ABSTRACT

Developing a Geospatial Model for Analysis of a Dynamic, Heterogeneous Aquifer: The Brazos River Alluvium Aquifer, Central Texas

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The Brazos River Alluvium aquifer extends from Bosque County to Fort Bend County and is one of 21 minor aquifers in Texas. In the past, this aquifer has mainly served as a source of irrigation water. However, increasing demands for water, especially in the Waco area, has renewed interest in this under-utilized source of shallow groundwater. Shallow, unconfined aquifers such as the Brazos River Alluvium aquifer present unique management challenges due to their lithologic heterogeneity, fluctuating saturated thickness, and proximity to surface sources of contamination. In this study, a geospatial approach was used to compile and analyze various datasets to model aquifer thickness and available water in the northern reach of the Brazos River Alluvium aquifer.

Developing a Geospatial Model for Analysis of a Dynamic, Heterogeneous Aquifer:
The Brazos River Alluvium Aquifer, Central Texas

by

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LIST OF ABBREVIATIONS

GAM ………………………	Groundwater Availability Model
GCD ……………………….	Groundwater Conservation District
NED ……………………….	National Elevation Data
IDW ……………………….	Inverse Distance Weighting
STGCD ………………….....	Southern Trinity Groundwater Conservation District
Texas BEG …………….…...	Texas Bureau of Economic Geology
TCEQ ..…………………….	Texas Commission on Environmental Quality
TNRIS ……………………..	Texas Natural Resources Information System
TWDB ……………………..	Texas Water Development Board
USGS ...……………………	United States Geological Survey
WIID ...…………………….	Water Information Integration and Dissemination System

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CHAPTER ONE

Introduction

Background

Alluvial aquifers are becoming more important groundwater resources as water levels in confined aquifers continue to decline from extensive use. In Central Texas, the Brazos River Alluvium aquifer represents a potential water resource that could supplement current water resources as demand increases due to a growing populace along the I-35 corridor.

Since the late 1800s, the groundwater needs of the region have been supplied primarily by the Trinity aquifer, a confined aquifer where pumping has resulted in significant water-level declines, particularly near populated areas such as Waco (Bené and others, 2004). In McLennan County, the Trinity aquifer is comprised primarily of two water-bearing units, the Hensell and the Hosston. By 1970, cones of depression had formed in both units in the Waco area (Figure 1). Between early 1960s and late 1980s, groundwater levels in the Hensell and the Hosston declined over 200 feet, falling at a rate of 10 feet or more per year (Figure 2). The groundwater availability model (GAM) for the Trinity aquifer predicts a future reduction in pumpage which could result in recovery of hundreds of feet of artesian pressure; however development is projected to continue along the IH-35 corridor, suggesting that the Trinity aquifer will continue to be utilized at existing or greater levels and water levels will continue to decline (Bené and others, 2004).

(a)

(b)

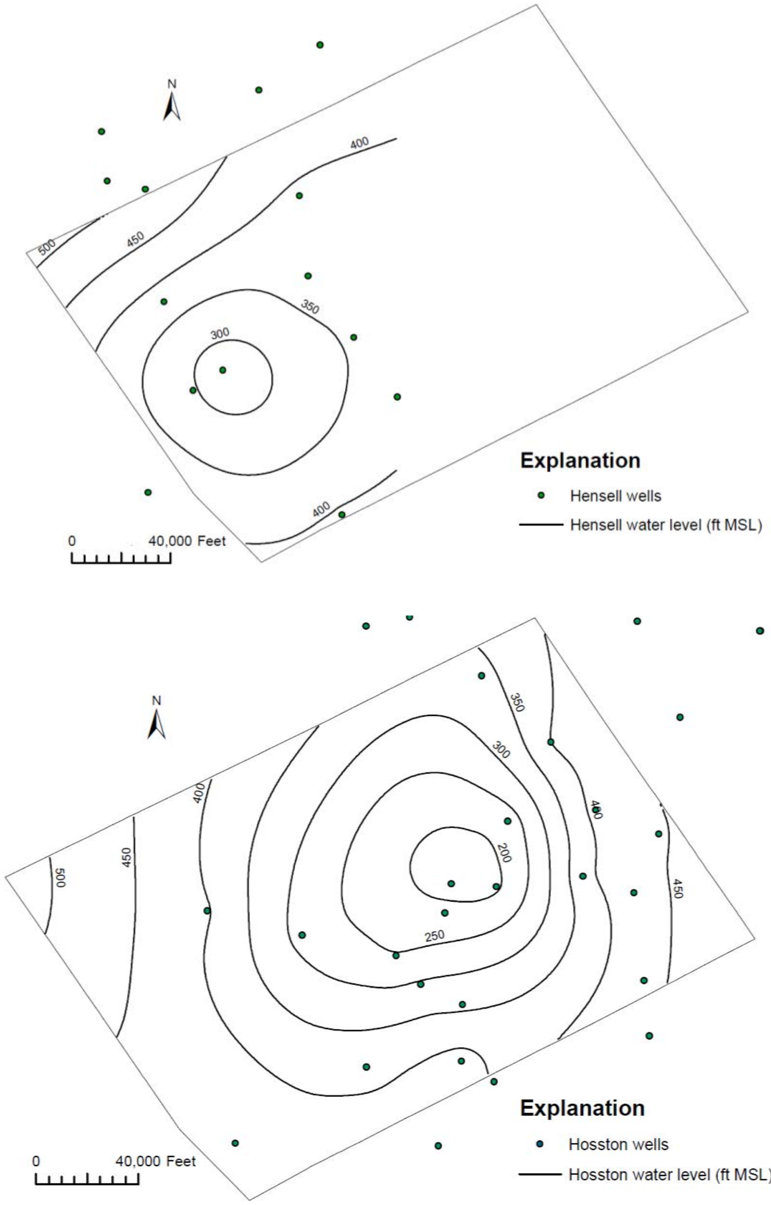

Figure 1. Contour maps showing 1970 water level for the Hensell (a) and Hosston (b) units comprising the Trinity aquifer (from Diehl, 2012). Contour interval is 50 feet.

Alternately, area residents, businesses and industry are using surface reservoirs and streams to satisfy water needs. However, surface water requires additional treatment prior to municipal distribution which can be costly. Additionally, surface water is not available in all areas of demand.

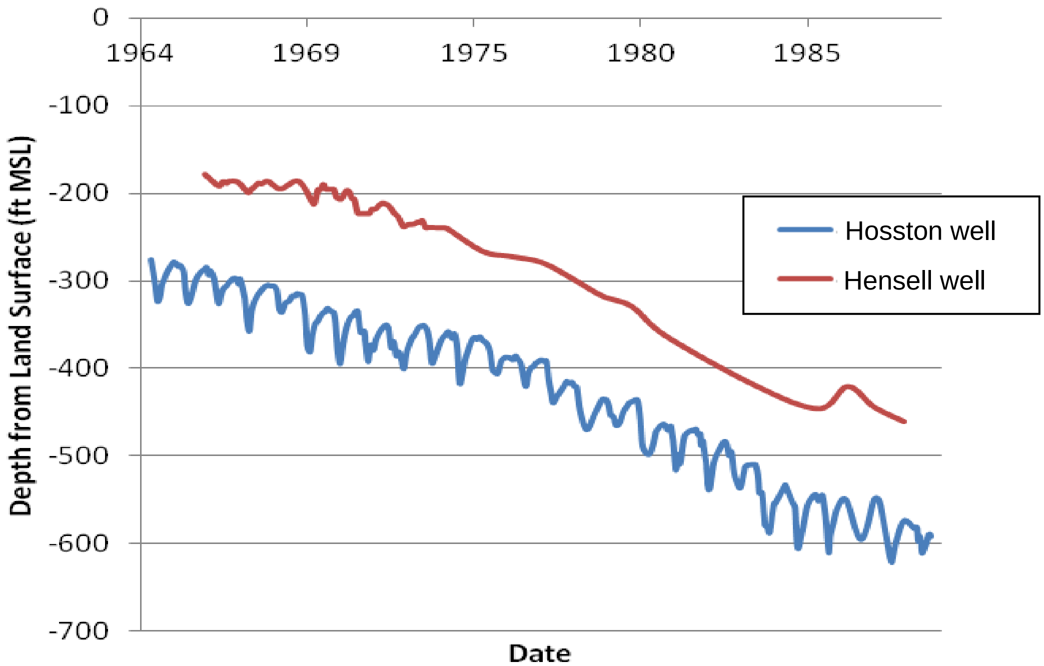

Figure 2. Hydrograph for two wells completed in the Hensell (Well 4030603) and Hosston (Well 4031802) units in the Waco area. Both show water level declines of over 10 feet per year, and a decline of about 300 feet over 25 years (from Diehl, 2012).

Shallow unconfined aquifers are an intermediary source of groundwater in terms of requiring treatment. Drilling wells that tap shallow aquifer water is less costly than completing wells in a deep, confined aquifer like the Trinity. At the same time, shallow groundwater requires less treatment infrastructure than surface water since the groundwater has already been filtered through the top layers of soil and sediment. Additionally, shallow unconfined aquifers adjacent to bodies of water lend themselves to bank infiltration, the process by which a nearby pumping well induces surface water flow through bank sediments, thereby also forcing the water through a natural filter. The utility of shallow unconfined aquifers in bank infiltration is particularly relevant to Central Texas, where 88 cases of cryptosporidiosis were confirmed in summer 2011 (KWTX, 2011). Several studies have demonstrated the efficacy of bank infiltration on the removal of *Cryptosporidium parvum* (Faulkner and others, 2010; Weiss and others, 2005; Metge and others, 2010). However, unconfined aquifers such as the Brazos River Alluvium aquifer are more vulnerable to physical degradation and contamination from surficial sources than confined aquifers. In addition, the section of Brazos River Alluvium aquifer in McLennan County, especially south of Waco, has been impacted by development and floodplain sand and gravel mining. Development covers aquifer surface with impervious surfaces that reduce recharge, while sand and gravel mining remove aquifer materials, reducing production potential. The combination of sand and gravel mine pits and development also resulted in landfills sited in old mine pits which have impacted the aquifer.

Groundwater in Texas is managed at a County or multi-County level by groundwater conservation districts. The counties included in the study area belong to different groundwater conservation districts (Figure 3). The Brazos River Alluvium aquifer begins north of Waco in Bosque and Hill Counties, which belong to the Middle Trinity Groundwater Conservation District and Prairielands Groundwater Conservation District respectively. The Brazos River Alluvium aquifer is currently not in the management plan of either conservation district. In McLennan County, the Southern Trinity Groundwater Conservation District has jurisdiction over the groundwater of the Trinity aquifer as well as the Brazos River Alluvium aquifer. Falls County is currently not part of a groundwater conservation district.

As urban, agricultural, and industrial development continue throughout the Brazos river basin, information from groundwater studies will be important to aid groundwater conservation districts in developing management plans and thresholds for water well permits completed in the aquifer.

The first thorough characterization of the Brazos River Alluvium aquifer was conducted by Cronin and Wilson (1967). Their report area encompassed the alluvium between Whitney Dam and Richmond, Texas, and established the baseline hydrogeological parameters of the Brazos River Alluvium aquifer.

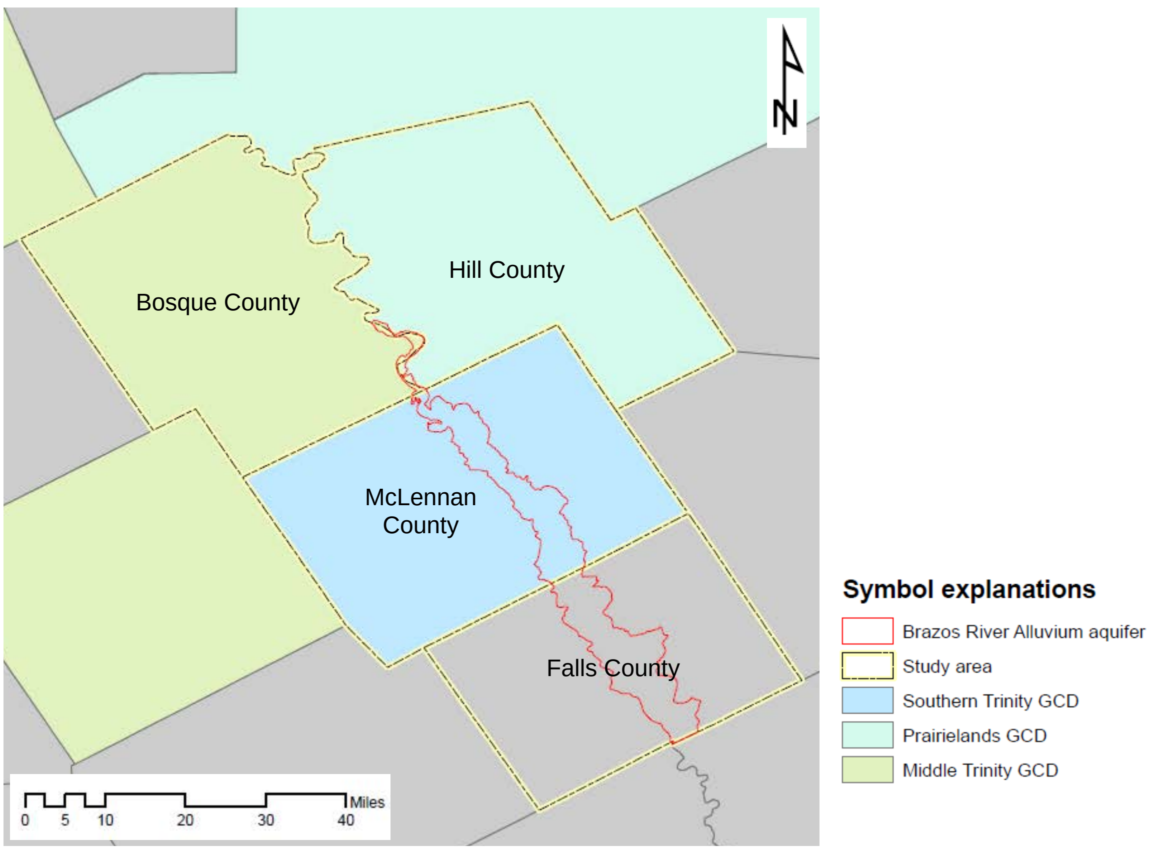

Figure 3. Counties in the study area and their respective groundwater conservation districts. Bosque County belongs to the Middle Trinity GCD, Hill County belongs to the Prairielands GCD and McLennan County comprises the Southern Trinity GCD. Falls County does not present belong to a groundwater conservation district.

A Baylor Geological Studies Bulletin by Epps (1973) utilized field data, flow records and topographic map analysis to provide insight into the depositional history and composition of the floodplain and terrace sediments associated with the Brazos River.

The late Quaternary history of a 75 km segment of the Brazos River floodplain just south of Falls County was constructed by Waters and Nordt (1995) which suggested a complex history resulting from varying climate conditions, river competence and sediment yield from 18 000 BP until Recent.

Harlan (1985) conducted a general survey of Brazos River Alluvium aquifer characteristics from the low water dam in Waco to the Falls of the Brazos State Park near Marlin. Harlan (1985) mapped water levels in the aquifer demonstrating that direction of groundwater flow was primarily toward the river.

As a follow up to his earlier research, Harlan (1990) developed a chemical baseline for the Brazos River Alluvium aquifer between Waco and Marlin. Harlan (1990) classified the groundwater to be predominantly a calcium bicarbonate type, but also recognized that groundwater chemistry varied depending on location in the alluvial basin and time of year. Harlan (1990) concluded that variable groundwater chemistry in the Brazos River Alluvium aquifer is a product of mineralogical differences in the terrace and floodplain as well as the residence time of the groundwater. Recharge in the Brazos River Alluvium aquifer occurs primarily through rainfall on terrace and floodplain surfaces (Harlan, 1990).

Pinkus (1987) evaluated the contamination potential at three solid waste disposal sites that were formerly sand and gravel excavation sites. Pinkus (1987) focused on the chemistry of groundwater found in alluvium water wells up-gradient and down-gradient from the disposal sites. Results suggested that water quality was affected down-gradient from the disposal sites, regardless of landfill design.

Shah and Houston (2007) compiled and summarized information from driller and borehole geophysical logs on the Brazos River Alluvium aquifer from Bosque County to Fort Bend County. Shah and Houston (2007) generated a geodatabase from these data, to be used in the development of a groundwater availability model (GAM) for the aquifer.

In 2007, Shah and others built upon the foundation of the developed database and produced a series of maps characterizing basic properties of the Brazos River Alluvium aquifer from Bosque County to Fort Bend County. The maps and statistics produced on aquifer properties were meant for input into a GAM for the Brazos River Alluvium aquifer.

Despite these recent studies, there is need for an updated detailed study to be completed on the Brazos River Alluvium aquifer. This is particularly needed in areas such as McLennan and Falls Counties, where continued urban growth has reignited interest in utilizing this aquifer to meet water needs. Additionally, although floodplain sand and gravel mining physically removes aquifer material, the effects of floodplain mining on the physical extent and hydrological properties of the aquifer have not yet been studied.

Purpose and Objectives

The purposes of this research are to improve hydrogeological characterization of the Brazos River Alluvium aquifer, and to develop a dynamic database for groundwater management in a heterogeneous unconfined aquifer using geospatial tools. Two specific objectives of this study are:

Objective 1: To examine the suitability of using well depth as a proxy for alluvium depth and thickness. The Brazos alluvium overlies confining layers of Cretaceous bedrock and generally occurs in a fining-upward sequence (Figure 4), meaning that the bottom of the unit possesses coarsest sediment with the highest hydraulic conductivity (K) and is almost always saturated. Coupled with the shallow depth and relative thinness of the alluvium, water wells are usually completed through the entire alluvial section as that would provide the most consistent water supply and still be economical. Therefore, it stands to reason that where water wells are completed in thin, fining-upward alluvial deposits over confining beds, well depth is a good surrogate for alluvial depth. Using well depths as a proxy for alluvium thickness may be informative in areas where lithological data are sparse.

Objective 2: To assess the temporal and volumetric impacts of floodplain sand and gravel mining using geospatial tools. Floodplain sand and gravel mining operations possess surface characteristics such as spoil piles, straight-sided excavation sites, and open pits that have been filled with water (Figure 5). These characteristics are distinguishable on aerial photos. The temporal change of mining operations in the Brazos River Alluvium aquifer may be assessed by comparing historical aerial photographs, and the impact of mining on aquifer volume may be assessed using geospatial tools through coupling analyses of total area mined and saturated section.

Study Area

The subject of this study is the Brazos River Alluvium aquifer in Texas, which begins just south of Whitney Dam and extends 350 river miles southeast toward the Gulf of Mexico (Shah and others, 2007). It is considered by the state of Texas to be one of 21 minor aquifers in the state (George and others, 2011).

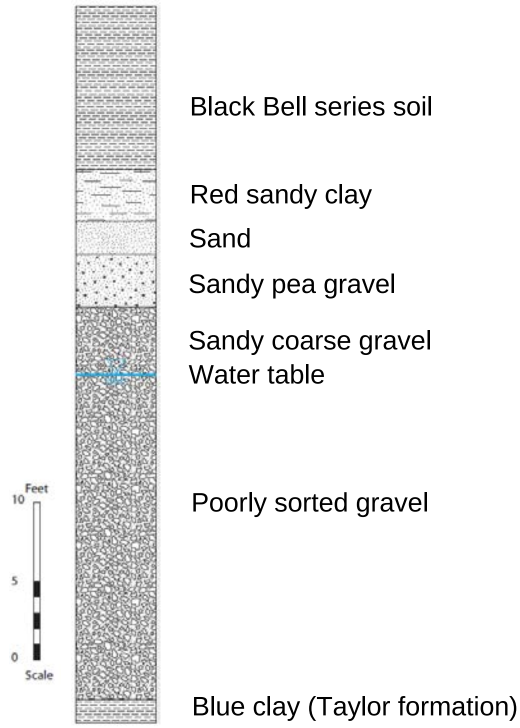

Figure 4. A representative alluvial sequence near Robinson, Texas (after Epps, 1973).

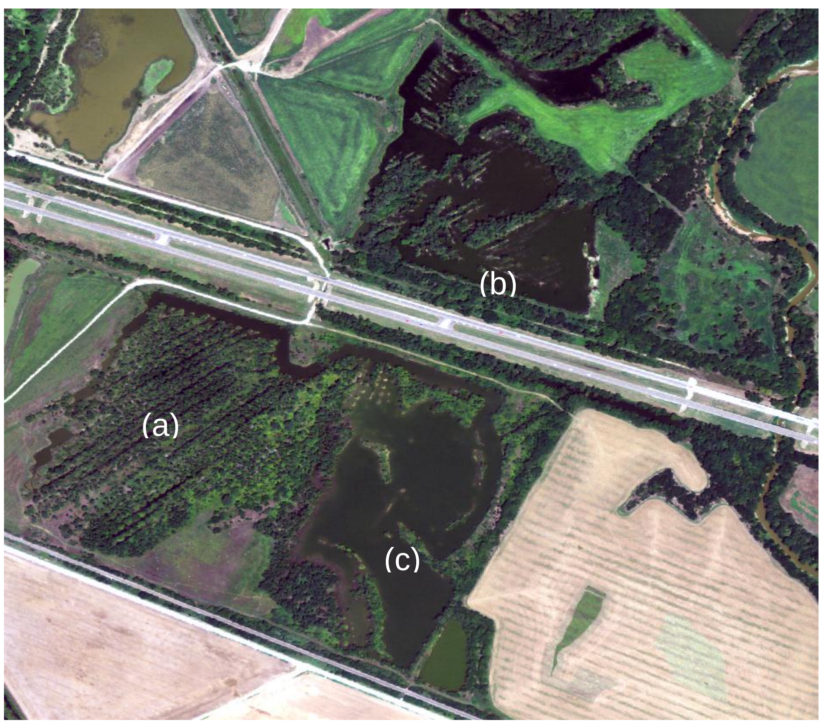

Figure 5. Example of an aerial photograph showing sand and gravel mining operations in the Brazos River floodplain. Excavation sites can be distinguished on aerial images by (a) rows of spoil piles, (b) straight sides, and (c) water-filled pits.

This study focuses on the reach between Whitney Dam and the county line between Falls County and Robertson/Milam Counties; that is, the Brazos River alluvium that is found in Bosque, Hill, McLennan, and Falls Counties (Figure 6). Mapping of groundwater flow direction focused on the southern section of Falls County due to availability of groundwater level data. The portion of the study that examining the impacts of floodplain gravel extraction on the Brazos River Alluvium aquifer focused on the Brazos River alluvium in McLennan County, because the most development has occurred in the area around Waco. These two focal areas are indicated by rectangles in Figure 6.

The length of the Brazos River within the study area is approximately 108 river miles (173.5 km). Major towns within the study area include Waco and Robinson in McLennan County, and Marlin in Falls County. The area of Brazos River alluvium from Whitney Dam to the southern extent of Falls County is 227 square miles. The focal area of Brazos River alluvium around Waco that was examined for impacts of floodplain gravel extraction is 47 square miles.

Aquifer Framework

The Brazos River valley is comprised of three components: bedrock of Cretaceous to Quaternary age, terrace alluvium deposited by the paleo-Brazos River, and floodplain alluvium deposited by the Brazos River.

Bedrock: The Brazos River valley is underlain and in some places bound by marine sedimentary rocks of Cretaceous to Quaternary age (Shah and others, 2007; Cronin and Wilson, 1967). The bedrock strata crop out in bands roughly parallel to the

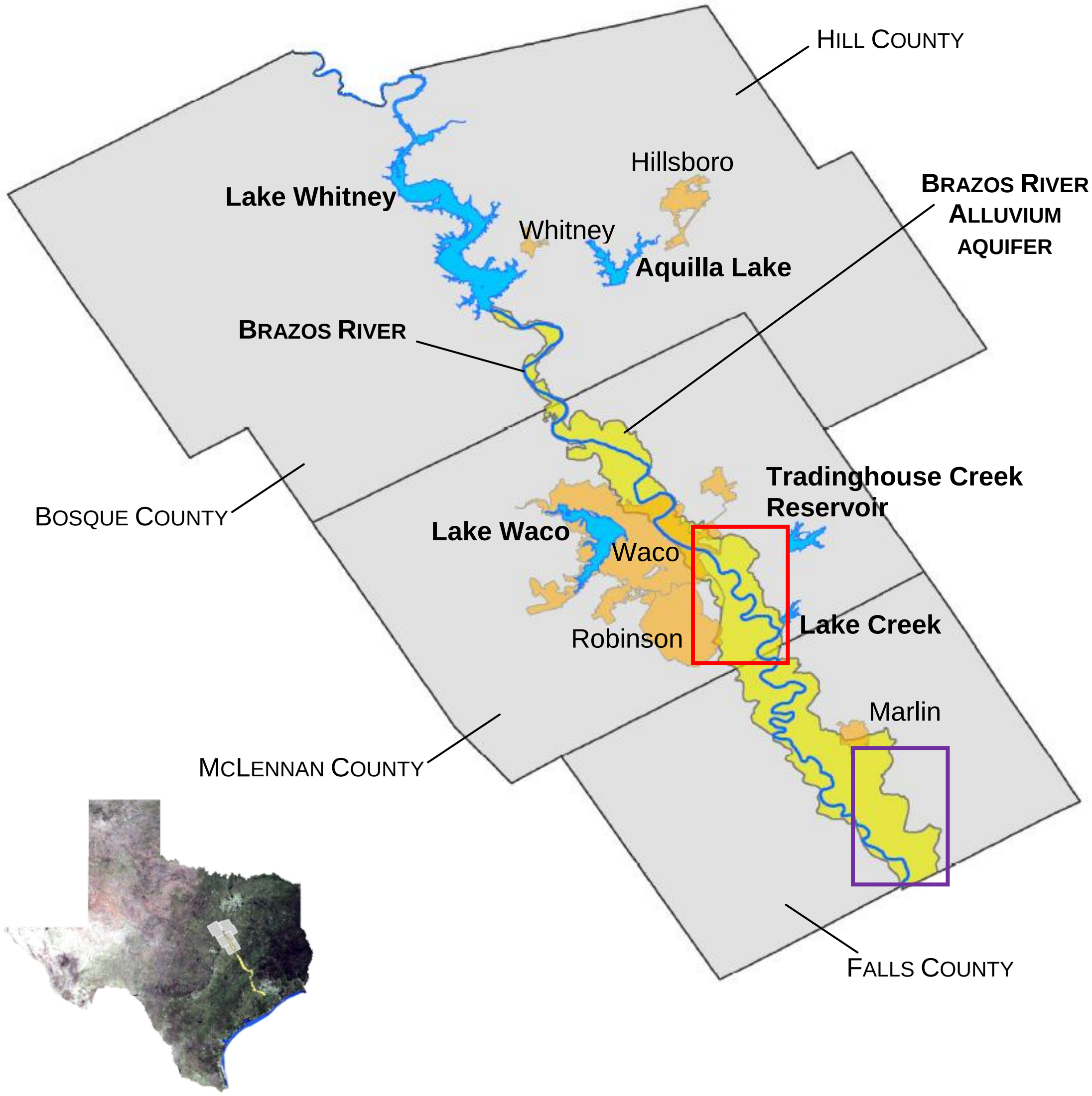

Figure 6. The extent of the Brazos River Alluvium aquifer to be covered in the study area, beginning just south of Lake Whitney to the southern county line of Falls County. The focal areas examined for: 1) groundwater flow direction and 2) impacts of gravel mining are indicated by boxed areas of alluvium.

Gulf of Mexico and dip southeast toward the coast (Figure 7, inset). In the study area, major underlying units include Austin Chalk and the Taylor Marl (Ozan Formation) in McLennan County, and the Wolfe City Sand, Pecan Gap Chalk, and the Neylandville and Marlbrook Marls in Falls County (Figure 7 and 8). These units are predominantly Cretaceous carbonates and mudrock that act as confining units below the alluvium.

Terrace alluvium: Sediments deposited by the Brazos River in the past were interpreted by Epps to form three major terraces above the present-day floodplain (Epps, 1973). Deussen (1924) determined the age of the terraces to range from Pleistocene to Recent. These alluvial deposits lie unconformably over bedrock, and are comprised mainly of clay, silt, sand, and gravel which can be slightly cemented in some places (Cronin and Wilson, 1967). Thickness of the terrace alluvium can be as much as 75 feet at certain locations, but is generally much thinner (Cronin and Wilson, 1967). The older terraces are not hydraulically connected to the floodplain alluvium, and in some places are physically separated from the floodplain by outcropping bedrock (Cronin and Wilson, 1967; Harlan 1985; Shah and others, 2007). The youngest terraces are relatively undissected by tributaries, and depressions such as partly-filled ox-bow lakes are still discernible in the terrace surface (Epps, 1973). In the study area, the youngest terrace grades into the floodplain without a distinct scarp, and is distinguished by a better-developed soil profile (Epps, 1973). Alluvium of the youngest terrace is hydraulically connected to floodplain alluvium, and contributes water to the floodplain alluvial aquifer through underflow (Cronin and Wilson, 1967). However, analysis suggests that the amount of water moving from the terraces into the floodplain is small (Cronin and Wilson, 1967).

Floodplain alluvium: The floodplain alluvium is the major water-bearing unit in the Brazos River basin. These sediments were deposited beginning in the late Pleistocene, and are comprised of several stacked fluvial sequences (Waters and Nordt, 1995). North of Waco, the alluvial belt narrows where the Brazos River crosses mostly carbonates. Moving southeast of Waco, the width of the deposit increases considerably as the Brazos River crosses the softer mudrock units (Rupp, 1974). In general, the alluvium thickens moving toward the Gulf Coast (Shah and others, 2007).

The alluvial sediment consists of buff to red siliceous gravels, sandy silts, and clays (Cronin and Wilson, 1967). They are poorly sorted sediment with lenses of clay and silt distributed throughout, but in general the sediment sequence is fining upwards (Cronin and Wilson, 1967). Coarse sands and gravels are found at the bottom of the aquifer and are the most hydraulically conductive (Cronin and Wilson, 1967). The aquifer is currently undergoing fine-grained alluviation, as dams along the Brazos River channel trap coarser sediment; sedimentation is estimated to occur at a rate of 2 feet/thousand years (Rupp, 1974).

A prime example of the fining-upwards alluvial sequence within the study area is located at what was the Edward Hay Farm circa 1985, a 1600 acre property located seven miles west of Marlin (Figure 9). In an excavated gravel pit on the farm, an exposed section was described as consisting of 6-9 feet of clean sand and gravel, overlain by 4-5 feet of sandy clay and clayey sand (Figure 10). The gravel deposit at the Edward Hay Farm is valued for its size and proximity to Marlin, and has historically supplied gravels to the Falls County Road Department (Harlan, 1985).

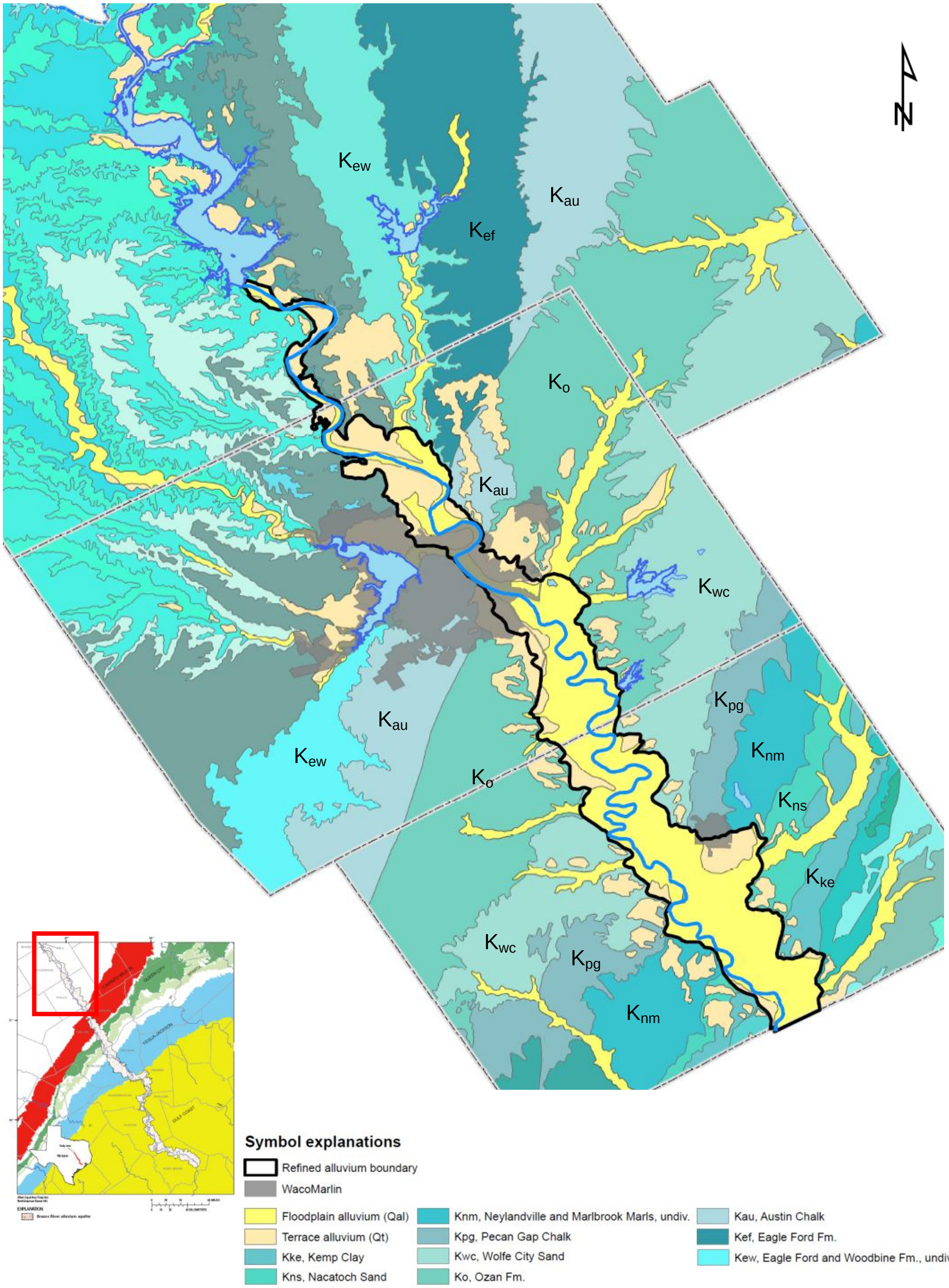

Figure 7. Bedrock units underlying the Brazos River alluvium run roughly parallel to the coast of the Gulf of Mexico (inset, Shah and others, 2007). The study area is the northern reach of the Brazos River alluvium.

Epoch	Group	Map Unit
Cretaceous	Taylor	Neylandville and Marlbrook Marls
		Pecan Gap Chalk
		Wolfe City Sand
		Ozan Formation
	Austin	Austin Chalk

Figure 8. Stratigraphic column of major units underlying Brazos River alluvium in the study area (modified from Harlan, 1985; Raney and others, 1987).

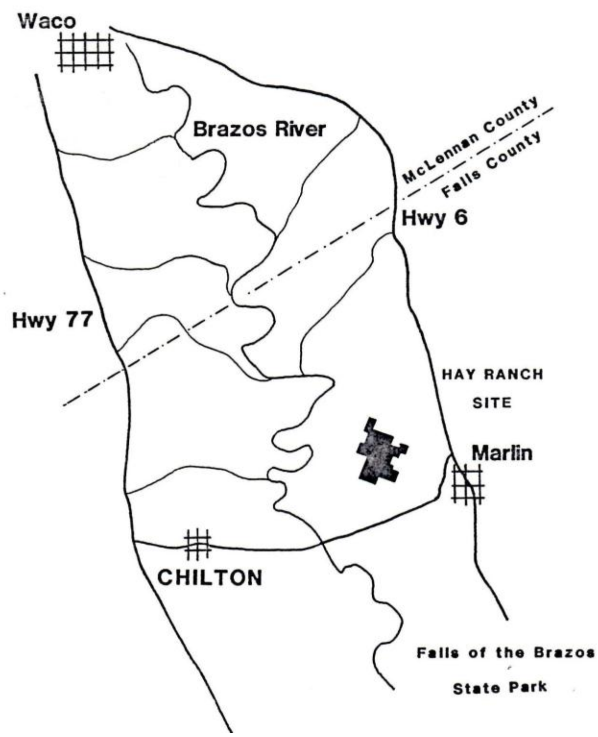

Figure 9. Location of the Edward Hay Ranch in Falls County. The ranch site is approximately 7 miles west of Marlin, and approximately 50 miles south of Waco (modified from Harlan, 1985).

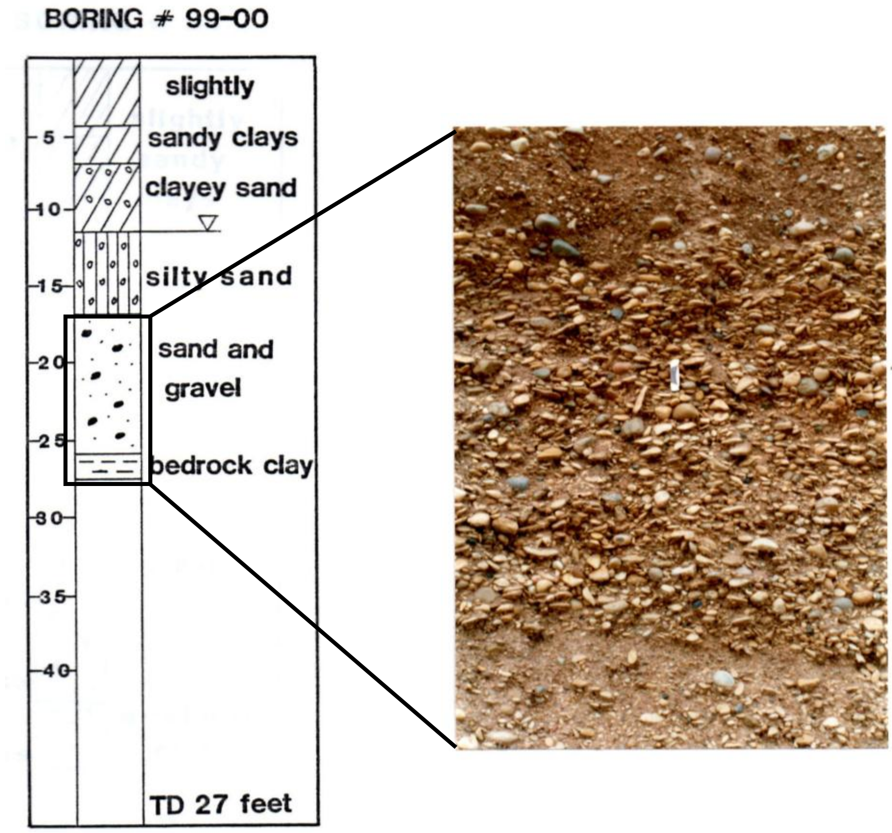

Figure 10. A representative log from the gravel pit at Edward Hay Farm, exhibiting a fining-upward sequence. Inset is an example of the sand and gravel deposit at this site (modified from Harlan, 1985).

Hydraulic Parameters

Cronin and Wilson described the Brazos alluvium as poorly sorted but generally exhibiting a fining-upward sequence on the macro-scale, and containing lenses of clay and silt (Cronin and Wilson, 1967). The heterogeneity of the Brazos alluvium was confirmed by wide ranging hydrogeologic properties determined through field and lab tests (Table 1).

Table 1: Hydrogeologic properties of the Brazos alluvial aquifer, as determined by Cronin and Wilson (1967).

Property	Values
hydraulic conductivity (K)	0.001 – 18 000 gpd/sq ft
porosity	24.7 – 59.5%
transmissivity	50 000 – 300 000 gpd/ft
specific yield	4.4 – 35.4%
specific capacity	6 – 134 gpm/ft

Flow Direction

Groundwater flow in the Brazos River basin is closely affected by surface topography and configuration of underlying confining beds (Harlan, 1985; Pinkus, 1987). Groundwater flow in the floodplain and first terrace, and flow in the upper terraces may be differentiated. In the floodplain and first terrace, the Brazos River acts as a discharge point, and flow is generally towards the Brazos River and slightly down-valley (Harlan, 1985; Pinkus, 1987). In the upper terraces, groundwater flows radially away from the terraces toward tributaries and the Brazos River (Harlan, 1990).

Climate

Because the Brazos River Alluvium aquifer is shallow and unconfined, groundwater flow and chemistry are sensitive to climatic variations. Therefore climate is an important consideration in studies on this aquifer. The Brazos River Alluvium aquifer through McLennan and Falls Counties falls within the subtropical-humid climate region. The northernmost tip of the study area, in Bosque and Hill Counties, is located in the transition zone between the subtropical-subhumid and subtropical-humid climate regions. A subtropical climate is the result of a predominant onshore flow of tropical maritime air from the Gulf of Mexico; seasonal mixing of continental air flow from east to west modifies the moisture content of onshore flow from the Gulf, hence the descriptors “subhumid” and “humid” (Larkin and Bomar, 1983).

The study area experiences wide seasonal variation in temperature. The average minimum temperature in McLennan County is 37°F in January and the average high temperature is 97°F in July (Smyrl, 1999), which is representative of the study area.

According to precipitation data collected by the National Weather Service and the TWDB, the study area generally experiences moist winter months and dry summer months. Most precipitation falls over the months of April and May, while July and August are typically the driest months. However, large anomalous storms can skew average precipitation amounts. For this reason, the median monthly precipitation values are more insightful than the mean monthly precipitation values (Figure 11).

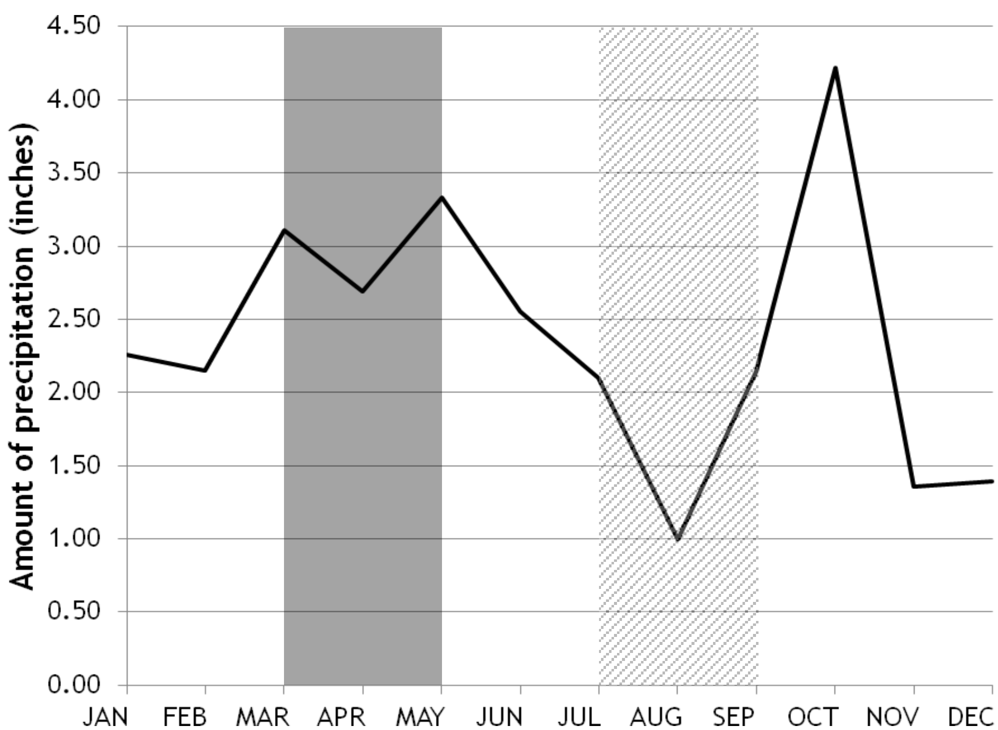

Figure 11. Median values for monthly precipitation from 2000 to 2010. Shaded box delineates the wet months (April to May), while hatched box delineates dry months (July to August). Raw data were collected by the National Weather Service and TWDB.

CHAPTER TWO

Methodology

Data from several sources were compiled and analyzed using geospatial tools to model the Brazos River Alluvium aquifer with the objectives of 1) estimating volume of the Brazos River Alluvium aquifer and its potential water resources, and 2) capturing the impact of floodplain sand and gravel mining on the Brazos River Alluvium through time. The methodology is summarized using a flowchart in Figure 12.

Boundary Refinement

The first step in this study was to define an accurate working boundary of the Brazos River Alluvium aquifer. This was accomplished by superimposing the TWDB boundary for the Brazos Alluvium Aquifer on a state geology map (generated by the Texas BEG) so that the two could be compared (Figure 13a). Where boundary discrepancies were over a bedrock contact, the TWDB boundary was adjusted to match the geologic contact (Figure 13b, 1.). Where the differences were vague, such as when the TWDB boundary crossed over floodplain and terrace alluvium deposits, the original boundary was not changed (Figure 13b, 2.). The resultant boundary of the Brazos River Alluvium aquifer was considered more accurate and was used to define the aquifer in subsequent analyses.

Determining Alluvium and Saturated Thickness

Well data from TWDB were acquired as a multipoint shapefile that is compatible with ArcGIS. Each well was accompanied by additional information: state identification

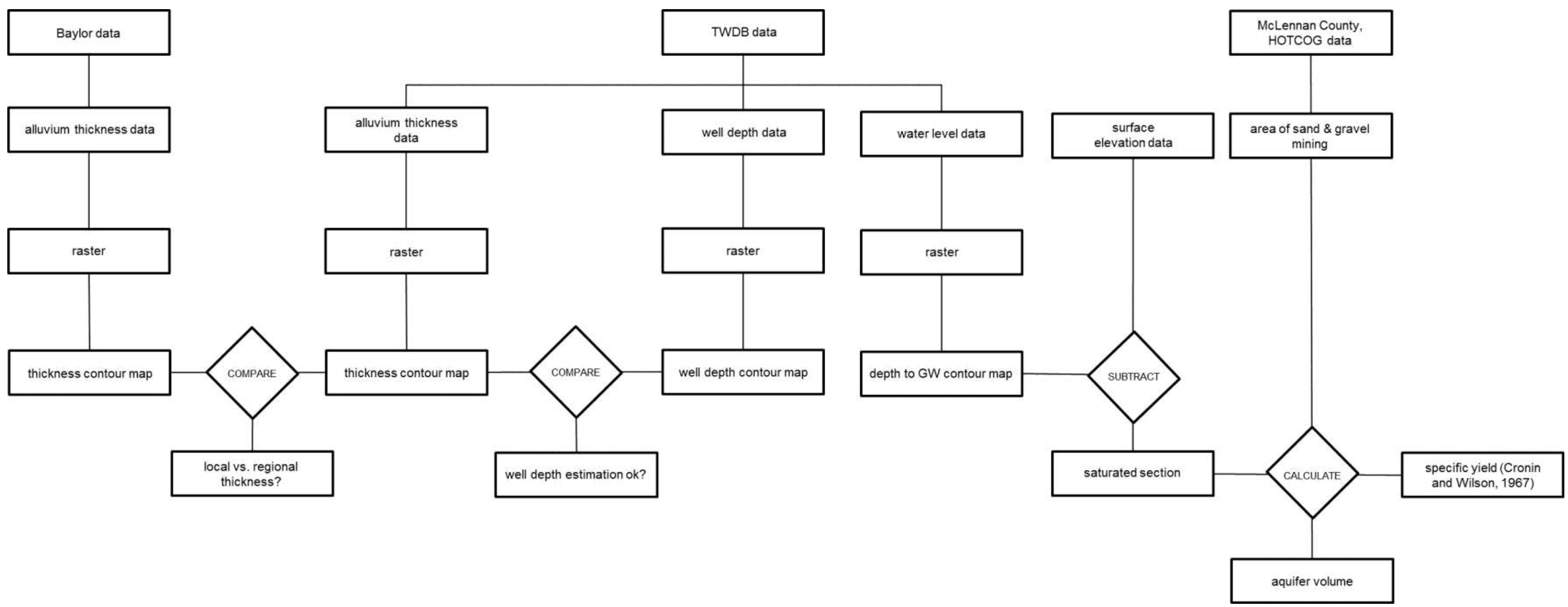

Figure 12. Summary flowchart of methodology.

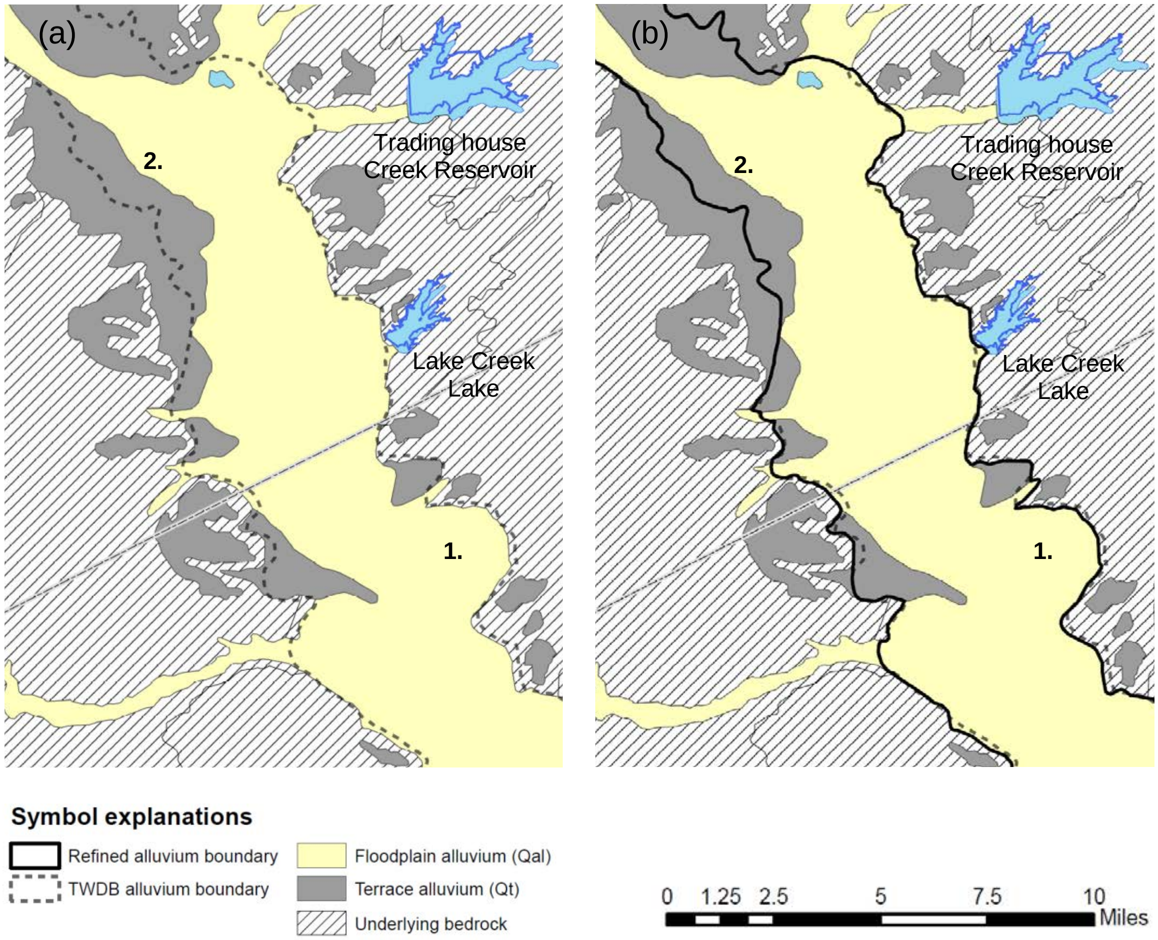

Figure 13. Comparing areal delineations of the Brazos River Alluvium aquifer. (a) Shows underlying geology overlain by the TWDB aquifer boundary. Brazos river floodplain and terrace alluvium are highlighted. (b) Shows the same area with the final refined aquifer boundary in red. Where the TWDB boundary crossed bedrock units (1), it was adjusted to match the alluvium boundary. Where the TWDB boundary cut across an alluvial unit (2), the boundary was left alone.

number, owner, primary use, aquifer in which the well was completed, and geographic coordinates. These state data were the basis for creating a wells database for the Brazos River Alluvium aquifer. The wells were first constrained to those located within the areal extent of the Brazos River alluvium in Bosque, Hill, McLennan, and Falls Counties. These wells were then further constrained to include only those completed in the Brazos River Alluvium aquifer. A total of 256 wells comprised the database for the Brazos River Alluvium aquifer (Appendix A). The primary uses of these wells were for irrigation, stock watering and domestic applications. Approximately 40% of wells in the database were reported to be currently unused. The average depth of these wells is 37 feet. The depths of these wells were used to interpolate a surface raster representing alluvium thickness via inverse-distance weighting (IDW) in ArcMap. IDW is an interpolation method whereby the value at unsampled locations is estimated through weighting the available data by the inverse distance between the sampled and unsampled location (Mito and others, 2011).

A second interpolation was conducted to estimate aquifer thickness using lithological data; sources of these data included lithological logs from boreholes and water wells from the TWDB Water Information Integration and Dissemination (WIID) System. Additional logs were obtained through personal communication with staff at TWDB and geotechnical reports.

Boreholes and wells that included lithological information in their driller reports were compiled to form a database in Microsoft Excel. Key information included geographic coordinates, total depth of the borehole or well, depth of the contact between alluvium and underlying bedrock, and depth to water. Lithological logs are recorded in Appendix B. A total of 62 wells comprised this database.

The geographic coordinates for each well or borehole were provided in degrees/minutes/seconds format; these were converted to decimal degrees. The dataset was then imported into ArcMap as a points shapefile and constrained to those wells that were within the Brazos alluvium boundary. Land surface elevations were assigned to each datapoint using the National Elevation Dataset (NED) 1 Arc Second raster product from the USGS (spatial resolution is approximately 30 m). Groundwater elevation and alluvium elevation were then calculated for each datapoint by subtracting water level from surface elevation and alluvium thickness from surface elevation respectively.

The contact depth was used to interpolate a raster representing the thickness of the alluvium. Inverse-distance weighting was the interpolation method used to create the thickness raster surface, as this method limits the range of interpolated thickness values to that of the original dataset. The saturated thickness over the study area was interpolated by subtracting a raster of the elevation of the bottom of the alluvium from a groundwater elevation raster. A groundwater flow map was created by contouring the groundwater elevation raster.

The estimation of alluvium thickness over the entire study area was compared to a local dataset from the Baylor University campus. Using lithological logs from boreholes drilled on campus, a database was created that identified boreholes, the surface elevation and bottom of alluvium, date drilled, and water level (Appendix C). A total of 96 wells comprised this database. For wells that reported water level, the average depth to water was 16.7 feet. The average depth to alluvium for wells that hit bedrock was 19.5 feet. Because geographic coordinates and elevation of the boreholes were not given in all reports, latitude and longitude coordinates were assigned using ArcMap. After a multipoint shapefile of boreholes was created by referencing hardcopy location maps, geographic coordinates in decimal degrees were calculated by first creating new fields in the attribute table of the shapefile, then using the "Calculate Geometry" function. A raster representing alluvium thickness was interpolated using inverse distance weighting. The resulting minimum, maximum and average alluvium thickness values were compared to those of a congruent area from the regional map.

Determining Extent of Floodplain Sand and Gravel Mining

Datasets ranging from 1941 to 2010 were obtained to quantify total alluvium removal through floodplain sand and gravel mining as well as the rate at which the excavation may have occurred.

Historical aerial images from 1941 and 1972 were obtained from the McLennan County Engineer Office as digital jpeg files (scanned at 200 dpi resolution). The images were imported into ERDAS Imagine and georeferenced to 2010 imagery. The resulting images were mosaicked to form a continuous scene representing the focal study area. This process of georeferencing was carried out for 1941 imagery as well as for 1972 imagery. The mosaicked scene from each year was then examined for sites of gravel and sand excavation, and the observed sites were digitized using heads-up digitization in ArcMap.

Digital orthophoto quarter-quads (DOQQs) from 1996 and 2010 were downloaded from TNRIS and used in this analysis. Color infrared imagery from 1996 was acquired as part of the Texas Orthoimagery Program (TOP) at 1 m resolution. The 2010 natural color/ color infrared imagery was acquired at half-meter resolution through the National Agriculture Imagery Program (NAIP). Using ArcMap, the quarter-quads were mosaicked together, and the resulting composite image examined for sites of gravel and sand extraction within the alluvium boundary. Excavation sites were digitized using heads-up digitization. This process was completed for 1996 imagery and 2010 imagery.

Additionally, locations of solid waste disposal sites in McLennan County were included because old excavation pits in the Brazos alluvium have historically been used as landfills, and therefore represent an important portion of the alluvium affected by mining activities. Landfill information was obtained through communications with staff from the Heart of Texas Council of Governments. Data for landfills completed within the aquifer boundary were digitized as points in ArcMap.

Following digitization and field checking, the amount of disturbed area relative to total alluvium area was determined for each year.

Field Confirmation

Field trips were conducted to confirm alluvium lithology, Brazos River alluvium thickness and gravel pits identified through heads-up digitizing. Two driving trips and one float trip were completed. The objective of the first driving trip, completed in July 2010, was to confirm the presence of gravel pits in the study area. A second driving trip was completed in September 2011, following analysis of 2010 imagery. On this trip, a route was driven through the focal area and an attempt was made to visit each mapped excavation site. It was noted whether a site was present, absent, or inaccessible. This trip also served as a ground check for any excavation sites that were missed during image analysis. A float trip down the Brazos River in the southern portion of the study area was taken in October 2010. On this trip, the lithology of exposed alluvium was observed, and the depth to bedrock was verified where possible.

Determining Aquifer Volume

The overall approach for determining the volume of the Brazos River Alluvium aquifer can be understood by the equation:

$$V = A \times b \quad \text{, where}$$

the volume of the alluvium (V) is equal to the product of the area of the alluvium (A) and alluvial thickness (b). In order to determine the volume of the aquifer, the above equation is modified such that A represents the productive area of the alluvium, and b is equal to the saturated thickness of the alluvium:

$$V_{aq} = A_{prod} \text{ x } b_{sat}$$

The productive area of alluvium (A_{prod}) is equal to the total area of alluvium, minus areas that have been removed due to sand and gravel mining and landfills:

$$A_{prod} = A - A_{mines} - A_{landfills}$$

Lastly, the porosity of the alluvium must be accounted for in a determination of volume. In unconfined aquifers, the effective porosity is approximately equal to the specific yield or the "drainable porosity". Cronin and Wilson (1967) determined specific yield values of 4.4-35.4% (average of 23.6%) for Brazos River alluvium from laboratory measurements, but suggested that these values were high since use of a centrifuge may expel more water than drainage by gravity. Cronin and Wilson (1967) suggested using a specific yield of 15%, determined by Cronin and others earlier. Although 15% is less than the average determined through laboratory tests, this value is a reasonable and possibly conservative estimate of the specific yield of Brazos River alluvium, particularly considering the presence of clays and silts, and lithologic heterogeneity in the alluvium.

Aquifer volumes of the focal area as well as the area encompassed by sand and gravel excavation sites in each time step were calculated using the Surface Volume function in ArcMap. The output was a text file containing the calculated area and volume. The productive aquifer volume was then determined by arithmetically subtracting extraction pit volumes from the focal area aquifer volume.

CHAPTER THREE

Results and Discussion

A composite map of the original TWDB boundary of the Brazos River Alluvium, Texas geology, and the refined alluvium delineation is shown in Figure 14. Defining the Brazos River Alluvium was important since it formed the bounding conditions of later geospatial analyses. The boundary set out by TWDB was compared to a geological map of Texas and then field checked where possible. The difference in age of the data, as well as difference of the spatial resolution of the data gave rise to differences in the maps. Discrepancies also exist because the maps were created for different purposes. The Texas BEG geological map distinguished between floodplain and terrace alluvial sediments. The TWDB map defines aquifers, and includes some terrace alluvium that is in hydrologic communication with floodplain alluvium. The Brazos River Alluvium aquifer within the study area covers an area of 226 square miles as defined by TWDB. Floodplain alluvium of the Brazos River and its tributaries within the study area, as defined by the Texas BEG map, encompasses an area of 241 square miles. The adjusted Brazos River Alluvium aquifer covers 227 square miles in the study area. Although overall difference between the TWDB delineation of the Brazos River Alluvium aquifer and the adjusted aquifer boundary is small and regional aquifer analysis would be minimally affected, boundary differences may become important at a local scale. For subsequent analyses, this intermediary of TWDB and Texas BEG delineations of the Brazos River Alluvium aquifer is the best working boundary as it captures the finer detail

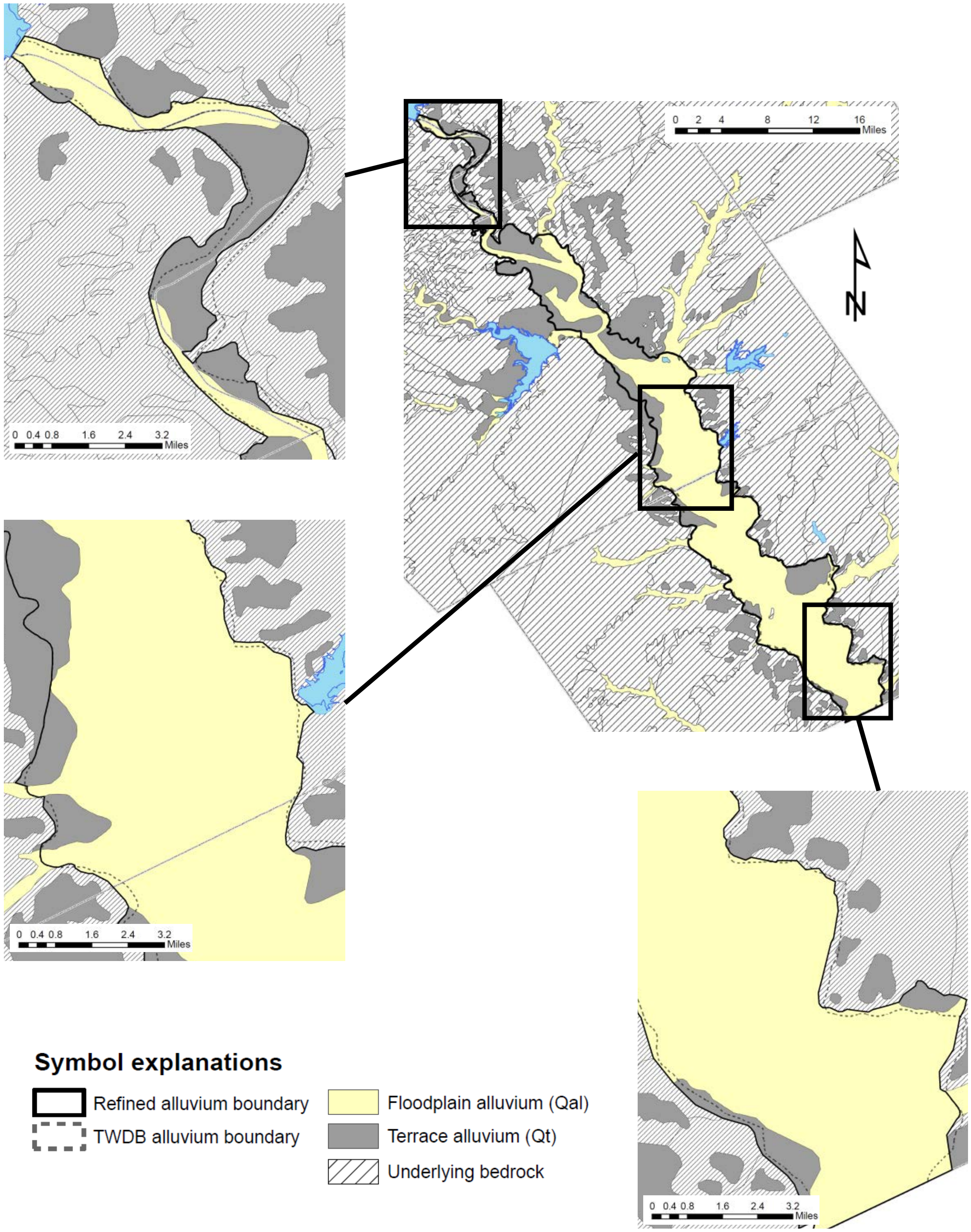

Figure 14. A map of the study area with the boundary of the Brazos Alluvium Aquifer superimposed. Close-up areas show the variation in the TWDB aquifer boundary (dashed line), geology, and the final refined boundary (bolded solid black line).

of the geology map while including all hydraulically connected sediments of the Brazos River Alluvium aquifer within the study area.

Maps showing the thickness of the Brazos River alluvium generated using well depths and lithological logs are shown in Figures 15 and 16. Histograms showing the occurrence frequency of thickness values in each map as well as tables summarizing raster statistics are included in with each Figure. Using well depth as a proxy for alluvium thickness produced values ranging from 10 feet to 80 feet and a mean thickness of 35 feet (Figure 15). Using lithological information from driller logs produced an alluvium thickness from 13 feet to 69 feet with a mean value of 40 feet (Figure 16). In both cases, aquifer thickness increases to the south; however there is variation in the surface likely as a result of the complex fluvial history of downcutting and alluviation that has occurred in the Brazos River basin (Waters and Nordt, 1996; Epps, 1973). Epps (1973) described an average thickness of 25 to 30 feet in the Robinson area which is within similar thickness contours shown on Figure 15.

Alluvium thickness produced by the well depth proxy is likely skewed slightly high, due to one well that was drilled to a depth of 80 feet. Excluding that well, well depths ranged from 10 feet to 66 feet (mean depth of 38 feet), which is more similar to the values generated using lithological information. Alluvium thickness produced by the well depth proxy exhibits a more normal distribution than alluvium thickness produced by lithological data, suggesting that well depth data provides a better representation of alluvium thickness.

Initially, splining was used to interpolate surfaces to minimize the effect of spatial bias created by clustered datapoints, and the interpolation was limited to the area of the

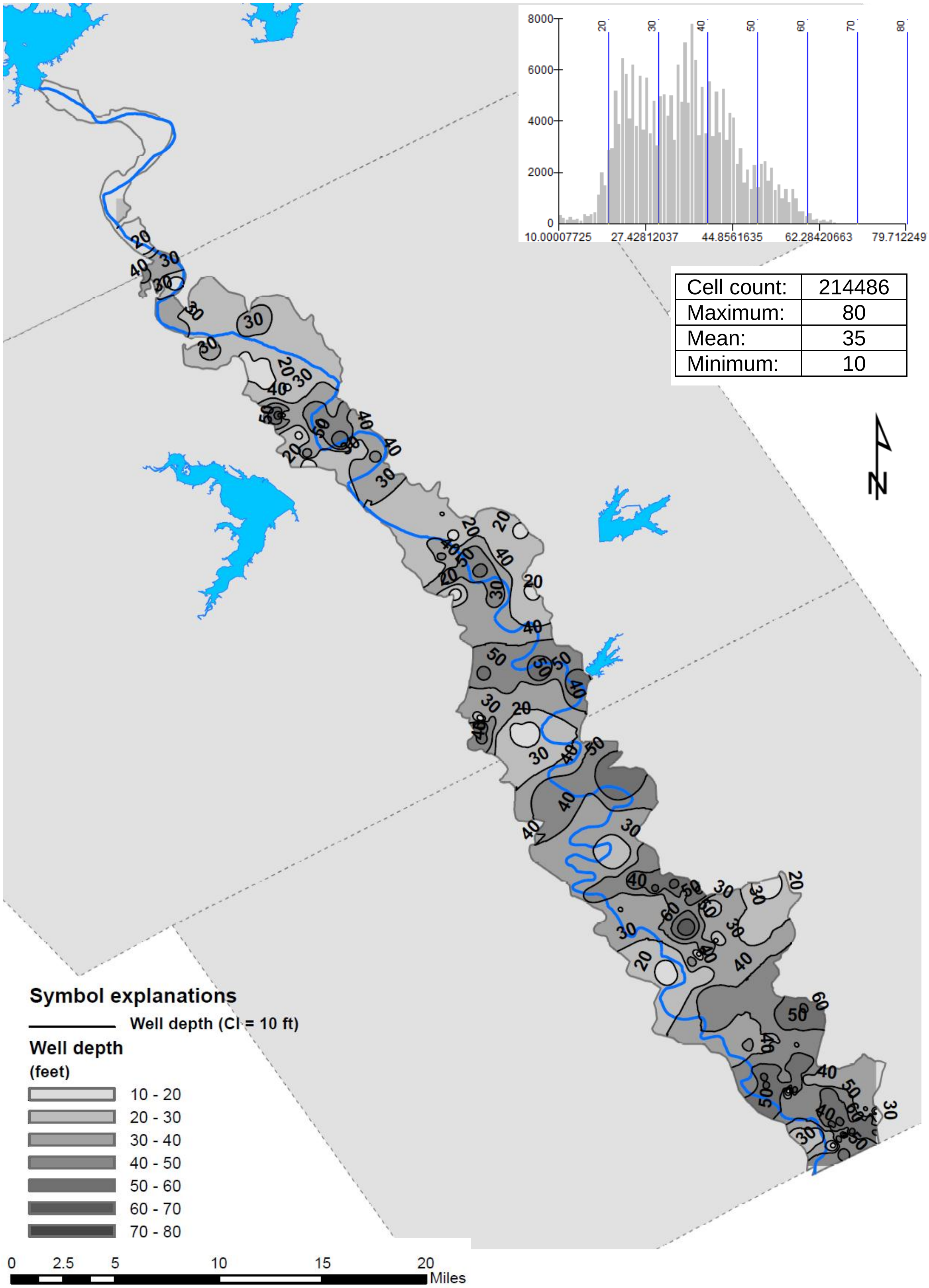

Figure 15. Interpolated surface water well depths completed in the Brazos River alluvium as a proxy for alluvium thickness. Contour interval is 10 feet.

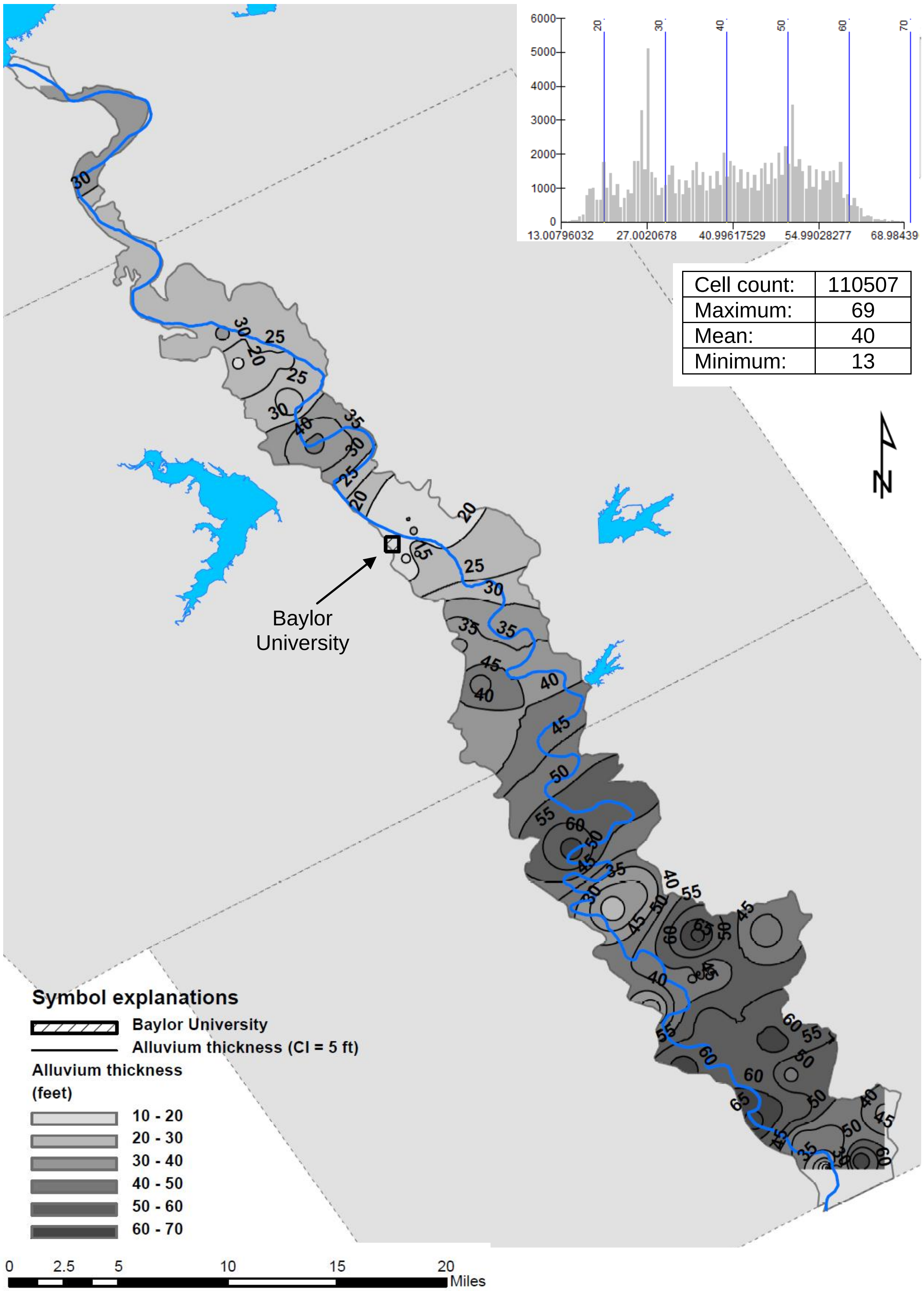

Figure 16. Isopach map of alluvium thickness, created from lithological data for wells located within the alluvium boundary. Contour interval is 5 feet. Baylor University is indicated in the context of the aquifer.

alluvium. However, the interpolated values were not realistic, yielding values that were beyond the actual data range. Splining, kriging, and IDW were compared and found to produce similar spatial patterns in the interpolated surface. However, IDW produced a range of values that best represented the dataset. Therefore, ultimately IDW was used to interpolate surfaces representing alluvium depth.

To examine how much difference existed between the two interpolations and where these differences occurred, alluvium thickness calculated using the well depth proxy was subtracted from alluvium thickness calculated using lithological data (Figure 17). The differences between the two interpolations were as little as 0 feet and as much as 53 feet in select localities within the study area.

Focusing specifically on McLennan County, a difference of 10 feet or less between the two interpolations occur over most of the county, which suggests that the well proxy works well in McLennan County. Agreement between the two interpolations in McLennan County is helped by a thinner alluvium unit, wherein water wells are likely drilled through the entire alluvial thickness. Also, due to a higher population around Waco and the corresponding demand for water, more wells are available to be used as datapoints.

Greater differences between well depths and actual alluvium depth are present toward Falls County. As the alluvial unit thickens moving southward, it is possible that water wells increasingly were not drilled to the bottom of the Brazos River Alluvium aquifer. This interpretation is supported by positive difference values when subtracting well data from lithological data (Figure 17). The costs of drilling a deeper well may

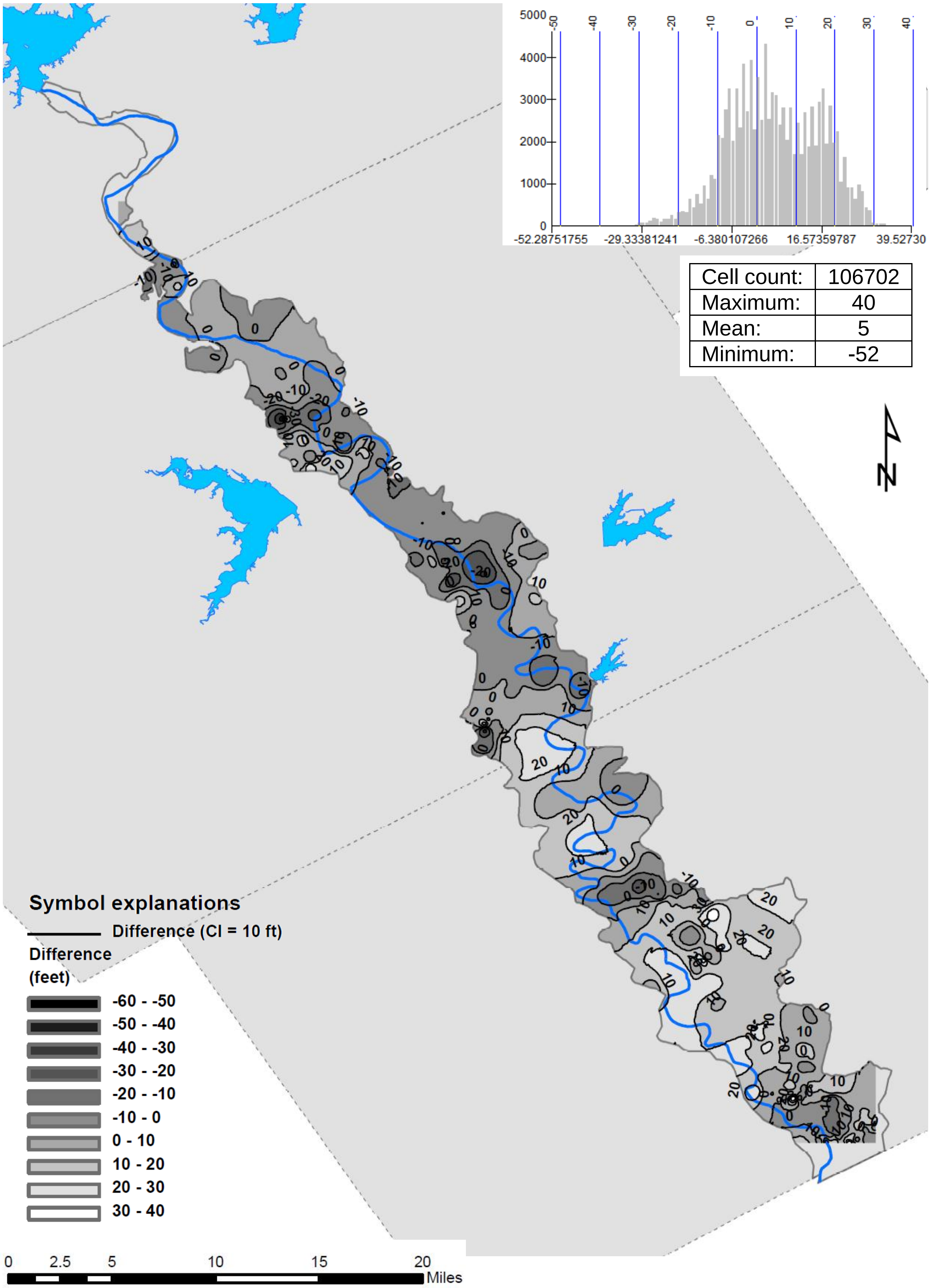

Figure 17. The calculated difference (in feet) between the estimation of alluvium thickness obtained using well depths versus lithological data. Contour interval is 15 feet.

discourage the drilling of wells through the entire thickness of the alluvium, and a thicker saturated section may negate the need to screen wells at the bottom of the alluvium. This interpretation is further supported when comparing lithological depths to the interpolated pixel value at the corresponding location from the well depth raster (Figures 18 to 20). Comparing combined datapoints in McLennan and Falls Counties (Figure 18) resulted in an R-squared value of 0.5. When McLennan and Falls Counties are compared separately (Figures 19 and 20), the correlation between interpolated values and lithological depths is stronger in McLennan County (R^2 = 0.4) than Falls County (R^2 = 0.2).

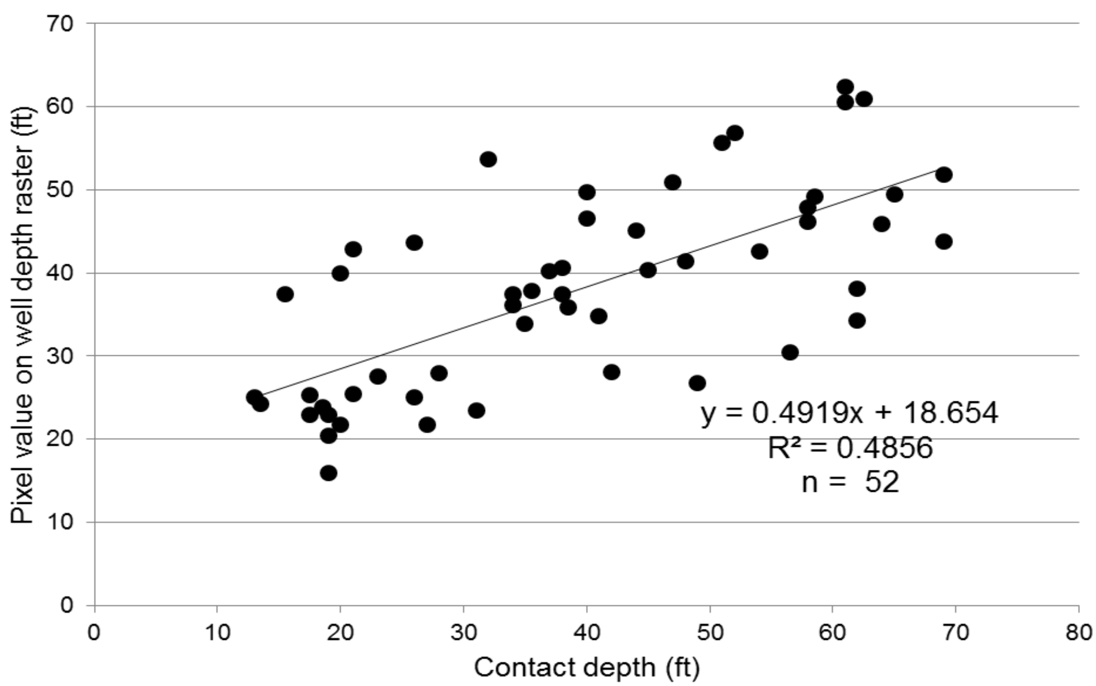

Figure 18. Comparison of interpolated depth values and lithological contact depths in McLennan and Falls Counties.

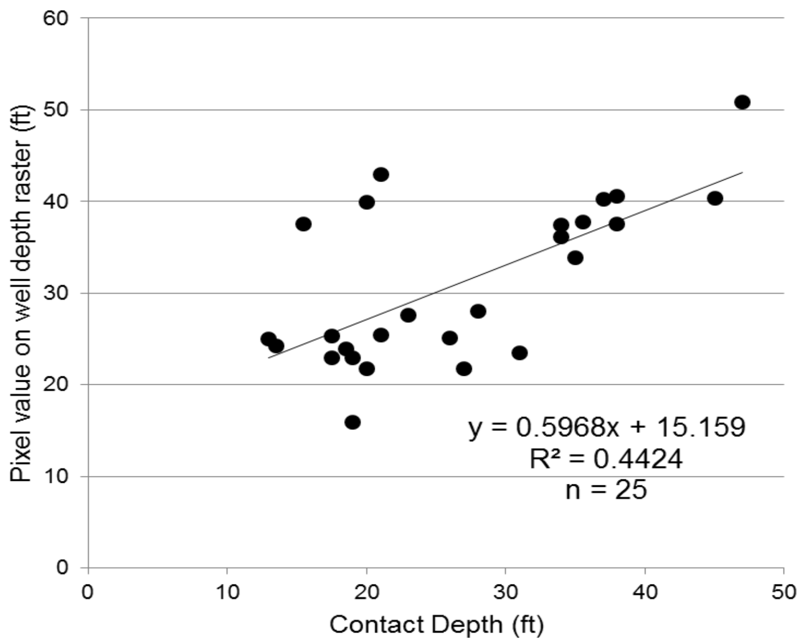

Figure 19. Comparison of interpolated depth values and lithological contact depths in McLennan County.

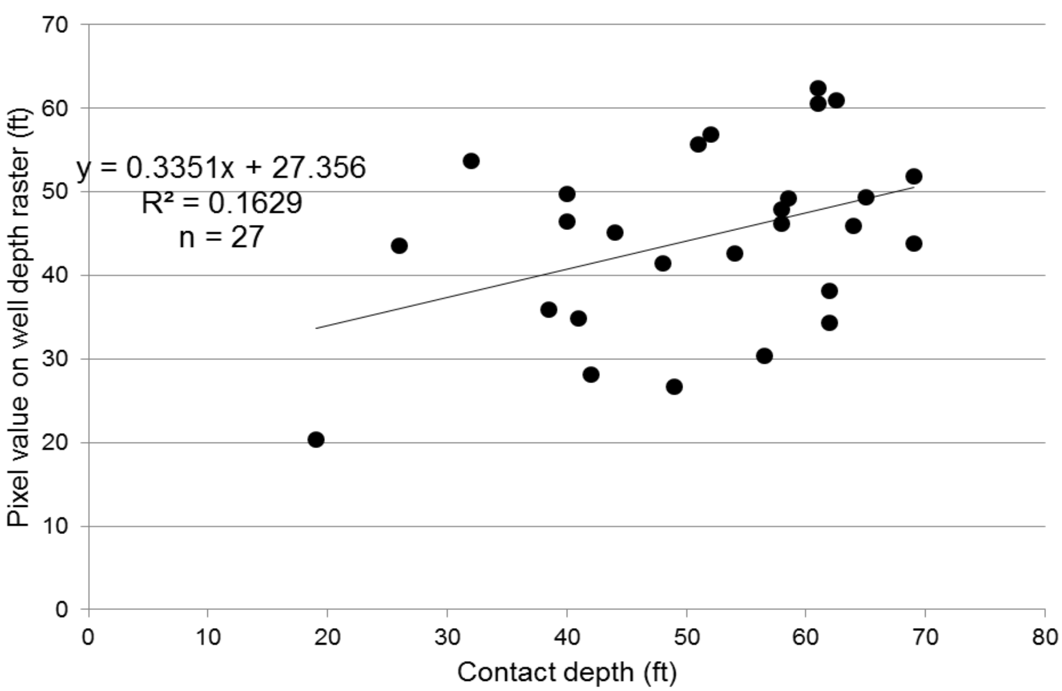

Figure 20. Comparison of interpolated depth values and lithological contact depths in Falls County.

South of the study area, the Brazos River Alluvium aquifer not only thickens but overlies major aquifers (Figure 21). A well depth proxy for alluvium thickness will likely not be accurate as it may be difficult to differentiate between Brazos River alluvium and other aquifer units.

Borehole data from Baylor University were analyzed to estimate alluvium thickness at a finer spatial resolution, and to compare it to the regional borehole data. An isopach map of Brazos River alluvium underneath the Baylor University campus is shown in Figure 18. Alluvium is thickest at 51 feet in the north part of campus, and is thinnest at 9 feet between South 4th and South 5th Streets. Average alluvial thickness is 18 feet. Boreholes in the northeast side of campus (Figure 22, inset) were not included in the mapping because they were not drilled to bedrock; as such the total thickness of the alluvial unit in these boreholes could not be determined.

The alluvial thickness determined for Baylor University was compared to a synonymous area located on the isopach map for the entire study area (Figure 16). The regional map also shows that alluvium in this area is 18 feet thick on average. The maximum alluvial thickness in this area is 18.3 feet, while the minimum thickness is 17.3 feet. The narrow range in thickness values is due to the comparatively sparse number of data points in this area; fine spatial variations that were evident in the Baylor interpolation were not captured in the regional interpolation.

Comparison of a regional and local model of alluvium thickness resulted in the same average thickness but different minimum and maximum thicknesses. The regional model was capable of capturing general trends over a large area. However, fine-scale variations in thickness which were evident using a concentrated dataset in a smaller area were lost in the regional model. The comparison demonstrates that the regional and local-

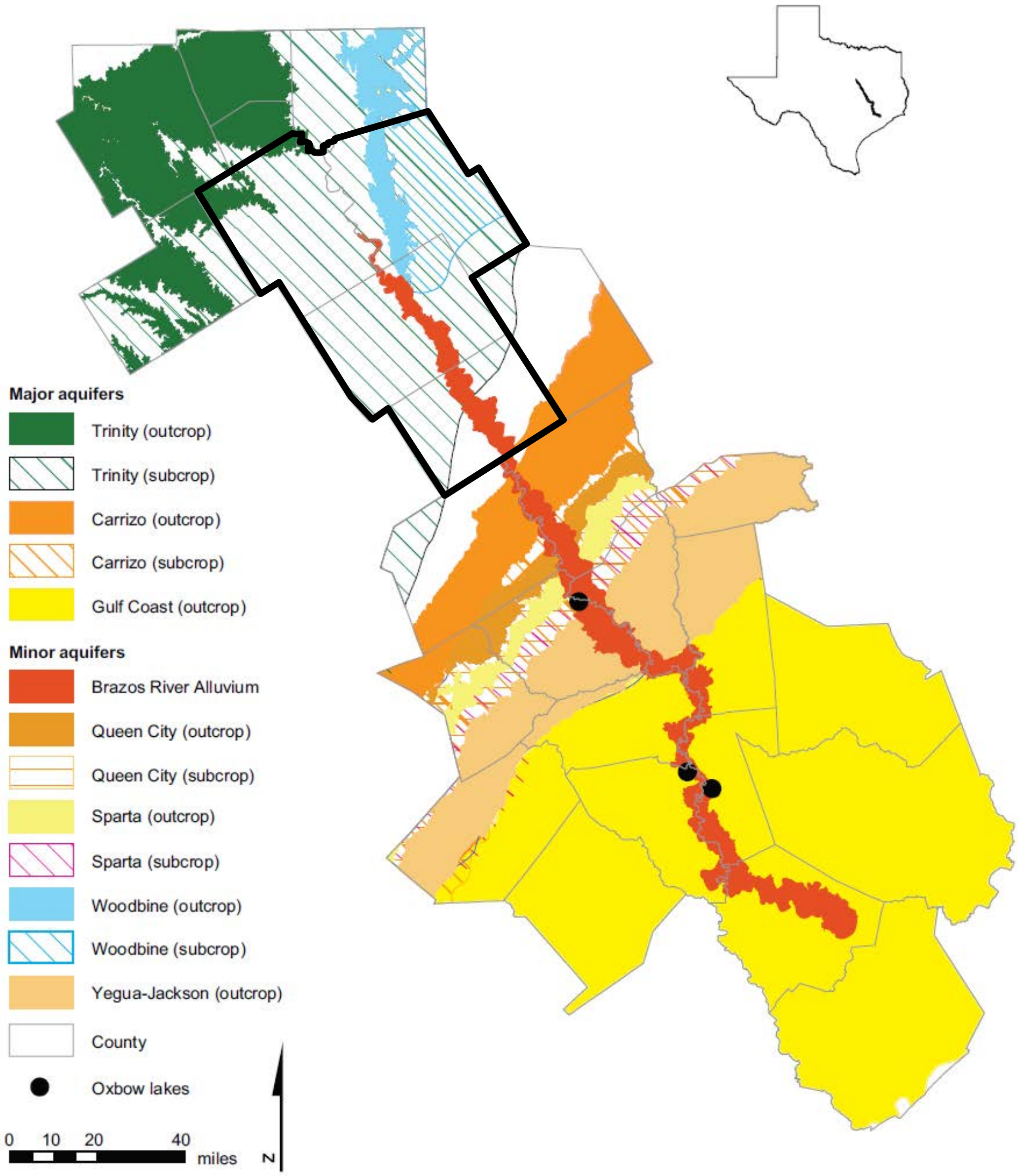

Figure 21. Map of the study area (bounded by bolded line) within the context of major aquifers to the south. The Brazos River Alluvium aquifer overlies Cretaceous confining beds within the study area, but is in contact with major aquifers moving southeast towards the Gulf Coast. The entire reach of the Brazos River Alluvium aquifer extends from Bosque County to Fort Bend County, Texas (Chowdhury and others, 2010).

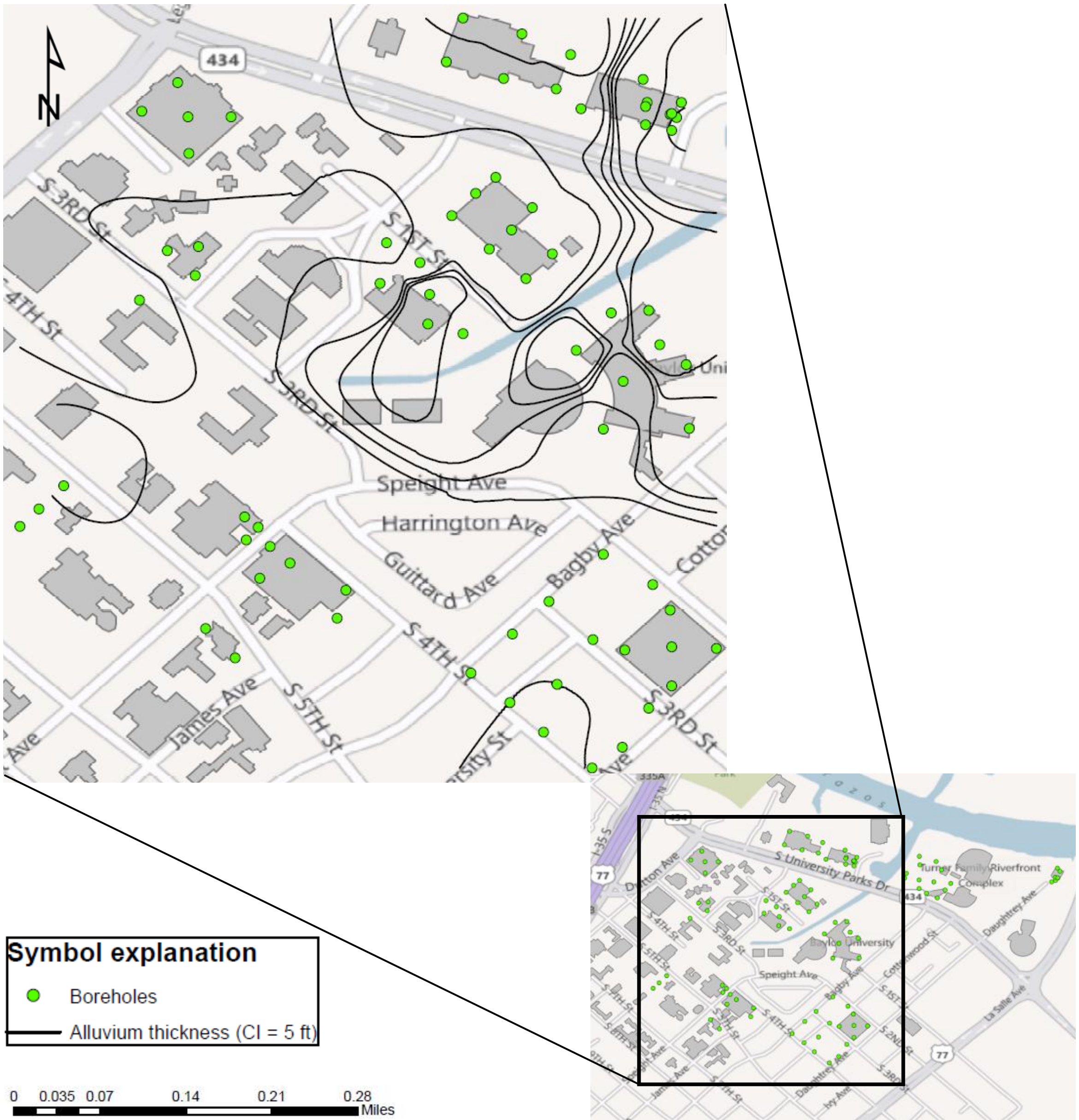

Figure 22. Alluvium thickness underneath Baylor University in Waco. Boreholes not included in inset were not used in the contouring because they did not reach bedrock.

scale models are complementary, and may be useful together in answering multi-scaled hydrogeological and management questions.

On Saturday October 23, 2010 a canoe trip was taken down a reach of the Brazos River to observe exposed sections of the Brazos River alluvium in Falls County. The total distance traveled was approximately 2.5 river miles, ending at the Falls on the Brazos State Park. Little gravel was observed in the exposed banks. The alluvium was mostly fine-grained. Sections of weathered chalk were observed, and these were directly overlain by fine-grained sands and clays. The alluvium was thin toward the Falls on the Brazos. Similarly, the depth to bedrock was observed to lessen toward the Falls on the Brazos. The interpolated thickness of the alluvium in this area is thin, around 30 feet (Figure 16). Field observations seem to support the interpolation shown on the maps.

Fewer Brazos River Alluvium aquifer well logs were found for Falls County compared to McLennan County. A reason for this data gap may be because this area of the aquifer is not as productive as other areas, resulting in fewer wells being completed in the alluvium. Gravel was not widely observed in exposed sections of alluvium during field checking; the absence of gravels in the alluvium supports the idea that the area upstream from the Falls on the Brazos State Park in Falls County may not the best part of the aquifer.

In order to estimate the volume of available water in the Brazos River Alluvium aquifer, the thickness of the saturated section needs to be determined. The groundwater exists under water table conditions and thickness of the saturated section fluctuates in response to climate, seasonal weather patterns and changing land use. Figure 23 is an estimation of the saturated thickness of groundwater in the Brazos River Alluvium aquifer, which ranges from 0.25 to 60 feet with an average of 25 feet. Saturated thickness patterns mirror alluvium thickness patterns. Saturated thickness is shallowest in the northern part of the study area around Waco, and is deepest towards Marlin in Falls County. Related to the saturated thickness of the aquifer is the depth to the water table from ground surface; Figure 24 is an estimation of depth of groundwater across the study area. Depth of groundwater ranges from 0.036 to 39 feet, with a mean depth of 18 feet.

Water level data were used to generate estimations of saturated thickness and depth of groundwater across the study area. The water level data were not collected in the same sampling period; rather they were taken after each well was completed. Nevertheless these data are useful because it is apparent from historical hydrographs (Figure 26 and 27) that the Brazos River Alluvium aquifer has not experienced a steady decline in water level as a result of pumping, such as that observed in the Trinity Aquifer (Figure 2). Rather, the aquifer experiences seasonal fluctuations largely in response to precipitation patterns (Figure 25). Annual hydrographs from several wells in McLennan and Falls Counties show that groundwater level fluctuations generally do not exceed 10 feet (Figure 26 and 27). This is also supported by data from the 1960's; annual hydrographs from several wells in McLennan and Falls Counties also show groundwater level fluctuations of around 10 feet or less (Cronin and Wilson, 1967).

Knowing that the aquifer experiences regular seasonal fluctuations in water level, average saturated thickness should not be the only parameter used to determine the volume of usable water. It would be useful particularly in resource planning to account for a high and low saturated thickness as well. Looking at historical hydrographs, groundwater levels did not vary in range by more than 10 feet (Figures 26 and 27), and therefore levels of +/- 5 feet may be suitable seasonal thresholds for managing groundwater levels.

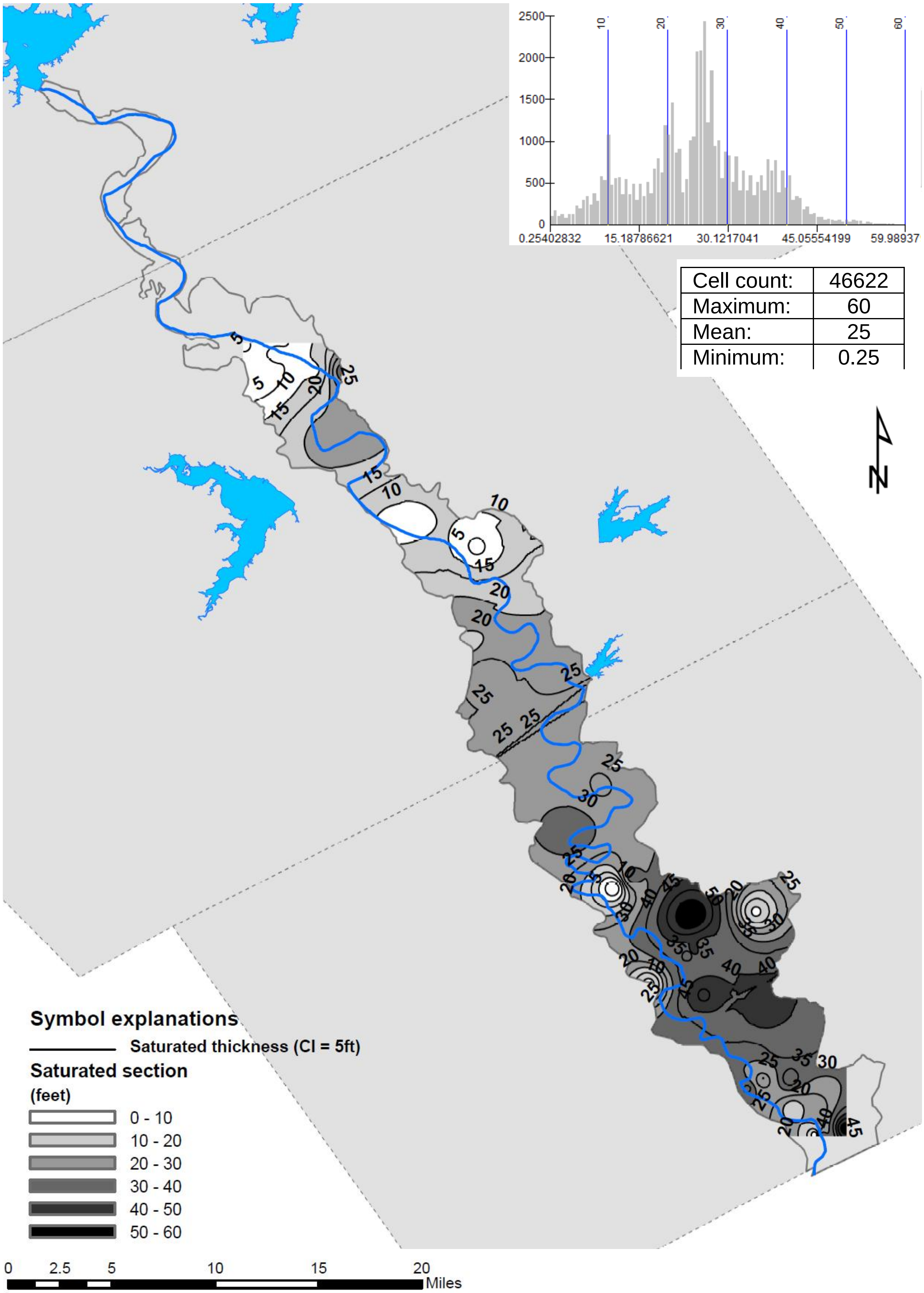

Figure 23. Saturated thickness of groundwater in the Brazos River Alluvium aquifer. Contour interval is 5 feet.

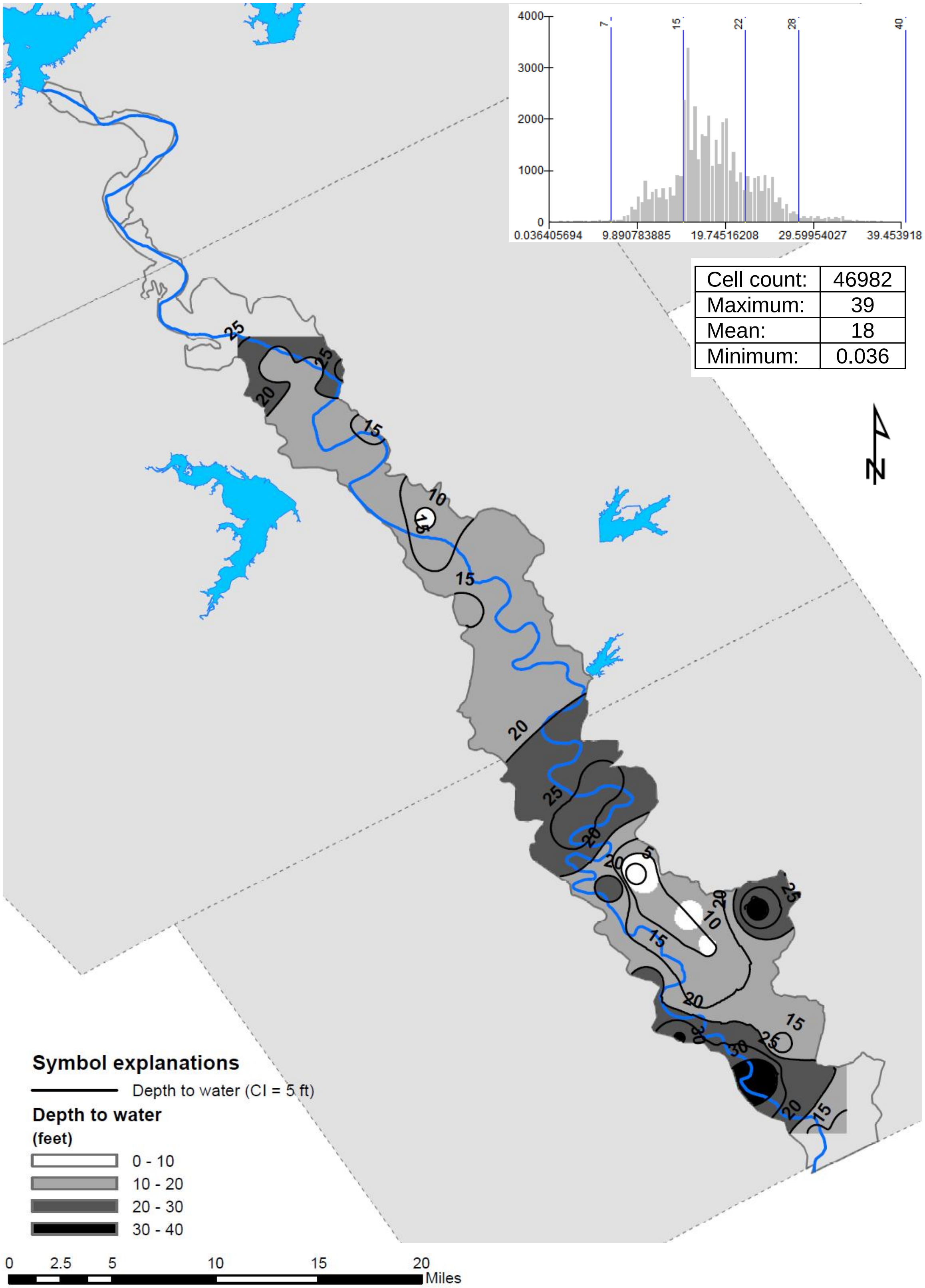

Figure 24. The depth to groundwater in the Brazos River Alluvium aquifer. Contour interval is 5 feet.

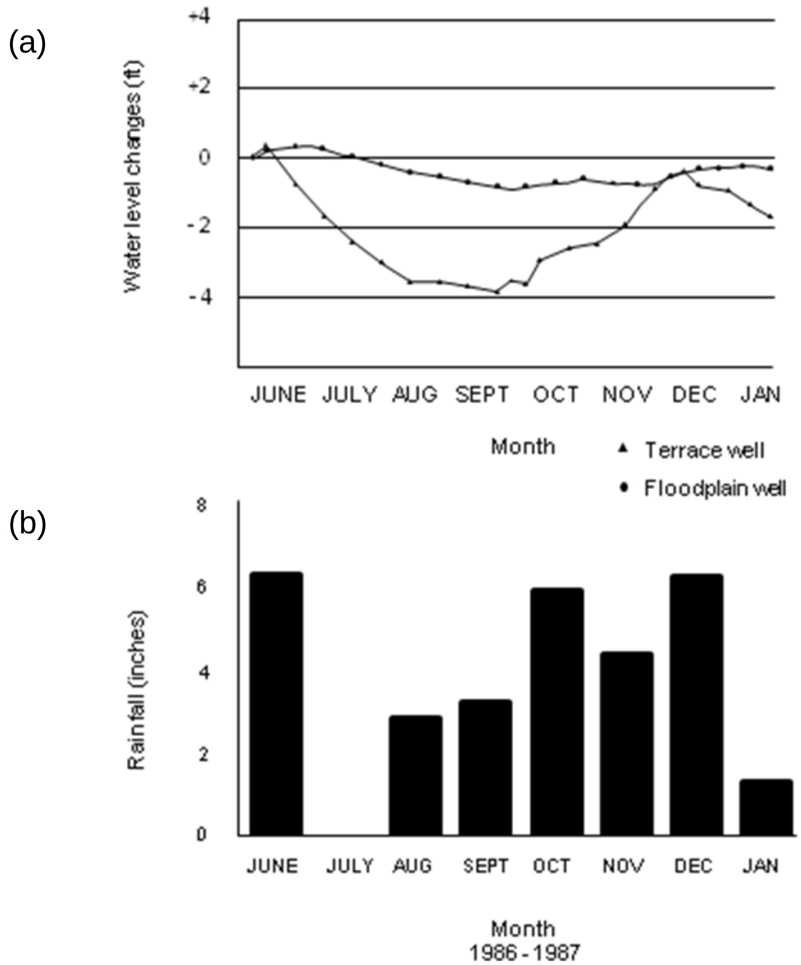

Figure 25. (a) Monthly hydrographs of wells completed in the Brazos River Alluvium aquifer. (b) A histogram of monthly rainfall amounts in inches (Harlan, 1990). Water level in the terrace well appeared to be closely tied to rainfall, while water level in the floodplain well remained fairly constant throughout the sampling period.

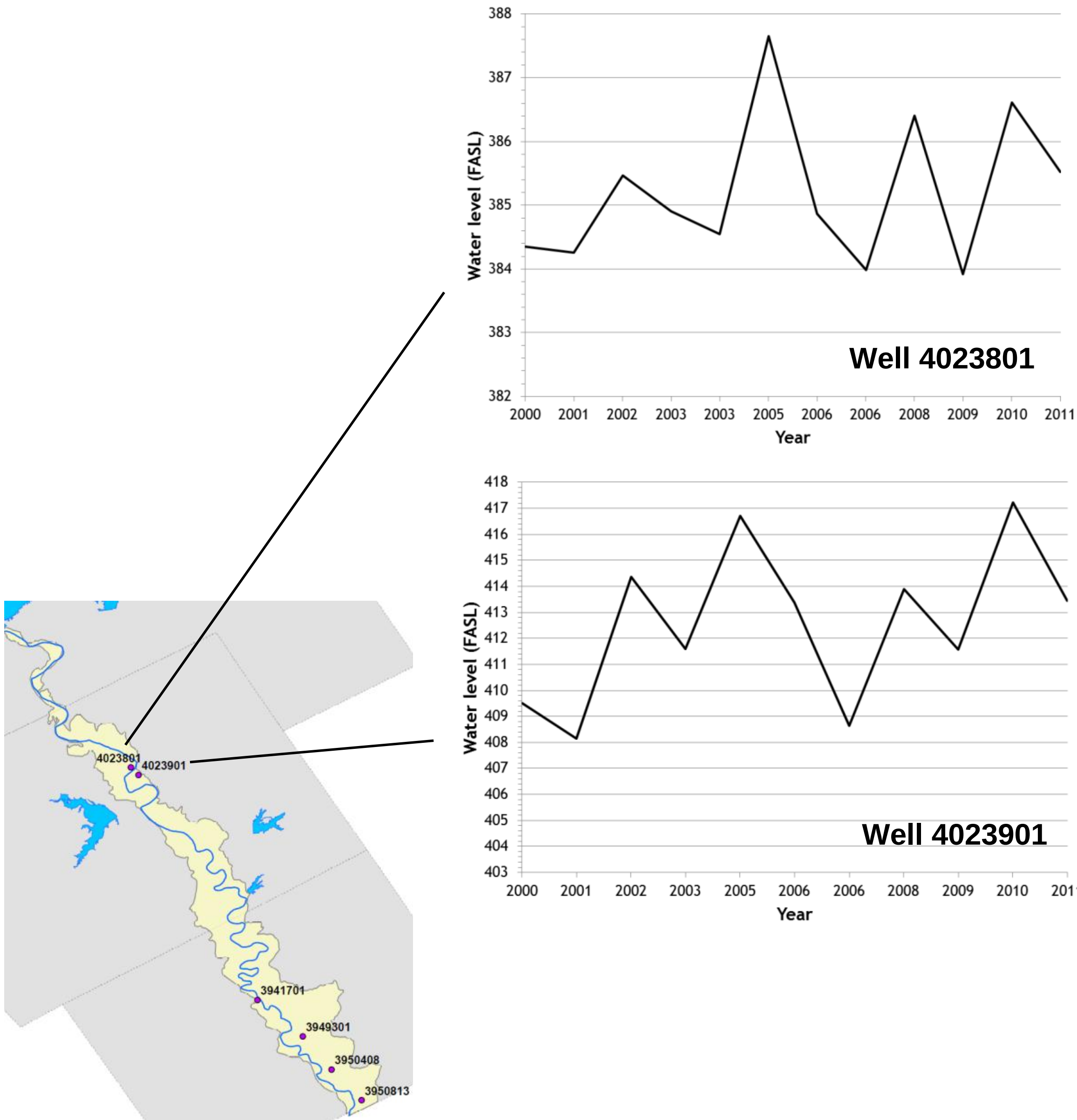

Figure 26. Annual hydrographs for two wells in McLennan County.

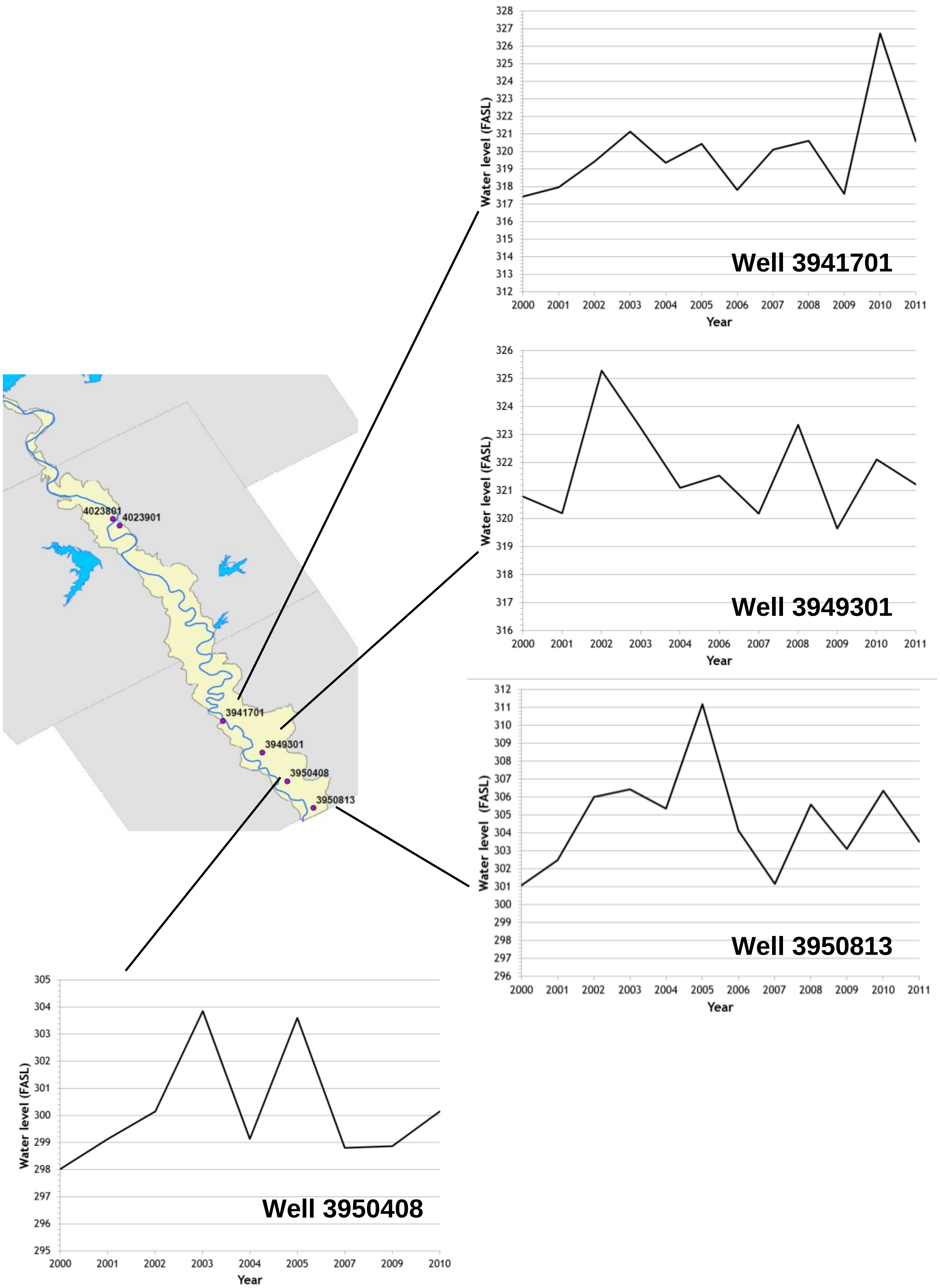

Figure 27. Annual hydrographs for four wells in Falls County.

Utilizing data generated from the interpolations, the volume of groundwater in the Brazos River Alluvium aquifer for the study area was calculated. Aquifer volume is the product of the study area and saturated thickness, multiplied by the specific yield of the alluvial sediments (15%). The volume of the Brazos River Alluvium aquifer within the study area was computed to be 6.2 x 10^5 acre feet. Cronin and Wilson (1967) calculated 2,760,000 acre feet for the entire Brazos River Alluvium aquifer from Bosque to Fort Bend County. The aquifer volume calculated for the study area is approximately 22% of the volume determined by Cronin and Wilson (1967). Considering that the study area is roughly a third of the total extent studied by Cronin and Wilson and that the study area represents the thinnest and narrowest portion of the Brazos River Alluvium aquifer, 6.2 x 10^5 acre feet is a comparable volume.

A groundwater elevation map for the eastern Brazos River floodplain in Falls County is shown in Figure 28. This portion of the study area was chosen because it had the best distribution of datapoints from which to create a groundwater elevation surface. Arrows running perpendicular to groundwater elevation contour lines show that groundwater flows down-valley and toward the Brazos River. This is in agreement with previous mapping that had been done in McLennan County by Harlan (1985, 1990).

A land use activity currently affecting the Brazos River Alluvium aquifer is floodplain mining of sands and gravels; therefore an attempt was made to quantify the impact of alluvial mining on the extent and volume of the Brazos River Alluvium aquifer. Historical aerial photos from 1941 and 1972 were only obtained for McLennan County. However, a preliminary survey of 2010 aerial imagery for the study area shows that the majority of mining activity takes place in McLennan County, around the Waco region. It

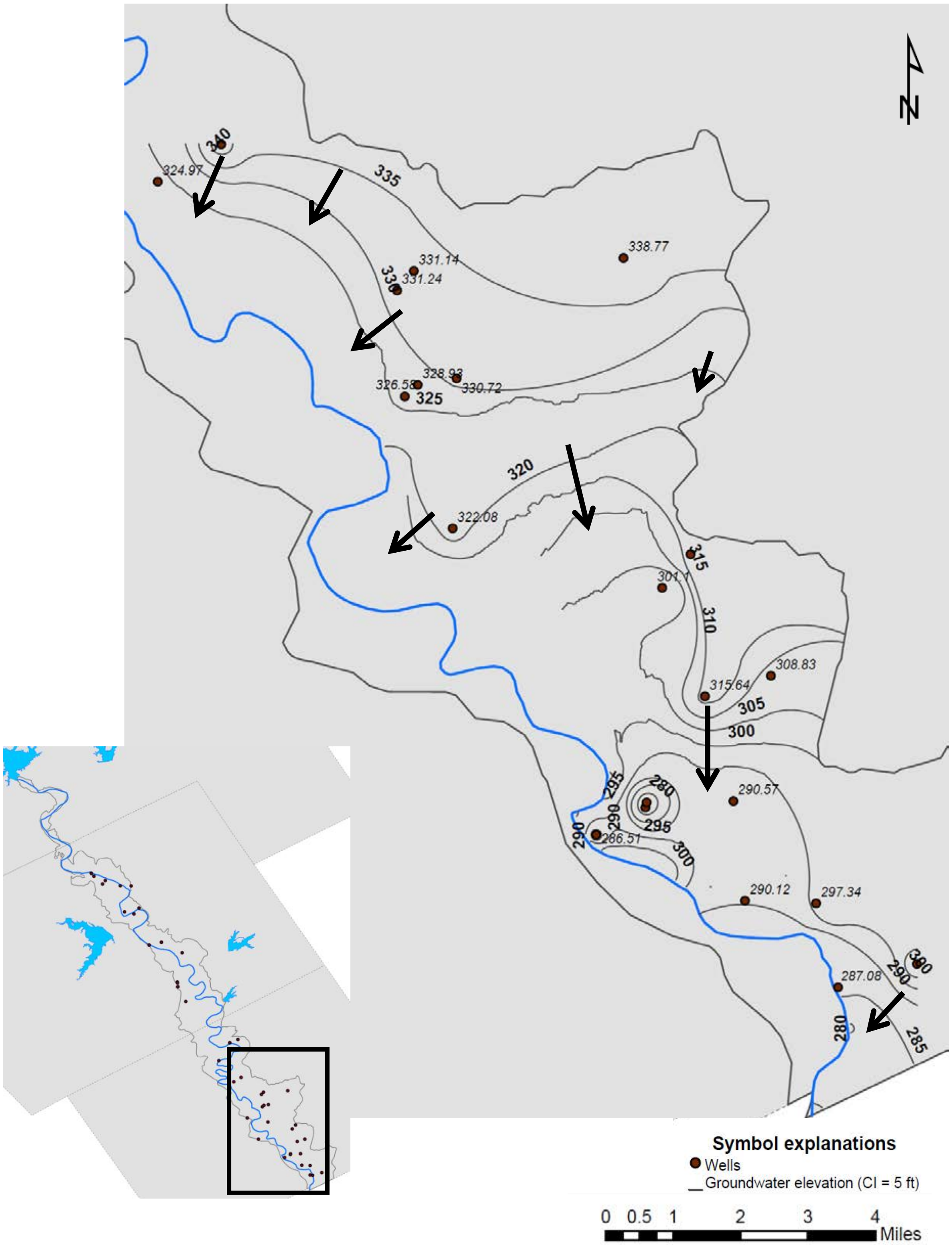

Figure 28. Groundwater elevation map of the eastern floodplain in Falls County. Arrows show that groundwater flow is generally down-valley and towards the Brazos river.

is likely that analysis of McLennan County images sufficiently captures most of the temporal change in sand and gravel mining within the study area.

The focal area of Brazos River Alluvium aquifer examined for sand and gravel extraction sites in McLennan County encompassed 47 square miles. Figure 29 shows the location of extraction sites for each time step. In 1941, the total impacted area was 0.14 square miles, which was 0.3% of the focal area. In 1972, the total impacted area was 1.31 square miles, which was 2.87% of the focal area. In 1996, the total impacted area was 2.53 square miles, which was 5.53% of the focal area. In 2010, the area of new excavation sites was negligible, and the total impacted area remained unchanged (2.53 square miles; 5.53% of the focal area).

Through these time-steps, it is apparent that sand and gravel mining in the Brazos river floodplain increased through time. A plot of the cumulative area mined through time shows that the overall area impacted by floodplain sand and gravel mining increases linearly between each time-step. Meanwhile the slope between each data point indicates that the rate at which new excavation sites are opened varies over time and has decreased recently (Figure 30). The increase in cumulative area impacted is explained by the expansion of previously mapped sand and gravel mining operations, as well as an increase in the number of mining operations through time. As the size and number of excavations increase, the area of floodplain that is suitable for mining sand and gravel decreases; this may explain the lessening of newly-impacted areas through time. Gravel mining is tied somewhat to the economy and development. The period between 1941 and 2010 also saw the increased urban development of Waco and surrounding communities. This development occurred mostly in the southern part of McLennan County, and

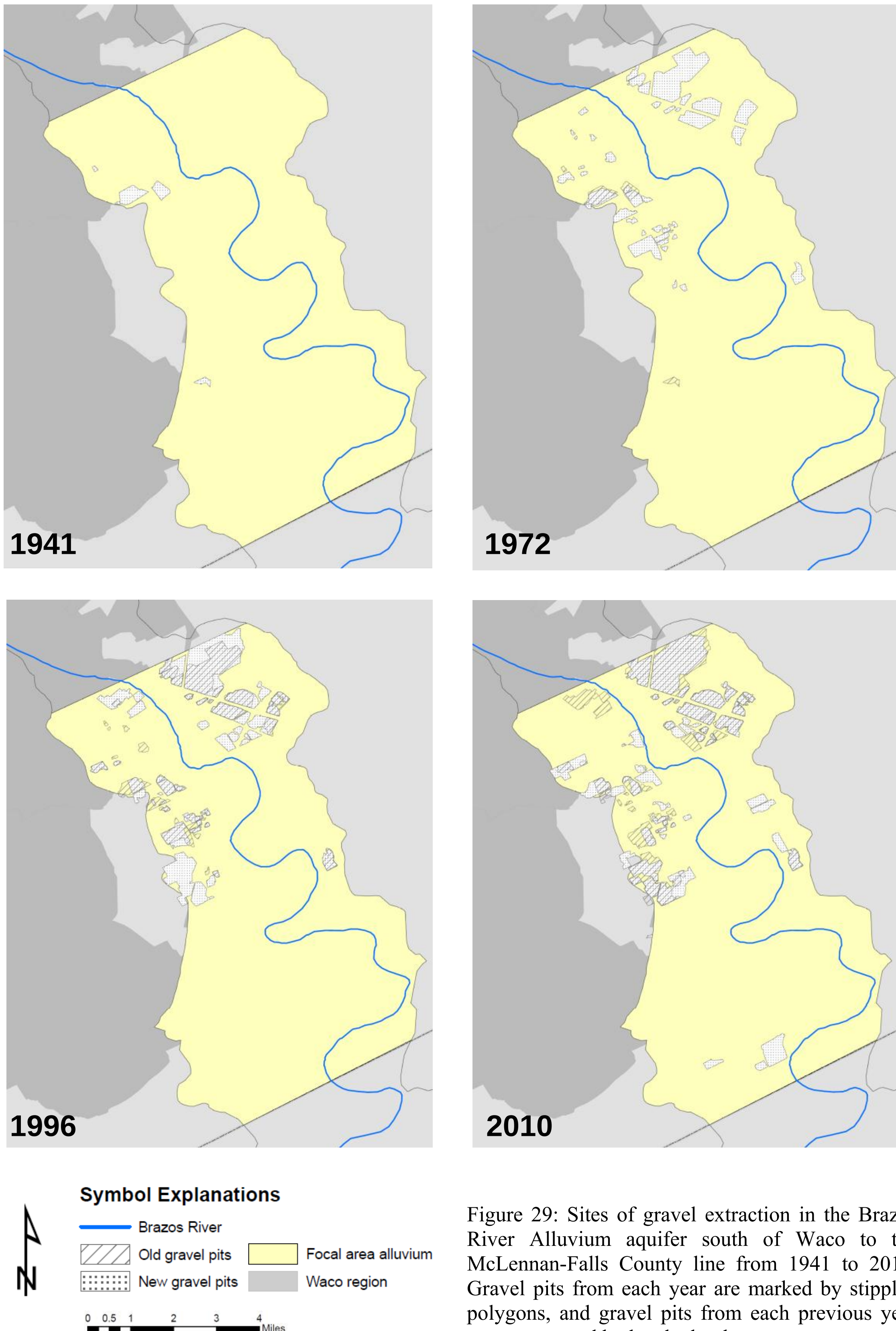

Figure 29: Sites of gravel extraction in the Brazos River Alluvium aquifer south of Waco to the McLennan-Falls County line from 1941 to 2010. Gravel pits from each year are marked by stippled polygons, and gravel pits from each previous year are represented by hatched polygons.

resulted in less available floodplain for sand and gravel extraction. In addition, gravel has been shipped by rail to the Dallas- Fort Worth area, and trucked to other cities within 50-100 miles. Also some sand and gravel is mined and stock-piled, thereby temporarily mitigating the impacts of the economy. A decrease in the rate of sand and gravel mining over time may be the combined result of continued mining activities, urban development, and stockpiling.

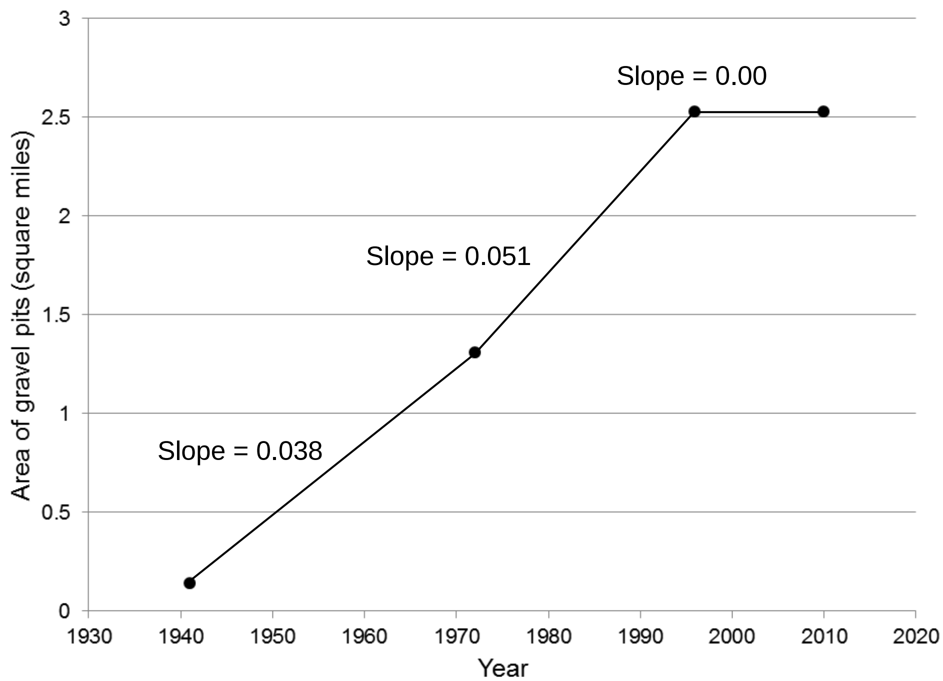

Figure 30. Amount of focal area lost through mining from 1941 to 2010. The series shows the overall increase of impacted alluvium from 1941 to 2010, while the slope of the line shows that the amount of newly-mined alluvium varies through time (rate of mining per year is indicated by the slope of each section of the graph).

Knowing the total area of alluvium that has been removed, the change in aquifer volume can be computed to quantify the impact of floodplain sand and gravel mining on the Brazos River Alluvium aquifer. Taking into account the volume of alluvium mined in 1941, aquifer volume was 3.91×10^4 acre feet. Taking into account the total mined volume in 1972, aquifer volume was 3.77×10^4 acre feet. Aquifer volume was 3.63×10^4

acre feet after taking out mines in 1996. As of 2010, aquifer volume is 3.61 x 10^4 acre feet. Table 2 summarizes the volume and percentages of aquifer removed.

In comparing the area of aquifer lost to the volume of aquifer lost to sand and gravel mining, it is evident that more productive aquifer is being lost than areal extent alone would indicate. Even though new mining was negligible from 1996 to 2010 in terms of area, volumetric calculations indicate that the volume of aquifer removed nevertheless increased (Table 2). Furthermore, mining areas coincide with the most productive areas of the aquifer, because these are where the coarse fraction of alluvium is located.

A driving trip was undertaken in September 2011 to field check for accuracy of the heads-up digitizing of gravel pits in the study area. Attempts were made to verify 53 out of 63 digitized sand and gravel extraction sites. 83% of the sites were found (that is, 9 sites were either not found or not accessible), suggesting that heads-up digitizing is an effective method for capturing the extent of floodplain sand and gravel mining. It is possible that digitization accuracy is greater than 83%, considering that some excavation sites were not verified due to inaccessibility.

The presence of landfills completed in former excavation pits is another factor affecting not only the physical extent of the Brazos River Alluvium aquifer, but the production potential and water quality in the aquifer. Landfill areas diminish the productive area of the aquifer since wells cannot be completed in a former landfill. The presence of landfills further diminishes the area of productive aquifer because well drillers and owners will not choose to drill water wells adjacent to landfills. Additionally, the contamination potential from landfills may be of concern. Pinkus (1987) compared

Table 2. Summary table of volume calculations.

Year	Aquifer remaining (acre feet)	Total volume removed (acre feet)	% volume removed
Focal area*0.15	39196	--	--
1941	39075	121	0.31
1972	37748	1447	3.69
1996	36285	2911	7.43
2010	36094	3101	7.91

TDS, specific conductance, sulfate, chloride and sodium in wells up-gradient and down-gradient from three municipal solid waste disposal sites located in the Brazos alluvium. Pinkus (1987) determined that the landfills affected water quality down-gradient from the disposal sites. Locations of registered sanitary municipal landfills in McLennan County are shown in Figure 31. Most of the documented landfills (6 out of 7) are located on the western floodplain. A possible explanation for this clustering of landfills is the proximity to Waco; old gravel pits on the eastern floodplain are not utilized as heavily since there are fewer major roads crossing the floodplain alluvium on the east side of the river near Waco. From reported values, the total area of these landfills equaled 0.30 square miles, or 0.62% of the alluvium area. This value is not expected to increase, as sanitary municipal landfills are no longer being sited or permitted within the floodplain. Even though the footprint of these landfills is small, their impact on the area of productive alluvium is likely greater than the physical boundaries of the sites due to the perceived and actual impact on groundwater quality.

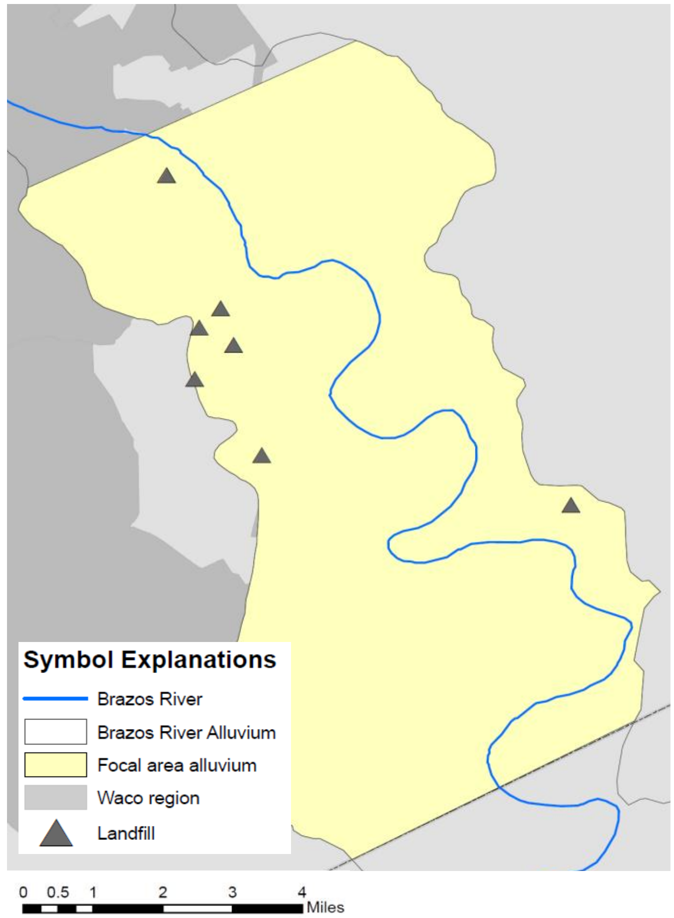

Figure 31. Registered landfills (open and closed) within the focal area alluvium.

CHAPTER FOUR

Summary and Conclusions

1. The boundary of the Brazos River Alluvium aquifer was refined. Before refinement, the aquifer boundary encompassed an area of 226 square miles. The adjusted aquifer boundary encompassed an area of 227 square miles. Even though there is little difference overall in the study area, these boundary adjustments may be important particularly at local scales.
2. Well depth can be a reasonable indicator of alluvium thickness under certain conditions. Where the alluvium is thin, the alluvial sequence exhibits a fining-upward sequence and is underlain by a confining unit; well depth provides a reasonable estimation of alluvium depth. A comparison of interpolated depths and lithological depths yielded an R^2 value of 0.5. Since information on well depth is often more easily-accessible than lithological logs in many aquifer areas, it may be a proxy for lithological information on alluvium thickness.
3. Floodplain sand and gravel mining has had a significant impact on the volume of the Brazos River Alluvium aquifer in the focal area south of Waco. Removal of aquifer material ultimately impacts the volume of groundwater that can be stored in the alluvium. As of 2010, the volume of the Brazos River Alluvium aquifer was 3.61×10^4 acre feet in the area south of Waco. This is about 3000 acre feet less than the computed volume of the aquifer un-impacted by mining activities (3.92×10^4 acre feet). In addition, the use of abandoned gravel pits as solid waste disposal sites may

have impacted water quality in a greater area of aquifer than the physical footprint of the landfills themselves, decreasing volume even more.

4. Geospatial tools were useful for defining and quantifying change in the Brazos River Alluvium aquifer. Specifically, they characterized the areal and volumetric impact of floodplain sand and gravel mining on the aquifer, and were able to show how impact changed through a period of 69 years. Heads-up digitization allowed for the identification of excavation sites to possibly greater than 83% accuracy. Geospatial tools efficiently and quantitatively analyzed a large study area. Databases established in this study, coupled with geospatial tools, will allow efficient incorporation of future data to improve analytical results and characterize further change in the Brazos River Alluvium aquifer.

CHAPTER FIVE

Recommendations

1. The database and maps that have been created can be useful management tools for conservation districts. As such, personnel at the districts need to be able to use appropriate software to maintain the database and reproduce current maps.
2. Because the Brazos River Alluvium aquifer is an unconfined system that experiences seasonal fluctuations in water level, seasonal averages – not an annual average – should be taken into consideration when making decisions on water management.
3. Due to the seasonal fluctuation and lithological heterogeneity in the Brazos River Alluvium aquifer, a fairly extensive monitoring network would be helpful in tracking aquifer changes and mapping groundwater flow. Because of the comparative shallow depth of the aquifer, a fairly extensive monitoring network should be feasible to implement and maintain.
4. In the future, attempts should be made to characterize and quantify recharge to the Brazos River Alluvium aquifer in the study area. Doing so will be useful for informing decisions on permitted pumping amounts and provide further understanding of the groundwater system in the Brazos River Alluvium aquifer. Understanding the effect of impervious surfaces resulting from development on the recharge of shallow aquifers is another research area that is relevant to the Brazos River Alluvium aquifer.

APPENDICES

APPENDIX A

Water Well Depths Used in Alluvium Thickness Proxy (n = 256)

Well Number	Owner	Primary Use	Elevation	Well Depth	Aquifer	Latitude	Longitude
3958209	Morse Scarmado	IRRIGATION	311	46	111ABZR	310642	964930
3958204	F. Abate	IRRIGATION	310	50	111ABZR	310657	964901
3958210	Tom Kelly, Jr	IRRIGATION	313	54	111ABZR	310714	964834
3950815		IRRIGATION	313	18	111ABZR	310734	964858
3950814	C.E. Dillon	IRRIGATION	310	42	111ABZR	310736	964737
3950905	C.E.Dillion	IRRIGATION	309	43	111ABZR	310737	964729
3950708	U.S.G.S.	UNUSED	322	21	111ABZR	310742	965012
3950810	Tony Abate	STOCK	316	43	111ABZR	310747	964820
3950813	Charles Fazz	UNUSED	317	49	111ABZR	310749	964836
3950812	Tony Abate	IRRIGATION	316	58	111ABZR	310750	964842
3950811	Tony Abate	UNUSED	316	45	111ABZR	310751	964827
3950820	Tony Abate	IRRIGATION	316	18	111ABZR	310757	964831
3950906	M. Scarmardo	IRRIGATION	310	56	111ABZR	310758	964719
3950822	U.S.G.S.	UNUSED	321	20	111ABZR	310801	964935
3950819		IRRIGATION	312	30	111ABZR	310804	964907
3950904		IRRIGATION	311	62	111ABZR	310804	964714
3950807	Tony Abate	IRRIGATION	313	60	111ABZR	310808	964746
3950808	Tony Abate	IRRIGATION	316	64	111ABZR	310809	964813
3950809	Tony Abate	IRRIGATION	317	49	111ABZR	310814	964824
3950823	U.S.G.S.	UNUSED	313	41	111ABZR	310815	964908
3950821	U.S.G.S.	UNUSED	315	56	111ABZR	310817	964902
3950804	Mrs. Sam Palasata	IRRIGATION	315	62	111ABZR	310822	964859
3950803	J.C. Salvato	UNUSED	316	63	111ABZR	310826	964905
3950818	Falco	IRRIGATION	316	59	111ABZR	310829	964829
3950806	Tony Abate	IRRIGATION	312	58	111ABZR	310831	964753
3950824	U.S.G.S.	UNUSED	316	66	111ABZR	310833	964838
3950817		IRRIGATION	315	54	111ABZR	310841	964828
3950902	Tony Abate	IRRIGATION	310	60	111ABZR	310843	964727
3950825	U.S.G.S.	UNUSED	313	42	111ABZR	310845	964810
3950903	Tony Abate	IRRIGATION	311	32	111ABZR	310849	964710
3950816		IRRIGATION	312	36	111ABZR	310850	964732
3950827	U.S.G.S.	IRRIGATION	316	34	111ABZR	310859	964745
3950909	Tony Abate	IRRIGATION	311	16	111ABZR	310859	964710
3950826	U.S.G.S.	UNUSED	312	41	111ABZR	310905	964738

Continued

Well Number	Owner	Primary Use	Elevation	Well Depth	Aquifer	Latitude	Longitude
3950901	Basil Abate	IRRIGATION	311	38	111ABZR	310916	964724
3950911	U.S.G.S.	UNUSED	307	32	111ABZR	310917	964710
3950805	J.C. Salvato	IRRIGATION	314	36	111ABZR	310920	964747
3950801		IRRIGATION	320	45	111ABZR	310937	964949
3950706		IRRIGATION	321	45	111ABZR	310942	965023
3950701	J.T. Falco	IRRIGATION	316	58	111ABZR	310944	965146
3950802	Barganier Farm	IRRIGATION	316	60	111ABZR	310945	964913
3950704	J.T. Palco	IRRIGATION	319	16	111ABZR	310951	965051
3950705		IRRIGATION	322	65	111ABZR	310953	965036
3950702	J.T. Falco	UNUSED	318	57	111ABZR	310955	965128
3950703	J.T. Palco	IRRIGATION	316	57	111ABZR	310956	965114
3950411	J. T. Falco	IRRIGATION	316	61	111ABZR	311004	965146
3950412	J.T. Falco	IRRIGATION	318	59	111ABZR	311004	965057
3950414		UNUSED	315	42	111ABZR	311011	965224
3950501	LaBarbera Farms	IRRIGATION	318	31	111ABZR	311016	964914
3950413	Louisa Musia	IRRIGATION	319	59	111ABZR	311018	965026
3950428	Falsone Bros.	DOMESTIC	322	32	111ABZR	311020	965006
3950502	Falsone Bros.	IRRIGATION	318	35	111ABZR	311020	964919
3950419		IRRIGATION	319	41	111ABZR	311021	965059
3950503		STOCK	315	31	111ABZR	311024	964854
3950410	J.T. Falco	IRRIGATION	315	61	111ABZR	311026	965152
3950418		IRRIGATION	319	52	111ABZR	311029	965034
3950408	La Barbera Farms	UNUSED	319	50	111ABZR	311042	965124
3950416		IRRIGATION	322	51	111ABZR	311044	965014
3950415		IRRIGATION	319	53	111ABZR	311048	965123
3950420		IRRIGATION	323	53	111ABZR	311053	965045
3950422		IRRIGATION	324	42	111ABZR	311105	965115
3950406	Falsone Bros.	IRRIGATION	323	58	111ABZR	311107	965027
3950407	Falsome Bros.	IRRIGATION	320	58	111ABZR	311111	965015
3950421		IRRIGATION	324	42	111ABZR	311115	965104
3949606	U.S.G.S.	UNUSED	324	32	111ABZR	311135	965309
3950417	D. Woodfin	IRRIGATION	322	43	111ABZR	311135	965006
3950404	D.M. Woodfin	IRRIGATION	324	39	111ABZR	311148	965028
3950423		IRRIGATION	322	41	111ABZR	311149	965132
3950405	D.M. Woodfin	UNUSED	324	43	111ABZR	311151	965023
3949602	Falco	UNUSED	324	43	111ABZR	311152	965237

Continued

Well Number	Owner	Primary Use	Elevation	Well Depth	Aquifer	Latitude	Longitude
3949605	U.S. Geological Survey	UNUSED	325	37	111ABZR	311159	965243
3950424	Falco	IRRIGATION	323	36	111ABZR	311159	965139
3950425		UNUSED	325	30	111ABZR	311203	965152
3950403	J. Salpetro	IRRIGATION	326	39	111ABZR	311220	965201
3950401	J.Salpetro	STOCK	328	45	111ABZR	311221	965158
3950427	U.S.G.S.	UNUSED	323	36	111ABZR	311222	965206
3950109	U.S.G.S.	UNUSED	328	45	111ABZR	311235	965135
3950102		IRRIGATION	326	52	111ABZR	311241	965017
3950103	Green	DOMESTIC	327	52	111ABZR	311243	965058
3950108	U.S.G.S.	UNUSED	327	58	111ABZR	311252	965105
3949302	C.E. Barganier	IRRIGATION	330	41	111ABZR	311254	965348
3949303	C.E. Barganier	DOMESTIC	330	40	111ABZR	311254	965339
3950107	U.S. G.S.	UNUSED	323	51	111ABZR	311309	965035
3950106	U.S.G.S.	UNUSED	324	62	111ABZR	311319	965012
3950205	U.S.G.S.	UNUSED	328	51	111ABZR	311332	964950
3949301	Moody Ranch	IRRIGATION	333	48	111ABZR	311347	965406
3950101	C.E. Barganier	STOCK	322	45	111ABZR	311353	965139
3949205	U.S. Geological Survey	UNUSED	355	28	111ABZR	311429	965641
3949204	U.S. Geological Survey	UNUSED	345	18	111ABZR	311441	965614
3949304		STOCK	336	24	111ABZR	311441	965429
3949201	N.P. Nehring	STOCK	335	19	111ABZR	311450	965553
3949202		UNUSED	335	19	111ABZR	311453	965546
3949203	U.S. Geological Survey	UNUSED	335	17	111ABZR	311454	965550
3941802	U.S. Geological Survey	UNUSED	333	22	111ABZR	311504	965524
3941907	U.S. Geological Survey	UNUSED	340	43	111ABZR	311517	965454
3941903	Frank Denena	IRRIGATION	338	16	111ABZR	311537	965435
3941902	Frank Denena	IRRIGATION	340	54	111ABZR	311544	965428
3941908	Margie Kramer	IRRIGATION	338	43	111ABZR	311557	965412
3941906	U.S. Geological Survey	UNUSED	336	45	111ABZR	311601	965401
3941905	U.S. Geological Survey	UNUSED	343	17	111ABZR	311608	965355
3941904	Shaw	DOMESTIC	364	32	111ABZR	311635	965322
3941901	T.B. Westbrook	IRRIGATION	333	28	111ABZR	311638	965236
3941801	Bill Dunkum	STOCK	339	65	111ABZR	311641	965506

Continued

Well Number	Owner	Primary Use	Elevation	Well Depth	Aquifer	Latitude	Longitude
3941708	U.S. Geological Survey	UNUSED	343	37	111ABZR	311716	965812
3941709	U.S. Geological Survey	UNUSED	344	35	111ABZR	311721	965757
3941702		STOCK	344	28	111ABZR	311725	965755
3941710	U.S. Geological Survey	UNUSED	342	32	111ABZR	311727	965734
3941601	H.H. Wornat	IRRIGATION	340	26	111ABZR	311733	965407
3941515	U.S. Geological Survey	UNUSED	343	37	111ABZR	311735	965709
3941510	U.S. Geological Survey	UNUSED	345	36	111ABZR	311741	965647
3941511	U.S. Geological Survey	UNUSED	344	35	111ABZR	311746	965626
3941507		STOCK	347	33	111ABZR	311748	965615
3941509		STOCK	347	30	111ABZR	311750	965620
3941512	U.S. Geological Survey	UNUSED	343	38	111ABZR	311752	965610
3941513	U.S. Geological Survey	UNUSED	343	44	111ABZR	311757	965552
3941514	U.S. Geological Survey	UNUSED	343	49	111ABZR	311808	965514
3941605	U.S. Geological Survey	UNUSED	341	53	111ABZR	311813	965458
3941504	C.M. Mears	IRRIGATION	347	52	111ABZR	311815	965533
3941606	U.S. Geological Survey	UNUSED	339	61	111ABZR	311816	965438
3941401	Smithwick Farms	IRRIGATION	354	44	111ABZR	311820	965822
3941501	L.O. Hay, Jr.	STOCK	349	62	111ABZR	311820	965626
3941402	Smithwick Farms	STOCK	354	46	111ABZR	311824	965849
3941505	C.M. Mears	IRRIGATION	348	64	111ABZR	311828	965538
3942403	J.W. Fillip	DOMESTIC	393	18	111ABZR	311828	965152
3941502	L.O. Hay, Jr.	IRRIGATION	349	55	111ABZR	311839	965715
3941403	Smithwick Farms	STOCK	352	35	111ABZR	311840	965859
3941404	U.S. Geological Survey	UNUSED	350	22	111ABZR	311940	965814
3941503	Duncan Farms	IRRIGATION	349	42	111ABZR	311955	965653
3941405		DOMESTIC	350	25	111ABZR	311958	965751
3941201	U.S. Geological Survey	UNUSED	350	34	111ABZR	312028	965723
3941102	George Scholander	STOCK	353	34	111ABZR	312144	965919
3941101	H.L. Safford	IRRIGATION	359	45	111ABZR	312159	965947
4048301	Jack Davis	IRRIGATION	355	45	111ABZR	312214	970044

Continued

Well Number	Owner	Primary Use	Elevation	Well Depth	Aquifer	Latitude	Longitude
3933701	Hal C. Mitchell	UNUSED	359	58	111ABZR	312250	965810
4040803	Lankart Seed Farm	IRRIGATION	376	28	111ABZR	312433	970236
4040802	Lankart Seed Farm	IRRIGATION	376	22	111ABZR	312437	970242
4040801	Paul Brown	UNUSED	397	51	111ABZR	312438	970340
4040902	Lankart Seed Farm	IRRIGATION	368	18	111ABZR	312439	970219
4040901	Lankart Seed Farm	IRRIGATION	368	18	111ABZR	312442	970222
4040903	Lankart Seed Farm	IRRIGATION	367	20	111ABZR	312444	970209
4040904	Lankart Seed Farm	IRRIGATION	366	19	111ABZR	312446	970204
4040602	Lankart Seed Farm	IRRIGATION	368	16	111ABZR	312503	970217
4040603	Lankart Seed Farm	IRRIGATION	368	18	111ABZR	312503	970217
4040605	Lankart Seed Farm	UNUSED	366	18	111ABZR	312504	970146
4040514	U.S.G.S.	UNUSED	397	66	111ABZR	312512	970344
4040501	Jess Radle	UNUSED	375	43	111ABZR	312526	970315
4040512		UNUSED	390	13	111ABZR	312530	970345
4040515	U.S.G.S.	UNUSED	376	36	111ABZR	312530	970301
4040506	Jess Radle	IRRIGATION	379	36	111ABZR	312541	970335
4040601	Howell & Anderson	IRRIGATION	369	28	111ABZR	312542	970204
4040505	Jess Radle	IRRIGATION	377	35	111ABZR	312546	970325
4040504	Jess Radle	IRRIGATION	376	34	111ABZR	312551	970315
4040516	U.S.G.S.	UNUSED	369	32	111ABZR	312551	970237
4040503	Jess Radle	IRRIGATION	375	35	111ABZR	312555	970305
4040513	Jess Radle	IRRIGATION	376	36	111ABZR	312556	970324
4040502	Jess Radle	IRRIGATION	375	35	111ABZR	312558	970256
4040508	Citizens National Bank	IRRIGATION	378	40	111ABZR	312601	970329
4040507	Citizens National Bank	IRRIGATION	375	35	111ABZR	312602	970319
4040606	U.S.G.S.	UNUSED	370	32	111ABZR	312605	970203
4040607	U.S.G.S.	UNUSED	368	32	111ABZR	312614	970141
4040608	U.S.G.S.	UNUSED	368	33	111ABZR	312626	970113
4040609	U.S.G.S.	UNUSED	367	34	111ABZR	312640	970043
4040509	Citizens National Bank	IRRIGATION	369	44	111ABZR	312651	970240
3933401	U.S.G.S	UNUSED	361	54	111ABZR	312654	965952
4040510		UNUSED	373	51	111ABZR	312720	970337
4040604	Warner	DOMESTIC	370	56	111ABZR	312725	970117
4040202	Jess Radle	IRRIGATION	395	38	111ABZR	312935	970429
4040201	Jess Radle	IRRIGATION	393	35	111ABZR	312941	970416
4040203	Jess Radle	UNUSED	394	39	111ABZR	312947	970419
4032902	Smith & Poage	IRRIGATION	381	27	111ABZR	313029	970204

Continued

Well Number	Owner	Primary Use	Elevation	Well Depth	Aquifer	Latitude	Longitude
4032901	Smith & Poage	IRRIGATION	381	27	111ABZR	313034	970159
4032805	Wind	IRRIGATION	381	44	111ABZR	313040	970307
4032804		UNUSED	395	18	111ABZR	313042	970449
4032904	Bierson	UNUSED	380	15	111ABZR	313042	970146
4032806		STOCK	383	35	111ABZR	313055	970345
4032807		STOCK	382	44	111ABZR	313105	970322
4032703	Dave Simon	IRRIGATION	388	50	111ABZR	313130	970509
4032801	Citizens National Bank	IRRIGATION	387	53	111ABZR	313140	970347
4032707		UNUSED	387	24	111ABZR	313146	970533
4032706		UNUSED	387	22	111ABZR	313151	970532
4032802	Orvid Youngblood	IRRIGATION	380	47	111ABZR	313208	970411
4032704		UNUSED	392	20	111ABZR	313210	970554
4032705	Williamson	DOMESTIC	387	43	111ABZR	313217	970526
4032903	Wardlaw	UNUSED	379	21	111ABZR	313217	970208
4032503	Wardlaw	UNUSED	382	21	111ABZR	313232	970241
4032409		IRRIGATION	384	38	111ABZR	313233	970526
4032601	Wardlaw	UNUSED	380	26	111ABZR	313239	970155
4032504	Wardlaw	UNUSED	378	21	111ABZR	313246	970235
4032505	Hicks	UNUSED	392	19	111ABZR	313309	970456
4032602	Wardlaw	UNUSED	383	19	111ABZR	313315	970205
4032401	Edgar Hicks	UNUSED	395	21	111ABZR	313350	970515
4032406	Edgar Hicks	UNUSED	403	23	111ABZR	313359	970531
4032407	Edgar Hicks	UNUSED	412	19	111ABZR	313405	970524
4032408	J. Buchheit	IRRIGATION	417	28	111ABZR	313416	970527
4031307	R. Allsup	UNUSED	400	33	111ABZR	313605	970855
4031205	Melton	DOMESTIC	397	10	111ABZR	313612	971103
4031209	Melton	UNUSED	423	20	111ABZR	313619	971005
4031204	Griffin	DOMESTIC	441	26	111ABZR	313621	971122
4031302	W. Carson	UNUSED	410	21	111ABZR	313622	970938
4031206		UNUSED	441	21	111ABZR	313628	971142
4031306		UNUSED	405	42	111ABZR	313631	970815
4031208	G.W. Taylor	UNUSED	448	45	111ABZR	313635	971104
4031207		UNUSED	454	30	111ABZR	313638	971139
4031303	D.L. Reed	UNUSED	409	27	111ABZR	313642	970857
4031304		UNUSED	409	20	111ABZR	313647	970842
4031305	Melton	UNUSED	404	37	111ABZR	313658	970826
4031308	Wayne Cox	IRRIGATION	400	58	111ABZR	313709	970938
4031202	Washington	UNUSED	456	25	111ABZR	313713	971148

Continued

Well Number	Owner	Primary Use	Elevation	Well Depth	Aquifer	Latitude	Longitude
4031203		UNUSED	437	19	111ABZR	313722	971124
4023803	Wayne Cox	IRRIGATION	405	43	111ABZR	313747	971042
4023806	Wayne Cox	IRRIGATION	0	38	111ABZR	313753	971033
4023804	Wayne Cox	IRRIGATION	407	42	111ABZR	313811	971026
4023808	J. Shakespeare	DOMESTIC	432	80	111ABZR	313813	971209
4023807		DOMESTIC	441	21	111ABZR	313813	971204
4023904	Wayne Cox		435	39	111ABZR	313813	970909
4023802	Wayne Cox	IRRIGATION	404	46	111ABZR	313819	971039
4023901	Wayne Cox	UNUSED	438	43	111ABZR	313825	970932
4023805	Wayne Cox	IRRIGATION	408	43	111ABZR	313828	971028
4023902	Wayne Cox	DOMESTIC	430	36	111ABZR	313832	971000
4023801	G.R. Campbell	UNUSED	410	32	111ABZR	313906	971016
4023811	J. Mitchner	STOCK	0	24	111ABZR	313907	971147
4023809		DOMESTIC	410	19	111ABZR	313920	971151
4023704	John McNamara	DOMESTIC	464	30	111ABZR	313922	971330
4023810	J. Mitchner	STOCK	0	25	111ABZR	313928	971120
4023905	Clark	DOMESTIC	402	25	111ABZR	313942	970940
4023701	Boat Hixson	UNUSED	429	12	111ABZR	313950	971251
4023702		STOCK	436	15	111ABZR	313951	971322
4023505		DOMESTIC	419	28	111ABZR	314008	971041
4023502	Hilton Howell	IRRIGATION	425	26	111ABZR	314010	971209
4023501	Hilton Howell	IRRIGATION	425	22	111ABZR	314014	971203
4023409		STOCK	432	16	111ABZR	314016	971304
4023602	Halbert	DOMESTIC	413	20	111ABZR	314021	970939
4023407	Carney	DOMESTIC	440	18	111ABZR	314036	971327
4023406	J. Ray	DOMESTIC	441	22	111ABZR	314040	971318
4023405	J. Ray	DOMESTIC	414	23	111ABZR	314059	971258
4022604	L.W. Knoll	DOMESTIC	468	32	111ABZR	314102	971502
4023504		UNUSED	416	20	111ABZR	314113	971016
4023503	R.N. McCarthney	UNUSED	420	22	111ABZR	314138	971212
4023402	J. Cox	STOCK	429	21	111ABZR	314149	971443
4022601	H. Kelly	UNUSED	421	32	111ABZR	314153	971621
4023401	J. Cox	UNUSED	440	21	111ABZR	314157	971438
4023403	A.C. York	UNUSED	461	35	111ABZR	314159	971333
4023404	Cassaway	UNUSED	434	34	111ABZR	314202	971259
4022602	H. Slough	UNUSED	453	21	111ABZR	314220	971517
4022305		UNUSED	451	19	111ABZR	314239	971554

Continued

Well Number	Owner	Primary Use	Elevation	Well Depth	Aquifer	Latitude	Longitude
4022303	Nix Bros.	UNUSED	455	31	111ABZR	314246	971618
4023101	Donaldson	DOMESTIC	469	28	111ABZR	314253	971356
4022304	Leif Jensen	UNUSED	452	35	111ABZR	314256	971630
4023105	Jody Remicks	UNUSED	470	30	111ABZR	314302	971406
4022306	C.Bryant	STOCK	439	17	111ABZR	314345	971634
4022201	John S. Harvey	DOMESTIC	478	41	111ABZR	314407	971753
4022301	John S. Harvey	IRRIGATION	435	32	111ABZR	314436	971652
4022302	John S. Harvey	UNUSED	435	40	111ABZR	314438	971648
4014805	Burnett	DOMESTIC	0	10	111ABZR	314532	971758
4014801		DOMESTIC	0	24	111ABZR	314718	971901

APPENDIX B

Water Wells with Lithological Logs (n = 62)

Tracking Number	Latitude	Longitude	Lithology (feet)	
221250	31.378611	-96.976944	0-35	S-Clay & Clay & Sand(B)
			35-51	Gravel
			51-53	Shale
221241	31.378611	-96.976944	0-35	S-Clay & Clay & Sand(B)
			35-51	Gravel
			51-53	Shale
221239	31.378611	-96.976944	0-35	S-Clay & Clay & Sand(B)
			35-51	Gravel
			51-53	Shale
211967	31.262778	-96.913611	0-1	Top Soil
			1-30	Sandy Clay
			30-36	Gravel Sand
			36-56.5	Gravel Sand and Gravel
211966	31.287222	-96.914444	0-1	Top Soil
			1-30	Sandy Clay
			30-61	Sandy Fine Gravel
			61-69	Gravel
			69-70	Shale
211963	31.264167	-96.905278	0-18	Fine Brown Sand
			18-22	Dark Brown Clay
			22-35	Reddish Blonde Sand with Layers of Dark Brown Clay
			35-44	Reddish Blonde Sand with Layers of Gravel
			44-55	Blue Shale
211907	31.283056	-96.918056	0-1	Top Soil
			1-38	Sandy Clay
			38-61	Gravel and Sand
211572	31.345556	-96.996944	0-15	Fine Red Sand
			15-22	Red Clay
			22-40	Fine Brown Silty Sand
			40-62	Coarse Blonde Sand and Gravel
			62-64	Blue Shale
209870	31.231944	-96.906111	0-38	Sandy Clay with Small Gravel
			38-50	Gravel and Clay
			50-58	Gravel
			58-63	Shale
205579	31.138333	-96.806389	0-25	Silty Clay
			25-65	Gravel with some Clay
			65-68	Shale
202090	31.239444	-96.944444	0-1	Top Soil
			1-6	Clay and Sand
			6-15	Iron Ore Gravel
			15-23	Clay
			23-32	Gravel and Sand
			32-40	Shale

Continued

Tracking Number	Latitude	Longitude	Lithology (feet)	
200689	31.384722	-96.961667	0-10	Silty Sand
			10-20	Sandy Clay
			20-30	Big Sand
			30-35	Sand
			35-42	Sand and Gravel
			42-52	Gravel
			52-52.5	Shale
193714	31.173056	-96.864444	0-1	topsoil
			1-36	clay
			36-62.5	gravel & sand
			62.5-63.5	shale
193628	31.200278	-96.837778	0-1	topsoil
			1-11	clay
			11-41	sand
			41-54	gravel sand & gravel
			54-55	shale
192314	31.133889	-96.828056	0-1	topsoil
			1-3	sand
			3-7	red sandy clay
			7-19	sandy gravel
			19-25	shale
191611	31.173333	-96.845833	0-1	topsoil
			1-19	sandy clay
			19-33	sand
			33-39	sandy gravel
			39-56	gravel and sand
			56-58.5	sandy gravel
			58.5-59.5	shale
182906	31.226389	-96.855	0-10	Clay
			10-24	(S) Clay
			24-58	Sand Gravel
			58-80	Shale
160574	31.260278	-96.916389	0-1	Top Soil
			1-35	Sandy Clay
			35-41	Gravel
			41-46	Shale
137430	31.306389	-96.969444	0-0.5	Concrete
			0.5-8	Dark brown clay
			8-13	Dark tan clay
			13-22	Dark reddish tan silty clay
			22-26	Dark red and tan sandy clay with gravel
			26-30	Light tan limestone
126964	31.200278	-96.923611	0-12	Black Gumbo
			12-45	Light Brown Clay
			45-55	Blue Clay
			55-62	Coarse Sand and Gravel
			62-69	Blue Shale

Continued

Tracking Number	Latitude	Longitude	Lithology	
118444	31.219167	-96.861111	0-1	TOPSOIL
			1-19	SANDY CLAY
			19-40	SANDY FINE GRAVEL
			40-45	GRAVEL W/CLAY
			45-64	GRAVEL & SAND
			64-65	SHALE
116342	31.151944	-96.843333	0-25	CLAY
			25-40	SANDY GRAVEL
			40-46	SHALE
106976	31.151389	-96.828056	0-12	CLAY
			12-20	SAND
			20-35	SAND/LITTLE GRAVEL
			35-40	GRAVEL
			40-44	SHALE
73439	31.29	-96.869444	0-2	Fine Sand
			2-17	Red Clay
			17-22	Pea Gravel
			22-42	Fine to Coarse Blonde Sand with Layers of Gravel
			42-54	Blue Shale
50612	31.166111	-96.875278	0-1	Topsoil
			1-38	Clay
			38-69	Gravel & Sand
			69-69	1/2 Shale
50432	31.171944	-96.864722	0-1	Topsoil
			1-28	Clay
			28-32	Sandy Clay
			32-36	Sand
			36-45	Gravel W/Clay
			45-61	Gravel & Sand
			61-63	Shale
31504	31.169722	-96.79	0-1	TOPSOIL
			1-19	CLAY
			19-38.5	GRAVEL & SAND
			38.5-39.5	SHALE
27102	31.195833	-96.851944	0-1	Top Soil
			1-8	Sand
			8-13	Sandy Clay
			13-39	Sand
			39-48	Gravel
			48-52	Shale
26722	31.314444	-96.955833	0-16	sandy clay
			16-32	sand and gravel
			32-240	gray shale
1328	31.133333	-96.823333	0-38	Red Clay
			38-49	Gravel & Sand
			49-80	Blue Shale

Continued

Tracking Number	Latitude	Longitude	Lithology
69313	31.422778	-97.063056	000-025 BROWN CLAY
			025-035 SANDY BROWN CLAY
			035-1185 GRAY SHALE AND LIME STREAKS
			1185-1473 GRAY SHALE
			1473-1800 LIME AND GRAY SHALE
			1800-2030 LIME
			2030-2100 SAND
			2100-2150 LIME
			2150-2270 LIME AND SAND STREAKS
			2270-2570 SAND
192915	31.455	-97.058333	0-27 Clay
			27-30 Clay and small Gravel
			30-47 Gravel
			47-50 Shale
187625	31.4825	-97.072778	0-7 sand
			7-16 red clay
			16-34 sand/gravel
			34-35 yellow shale/clay
			35-80 gray shale
21685	31.489444	-97.073611	0-12 Clayey Sand, Gravelly Clay, Sandy Clay, tan
			12-30 Gravel, reddish tan
			30-35 Clayey Sand, reddish brown to brown
			35-38 Gravel tan to gray
			38-75 Shale, dark gray
21683	31.491111	-97.073889	0-8 Clay, light brown to brown
			8-13 Sandy Fat Clay, brown
			13-30 Clayey Sand, reddish brown
			30-35.5 Gravel, reddish brown to tan
			35.5-75 Shale, dark gray
150752	31.538611	-97.106389	0 -6" Concrete Asphalt
			6"-7' Dark Brown Clay
			7’-11' Reddish Brown Clay
			11’-13' Sand & Gravel
			13’-15' Gray Shale
150756	31.538611	-97.106389	0-6" Concrete Asphalt
			6"-10' Reddish Brown Clay
			10’-12.5' Sand/Med Gravel
			12.5’-14' Gray Shale
16313	31.541389	-97.1	0-5 Dark Brown Sandy Clay
			5-20 Brown Silty Sand
			20-26 Sand And Gravel
			26-30 Gray Shale
126998	31.545278	-97.065	0-8 sand, gravel and clay
			8-20 gravel
			20-40 shale
162653	31.557222	-97.102222	0-3 Clay Sand Fill
			3-8 Dark Brown Clay
			8-21 Brown Coarse Sand & Gravel
			21-25 Dark Gray Shale

Continued

Tracking Number	Latitude	Longitude	Lithology	
162654	31.557222	-97.102222	0-3	Clay Sand Fill
			3-8	Dark Brown Clay
			8-21	Brown Coarse Sand & Gravel
			21-25	Dark Gray Shale
171891	31.557222	-97.102222	0-7	Brown Clay
			7-13	Olive Brown Sandy Clay
			13-18	Tan Sand & Gravel
			18-20	Gray Shale
227043	31.558056	-97.092778	0-5	Black Silty Clay
			5-10	Med Brown to Lt. Brown Clay
			10-13	Light Brown Sandy Clay
			13-19	Med Brown Sand
			19-20	Dark Grey Shale
227047	31.558056	-97.092778	0-8	Black Silty Clay
			8-13	Light Brown Sand
			13-17.5	Light Brown Sandy Clay
			17.5	Shale
29713	31.564722	-97.105278	0-2	Medium Brown Clayey Sand
			2-5	Light Brown Sandy Clay
			5-7	Medium Brown Sandy Gravel
			7-9	Light Gray Sandy Clay
			9-12	Medium Reddish Brown Sandy Clay
			12-13.5	Olive Green to Gray Clay
			13.5-15	Medium Gray Shale to Cla
45245	31.564722	-97.103333	0-5	Dark Gray Silty Sandy Clay
			5-10	Light Gray Sandy Clay
			10-14.5	Light Bluish Gray Silty Sandy Clay
			14.5-15	Orange Sandy Clay
			15-18.5	Orange Sand
			18.5-19.5	Dark Gray Clay/Shale
29712	31.565556	-97.105556	0-13	Brown Sandy Gravel
			13-14.5	Light Brown Slightly Gravely Sand
			15.5-15	Medium Gray Silty Clay to Shale
64752	31.581944	-97.108611	0-5	Brown Sandy Clay
			5-17	Tan Sand
			17-17.5	Gravel
			17.5-18	Gray Shaley Clay
64753	31.581944	-97.108611	0-5	Brown Sandy Clay
			5-17	Tan Sand
			17-17.5	Gravel
			17.5-18	Gray Shaley Clay
64754	31.581944	-97.108611	0-5	Brown Sandy Clay
			5-17	Tan Sand
			17-17.5	Gravel
			17.5-18	Gray Shaley Clay
15366	31.616111	-97.168056	0-10	sand
			10-45	sand & gravel
			45-250	blue shale

Continued

Tracking Number	Latitude	Longitude	Lithology	
74715	31.617222	-97.154167	0-17	S-Clay
			17-28	Sand w/FEW Gravel
			28-38	Gravel
			38-41	Shale
182138	31.620833	-97.171667	0-23	Sandy Clay
			23-37	Sand and Gravel
			37-60	Shale
76746	31.627778	-97.145	0-4	sand
			4-12	red clay
			12-34	sand/gravel
			34-60	gray lime
32265	31.64	-97.182778	0-8	SAND & CLAY
			8-21	GRAVEL
			21-22	ROCK
			22-30	SHALE & ROCKS
400	31.668056	-97.218333	0-5	red clay
			5-19	sand/gravel
			19-240	graylime/shale
177610	31.669167	-97.179444	0-15	Sand and Clay
			15-28	Gravel
			28-38.5	Blue Shale
32262	31.669444	-97.182778	0-18	CLAY
			18-23	GRAVEL & SAND
			23-40	SHALE
177624	31.6725	-97.2125	0-13	Sand
			13-20	Gravel
			20-30	Blue Shale
177627	31.678889	-97.2075	0-15	Sandy Clay
			15-27	Sand and Gravel
			27-38	Blue Shale
159287	31.686944	-97.228333	0-23	sand
			23-31	gravel
			31-33	rock
5298	31.851667	-97.349444	0-25	Red Sandy Clay
			25-35	Red Silty Sandy Clay
			35-37	Gray Limestone

APPENDIX C

Baylor University Campus Boreholes (n = 96)

Report	Boring	Latitude	Longitude	ReportName	Year	Month	Depth to Water	Depth to Alluvium
A	B-1	31.55055	-97.10436	BU Substation	2003	3	20	-
A	B-2	31.55068	-97.10437	BU Substation	2003	3	-	-
A	B-3	31.55066	-97.10427	BU Substation	2003	3	-	-
A	B-4	31.55092	-97.10418	BU Substation	2003	3	-	-
A	B-5	31.55105	-97.10428	BU Substation	2003	3	-	-
A	B-6	31.55049	-97.10452	BU Substation	2003	3	-	-
B	B-1	31.55132	-97.10923	Proposed Tennis Complex, BU	2000	2	-	-
B	B-2	31.55118	-97.10989	Proposed Tennis Complex, BU	2000	2	-	-
B	B-3	31.55084	-97.11044	Proposed Tennis Complex, BU	2000	2	-	-
B	B-4	31.55057	-97.10992	Proposed Tennis Complex, BU	2000	2	-	-
B	B-5	31.55049	-97.10932	Proposed Tennis Complex, BU	2000	2	12	-
B	B-6	31.55003	-97.10962	Proposed Tennis Complex, BU	2000	2	9	-
B	B-7	31.55016	-97.10886	Proposed Tennis Complex, BU	2000	2	14.5	-
B	T-1	31.55098	-97.10901	Proposed Tennis Complex, BU	2000	2	-	-
B	T-2	31.55153	-97.10991	Proposed Tennis Complex, BU	2000	2	-	-
B	T-3	31.55043	-97.10863	Proposed Tennis Complex, BU	2000	2	-	-
B	T-4	31.55022	-97.10992	Proposed Tennis Complex, BU	2000	2	-	-
B	T-5	31.54984	-97.10918	Proposed Tennis Complex, BU	2000	2	-	-
B	T-6	31.55065	-97.11051	Proposed Tennis Complex, BU	2000	2	-	-
C	B-10	31.55149	-97.11289	Simpson Athletics and Academic Center	2007	5	-	44
C	B-2	31.55114	-97.11258	Simpson Athletics and Academic Center	2007	5	20	-
C	B-3	31.55178	-97.11294	Simpson Athletics and Academic Center	2007	5	15	-

Continued

Report	Boring	Latitude	Longitude	ReportName	Year	Month	Depth to Water	Depth to Alluvium
C	B-4	31.55144	-97.11291	Simpson Athletics and Academic Center	2007	5	-	43
C	B-5	31.55121	-97.11291	Simpson Athletics and Academic Center	2007	5	15	-
C	B-8	31.55130	-97.11252	Simpson Athletics and Academic Center	2007	5	-	51
C	B-6	31.55134	-97.11260	Simpson Athletics and Academic Center	2007	5	19	-
C	B-9	31.55135	-97.11258	Simpson Athletics and Academic Center	2007	5	-	48
C	B-7	31.55149	-97.11246	Simpson Athletics and Academic Center	2007	5	24	-
C	B-1	31.55141	-97.11372	Simpson Athletics and Academic Center	2007	5	17.7	24.5
Da	B-6	31.54888	-97.11287	BU Science Building	2002	2	35	39
Da	B-5	31.54820	-97.11240	BU Science Building	2002	2	34	35
Da	B-4	31.54740	-97.11236	BU Science Building	2002	2	-	27
Da	B-2	31.54799	-97.11319	BU Science Building	2002	2	24	23
Da	B-1	31.54739	-97.11344	BU Science Building	2002	2	18	19
Da	B-3	31.54838	-97.11378	BU Science Building	2002	2	34	37
Db	B-8	31.54885	-97.11334	BU Special Events Center	1983	11	19.1	28
Db	B-7	31.54845	-97.11273	BU Special Events Center	1983	11	23	36
E	B-1	31.54462	-97.11317	BU Parking Garage Sec S. 2nd St. and Cottonwood	2003	6	11	13

Continued

Report	Boring	Latitude	Longitude	ReportName	Year	Month	Depth to Water	Depth to Alluvium
E	B-2	31.54512	-97.11260	BU Parking Garage Sec S. 2nd St. and Cottonwood	2003	6	11	12
E	B-3	31.54464	-97.11202	BU Parking Garage Sec S. 2nd St. and Cottonwood	2003	6	8	12
E	B-4	31.54417	-97.11258	BU Parking Garage Sec S. 2nd St. and Cottonwood	2003	6	10	13
E	B-5	31.54466	-97.11258	BU Parking Garage Sec S. 2nd St. and Cottonwood	2003	6	7	13
F	B-1	31.54582	-97.11344	Baylor East Village Residential Comm	2011	6	-	13.6
F	B-2	31.54544	-97.11282	Baylor East Village Residential Comm	2011	6	-	12.5
F	B-3	31.54523	-97.11412	Baylor East Village Residential Comm	2011	6	13.3	12.5
F	B-4	31.54475	-97.11357	Baylor East Village Residential Comm	2011	6	10	11.5
F	B-5	31.54389	-97.11287	Baylor East Village Residential Comm	2011	6	9.1	11.5
F	B-6	31.54482	-97.11458	Baylor East Village Residential Comm	2011	6	-	13
F	B-7	31.54419	-97.11402	Baylor East Village Residential Comm	2011	6	-	15
F	B-8	31.54340	-97.11320	Baylor East Village Residential Comm	2011	6	10.8	14.5

Continued

Report	Boring	Latitude	Longitude	ReportName	Year	Month	Depth to Water	Depth to Alluvium
F	B-9	31.54433	-97.11510	Baylor East Village Residential Comm	2011	6	-	12.5
F	B-10	31.54396	-97.11461	Baylor East Village Residential Comm	2011	6	-	15
F	B-11	31.54359	-97.11419	Baylor East Village Residential Comm	2011	6	14.1	17
F	B-12	31.54314	-97.11358	Baylor East Village Residential Comm	2011	6	12.6	15
G	B-1	31.55200	-97.11541	Proposed Mayborn Museum	2001	4	21	23
G	B-2	31.55255	-97.11520	Proposed Mayborn Museum	2001	4	18	19.5
G	B-3	31.55179	-97.11469	Proposed Mayborn Museum	2001	4	17.5	21.5
G	B-4	31.55235	-97.11446	Proposed Mayborn Museum	2001	4	16	18
G	B-5	31.55166	-97.11403	Proposed Mayborn Museum	2001	4	19.5	22
G	B-6	31.55209	-97.11385	Proposed Mayborn Museum	2001	4	17	19
H	B-1	31.54928	-97.11441	BU Fine Arts Center	1978	8	-	18.4
H	B-2	31.54959	-97.11408	BU Fine Arts Center	1978	8	-	19.3
H	B-3	31.54965	-97.11487	BU Fine Arts Center	1978	8	-	17.4
H	B-4	31.55007	-97.11534	BU Fine Arts Center	1978	8	-	18.5
H	B-6	31.55055	-97.11479	BU Fine Arts Center	1978	8	17	19
H	B-5	31.55035	-97.11504	BU Fine Arts Center	1978	8	-	19
H	B-7	31.55017	-97.11433	BU Fine Arts Center	1978	8	-	20
H	B-8	31.54989	-97.11459	BU Fine Arts Center	1978	8	-	20

Continued

Report	Boring	Latitude	Longitude	ReportName	Year	Month	Depth to Water	Depth to Alluvium
I	B-1	31.54973	-97.11616	Baylor School of Music Building	1989	3	-	13.5
I	B-6	31.54922	-97.11624	Baylor School of Music Building	1989	3	-	17
I	B-2	31.54948	-97.11574	Baylor School of Music Building	1989	3	-	18
I	B-3	31.54908	-97.11562	Baylor School of Music Building	1989	3	20	33.5
I	B-5	31.54871	-97.11564	Baylor School of Music Building	1989	3	17	34
I	B-4	31.54859	-97.11520	Baylor School of Music Building	1989	3	18	27.5
J	B-2	31.55138	-97.11923	BU Parking Structure Univ Parks Dr at Dutton Ave	2002	1	19	18
J	B-3	31.55131	-97.11865	BU Parking Structure Univ Parks Dr at Dutton Ave	2002	1	18	18
J	B-4	31.55131	-97.11811	BU Parking Structure Univ Parks Dr at Dutton Ave	2002	1	16	15
J	B-5	31.55085	-97.11864	BU Parking Structure Univ Parks Dr at Dutton Ave	2002	1	19.5	18
J	B-1	31.55174	-97.11878	BU Parking Structure Univ Parks Dr at Dutton Ave	2002	1	19	19
K	B-2	31.54963	-97.11891	Communications Building	1970	2	-	13.5
K	B-1	31.54968	-97.11852	Communications Building	1970	2	-	13
K	B-3	31.54932	-97.11856	Communications Building	1970	2	-	11
L	B-1	31.54901	-97.11926	Hazardous Waste Facility	1988	2	-	18.4
M	B-2	31.54639	-97.12052	Water Feature and Plaza Development	1981	9	-	13
M	B-1	31.54617	-97.12076	Water Feature and Plaza Development	1981	9	-	15
M	B-3	31.54668	-97.12021	Water Feature and Plaza Development	1981	9	-	9

Continued

Report	Boring	Latitude	Longitude	ReportName	Year	Month	Depth to Water	Depth to Alluvium
N	B-3	31.54629	-97.11794	Hankamer School of Business	1982	6	-	10
N	B-2	31.54616	-97.11777	Hankamer School of Business	1982	6	-	10
N	B-1	31.54600	-97.11792	Hankamer School of Business	1982	6	-	15
O	B-1	31.54592	-97.11762	Parking Garage, BU	1997	11	-	10
O	B-3	31.54571	-97.11737	Parking Garage, BU	1997	11	-	10.5
O	B-2	31.54552	-97.11775	Parking Garage, BU	1997	11	10	13.5
O	B-5	31.54537	-97.11667	Parking Garage, BU	1997	11	8	10
O	B-4	31.54502	-97.11678	Parking Garage, BU	1997	11	-	11.5
P	B-1	31.54489	-97.11843	Baptist Student Union Center	1980	5	-	15
P	B-2	31.54452	-97.11806	Baptist Student Union Center	1980	5	7.5	15

BIBLIOGRAPHY

Bené, J., Hardin, B., O'Rourke, D., Donnelly, A., and Yelderman, J., 2004, North Trinity/Woodbine Aquifer Groundwater Availability Model prepared for the Texas Water Development Board, 391 p.

Chowdhury, A.H., Osting, T., Furnans, J. and Mathews, R., 2010. Groundwater-Surface Water Interaction in the Brazos River Basin: Evidence from Lake Connection History and Chemical and Isotopic Compositions, Texas Water Development Board Report 375.

Cronin, J.G. and Wilson, C.A., 1967. Ground Water in the Floodplain Alluvium of the Brazos River, Whitney Dam to Vicinity of Richmond, Texas, Texas Water Development Board Report 41.

Deussen, A., 1924. Geology of the Coastal Plain of Texas West of Brazos River: Department of the Interior USGS Professional Paper 126.

Diehl, M., 2012, Intra-aquifer characterization and potential management impacts: the Trinity aquifer, central Texas: Baylor University, unpublished Master thesis.

Epps, L.W., 1973, A Geologic History of the Brazos River: Baylor Geological Studies, Bulletin No. 24.

Faulkner, B.R., Olivas, Y., Ware, M.W., Roberts, M.G., Groves, J.F., Bates, K.S. and McCarty, S.L., 2010, Removal efficiencies and attachment coefficients for *Cryptosporidium* in sand alluvial riverbank sediment. *Water Research* 44, 2725-2734.

George, P.G., Mace, R.E. and Petrossian, R., 2011. Aquifers of Texas, Texas Water Development Board Report 380.

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

Harlan, S.K., 1990, Hydrogeologic Assessment of the Brazos River Alluvial Aquifer Waco to Marlin, Texas: Baylor University, unpublished Master thesis.

KWTX News. 2011, "Nearly 90 Cryptosporidiosis Cases Confirmed in Central Texas". (http://www.kwtx.com/home/headlines/Two_More_Cryptosporidiosis_Cases_Reported_In_Central_Texas_129493383.html), accessed December 02, 2011.

Larkin, T.J. and Bomar, G.W., 1983. Climatic Atlas of Texas, Texas Department of Water Resources LP-192.

Metge, D.W., Harvey, R.W., Aiken, G.R., Anders, R., Lincoln, G. and Jasperse, J., 2010. Influence of organic carbon loading, sediment associated metal oxide content and sediment grain size distributions upon *Cryptosporidium parvum* removal during riverbank filtration operations, Sonoma County, CA. *Water Research* 44, 1126-1137.

Mito, Y., Ismail, M.A.M. and Yamamoto, T., 2011. Multidimensional scaling and inverse distance weighting transform for image processing of hydrogeological structure in rock mass. *Journal of Hydrology* 411, 25-36.

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

Raney, J.A., Allen, P.M., Reaser, D.F. and Collins, E.W., 1987. Geologic Review of Proposed Dallas – Fort Worth Area Site for the Superconducting Super Collider (SSC).

Rupp, S., 1974. Urban Geology of Greater Waco Part III: Water Subsurface Waters of Waco: Baylor University, unpublished Bachelor thesis.

Shah, S.D. and Houston, N.A., 2007. Geologic and hydrogeologic information for a geodatabase for the Brazos River alluvium aquifer, Bosque County to Fort Bend County, Texas: U.S. Geological Survey Open-File Report 2007-1031 [version 3].

Shah, S.D., Houston, N.A. and Braun, C.L., 2007. Hydrogeologic Characterization of the Brazos River Alluvium Aquifer, Bosque County to Fort Bend County, Texas, Scientific Investigation Map 2989.

Smyrl, V.E., 1999. "MCLENNAN COUNTY," *Handbook of Texas Online* (http://www.tshaonline.org/handbook/online/articles/hcm08), accessed October 06, 2011. Published by the Texas State Historical Association.

Southern Trinity Groundwater Conservation District (STGCD). 2010. Southern Trinity Groundwater Conservation District Management Plan.

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

Weiss, W. J., Bouwer, E.J., Aboytes, R., LeChevallier, M.W., O'Melia, C.R., Le, B.T. and Schwab, K.J, 2005. Riverbank filtration for control of microorganisms: Results from field monitoring. *Water Research* 39, 1990-2001.