295
3950703	31.165556	-96.853889	294
3950704	31.164167	-96.8475	297
3950705	31.164723	-96.843334	299
3950706	31.161667	-96.839722	299
3950708	31.128333	-96.836667	310
3950801	31.160278	-96.830278	305

3950802	31.162501	-96.820278	310
3950803	31.140556	-96.818055	292
3950804	31.139445	-96.816389	292
3950805	31.155556	-96.796389	303
3950806	31.141945	-96.798056	299
3950807	31.135556	-96.796111	301
3950808	31.135834	-96.803612	296
3950809	31.137222	-96.806667	296
3950810	31.129722	-96.805556	296
3950811	31.130833	-96.807501	293
3950812	31.130555	-96.811667	291
3950813	31.1302778	-96.81	293
3950814	31.126667	-96.793611	299
3950815	31.126111	-96.816112	287
3950816	31.147222	-96.792222	296
3950817	31.144722	-96.807778	296
3950818	31.141389	-96.808056	295
3950821	31.138056	-96.817222	289
3950822	31.133611	-96.826389	308
3950823	31.1375	-96.818889	289
3950824	31.1425	-96.810556	291
3950825	31.145834	-96.802778	298
3950826	31.151389	-96.793889	297
3950827	31.149722	-96.795834	300
3950901	31.154445	-96.79	301
3950902	31.145278	-96.790834	299
3950903	31.146945	-96.786111	301
3950904	31.134445	-96.787222	305
3950905	31.126944	-96.791389	299
3950906	31.132778	-96.788611	296
3953880	31.148056	-96.786945	292
3953973	31.149722	-96.786111	292
3954066	31.148889	-96.787778	290
3954160	31.154723	-96.786111	295
3954253	31.115834	-96.816944	289
3954346	31.120555	-96.809445	292
3954439	31.370555	-97.012223	335
4014103	31.859167	-97.355278	449
4014104	31.850834	-97.353612	457
4014105	31.854445	-97.364167	510
4014502	31.813056	-97.298334	439
4014505	31.822778	-97.292222	449
4014508	31.831389	-97.304167	494

4014510	31.814723	-97.296667	443
4014609	31.824444	-97.288334	446
4014801	31.788334	-97.316944	457
4014802	31.787778	-97.307223	449
4014805	31.758889	-97.299445	438
4014806	31.752501	-97.305556	471

APPENDIX B

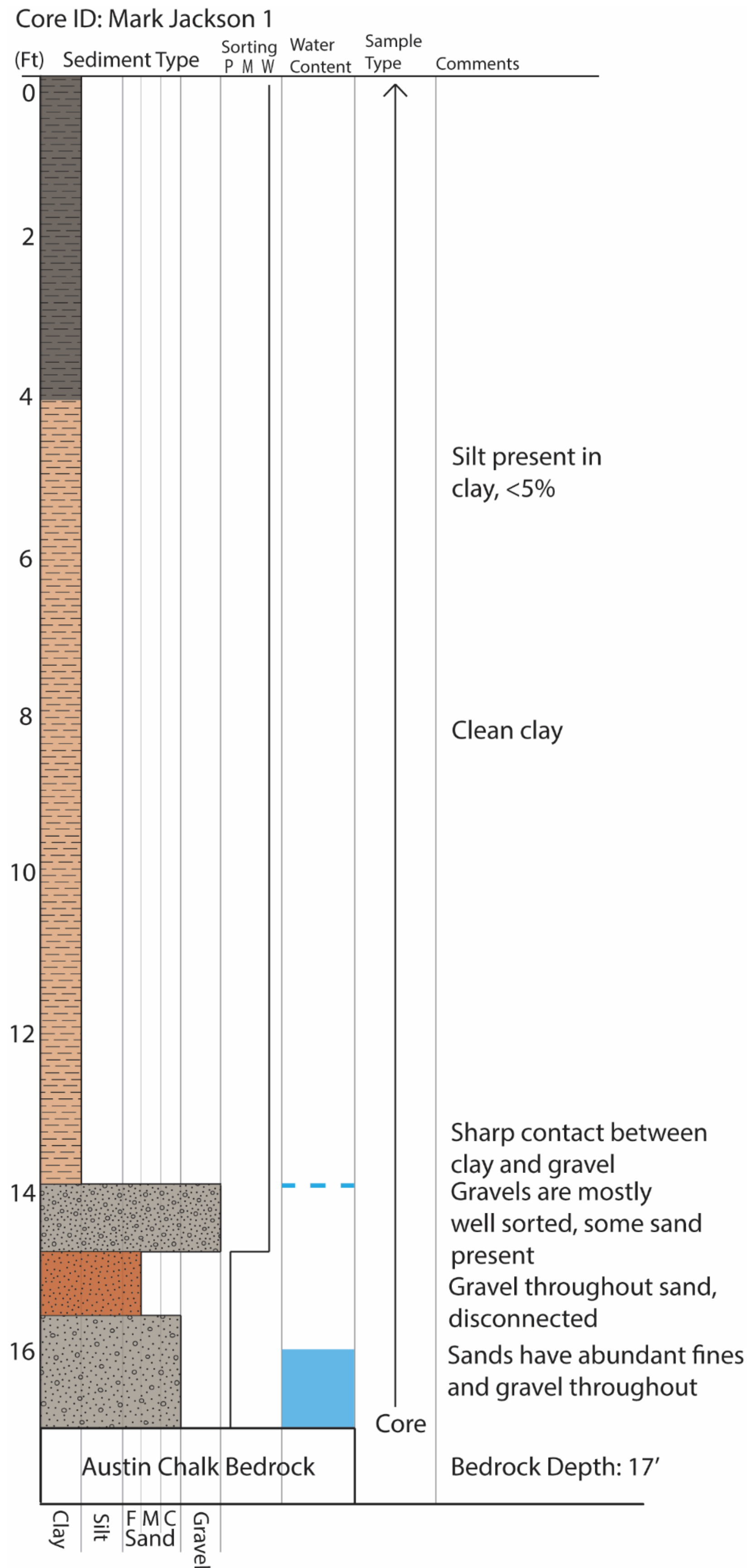
Submitted Driller's Reports Used in Flow Map

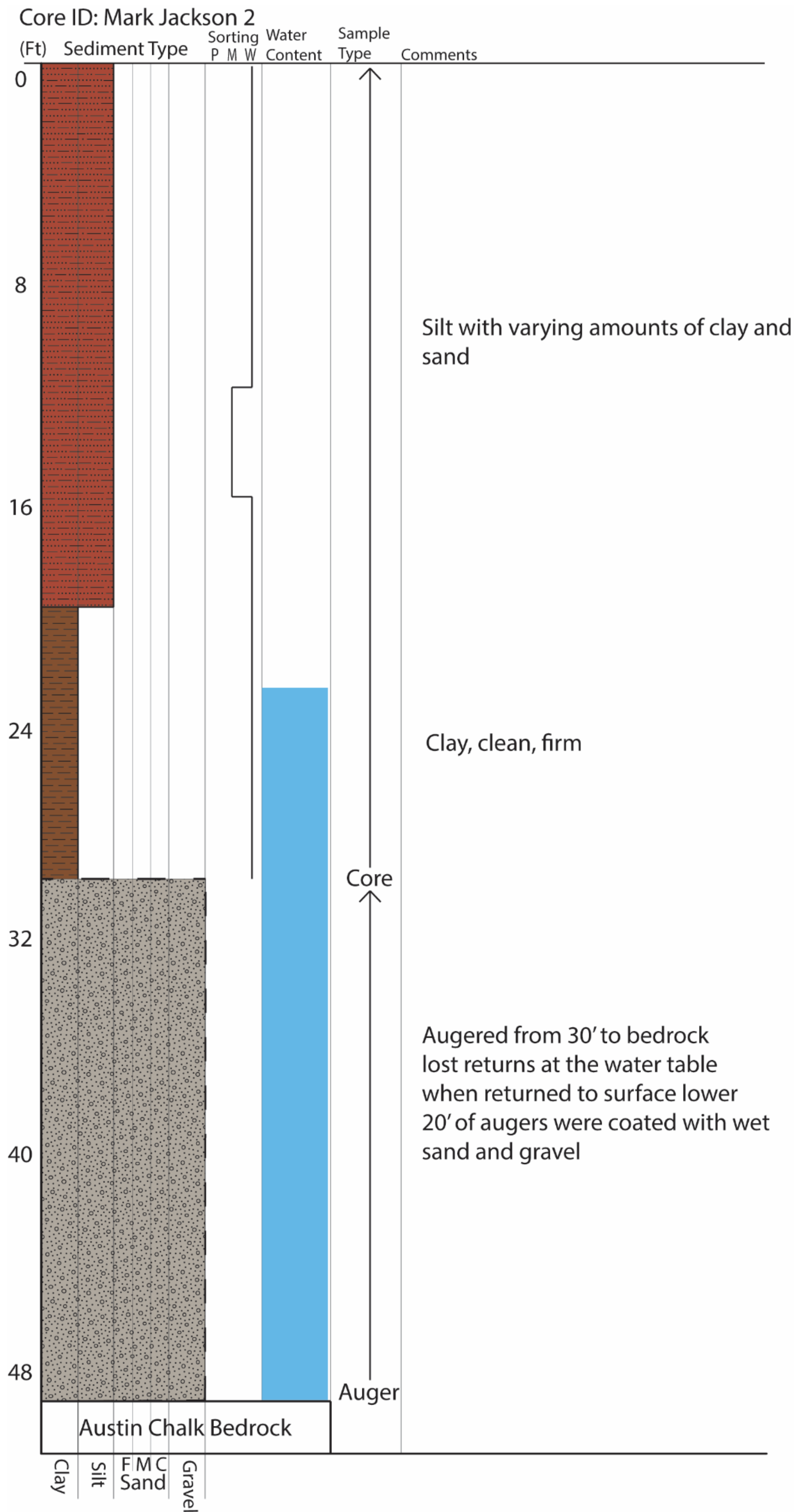
State Well Number	Latitude	Longitude	Water Table Elevation (ft)
1328	31.133334	- 96.82333	298
21663	31.49	-97.079444	387.88
21681	31.486111	-97.073611	390.44
21683	31.491111	-97.073889	378.93
21685	31.489445	-97.073611	378.72
21686	31.483889	-97.082222	389.26
27102	31.195834	-96.851945	320
32262	31.669444	-97.182778	403
32265	31.64	-97.182778	403
50432	31.171944	-96.864723	278
50612	31.166112	-96.875278	285
59144	31.314723	-96.878889	392
73439	31.29	-96.869444	336.92
74715	31.617222	-97.154167	386
76746	31.627778	-97.145	396
113930	31.559723	-97.130555	393
113933	31.559723	-97.130555	382.5
113934	31.559723	-97.130555	373
116342	31.151945	-96.843334	291
118444	31.219167	-96.861112	306
126964	31.200278	-96.923611	299.5
126998	31.545278	-97.065001	372
137429	31.306389	-96.899445	369
137430	31.306389	-96.969444	326
137431	31.306389	-96.899167	368
159287	31.686945	-97.228333	393
159418	31.691945	-97.233055	389
160574	31.260278	-96.916389	329
177610	31.669167	-97.179444	389
177624	31.6725	-97.212501	419
177627	31.678889	-97.207501	408
182138	31.620833	-97.171667	320
182906	31.226389	-96.855001	318
187625	31.4825	-97.072778	390
191611	31.173333	-96.845834	299
192314	31.133889	-96.828055	307
192915	31.455001	-97.058334	351
193628	31.200278	-96.837778	309
193714	31.173055	-96.864445	279
195367	31.488334	-97.087222	395.25
200689	31.384722	-96.961667	331

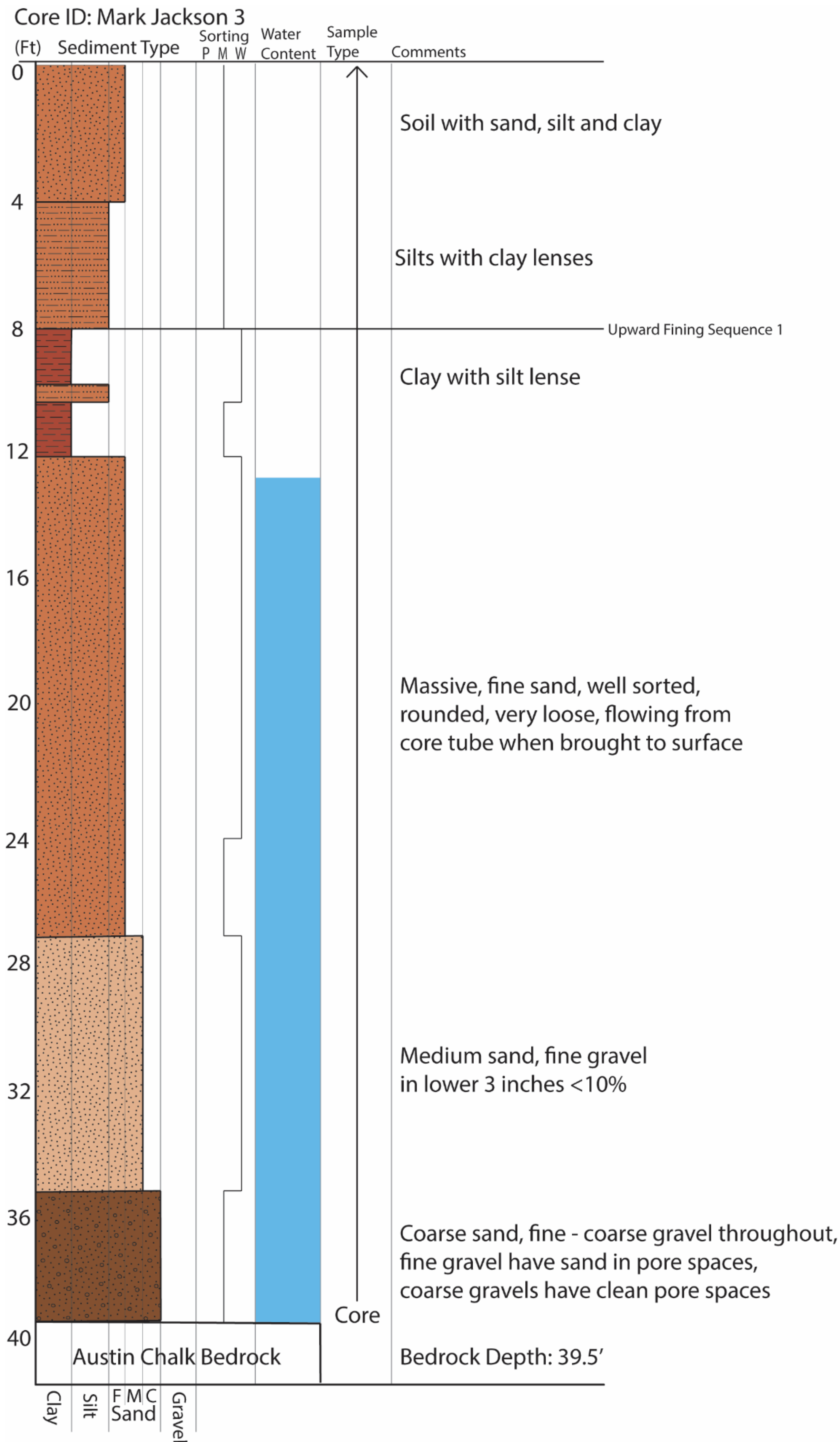
202090	31.239445	-96.944445	351
205579	31.138334	-96.806389	295
209870	31.231944	-96.906112	326
211572	31.345556	-96.996945	325
211907	31.283055	-96.918055	338
211927	31.310556	-96.869722	397
211963	31.264167	-96.905278	326
211966	31.287222	-96.914445	335
211967	31.262778	-96.913612	328
221239	31.378611	-96.976944	313
252771	31.130555	-96.821111	276
267462	31.560278	-97.115001	375
273439	31.166667	-96.783334	294
273497	31.166667	-96.866944	286
276617	31.624444	-97.160556	384
285587	31.562501	-97.132778	388
285597	31.560278	-97.132222	372

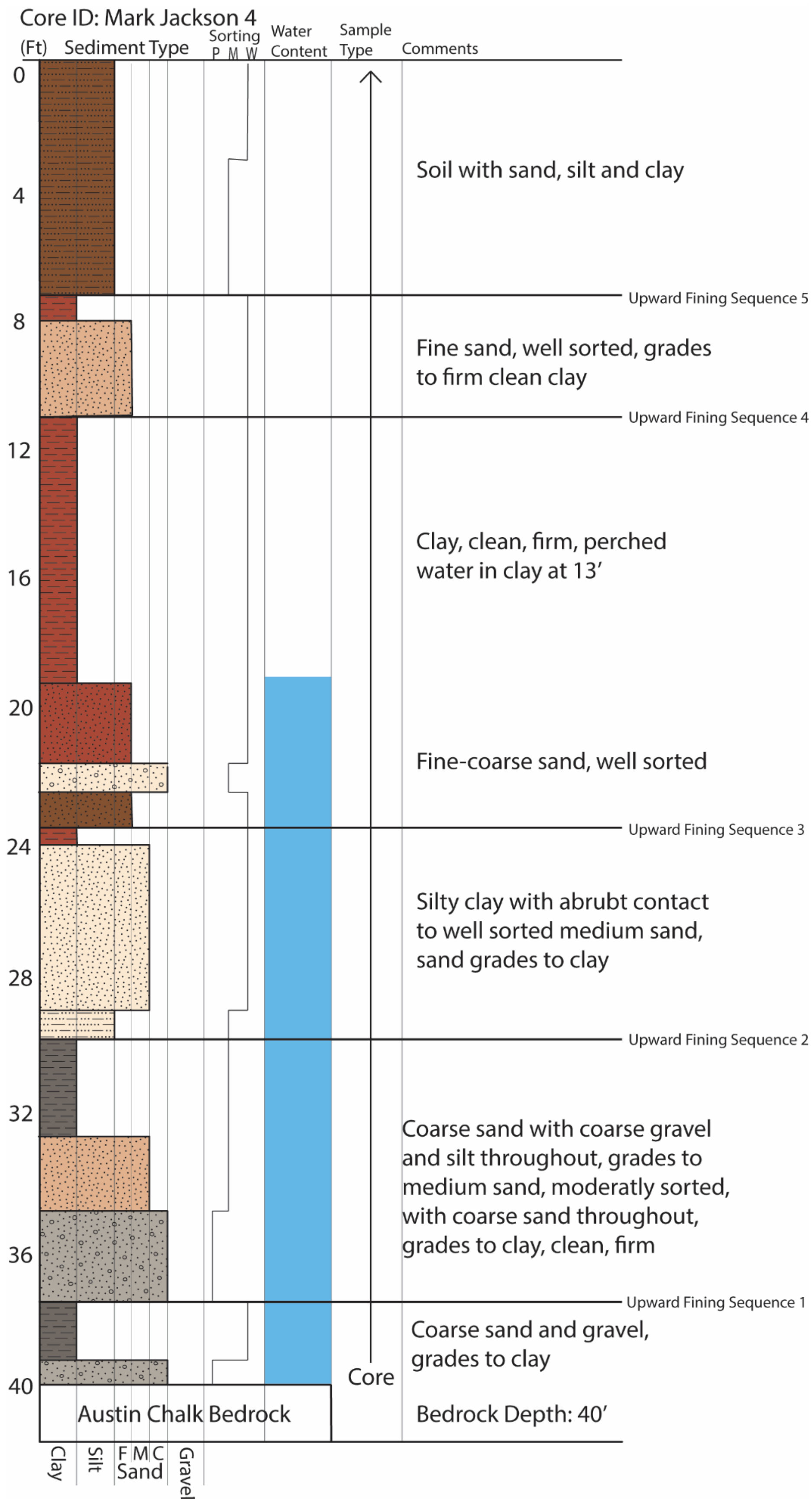
APPENDIX C

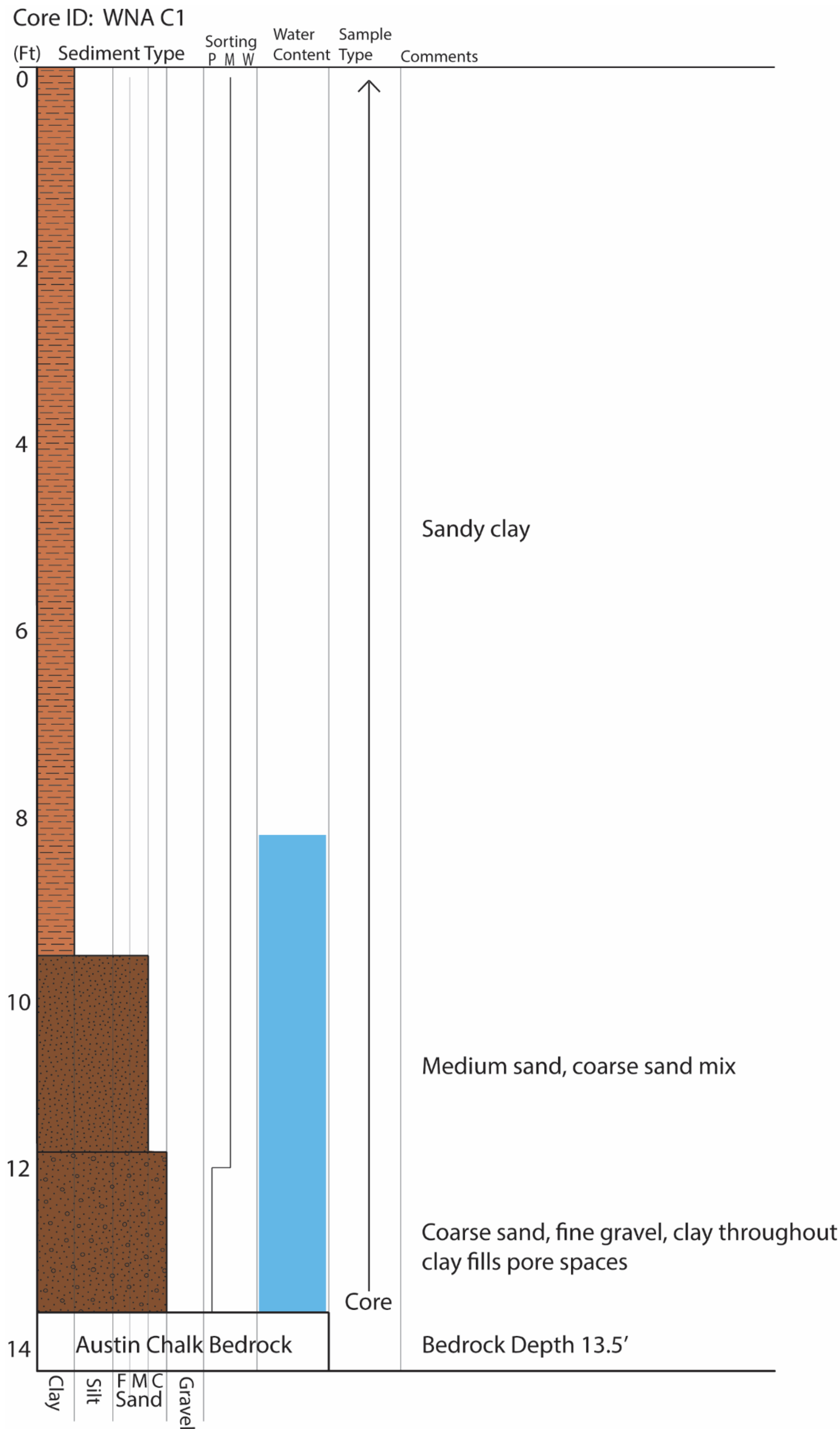
Detailed Core Diagrams Used in Cross Sections

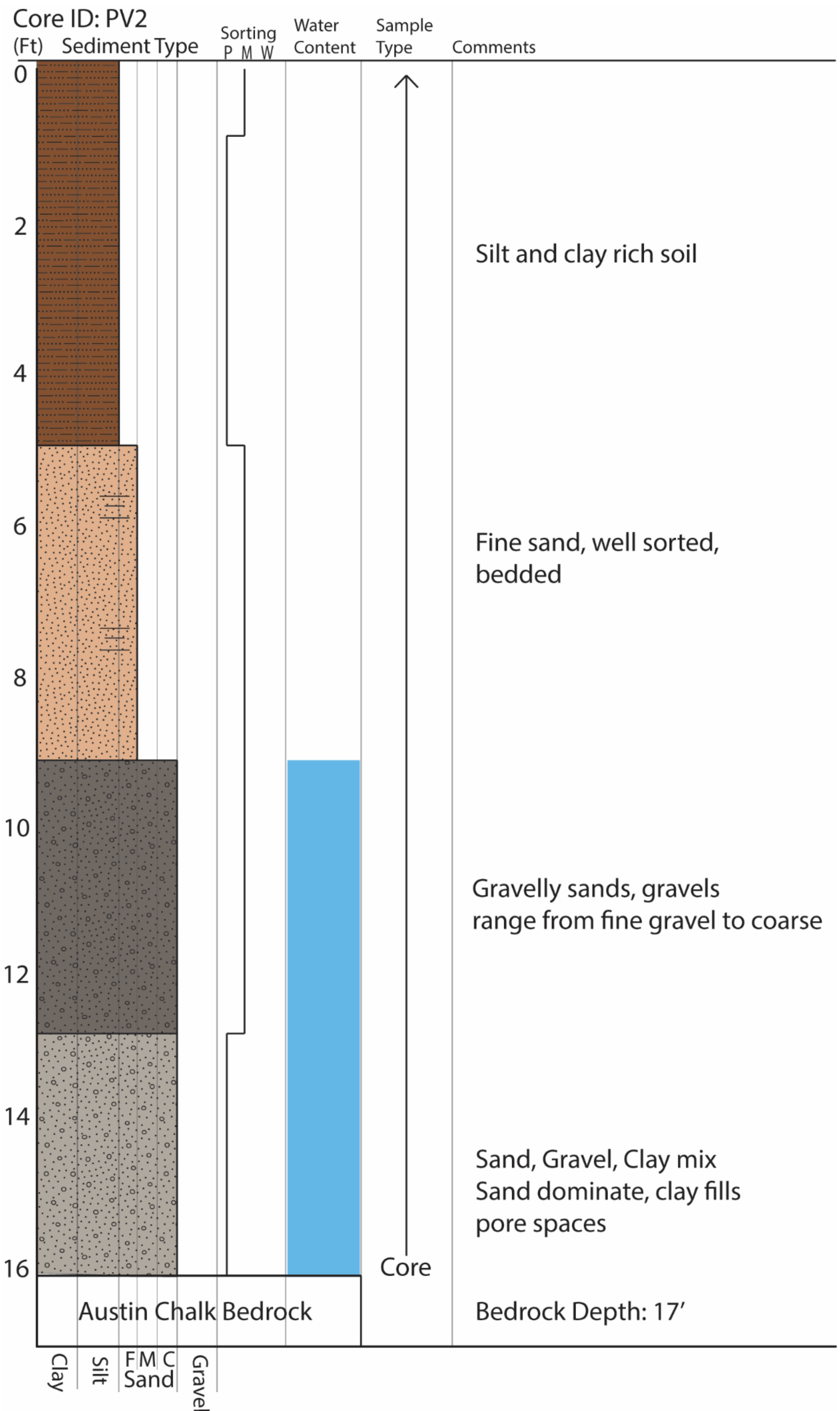

Core ID: Mark Jackson 1
(Ft)
Sediment Type
Sorting
P M W
Water Content
Sample Type
Comments
0
2
4
6
8
10
12
14
16
Silt present in clay, <5%
Clean clay
Sharp contact between clay and gravel
Gravels are mostly well sorted, some sand present
Gravel throughout sand, disconnected
Sands have abundant fines and gravel throughout
Core
Austin Chalk Bedrock
Bedrock Depth: 17’
Clay
Silt
F M C
Sand
Gravel


Core ID: Mark Jackson 2
(Ft)
Sediment Type
Sorting
P M W
Water Content
Sample Type
Comments
0
8
16
24
32
40
48
Silt with varying amounts of clay and sand
Clay, clean, firm
Core
Augered from 30' to bedrock lost returns at the water table when returned to surface lower 20' of augers were coated with wet sand and gravel
Auger
Austin Chalk Bedrock
Clay
Silt
F M C
Sand
Gravel

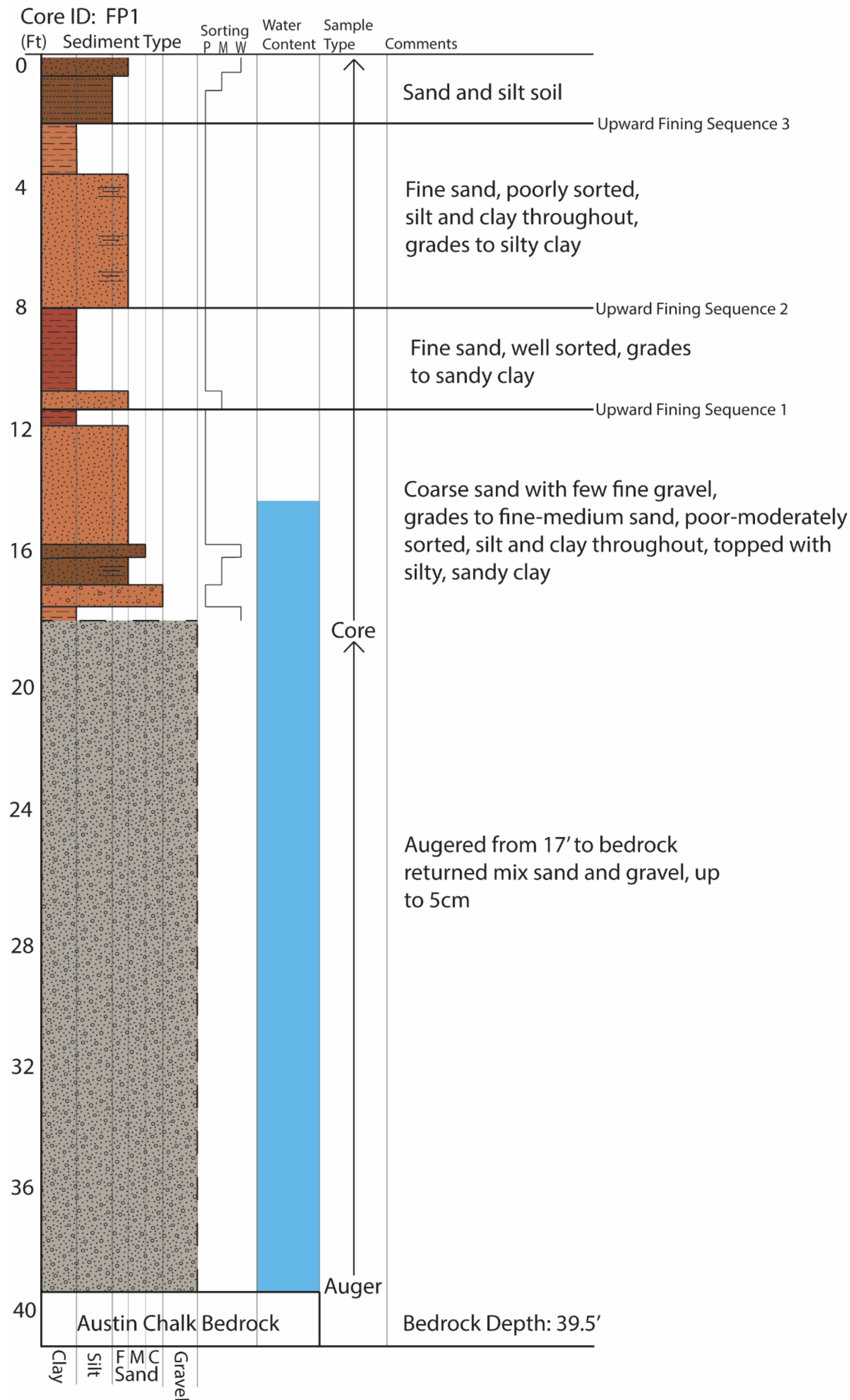

Core ID: Mark Jackson 3
(Ft)
Sediment Type
Sorting
P M W
Water Content
Sample Type
Comments
0
4
8
12
16
20
24
28
32
36
40
Soil with sand, silt and clay
Silts with clay lenses
Upward Fining Sequence 1
Clay with silt lense
Massive, fine sand, well sorted, rounded, very loose, flowing from core tube when brought to surface
Medium sand, fine gravel in lower 3 inches <10%
Coarse sand, fine - coarse gravel throughout, fine gravel have sand in pore spaces, coarse gravels have clean pore spaces
Core
Austin Chalk Bedrock
Bedrock Depth: 39.5′
Clay
Silt
F M C
Sand
Gravel

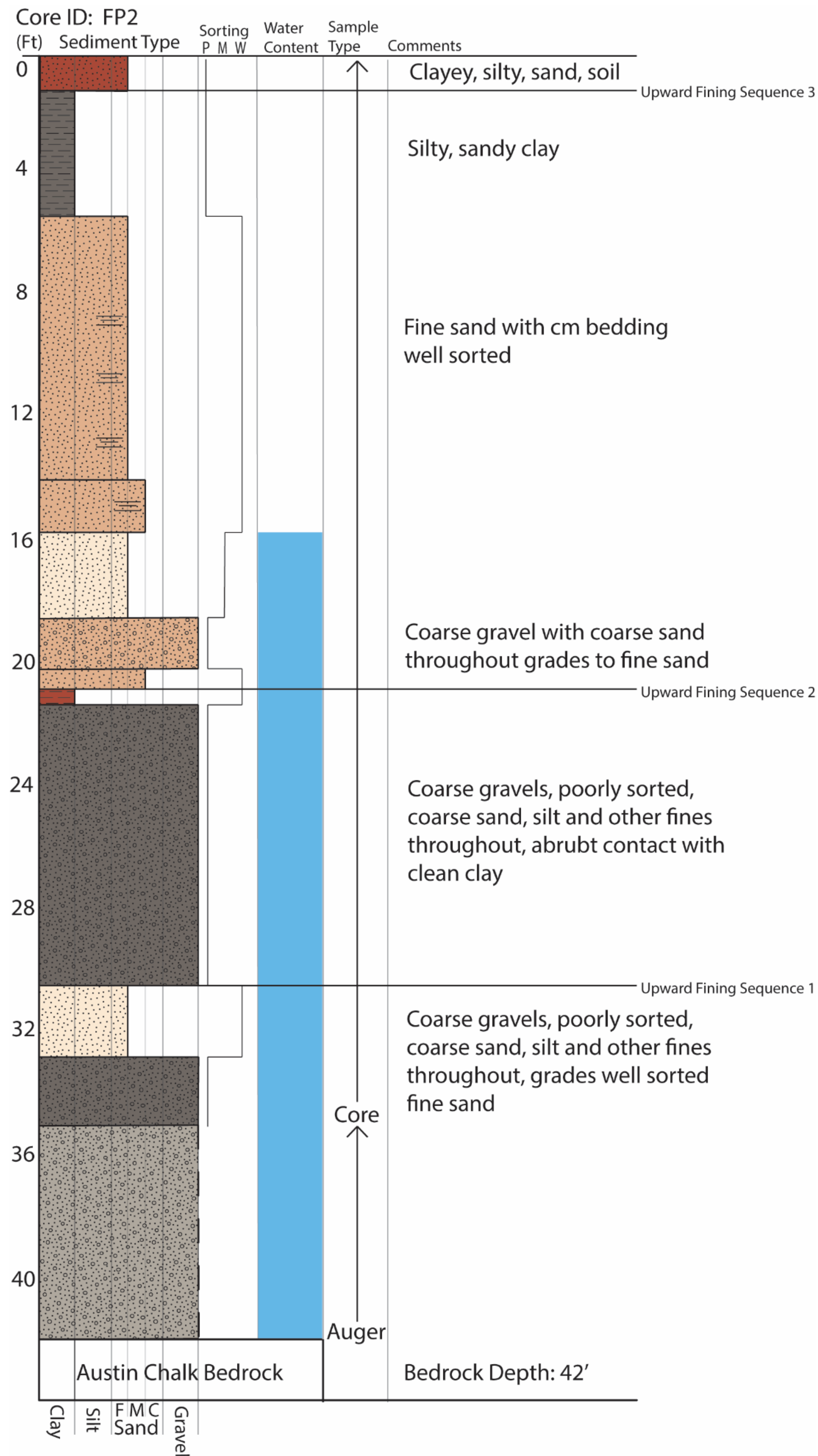

Core ID: Mark Jackson 4
(Ft)
Sediment Type
Sorting
P M W
Water Content
Sample Type
Comments
0
4
8
12
16
20
24
28
32
36
40
Soil with sand, silt and clay
Upward Fining Sequence 5
Fine sand, well sorted, grades to firm clean clay
Upward Fining Sequence 4
Clay, clean, firm, perched water in clay at 13’
Fine-coarse sand, well sorted
Upward Fining Sequence 3
Silty clay with abrubt contact to well sorted medium sand, sand grades to clay
Upward Fining Sequence 2
Coarse sand with coarse gravel and silt throughout, grades to medium sand, moderatly sorted, with coarse sand throughout, grades to clay, clean, firm
Upward Fining Sequence 1
Coarse sand and gravel, grades to clay
Core
Austin Chalk Bedrock
Bedrock Depth: 40’
Clay
Silt
F M C
Sand
Gravel

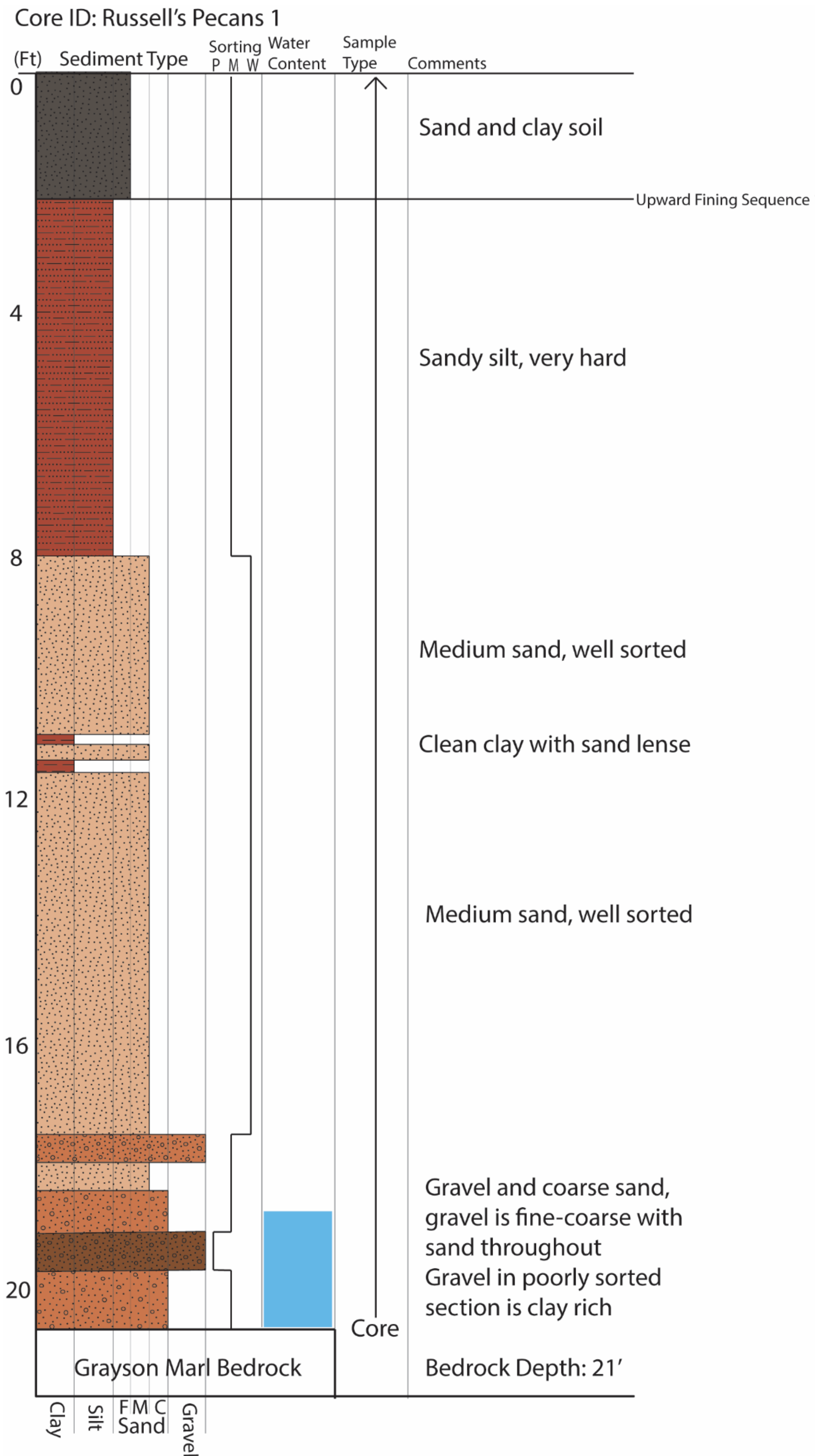

Core ID: WNA C1
(Ft)
Sediment Type
Sorting
P M W
Water Content
Sample Type
Comments
0
2
4
6
8
10
12
14
Sandy clay
Medium sand, coarse sand mix
Coarse sand, fine gravel, clay throughout clay fills pore spaces
Core
Austin Chalk Bedrock
Bedrock Depth 13.5’
Clay
Silt
F M C
Sand
Gravel



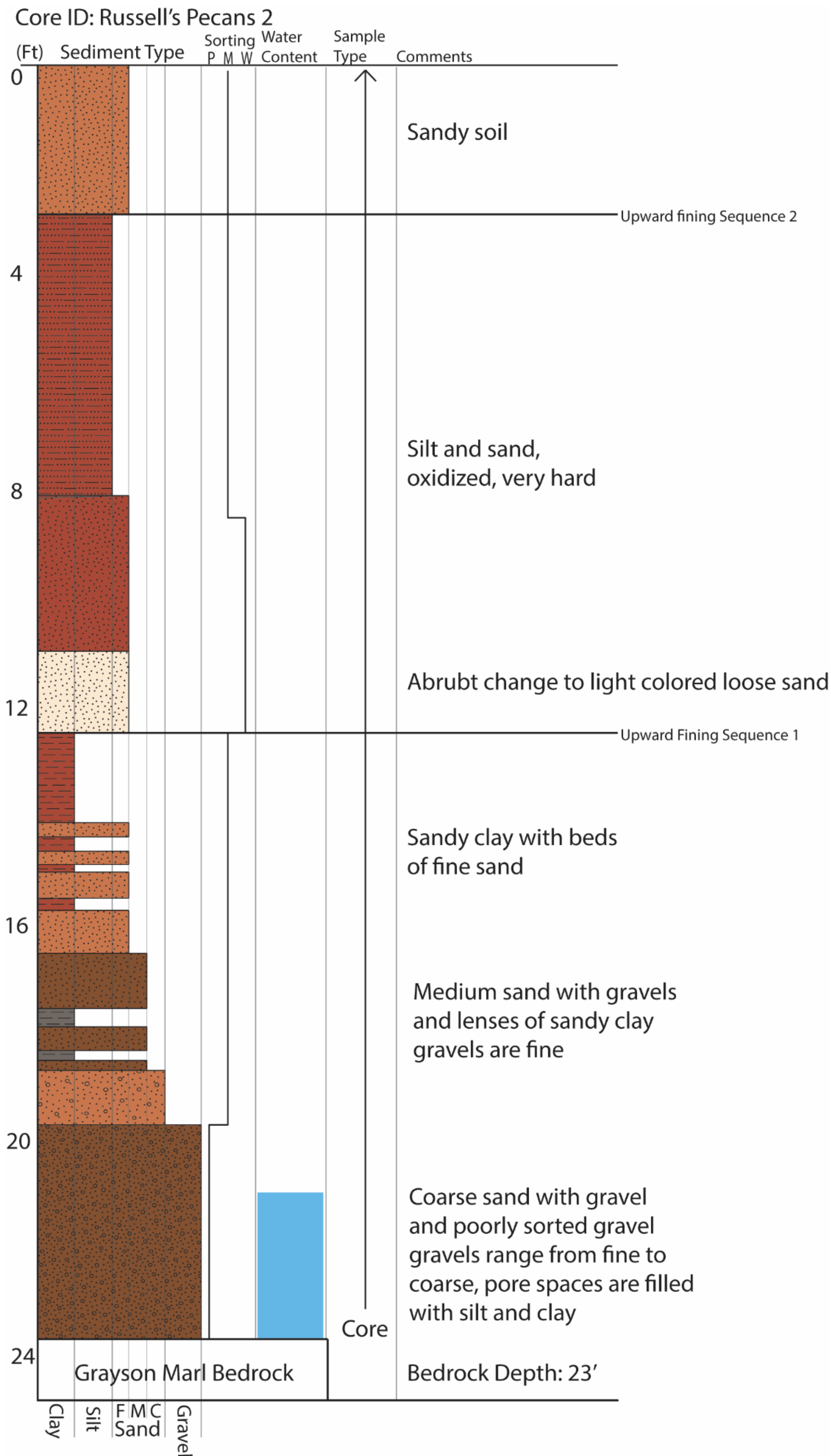
Core ID: PV2
(Ft)
Sediment Type
Sorting
P M W
Water Content
Sample Type
Comments
0
2
4
6
8
10
12
14
16
Silt and clay rich soil
Fine sand, well sorted, bedded
Gravelly sands, gravels range from fine gravel to coarse
Sand, Gravel, Clay mix
Sand dominate, clay fills pore spaces
Core
Austin Chalk Bedrock
Bedrock Depth: 17'
Clay
Silt
F M C
Sand
Gravel

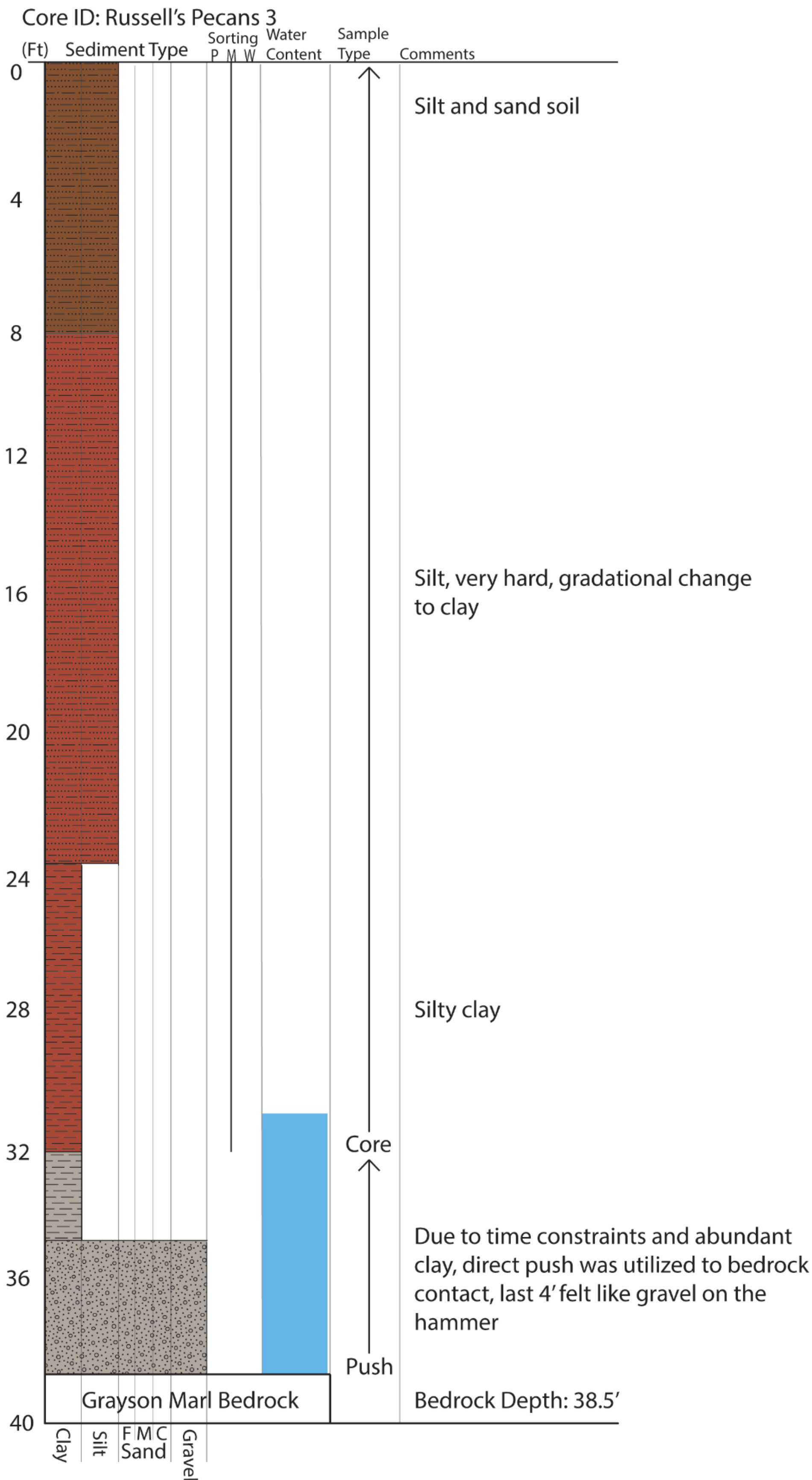

Core ID: FP1
(Ft)
Sediment Type
Sorting
P M W
Water Content
Sample Type
Comments
0
4
8
12
16
20
24
28
32
36
40
Sand and silt soil
Upward Fining Sequence 3
Fine sand, poorly sorted, silt and clay throughout, grades to silty clay
Upward Fining Sequence 2
Fine sand, well sorted, grades to sandy clay
Upward Fining Sequence 1
Coarse sand with few fine gravel, grades to fine-medium sand, poor-moderately sorted, silt and clay throughout, topped with silty, sandy clay
Core
Augered from 17' to bedrock returned mix sand and gravel, up to 5cm
Auger
Austin Chalk Bedrock
Bedrock Depth: 39.5'
Clay
Silt
F M C
Sand
Gravel

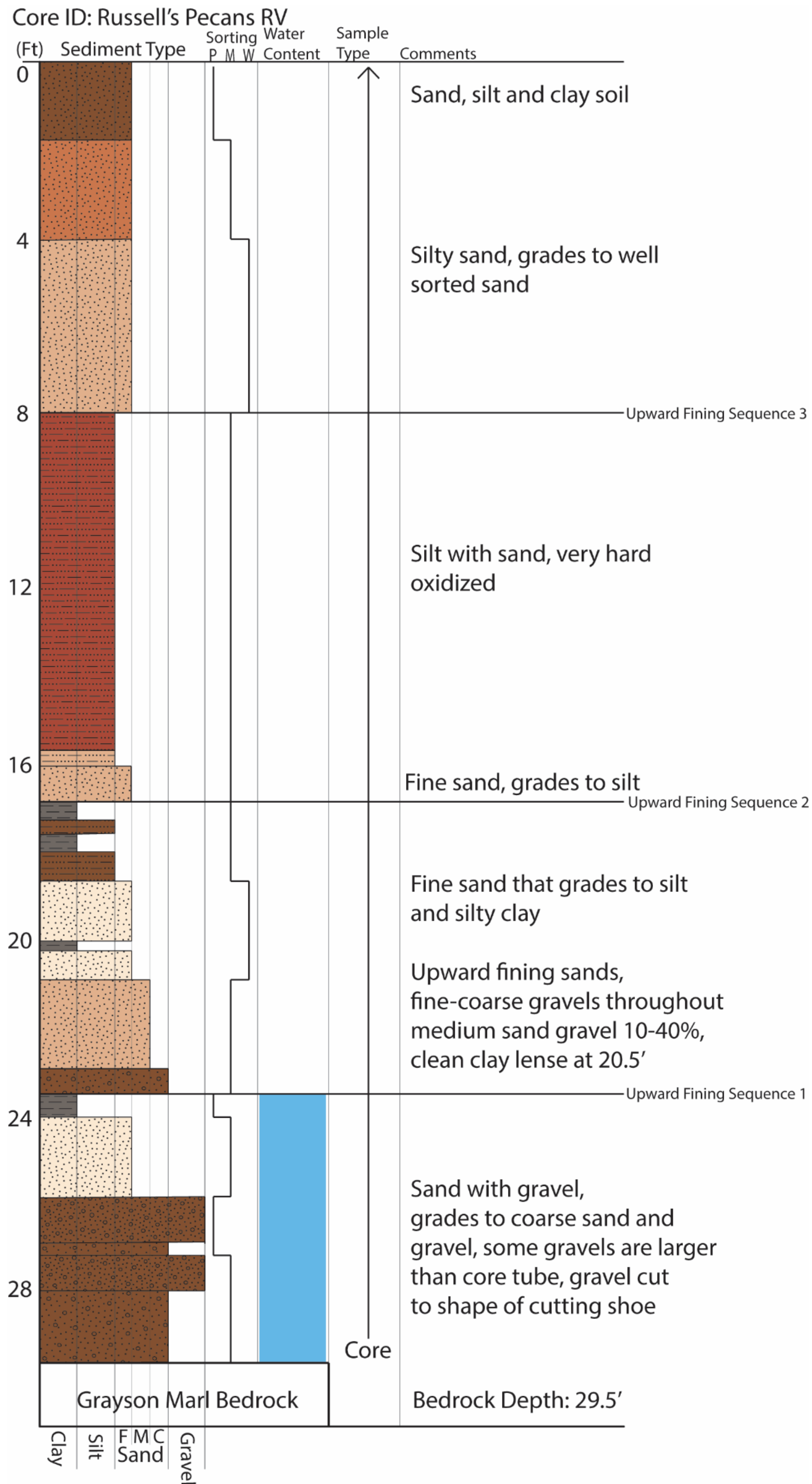

Core ID: FP2
(Ft)
Sediment Type
Sorting
P M W
Water Content
Sample Type
Comments
0
4
8
12
16
20
24
28
32
36
40
Clayey, silty, sand, soil
Upward Fining Sequence 3
Silty, sandy clay
Fine sand with cm bedding well sorted
Coarse gravel with coarse sand throughout grades to fine sand
Upward Fining Sequence 2
Coarse gravels, poorly sorted, coarse sand, silt and other fines throughout, abrubt contact with clean clay
Upward Fining Sequence 1
Coarse gravels, poorly sorted, coarse sand, silt and other fines throughout, grades well sorted fine sand
Core
Auger
Austin Chalk Bedrock
Bedrock Depth: 42'
Clay
Silt
F M C
Sand
Gravel



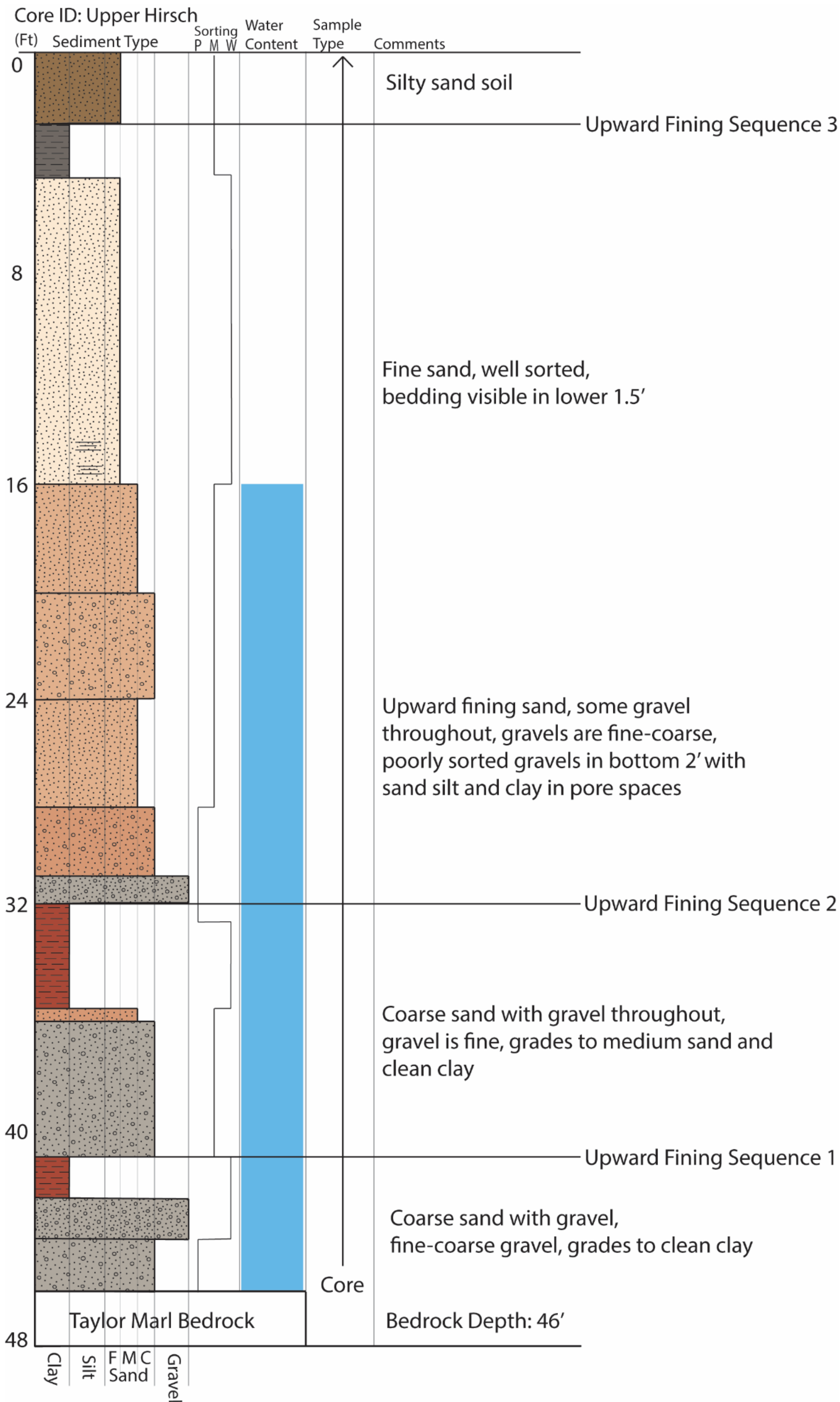
Core ID: Russell's Pecans 1
(Ft)
Sediment Type
Sorting
P M W
Water Content
Sample Type
Comments
0
4
8
12
16
20
Sand and clay soil
Upward Fining Sequence 1
Sandy silt, very hard
Medium sand, well sorted
Clean clay with sand lense
Medium sand, well sorted
Gravel and coarse sand, gravel is fine-coarse with sand throughout
Gravel in poorly sorted section is clay rich
Core
Grayson Marl Bedrock
Bedrock Depth: 21'
Clay
Silt
F M C
Sand
Gravel

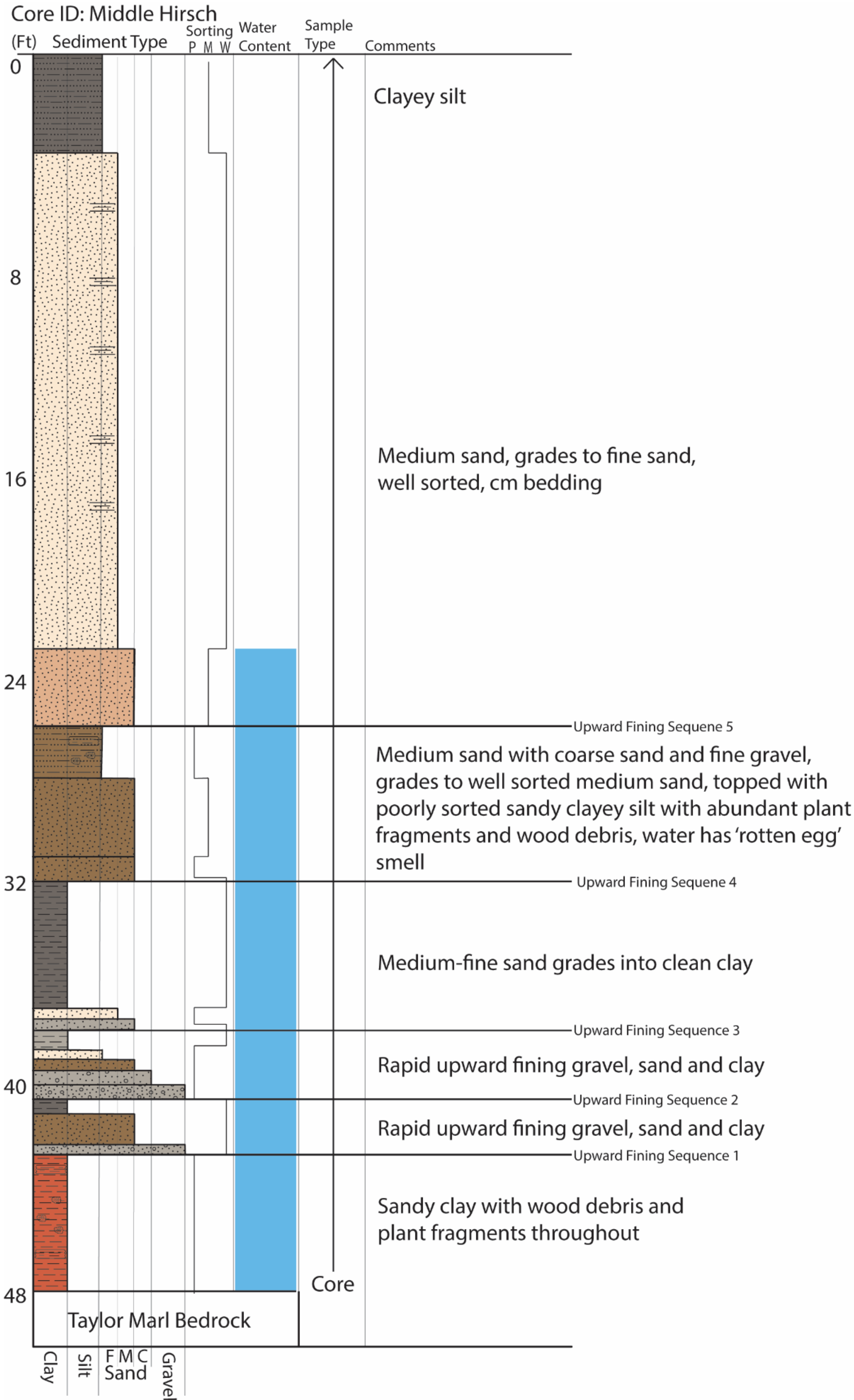

Core ID: Russell's Pecans 2
(Ft)
Sediment Type
Sorting
P M W
Water Content
Sample Type
Comments
0
4
8
12
16
20
24
Sandy soil
Upward fining Sequence 2
Silt and sand, oxidized, very hard
Abrubt change to light colored loose sand
Upward Fining Sequence 1
Sandy clay with beds of fine sand
Medium sand with gravels and lenses of sandy clay gravels are fine
Coarse sand with gravel and poorly sorted gravel gravels range from fine to coarse, pore spaces are filled with silt and clay
Core
Grayson Marl Bedrock
Bedrock Depth: 23'
Clay
Silt
F M C
Sand
Gravel

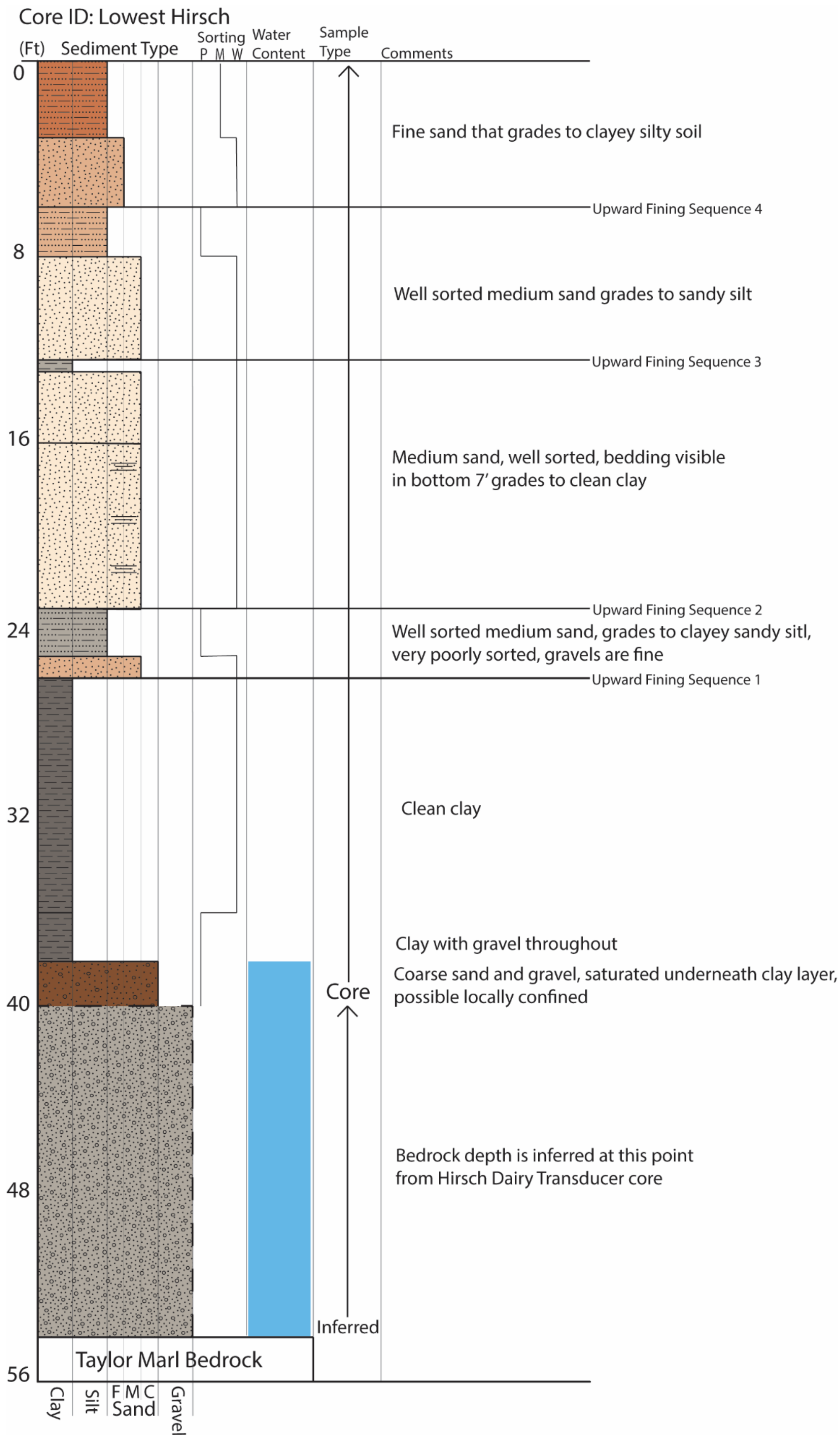

Core ID: Russell's Pecans 3
(Ft)
Sediment Type
Sorting
P M W
Water Content
Sample Type
Comments
0
4
8
12
16
20
24
28
32
36
40
Silt and sand soil
Silt, very hard, gradational change to clay
Silty clay
Core
Push
Due to time constraints and abundant clay, direct push was utilized to bedrock contact, last 4' felt like gravel on the hammer
Grayson Marl Bedrock
Bedrock Depth: 38.5'
Clay
Silt
F M C
Sand
Gravel

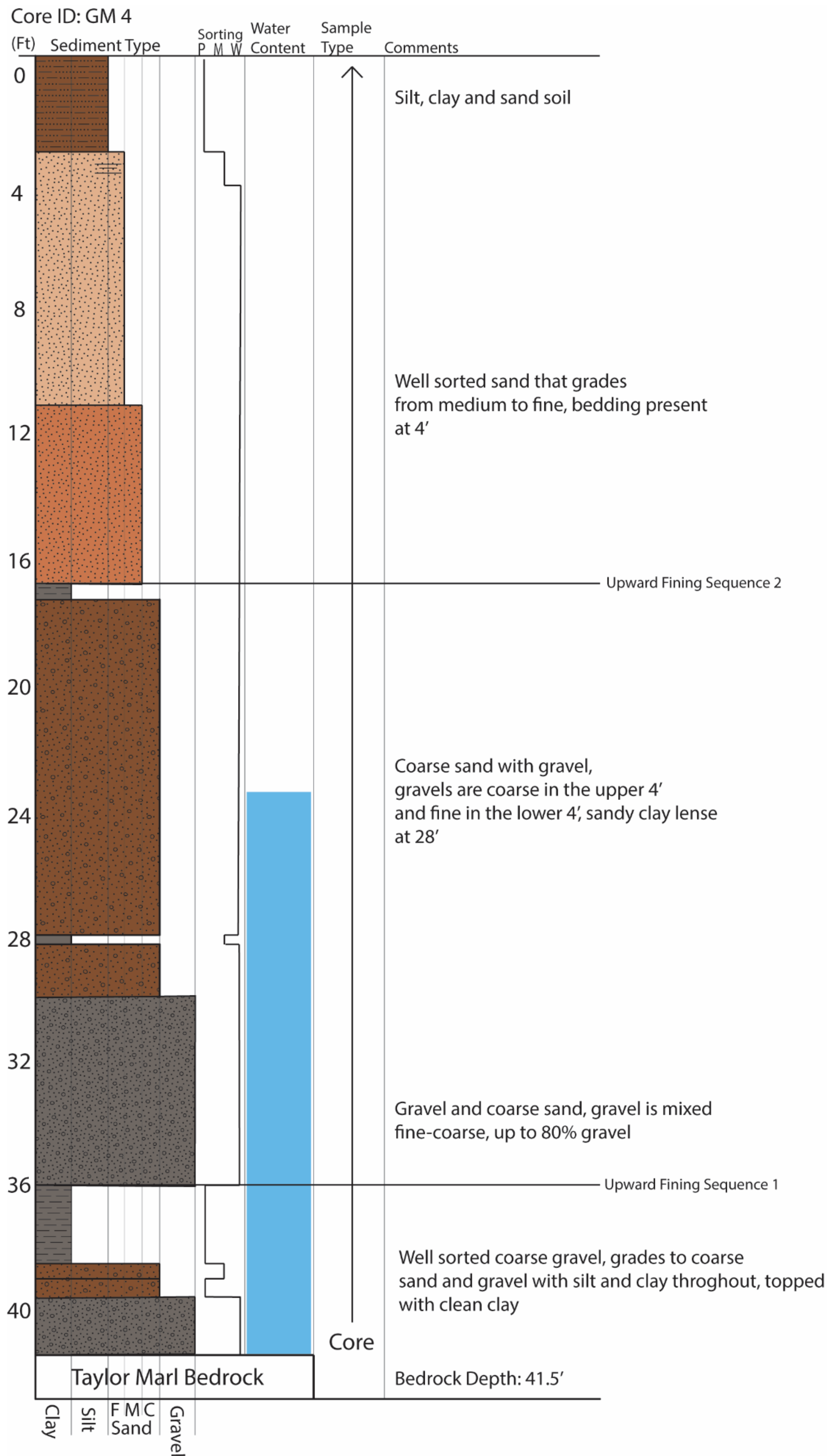


Core ID: Russell's Pecans RV
(Ft)
Sediment Type
Sorting
P M W
Water Content
Sample Type
Comments
0
4
8
12
16
20
24
28
Sand, silt and clay soil
Silty sand, grades to well sorted sand
Upward Fining Sequence 3
Silt with sand, very hard oxidized
Fine sand, grades to silt
Upward Fining Sequence 2
Fine sand that grades to silt and silty clay
Upward fining sands, fine-coarse gravels throughout medium sand gravel 10-40%, clean clay lense at 20.5'
Upward Fining Sequence 1
Sand with gravel, grades to coarse sand and gravel, some gravels are larger than core tube, gravel cut to shape of cutting shoe
Core
Grayson Marl Bedrock
Bedrock Depth: 29.5'
Clay
Silt
F M C
Sand
Gravel

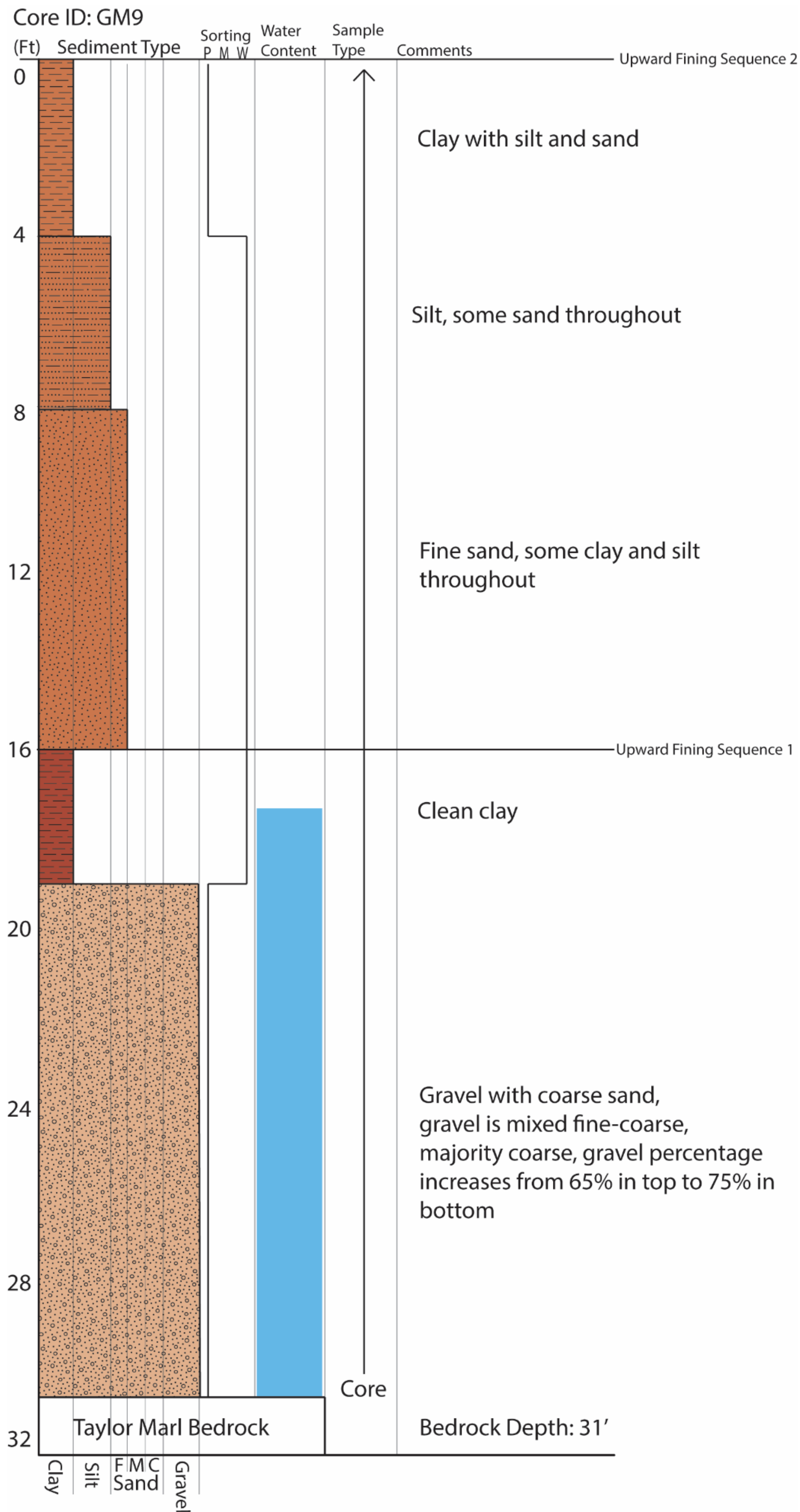

Core ID: Upper Hirsch
(Ft) Sediment Type
Sorting
P M W
Water Content
Sample Type
Comments
0
8
16
24
32
40
48
Silty sand soil
Upward Fining Sequence 3
Fine sand, well sorted, bedding visible in lower 1.5′
Upward fining sand, some gravel throughout, gravels are fine-coarse, poorly sorted gravels in bottom 2′ with sand silt and clay in pore spaces
Upward Fining Sequence 2
Coarse sand with gravel throughout, gravel is fine, grades to medium sand and clean clay
Upward Fining Sequence 1
Coarse sand with gravel, fine-coarse gravel, grades to clean clay
Core
Taylor Marl Bedrock
Bedrock Depth: 46′
Clay
Silt
F M C
Sand
Gravel

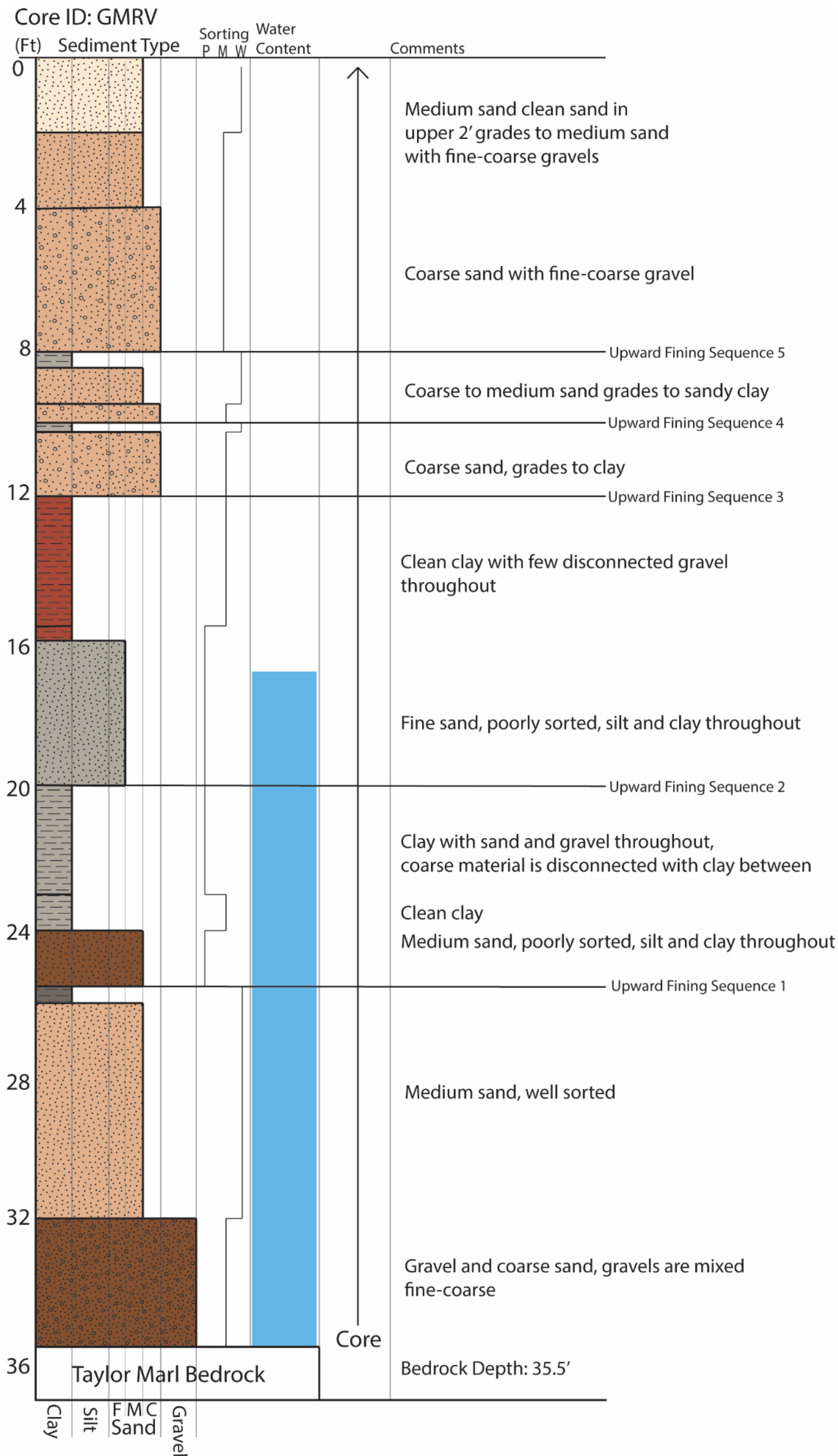

Core ID: Middle Hirsch
(Ft)
Sediment Type
Sorting
P M W
Water Content
Sample Type
Comments
0
8
16
24
32
40
48
Clayey silt
Medium sand, grades to fine sand, well sorted, cm bedding
Upward Fining Sequene 5
Medium sand with coarse sand and fine gravel, grades to well sorted medium sand, topped with poorly sorted sandy clayey silt with abundant plant fragments and wood debris, water has 'rotten egg' smell
Upward Fining Sequene 4
Medium-fine sand grades into clean clay
Upward Fining Sequence 3
Rapid upward fining gravel, sand and clay
Upward Fining Sequence 2
Rapid upward fining gravel, sand and clay
Upward Fining Sequence 1
Sandy clay with wood debris and plant fragments throughout
Core
Taylor Marl Bedrock
Clay
Silt
F M C
Sand
Gravel

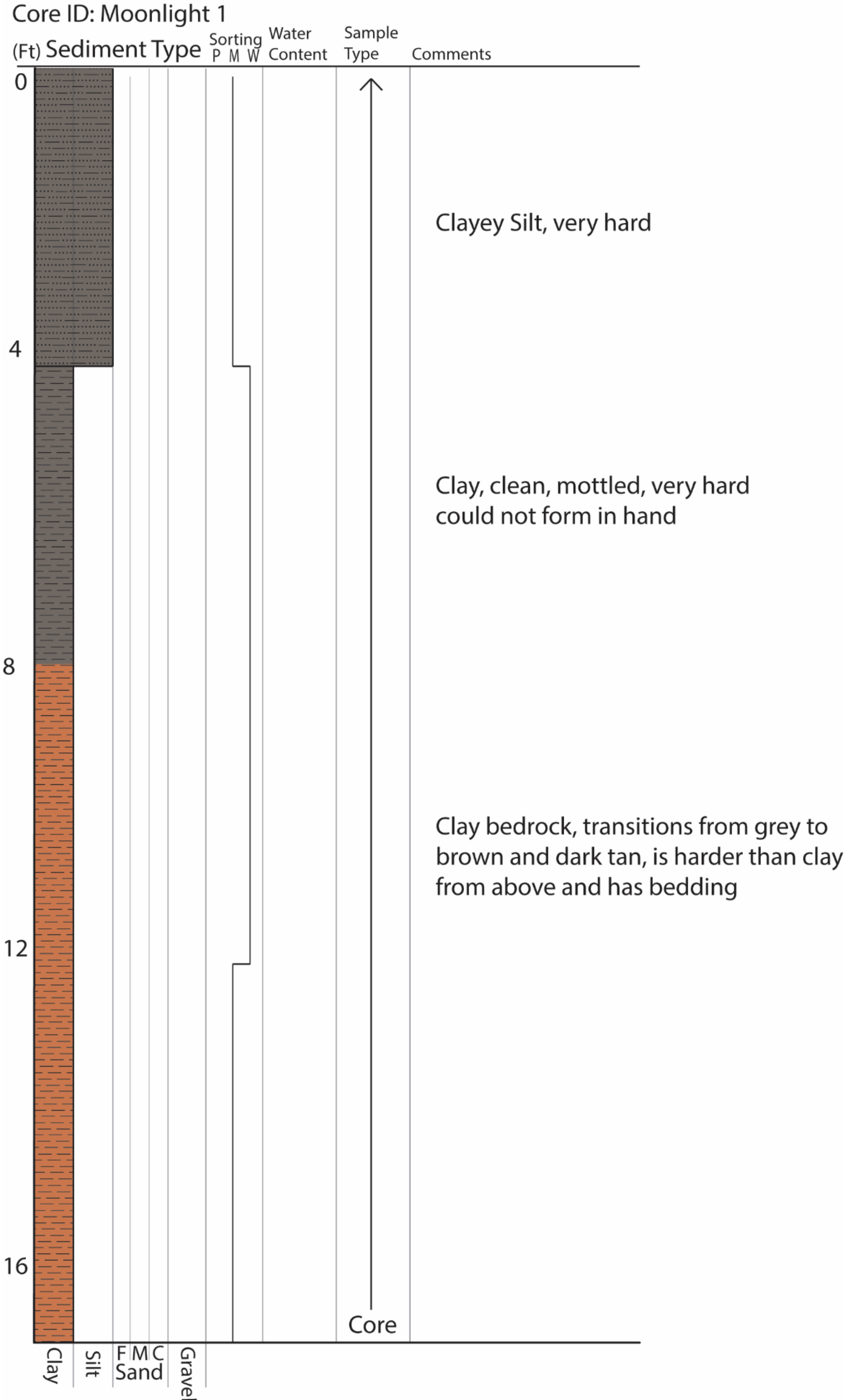

Core ID: Lowest Hirsch
(Ft)
Sediment Type
Sorting
P M W
Water
Content
Sample
Type
Comments
0
8
16
24
32
40
48
56
Fine sand that grades to clayey silty soil
Upward Fining Sequence 4
Well sorted medium sand grades to sandy silt
Upward Fining Sequence 3
Medium sand, well sorted, bedding visible
in bottom 7' grades to clean clay
Upward Fining Sequence 2
Well sorted medium sand, grades to clayey sandy sitl,
very poorly sorted, gravels are fine
Upward Fining Sequence 1
Clean clay
Clay with gravel throughout
Coarse sand and gravel, saturated underneath clay layer,
possible locally confined
Core
Bedrock depth is inferred at this point
from Hirsch Dairy Transducer core
Inferred
Taylor Marl Bedrock
Clay
Silt
F M C
Sand
Gravel

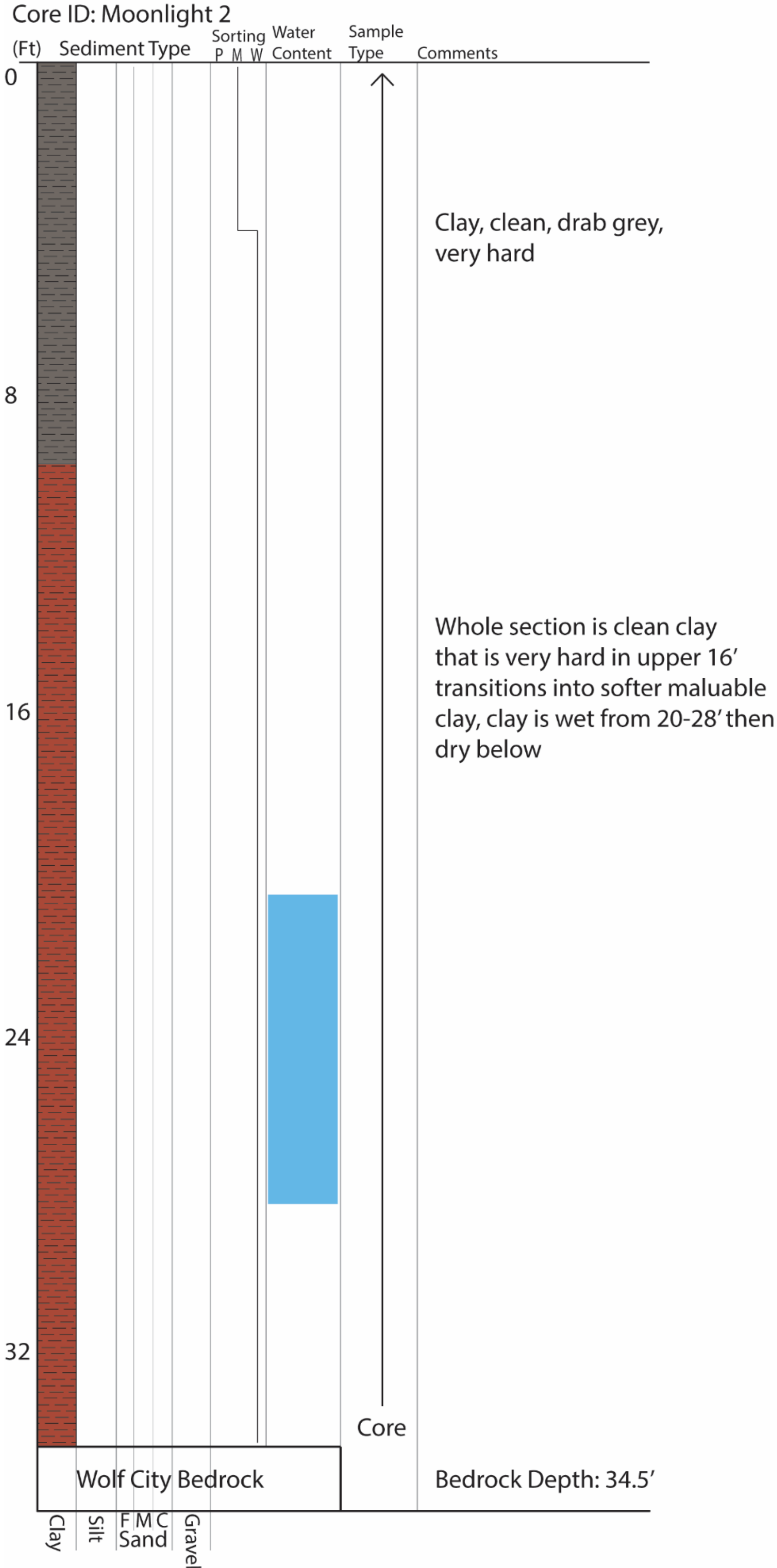


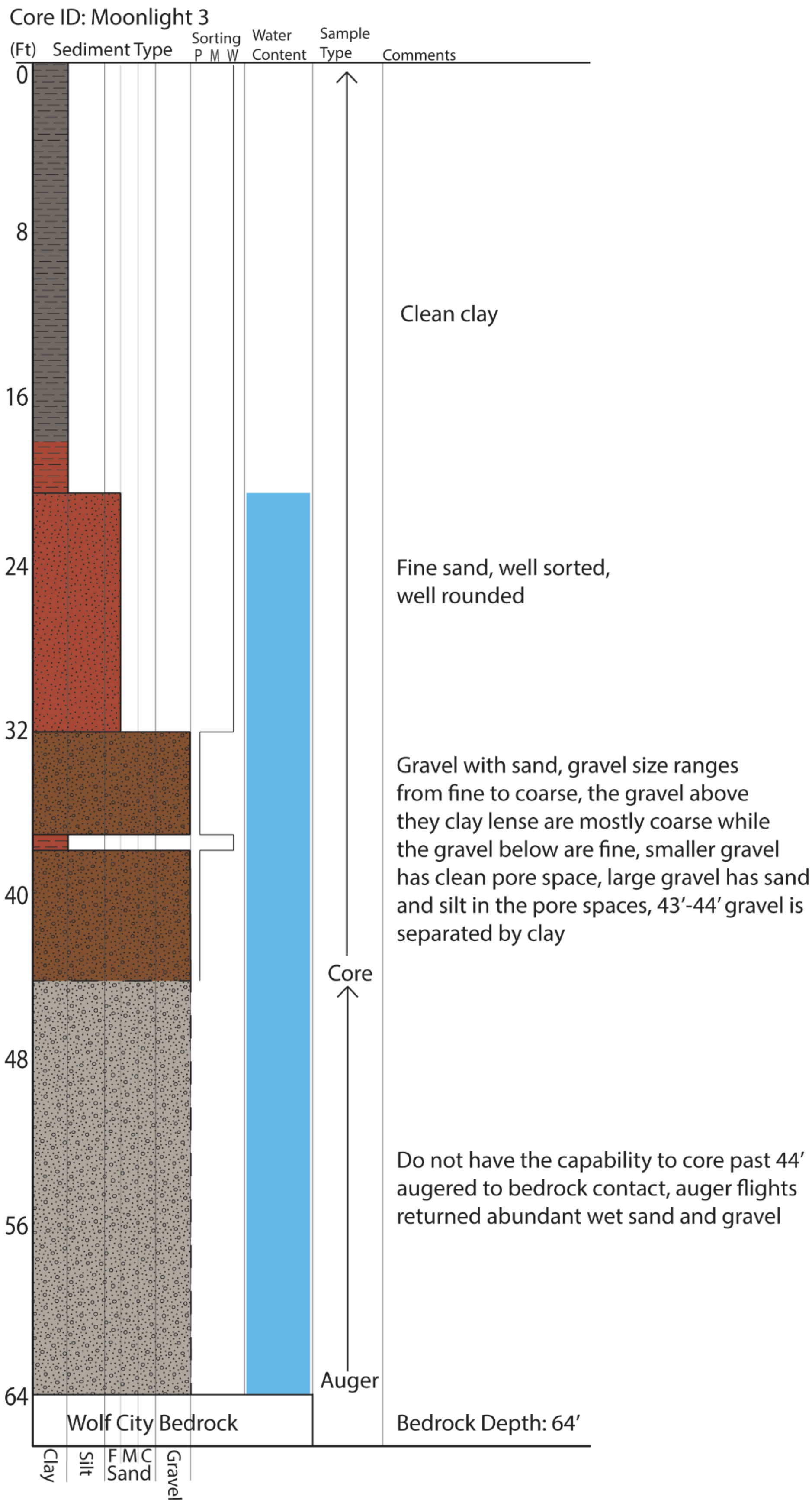
Core ID: GM 4
(Ft)
Sediment Type
Sorting
P M W
Water Content
Sample Type
Comments
0
4
8
12
16
20
24
28
32
36
40
Silt, clay and sand soil
Well sorted sand that grades from medium to fine, bedding present at 4′
Upward Fining Sequence 2
Coarse sand with gravel, gravels are coarse in the upper 4′ and fine in the lower 4′, sandy clay lense at 28′
Gravel and coarse sand, gravel is mixed fine-coarse, up to 80% gravel
Upward Fining Sequence 1
Well sorted coarse gravel, grades to coarse sand and gravel with silt and clay throghout, topped with clean clay
Core
Taylor Marl Bedrock
Bedrock Depth: 41.5′
Clay
Silt
F M C
Sand
Gravel


Core ID: GM9
(Ft)
Sediment Type
Sorting
P M W
Water Content
Sample Type
Comments
Upward Fining Sequence 2
0
4
8
12
16
20
24
28
32
Clay with silt and sand
Silt, some sand throughout
Fine sand, some clay and silt throughout
Upward Fining Sequence 1
Clean clay
Gravel with coarse sand, gravel is mixed fine-coarse, majority coarse, gravel percentage increases from 65% in top to 75% in bottom
Core
Taylor Marl Bedrock
Bedrock Depth: 31'
Clay
Silt
F M C
Sand
Gravel


Core ID: GMRV
(Ft)
Sediment Type
Sorting
P M W
Water Content
Comments
0
4
8
12
16
20
24
28
32
36
Medium sand clean sand in upper 2' grades to medium sand with fine-coarse gravels
Coarse sand with fine-coarse gravel
Upward Fining Sequence 5
Coarse to medium sand grades to sandy clay
Upward Fining Sequence 4
Coarse sand, grades to clay
Upward Fining Sequence 3
Clean clay with few disconnected gravel throughout
Fine sand, poorly sorted, silt and clay throughout
Upward Fining Sequence 2
Clay with sand and gravel throughout, coarse material is disconnected with clay between
Clean clay
Medium sand, poorly sorted, silt and clay throughout
Upward Fining Sequence 1
Medium sand, well sorted
Gravel and coarse sand, gravels are mixed fine-coarse
Core
Taylor Marl Bedrock
Bedrock Depth: 35.5'
Clay
Silt
F M C
Sand
Gravel


Core ID: Moonlight 1
(Ft) Sediment Type
Sorting P M W
Water Content
Sample Type
Comments
0
4
8
12
16
Clayey Silt, very hard
Clay, clean, mottled, very hard could not form in hand
Clay bedrock, transitions from grey to brown and dark tan, is harder than clay from above and has bedding
Core
Clay
Silt
F M C Sand
Gravel


Core ID: Moonlight 2
(Ft)
Sediment Type
Sorting
P M W
Water Content
Sample Type
Comments
0
8
16
24
32
Clay, clean, drab grey, very hard
Whole section is clean clay that is very hard in upper 16' transitions into softer maluable clay, clay is wet from 20-28' then dry below
Core
Wolf City Bedrock
Bedrock Depth: 34.5'
Clay
Silt
F M C
Sand
Gravel


Core ID: Moonlight 3
(Ft)
Sediment Type
Sorting
P M W
Water Content
Sample Type
Comments
0
8
16
24
32
40
48
56
64
Clean clay
Fine sand, well sorted, well rounded
Gravel with sand, gravel size ranges from fine to coarse, the gravel above they clay lense are mostly coarse while the gravel below are fine, smaller gravel has clean pore space, large gravel has sand and silt in the pore spaces, 43'-44' gravel is separated by clay
Core
Do not have the capability to core past 44' augered to bedrock contact, auger flights returned abundant wet sand and gravel
Auger
Wolf City Bedrock
Bedrock Depth: 64'
Clay
Silt
F M C
Sand
Gravel

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