ABSTRACT

Unstressed Groundwater Flow in the Brazos River Alluvium Aquifer with Implications for Temporal Ranges in Groundwater to Surface Water Interactions

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Groundwater flow paths and flow rates through alluvium aquifers are often oversimplified. This oversimplification may be due to sediment description limitations or aquifer properties obtained using well hydraulics that assume homogeneity. Groundwater travel times to the Brazos River channel can be longer than anticipated when the aquifer gradient is low and flow paths encounter heterogeneity within the lithologic framework. Conversely, travel times to the river channel can be less than anticipated when gradients are steep and homogeneous coarse sediment dominate the lithology within the aquifer while connecting directly to the river. This thesis investigates unstressed groundwater flow rates and flow paths under natural conditions using detailed lithologic logs to recreate more realistic heterogeneity of the Brazos River Alluvium Aquifer characteristics and a 2D finite element steady state model. These estimations provide important insight for surface to groundwater interactions within alluvium aquifers

Unstressed Groundwater Flow in the Brazos River Alluvium Aquifer with Implications for Temporal Ranges in Groundwater to Surface Water Interactions

by

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A Thesis

Approved by the Department of Geosciences

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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To my professors, role models and friends: Dr. Joe Yelderman, and Wayne Hamilton, I will forever cherish our time spent together. Your devotion in molding me into a professional geoscientist is a testament to the character you both have. The passion you both carry for the pursuit of knowledge and its distribution to future generations of geoscientists is profound. Thank you to my committee members Dr. Stacy Atchley, Dr. Jacquelyn Duke, and Dr. Thad Scott for taking time to provide valuable feedback and insight to my project. To the Baylor University Geosciences Department: I’m deeply indebted to you for challenging and supporting me to become the geoscientist I am today. To my colleagues: Thank you for guidance and support. Special thanks to Will Brewer, Claudia Dawson, and Toluwaleke Ajayi for your contributions to my work and the valuable feedback you have given me. To my parents: I owe to you both everything I’ve ever achieved, your guidance and support are the foundation of my being. To my siblings: Seth and Ryan, thank you both for always supporting me.

CHAPTER ONE

Introduction

Background

Groundwater flow rates in unconfined aquifers are one of the least understood topics in hydrogeology. It is difficult to conceptualize the physical process of groundwater flow without visualization. This complexity is compounded with seasonal variations in the water table due to responses from changes in aquifer recharge and discharge (Olivares, 2020). Groundwater and surface water interactions occur in most alluvium aquifers, as groundwater contributes baseflow to the stream associated with alluvium valleys (Figure 1.1). Groundwater is a renewable resource, but if mismanaged it can be exhausted when discharge exceeds recharge. Groundwater flow rates vary depending on the hydrogeologic characteristics of an aquifer. A velocity of 1 meter per day is considered a high rate of movement for most groundwater systems and occurs where flow is predominantly through coarse sediment while following a steep gradient. Groundwater can also move as slowly as 1 meter per month or slower where fine-grained sediments dominate, and a negligible gradient is present. In contrast, surface water flow dynamics are much easier to conceptualize due to the ease of its visual confirmation and its easily observed velocity, usually measured in meters per second.

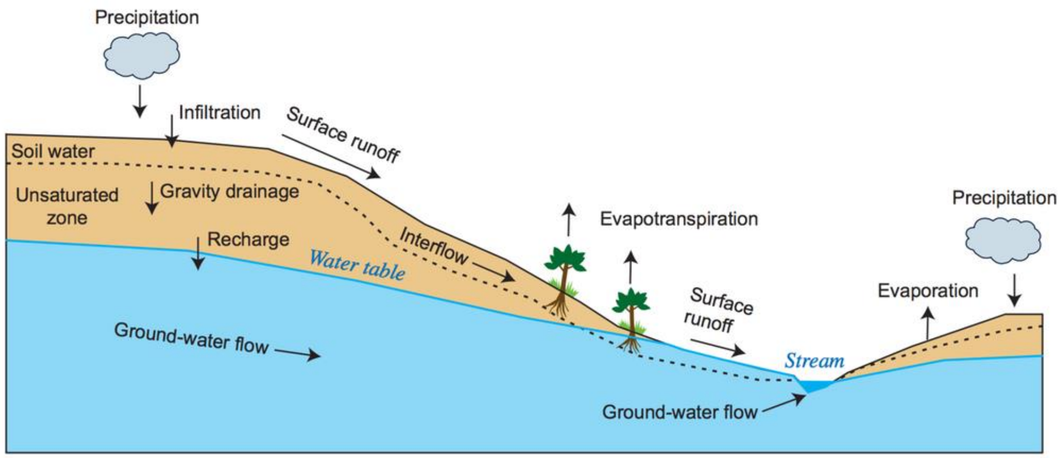

Figure 1.1 Gaining stream groundwater flow dynamics illustrating the processes that make up groundwater flow in a system similar to the Brazos River Alluvium Aquifer (modified from, GSFLOW MANUAL, USGS).

Under natural conditions, groundwater moves along flow paths from areas of recharge to areas of discharge. In terms of the Brazos River Alluvium Aquifer, groundwater travels from the distal portions of the alluvium to the Brazos River channel along flow paths that run nearly perpendicular to the river and slightly downstream based on the regional water table gradient (Figure 1.2). These idealized descriptions of near perpendicular flow from groundwater contour maps can be altered by preferential flow paths through coarser sediment or gradient deviations within the aquifer. These deflections away from perpendicular flow should be expected in the dynamic system of groundwater flow. The perpendicular flow paths generated in 2-dimensional conceptualizations of groundwater flow dynamics provide a more in-depth understanding of flow systems but may not reproduce the dynamic behavior of groundwater flow precisely.

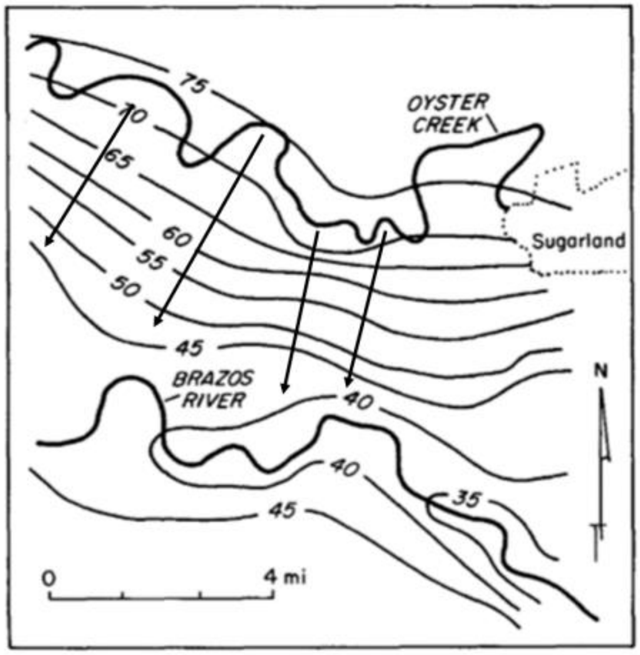

Figure 1.2. Brazos River Alluvium Aquifer groundwater elevation contours with the predominate flow direction being perpendicular to the Brazos River (modified from Larkin and Sharp, 1992).

Location

The Brazos River Alluvium Aquifer is an unconfined aquifer found along most portions of the lower Brazos River extending from Bosque County in central Texas to Fort Bend County near the Gulf Coast. This distance accounts for 350 river miles whereas the aquifer averages a width of around 7 miles (Jarvis, 2019). The width of the alluvium is controlled by the resistance to weathering from bedrock. Where the Brazos River flows over chalk and limestone the floodplain is narrow and restricted (Stricklin, 1961). This restriction allows for more substantial groundwater gradients in the floodplain as there is greater elevation changes over shorter lateral distances to the river. Inversely, where the Brazos River flows over the less resistant units such as marls, the floodplain is wider causing low gradients and the presence of more fine-grained sediments (Cronin and Wilson, 1967).

For this study, the portion of the river where the channel can migrate freely without the restrictions of bedrock will be referred to as the meandering portion of the Brazos River, whereas the portion with a bedrock confined floodplain will be referred to as the incised segment of the Brazos River.

The Brazos River Alluvium Aquifer is comprised of various lithologic layers containing sandy gravel, sand, and clay (Stricklin Jr, 1961). There is a general fining upward succession with coarser sediments near the bottom of the alluvium framework and finer sediments near the top (Cronin & Wilson, 1967). However, a site-specific analysis reveals more complex lithologic structures with various sediment layers and bedrock configurations that are not usually accounted for on larger scales. These sediments also vary spatially as there is a larger fraction of fine-grained sediments found in the southern meandering portion of the Brazos River as opposed to the northern incised portion. The overall thickness of the aquifer ranges from the surface to 168 feet at its deepest point, with an average depth of about 50 feet (Jarvis, 2019). The water table in the aquifer slopes toward the Brazos River indicating that the river is supplied by groundwater flow and is a gaining stream (Shah et al., 2007). The regional water table is mostly supplied by precipitation which acts as recharge to the Brazos River Alluvium Aquifer (Cronin and Wilson, 1967). Discharge from the aquifer occurs through both baseflow as groundwater is added to the Brazos River and through pumping from wells for domestic and irrigation uses (Cronin & Wilson, 1967). Discharge also takes place as transpiration from phreatophytes and riparian vegetation extract groundwater for photosynthesis.

Purpose

This study applies a quantifiable 2-dimensional groundwater flow model with detailed lithologic and hydraulic conditions representing the Brazos River Alluvium Aquifer to estimate more realistic flow paths and travel times for groundwater flowing towards the Brazos River channel on a site-specific scale. These calculations will then be compared to regional models which use more general lithologic interpretations to represent the aquifers hydrogeologic characteristics. Traditional groundwater models of the Brazos River Alluvium Aquifer are based on regional lithology and gradients that don't consider the complexity of small-scale changes in sediment layers and bedrock features. These features can cause variations in flow paths and travel times that cannot be accounted for in the resolution of large-scale models. This emphasis on site specific travel times and flow paths allows for a more detailed approach to understanding the connectivity the aquifer has with the Brazos River and the timescales in which this connection takes place on.

Objective 1: Create a 2D representation of multiple sites in the Brazos River Alluvium Aquifer and calculate the travel times and flow paths of groundwater flow based on the specific sediment descriptions from Jarvis (2019).

Objective 2: Create 2D representations of the aquifer using data from regional studies by Cronin and Wilson (1967). This regional perspective provides a more general lithologic framework for the aquifer.

Objective 3: Estimate the connectivity the Brazos River Alluvium Aquifer has with the Brazos River channel based on the flow paths and travel times calculated at each site.

Previous Works

- Cronin and Wilson (1967) assessed the Brazos River Alluvium Aquifer. As one of the first studies of the aquifer this study created an excellent baseline for aquifer studies today. This assessment was created on a regional scale as it encompasses the entire aquifer from Bosque County to Fort Bend County, Texas.
- Freeze and Cherry (1979) published a textbook describing groundwater flow mechanisms. This publication focuses on geological environments that control the occurrence of groundwater and the physical laws that describe its flow.
- Randall G. Larkin and John M. Sharp Jr. (1992) characterized relationships between river-basin geomorphology, aquifer hydraulics, and ground-water flow direction in alluvium aquifers.
- Paul A Hsieh (2001) demonstrates how Topodrive and Particleflow models for simulation and visualization of ground-water flow and transport of fluid particles in two dimensions are used.
- Sachin D. Shah and Natalie A. Houston (2007) characterized hydrogeologic variables in the Brazos River Alluvium Aquifer from Bosque County to Fort Bend County, Texas.
- Texas Water Development Board (2016) developed a report for the Brazos River Alluvium Aquifer Groundwater Availability in a numerical model. This GAM (Groundwater Availability Model) was created to better understand the resources of the alluvium aquifer with implications for sustainable management of the region.

- Kimberly Rhodes (2016) used pressure transducers to better understand water exchange between the Brazos River and the Brazos River Alluvial Aquifer with high temporal resolution measurements.
- Jarvis (2019) is the primary study that has characterized and interpreted heterogeneity on a site-specific scale for the Brazos River Alluvium Aquifer. This study took core from numerus locations in the alluvium and characterized the lithology in 2-dimensional cross sections.
- Claudia Dawson (2022) investigated groundwater and surface water interactions between the Brazos River Alluvium Aquifer and gravel pit lakes to assess the connectivity these lakes have with groundwater sources.
- Mehmood, et al (2022) used conceptual models to assume the connectivity of the Brazos River Alluvium Aquifer to the river. The small-scale, high resolution transects across the river were modeled using HYDRUS 2D. The conceptual models assume different levels of connectivity between the alluvium aquifer and the river.

CHAPTER TWO

Aquifer Setting

Geology

The geology of the Brazos River Alluvium Aquifer in the northern segment is characterized by river derived alluvial sediments overlaying Cretaceous limestones, shales, and chalk (Taormina et al., 2022). These alluvial deposits transition laterally into terraces that were deposited by the paleo Brazos River in the Pleistocene. The low permeability shales and chalks extend past the regional bounds of the alluvium aquifer creating a bedrock boundary on the sides of the floodplain. These confining units also form the vertical extent of the alluvium (Adkins, 1923). The floodplain alluvium serves as the primary groundwater repository within the Brazos River Alluvium Aquifer. The exact composition of the floodplain alluvium varies by location and has a general fining upward succession on the regional scale that transitions upward from gravels to clays (Cronin and Wilson, 1967). This fining upward succession follows the pattern for a typical stratigraphic profile of floodplain deposited sediment (Larkin and Sharp, 1992). The lowest portion of this sediment is saturated and forms the aquifer (Figure 2.1).

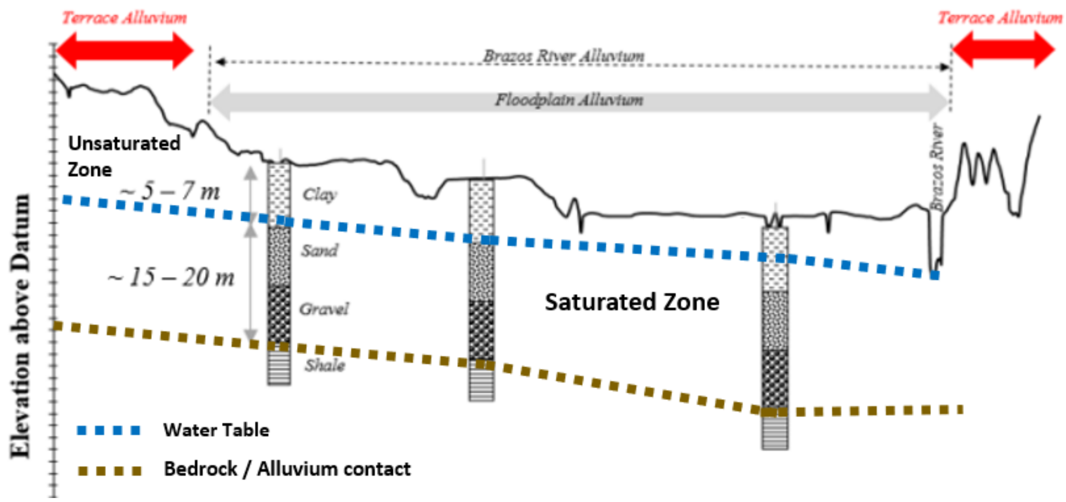

Figure 2.1. General alluvium aquifer lithologic interpretations depict the lithologic interpretations common with descriptions of regional sediment layering of the Brazos River Alluvium Aquifer (modified from Mehmood, 2018).

Hydrogeology

The Brazos River Alluvium Aquifer's hydraulic characteristics are dependent on the gradient, boundary confining units, surface water boundaries, and the hydraulic conductivity of its sediments. The groundwater flow in the aquifer is primarily driven by the difference in head between the distal portions of the aquifer and the Brazos River channel. It is understood that not all groundwater flow paths in the aquifer will follow an exactly perpendicular path to the river. The meandering river system will alter flow paths by deflecting them based on constantly changing gradients to the river channel as it erodes and deposits sediment. However, this will have little consequence to the general accuracy of the flow paths and travel times in this study. The flow direction is generally toward the stream and slightly down-valley (Cronin and Wilson, 1967; Harlan, 1986). Most transects used in this study fall within areas where interpreted groundwater contours have nearly straight flow paths towards the river, as seen at Steinbeck Bend (Figure 2.2).

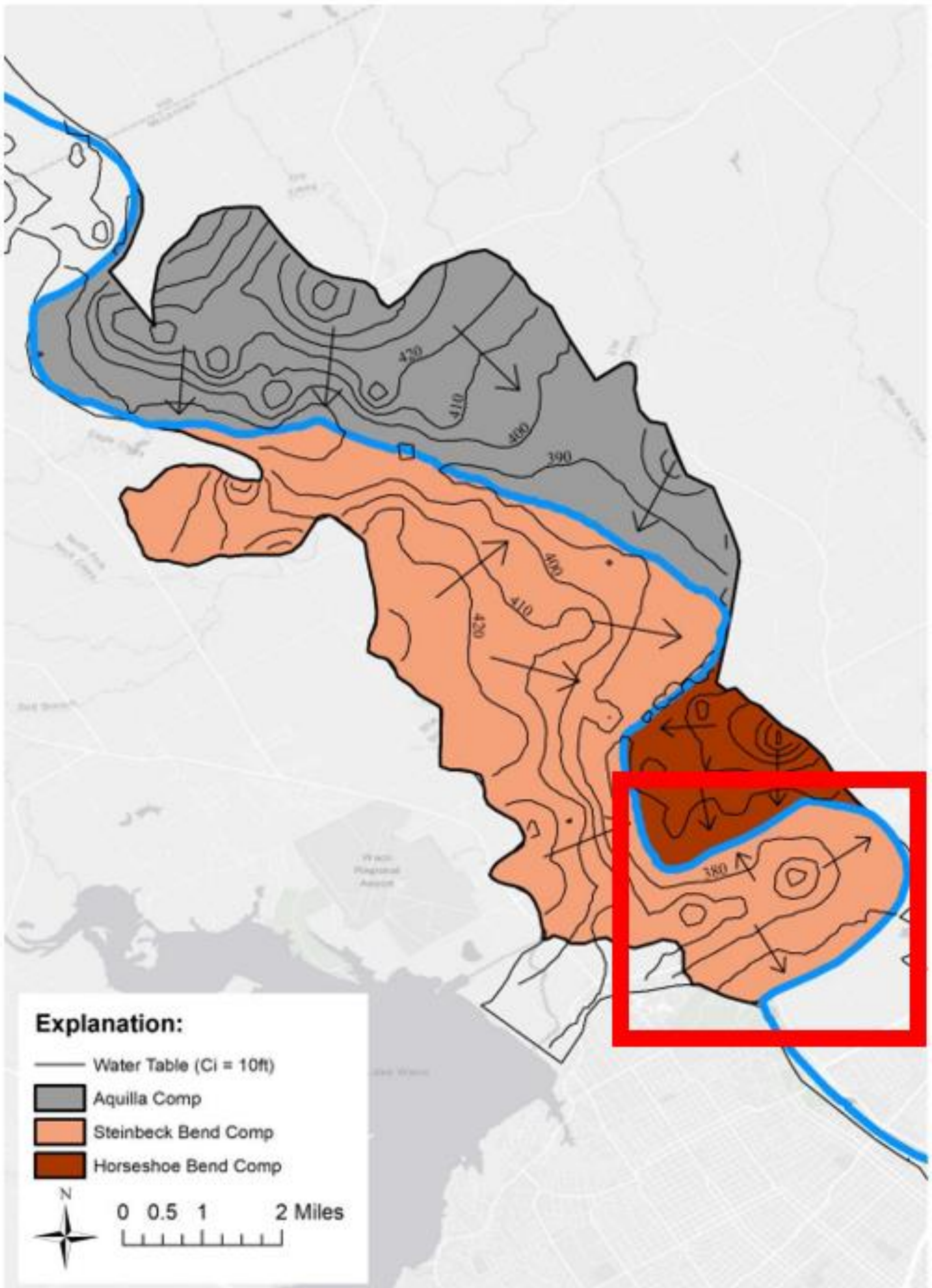

Figure 2.2. Steinbeck Bend groundwater contours show the near perpendicular flow of groundwater from the middle of Steinbeck Bend to the Brazos River channel (modified from Jarvis, 2019).

Hydraulic conductivity of sediment is another important factor affecting groundwater flow to the Brazos River. In the aquifer, hydraulic conductivity is variable due to heterogeneity (Wong et al., 2012). This heterogeneity is not captured by aquifer well tests as sediment types are assumed homogenous across screen intervals in pumping wells. Pumping tests find a transmissivity value for the aquifer in a specific location which is the average hydraulic conductivity over the entire screen of the well and the entire cone of depression (Shah et al., 2007). This composite transmissivity value can cause misconceptions about the flow rates in the aquifer due the average value lacking representative coverage of aquifer characteristics (Yelderman, et al., 2019). Composite transmissivity values have value for general interpretations about an aquifer's characteristics and production rates but may result in misinformed interpretations about an aquifer's connectivity to a river and its flow rates.

Recharge to the aquifer is primarily through direct precipitation over the Brazos River Alluvium Aquifer (Cronin and Wilson, 1967). This inflow is supplemented by occasional floodwaters from the Brazos River and other tributaries, and possibly by lateral flow from bedrock (Jarvis, 2019). The amount of precipitation that infiltrates into the saturated zone of the aquifer is correlated to rain event magnitude, soil moisture, and land use. Discharge occurs through dewatering during construction projects, transpiration from plants, evaporation of water at gravel pit lakes, and baseflow additions to the Brazos River (Dawson, 2022). The regional groundwater flow toward the Brazos River is constrained by boundary conditions that govern the system.

The first boundary condition is the bedrock boundary below the aquifer, as it confines groundwater to the alluvium sediment with its low permeability. In reality, the bedrock does allow groundwater flow through it as underlying aquifers are connected to the Brazos River Alluvium Aquifer, but at extended timescales (Turco et al., 2007). For the purpose of this study, the bedrock boundary layer will be assumed to be an impermeable unit confining all groundwater in the alluvium sediments (Figure 2.3). The second boundary condition is the gradient boundary, as all water in the distal portions of the aquifer is assumed to eventually make its way to the river. This boundary condition could be affected by pumping which could cause fluctuations in the gradient to the river. The final boundary condition is the stream boundary. This boundary indicates that no groundwater flowing on one side of the floodplain can flow beneath the Brazos River and be discharged on the opposite side of the river (Figure 2.3). These boundary conditions are derived from the reality of groundwater flow in the Brazos River Alluvium Aquifer and will allow for realistic parameters to govern the 2-dimensional model domain of TopoDive.

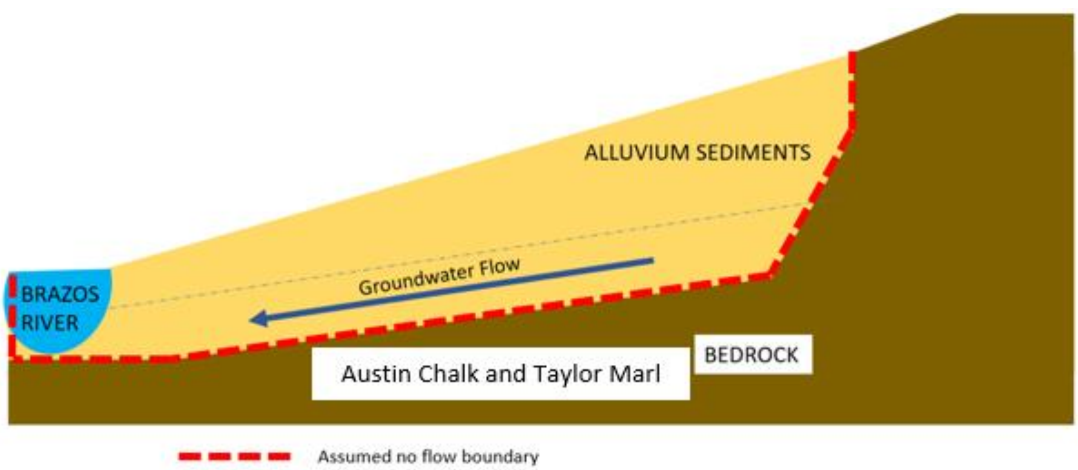

Figure 2.3. Alluvium aquifer boundary conditions for modeling interpretations.

CHAPTER THREE

Methodology

Overview

This project will use alluvium cross-sectional data from Jarvis (2019) to build a detailed two-dimensional aquifer in the TopoDrive modeling software. TopoDrive will then be used to calculate travel times and estimate flow paths within the aquifer. The cross sections constructed by Jarvis (2019) integrates core data from the Baylor Geosciences Geoprobe 6620DT. These core logs were correlated together to create transects of the Brazos River Alluvium Aquifer at six different sites. The cross sections created by Jarvis (2019) give this project detailed site-specific lithologic interpretations for the aquifer with accompanying water table elevations. The TopoDrive 2-dimensional finite element model is designed to simulate water table driven groundwater flow and advective transport of fluid particles under steady state conditions. The combination of a detailed subsurface representation based on Jarvis (2019) and calculated groundwater travel times through the aquifer will aid in the understanding of alluvium groundwater flow processes and aquifer to river connectivity. The site-specific cross sections will then be compared to more general data from a regional cross section constructed by Cronin and Wilson (2019). This comparison between aquifer interpretations will provide further insight into differences associated with aquifer management on a site-specific scale compared to a regional scale.

Jarvis 2019 Lithologic Cross Sections Data

To understand the complex lithology of the Brazos River Alluvium Aquifer, Jarvis (2019) conducted a series of drilling projects to obtain site specific data on the stratigraphy of the aquifer. Jarvis (2019) took a series of sediment core in transects nearly perpendicular to the Brazos River channel. These core were described in the lab to categorize grain size and sorting, but hydraulic conductivity values were not calculated. Jarvis (2019) collected 21 cores that were taken along six transects in the aquifer. Three of the transects are in the incised portion of the study area and three are in the meandering section of the river. Continuous core were taken from land surface to the contact between the alluvium and the Taylor Marl or Austin Chalk in order to capture the entire alluvium section. However, in some cases it was not possible to core the complete section (Jarvis, 2019). In circumstances when a full core was not possible to obtain, augers were utilized to drill down to the bedrock contact to record the alluvium thickness at the site (Jarvis, 2019). Coring and augering were conducted with the Baylor Geosciences Geoprobe 6620DT (Figure 3.1).

Figure 3.1. Baylor Geoscience Geoprobe 6620DT and sediment core (modified from Jarvis, 2019).

The Geoprobe is a tracked mobile drill rig that has multipurpose functionality. The Geoprobe can be operated to hydraulically hammer when coring and rotary drill when augering. The core for Jarvis (2019) was collected with MC5 dual-tube technology that allows for capture of continuous undisturbed 2.25-inch diameter sediment core. This core is stored within a 4-foot core barrel (Figure 3.2). Once a core was extracted it was sealed and stored in the laboratory. Water levels were estimated in the field based on the depth the sediment was saturated within the core tube when it was returned to the surface. In the lab, cores were stored and sealed until they could be described. Core were stored approximately 3 years in a laboratory facility before they were re-examined for this study. In order to estimate hydraulic conductivity of the sediments, each sediment type according to interpretations by Jarvis (2019) were reanalyzed according to sorting and grainsize.

Figure 3.2. Bedrock and alluvium contact and lab storage of core samples (modified from Jarvis, 2019).

The grainsize and sorting were then corelated to the hydraulic conductivity estimation chart of Duffield (2019). The table uses minimum and maximum hydraulic conductivities for each sediment type to build a possible range for the hydraulic conductivity values within them. Because these ranges extended over multiple orders of magnitude, a median value for each sediment type was selected as a standard in this study (Table 3.1).

Table 3.1. Hydraulic Conductivity values for sediment described in Jarvis (2019).

Sediment Type	Hydraulic Conductivity Estimation in m/s	Effective Porosity
Bedrock	1.0 E^{-25}	20%
Clay	4.7 E^{-10}	20%
Fine Sand/Silty Sand	2.0 E^{-5}	20%
Coarse Sand	6.0 E^{-4}	20%
Sandy Gravel	5.0 E^{-3}	20%

The estimated hydraulic conductivity for sediment descriptions derived from Jarvis (2019) using Duffield (2019) were then compared to hydraulic conductivity values for similar sediment types from Freeze and Cherry (1979). This process ensured that the sediment hydraulic conductivity used in the TopoDrive model is consistent with accepted literature values from historically accurate documents. Every sediment hydraulic conductivity fell within the accepted range for its sediment type (Figure A.1). Effective porosity was assigned as 20% for all sediment types in the model. Unconsolidated sediment effective porosity ranges from 5 to 35% (Stephens, 1998). Given this range, a median value of 20% was assigned to remain consistent across all model domains.

The use of individualized cores to reconstruct detailed lithologic cross sections of the Brazos River Alluvium Aquifer with assumed groundwater levels gives a much more detailed interpretation of the heterogenous sediment features in the alluvium (Figure 3.3).

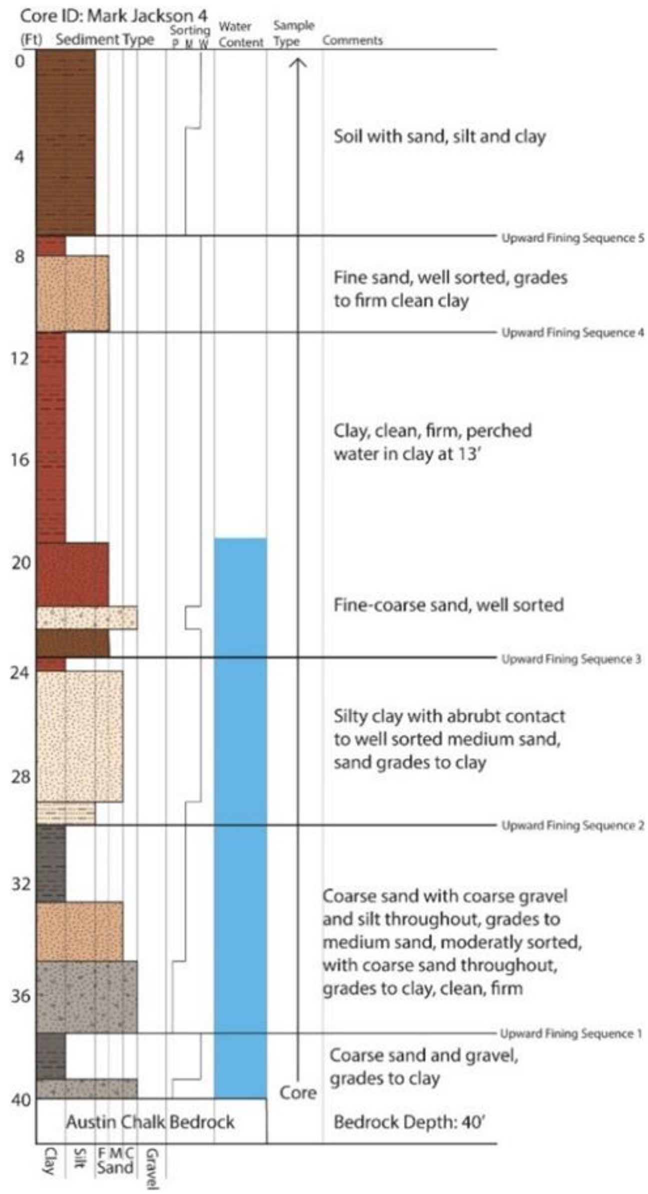

Figure 3.3. Interpreted core logs that core consists of varying sediment types such as clay, fine sand, coarse sand, and gravel (Jarvis, 2019).

Each site has multiple core logs taken along a perpendicular axis relative to the river. These individualized high resolution core segments were then correlated together by Jarvis (2019) to create detailed transects with assumed stratigraphic assemblages based on related bedding from each core log (Figure 3.4). The saturated thickness of each core log also allowed Jarvis to accurately estimate a water table within each transect. The estimated water level can be used to calculate the gradient of each site based on the elevation change of the water table from the distal portions of the aquifer compared to the water level at the river. Distance and elevation are also provided by Jarvis (2019) on the X and Y axis of each transect.

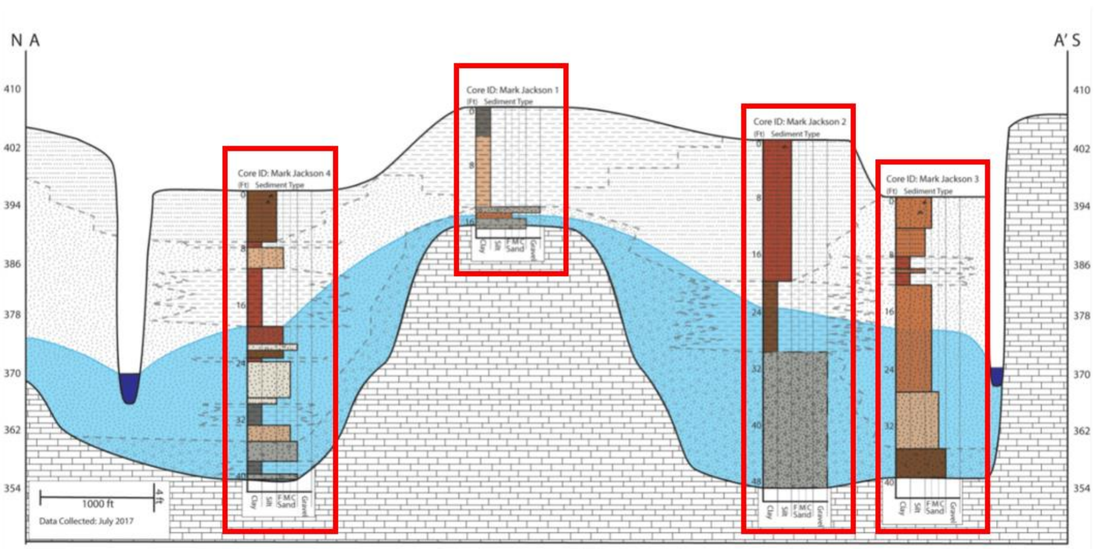

Figure 3.4. Multiple interpreted core logs used to construct a detailed 2-dimensional transect (modified from Jarvis, 2019).

Regional Cross Section Data

For the regional interpretation of groundwater flow within the aquifer, a cross section from Cronin and Wilson (1967) is used (Figure 3.5). This cross section was constructed by correlating seven power auger sites where sediment was cataloged based on the depth of the auger. These data have accompanying lithologic descriptions of the sediment types found within the Brazos River Alluvium Aquifer. The Cronin and Wilson (1967) cross section will function as more general aquifer interpretation with larger distances and more general sediment layers contrasting the Jarvis (2019) more site specific approach (Figure 3.5). The more homogeneous descriptions of the Brazos River Alluvium Aquifer will be compared to the site-specific interpretations made from the work of Jarvis (2019).

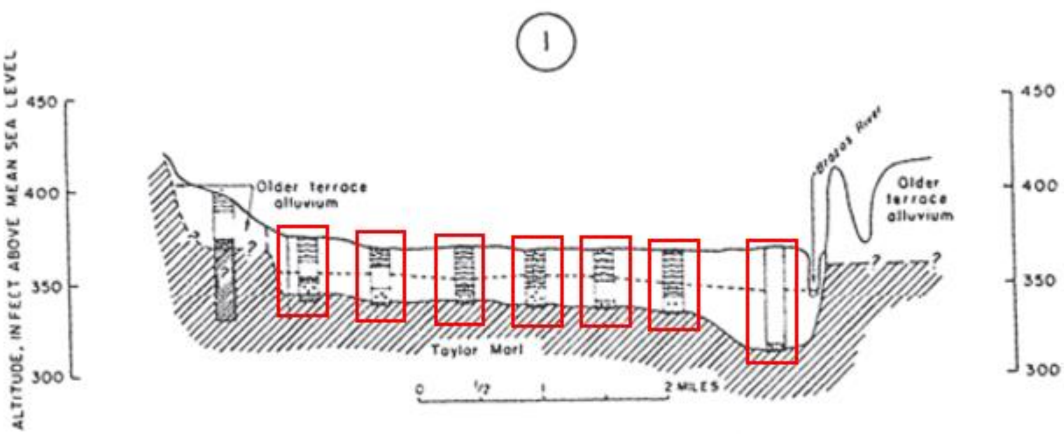

Figure 3.5. Regional cross section with interpreted core logs used to construct a regional transect of the Brazos River Alluvium Aquifer (modified from Cronin and Wilson, 1967).

Topo Drive Analysis

The TopoDrive model software simulates advective groundwater flow and transport of fluid particles through an aquifer. This model operates under steady state conditions that don't account for changing variables such as recharge or discharge alterations during its runtime. TopoDrive provides a visual capability that enables viewers to understand groundwater flow processes in terms of temporal and spatial resolution (Hsieh, 2001). This model only recreates conditions below the water table, so portions of the aquifer that are unsaturated are not modeled. The boundary of the water table is represented by line (AB) where A is assumed to be the elevation of the Brazos River (Figure 3.6). The two vertical boundaries (BC and AD) and the bottom boundary (CD) represent no flow boundaries (Hsieh, 2001). The vertical no flow boundary (BC) represents the lateral extent of the aquifer (Figure 3.6). Boundary (AD) represents a groundwater flow divide such as the Brazos River. Boundary (DC) serves as the low-permeability bedrock contact that bounds the basin and confines the groundwater in the alluvium aquifer.

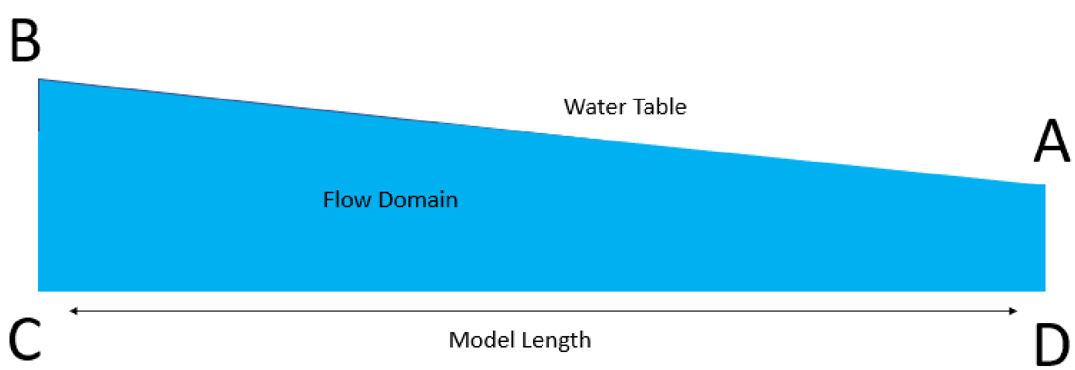

Figure 3.6. TopoDrive model domain with boundary conditions (modified from Hsieh, 2001).

Note that the (BC) no flow boundary on the edge of the transect distal to the river is not a true no-flow boundary. This boundary would have lateral groundwater flow from the further portions of the floodplain alluvium, but the length of the cross sections created by Jarvis (2019) only reconstruct portions of the alluvium that extend up to 3,000 meters into the floodplain. In terms of the model accuracy to actual conditions, the flow paths and travel times are lengthened near the distal no flow boundary due to a boundary error that will cause flow paths to have more vertical flow in the aquifer, thus adding travel time. This vertical error in the initial flow of the groundwater should not alter the model's general reliability as this error has less effect on flow paths occurring further from the (BC) boundary.

For the conversion of hydraulic conductivity values in TopoDrive, sediment types are given a vertical hydraulic conductivity value, a horizontal hydraulic conductivity value, and a percent effective porosity. The hydraulic conductivity value assigned to each sediment type is represented by a specific color in the aquifer model domain. The anisotropy of the Brazos River Alluvium Aquifer sediments is assumed to be 10 to 1, whereas the porosity of the sediment is assumed to be 20 percent (Stephens, 1998). These hydraulic variables are within the range of accepted values of both anisotropy and effective porosity to provide accurate data for the flow paths and travel times (Figure 3.7).

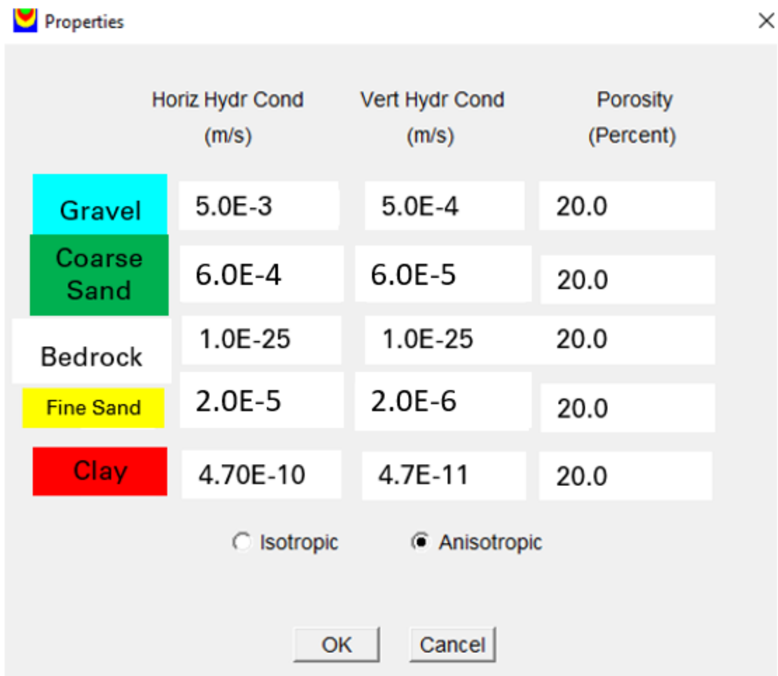

Figure 3.7. Hydraulic Conductivity Conversion into TopoDrive.

The variable input step is followed by the creation of the model domain. When building the model domain in TopoDrive the length of the cross section is recreated using the distances given from the transects in Jarvis (2019). The dimensions of each cross section created by Jarvis (2019) were measured in feet, however, the TopoDrive model deals in metric. This means that distances from Jarvis (2019) had to be converted to meters before they could be accurately reproduced in TopoDrive. Once the height and width of each TopoDrive cross section was input, a vertical exaggeration had to be chosen for each model domain. The vertical exaggerations for each site varied but are generally within the ranges of 40 to 60.

Next comes the input of rows and columns to discretize the flow domain. The number of rows and columns assigned in the mesh will affect how the fineness or coarseness of the domain computation. The more rows and columns in the mesh, the larger amount of computation cells will be created to calculate head based on the gradient and K (Hsieh, 2001). Each of the models in this project will use 50 columns and 25 rows to maintain a standard mesh throughout every site. The program generates a deformed rectangular mesh and then splits each rectangular element into two triangular elements where a hydraulic conductivity value can be assigned (Hsieh, 2001). Once the mesh is created, each cell must be filled with a hydraulic variable such as hydraulic conductivity, porosity, and isotropy or anisotropy. A maximum of five sediment types may be assigned within the model domain. The K values are in m/s. These five sediment types are each represented by a different color. Each cell in the mesh is assigned a value based on the parameters given in the properties section. This value will then be calculated in a summation integral for the extent of the model with gradient and hydraulic head considered (Hsieh, 2001).

The model flow domain is filled with various colors representing different sediment types. Hydraulic head is calculated and shown by equipotential lines in the TopoDrive model domain. These lines are equally spaced between the highest and the lowest head values (Hsieh, 2001). This is where the computational aspect of the program takes place. In terms of groundwater flow, the flow paths will flow perpendicular to these equipotential lines. Once the computation of hydraulic head is complete, the model can be run with flow paths being selected from any point in the model domain. During the run time, the estimated time elapsed is displayed near the bottom of the program page. This time elapsed function of the program is used to document the travel time of each flow path in the cross section.

Limitations of the TopoDrive 2D Finite Element Model

The TopoDrive 2D finite element model's major limitation is its steady state conditions. During the runtime of the model where flow paths and flow rates are calculated, the water table does not evolve and remains in steady state over long periods of time. This is a false assumption as the water table is a constantly changing variable that is influenced by recharge, discharge, and soil moister (Merket, 2017). The water table's dynamic nature has important roles in the relationships between groundwater, surface water, and vegetation (Levine and Salvucci, 1999; Cohen et al., 2006; Maxwell and Kollet, 2008). The dynamics of the river may also affect the aquifer. Higher groundwater discharges at lower river flows and lower groundwater discharges at higher river flows are also not accounted for in the TopoDrive model (Rhodes, 2016). The dynamic nature of the water table is observed in the TopoDrive 2D model domain but is not expressed. There are flow paths within the model that never reach the discharge point at the Brazos River and instead intersect the top of the water table's no flow boundary at varying locations. These flow paths indicate a rise in the water table as water is competing for a shrinking volume of saturated sediment near the Brazos River. The steady state conditions in TopdoDrive can not account for this rise in the water table or its possible drop when recharge is limited through events such as droughts. These limitations in the TopoDrive model domain conceal some of the complex processes associated with the water table but do not detract from the overall knowledge gained from its calculations. For the purpose of this study, only flow paths that reach the discharge point of the Brazos River are analyzed.

CHAPTER FOUR

Study Locations

Overview

This project focuses on the northern segment of the Brazos River Alluvium Aquifer which spans from Whitney Dam to the southern end of Falls County (Figure 4.1). Within the study area, Steinbeck Bend, Hirsch Dairy, and a regional site near the border between McLennan and Falls County are analyzed. The spatial variability in the four cross sections used in this study represent a diverse set of hydrogeological variables for the aquifer.

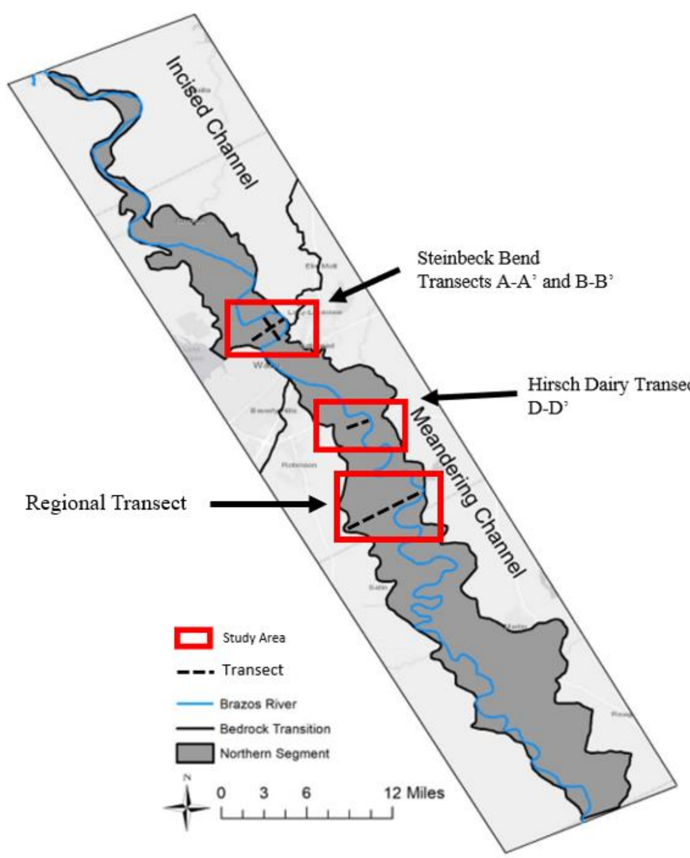

Figure 4.1. Study Location Regional Map: (Modified from Jarvis, 2019).

Steinbeck Bend

Cross section A-A’ begins north of the Brazos River and passes through the Steinbeck Bend meander with a northwest to southeast direction (Figure 4.2). This transect is located in the incised portion of the Brazos River channel which is bedrock controlled and has a small fraction of fine-grained sediment. Steinbeck bend is dominated by bedrock relief as the center of the meander is on top of a buried bedrock ridge with significant elevation changes over the length of the transect (Figure 4.3).

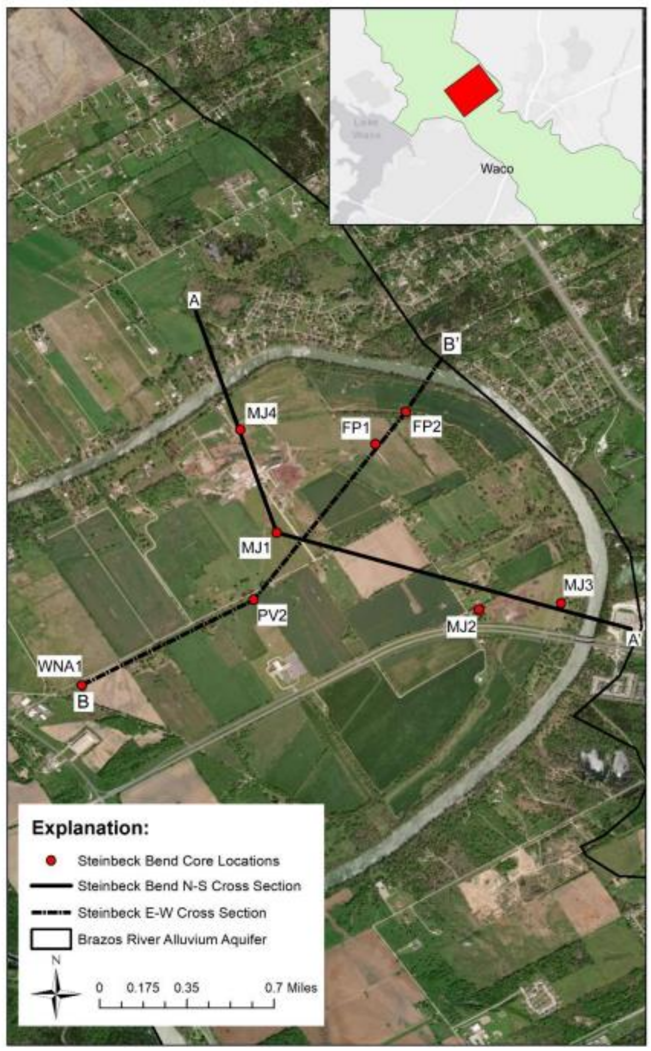

Figure 4.2. Steinbeck Bend Transect A-A’ and B-B’ Map View (Jarvis, 2019).

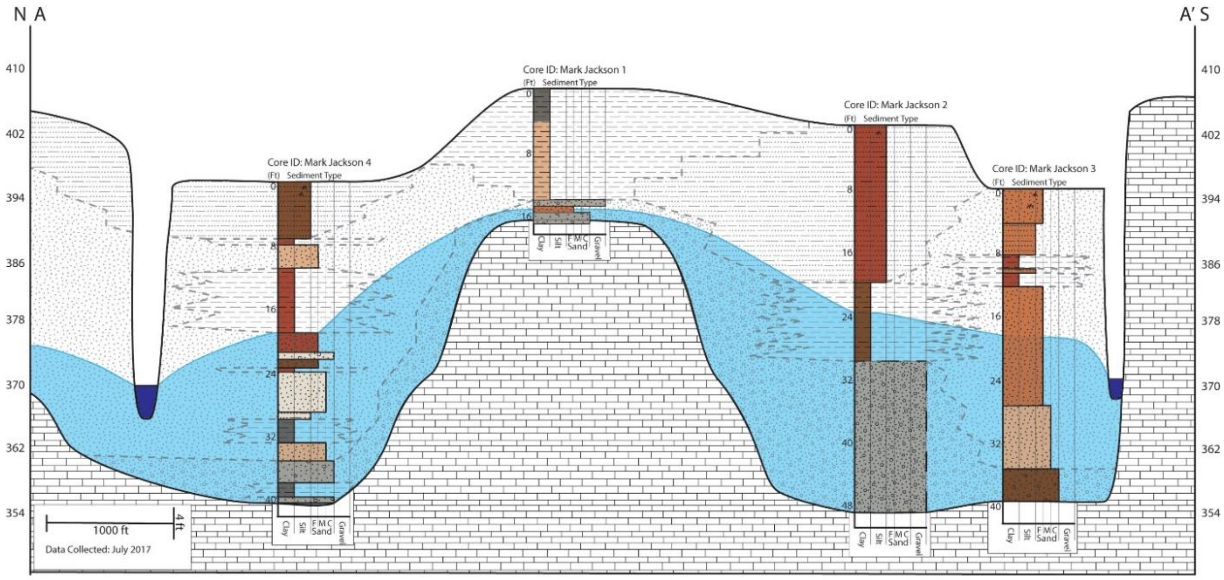

Figure 4.3. Transect A – A' (Jarvis, 2019).

The alluvium saturated thickness also varies considerably over the length of the cross section as does the groundwater gradient. Cross section A-A' consists of four cores, MJ1, MJ2, MJ3, and MJ4. The alluvium thickness on top of the bedrock ridge is relatively thin compared to the sections closer to the river that have much more depth in terms of the saturated sediment. The water table is represented in blue and has large variations in thickness (Figure 4.3). Sediment in this transect is dominated by gravel and sand near the lower portions of the aquifer and grades into coarse sand with clay lenses up stratigraphic section. The geometry of the meander causes an appearance of two Brazos River channels to be present in cross sectional view. This is an unusual feature that creates a natural hydraulic boundary condition in the model domain. The river boundary creates a groundwater divide that differentiates flow to either side of the Brazos River channel (Figure 4.4).

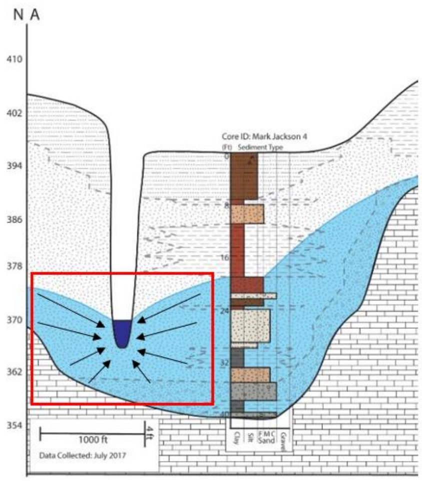

Figure 4.4. Transect A – A’ Stream boundary (modified from Jarvis, 2019).

Cross section B-B’ is along the northeast to southwest axis of the Steinbeck Bend meander. Alluvium thickness and saturated section again vary considerably in B-B’. The bedrock ridge is seen again in cross section and controls the thickness of the alluvium sediments (Jarvis, 2019). Transect B-B’ contains core WNA1, PV2, FP1, and FP2. The sediment represents a fining upward succession that is reflected by large gravel deposits near the bedrock contact making up most of the saturated sediment (Figure 4.5).

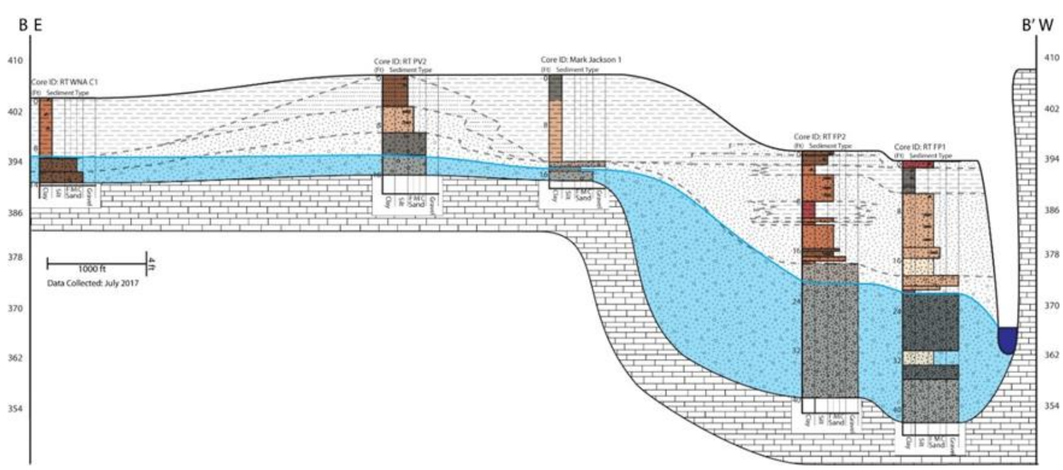

Figure 4.5. Transect B -B’ (Jarvis, 2019).

Hirsch Dairy

Cross section D-D' was collected south of Waco in the floodplain meandering portion of the Brazos River Alluvium Aquifer. The bedrock relief in this portion of the aquifer has minimal effects on saturated thickness compared to the incised portion of the channel. There is an eight-foot bedrock elevation change from the Upper Hirsch to Lower Hirsch (Jarvis, 2019). The saturated thickness is more consistent in cross section D-D' compared to the cross sections in the incised portion (Jarvis, 2019). This transect was correlated with core from 'Upper Hirsh', 'Middle Hirsh', and 'Lower Hirsh' (Figure 4.6).

Figure 4.6. Hirsch Dairy Transect D-D' Map View (Jarvis, 2019).

There are two clay beds within the saturated section that could cause localized confining and vertical isolation of groundwater flow systems (Figure 4.7). This transect follows a west to east path. According to Jarvis (2019) coarse-grained material in the saturated section is discontinuous and contains 48% clay.

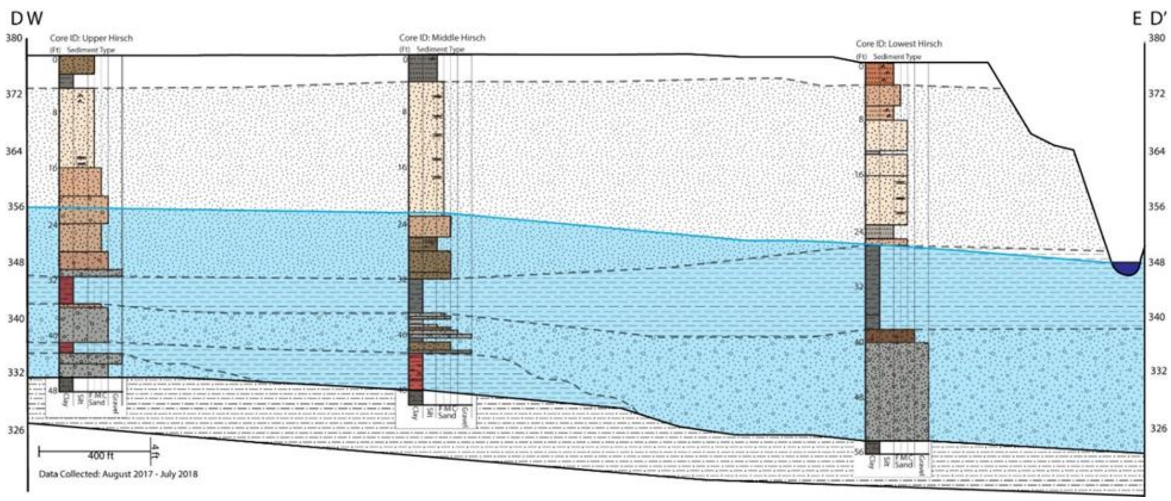

Figure 4.7. Transect D – D' (Jarvis 2019).

Regional Transect: McLennan County Transect 1

The regional cross section of the Brazos River Alluvium Aquifer represents historical depictions of alluvium aquifers with large scale general sediment descriptions. This transect extends nearly four miles over Brazos River alluvium and has only three main sediment types within a fining upward succession. The sediments transition up stratigraphic section from sandy gravel, coarse sand, and fine sand with admixed clay in the saturated portions of the transect (Figure 4.8). To obtain sediment descriptions and hydrologic data, cores were bored with a power auger. The interpretation of the water table for the transect was generated from groundwater contours using monitor wells in the study area. Cronin and Wilson (1967) provide the basis for more traditional interpretations of alluvium aquifer flow dynamics on regional scales.

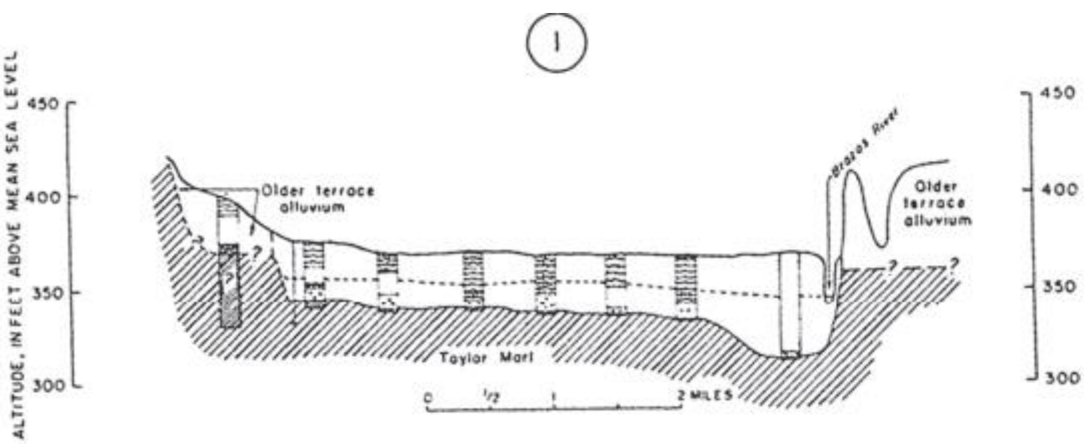

Figure 4.8. McLennan Country Brazos River Alluvium Aquifer Regional Transect 1 (modified from Cronin & Wilson 1967).

CHAPTER FIVE

Results & Discussion

Steinbeck Bend Cross Section A – A'

Steinbeck Bend transect A – A' extends across the incised portion of the Brazos River Alluvium Aquifer (Figure 4.1). The groundwater table resembles the surface topography of the Steinbeck Bend meander and is heavily influenced by the bedrock beneath it (Figure 5.1). The presence of a large bedrock plateau at the center of the meander results in a noticeable variation of the alluvium saturated sediment thickness (Jarvis, 2019). Bedrock dominated relief also significantly affects the water table gradient.

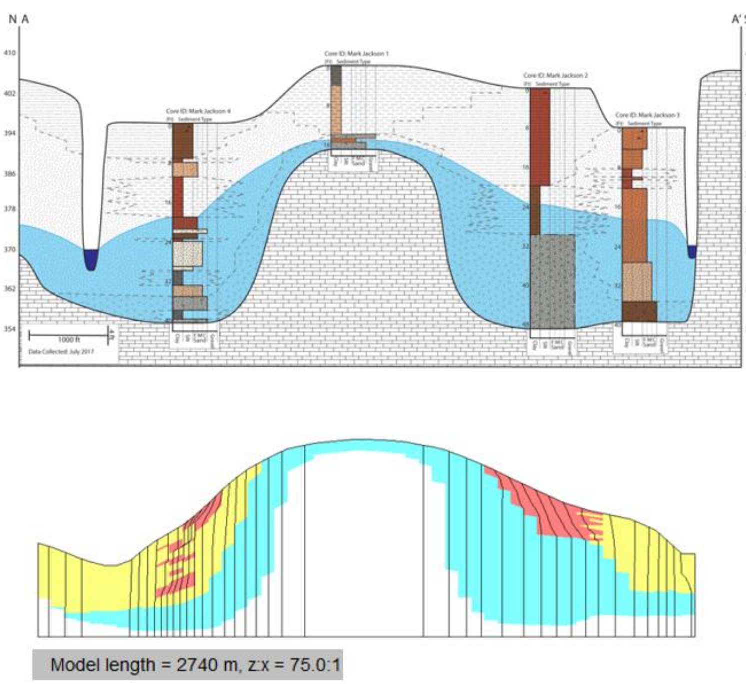

Figure 5.1. Steinbeck Bend transect A-A' with Analogous TopoDrive Modeled Cross Section (modified from Jarvis 2019).

The elevation in the water table changes from its highest point at the center of the bedrock plateau to the lateral edge of the plateau by about 1.5 meters (Figure 5.2). This elevation drop occurs over a distance of around 250 meters resulting in a drop of 0.006 meters of water table elevation for every meter traveled towards the river channel in this portion of the aquifer. In comparison, there is around a 6.5-meter water table elevation change from the lateral extent of the bedrock plateau to the river channel. This is a distance of around 755 meters which correlates to a 0.0086-meter elevation decrease in the water table for every lateral meter traveled toward the river in this portion of the aquifer. This is a 43% increase in gradient between the flat center of the meander and the proximal portions of the aquifer.

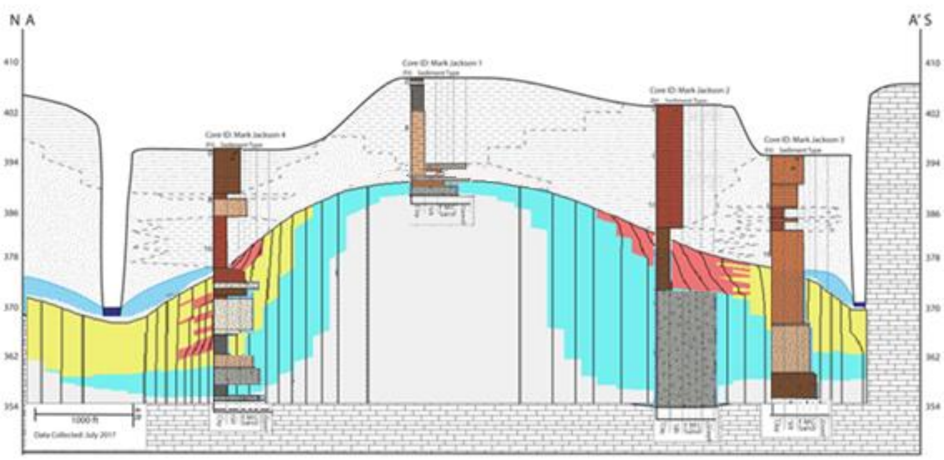

Figure 5.2. Transect A-A’ with Overlaying TopoDrive Modeled Water Table (modified from Jarvis 2019).

Cross section A – A’ is dominated by coarse sandy gravel in its lower portion with clay and fine sand near the top of the water table (Figure 5.2). The bedrock beneath the saturated alluvium sediments is shown in white and is assumed to be impermeable with an assigned K value of 1 x 10^{-25} m/s. The underlining well-sorted sandy gravels are represented as light blue in the model with a hydraulic conductivity of $5x10^{-3}$ m/s. The fine sand is depicted as yellow in the TopoDrive model with a hydraulic conductivity of $2x10^{-5}$ m/s. The clay lenses located throughout the proximal portions of the aquifer are depicted in red with a hydraulic conductivity of $4.7x10^{-10}$ m/s (Figure 5.2). These variable hydraulic conductivities result in preferential flow paths through the coarsest sediment fraction within the aquifer.

Flow paths that begin at the center of the meander predominantly travel through the sandy gravel and fine sand. These flow paths travel near the bedrock alluvium contact and eventually flow into to the Brazos River channel at the discharge point (Figure 5.3). This vertical flow to the lower portion of the aquifer is not consistent across all flow paths as flow paths that start on the edge of the bedrock plateau don't necessarily travel deeper into the aquifer. Instead, these flow paths move laterally toward the Brazos River channel.

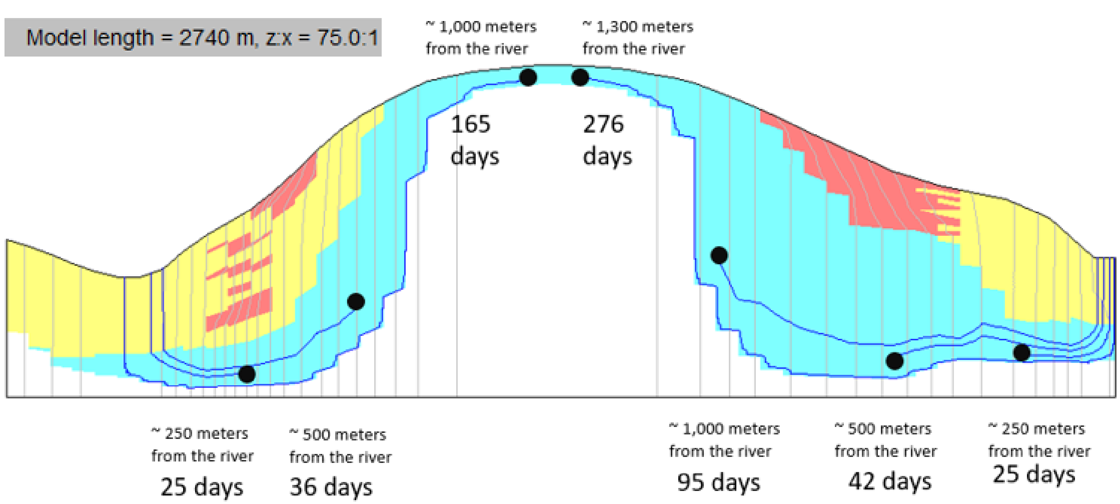

Figure 5.3. Transect A-A' Travel Times.

In terms of travel times, transect A-A' has a bimodal distribution for the length of time it takes for water in the aquifer to reach the river. Flow paths that originate on top of the bedrock plateau are influenced by low gradients and the bedrock limiting the potential vertical space for groundwater to move downward within the aquifer. Travel times to the river are in the hundreds of days range for this segment (Figure 5.3). The shallow gradient and limited saturated thickness transition into a steep gradient with a 43% increase in slope near the subsurface bedrock cliff. The increase in gradient is accompanied by approximately eight meters of additional saturated thickness. Once groundwater reaches the increased gradient, travel times are significantly decreased and are in the range of tens of days to reach the river channel. For flow paths that initiate 1,000 meters from the river it takes 165 days for the groundwater to reach the channel. For 1,300 meters from the river, it takes around 276 days. The 100-day difference in travel times between the 1,000 meter and 1,300-meter flow paths reflect the influence a low gradient has on the groundwater travel time. For flow paths that initiate 250 meters from the river, it takes around 25 days to reach the river channel. This travel time increases to around 40 days at 500 meters from the river. These flow paths are both affected by a steep gradient and are also both predominantly through coarse sediment (Figure 5.3).

Steinbeck Bend Cross Section B – B'

The Steinbeck bend cross section B – B' is also located in the incised portion of the Brazos River and is controlled by its bedrock relief (Figure 4.1). The relief causes the water table gradient to have two distinct sections that influence travel times in opposing fashions comparable to transect A-A'. Transect B-B' intersects cross section A-A' near 90 degrees in a northeast to southwest direction. This leads to a longitudinal geometry similar to transect A-A'; however, there is greater distance to the river from the distal portions of the longitudinal cross section (Figure 5.4).

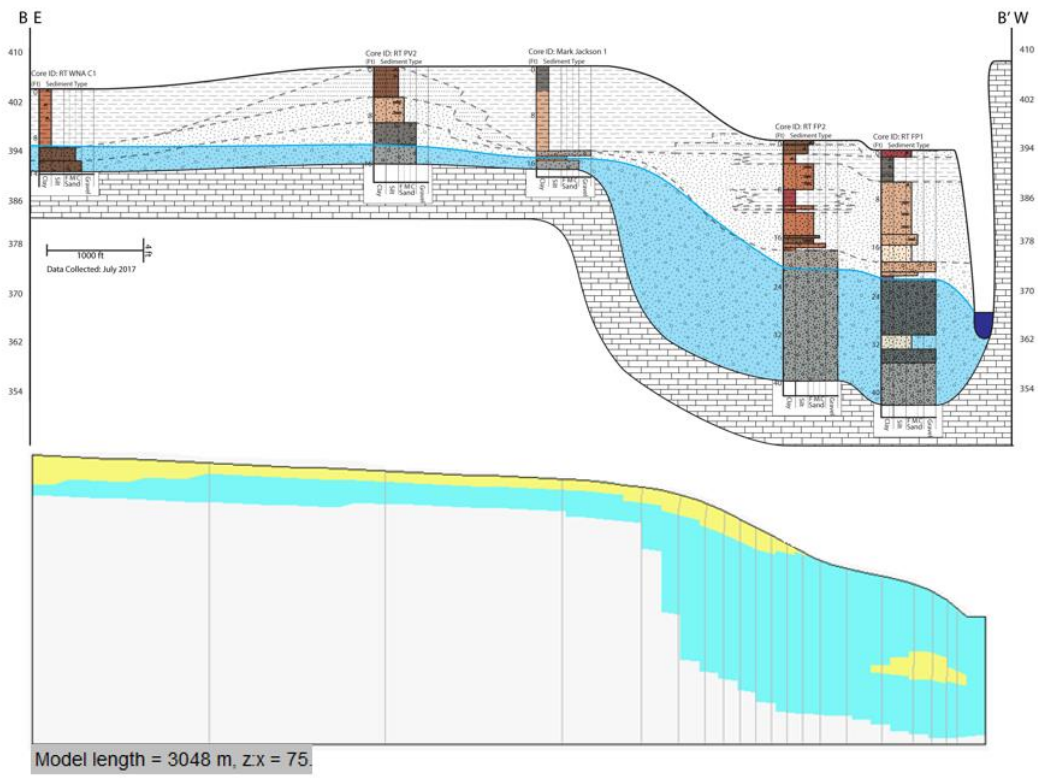

Figure 5.4. Transect B-B' with Analogous TopoDrive Modeled Cross Section (modified from Jarvis 2019).

In terms of preferential flow, transect B-B’ does not indicate the most likely flow path to the Brazos River channel from areas on top of the bedrock plateau. Groundwater most likely flows perpendicular to transect B-B’ which is a shorter lateral distance to the river; however, this cross section provides better insight into the flow dynamics of groundwater that could hypothetically follow this transect and will represent some of the maximum travel times possible at Steinbeck Bend.

Saturated alluvium sediment above the subsurface bedrock plateau has a two-meter elevation drop over a 2,000-meter distance in cross section. This reflects a vertical drop of .001 meters for every lateral meter toward the Brazos River channel. The flat gradient means that hydraulic head is low for flow paths in this portion of the aquifer. Low hydraulic head differences add significant travel time to all saturated areas above the subsurface bedrock plateau. The gradient transitions to a more substantial slope near the Brazos River. The water table is influenced by the bedrock slope where the paleo Brazos River channel eroded into the chalks and marls. In this more proximal region to the river, the water table elevation drops around 6 meters over a lateral distance of 1,000 meters to the river (Figure 5.5). This substantial change in water table elevation allows much faster travel times near the river contrast to the flat distal portions of the aquifer. The two distinct gradients have a 500% difference in slope.

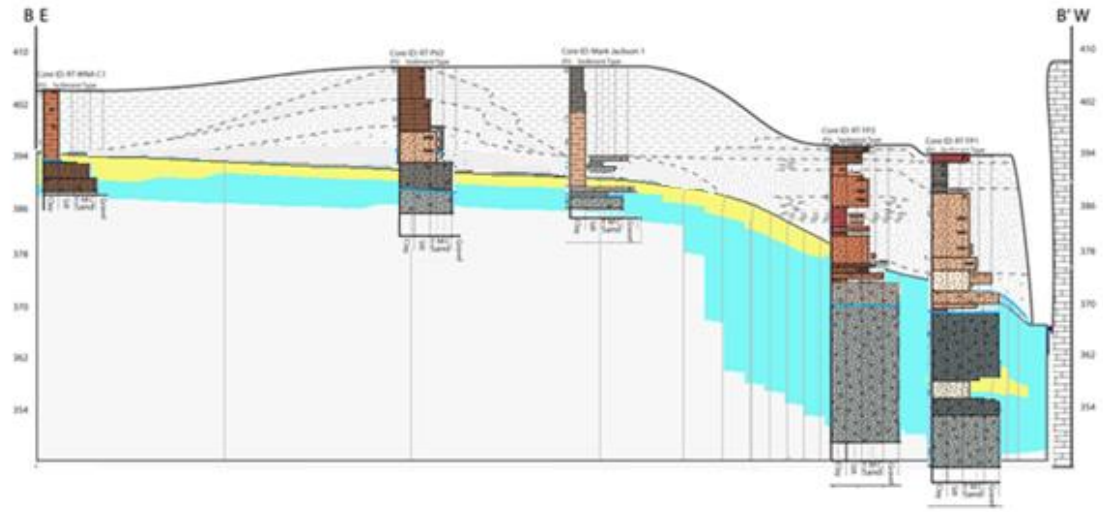

Figure 5.5. Transect B-B'' with Overlaying TopoDrive Modeled Water Table (modified from Jarvis 2019).

Sediment type and distributions are another key factor that influence travel times on this cross section. The Brazos River Alluvium at Steinbeck Bend is dominated by sandy gravel (shown in the blue) and fine sand (shown in yellow) at its base (Figure 5.5). Sandy gravels have an estimated hydraulic conductivity of 5 $x10^{-3}$ m/s whereas fine sand has an estimated hydraulic conductivity of 2 $x10^{-5}$ m/s. Coarse, unconsolidated sediment dominates this transect. Silty sand is observed in gravel interparticle volume in floodplain deposits; however, this fine-grained sediment makes up a small fraction of the overall sediment volume. Flow paths starting 250 meters from the river take around 30 days to reach the channel. The travel time doubles to 60 days for flow paths starting 500 meters from the river. Travel time increases to around 90 days 1,000 meters from the river. These three flow paths all originate in the high gradient segment of the alluvium cross section and have relatively high connectivity to the river. The travel times significantly increase when flow paths originate on the bedrock plateau. Around 2,000 meters away from the river channel it takes approximately two years for water to reach the discharge point. This travel time doubled to four years 3,000 meters from the river. The segment of the aquifer that lies on top of the bedrock has low connectivity to the river (Figure 5.6).

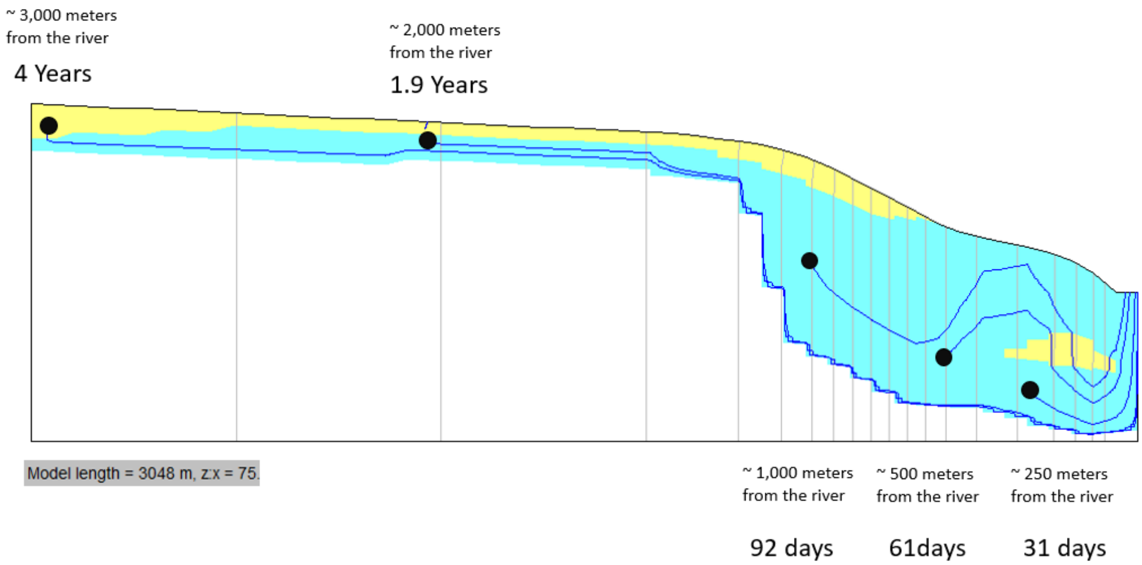

Figure 5.6. TopoDrive Modeling Interpretations of Transect B-B' showing travel times to the Brazos River.

Steinbeck Bend Alluvium Aquifer Connectivity to The Brazos River

Aquifer connectivity to the Brazos River for the Steinbeck Bend transects A - A' and B - B' is segmented into a connected portion and non-connected portion. Groundwater is well connected to the Brazos River under natural conditions in all areas adjacent to the bedrock plateau (Figure 5.7).

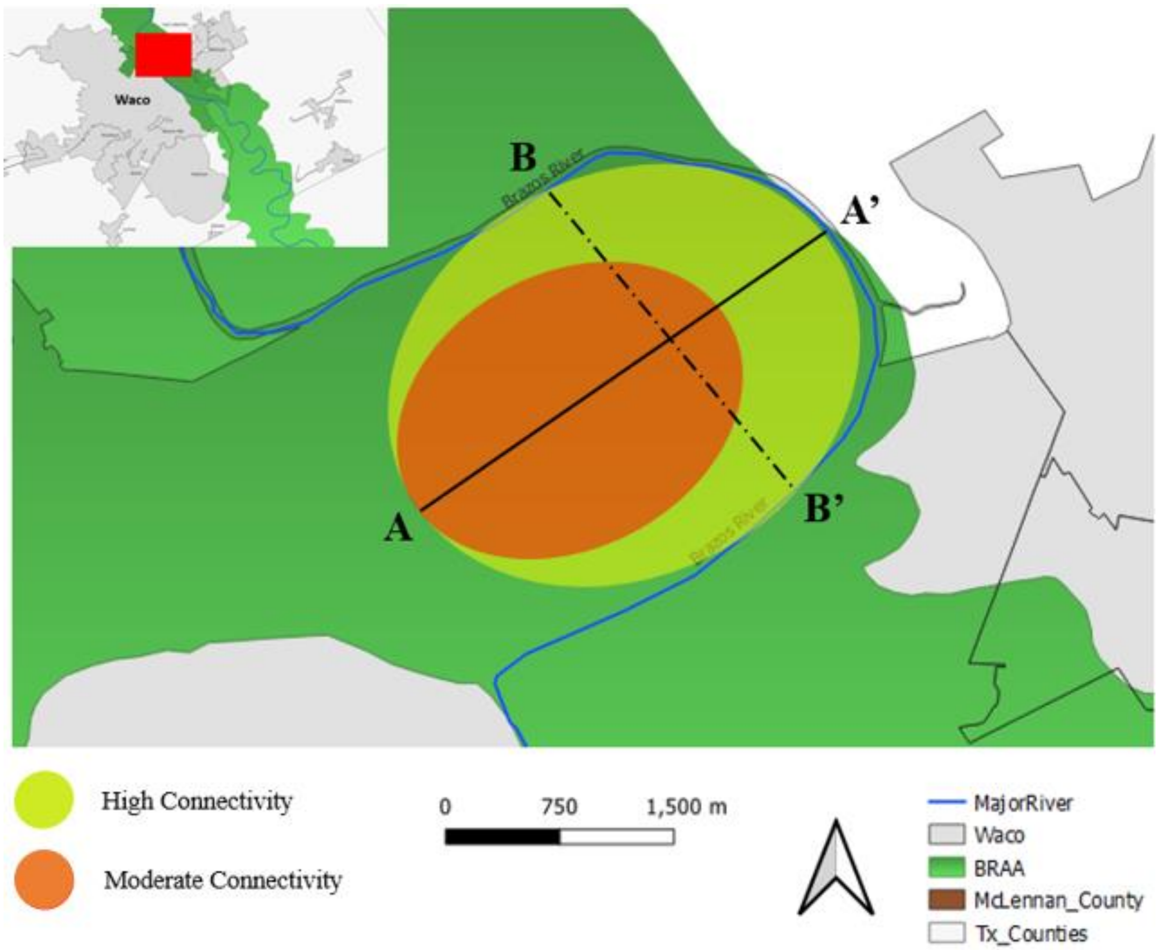

Figure 5.7. Connectivity estimations of Steinbeck Bend.

This high connectivity is based on the steep gradient, large proportion of coarse sediment, and its proximal distance to the river. The unique location of these transects also adds to the overall connectivity of the Brazos River Alluvium Aquifer to the Brazos River at this location. Being in the center of a river meander causes this portion of the aquifer to be surrounded by the Brazos River channel on three sides thus allowing for a much more connected aquifer. Flow distances are relatively short compared to other areas of the alluvium valley.

Conversely, the connectivity of Steinbeck Bend in the center of the meander is moderate to low. Saturated thickness of transects A - A' and B - B' on top of the bedrock plateau are dominated by a low gradient, small volume of saturated thickness, and location at a relatively extended distance from the river. These factors cause a low connectivity estimation under natural conditions for this portion of the alluvium aquifer (Figure 5.7). The closer the segment of an alluvium aquifer is to a stream, the greater the impact that stream has on the water table of the aquifer (Pinkus, 1987). Inversely, the further the aquifer is from the river, the response to changing river levels becomes more subdued. Pinkus (1987) observed that at approximately 2200 ft (670 m) from the river, there is little to no influence on monitor wells from changes in river levels.

Hirsch Dairy Cross Section D –D’

The Hirsch Dairy cross section is within the meandering portion of the Brazos River (Figure 4.1). The meandering portion is characterized by a lack of bedrock relief and a greater fraction of fine sediment compared to the incised portion. Hirsh Dairy has a more gradual gradient compared to other cross sections with a 2.4-meter elevation change from the distal portions of the alluvium aquifer to the Brazos River. This minimal gradient and abundance of intercalated clay baffles add significant groundwater travel time and creates shallow, confined segments of the aquifer (Figure 5.8).

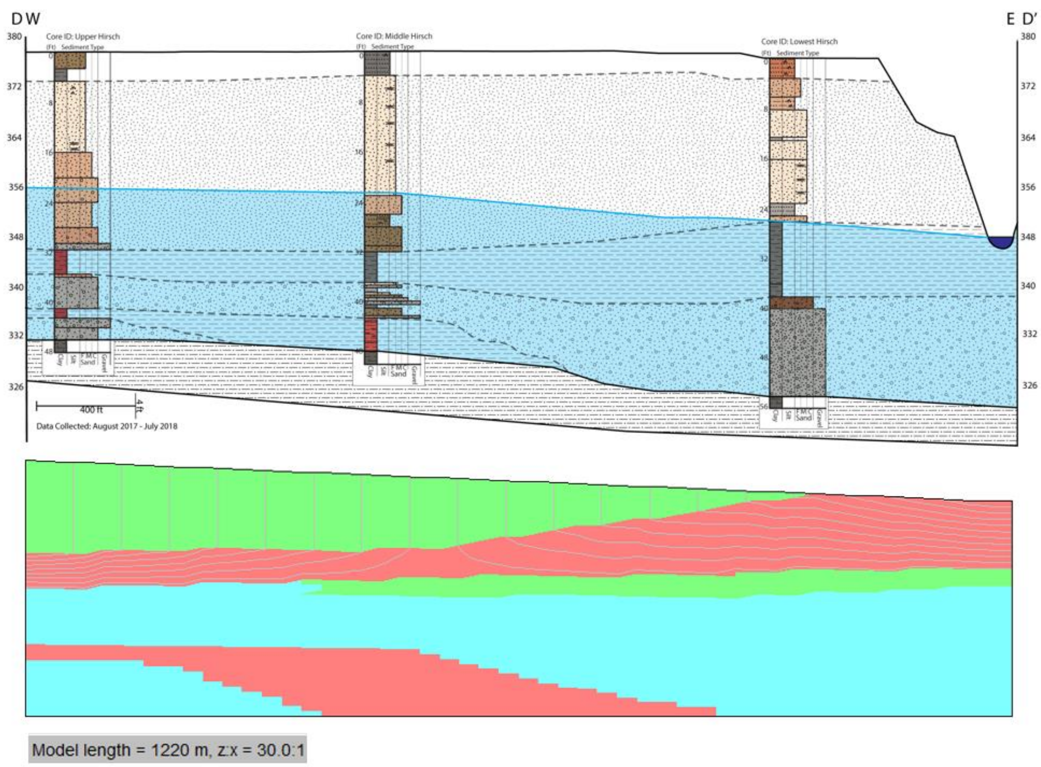

Figure 5.8. Transect D-D’ with Analogous TopoDrive Modeled Cross Section (modified from Jarvis 2019).

With two significant clay layers, the Hirsch Dairy transect can be partitioned into three segments: an unconfined zone above the first clay lens, a confined zone between the two clay lenses, and a tertiary confined layer below the second clay lens and above the bedrock boundary layer. The flowrates in the unconfined portion of the Hirsch Dairy cross section have flowrates that are tens of days in length. This segment is dominated by coarse sand (shown in green) (Figure 5.9). Flow paths that originate in the middle-confined portion of the aquifer have travel times in the range of years to tens of years. This is surprising considering the two segments of the aquifer have similar sediment types with gravel making up the majority of both.

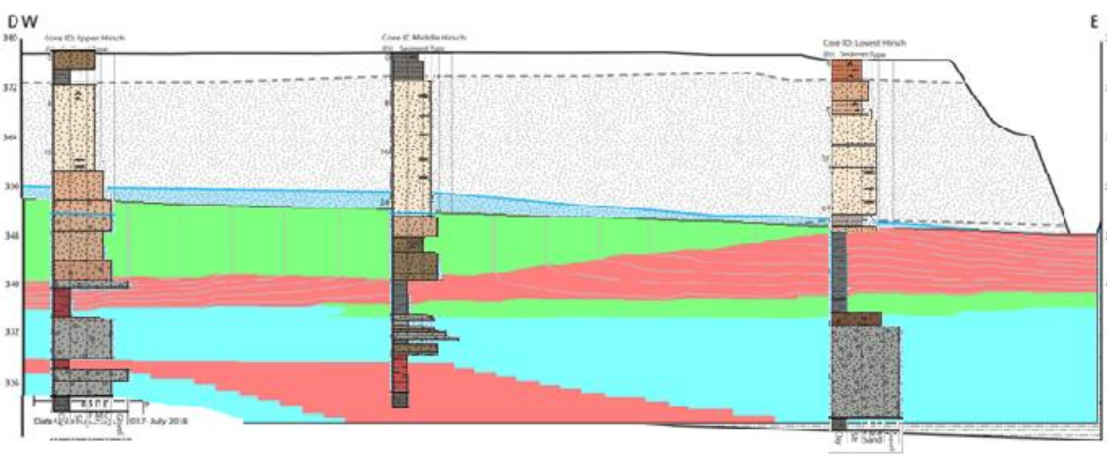

Figure 5.9. Transect D-D' with Overlaying TopoDrive Modeled Water Table (modified from Jarvis 2019).

The difference between the twos coarse grained sandy gravel flow units is the proportionally thick clay layers that limit vertical flow between them. The clay limits the hydraulic conductivity and lengthens travel times considerably. Even though much of the middle layer includes coarse sediment such as gravels and sands, the discharge point near the Brazos River is obstructed by clay (Figure 5.10). The flow paths are forced to travel through the clay, which in turn lengthens the travel times of all the water in the gravel. The clay near the discharge point forces the hydraulic conductivity of the gravels to be constrained by the hydraulic conductivity of the clay. The water can only move as fast as the sediment near the discharge point allows it. For the deeper confined portion, it takes water even longer to reach the river. This segment of the cross section is governed by two thick clay layers that limit flow and force water to move even more slowly through the aquifer. The deeper confined portion of Hirsch Dairy is dominated by lateral flow that is through the thickest portions of the clay (Figure 5.10).

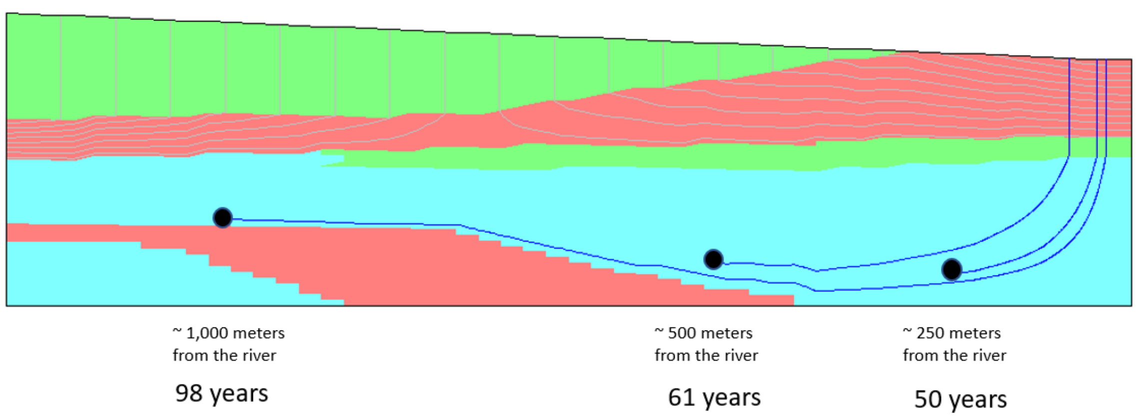

Figure 5.10. TopoDrive Modeling Interpretations of Transect D-D'.

Hirsch Dairy's Alluvium Aquifer Connectivity to The Brazos River

Hirsch Dairy is dominated by hydraulic variables that limit flow and reduce aquifer connectivity to the Brazos River. The gradient is low and there is minimal change in elevation from the distal portions of the alluvium aquifer to the Brazos River channel. The small hydraulic head difference between the two areas generates slower flow rates. This limiting factor is compounded by the high clay sediment fraction observed in cross section. Clay causes low hydraulic conductivity as they completely block the discharge point. Lack of a sizable gradient due to minimal bedrock relief and large expanses of floodplain limit connectivity (Figure 5.11).

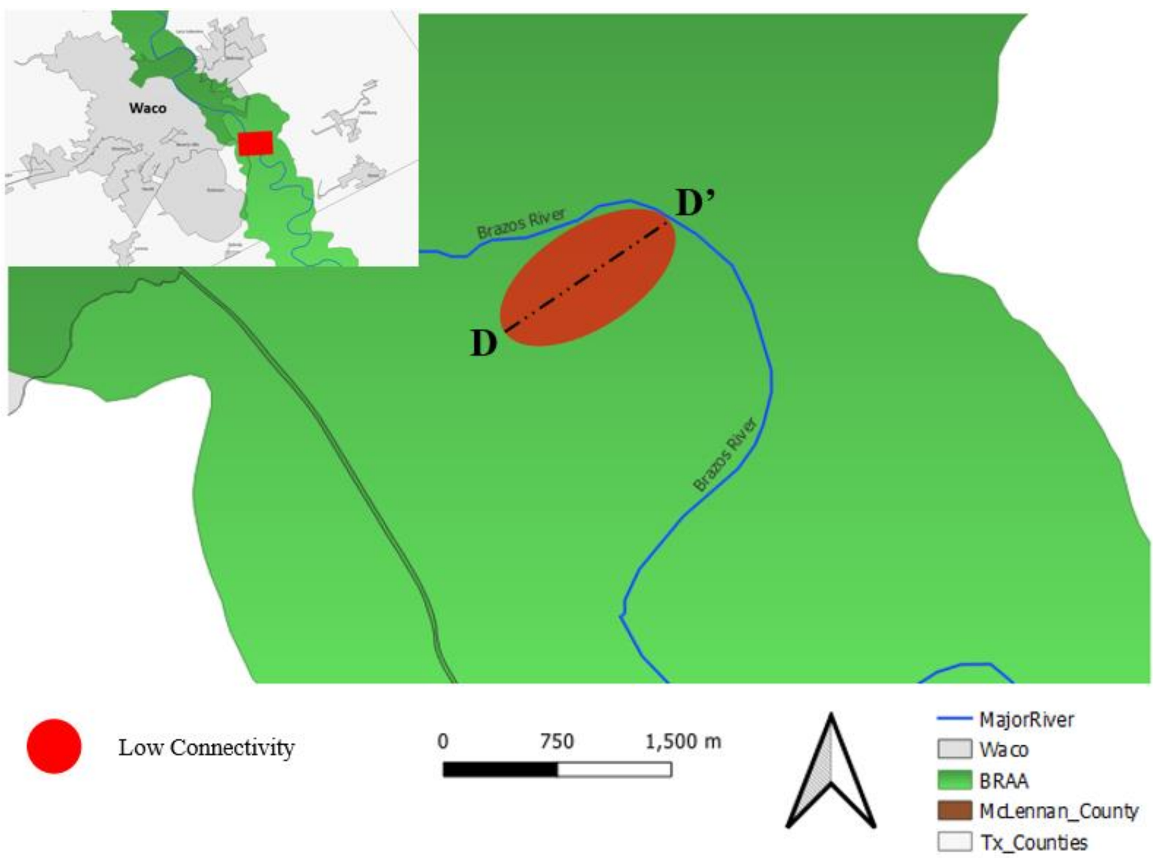

Figure 5.11. Map View of connectivity estimations of Steinbeck Bend.

Regional Cross Section 1

The regional model constructed by Cronin and Wilson (1967) has a less resolving lithologic interpretation for the Brazos River Alluvium Aquifer and broadly characterizes the aquifers entire lateral distance in the McLennan County region (Figure 5.12).

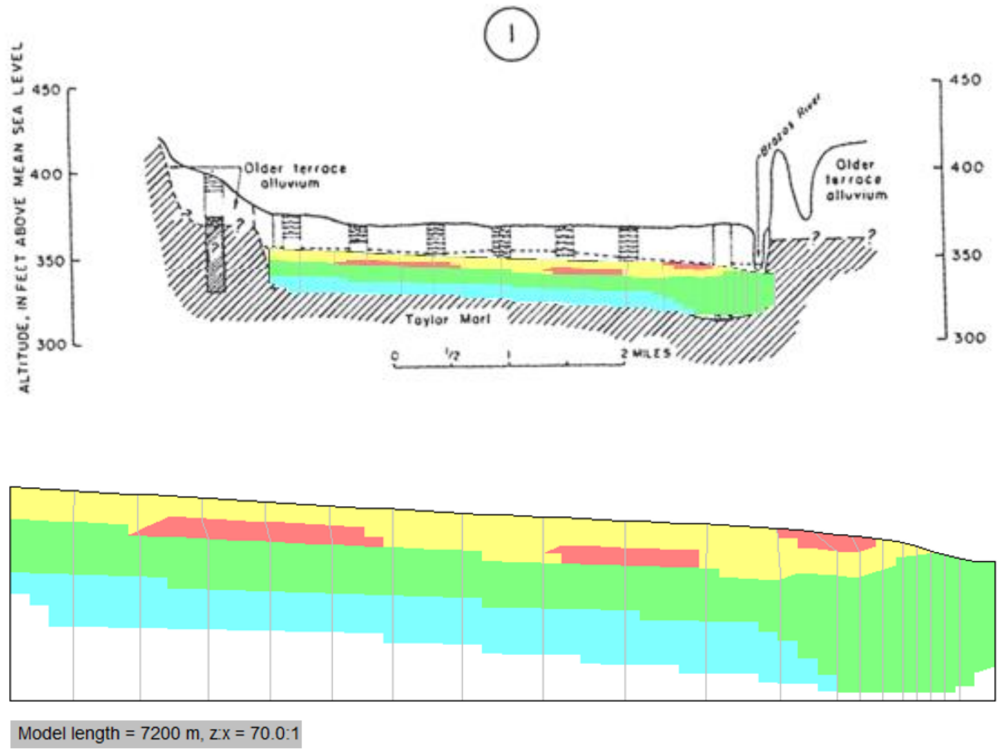

Figure 5.12. TopoDrive sediment interpretation of Transect 1 (modified from Cronin and Wilson 1967).

Most flow paths calculated by the model travel through the coarsest sediment fraction. The sandy gravels and coarse sands dominate the lower portions of the aquifer and allow for flow through high hydraulic conductivity sediment. The TopoDrive model calculates a time of 1.6 years for groundwater to make its way to the Brazos River channel from 250 meters away. Travel time is increased to approximately two years for areas at

500 meters away from the channel and 5 years from 1,000 meters from the channel (Figure 5.13). These travels times are influenced more by the regional gradient than they are the sediment types in the cross section. Even though flow is predominately through the coarsest fraction of sediment, the speed at which the groundwater flows is governed by the gradient. Cronin and Wilson (1967) document an approximately 7.5-meter drop in water table elevation from the distal portions of the aquifer to the river channel. This 7.5-meter drop in elevation is accompanied by a 7,220-meter lateral distance to the river and indicates a 0.001 gradient along the section. This gradient is extremely shallow and limits the hydraulic head in the aquifer. Limitations on hydraulic head have a direct impact on the travel times associated with the regional model (Figure 5.13).

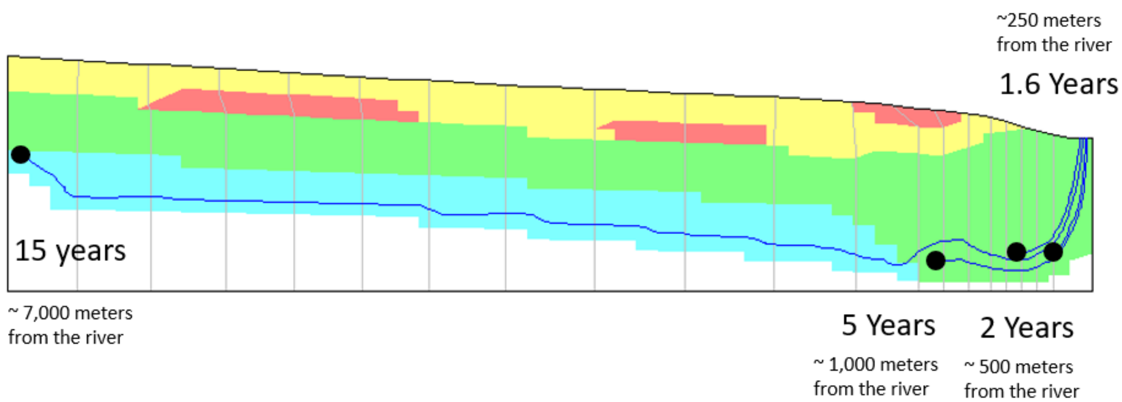

Figure 5.13. TopoDrive calculated travel times of Transect 1.

Regional Alluvium Aquifer Connectivity to The Brazos River

The connectivity to the Brazos River displayed by the regional model is based on two opposing hydrogeologic variables. The extremely low gradient of 0.001 limits the hydraulic head of the transect and governs flow. Conversely, the high percentage of sandy gravels and coarse sand allow for groundwater to easily flow throughout the aquifer. These two factors combine to form an estimated moderate connectivity for the aquifer to the Brazos River channel on a regional scale (Figure 5.14).

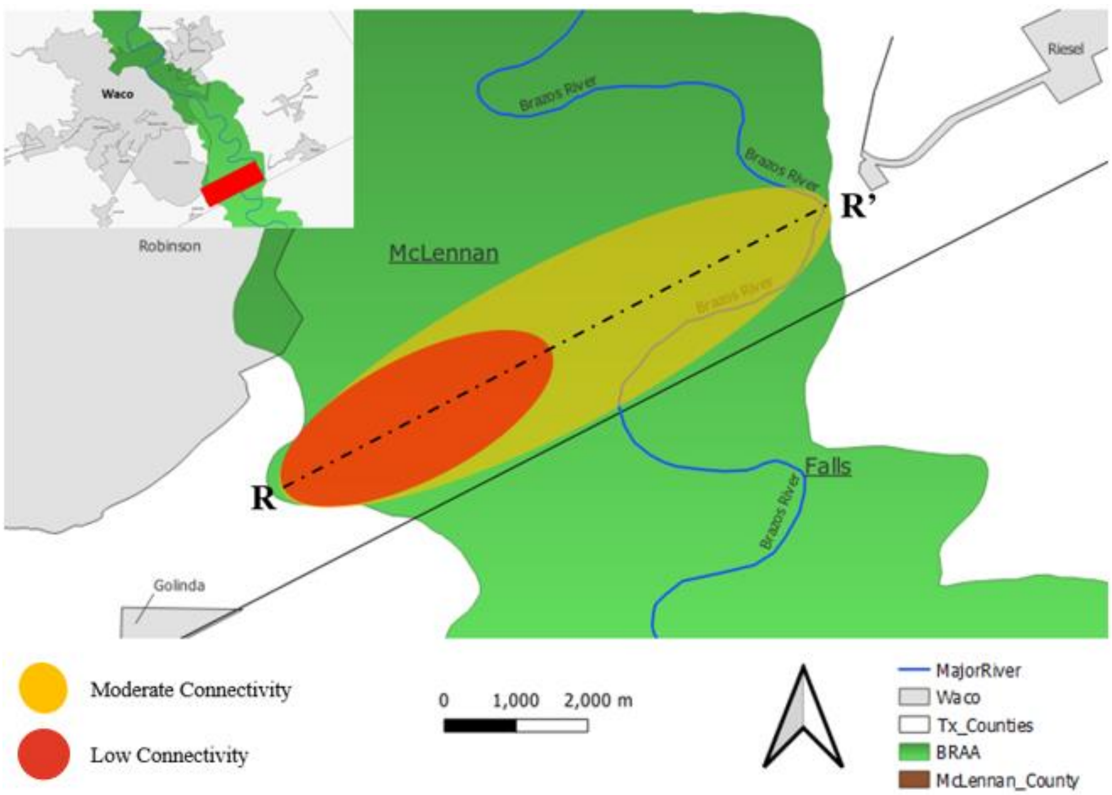

Figure 5.14. Regional Connectivity Estimations.

Brazos River Alluvium Aquifer Connectivity Based on Different Interpretations

Flow rates and paths within the Brazos River Alluvium are directly influenced by the interpretations made when considering the hydrogeological variables in the aquifer. Gradient and sediment hydraulic conductivity directly impact groundwater travel times while interpretations of sediment heterogeneity/homogeneity have minimal effect on the connectivity the alluvium has to the river depending upon the location of the sediments. Sediment heterogeneity/homogeneity does not have major effects on travel times within the model as groundwater preferentially flows through the coarsest sediment fraction. Complex lithologic features will not drastically affect flow rates as groundwater preferentially bypasses flow around areas of low hydraulic conductivity. This is demonstrated in cross section A-A' where groundwater flow paths preferentially flow beneath fine-grained clay layers to reach the Brazos River. Only when groundwater is forcibly constrained by low hydraulic conductivity sediments that block flow within the aquifer, will travel times be increased by aquifer heterogeneity. This phenomenon takes place at the Hirsch Dairy transect D – D' where clay layers block the Brazos River discharge point and add significant travel time to groundwater flow even though groundwater is predominantly moving through coarse sandy gravel. Clay and silt alluvium sediment assemblages that impede the discharge point limit flow and cause a compartmentalization effect between the aquifer and the river.

Mehmood, et al. (2022) uses conceptualized sediment distributions that both isolate and connect the aquifer to the river channel based on aquifer heterogeneity. The conceptual diagrams of Mehmood, et al. (2022) include two distinct categories: 1). aquifer sediments that restrict the groundwater with low K values blocking the discharge point, and 2).

aquifer sediment assemblages that have no blocking sediments. Conceptual models such as CM 4, CM 5, and CM 6 all show similar aquifer dynamics where clay blocks flow to the river and restrict effective groundwater flow to the river channel (Figure 5.15) e.g., Rhodes et al., (2017). In comparison, conceptual models such as CM 2, and CM 3 would have an assumed higher connectivity based on the ability of the groundwater to circumvent the intervals with abundant fine-grained clay.

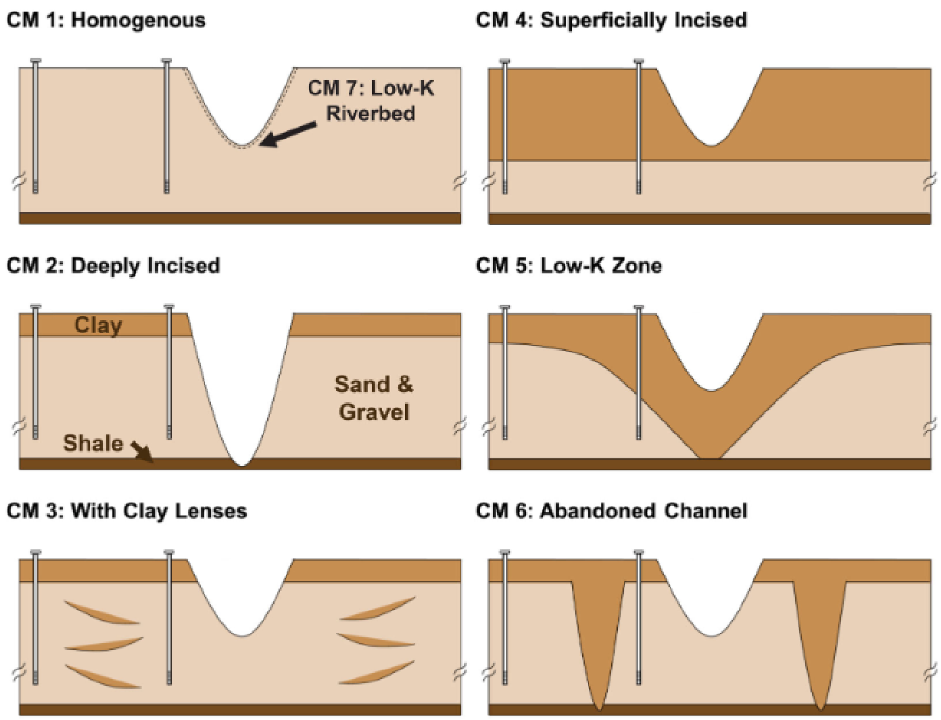

Figure 5.15. Conceptual Brazos River Alluvium sediment assemblages that could either compartmentalize or connect the aquifer to the Brazos River (Mehmood et al., 2022).

This study emphasizes the possibility that fine grained sediments found in large quantities around the channel have the greatest sedimentological impact on aquifer connectivity to the river. The various conceptual interpretations of the sediment distribution from Mehmood et al. (2022) have characteristics that either enable or limit flow to the Brazos River channel. These same characteristics are observed in the TopoDrive interpretations constructed from the data in Jarvis (2019). Hirsch Dairy transect D-D' follows the Low-K Zone interpretation of aquifer connectivity as flow paths through sandy gravel are blocked by large clay layers proximal to the river. This low K Zone drastically limits flow and adds significant travel time to the cross section (Figure 36). Steinbeck Bend transect A-A' fits the Mehmood et al. (2022) conceptual model for clay lenses. The clay lenses don't limit connectivity as groundwater circumvents the low K zone and travels through coarser sediment to reach the Brazos River channel. The regional transect matches the Mehmood et al. (2022) homogenous conceptual model because homogenous coarse sand dominate the sediment distribution close to the river (Figure 5.16).

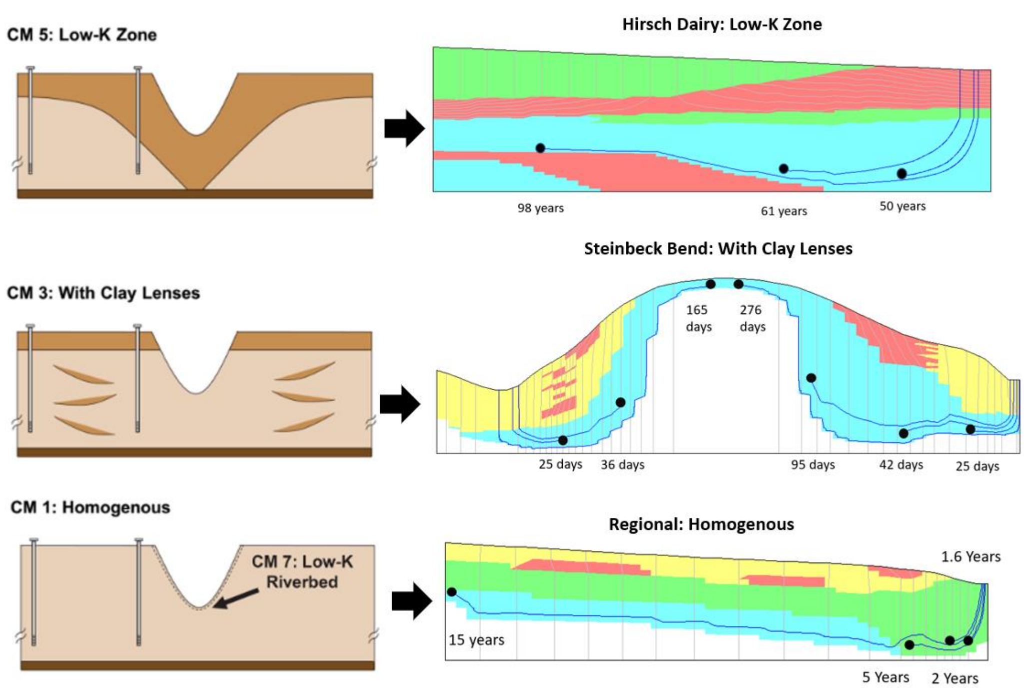

Figure 5.16. Conceptual Brazos River Alluvium sediment assemblages compared to TopoDrive modeled cross sections (modified from Mehmood et al., 2022).

Flow rates and flow paths are also directly impacted by the groundwater gradient in the aquifer. In the incised portion of the Brazos River, the gradient is steep and lateral alluvium distances are short. These two combined factors create comparatively fast travel times and high aquifer connectivity. In contrast, in the meandering portion of the river, gradients are low and lateral alluvium distances are long. These factors drastically increase travel times and cause low aquifer to river connectivity. Steep gradients indicate large hydraulic head differences between recharge and discharge areas and thus increase flow rates, whereas low gradients perform oppositely by limiting the head difference between the two regions. This makes the estimated water table levels of the Brazos Alluvium Aquifer a key component in travel time calculations. In regional depictions of the water table, bedrock features found in transects A-A’ and B-B’ can be lost. Regional descriptions of the aquifer sacrifice high resolution sediment descriptions and water table gradients for homogenous average water table levels. The basic sediment descriptions and a overall gradient create moderate aquifer to river connectivity estimations which are most likely accurate when compared with average travel times across the entire Brazos River Alluvium Aquifer.

CHAPTER SIX

Conclusions

Connectivity Relationships

I. The Brazos River Alluvium Aquifer (BRAA) has a variable and dynamic relationship with the Brazos River. The interconnection between the BRAA is variable because the connection is affected by the sediment type and distribution. The aquifer and river interactions are dynamic because recharge, river level, pumping and land use activities affect gradients altering groundwater travel time and flow paths.

II. The connectivity of the aquifer has a correlation to the upstream and downstream portions of the aquifer. The incised portion of the aquifer occurs upstream from the City of Waco. This portion of the aquifer generally has a steeper gradient to the river channel causing increased groundwater flow rates in many areas.

III. The meandering portion of the aquifer occurs downstream from the City of Waco. Here the groundwater gradients are lower than many of the gradients in the incised portion above Waco. In addition, the sediments are finer, and the floodplain is wider in the meandering portion of the BRAA compared to the incised portion. These characteristics result in slower groundwater flowrates and longer storage time in the aquifer before reaching the river.

IV. Heterogeneity in aquifer sediments usually adds length to the groundwater travel times. However, heterogenous sediment distribution does not always lengthen travel time as groundwater flow paths attempt to avoid low K zones when possible.

V. Where the river channel occurs entirely within clay sediments the river and aquifer are essentially isolated from each other. The confinement of clay, low gradients, and distance from the river play the largest roles in limiting connectivity to the Brazos River channel.

VI. Maximum groundwater travel times from boundaries to the river channel range from less than a year to more than 100 years depending upon the sediment type and distribution, the groundwater gradient, and the width of the floodplain.

Recommendations

I. Management of the Brazos River Alluvium Aquifer should prioritize the scale of the aquifer interpretation as a key variable. Aquifer management for the whole aquifer is very different than managing with a landowner. The resolution for aquifer hydrogeologic data should match the scale of management practices to ensure the most effective management of the aquifer.

II. Time is an important variable when considering aquifer management. The Brazos River Alluvium Aquifer is a dynamic system that is affected on both relatively short timescales as well as longer periods of time. It will be necessary to conduct further investigations that quantify recharge, discharge, and groundwater availability throughout the aquifer under transient conditions.

APPENDICES

APPENDIX A

Table A.1. Hydraulic conductivity of sediment types (modified from Duffield 2019).

Soil Description	Hydraulic Conductivity, k ft/s Minimum	ft/s Maximum	m/s Minimum	m/s Maximum
Fine Sand	6.5E-07	6.55E-04	2.00E-07	2.00E-04
Medium Sand	2.95E-06	1.64E-03	9.00E-07	5.00E-04
Corse Sand	2.95E-06	1.97E-02	9.00E-07	6.00E-03
Sand; Clean; Good Aquifer	3.28E-05	3.28E-02	1.00E-05	1.00E-02
Sand/Gravelly Sand; Poorly Graded; Little to No Fines	8.37E-05	1.76E-03	2.55E-05	5.35E-04
Sand/Gravelly Sand; Well Graded; Little to No Fines	3.28E-08	3.28E-06	1.00E-08	1.00E-06
Silty Sand	3.28E-08	1.64E-05	1.00E-08	5.00E-06
Clayey Sand	1.80E-08	1.80E-05	5.50E-09	5.50E-06
Sand/Gravel; Uniform	1.31E-02	1.31E+00	4.00E-03	4.00E-01
Sand/Gravel; Well Graded; No fines	1.31E-04	1.31E-02	4.00E-05	4.00E-03
Gravel	9.84E-04	9.84E-02	3.00E-04	3.00E-02
Gravel/Sandy Gravel; Poorly Graded; Little to No Fines	1.64E-03	1.64E-01	5.00E-04	5.00E-02
Silty Gravel/Silty Sandy Gravel	1.64E-07	1.64E-05	5.00E-08	5.00E-06

Soil Description	Hydraulic Conductivity, k			
	ft/s		m/s	
	Minimum	Maximum	Minimum	Maximum
Silt; Compacted	2.30E-09	2.30E-07	7.00E-10	7.00E-08
Inorganic Clay/Silty Clay/Sandy Clay; Low Plasticity	1.60E-09	1.64E-07	5.00E-10	5.00E-08
Organic Clay/Silty Clay; Low Plasticity	1.64E-08	3.28E-07	5.00E-09	1.00E-07
Marine Clay; Unweathered	2.62E-12	6.56E-09	8.00E-13	2.00E-09
Organic Clay; High Plasticity	1.60E-09	3.28E-07	5.00E-10	1.00E-07
Inorganic Clay; High Plasticity	3.00E-10	3.28E-07	1.00E-10	1.00E-07
Clay	3.28E-11	1.54E-08	1.00E-11	4.70E-09
Clay; Compacted	3.28E-10	3.28E-09	1.00E-10	1.00E-09
Limestone / Dolomite	3.28E-09	1.97E-05	1.00E-09	6.00E-06
Sandstone	9.84E-10	1.97E-05	3.00E-10	6.00E-06
Shale	3.28E-13	6.56E-09	1.00E-13	2.00E-09
Igneous/Metamorphic Rock; Fractured	2.62E-08	9.84E-04	8.00E-09	3.00E-04
Granite; Weathered	1.08E-05	1.71E-04	3.30E-06	5.20E-05
Igneous/Metamorphic Rock; Unfractured	9.84E-14	6.56E-10	3.00E-14	2.00E-10

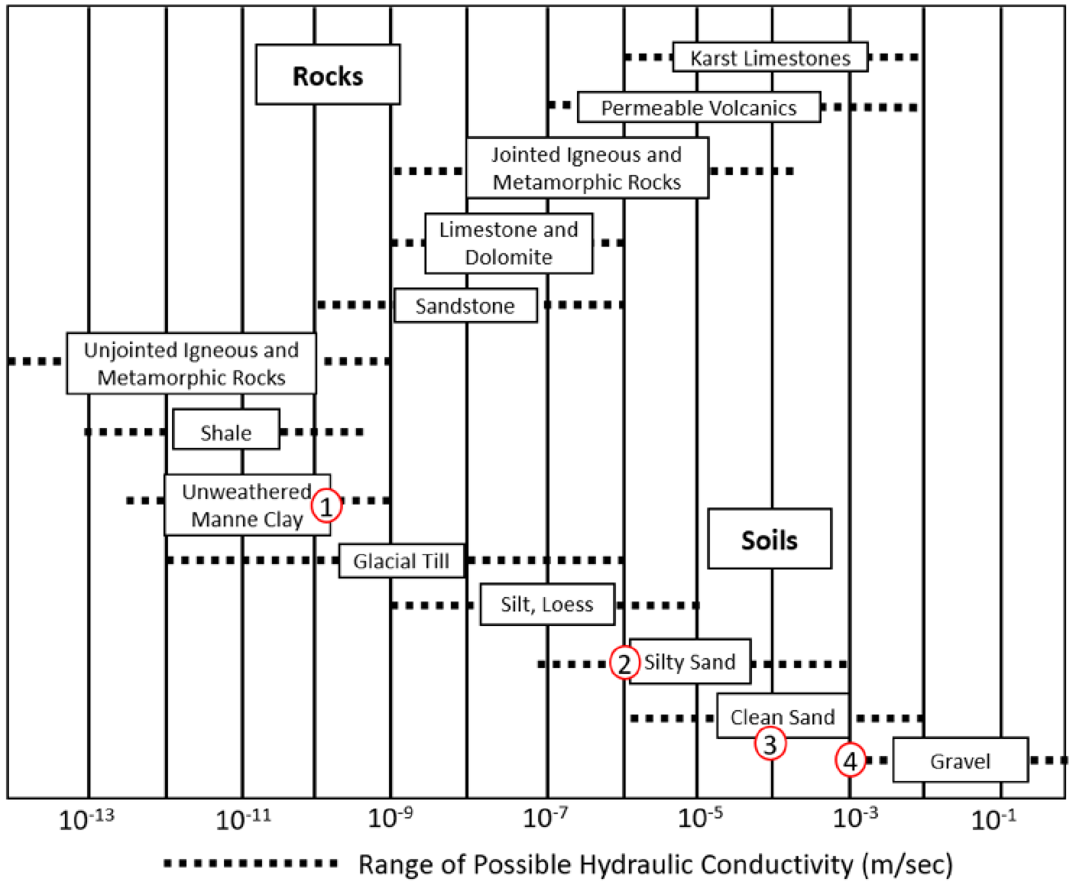

Figure A.1. Hydraulic conductivity values: The red circles indicate where sediment hydraulic conductivity values used in this study are compared to historical data. 1: Clay, 2: Fine Sand, 3: Coarse Sand, 4: Sandy Gravel. (Modified from Freeze and Cherry, 1979).

APPENDIX B

Table B.2. Travel Times from the aquifer to the river based on distance.

Transect	**250 Meters**	**500 Meters**	**1,000 Meters**
A-A’	25 days	39 days	130 days
B-B’	31 days	62 days	92 days
C-C’	14 days	34 days	106 days
D-D’	50 years	61 Years	98 years
E-E’	131 days	1.2 Years	5 years
Regional Cross Section	1.6 Years	2 Years	4.7 Years

Table B.3. Flow paths measured in meters per day.

	Steinbeck Bend A-A'	Steinbeck Bend B-B'	Hirsch Dairy D-D'	Regional Cross Section
Flow Path	(From Left to Right on Transect)			
1	10 m/d	2.1 m/d	.028 m/d	.68 m/d
2	13.9 m/d	2.9 m/d	.025 m/d	.68 m/d
3	6 m/d	10.9 m/d	.014 m/d	.54 m/d
4	4.7 m/d	8.2 m/d		1.27 m/d
5	10.5 m/d	8 m/d		
6	11.9 m/d			
7	10 m/d			

APPENDIX C

Supplemental Cross Sections

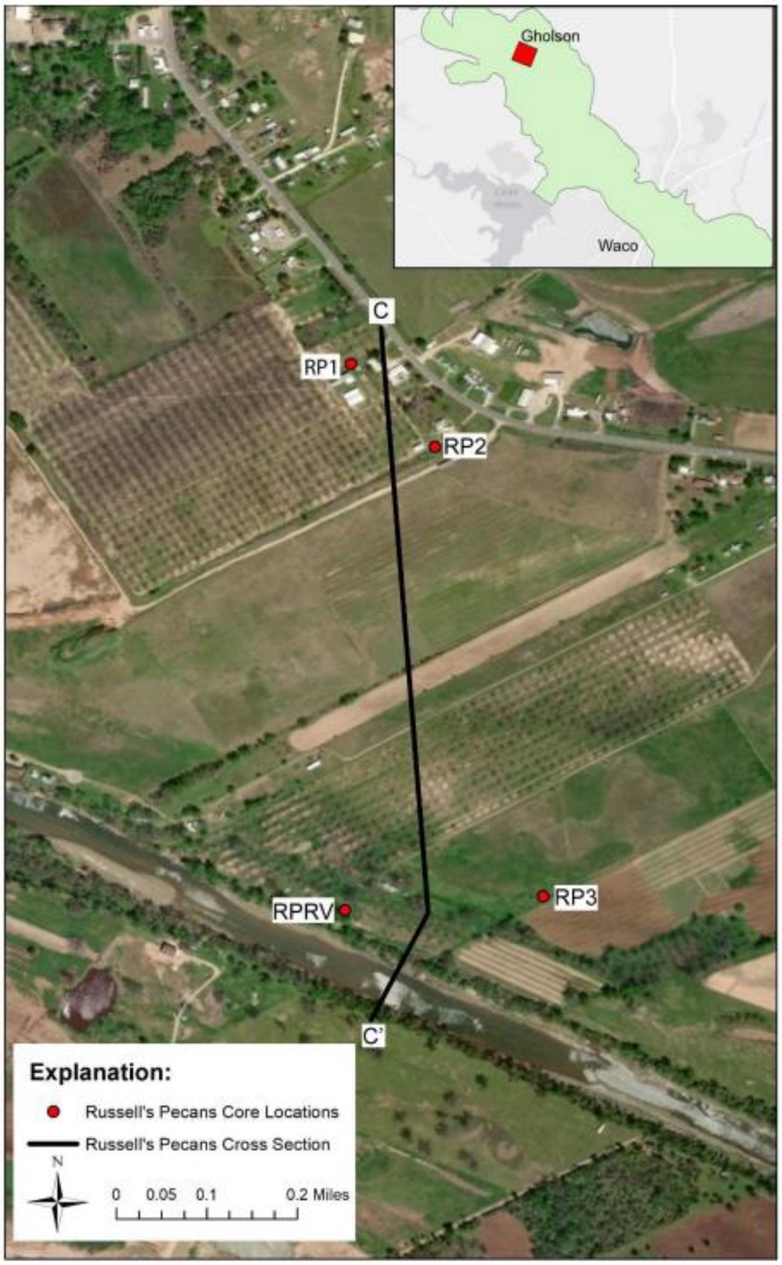

Figure C.1: Transect C-C' Map View

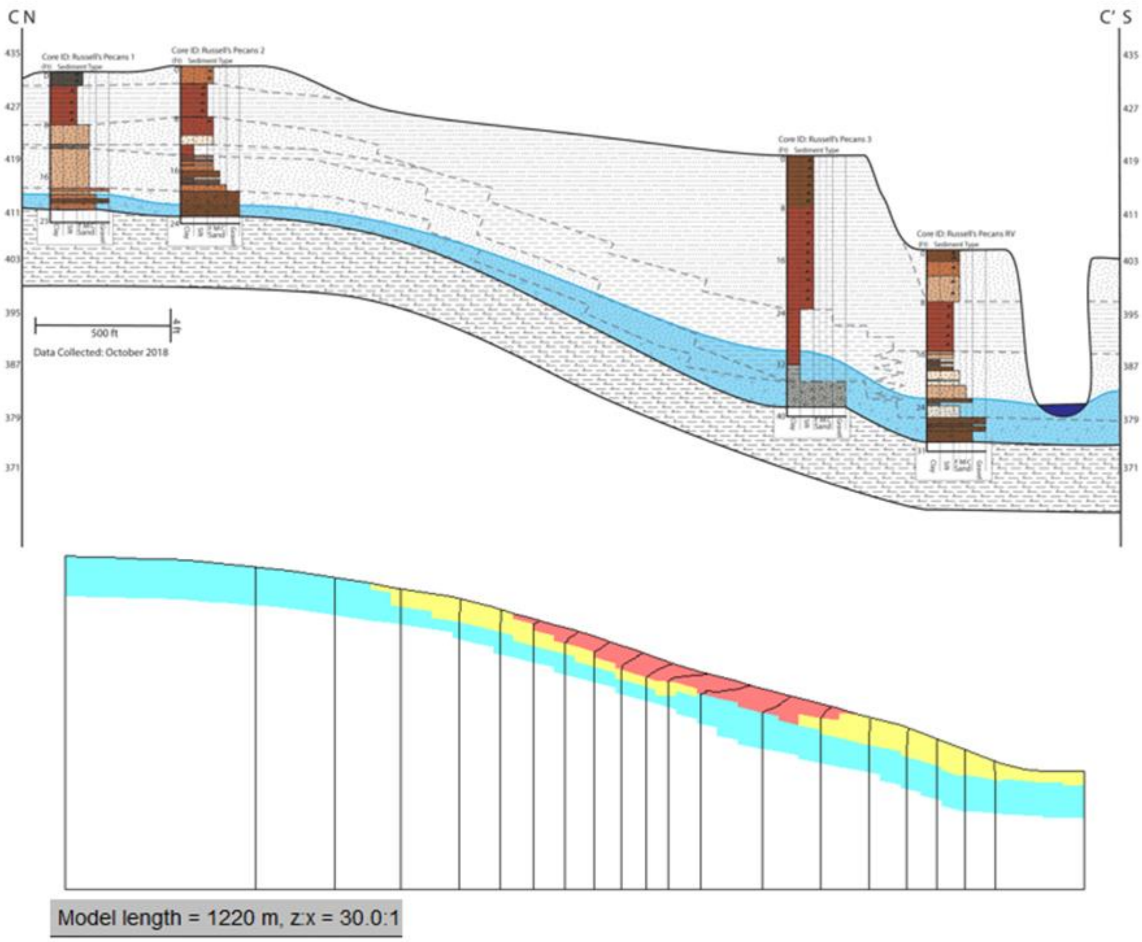

Figure C.2: Transect C-C' with Analogous TopoDrive Modeled Cross Section.

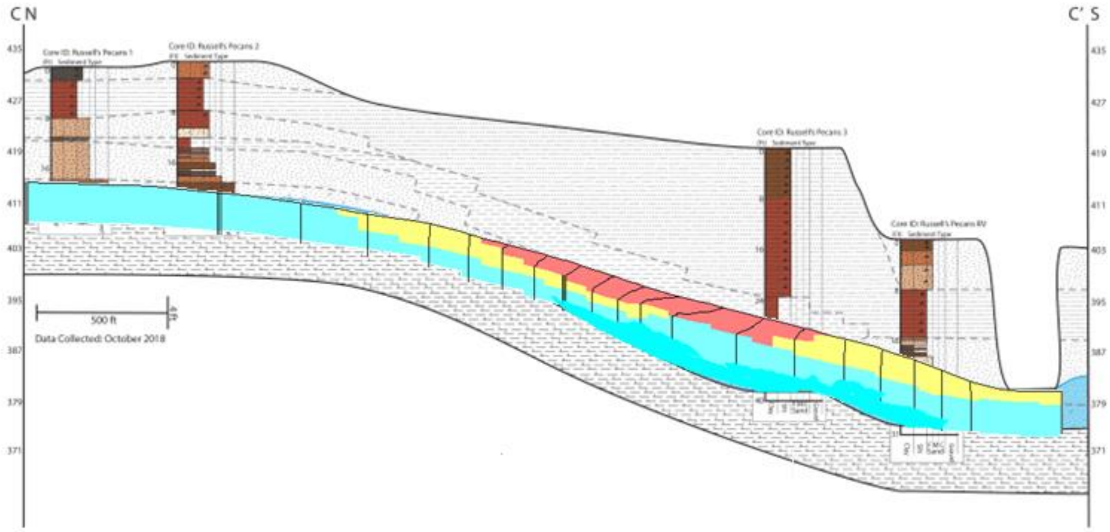

Figure C.3: Transect C-C'' with Overlaying TopoDrive Modeled Water Table.

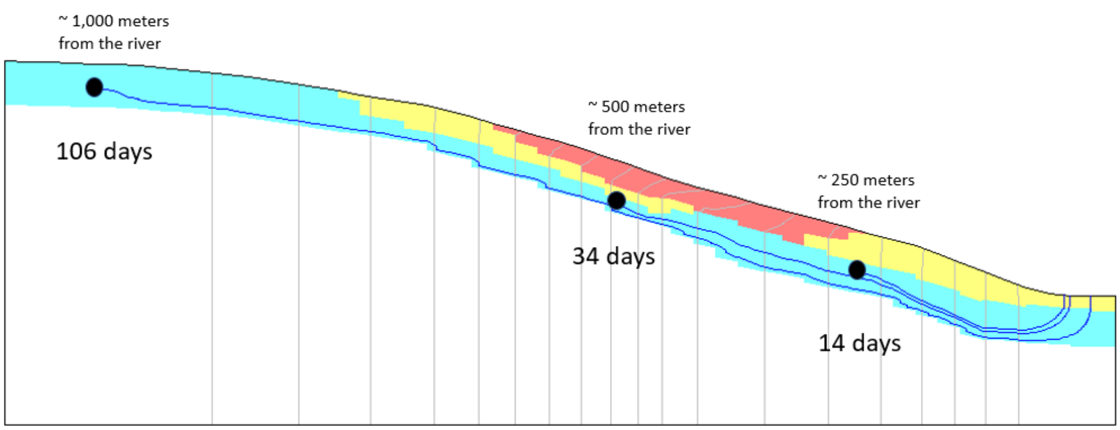

Figure C.4: TopoDrive Modeling Interpretations of Transect C-C'.

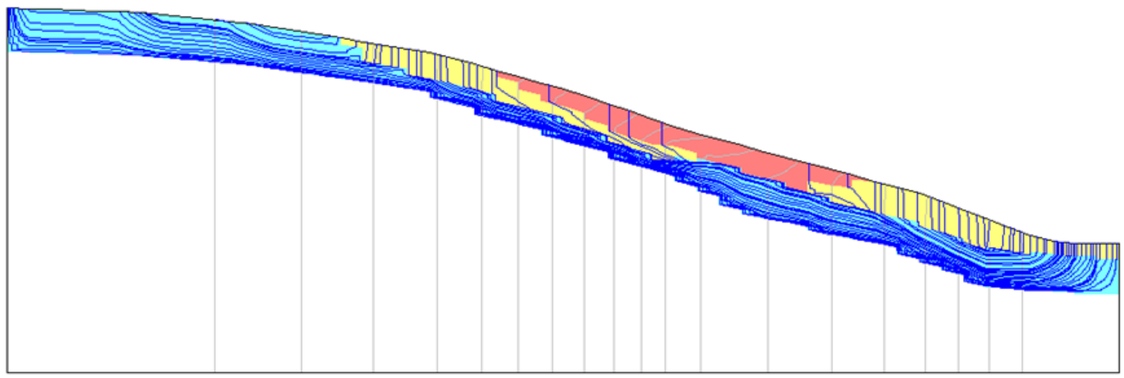

Figure C.5 Flow path interpretation C-C’

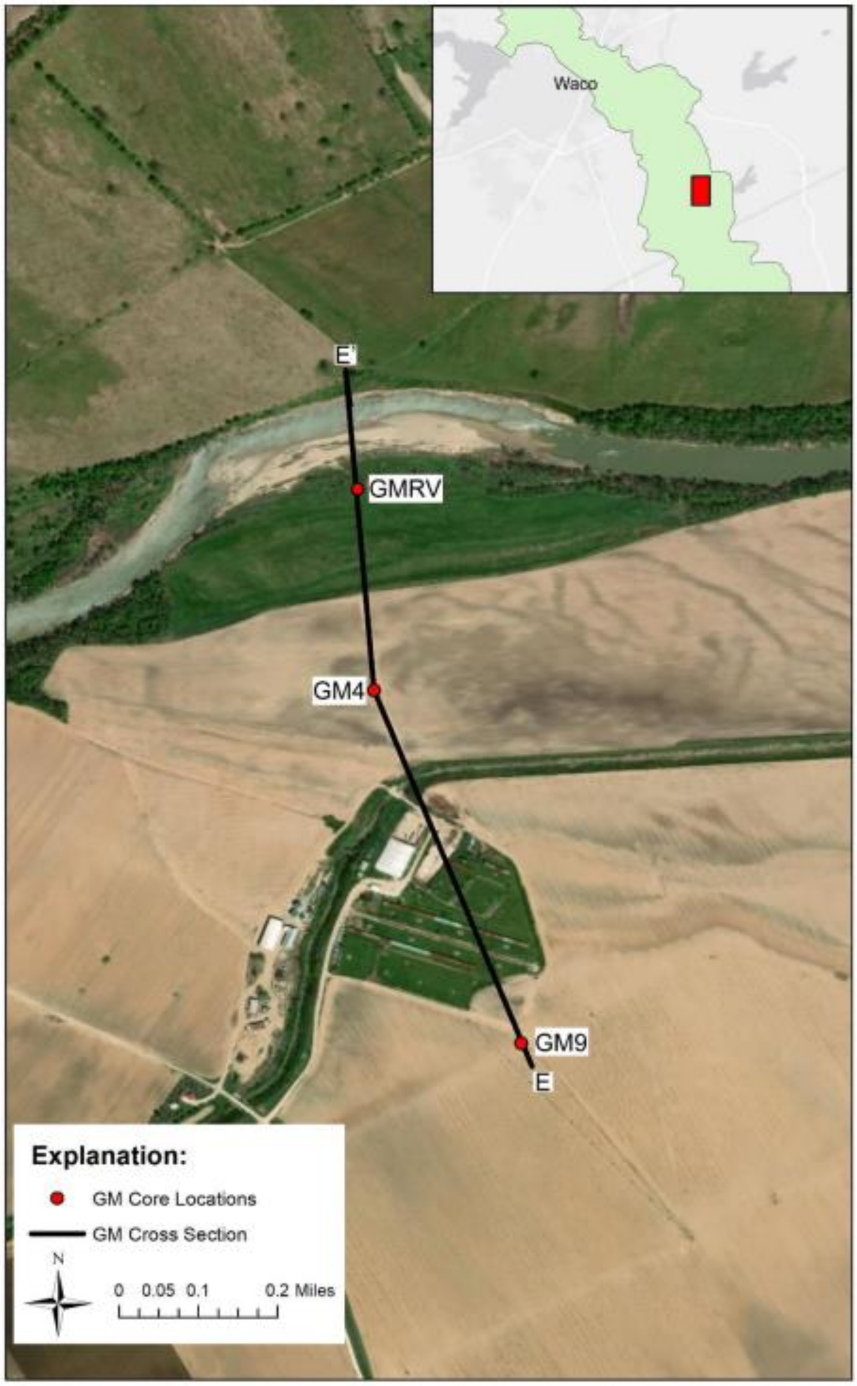

Figure C.6: Transect E-E' Map View

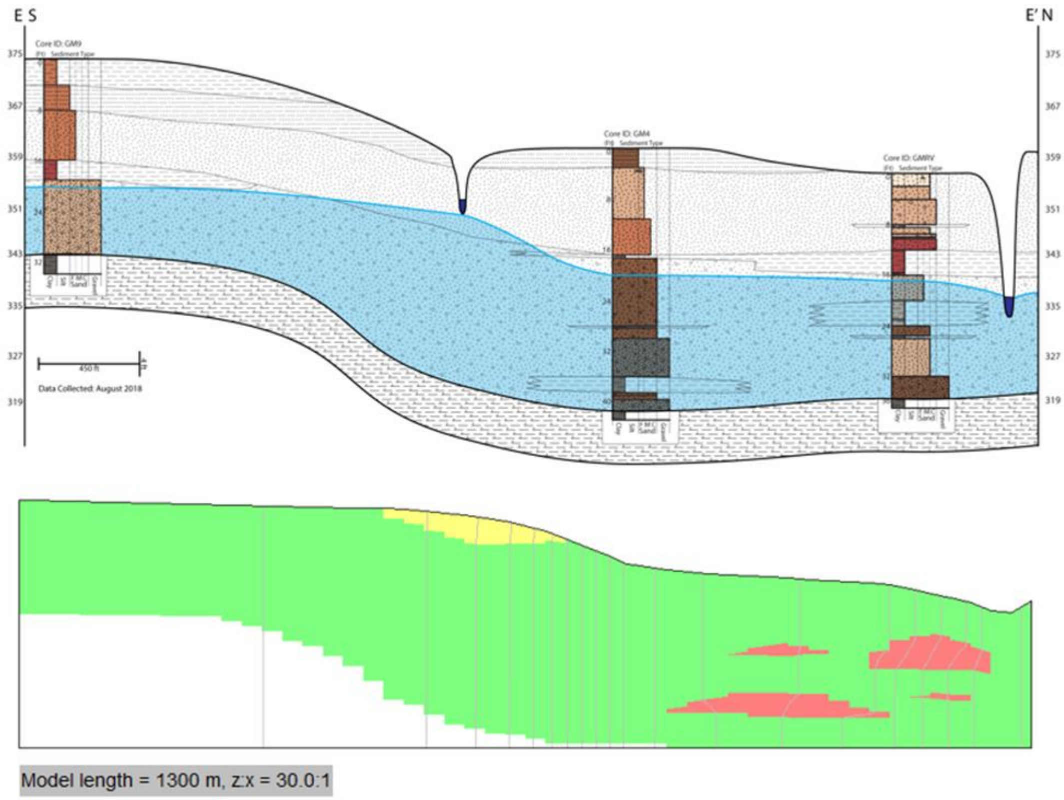

Figure C.7: Transect E-E’ with Analogous TopoDrive Modeled Cross Section

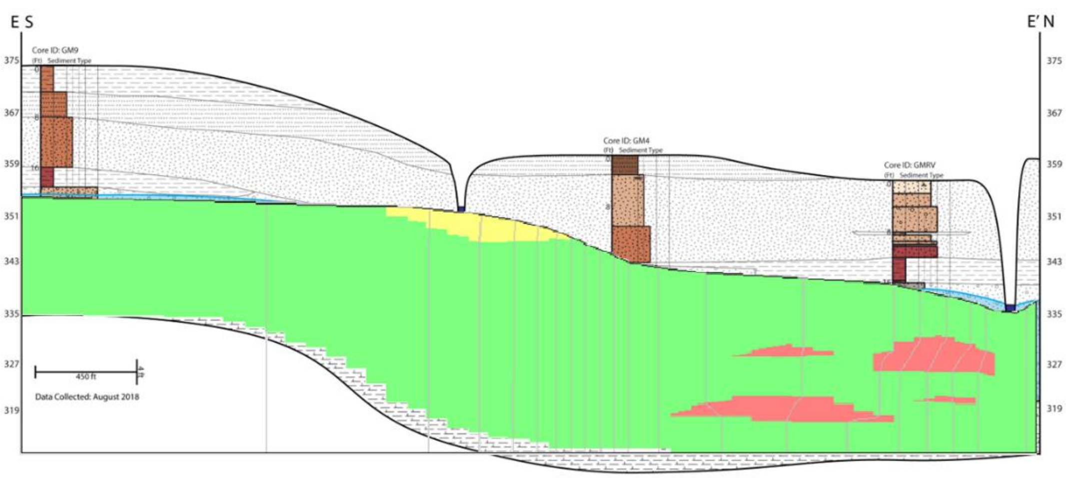

Figure C.8: Transect E-E’ with Overlaying TopoDrive Modeled Water Table

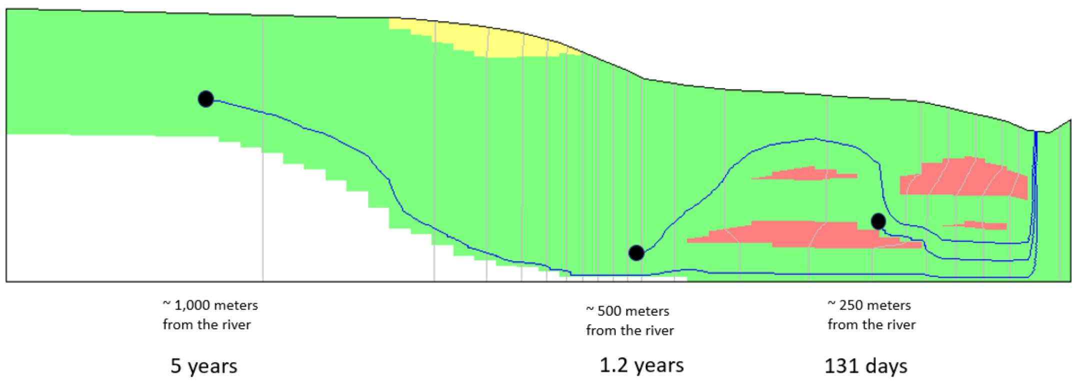

Figure C.9: TopoDrive Modeling Interpretations of Transect E-E'

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