ABSTRACT

Intra-Aquifer Characterization and Potential Management Impacts:
Trinity Aquifer, Central Texas

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Management of groundwater resources is a critical issue in Texas and groundwater conservation districts have been given this responsibility. While large databases containing well characteristics are available for use from state agencies, they have not been organized for spatial correlation and analysis. As a new entity (2007), the Southern Trinity Groundwater Conservation District (STGCD) is faced with developing and analyzing such data. An unusual challenge for the STGCD is managing groundwater production among wells completed either solely in the upper aquifer (Hensell unit), lower aquifer (Hosston unit), or dually completed in both units of the Trinity Aquifer. The goals of this project were to develop a spatially-based well data set that can be used for management decisions. Results include a report to the STGCD with a database, contour maps for different aquifer characteristics, and well hydraulics analysis.

Intra-Aquifer Characterization and Potential Management Impacts:
Trinity Aquifer, Central Texas

by

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A Thesis

Approved by the Department of Geology

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LIST OF ABBREVIATIONS

STGCD: Southern Trinity Groundwater Conservation District

HNSL: Hensell

HSTN: Hosston

HNHS: Dual-completed well

TWDB: Texas Water Development Board

TCEQ: Texas Commission on Environmental Quality

PGMA: Priority Groundwater Management Area

TDS: Total Dissolved Solids

MSL: mean sea level

GCD: Groundwater Conservation District

GMA: Groundwater Management Area

ACKNOWLEDGMENTS

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CHAPTER ONE

Introduction

Location

The hydrogeologic unit of interest for this study is the Trinity aquifer, a major aquifer extending throughout much of Central Texas. Although the Trinity aquifer occurs in over fifty-six Texas counties, the focus of this study is the aquifer specific to McLennan County (Figure 1), and the Southern Trinity Groundwater Conservation District (STGCD).

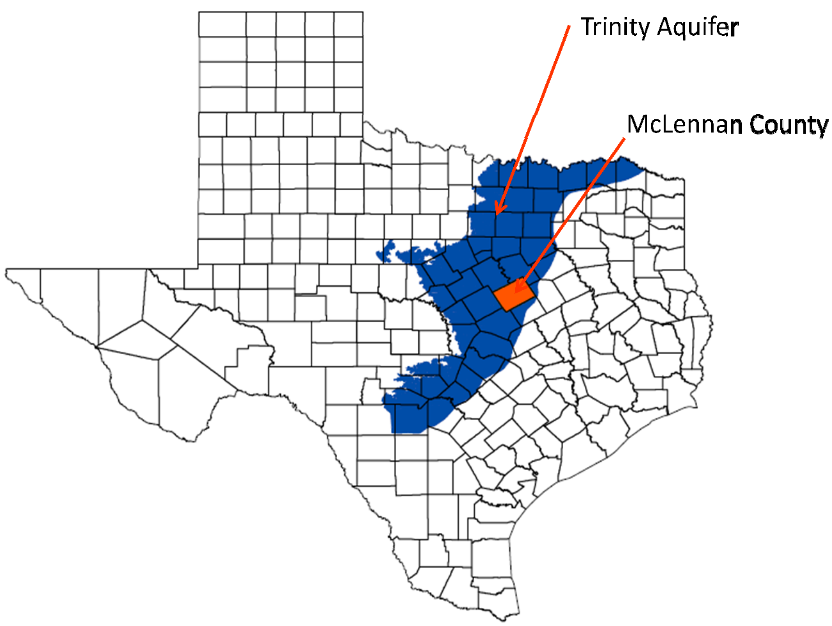


Figure 1: Location of McLennan County within the regional boundaries of the Trinity aquifer.

Since the discovery of the deep artesian Trinity aquifer in Waco, (Hill, 1901) water removed from storage has resulted in water level declines. The continued water level declines in this area of the Trinity aquifer (McLennan County) resulted in its designation as a Priority Groundwater Management Area (Texas Commission on Environmental Quality, 2008). The Southern Trinity Groundwater Conservation District (Texas Legislature, 2007) was created in 2007 and requires sound hydrogeologic information in order to manage the groundwater effectively. Because the Trinity aquifer in McLennan County is a multi-unit aquifer, (Hensell and Hosston) management strategies may affect each water-bearing unit differently. Intra-aquifer characterization of the Trinity aquifer may be important to develop the most effective management strategies, and lead to a more sustainable groundwater resource. This study evaluates the hydrogeology of the Hensell and Hosston units within the Trinity aquifer and the potential effects on management strategies.

Aquifer Framework

The Trinity aquifer was originally deposited by a fluvial system during the Cretaceous period, and later reworked by transgressive and regressive marine systems (Boone, 1968). Additionally, the Trinity aquifer has different nomenclature depending on location (Figure 2, 3). Approximately seventy miles northwest of McLennan County, the Trinity aquifer crops out as a single unit termed the Antlers Formation, where the unit receives aerial recharge. Where the Glen Rose Limestone begins to separate the Trinity aquifer into the Paluxy unit and the basal Trinity sands, it is known as the Twin Mountains Formation. Where the aquifer occurs in subsurface (Figure 2), it is separated into two water-bearing units known as the Hensell and Hosston sands. These two subsurface units are present throughout McLennan County and are separated by about one hundred feet of less permeable confining material. The Trinity aquifer dips to the southeast at about forty feet per mile (Klemt and others, 1975). The dip increases and the Trinity Aquifer thickens to the southeast as well (Nordstrom, 1982). The Balcones Fault Zone also strikes northeast to southwest through the middle of McLennan County and is known to displace the aquifer by up to four-hundred feet (Klemt and others, 1975). Another important structural feature of the aquifer is the McGregor High, an area of non-deposition of the Hosston unit near the City of McGregor. The McGregor High is thought to have been an erosional surface where a limestone ridge or mesa once occurred (Klemt and others, 1975).

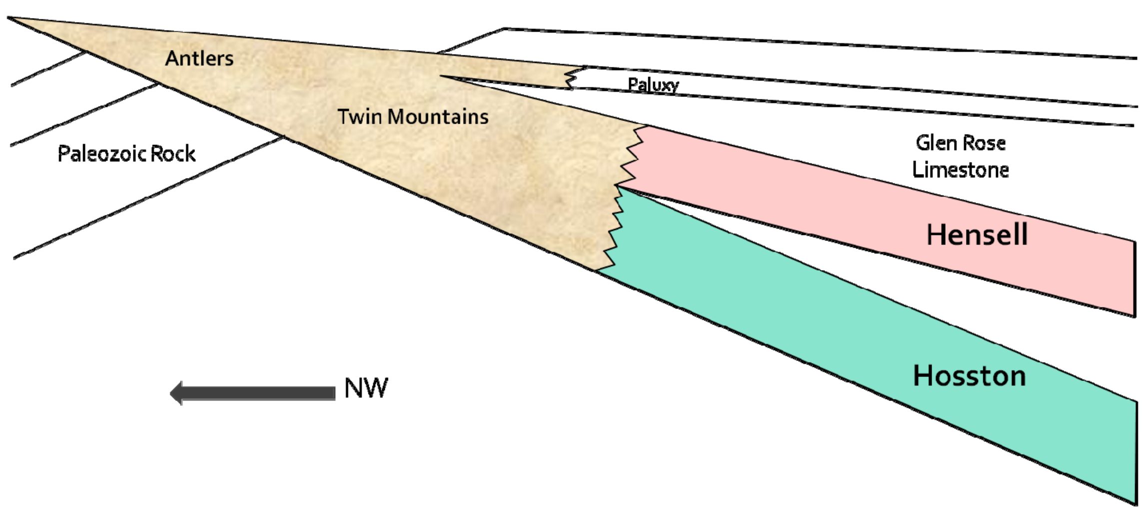


Figure 2: General Trinity aquifer framework (modified from Rapp, K., 1986).

The two water-bearing zones, the Hensell and the Hosston units, differ in productivity primarily as a result of differences in thickness. The Hensell unit is on average sixty feet thick, whereas the thicker and more productive Hosston unit averages around three hundred feet thick in McLennan County. Most wells in McLennan County are also drilled into the Hosston unit. According to Texas Water Development Board data, only one-hundred three Hensell wells compared to one-hundred seventy-seven Hosston wells have been drilled in McLennan County.

Discovery, Value and Problem

Extensive development of the Trinity aquifer began in the late 1800s when numerous artesian, flowing wells were completed in the aquifer throughout central Texas. The first artesian well in McLennan County was drilled in Waco in 1889. It was 1,830 feet deep, the water was one-hundred-three degrees Fahrenheit, and it flowed freely at the surface at a rate of about 400,000 gallons per day (Cutter, 1894). Naturally, this discovery attracted many people to the Waco area, and it was even advertized as "Geyser City" (Figure 4). However, by 1894, some wells ceased to flow at the surface, and turbine pumps had to be introduced (Hill, 1901). The practice of leaving flowing artesian Trinity wells uncapped, combined with the newfound availability of fresh water led immediately to regional artesian pressure declines (Kaiser, 2002).

An interval of reduced groundwater production in the Trinity aquifer was experienced in the region through the 1930's. This period was followed by many decades of increased groundwater withdrawal in Central Texas to meet the local water demands of a growing population. Surface water has now been incorporated into many water systems; however, groundwater levels continue to drop, creating a need for improved groundwater management (Figure 5).

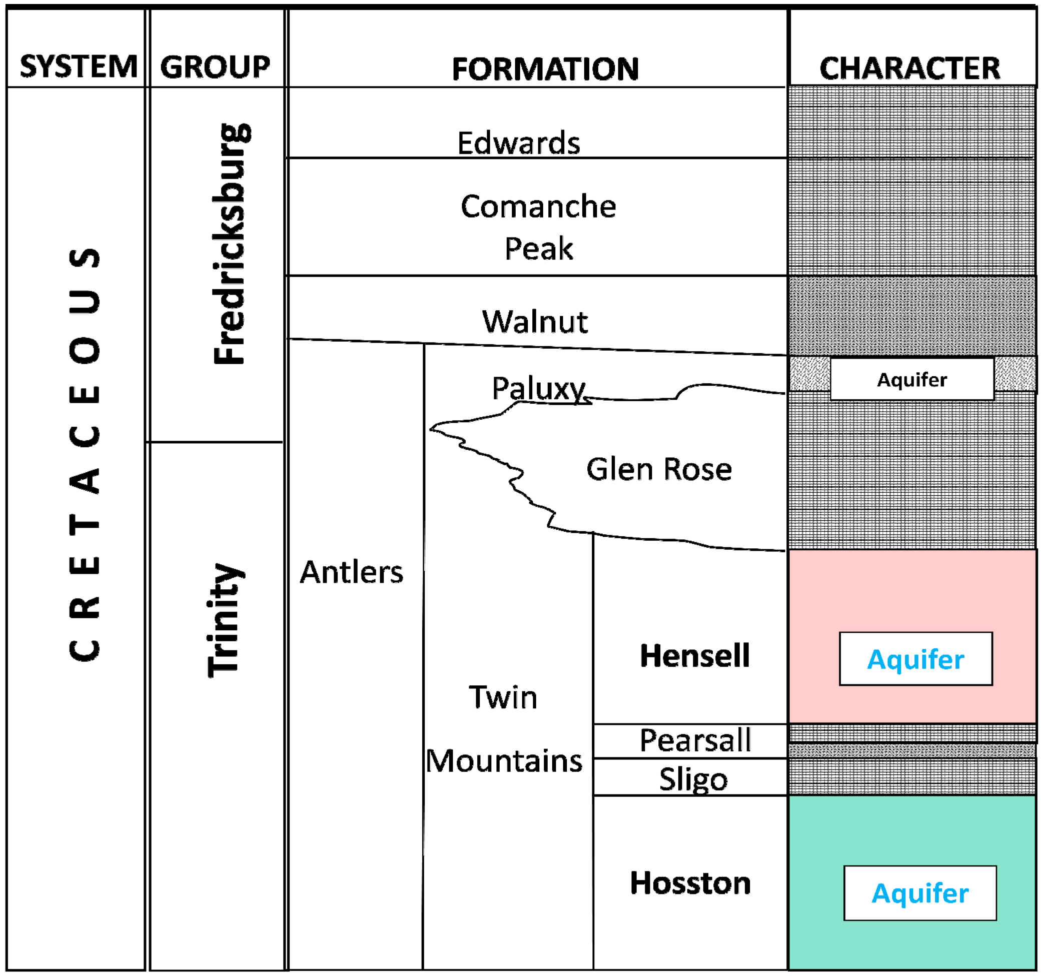


Figure 3: General stratigraphy of the Trinity aquifer (modified from Rapp, K., 1986).

Purpose and Proposed Management Strategy

Many other urban areas throughout Texas are also experiencing large groundwater level declines. The Texas Commission for Environmental Quality (TCEQ) has designated seven Priority Groundwater Management Areas (PGMAs, Figure 6). According to Texas water code, PGMAs are those areas experiencing or are expected to experience, within the immediately following twenty-five year period, critical groundwater problems, including shortages of surface water or

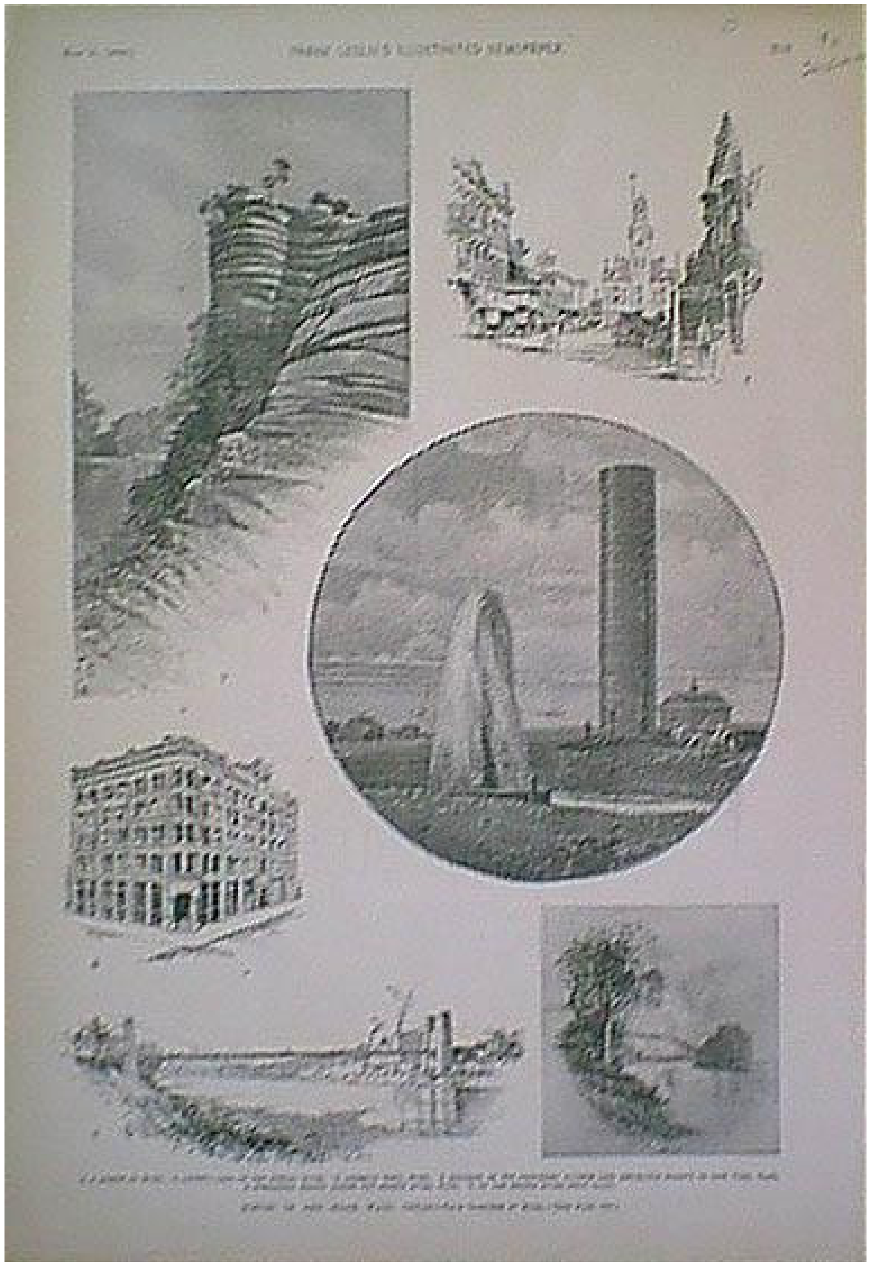


Figure 4: Pamphlet from the late 1800s advertizing the Waco area, with a photo of freely flowing artesian water in the center (Cutter, 1894).

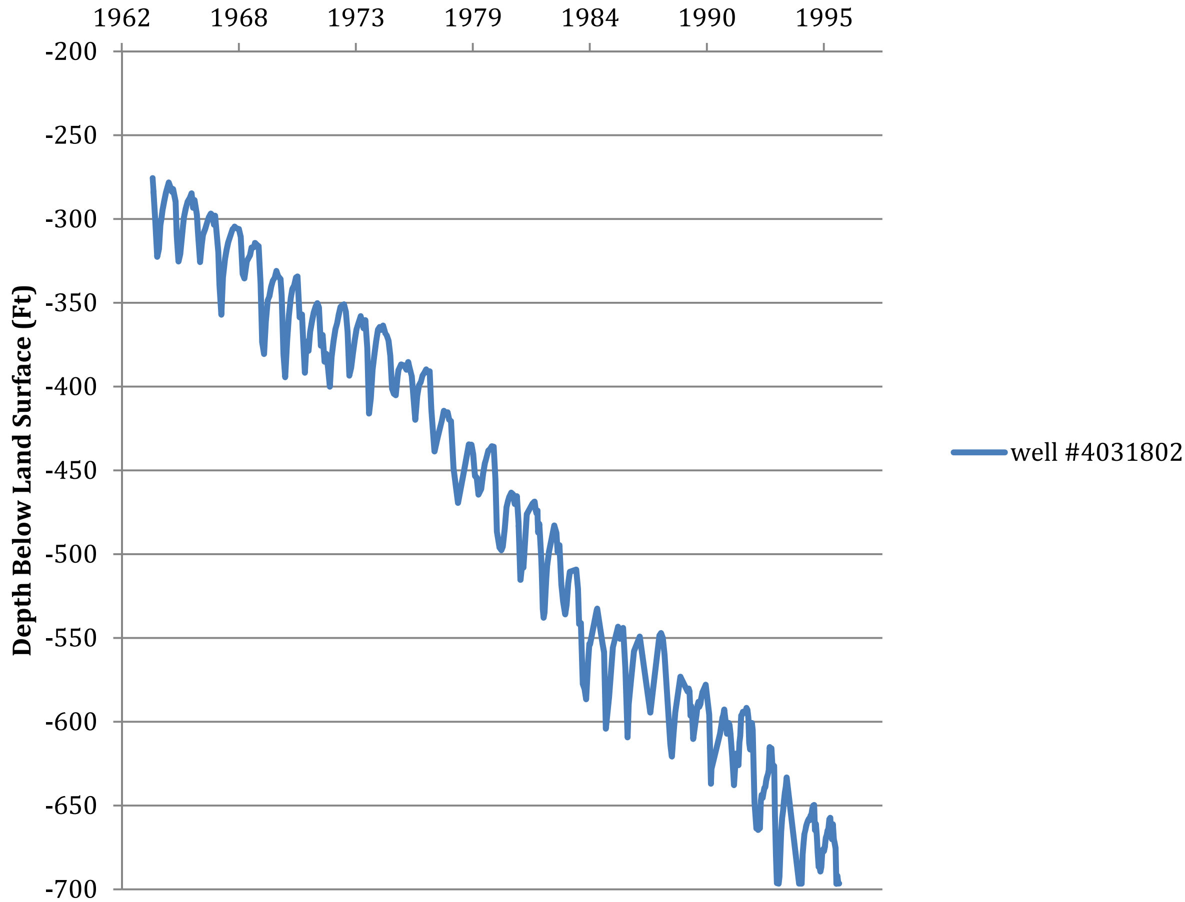


Figure 5: Hydrograph of a Hosston well in the Waco area, the cyclicity pattern shown is not due to changes in recharge, but to seasonal changes in demand, or drawdown and recovery. The average annual decline is over ten feet per year.

groundwater, land subsidence resulting from groundwater withdrawal, and contamination of groundwater supplies (Texas Water Code, 2009). McLennan County became part of the Central Texas Trinity Aquifer PGMA in 2008, along with Bosque, Hill, Coryell, and Somervell County. Areas in PGMAs take precedence in groundwater management, and are required by law to belong to a Groundwater Conservation District.

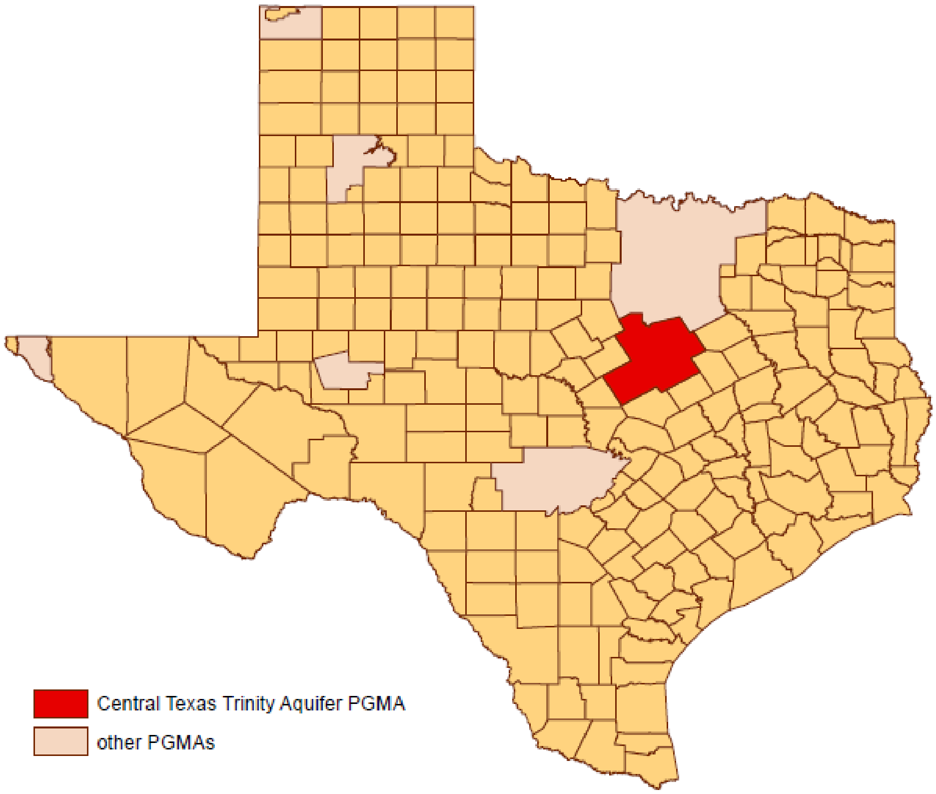


Figure 6: The STGCD became part of the Central Texas Trinity Aquifer PGMA in 2008.

Currently, the preferred method of groundwater management in Texas is through Groundwater Conservation Districts (Texas Water Code §36.0015, 2009). The lack of a comprehensive statewide management system is partly the result of public distrust of government, a history of individualism, and strong private property rights. These Groundwater Conservation Districts offer local or regional control of groundwater management, which is usually preferred over statewide regulations. The Texas legislature recently passed several bills that have had the effect of increasing the formation of groundwater conservation districts, with a goal of all Texas counties eventually belonging to a groundwater conservation district.

Texas water code requires the Texas Commission for Environmental Quality (TCEQ) to determine whether a groundwater conservation district is feasible (Texas Water Code §36.011, 2009). The governing boards for these new districts seldom contain hydrogeologists or groundwater engineers. Therefore, there is often a need for more knowledge about local aquifers and well hydraulics directly related to a new district.

The Southern Trinity Groundwater Conservation District (STGCD) was created by legislation in the 80th Texas Legislature in 2007 (Texas Legislature, 2007), and amended by the 81st Texas Legislature in 2009 (Texas Legislature, 2009). The purpose of the district is to preserve, conserve, protect, and prevent the waste of groundwater and to control subsidence caused by groundwater withdrawals, consistent with Section 59, Article XVI, Texas Constitution and Chapter 36, Texas Water Code (2009). Since Trinity aquifer water levels in McLennan County have declined over four-hundred feet in about one-hundred-twenty years, and the population in McLennan County is expected to grow, improved management based on sound hydrogeological principles is needed for the Trinity aquifer.

Most districts consist of multiple counties, but the STGCD consists of only McLennan County. It is responsible for the management of the Trinity aquifer, but also manages the Brazos River Alluvium aquifer, a minor aquifer in the State of Texas, and the Paluxy Aquifer in McLennan County. All groundwater conservation districts (GCDs) are required to develop a groundwater management plan and submit it to the TWDB for approval. A newly created district is required to submit its management plan no later than three years after its creation (Texas

Administrative Code, §356.3). A groundwater management plan describes a district's groundwater management goals. These goals include providing the most efficient use of groundwater, controlling and preventing waste of groundwater, controlling and preventing subsidence, addressing conjunctive surface water management issues, addressing natural resource issues, addressing drought conditions, addressing conservation, groundwater recharge, and desired future aquifer conditions (Texas Administrative Code, §§356.5 and 356.6). Since its creation in 2007, the STGCD has also created a management plan and a set of rules approved by the TWDB. The STGCD rules contain management strategies employed by the district including well spacing rules and well permits (Southern Trinity Groundwater Conservation District, 2007). The District spacing rules state that all new wells drilled into the Trinity aquifer must be a minimum distance of one thousand feet away from an adjacent Trinity well, and an additional twenty feet away for each additional gallon per minute of capacity over fifty gallons per minute, in order to minimize overlapping cones of depression between wells. The STGCD regulates withdrawal from the Trinity aquifer by requiring all wells in McLennan County to have permits, and collects fees from all well owners who have the ability to pump over twenty-five thousand gallons per day. Each well owner who has the ability to pump over twenty-five thousand gallons per day (non-exempt well owner) must have a Historic Use Production Permit (HUPP), which specifies how much water an owner can pump. There are two different types of production permits: Historic and Non-Historic. A HUPP is a permit where the amount of water allotted is based upon how much has been pumped in the past (before the formation of the

District in 2007), whereas a Non-Historic Use Production Permit (NHUPP) is primarily given to new well owners and is based upon how much water is needed by the owner and how much water is left in the Managed Available Groundwater for the Trinity aquifer in the STGCD.

The STGCD is part of a larger area designated Groundwater Management Area Eight (GMA 8, Figure 7) that covers the northern portion of the Trinity aquifer, and the participating districts within GMA 8 work together to develop management strategies which promote sustainability of the Trinity aquifer within GMA 8.

One of the main purposes of a GMA is to determine the desired future condition (DFC) for the aquifers within their boundaries. Examples of a DFC include establishing a sustained water level decline rate, or maintaining streamflow. In order for the districts in a GMA to meet their DFC, the Managed Available Groundwater (MAG) must be determined from a Groundwater Availability Model (GAM). The Texas Water Development Board (TWDB) contracted R.W. Harden and Associates, along with other experts, to develop a numerical groundwater flow model for the Northern portion of the Trinity Aquifer, with the purpose of determining groundwater availability. The final GAM (Figure 8) was completed in 2004 (Bené and others, 2004), and was modified in 2007 (Bené and others, 2007).

The MAG determined from the GAM for the Trinity aquifer in McLennan County is 20,690 acre-feet per year (Wade, 2009). Currently, 16,161 acre-feet per year are permitted to well owners in the form of Historic Use Production Permits, leaving 4,529 acre-feet per year still available.

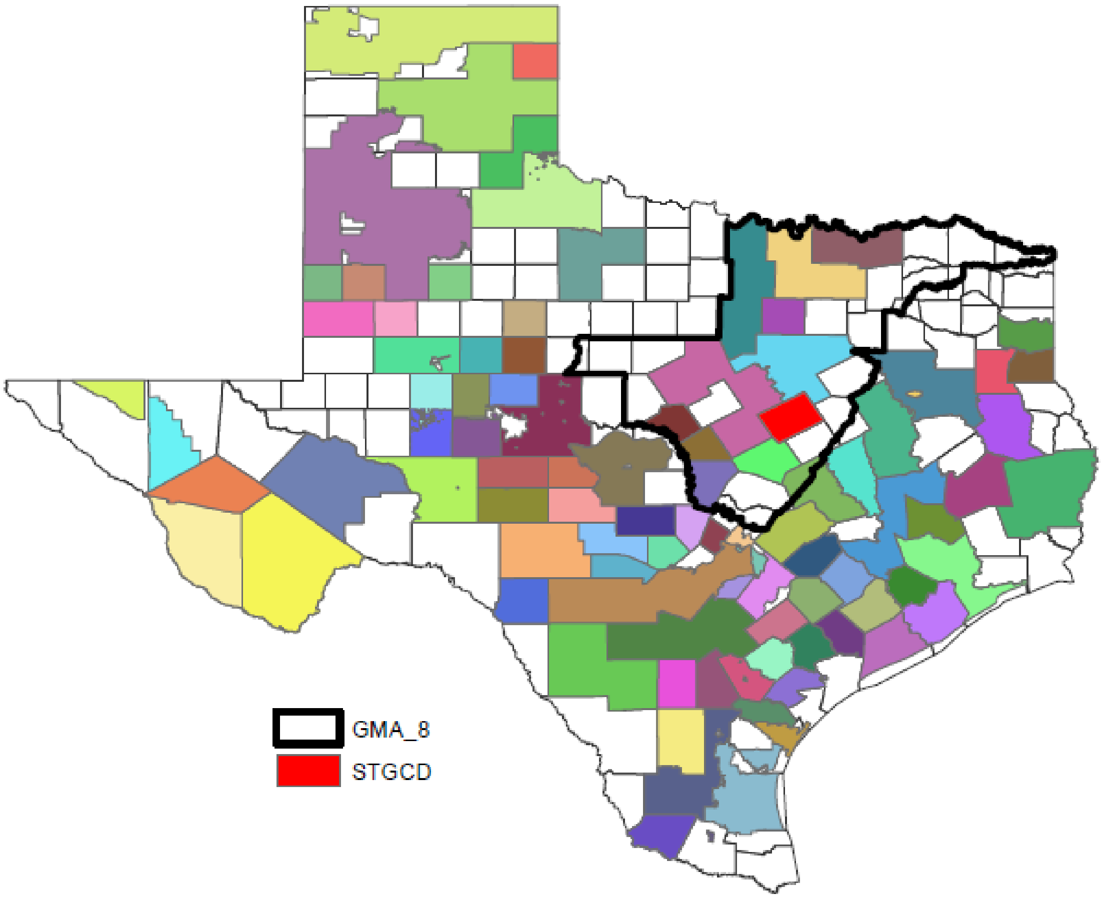


Figure 7: Groundwater conservation districts in Texas, and the extent of GMA 8.

Under the present STGCD management plan, the Hensell and Hosston units in McLennan County are managed as one unit. However, the GMA 8 approved a DFC for each Trinity Aquifer unit separately:

- "From estimated 2000 conditions, the average drawdown of the Hensell Aquifer should not exceed approximately 489 feet after 50 years."
- "From estimated 2000 conditions, the average drawdown of the Hosston Aquifer should not exceed approximately 527 feet after 50 years."

The separate DFC equates to 9.78 feet per year of drawdown for the Hensell and 10.54 feet per year for the Hosston. The TWDB also specifies separate amounts of MAG for each unit. In the STGCD management plan, the DFC for the Trinity aquifer is averaged between the two units and the MAG is the total for the entire Trinity Aquifer because: "Groundwater wells in the Trinity Aquifer are completed in a variety of ways and may be open, perforated, or screened in both the Hensell and Hosston formations. Therefore, the District manages them as a single aquifer" (Southern Trinity Groundwater District, 2007).

Because Trinity aquifer wells in McLennan County are completed in the Hensell and Hosston units both separately and in combination, this poses the question of whether the Hensell and Hosston members would be managed better separately or as one unit. In order to try to answer this question, two different hypotheses were evaluated:

1. The Hensell and Hosston are separate hydrogeologic units in McLennan County.
2. Boundary effects are significant and aquifer management in surrounding counties will affect the groundwater in the STGCD.

The primary hypothesis is that the Hensell and Hosston are separate hydrogeologic units (1). Secondly, it is estimated that boundary effects are significant and aquifer management in surrounding counties will affect the groundwater in the STGCD (2). Although hypothesis 2 is not the primary hypothesis, its methodology was completed first, because it could affect the results of analyses for hypothesis 1.

Previous Studies

There have been numerous other studies including reports, models, and maps, published on the Trinity aquifer, both old and new. However, the studies with the most applicable information, such as TWDB report 195 (Klemt and others, 1975), were completed in the sixties and seventies, whereas newer studies, such as the TWDB GAM (Bené and others, 2004, and Bené and others, 2007) have been regional in scale. Other previous studies provide useful information and data for Trinity aquifer, but more current and locally specific information on the Hensell and Hosston units in McLennan County are needed.

The first relevant, and enduring descriptions of Cretaceous strata in North-Central Texas were written by R.T. Hill (1901). The data and information in Hill (1901) were from the late 1800s and early 1900s, and give excellent indications of Trinity aquifer conditions before extensive development. In the 1930s, the Texas State Board of Engineers began compiling driller logs, water level data, and water quality data on wells located in many northern and central Texas counties (Bené and others, 2004). By the mid-twentieth century, when the population in northern and central Texas experienced growth, the methods of C.V. Theis (1935) came into widespread use, and there began an increased interest of researchers and state agencies in the hydrogeologic properties of the Trinity Aquifer. The population began to grow even more into the 1960s and 1970s, and during this time, county and regional studies funded by the TWDB such as Klemt and others (1975), were published. The work by Klemt and others (1975) is especially relevant to Trinity Aquifer research, as it includes numerous maps detailing the regional structure and lithologic properties of the aquifer, as well as historical water level and water quality data for individual strata in the central Texas area. The purpose of the report was to determine the occurrence, availability, dependability, quality, and quantity of groundwater for public supply, industry, and irrigation from the Antlers and Travis Peak Formations (Trinity Aquifer), and to establish a relationship between pumpage and water level decline. During this time, researchers at Baylor University also focused on Trinity aquifer dependability in North-Central Texas. Important Baylor Geological Society bulletins include: Holloway (1961), Henningsen (1962), Boone (1968), Rupp (1974), Bain (1973), and Hayward (1978). State and federal funding for research on the Trinity Aquifer continued into the 1980s. In TWDB Report 269 (Nordstrom, 1982), tables and maps of occurrence, availability, chemical quality of groundwater in North-Central Texas were published. Rapp (1986) also wrote a Baylor University thesis concerning groundwater recharge in the Trinity Aquifer, providing evidence that the aquifer receives more recharge from other geologic units than from its outcrop zone.

Over the last two decades, the volume of new information published about the Trinity Aquifer has decreased. However, studies on aquifer properties in North-Central Texas have continued. Mace and others (1994) discussed water level declines in North-Central Texas aquifers. A Baylor University thesis about the chemistry of the Trinity Aquifer in McLennan County (Thomas, 1997) was also completed. When the GAM was published for the first time in 2004, previous research on the hydrogeologic properties Trinity aquifer was summarized and put into model form in order that it could be applied to groundwater management (Bené and others, 2004, 2007).

Significance

The results of this study will improve knowledge of the Hensell and Hosston units in McLennan County and provide a current database that will enable the STGCD to better manage drawdown and water quality within the Trinity aquifer. The methods used in this study can also be extrapolated to other districts to solve similar problems in other aquifer systems. Following the analyses of the four hypotheses, a recommendation was presented to the STGCD regarding management of dual-completed wells and the Hensell and Hosston units.

CHAPTER TWO

Data and Methods

The first and primary step to provide data for use of all hypotheses was to create a reliable, organized, and thoroughly edited database that included characteristics such as well depth, screen intervals, chemical analysis data, water level, and re-completions for each well. The initial and primary sources of data for the master database were text files provided by the TWDB that included well data. However, the data from these files needed to be re-organized and edited to be more useful in characterizing the Hensell and Hosston units. The first step in database editing was to verify TWDB aquifer designations for each well. Many well designations such as "Travis Peak," or "Trinity," were vague and not specific enough to differentiate as Hensell or Hosston units. The wells with vague aquifer designations were corrected by checking well depths and locations against the structure contour maps of the aquifer contacts in Klemt and others, 1975. The results of this analysis are shown in Table 1.

Table 1: Analysis of unknown wells, part of database refinement

Analysis	Unknown Wells	Hensell Wells	Hosston Wells	Dual Wells
Before Analysis	38	93	142	9
After Analysis	2	105	166	9

Data

After refining and organizing the TWDB text files, more sources were needed to complete the master database and prepare it for aquifer analysis. A large literature review was conducted. Data from the TWDB did not include depth or elevation data for the Trinity aquifer zone contacts needed to create structure contour maps and isopach maps. Therefore, contacts for each aquifer were determined by interpreting available driller logs (see Figure 8 for an example) and well reports for each Trinity well in McLennan County, also provided by the TWDB, and finding the depth of the top and bottom contact of each aquifer. Driller logs and well reports were used as a "first cut" for aquifer contacts, because they were the most plentiful source of data.

Criteria used to carefully determine the contacts of the aquifers included: whether or not the unit of interest was at a reasonable depth (the well's location was determined spatially through the use of GIS, and compared to maps and data from TWDB report 195), whether it fell within the correct order of formations (ex. the Hensell underlies the hard Glen Rose limestone), whether it was a reasonable thickness, and whether or not there was a unit that fit the lithologic description of the aquifer present. If these criteria were not met, the data for that well were not included (40%, of wells did not have driller logs or the logs were unusable). Once the criteria were evaluated, the depths of the aquifer contacts chosen were converted to elevations relative to mean sea level.

Due to the inconsistency and unreliability of driller logs, geophysical logs (Figure 9), although less numerous, were used to refine aquifer contacts. Because

JOB NAME: City of West, Well #5
LOCATION: South end of Reagan Street
DRILLER: Jim Wagoner, D. E. Atchison
DATE: 7/28/81

DRILLERS LOG

DEPTH	DESCRIPTION	THICKNESS
0' - 5'	Top soil	5'
5' - 85'	Limestone and shale streaks	80'
85' - 159'	Limestone	74'
159' - 250'	Shale with sandy limestone streaks	91'
250' - 300'	Shaley limestone	50'
300' - 352'	Shale with sandy limestone streaks	52'
352' - 367'	Sand with shale streaks	15'
367' - 585'	Shale	218'
585' - 679'	Shale with sand streaks	94'
679' - 775'	Shaley limestone	96'
775' - 897'	Limey shale	122'
897' - 1013'	Shaley limestone	116'
1013' - 1023'	Sand	10'
1023' - 1128'	Shale	105'
1128' - 1165'	Shaley limestone	38'
1165' - 1172'	Sandy shale	7'
1172' - 1216'	Limestone with shale streaks	44'
1216' - 1318'	Sand	102'
1318' - 1390'	Limestone with shale streaks	72'
1390' - 1400'	Shale	10'
1400' - 1524'	Sand	124'
1524' - 1650'	Limestone	126'
1650' - 1731'	Shale with sand streaks	81'
1731' - 1765'	Limestone and shale streaks	34'
1765' - 1790'	Sand	28'
1790' - 1798'	Shale with sandy streaks	8'
1798' - 1807'	Sand	9'
1807' - 1830'	Shale, red	23'
1830' - 1837'	Sand	7'
1837' - 1933'	Sandy shale	96'
1933' - 1961'	Sandy shale with sand streaks	28'
1961' - 1980'	Shale, red, with limestone streaks	19'
1980' - 2042'	Sandy shale with sand streaks	62'
2042' - 2069'	Shale with limestone streaks	27'

Figure 8: Example of a driller log. Driller logs were first used as a data source to evaluate aquifer contacts because there were more driller logs than any others type of subsurface data.

driller logs are interpretive descriptions of lithologies from cuttings at the surface, and geophysical logs are direct measurements in the borehole, the geophysical logs were used to quantitatively compare the lithologies of the Hensell and Hosston units with regard to percent sand. Besides driller logs and geophysical logs, other data, such as transmissivity and storage coefficient, were also obtained from the literature for analyses.

Boundary Conditions Analysis

Although hypothesis 4 is not the primary hypothesis, it was tested first, because it could affect the results of the other hypotheses. Hypothesis four was completed after the well data from TWDB text files and aquifer contact data from driller logs were gathered and organized into the master database. In order to test hypothesis 4, aquifer contact depths were first evaluated through the use of structure-contour maps for each contact. The structure-contour maps were first evaluated using only McLennan County data, then additional data from nearby wells from surrounding counties were added (Figure 10), resulting in maps with extended boundary conditions for comparison to the maps restricted to McLennan County. A difference of greater than five percent in the area contained within of a contour interval or elevation of a contact was considered significant and any significant difference would indicate a need for extended boundaries to attain satisfactory accuracy.

The chosen method of evaluating the effects of boundary conditions was the comparison of structure-contour maps from driller logs. Structure-contour maps for each aquifer contact were first created using only data within McLennan County, and then another set of maps was created including nearby wells from surrounding counties.

Data for nearby wells were added from surrounding counties to the master database where layer gaps occurred along the county boundary. Then, a separate database was created from the original one, and consolidated to only include data required to project structure-contour maps for use in Arcmap (ESRI, 2010).

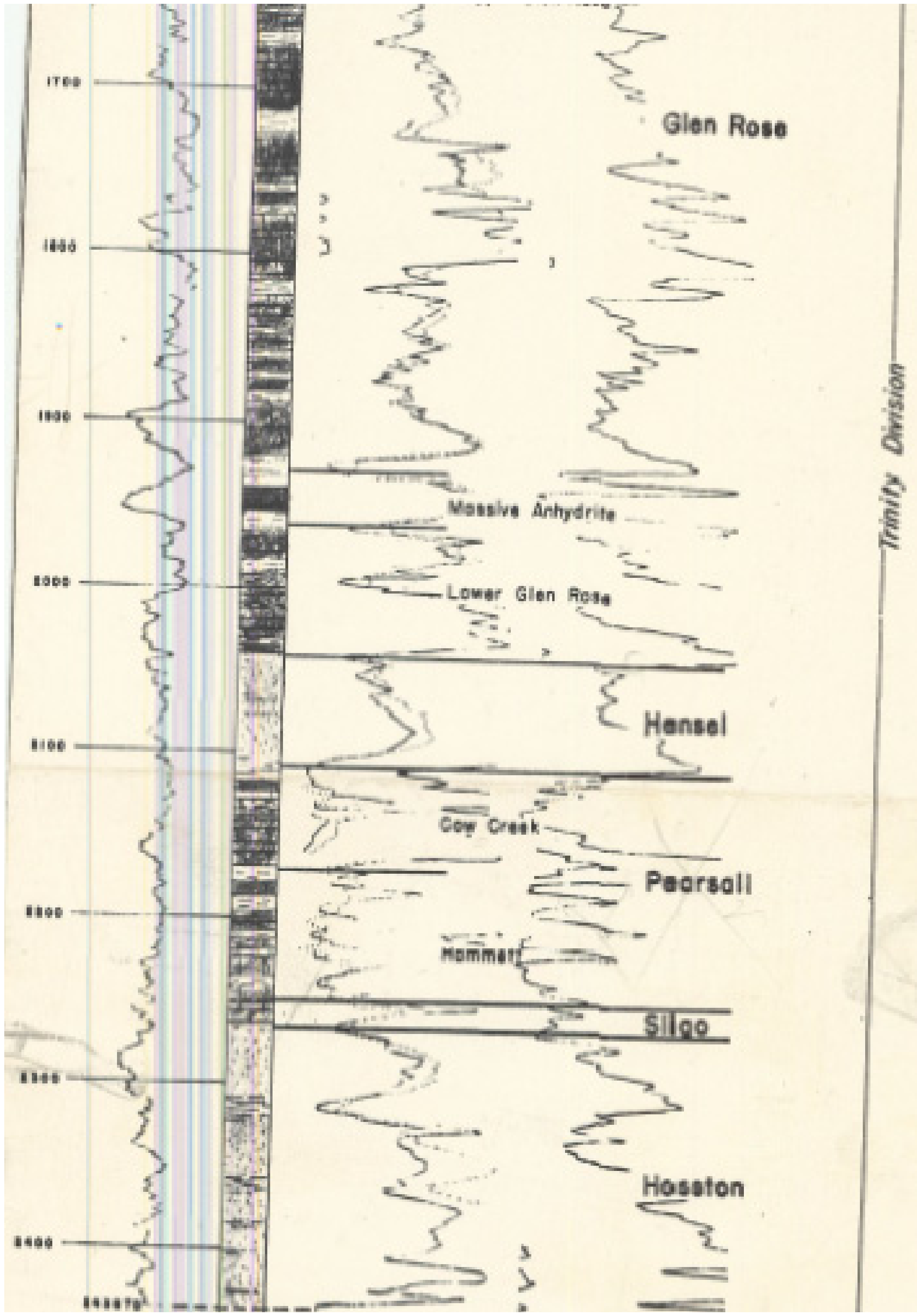


Figure 9: Baylor Geological Society Type Log (Flawn, 1965) with lithologies and aquifer contacts chosen (Texas State well number 4024803).

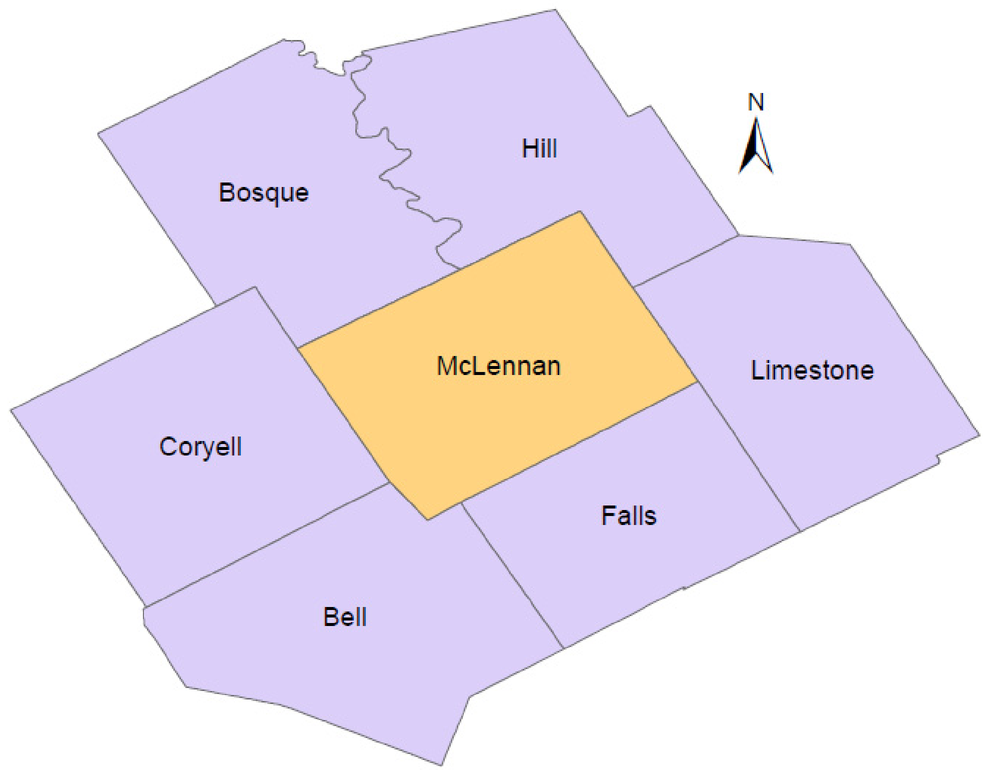


Figure 10: Areal extent of surrounding counties with nearby well data included in this study.

The data could then be projected into the eight required maps for each contact of the Hensell and Hosston units (Figure 11 shows an example of one of the contacts).

The effects of the boundaries were quantified by categorizing the colored contour intervals on the structure-contour maps and calculating the percent difference in area of each colored category from the maps (see Figure 11). This was accomplished by first cropping the maps with extended boundaries to match the same area as the maps containing only McLennan County data, and then performing a cell count to obtain area in Arcmap. An average total percent difference was then calculated by averaging the percent differences of the categories.

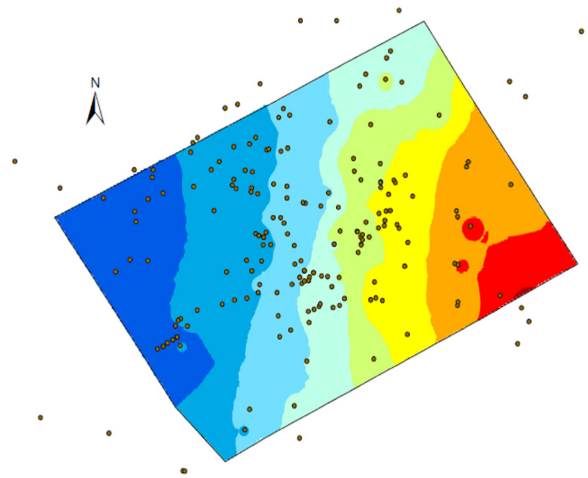


Figure 11: An example of a structure-contour map created from driller logs used in the boundary analysis (bottom of the Hensell contact).

Cross Sections and Recalibrated Structure-Contour Maps

Although geophysical logs are a less plentiful source of data than driller logs, they provide more reliable information; and there were enough of them to create cross sections and improve the previously structure-contour maps created from the driller logs. Aquifer contact elevations were evaluated using geophysical logs from twenty-nine different wells provided by the TWDB and recorded. From these data, three cross sections were created: a northern dip section, a southern dip section, and a strike section, to observe aquifer structure and framework through McLennan County.

The structure-contour maps previously created were improved by recalibrating with the contacts chosen from available geophysical logs. Isopach maps for the Hensell and Hosston unit were also created from the recalibrated data in order to observe trends in aquifer thickness.

Chemistry

Differences in aquifer chemistry between the two units were first investigated through the analysis of Total Dissolved Solids (TDS, mg/L) in order to get a general idea of differences in aquifer chemistry between the Hensell and Hosston units. Contour maps of TDS were created in ArcMap (GIS) in order to observe spatial trends for the Hensell and Hosston unit, then a statistical analysis of averages, ranges, medians, and modes was completed and the averages tested for significance with Student T Test. After wells outside of the average TDS standard deviation were removed, initial TDS values for each well were next plotted against depth (ft), in order to assess the impact of aquifer depth on water quality. Wells with TDS measurements that spanned the greatest amount of time were also selected in order to analyze whether TDS values changed through time and therefore whether production has impacted water quality in the Trinity aquifer within McLennan County.

Sulfate was chosen as a chemical constituent to analyze due to the presence of anhydrites (calcium sulfate) at the base of the Glen Rose Formation (Davis, 1974). Stratigraphically, the Hensell unit lies immediately below the Glen Rose Formation and could have a higher concentration of sulfate than the lower Hosston unit, because the Glen Rose Formation has been reported to contribute water to the Hensell unit (Rapp, 1986). There is no confining layer between the Glen Rose Formation and the Hensell unit and the head in the Glen Rose is thought to be higher than the head in the Hensell in McLennan County. Confining units separate the Hensell and Hosston units by about one hundred feet in most parts of the county and the head in the Hosston is greater than the Hensell in much of the county. Calcium and magnesium are also present in the Glen Rose Formation (Davis, 1974); however, on average, their concentrations are not nearly as high (fifteen milligrams per liter for calcium and four milligrams per liter for magnesium according to the TWDB text file data) as sulfate in the Trinity Aquifer in McLennan County (Texas Water Development Board, 2010). All water quality data for sulfate from the TWDB were imported into a separate sulfate database, and then refined to only include sulfate data, dates, and well numbers. Next, each measurement was given a previously assigned aquifer designation, and all non-Trinity wells were removed. The sulfate analysis was conducted in two steps, with the first analysis including only initial measurements from the date of the earliest sample in each well, and the second only including measurements recorded within the last ten years. For the first analysis, all measurements taken after the initial measurement were removed for each well, leaving 171 wells with initial sulfate data. Wells were also carefully evaluated for obvious anomalies. A well over the McGregor High (Klemt and others, 1975) with the Hosston unit only ten feet thick and a sulfate value of 2,649 mg/L was the only anomaly found and removed because the unusually high sulfate value and the unusual thickness were not considered representative of the aquifer within the county. An analysis including averages, ranges (measurements and dates), medians, and modes was then performed on the data for Hensell, Hosston, dual completed wells, and a total for all wells. A total for all wells was necessary to compare the Hensell and Hosston values with the values of the Trinity managed as one unit. Once the analysis was complete, an unpaired/independent Student T-Test was calculated for statistical significance of the Hensell and Hosston sulfate averages. For the second analysis, the same dataset was used, with all chemical measurements before 2001 removed. Duplicate measurements of chemical samples for each well were also deleted, and the most recent measurements were chosen over older ones. Once each remaining measurement was given an aquifer designation, another analysis was performed including averages, ranges (measurements and dates), medians, and modes. No chemical measurements on dual-completed wells within in the last ten years were found. The averages were once again tested for statistical significance. Next, all initial sulfate values were plotted through time. Additionally, four Hensell wells were selected to see trends through time for individual wells. The wells selected contained sulfate concentration data that spanned the greatest amount of time.

Piper Trilinear diagrams were also used to compare water chemistry within Hensell, Hosston, and dual-completed wells. Thirty-eight wells with chemical analyses were chosen randomly for the Hensell and Hosston units' Piper-Trilinear diagrams, and all nine dual-completed wells were chosen for the dual-completed diagrams.

Lithology

Percent sand was selected as a lithologic comparison for the Hensell and Hosston units and was calculated through the use of twenty-three geophysical logs with spontaneous potential curves. After percent sand was calculated for each well, average percent sand, along with median, mode, and range, was computed for each unit. The averages were tested for significance using a Student's T-Test.

Water Level

Although hydrographs of water level declines in McLennan County are available, they do not show the spatial distribution of drawdown within the Hensell and Hosston units. Other studies on water level have been completed in the past, such as the TWDB GAM, but they have been at a regional scale, therefore more detail was needed to be specific to McLennan County. This study evaluated hydraulic head between the Hensell and Hosston units, both spatially and over time, through the creation of water level contour maps, created in Arcmap from TWDB data.

All water level data were obtained from the TWDB in the form of text files and imported to a water level database compatible with ARCGIS, where it could be projected into map form. A twenty-year time interval was chosen for each set of maps (Hosston and Hensell), spanning from 1970 to 2010. Predevelopment and 1901 maps were also created. In an effort to populate these datasets with as many measurements as possible, water levels for two years on either side of the "target" year were selected (ex. 1988 to 1992 for 1990 maps). For all measurements not taken during the target year, hydrographs were created in order to determine the rate of drawdown, and the wells were "normalized" by adding or subtracting the appropriate amount of drawdown. For example, if your target year was 1990, and a measurement was taken in 1989, and the rate of water level decline from the hydrograph was ten feet per year, ten feet would be subtracted from that water level measurement to approximate the level in the target year 1990. Because of changes in pumping rates due to seasonal demand (drawdown and recovery), only winter water level measurements were included in the database (months 11, 12, 1, 2, and 3). Due to the effects of boundary conditions, nearby wells from other counties were also added to the dataset and normalized. Because data could be selected from five different months over a five year span for each of the target years, most wells contained several water level values in the resulting data set, so redundant values were also removed in the process, with the most representative value for that time period carefully selected. Once the data were ready for each well, the wells were projected using Arcmap (GIS) and used to create an interpolated surface, or raster, using the "Topo to Raster" tool in order to create the most hydrologically correct surface. The raster was then cropped to McLennan County, and 50 foot contours were created from the surface for the final contour maps.

Predevelopment and 1901 maps presented a challenge due to lack of data. Predevelopment data were obtained from Hill (1901), and the TWDB GAM, in order to best represent pre-drilling conditions. Another map was created using Hill's data, representing conditions circa 1900. Unfortunately, not enough information is provided in order to differentiate which wells are Hensell or Hosston from this time period.

Three-dimensional figures of the water level surfaces of the Hensell, Hosston, and dual-completed wells were also created through the use of Arcscene (GIS) in order to evaluate their general positions in relation to each other.

Well Hydraulics

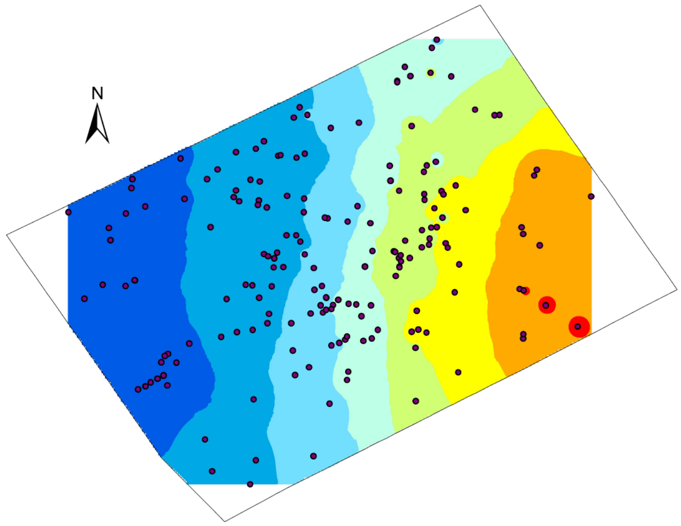
A literature review was completed in order to find all available transmissivity and storage values for the Hensell and Hosston units computed from pumping test data within McLennan County. The chosen set of values to create a table of transmissivity (T) and storage coefficient values (S) came from Klemt and others (1975). Next, the district rule that states for every gallon per minute over fifty gallons per minute that a well pumps, to add twenty feet to its spacing radius was applied to a hypothetical well pumping eighty gallons per minute. A diagram was created in Arcmap (GIS) showing the spacing radius for the hypothetical well as a dual-completed well managed as one unit, and as only Hensell, and only Hosston contribution if the rule were applied separately to each unit. Two tables were created from drawdown calculations for different units affected by the rule to compare drawdown that would occur in the Hensell, Hosston, and dual-completed wells based on the T and S values available.

CHAPTER THREE

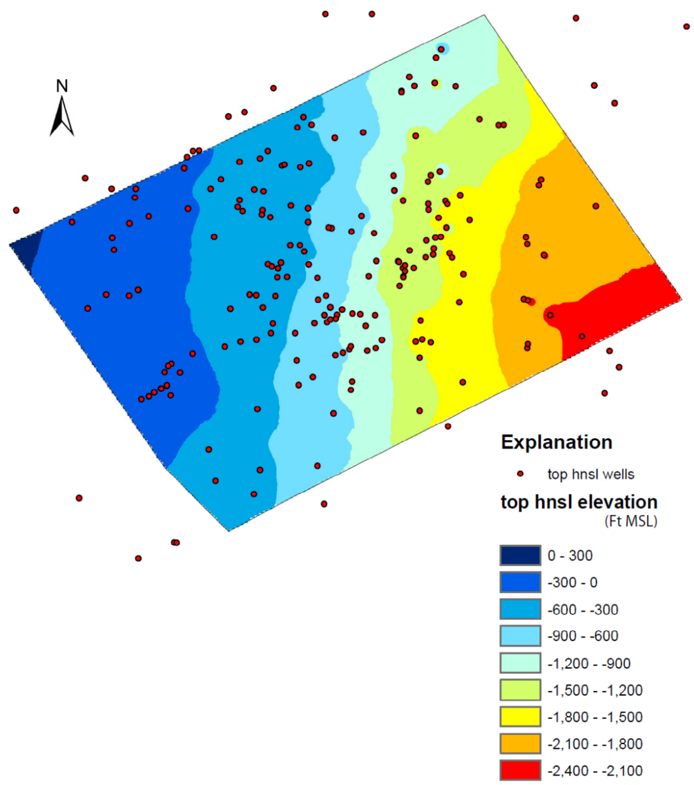
Discussion and Results

The structure-contour maps created from driller logs displayed the pattern expected from the literature of the Hensell and Hosston units dipping to the southeast (Figures 12 and 13) at about forty feet per mile. Figure 12 shows the structure-contour maps of the top of the Hensell unit before (A), and after (B) data outside of the county were added. As expected, the improvements in map B from map A are mainly on the edges and the corners of McLennan County. This is important in the eastern corner where the depth to the aquifer may be of significant interest. Understanding the aquifer at the District boundaries may also be important when management decisions are made in GMA 8. Figure 13 also showed similar differences in the Hosston between maps A and B, even with more limited data than the Hensell. Because there are fewer wells penetrating to the bottom of the Hosston unit, the eastern corner of the county was still not filled with a rasterized contour interval.

The effects of boundary conditions on the average area represented by three-hundred foot contour intervals on aquifer boundaries (Figure 14, Table 2) were found to be important overall (>5%), with the exception of the top of the Hensell (<1%). The bottoms of each aquifer zone varied the greatest, which can be attributed to geology and the quality of driller logs.



A.



B.

Figure 12: Structure-Contour maps created from driller logs of the top of the Hensell. Map A used only data in McLennan County, and map B used wells in adjacent counties as well as McLennan County.

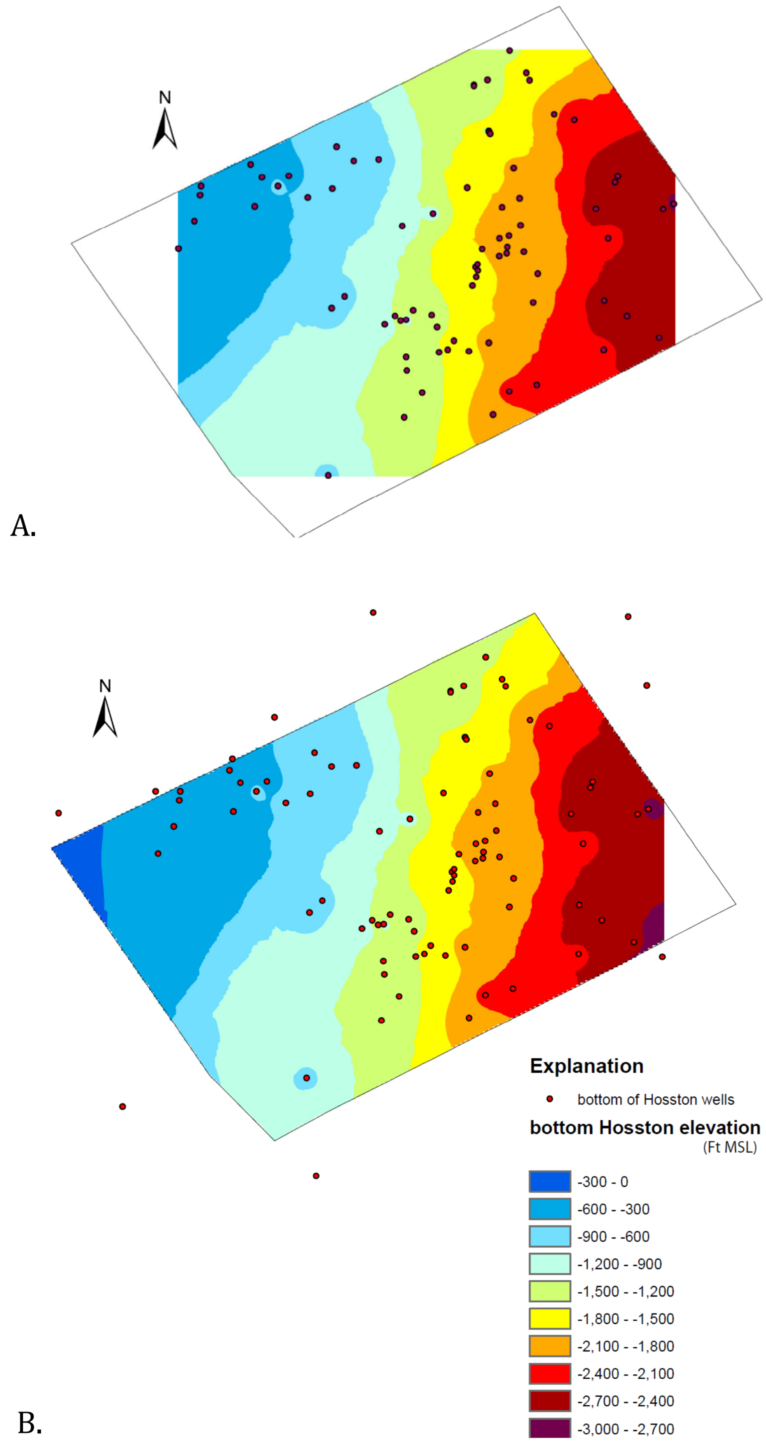


Figure 13: Structure-Contour maps created from driller logs of the lower contact of the Hosston, first using only data in McLennan County (A), and then with extended boundaries including nearby wells (B).

Category	B Hnsl %Δ
1	0
2	0
3	90
4	1
5	4
6	1
7	12
8	12
9	2806*

Figure 14: An example of percent difference in area calculated for each colored category for the bottom of the Hensell surface. The exceedingly large number for category nine was not used in the analysis, because category nine was not present in the map without extended boundaries.

Table 2: Average, minimum, and maximum percent change for extended boundary conditions for each contact.

%Δ	T Hnsl	B Hnsl	T Hstn	B Hstn
Min.	<1,	0	4	8,
Ave.	**<1**	**15***	**5**	**30**
Max.	3	90*	14	98

Geology plays a role in distinguishing the bottom of the Hensell (which had the greatest percent change) because there is not always a clear transition from the aquifer zone to the underlain confining unit, as both units usually contain similar lithology of interbedded sands and clays. The bottom of the Hosston had a large percent change due to the limited amount of data (and therefore the greatest uncertainty). Because of the greater depth and thickness of the Hosston, few wells penetrate completely to the bottom; resulting in fewer data points of the lower contact. Based on the results of this analysis, nearby wells were included in the analyses of Trinity aquifer characteristics in McLennan County.

Geophysical Log Cross Sections

The cross sections created for different parts of the county (Figure 14), showed the pattern expected from the literature, with the Hensell and Hosston dipping to the southeast, and with little change along the strike section (Figure 18). While the northern dip section, or cross section A (Figure 16), showed the units smoothly dipping to the southeast, the southern dip section, or cross section B, (Figure 17, B-B') showed more of a stair step pattern, indicative Balcones Fault Zone effects on aquifer structure. Cross section B also showed the Hosston unit thickening to the southeast, while the Hensell unit exhibited a more uniform thickness. The data used for these cross-sections were limited to the well logs along the line of section and interpretation was minimized. A more detailed interpretation or additional well data could result in more fault related effects associated with the dip. An example of a fault-related, regional Trinity aquifer map that runs through McLennan County can be found in Klemt and others (1975).

Recalibrated Structure-Contour and Isopach Maps

Overall, the recalibrated structure-contour maps (Figures 20 and 21) did not show considerable change from the originals, which indicates that the driller logs

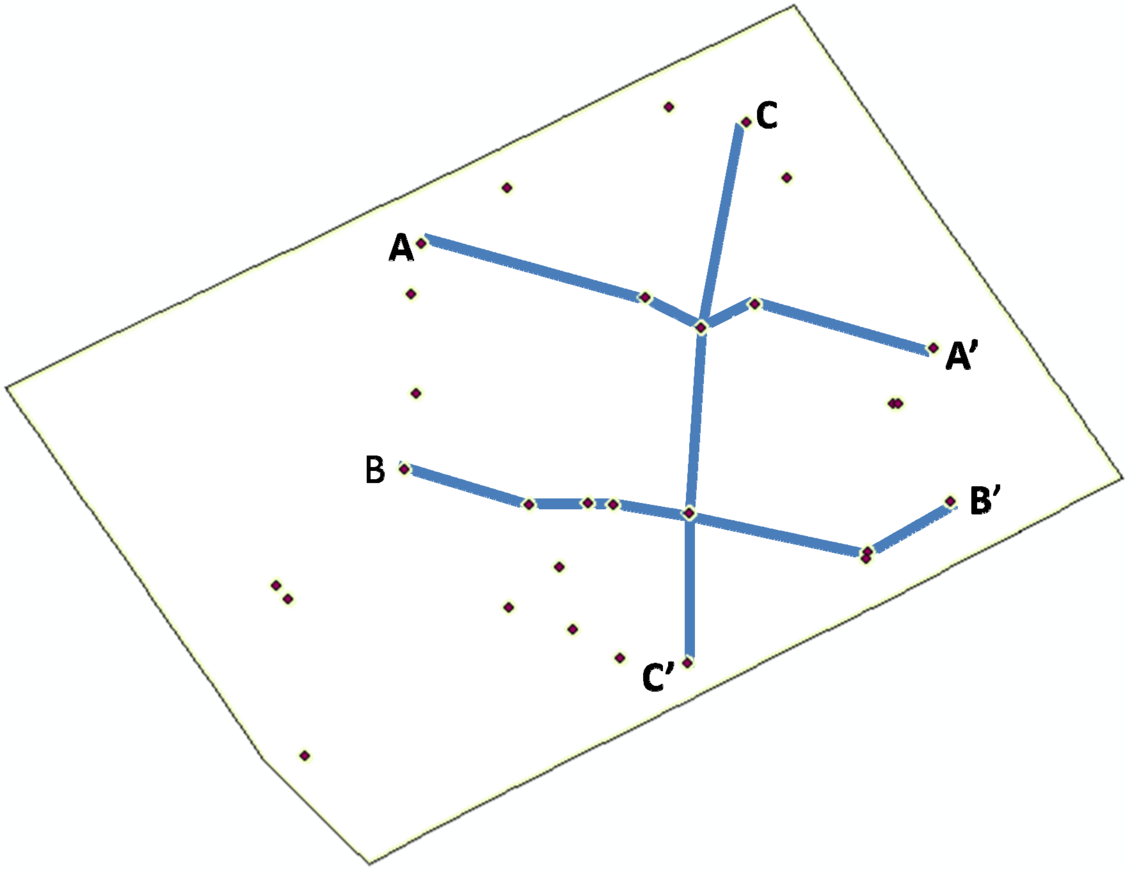


Figure 15: Geophysical log cross section locations.

chosen (only sixty percent of driller logs were usable), were reliable enough to use in general trend analysis (see Appendix A for data used to create maps). All structure-contour maps produced displayed the correct general pattern of the aquifer contacts (dipping southeast). Fault lines are not displayed on the maps, however, the elevation contours are more closely spaced where the Balcones Fault Zone occurs on all maps: through the center of the county. Regional maps with fault line locations in McLennan County can be found in Klemt and others (1975). Because the fault zone is known to displace the aquifer by up to four-hundred feet

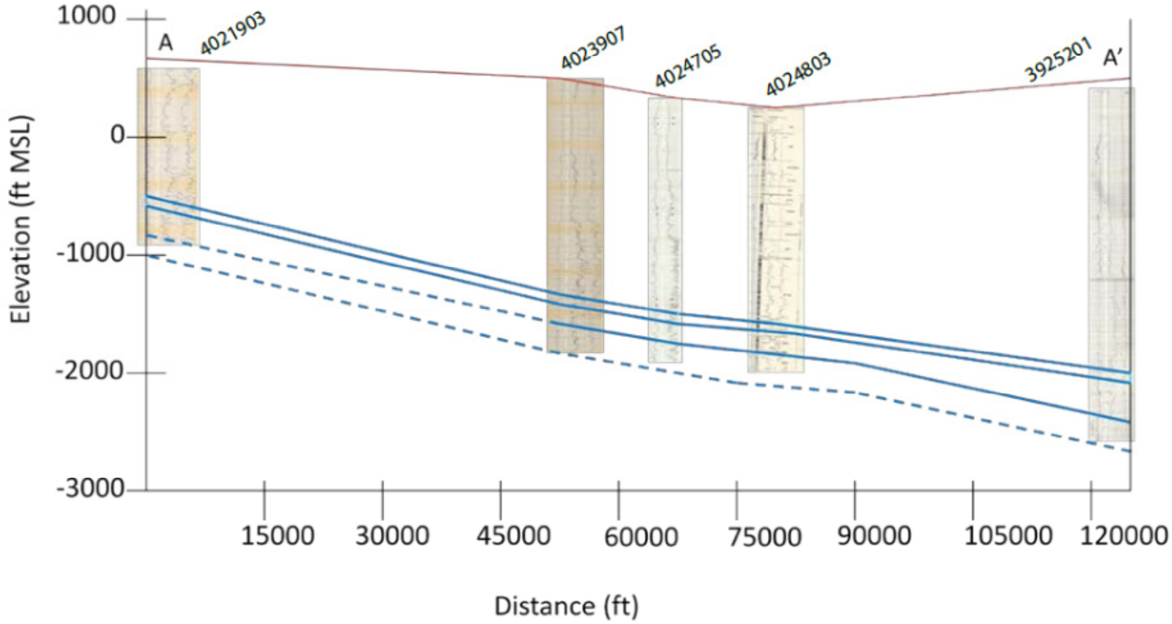


Figure 16: Example of A – A’ northern dip section with geophysical log locations and selected aquifer contacts (well numbers are above geophysical logs).

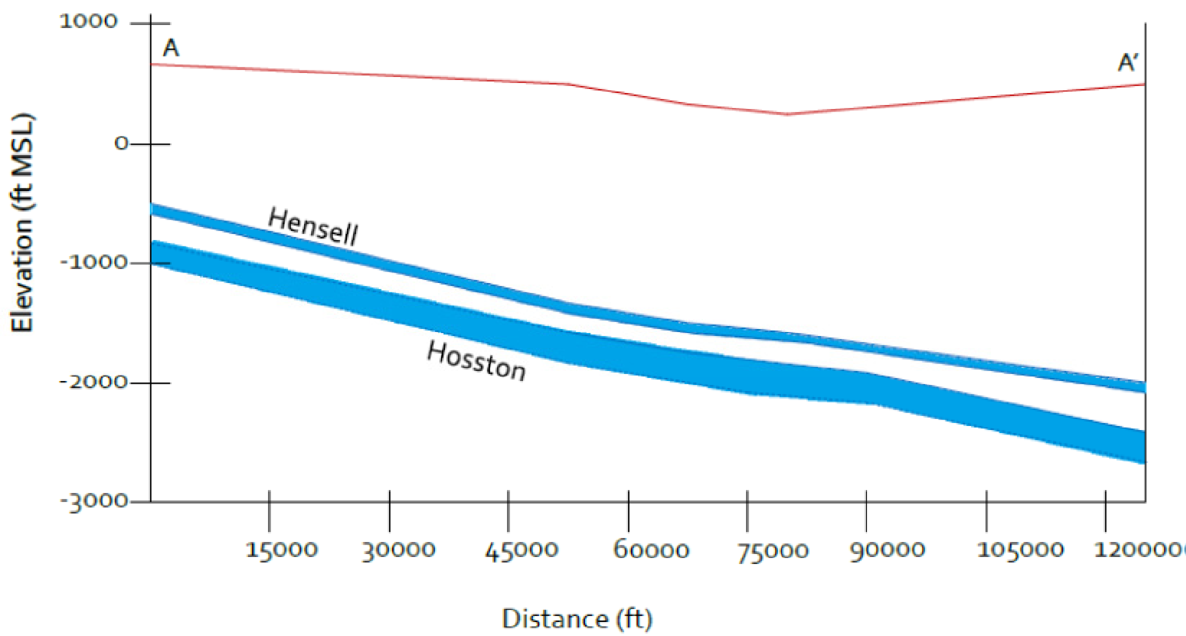


Figure 17: Cross section created from geophysical logs of the northern dip section of McLennan County.

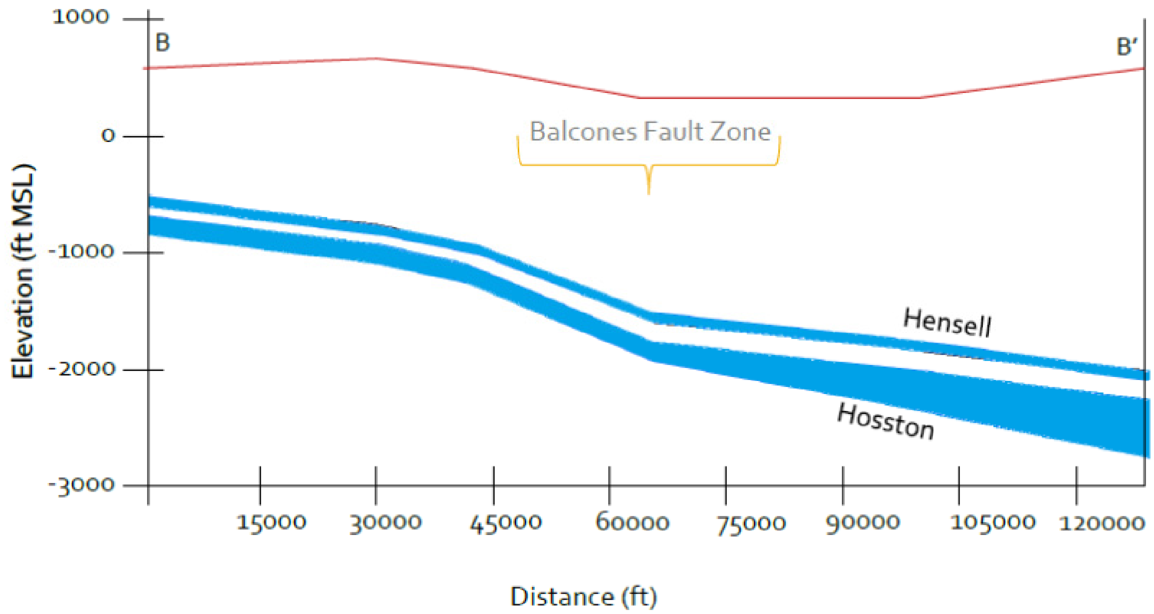


Figure 18: Cross section created from geophysical logs of the southern dip section of McLennan County.

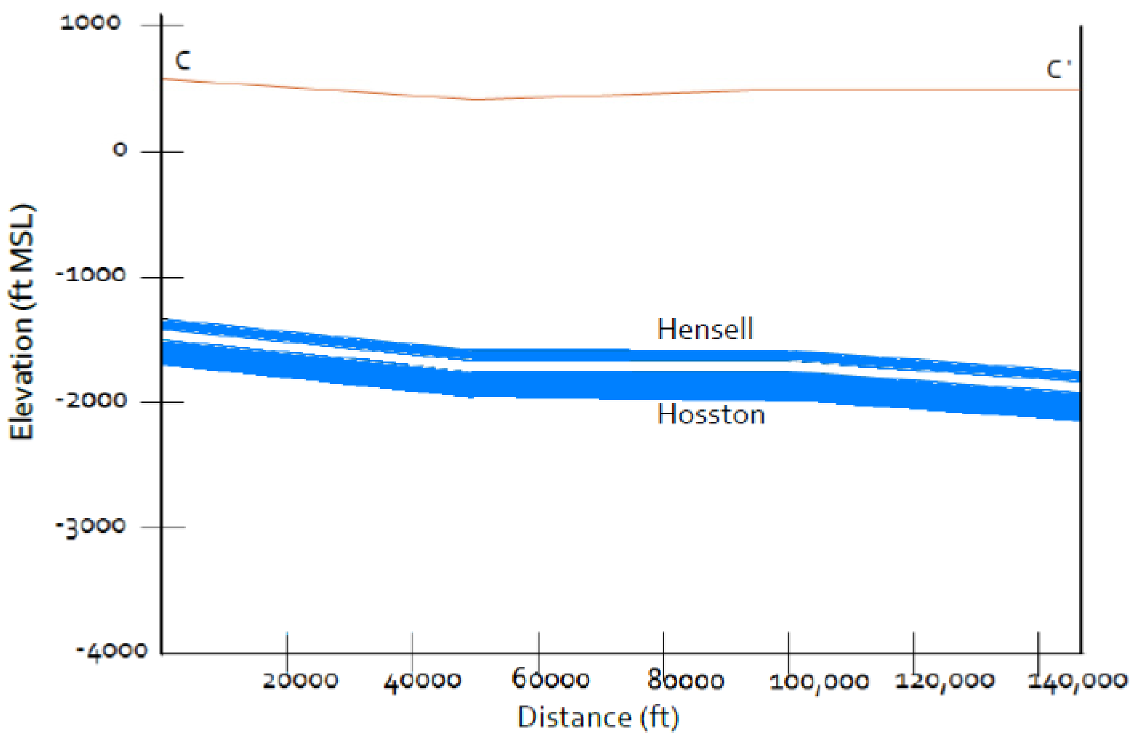


Figure 19: Cross section created from electric logs of the strike section of McLennan County.

(Klemt and others, 1975), and the elevation contour intervals are three-hundred feet, the faults are not as obvious as they would be with smaller contour intervals.

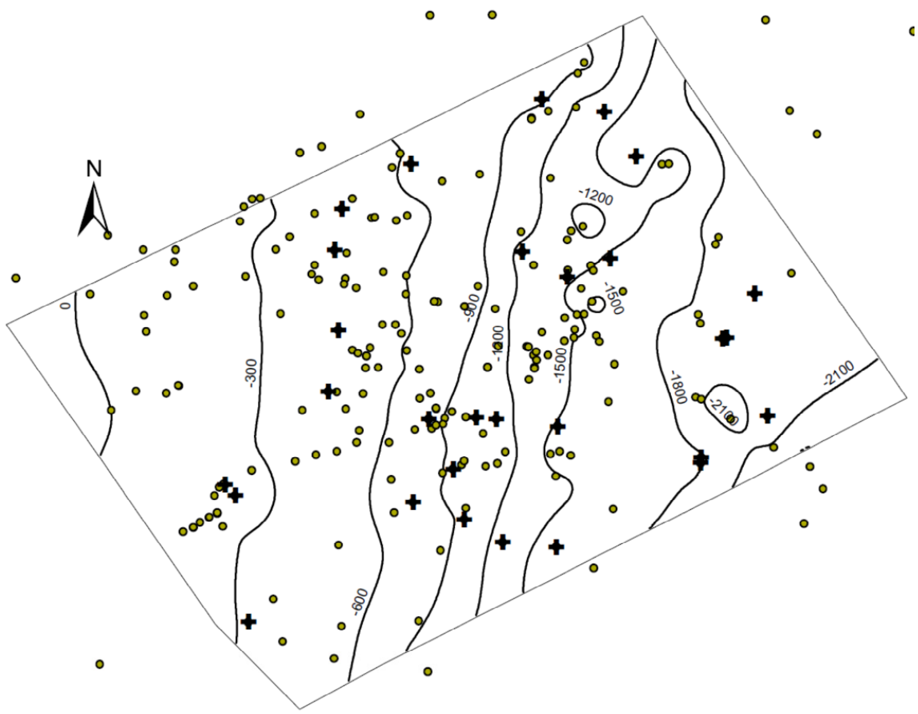
Isopach maps (Figures 22 and 23) from the same data used in the structure-contour maps show the Hosston thickening to the southeast, with contour gradients steepening to the southeast as well. Unlike the Hosston however, the Hensell unit's isopach map showed a more uniform thickness throughout the county (contours varied less than fifty feet, whereas the Hosston unit varied over three-hundred feet). Although the Hensell thickness is fairly heterogenous in Figure 22, the pattern shown may be the results of a remnant fluvial channel once present.

The cross sections, structure-contour maps, and isopach maps created for the Hensell and Hosston units of the Trinity aquifer indicate the two units have unique depths and thicknesses throughout the county. With only well completion (screen) depth and location information, one can determine whether a well is completed in the Hensell or Hosston unit.

Chemistry

At first glance, the Hensell TDS contour map (Figure 24) appears to have a clear trend with TDS increasing to the eastern part of the county. This makes sense, because TDS within deep confined aquifers increases with depth (Chebotarev, 1955). However, when a closer look is taken, the trend in the Hensell unit's steep TDS gradient in the eastern portion of the map is largely due to a few wells with very large TDS values skewing the trend. Whether or not the trend is real is debatable, because Hensell wells become sparser towards the southeastern portion

A.



B.

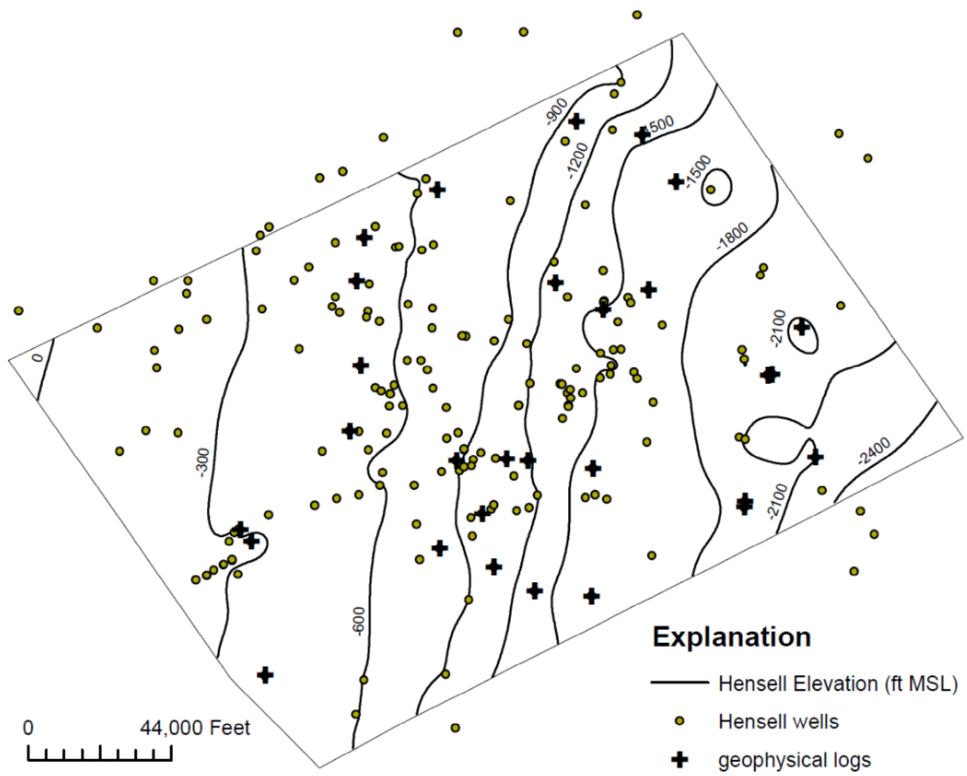


Figure 20: Structure-contour maps of the top (A) and bottom (B) of the Hensell unit recalibrated with geophysical logs (contour interval=300 ft).

Figure 21: Structure-contour maps of the top (A) and bottom (B) of the Hosston unit recalibrated with geophysical logs (contour interval=300 ft).

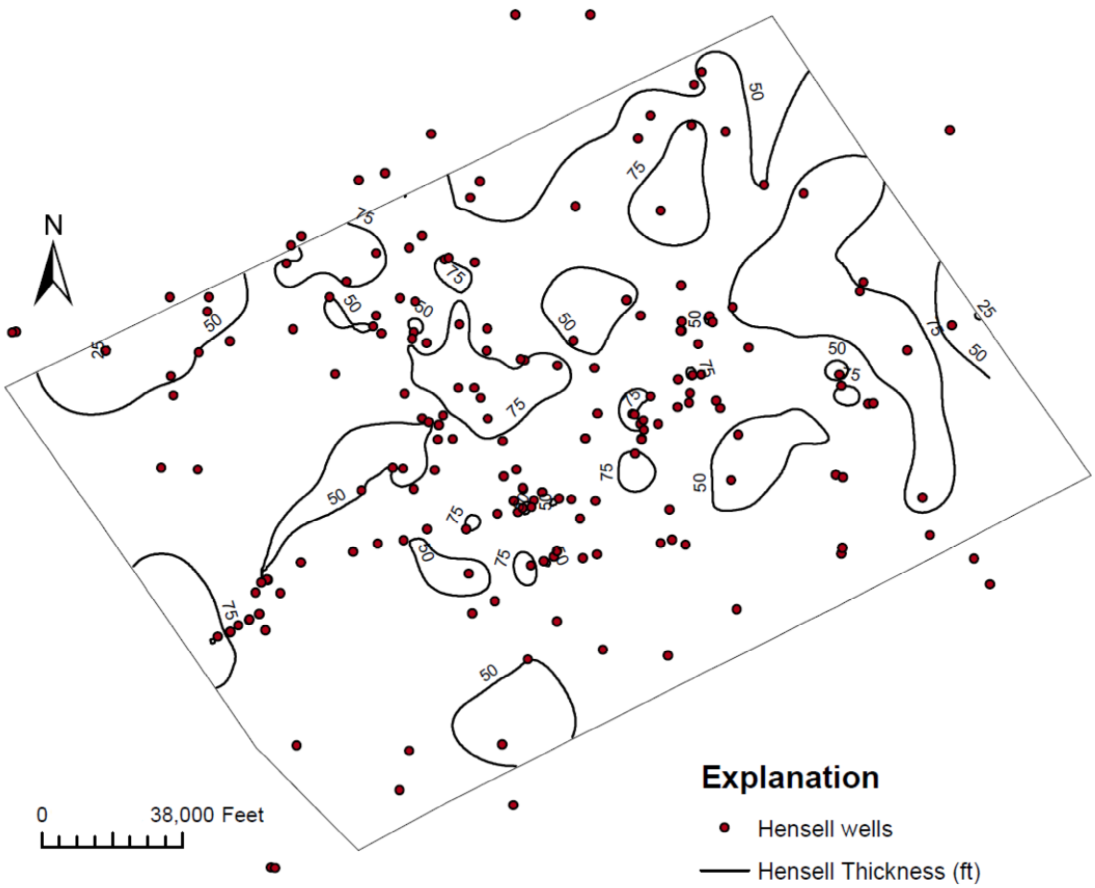


Figure 22: Isopach map of the Hensell unit (contour interval= twenty-five feet).

of McLennan County. State well number 4022502 is the well that creates the deepening trend in the northern portion of the county. This is a domestic well with a TDS value of 2659 milligrams per Liter. No explanation was found to explain this unusually high value.

For the TDS contour map of the Hosston (Figure 25), the TDS values in general are lower overall (see Table 3 for averages), and there appears to be less of a trend. The lower TDS values of the Hosston unit are most likely due to its separation from the overlying the Glen Rose Limestone which contains anhydrites and high TDS values at its base.

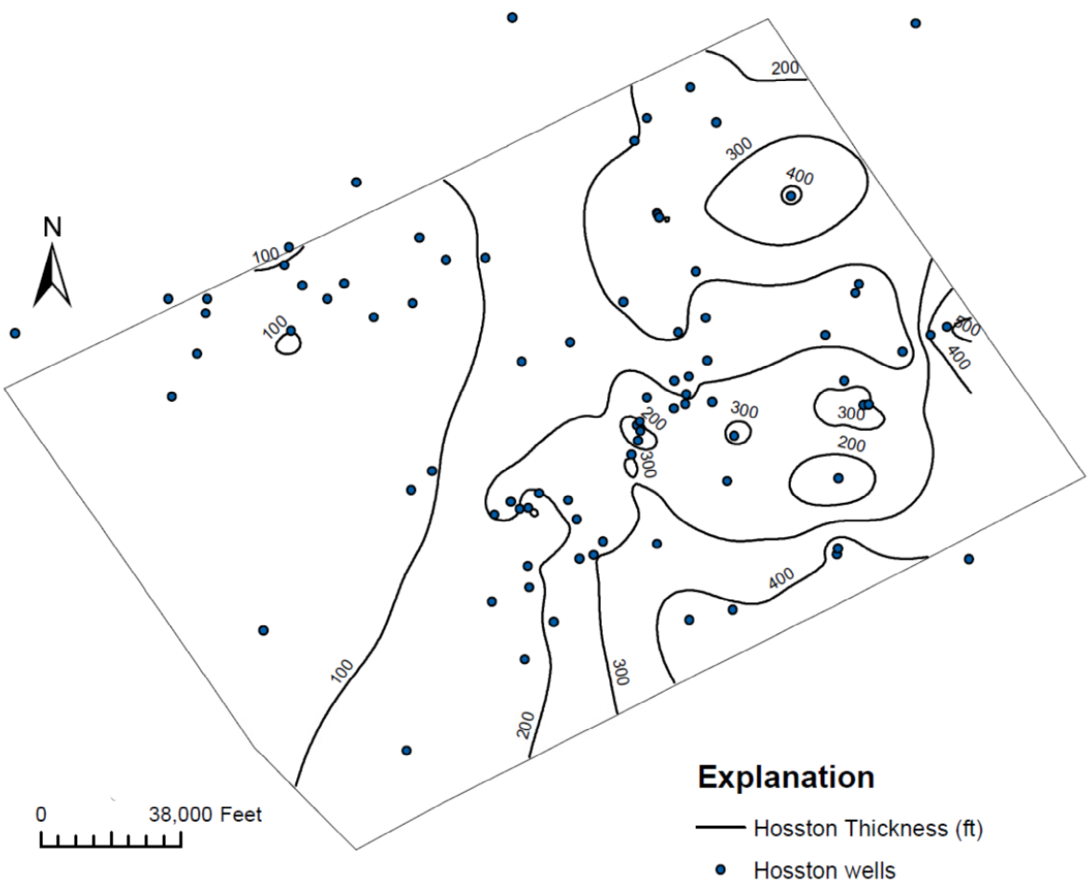


Figure 23: Isopach map of the Hosston unit (contour interval= one-hundred feet).

As expected for deep confined aquifers, TDS increases with depth (Sokol, 1963) in both units (Figures 26 and 27). However, the slope of the Hensell trend line is slightly steeper than that of the Hosston, indicating that depth affects the Hensell unit more than the Hosston. An interesting note on the data exhibited in Figure 27 is the freshness (low TDS) of the groundwater even with great depth. Because the correlation coefficients of the deepening trend are poor and the deeper areas occur in the same area as the fault zone, it is feasible higher TDS values may be affected by fault restricting flow.

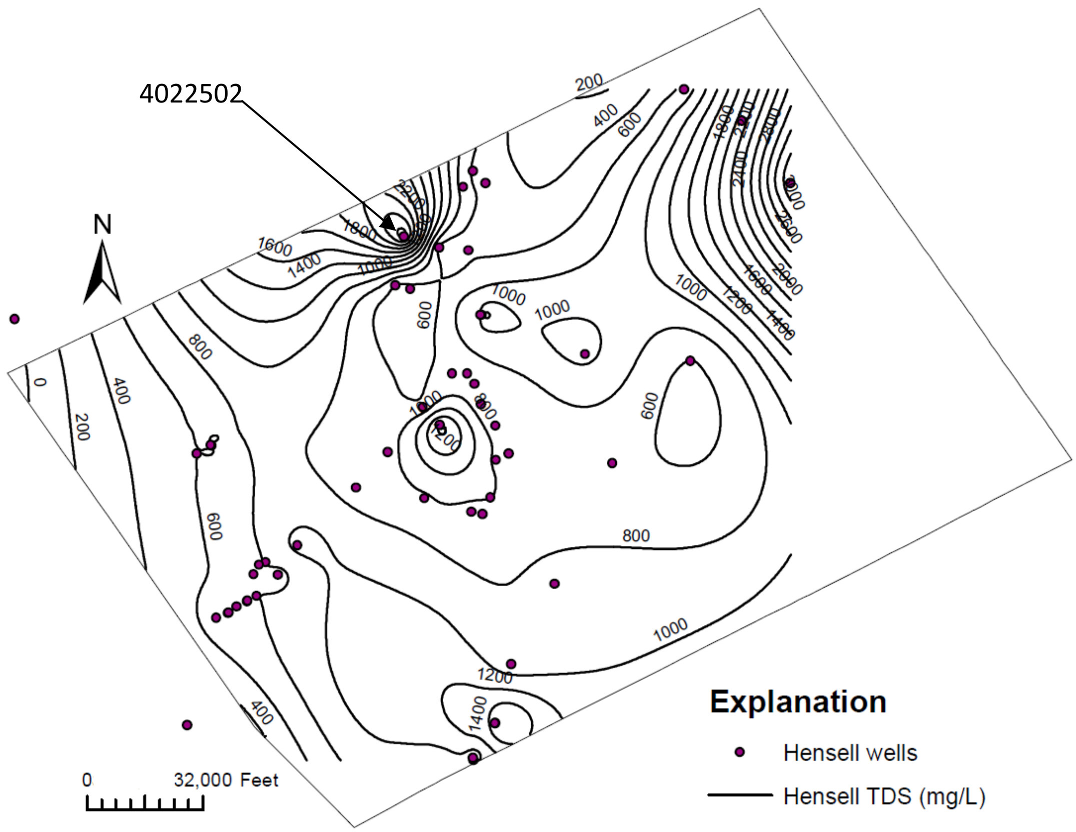


Figure 24: Spatial distribution of TDS (mg/L) in the Hensell unit within the county (contour interval=200 feet).

TDS values were also plotted over time using the seven wells with the most measurements through time (all of which were Hosston wells). All but one of the wells plotted showed a pattern similar to that of Figure 28, with TDS increasing slightly over time. However, there were a few aberrant wells found that displayed patterns more similar to Figure 29, with TDS either spiking up and down, or decreasing over time in general. No evidence for well recompletion or a contamination or cleanup event was discovered.

In contrast, when all recorded initial TDS values for wells in McLennan County were plotted through time (Figure 30), both the Hensell and Hosston units showed a decreasing trend over time, with the Hensell (the upper line on the graph), decreasing slightly more than the Hosston (lower line).

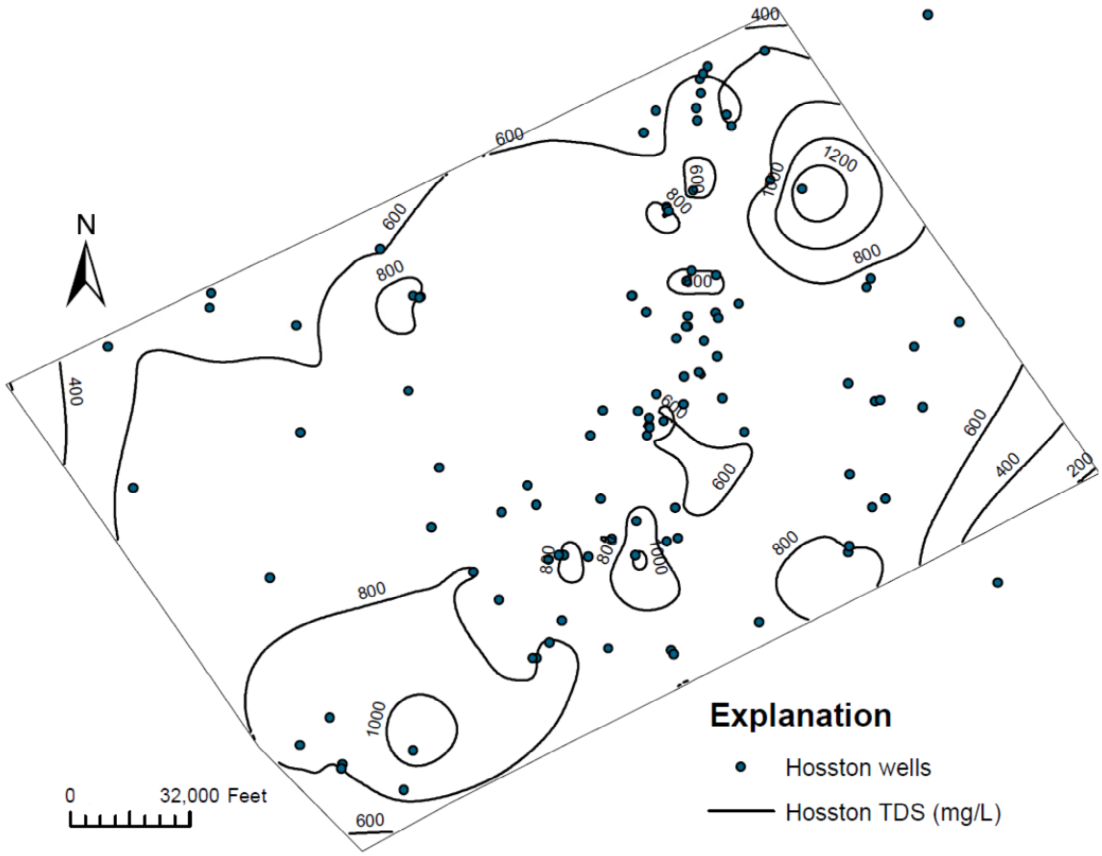


Figure 25: Spatial distribution of Hosston TDS (mg/L) within the county (contour interval=200 feet).

The decrease in TDS values may be the result of better completion intervals aided by greater geologic knowledge of aquifer boundaries and improved geophysical data available prior to completion.

The result of the TDS graphs for individual wells through time, exemplified by Figure 28, indicate individual well TDS concentrations may increase over time, which may be due to the effects of production inducing water from higher TDS zones such as confining units, clay lenses, or restricted zones.

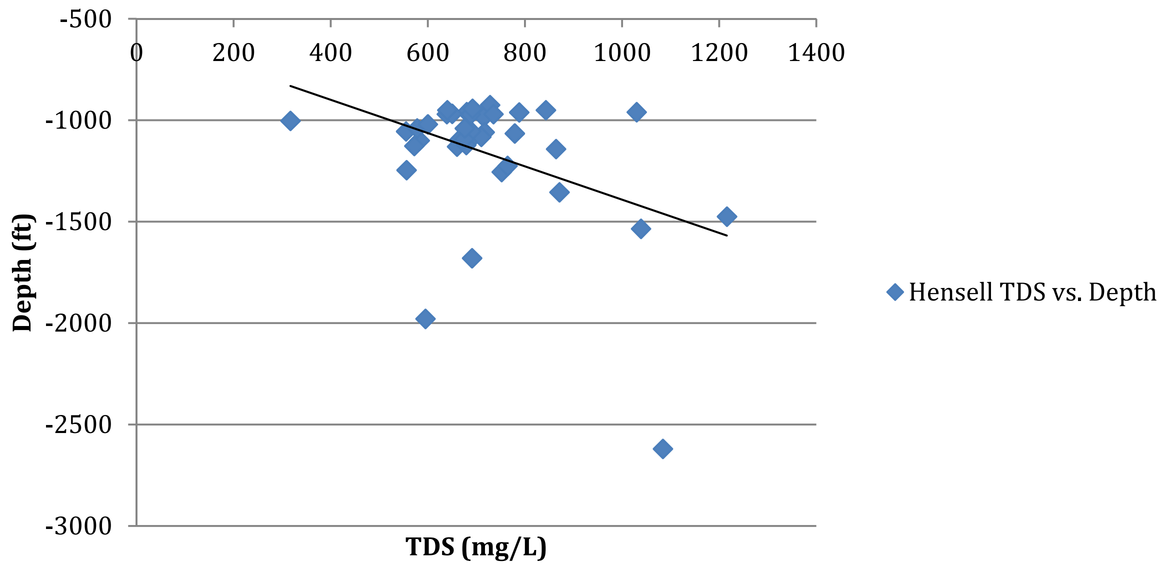


Figure 26: Hensell initial TDS (mg/L) measurements vs. depth (feet from land surface to the top of the Hensell unit) for wells in McLennan County. The R^2 value for the Hensell was 0.1667.

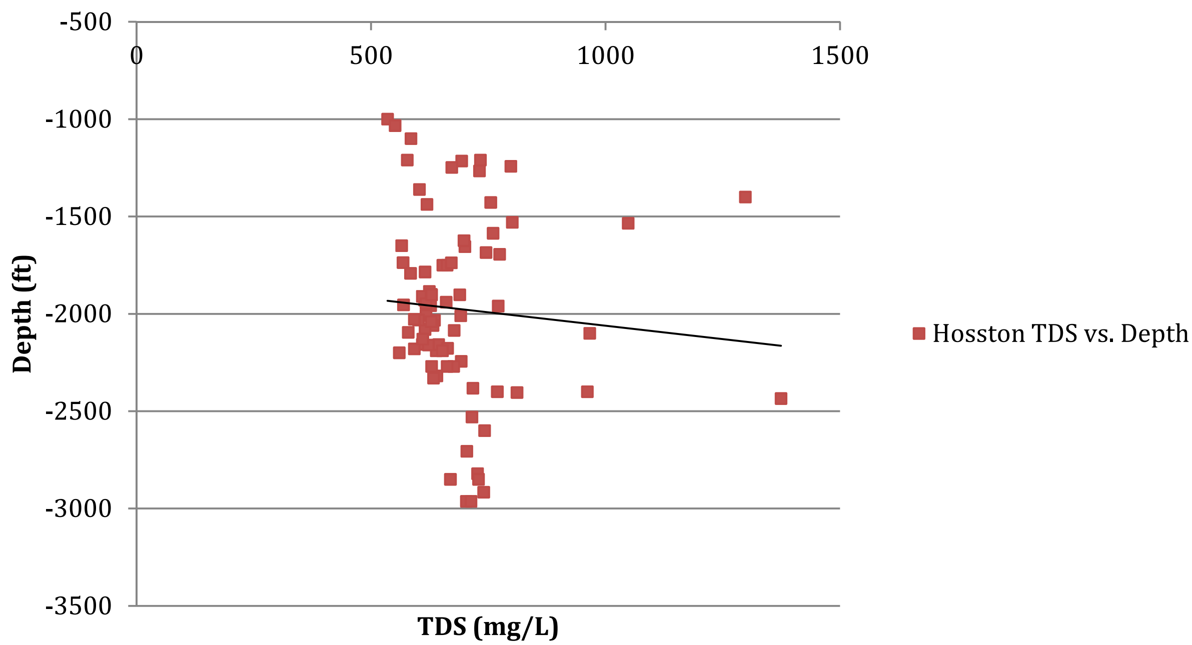


Figure 27: Hosston initial TDS (mg/L) measurements vs. depth (feet from land surface to the top of the Hosston unit) for wells in McLennan County. The R^2 value for the Hosston was 0.0067.

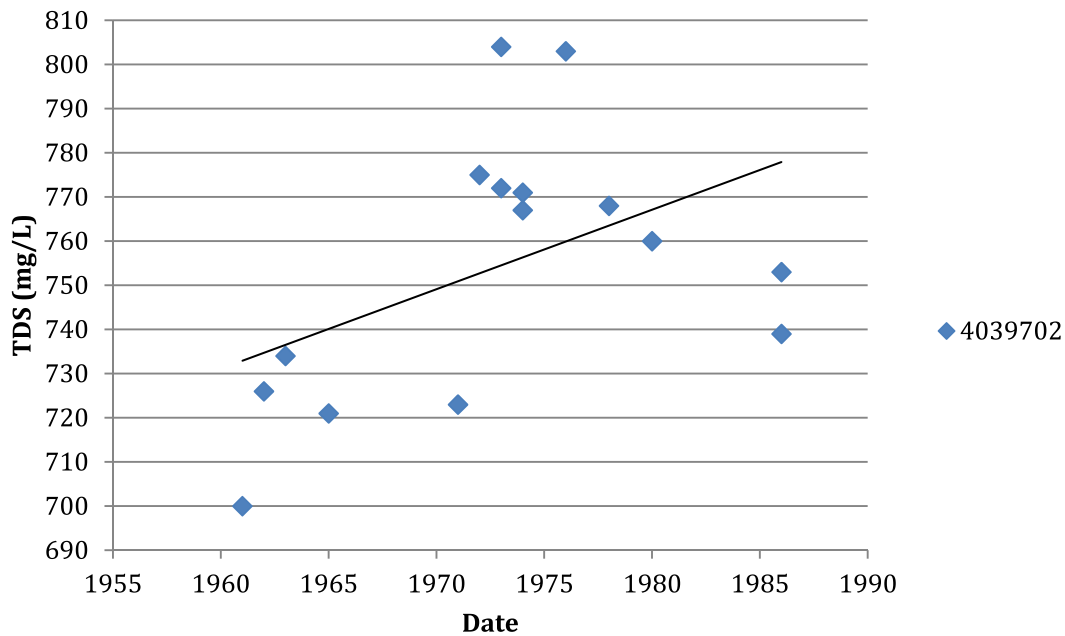


Figure 28: Typical pattern for TDS (mg/L) through time for a Hosston well through time. The R^2 value for this well was 0.2181.

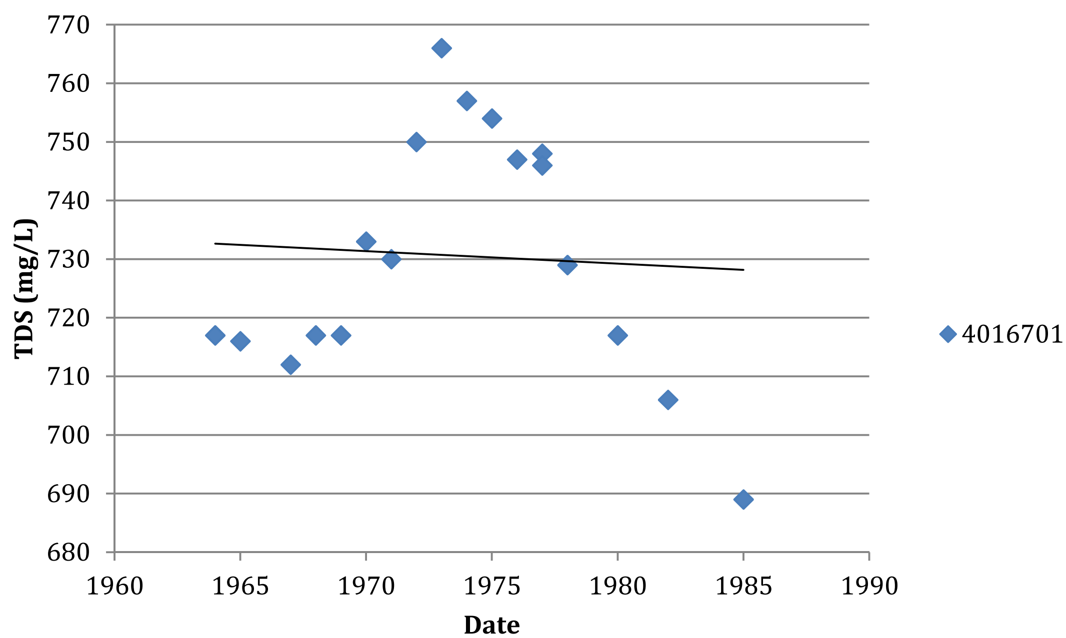


Figure 29: a non-typical pattern for TDS (mg/L) of a Hosston well through time. The R^2 value for this well was 0.0036.

When all initial TDS values are plotted, on the other hand, the decreasing trend shown in Figure 30 may be the result of better screen intervals being chosen for newer wells.

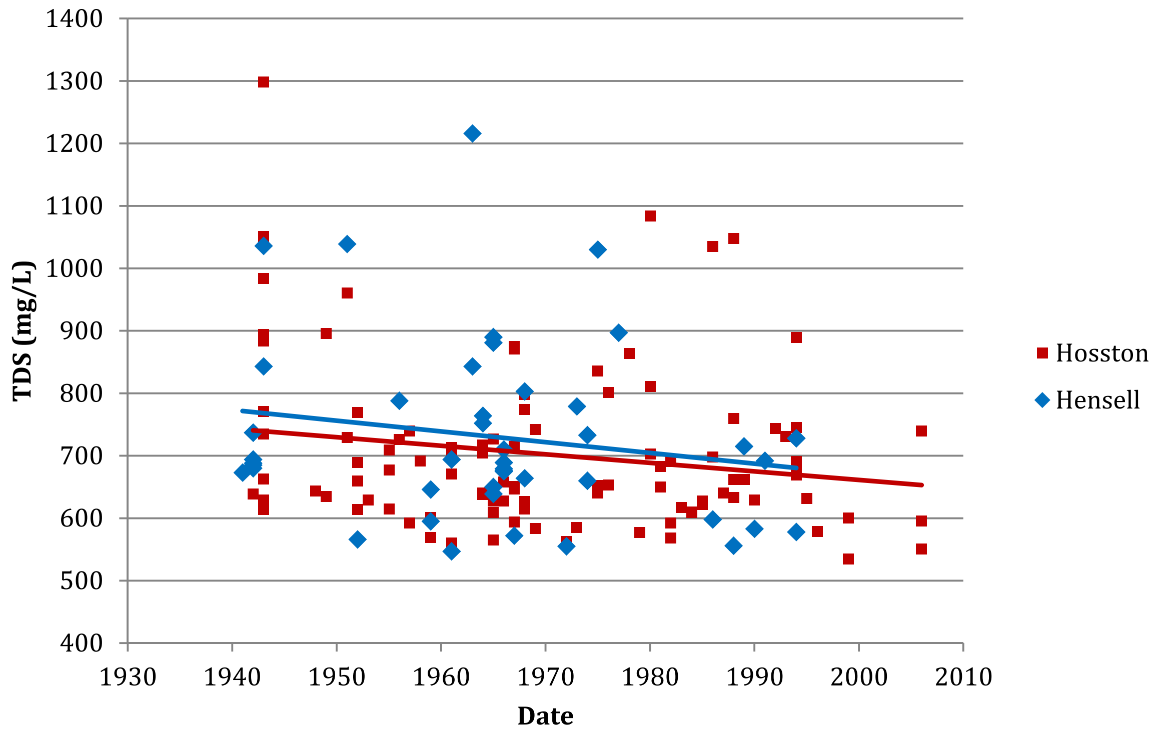


Figure 30: Initial TDS (mg/L) measurements through time for Hensell and Hosston wells in McLennan County. The R^2 values for the Hensell and Hosston were 0.0363, and 0.0334, respectively.

This could be due to drillers becoming more knowledgeable about the geology of the Trinity aquifer over time, enabling them to choose the best depth intervals for screening.

The TDS analysis (Table 3) comparing initial TDS values among Hensell, Hosston, and dual-completed wells showed the average TDS concentration of the

Hensell unit was greater than the Hosston average TDS concentration but the difference was not statistically significant, according to a Student T Test. However, the value was still close to 0.05 (0.063), providing evidence that difference between the units may be concern for management decisions. The average, range, median, and mode TDS concentrations for the Hensell were also higher than the Hosston. Only nine dual-completed wells were found with initial TDS values. The mean for the dual-completed wells was closer to the Hosston value. The greater transmissivity of the Hosston may skew the dual-completed well values toward the Hosston values. The lowest TDS value found in any well (317 mg/L) occurred in a dual-completed well.

Table 3: Initial TDS (mg/L) measurements from Trinity wells in McLennan County.

Aquifer	Hensell	Hosston	All Wells	Dual
Number of measurements	52	105	166	9
Average TDS	944	739	800	681
Range TDS	547 – 4865	535 – 3795	317 – 4865	317 – 966
Median TDS	712	662	687	693
Mode TDS	694	628	628	No Data
Range Date	1941 – 1994	1942 – 2006	1941 – 2006	1942 – 1986

Initial sulfate values were also analyzed. Overall, the Hensell unit had measurements that contained a significantly higher concentration of sulfate compared to the Hosston unit, according to a Student T-Test (0.006). Table 4 shows that the sulfate concentrations differ between the Hensell and Hosston units, even though the range of values for each unit almost completely overlaps. However, the much lower median values indicate that there are just a few very large measurements skewing the averages. Average sulfate values for dual-completed wells on average had values much closer to the Hosston than the Hensell. This may be due to the larger transmissivity of the Hosston, and therefore more water would be produced from the Hosston than the Hensell if the well was completed through the entire section of both units.

Table 4: Analysis of sulfate (mg/L) within the Trinity aquifer using initial measurements.

Aquifer	Hensell	Hosston	All Wells	Dual
Number of measurements	53	108	170	9
Average SO_4	271	141	181	142
Range SO_4	84 – 1830	68 – 1559	25 – 1559	25 – 320
Median SO_4	156	102	119	129
Mode SO_4	142	90	90	None
Range Date	1941 – 1994	1937 – 2006	1941 – 2006	1942 – 1986

When only initial sulfate measurements taken with the most recent data available over the last ten years were considered in Table 5, a similar trend to the entire data set occurred, even though there were only three initial Hensell measurements in the last ten years. Unlike Table 4, the difference between the average initial sulfate values of the Hensell and Hosston units using recent data were not found to be significant according to a Student T-Test (a value of 0.13). The Hensell and Hosston had lower average sulfate values in Table 5 than they did in Table 4. This may be an indication that drilling methods have improved within the last ten years, and newer wells may be screened in more desirable parts of the aquifer with lower amounts of chemical constituents. The medians of Table 5 were higher than those calculated in Table 4, but this may not be a good representation of

Hensell unit because there are only three Hensell sulfate values for recent years. The range in sulfate values in Table 5 is also smaller than that of Table 4, which is probably due to less data. Unfortunately, there were no measurements for dual-completed wells recorded in the TWDB data for the last ten years.

Table 5: Statistical analysis of sulfate (mg/L) within the Trinity aquifer using the most recent data available over the last ten years.

Aquifer	Hensell	Hosston	Both Units
Number of measurements	3	21	24
Average SO_4	183	125	132
Range SO_4	114 – 241	77 – 287	77 – 287
Median SO_4	194	107	112
Mode SO_4	None	84	84
Date Range	2006 – 2006	2003 – 2006	2003 - 2006

When plotted through time, all initial sulfate values show a similar trend to that of TDS, with both units decreasing in sulfate concentration through time (Figure 31). Both the Hensell trend line (upper line) and the Hosston (lower line) have similar slopes (Figure 31). Only twenty Hensell wells (forty-five percent) and thirteen Hosston wells (thirteen percent) had concentrations greater than one hundred-fifty milligrams per Liter. The four individual Hensell wells plotted through time (Figure 32) show a general increase with time.

When all sulfate values are plotted through time (Figure 33), different trends are observed for the Hensell, Hosston, and dual-completed wells. Sulfate concentrations generally increase over time for the Hensell, decrease for dual-completed wells, and remain almost constant for the Hosston unit. However, none of the trends are strong correlations.

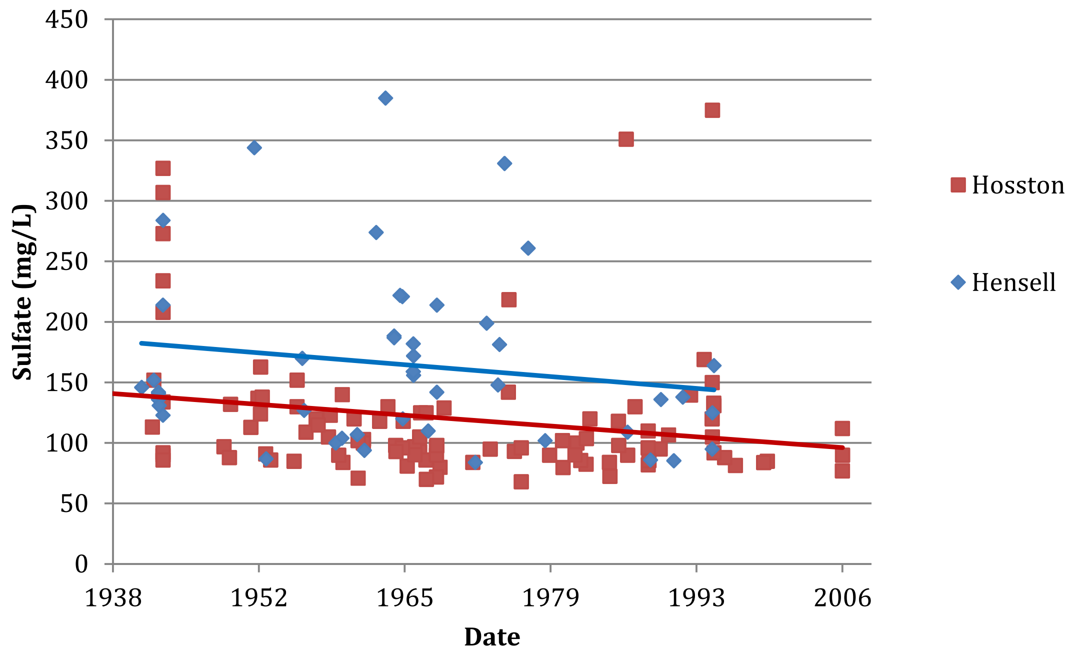


Figure 31: All initial sulfate measurement values for wells in McLennan County through time. R^2 values for the Hensell and Hosston were 0.0262, and 0.0413, respectively.

The Piper Trilinear diagrams (Figures 34, 35, and 36) all show a similar proportion of chemical constituents for Hensell, Hosston, and dual-completed wells. The primary constituents for the wells are Sodium, Potassium, Chloride, Sulfate, and Bicarbonate.

Overall, the median values for TDS and sulfate may be closer to a typical TDS or sulfate concentration found in the aquifer than the mean values. Because the median values are considerably lower than the mean values, they indicate there are a few wells with large concentrations skewing the mean values. Since the median sulfate concentrations for Table 5, unlike the mean values, are slightly higher than those in Table 4, it is unlikely that sulfate conditions within the Trinity aquifer have

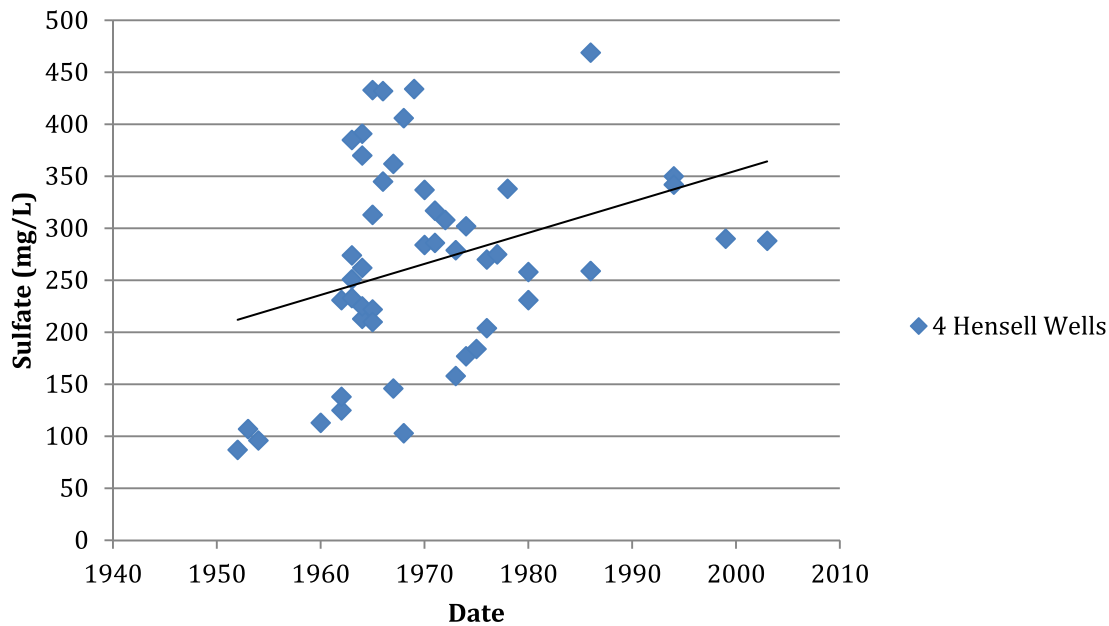


Figure 32: Change in sulfate concentrations over time for four Hensell wells (state well numbers 4029802, 4029805, 4046602, 4047403). The R^2 value for the Hensell wells was 0.1102.

changed considerably over time. Nevertheless, more information is still needed in order to determine why the averages in Table 5 are lower. It is possible that the decrease in average sulfate concentrations found in Table 5 may be either due to aquifer response to increased pumping by pulling water with fewer sulfates from other geologic units, or more likely, improved drilling and completion methods. The idea of improved selection of screen intervals improving water quality is possibly supported when initial sulfate and TDS are plotted through time, showing a steady decrease in concentrations (Figure 30, 31). For individual wells, on the other hand, TDS and sulfate concentrations increase over time, perhaps due to the effects of production. The Piper Trilinear diagrams for the Hensell, Hosston, and dual-completed wells all showed similar concentrations of chemical constituents

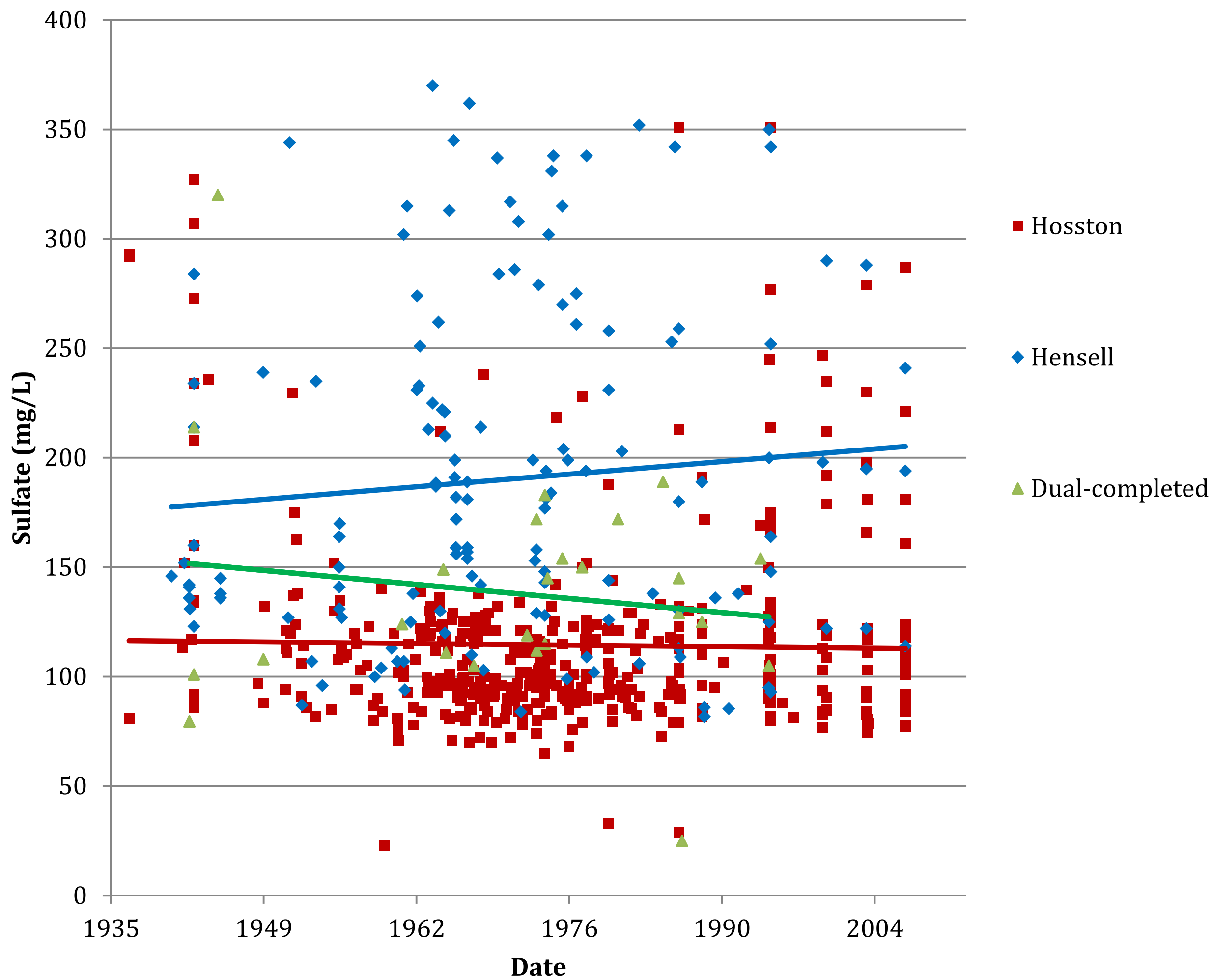


Figure 33: All recorded sulfate values for wells in McLennan County through time. R^2 values for Hensell, Hosston, and dual-completed wells are 0.0078, 0.0215, and 0.0004, respectively.

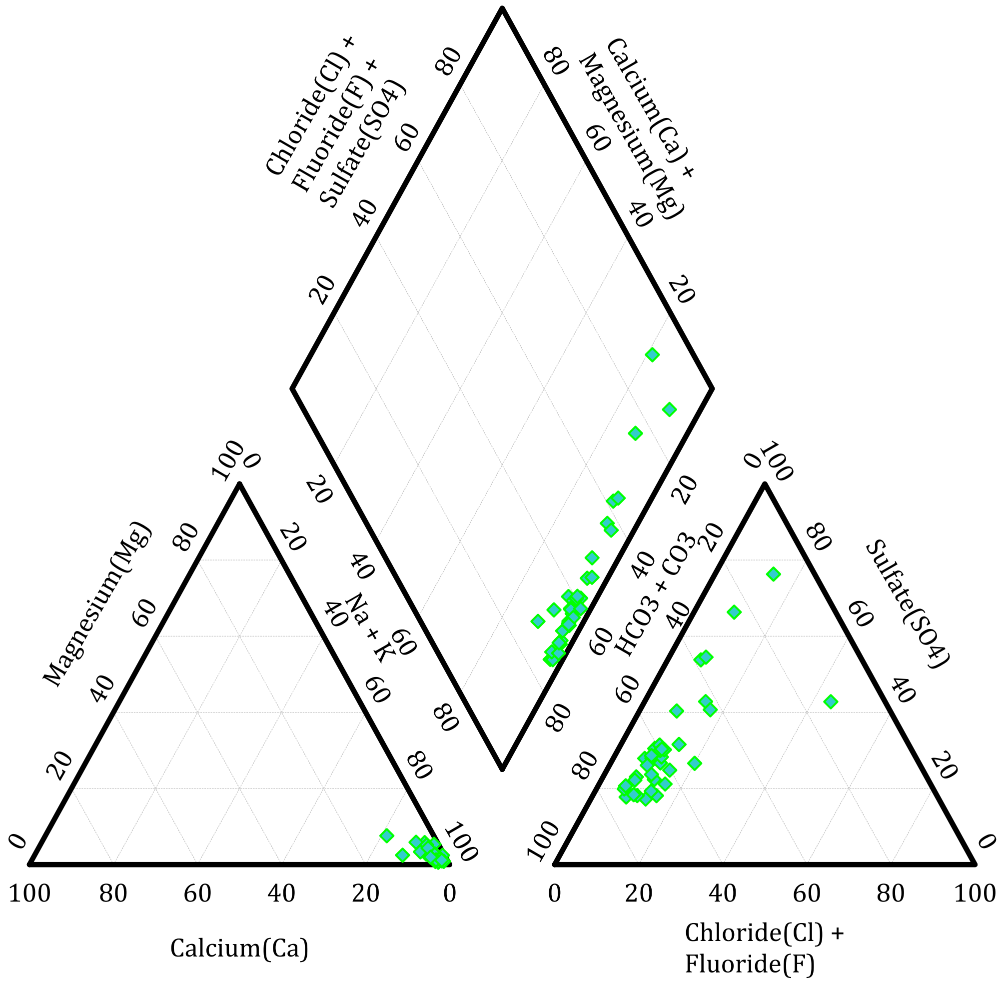


Figure 34: Piper Trilinear diagram of the Hensell unit including initial chemical analysis results of thirty eight wells.

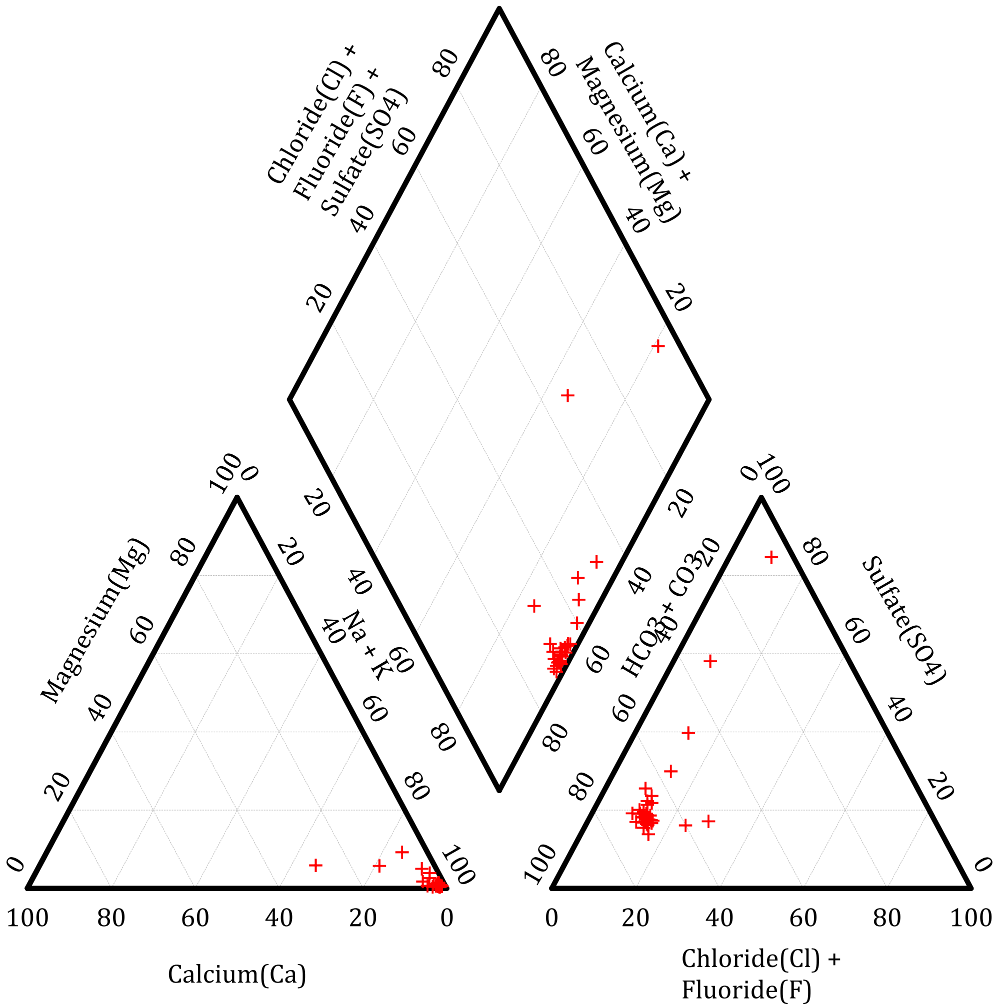


Figure 35: Piper Trilinear diagram of the Hosston unit including initial chemical analysis results of thirty eight wells.

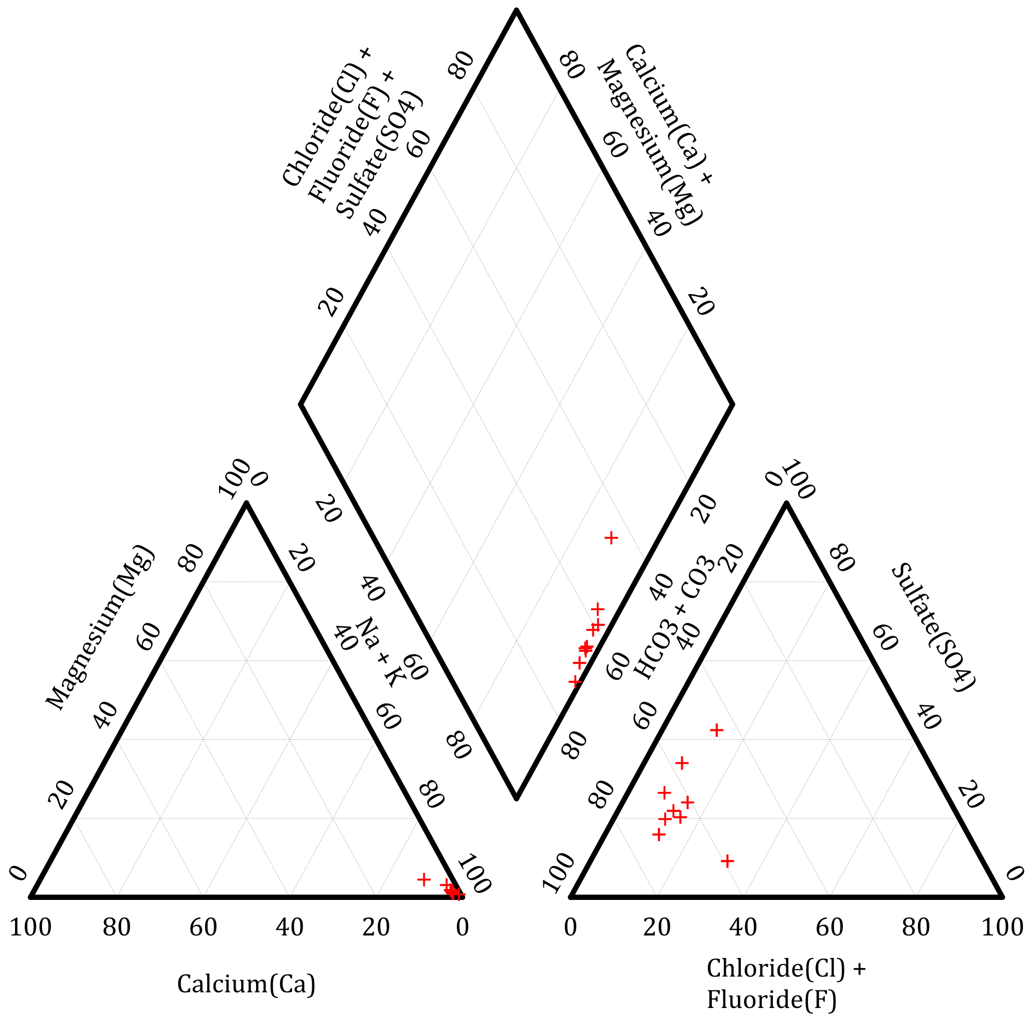


Figure 36: Piper Trilinear diagram of dual-completed wells in McLennan County (using initial measurements).

in their water. Although the chemistry data are not sufficient to determine in which unit a well is completed, it can still be used as evidence for separate management, since the Hensell's sulfate concentrations are significantly different than that of the Hosston.

According to the chemistry data analyzed, a well cannot be determined as either Hensell, Hosston, or dual-completed solely by looking at chemistry data. The Hensell wells clearly have average sulfate values that are higher than Hosston values, but the ranges in values overlap considerably. Dual-completed wells have TDS and sulfate values that more closely resemble the thicker, more productive and transmissive Hosston unit, but still cannot be distinguished solely on their TDS content, or any one chemical constituent.

Lithology

Lithology did not prove to be a significant factor in differentiating the Hensell and Hosston units, according to a Student T-Test performed on the percent sand calculations from geophysical logs (0.56). According to Table 6, the averages of the two units only vary by two percent, and the median, mode, and range also have little variability (see Appendix B for data used).

Overall, aquifer lithology provided little differentiation between the Hensell and Hosston unit. Boone, 1968, supports this finding.

Table 6: Percent sand analysis for the Hensell and Hosston unit.

Aquifer	% Sand	Median	Mode	Range
Hensell	77	83	83	60-93
Hosston	79	80	80	60-89

Water Level

The hydrographs created through the normalization process (over sixty-six hydrographs were created) for the water level contour maps showed water level declines of ten to twelve feet per year for both the Hensell and Hosston units in McLennan County (Figure 37).

Although it is impossible to create an accurate map of predevelopment conditions, because once a well is drilled, drawdown occurs immediately, a reasonable estimation was still be created from Hill (1901) and the TWDB GAM's data and maps. Figure 38 shows that although the water level for the Trinity aquifer slopes downward to the southeast, the water level throughout the county probably varied less than one-hundred feet.

Upon examination of recent water level contour maps, the water level contours show different patterns for the Hensell and Hosston units over time. By around 1901, a prominent cone of depression already had begun to expand around the Waco area (Figure 39). F or the Hensell unit, a cone of depression formed in the eastern portion of the county (near the City of McGregor) around 1970 (Figure 40), and grew larger by 1990 (Figure 41). In 2010, however, the cone of depression dissipates into a gradually deepening slope to the southeast (Figure 42). The Hensell 2010 water level pattern could be evidence that the Hosston cone of depression has affected the Hensell water levels, but more research is needed to prove this relationship.

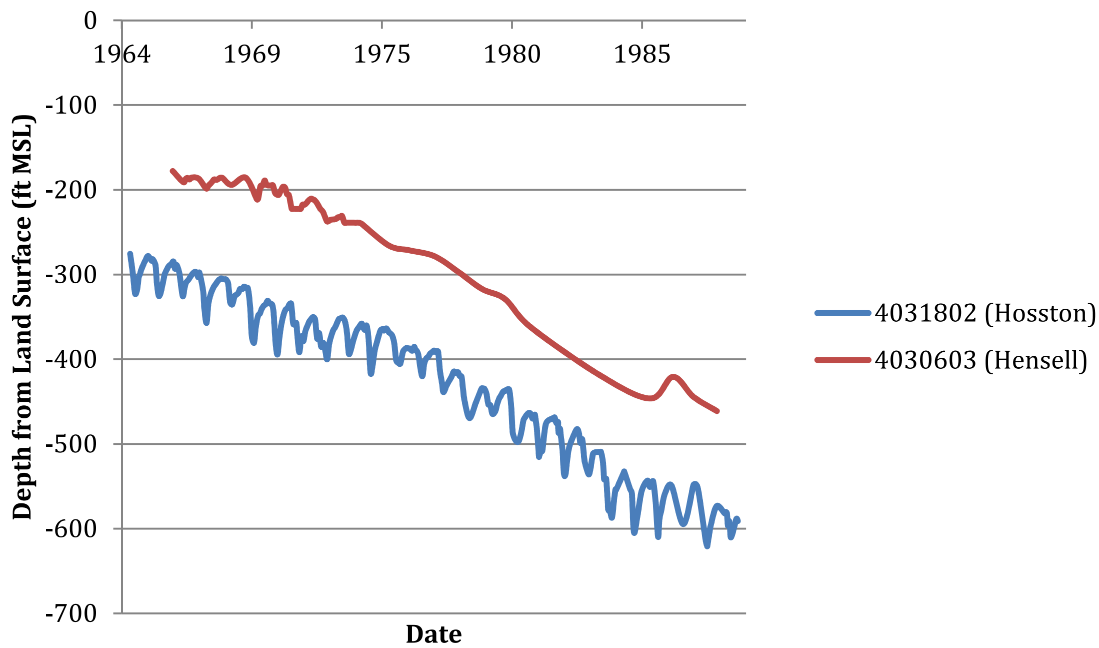


Figure 37: Hydrograph of a Hosston and Hensell well in the Waco area, both showing water level declines of over ten feet per year.

For the Hosston, the cone of depression around the Waco area is fully developed in the 1970s (Figure 43). By the 1990s, the cone of depression shifts to the outlying communities in the western part of the county (Figure 44). This makes sense, because the western part of the county has experienced population increases while more of the Waco area was serviced by surface water. In 2010, the water levels for two cones of depression, one in the western area, and the other in the eastern area of the county (Figure 45).

Three-dimensional water-level contour surfaces (Figure 46) for 2010 provide direct comparison of the spatial relationship between the water levels within Hensell and Hosston wells in one figure. In the portion of the county where Hensell wells occur, the water level is generally lower than the Hosston's water level. Dual-completed wells (there were only two wells with 2010 water level data) water levels were, for the most part, in between the Hensell and Hosston unit's

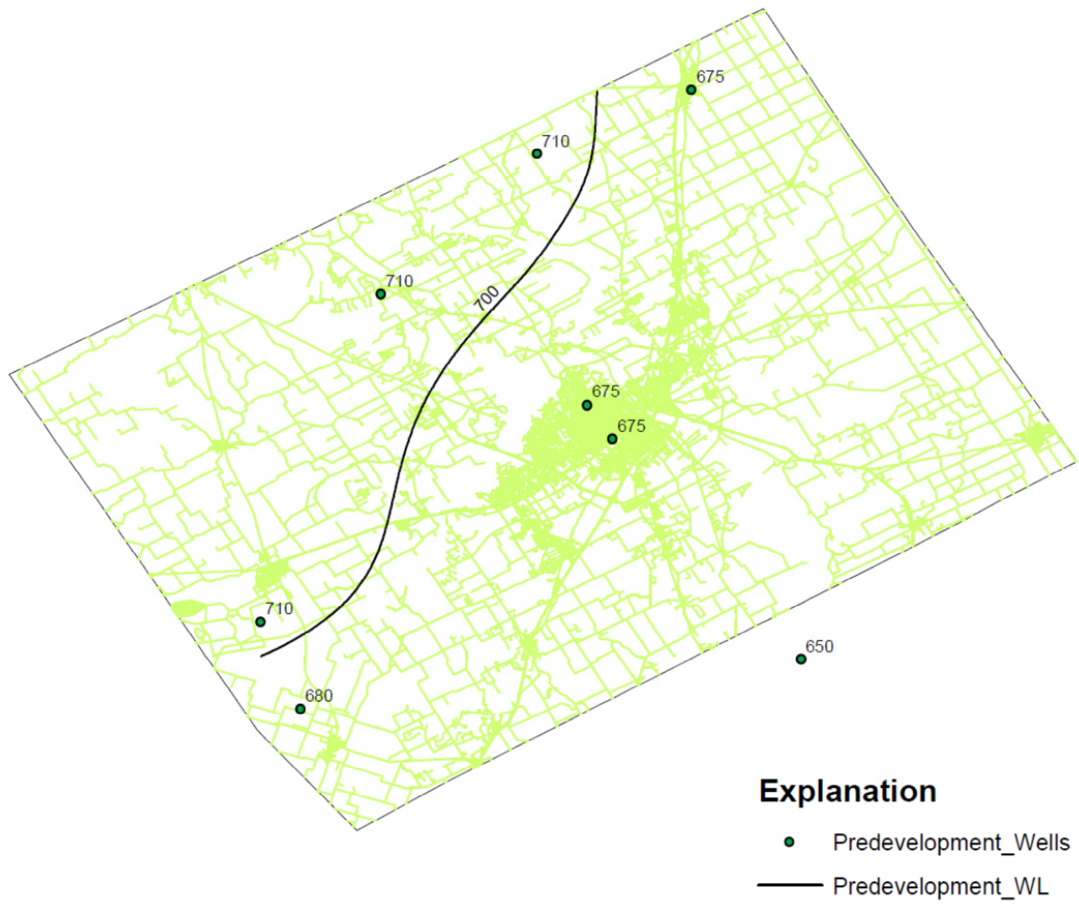


Figure 38: Water level contour map (in feet above MSL) representing predevelopment conditions (data from Hill, 1901, and Bené et. al., 2004).

water level, but more closely resembled the Hosston's water level than the Hensell's (not shown in Figure 46). The three-dimensional Hosston surface also shows the two cones of depression.

When water level was mapped for the units, a unique water level surface resulted for both the Hensell and Hosston for any given year (with the exception of early and predevelopment conditions). The two units show different cones of depression and water level maps. When a three-dimensional image of the water levels is projected, it is even more evident that well water levels are dependent

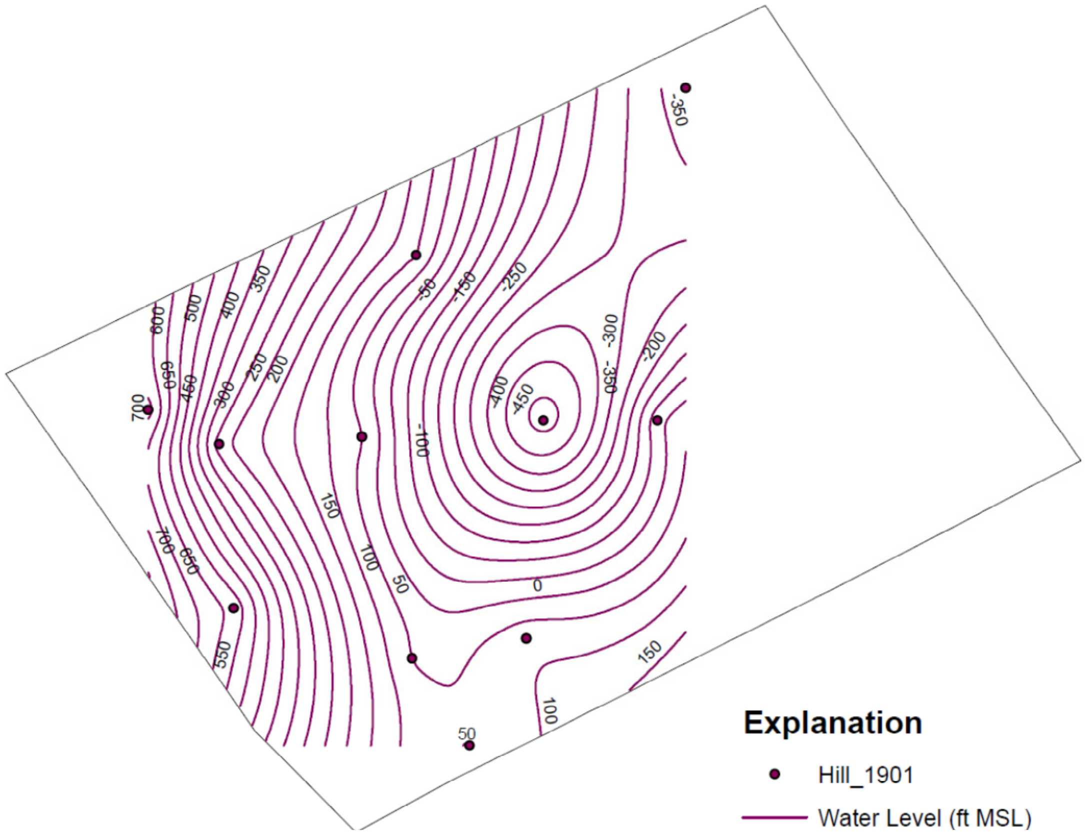


Figure 39: Water level contour map (CI=50 ft) of the Trinity Aquifer circa 1901 (data from Hill, 1901).

upon the completion unit. Dual-completed water levels are similar, but not exactly the same as, the Hosston unit. The greater transmissivity of the Hosston probably skews the water levels closer to the Hosston level than the Hensell level.

Well Hydraulics

Reliable transmissivity and storage values from pumping test data were difficult to find for the Hosston unit. Hensell data were less complete, with only one transmissivity value found in all the literature and no storage value at all (there is

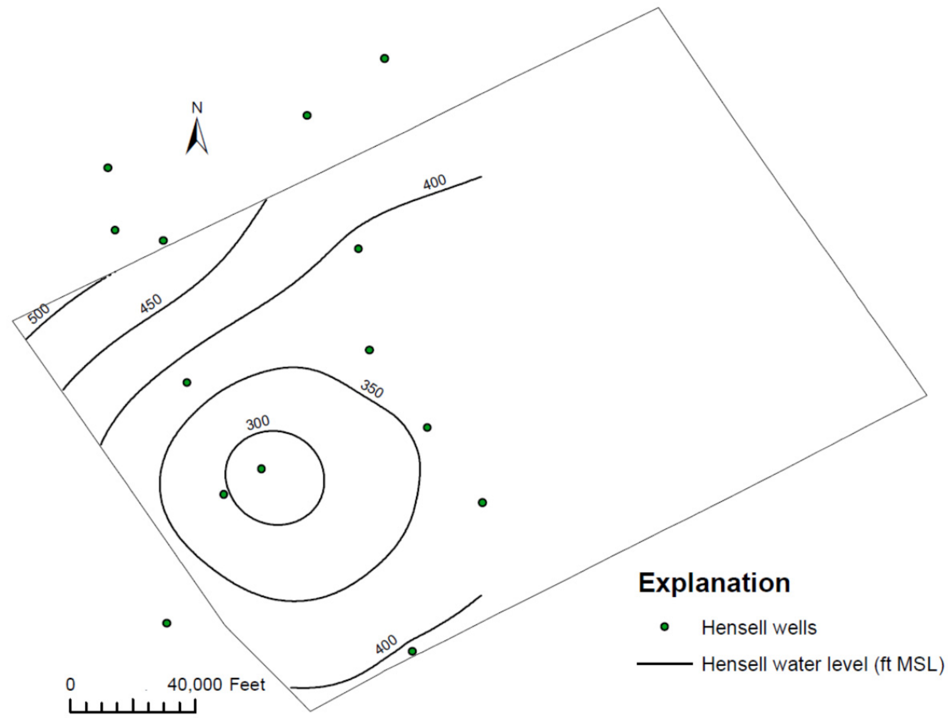


Figure 40: 1970 water level contour map of the Hensell unit (CI=50 ft).

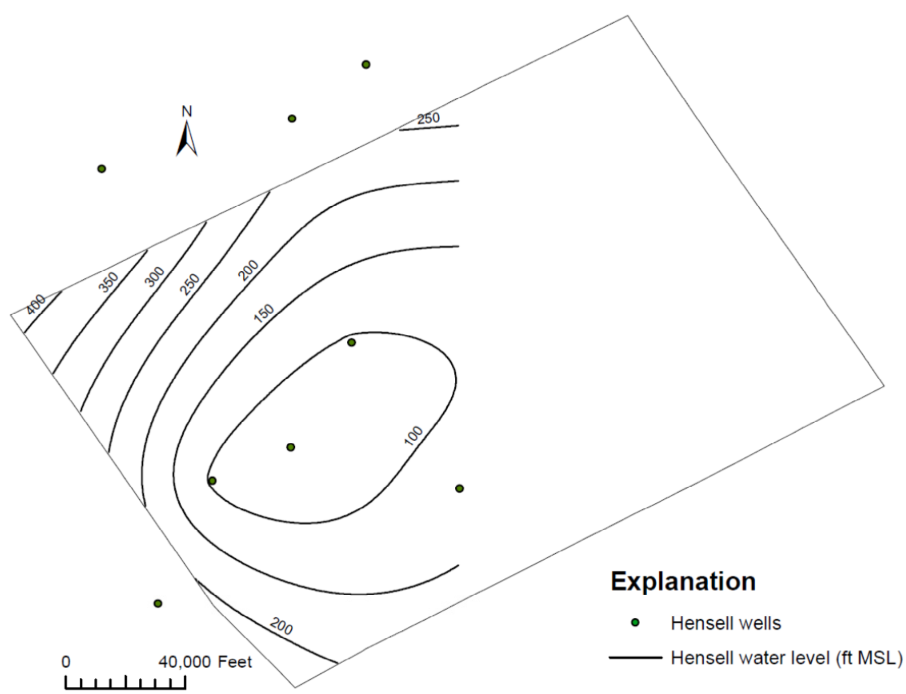


Figure 41: 1990 water level contour map of the Hensell unit (CI=50 ft).

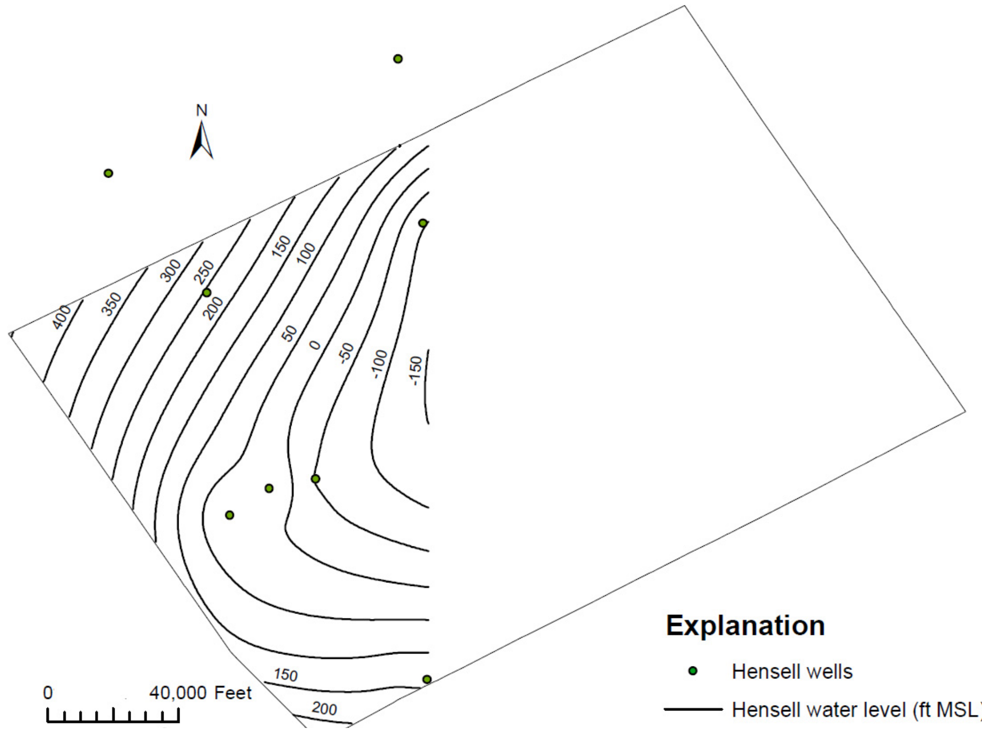


Figure 42: 2010 water level contour map of the Hensell unit (CI=50 ft).

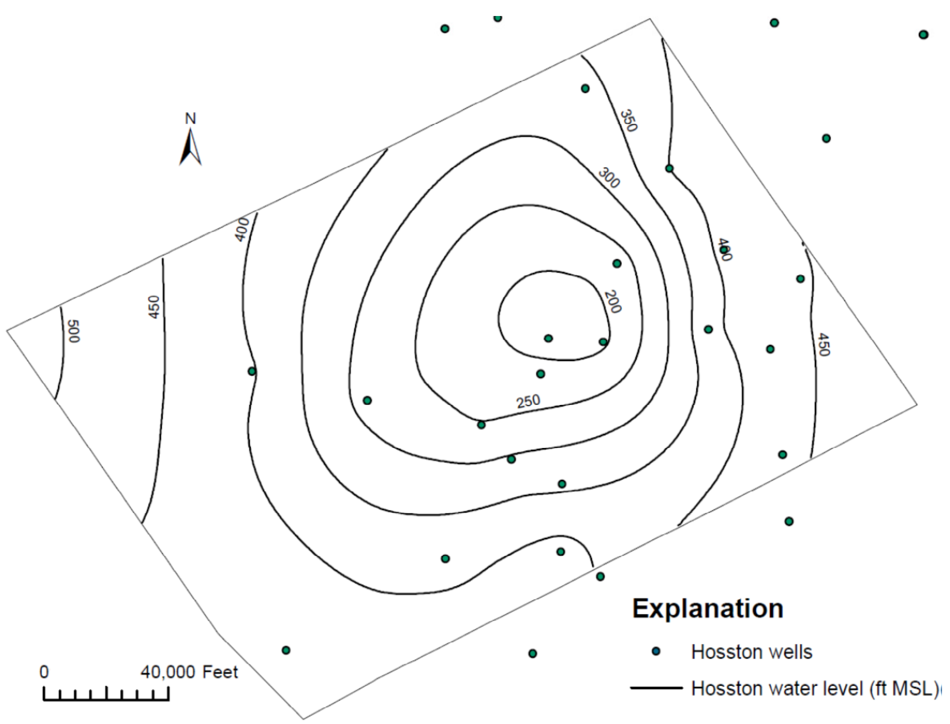


Figure 43: 1970 Water level contour map of the Hosston unit (CI=50 ft).

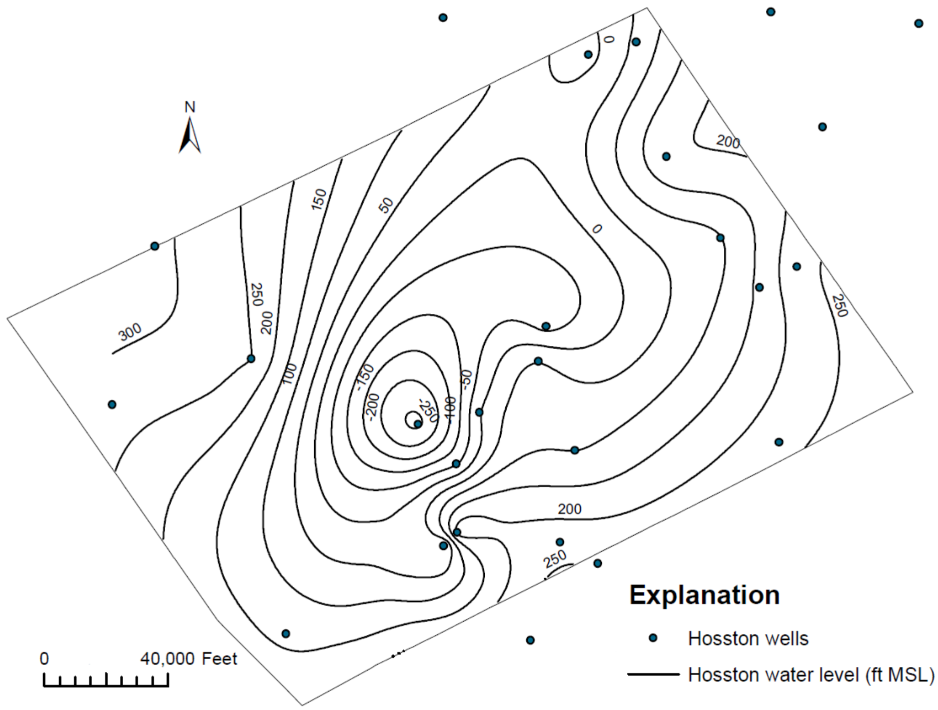


Figure 44: 1990 Water level contour map of the Hosston unit (CI=50 ft).

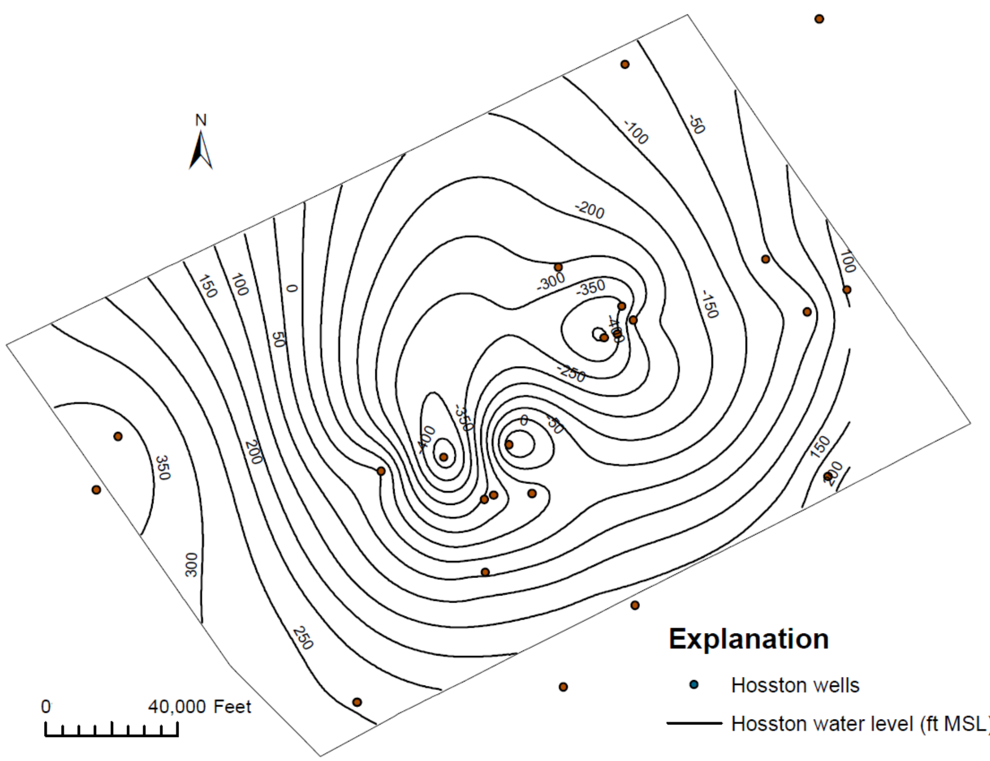


Figure 45: 2010 Water-level contour map of the Hosston unit (CI= 50 ft).

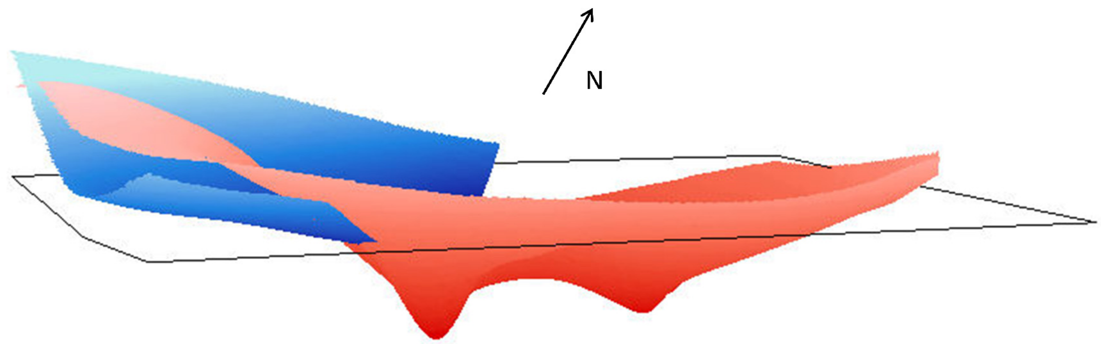


Figure 46: 3-D image of 2010 water levels within each unit viewed from the southern part of the county (red=Hosston, blue=Hensell, county outline shown in black).

only one storage value known for the Hensell unit, and it is in Hamilton county, near the outcrop area, found in Klemt and others, 1975). The Hosston unit is thicker and more productive than the Hensell, and has a higher average transmissivity (about five times that of the Hensell). Although there is no known storage value for the Hensell in the vicinity of McLennan County, because its transmissivity is about five times lower, and both units have similar permeability due to similar lithology, the storage value used in the well hydraulics calculations for this section was estimated to be one fourth that of the Hosston storage value (a storage value of 0.0000125 for the Hensell unit). One fourth of the Hosston storage value was chosen instead of one fifth for the Hensell unit, because total storage of the Trinity aquifer was taken into account (Hosston represents eighty percent, Hensell is twenty percent, and therefore one fourth of Hosston storage).

From the transmissivity and storage values below (Table 7), a dual-completed well that pumps eighty gallons per minute would pump water that yields eighty percent Hosston water and twenty percent Hensell water. A well that pumps

Table 7: Average transmissivity and storage values for the Hensell and Hosston units, along with the number of recorded values (N) found from pumping tests (data from Klemt and others, 1975).

Aquifer	N_T	T_{ave} (ft^2/d)	N_S	S_{ave}
Hensell	1	147	0	No Value
Hosston	13	859	2	0.00005

eighty gallons per minute would have different radii according to the district's spacing rules if it were managed as one unit, as a Hensell well, or a Hosston well (Figure 47). The well would have a spacing radius that is three-hundred-twenty feet smaller if it were managed as a Hosston well, and six-hundred feet smaller if it were managed as a Hensell well, compared to being managed as one unit.

A well completed in the Trinity that pumps eighty gallons per minute would also have different drawdowns after twenty-four hours depending on whether it is a Hensell, Hosston, or dual-completed well. Table 8 shows the results of drawdown calculations for the same well pumping for a twenty-four hour period, according to the Theis, or nonequilibrium, equation for drawdown in each unit if the Trinity aquifer is managed as one unit (Theis, 1935).

At a radius of 1600 feet, there is little difference in drawdown between a well completed in the Hosston unit and a dual-completed well. Drawdown in the Hensell, on the other hand, is considerably greater.

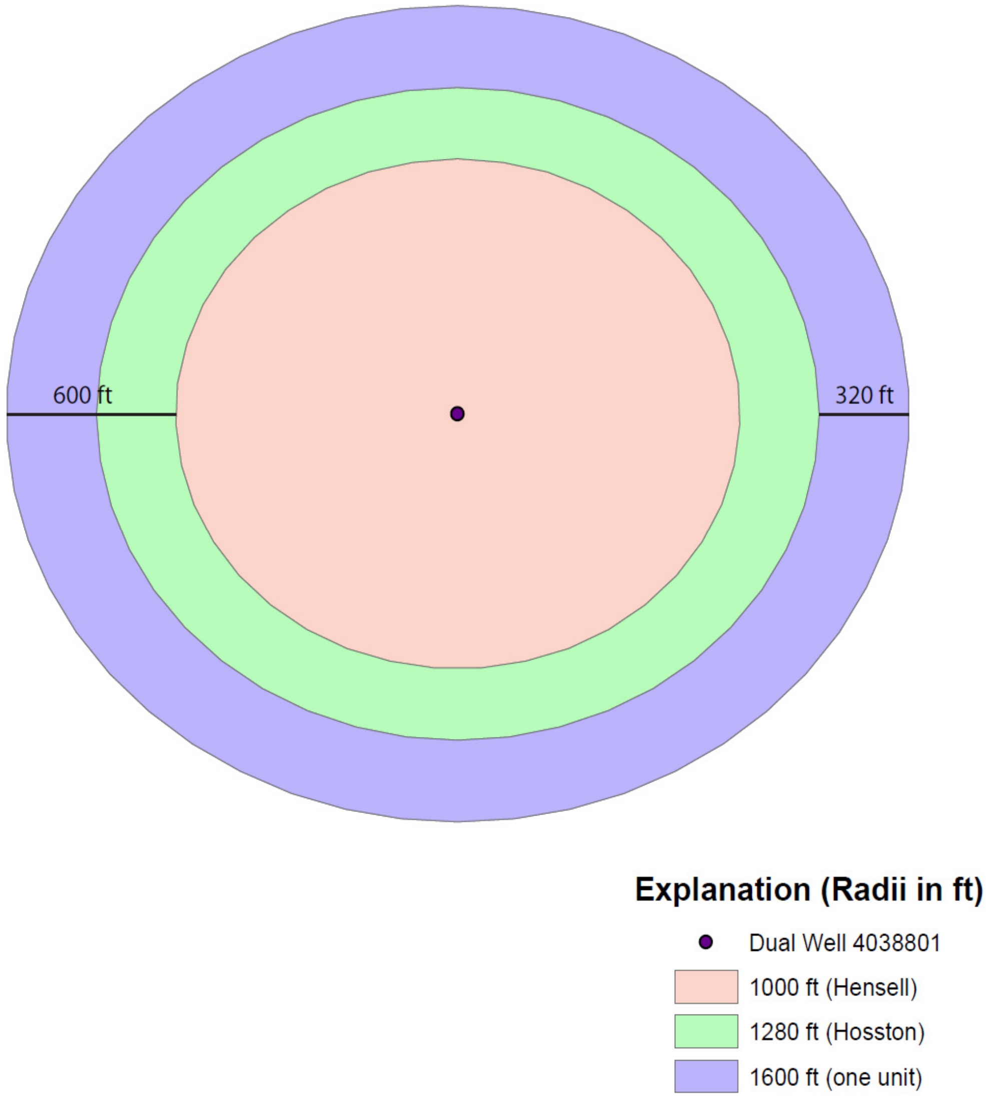


Figure 47: Well spacing calculation for a dual-completed well with separate radii for if it were managed as one unit (1600 ft), a Hosston well (1280 ft), and a Hensell well (1000 ft).

Table 8: Drawdown of a Hensell, Hosston, and dual-completed well at the spacing radius it would have with the Trinity aquifer managed as one unit.

Unit	GPM (gal/min)	Radius (ft)	h_o-h at radius (ft)
Hensell	80	1600	20.6
Hosston	80	1600	3.8
Dual	80	1600	3.3

If the Trinity Aquifer was managed as two separate units, a well would have different protected radius depending on the unit(s) in which it was completed. Table 9 shows drawdown in a dual completed well pumping eighty gallons per minute for twenty-four hours, both as if its two aquifer components were managed separately, and managed as one unit for comparison. There is not a considerable

Table 9: Drawdown of a Hensell, Hosston, and dual-completed well at the spacing radius it would have with the Trinity aquifer managed as separate Hensell and Hosston units (see Figure 47).

Unit	GPM (gal/min)	Radius (ft)	h_o-h at radius (ft)
Dual	80	1600	3.3
$Dual_{hnsl}$	16	1000	5.6
$Dual_{hstn}$	64	1280	3.8

difference between the dual-completed well managed as one unit and its Hosston component, due to the Hosston's higher transmissivity. The Hensell component of the dual-completed well shows a much greater drawdown than both other options.

However, the Hensell unit drawdown is still much less than a well completed in solely the Hensell unit, because it contributes less water in a dual-completed well.

The Hosston unit has a transmissity value that is about five times larger than that of the Hensell unit due to its thickness (over three times the thickness of the Hensell on average), and therefore experiences less drawdown than the Hensell unit. If they are managed separately, Hensell and Hosston wells completed separately could be drilled closer to each other because they would be considered hydrogeologically separate.

CHAPTER FOUR

Summary, Conclusions, and Recommendations

Summary and Conclusions

The results of the Boundary evaluation showed the need to use data from adjacent counties (Hill, Limestone, Falls, Bell, Coryell, and Bosque), because data from nearby wells can have an important effect on the spatial distribution of aquifer characteristics.

The following summary statements can be made based upon the analyses conducted in this study:

1. Water levels in the Hensell and Hosston are decreasing over ten feet per year.
2. The Hensell unit will experience greater drawdown when pumped than the Hosston due to the Hosston's greater transmissivity and storage coefficient.
3. The cone of depression from groundwater consumption in the Hosston has produced a different pattern than that of the Hensell.

The following evidence supports hypothesis one, that the Hensell and Hosston are two separate hydrogeologic units:

1. The Hensell and Hosston units have unique contact depths and thicknesses throughout McLennan County, according to cross sections and structure-contour maps. The Hosston is generally thicker than the Hensell and also thickens down dip, whereas the Hensell remains rather uniform in thickness.

2. The Hensell unit has an average sulfate value that is significantly higher than the Hosston.
3. The TDS and sulfate values have not increased significanty over time.
4. Both units have a unique water level surface throughout the entire county.

Also based on the results of this study, the following evidence does not support hypothesis one:

1. Both the TDS analysis and Piper-Trilinear diagrams completed for each unit do not show significant difference between the Hensell and Hosston groundwater chemistry.
2. The lithologic analysis (percent sand) interpreted from geophysical logs did not show a significant difference between the two units as both units contained approximately eighty percent sand.

The summary table (Table 10) shows the general findings of this study with regard to the characterization of the Hensell and Hosston units.

Based on the results of this study, there is sufficient evidence to support the hypothesis (1) that the Hensell and Hosston are two distinct and separate hydrogeologic units in McLennan County. Hypothesis 2, that boundary conditions are significant, is also supported by the findings in this study. Separate management of the Hensell and Hosston units may lead to greater sustainability, especially in the case of the thinner Hensell unit.

Overall, when deciding on best management strategies for deep, multi-unit aquifers, characteristics such as aquifer framework and structure, chemistry, lithology, water level, and well hydraulics should be compared.

Table 10: Summary Table of aquifer unit attributes. Significance pertains to the results of a Student's T-test.

Characteristic	Hensell	Hosston	Significant?	Together or Separate
Aquifer Framework	Unique depth and thickness throughout county	Unique depth and thickness throughout county	Depth= Yes(9^{-11}) Thickness= Yes(7^{-6})	S
Average TDS (mg/L)	944	739	No(.06)	?
Average SO_4 (mg/L)	271	141	Yes(.006)	S
% Sand	77	79	No(.56)	T
Water Level	Unique surface throughout county, with declines of 10-12ft/yr	Unique surface throughout county, with declines of 10-12ft/yr	Yes(.032)	S
Transmissivity (ft^2/d)	147	859	---	S
Storage	No Value	0.00005	---	?
Cone of Depression	Unique pattern for all years	Unique pattern for all years	N/A	S

Recommendations

Based on the results of this study, it is recommended that the STGCD consider managing the Hensell and Hosston units as separate aquifer zones rather than one Trinity unit. Recommended management strategies could first include amending the usage of spacing rules. Instead of applying the same rule to every well, the rule would be applied based on the unit of completion, which means different radii for wells completed in the Hensell and Hosston based on pumping rates. Because considerably more drawdown occurs for Hensell wells, it is recommended that the starting radius for Hensell wells be re-evaluated and probably increased. For dual-completed wells, it is recommended that the spacing rule be applied to both units separately.

Treating the Hensell and Hosston units as two separate aquifer zones would also affect the DFC and MAG section of the management plan and the permitting process. Instead of the District averaging the separate DFCs set by GMA 8, the two different DFCs would be adhered to (Southern Trinity Groundwater Conservation District, 2010), and the MAG calculated by the TWDB of 4,190 acre-feet per year for the Hensell and 16,004 acre-feet per year for the Hosston would be reflected in the well permits. Currently, there is MAG for the Pearsall/Cow Creek/Hammet and Sligo that is included in the District's management plan. If the District decides to manage the Hensell and Hosston units separately, they would need to make the decision on whether the confining unit's MAG would be omitted completely or added to one of two the unit's MAG.

Separate management may be more complicated and require further edits to the management plan, but it could lead to greater sustainability of the Trinity aquifer in McLennan County. Separate management would be beneficial for the Trinity aquifer in the long run, so that one unit is not more depleted than the other. The methodology developed in this study could also potentially help other districts who manage aquifers with more than one water bearing unit. When deciding on management strategies for deep, multi-unit aquifers, characteristics such as aquifer framework, chemistry, lithology, water level, and well hydraulics should be studied before deciding how to manage the aquifer most efficiently.

APPENDICES

APPENDIX A

Well Unit Designations, selected Aquifer Contacts, and Thicknesses

well_no.	aquifer_code	GE	THLelev	BHLelev	THNelev	BHNelev	isoHnsl	isoHstn
3917701	217HSTN	528	-1832	-1926	-2435	-2562	94	127
3917702	217HSTN	457			-2313	-2493		180
3917703	217HSTN	549	-1940	-2001	-2367	-2531	61	164
3917901	217HSTN	560	-1832	-1864	-2261	-2755	32	494
3917903	217HSTN	529			-2181	-2621		440
3925101	217HSTN	505	-1800	-1835	-2060		35	
3925102	217HSTN	491	-2044	-2131	-2215		87	
3925103	217HSTN	511			-2052	-2334		282
3925201	217HSTN	515	-2035	-2135	-2475	-2625	100	150
3925401	217HSTN	458	-1882	-1952	-2072	-2472	70	400
3925402	217HSTN	470	-1920	-1980	-2130	-2400	60	270
3925501	217HSTN	493			-2357			
3925701	217HSTN	478	-1792	-1857	-2082		65	
3925702	217HSTN	484	-2226	-2282	-2366	-2488	56	122
3925801	217HSTN	520	-2020	-2100	-2210	-2720	80	510
3925802	217HSTN	473	-2147			-2692		
3933101	217HSTN	410	-1790	-1860	-1990	-2390	70	400
3933102	217HSTN	429	-1781	-1851	-1971	-2421	70	450
3933104	217HSTN	462						
3933201	217HSTN	510				-2650		
3933202	217HSTN	490	-2130	-2195			65	
4015901	217HSTN	594	-891	-946	-1056	-1256	55	200
4015904	217HSTN	609	-891	-951	-1128	-1336	60	208
4015905	217HSTN	593	-1037			-1307		
4016401	218HNSL	648						
4016402	217HSTN	648						
4016403	217HSTN	645	-936	-981	-1140	-1400	45	260
4016404	217HSTN	645	-855	-909	-1147		54	
4016405	217HSTN	644						
4016501	217HSTN	585						
4016701	217HSTN	635	-1272	-1352	-1747		80	
4016703	217HSTN	626						
4016705	218HNSL	611	-989			-1289		
4016801	218HNSL	577						
4016802	217HSTN	580	-1380	-1440	-1550		60	

4016803	217HSTN	582			-1513	-1728		215
4021604	217HSTN	615	-243	-325	-416	-506	82	90
4021801	217HSTN	699	-161	-191	-301	-396	30	95
4021802	217HSTN	742	-163	-198	-291	-382	35	91
4021901	217HSTN	685						
4021902	217HSTN	685	-270	-335	-415	-515	65	100
4021903	217HSTN	590			-532	-560		28
4022307	218HNSL	533	-594	-627			33	
4022308	218HNSL	525	-555	-602			47	
4022501	218HNSL	615						
4022502	218HNSL	566	-448	-504			56	
4022503	217HSTN	501	-479	-534	-634	-704	55	70
4022504	217HSTN	627	-393	-473	-556		80	
4022605	218HNSL	561	-494	-589			95	
4022606	218HNSL	551	-499	-554	-654	-716	55	62
4022607	218HNSL	483	-557	-629			72	
4022608	218HNSL	551						
4022609	218HNSL	510						
4022701	218HNSL	630	-332	-410	-496	-556	78	60
4022702	218HNSL	506	-374	-424	-559	-630	50	71
4022801	217HSTN	620						
4022802	217HSTN	597						
4022803	218HNSL	518	-407	-471			64	
4022804	218HNSL	595						
4022805	218HNSL	625						
4022806	218HNSL	625						
4022807	218HNSL	555	-405	-455			50	
4022808	218HNSL	591						
4022809	217HSTN	600	-463	-523	-610	-681	60	71
4022810	218HNSL	587	-379	-436	-564	-623	57	59
4022811	217HSTN	550	-465	-508	-675		43	
4022812	218HNSL	600	-500	-560			60	
4022901	218HNSL	560						
4022902	218HNSL	562	-558	-638			80	
4022903	218HNSL	555						
4022904	218HNSL	540						
4023103	218HNSL	435	-660					
4023104	218HNSL	477	-769	-883			114	
4023201	218HNSL	488	-768	-832			64	
4023410	217HSTN	457	-551	-656	-750	-863	105	113
4023603	217HSTN	537	-1121	-1225	-1508		104	
4023705	218HNSL	522						
4023706	218HNSL	528	-602	-659			57	

4023707	218HNSL	459						
4023812	218HNSL	440						
4023903	217HSTN	505	-1245	-1285	-1405	-1609	40	204
4023906	217HSTN	470	-1317	-1385	-1538		68	
4023907	217HSTN	513	-1387	-1437	-1527		50	
4023908	217HSTN	421						
4024101	217HSTN	568	-1270	-1357	-1386	-1661	87	275
4024102	217HSTN	572			-828	-1116		288
4024103	217HSTN	564			-1464			
4024104	217HSTN	564			-1496	-1796		300
4024201	217HSTN	522	-1678	-1728	-1882		50	
4024301	217HSTN	495	-1380		-1940	-2348		408
4024302	218HNSL	492	-1354	-1438	-1728		84	
4024401	217HSTN	533	-1385		-1499			
4024402	217HSTN	505	-1010		-1622	-1835		213
4024501	217HSTN	483						
4024502	217HSTN	485						
4024701	217HSTN	492	-1418	-1488	-1593	-1802	70	209
4024702	217HSTN	485		-1480				
4024703	217HSTN	537	-1373	-1433	-1663	537	60	
4024704	217HSTN	495	-1410	-1475	-1579		65	
4024705	217HSTN	485	-1495	-1545	-1705		50	
4024801	217HSTN	465	-1508	-1556	-1725	-1889	48	164
4024802	217HSTN	465	-1510	-1561	-1712		51	
4024803	217HSTN	460	-1585	-1665	-1810		80	
4028203	217HSTN	890						
4028302	217HSTN	883	-42	-67	-111		25	
4028902	217HSTN	857	-3	-123	-203		120	
4029104	217HSTN	711	-133	-184	-286	-369	51	83
4029105	218HNSL	785	-109	-155			46	
4029201	218HNSL	749	-166	-226			60	
4029301	217HSTN	687						
4029401	217HSTN	759	-141	-206	-306	-361	65	55
4029601	217HSTN	675						
4029701	218HNSL	755	-178	-240			62	
4029702	218HNSL	810	-101	-169			68	
4029801	218HNHS	682						
4029802	218HNSL	735	-185					
4029805	218HNSL	735	-174					
4030101	218HNHS	651	-352	-412	-487		60	
4030102	218HNSL	610						
4030201	218HNSL	545	-445	-515			70	
4030202	218HNSL	550	-450	-525			75	

4030203	217HSTN	509						
4030301	218HNSL	475	-565	-651			86	
4030302	218HNSL	480	-574	-660			86	
4030403	218HNSL	600						
4030501	218HNHS	568	-506	-561	-680		55	
4030502	217HSTN	560	-390	-460			70	
4030503	218HNSL	598						
4030601	218HNSL	537						
4030602	218HNSL	520						
4030603	218HNSL	568	-530	-578			48	
4030604	218HNSL	498	-584	-673			89	
4030605	218HNSL	531	-539	-589			50	
4030606	218HNSL	540	-520	-590			70	
4030607	218HNSL	553	-517	-577			60	
4030608	217HSTN	539						
4030609	218HNSL	541	-499	-559			60	
4030610	218HNSL	540	-527	-585			58	
4030701	218HNSL	550	-394	-444			50	
4030702	218HNSL	564						
4030801	218HNHS	560	-499	-530			31	
4030802	218HNSL	592	-508	-558	-618		50	
4030803	217HSTN	542	-499	-559	-648	-708	60	60
4030901	217HSTN	522	-508	-567	-720	-813	59	93
4031101	218HNHS	497	-701	-785	-864	-1001	84	137
4031102	218HNHS	504	-686	-751	-934		65	
4031103	217HSTN	512	-598	-670			72	
4031104	218HNSL	491						
4031201	217HNSL	420	-1115	-1170			55	
4031210	218HNSL	455	-745	-829			84	
4031211	217HSTN	400	-816	-860	-962	-1145	44	183
4031301	217HSTN	418						
4031402	218HNSL	493	-629	-691			62	
4031403	218HNSL	476	-617	-716			99	
4031404	218HNSL	501						
4031503	218HNSL	547	-1103	-1155			52	
4031504	217HSTN	547	-1108	-1163	-1355		55	-
4031505	218HNSL	505						
4031601	217HSTN	415	-1290	-1385	-1545		95	
4031602	217HSTN	408	-1316	-1407	-1511	-1680	91	169
4031603	217HSTN	438						
4031604	217HSTN	416	-1334	-1384	-1664		50	
4031605	217HSTN	416	-1384	-1434	-1554	-1697	50	143
4031608	217HSTN	417						

4031609	217HSTN	417	-1288	-1353	-1513	-1723	65	210
4031611	217HSTN	361	-1349	-1409	-1524	-1724	60	200
4031612	217HSTN	415	-1345	-1420	-1543	-1800	75	257
4031613	217HSTN	361	-1336	-1397	-1605		61	
4031614	217HSTN	547	-1150	-1211	-1393		61	
4031615	217HSTN	523						
4031701	217HSTN	589	-846	-896	-949	-1210	50	261
4031702	217HSTN	630	-930	-980	-1139		50	
4031704	217HSTN	632	-828	-888			60	
4031705	218HNSL	456	-769	-828			59	
4031706	218HNSL	502	-753	-810			57	
4031707	217HSTN	632	-826	-893	-1053		67	
4031708	217HSTN	630	-780	-850	-960	-1134	70	174
4031801	217HSTN	632	-963	-1023	-1119	-1310	60	191
4031802	217HSTN	589	-951	-1021	-1136	-1396	70	260
4031803	217HSTN	632	-964	-1018	-1168		54	
4031804	217HSTN	595	-1015	-1065	-1165		50	
4031805	217HSTN	525	-1105	-1175	-1295		70	
4031901	218HNSL	495						
4031902	217HSTN	500	-1308	-1394	-1409	-1711	86	302
4032101	218HNSL	445	-1534	-1596			62	
4032102	217HSTN	435	-1440	-1500	-1723	-1861	60	138
4032103	217HSTN	440	-1485	-1565	-1740	-1930	80	190
4032104	217HSTN	478						
4032105	217HSTN	451						
4032106	217HSTN	440						
4032107	217HSTN	481	-1640	-1699	-1838		59	
4032201	217HSTN	440	-1650	-1715	-1908		65	
4032202	217HSTN	470	-1450		-1800	-1950		150
4032402	218HNHS	425	-1411	-1462	-1675	-1872	51	197
4032403	217HSTN	407	-1458	-1518	-1626	-1900	60	274
4032404	217HSTN	405	-1515	-1580	-1759	-1969	65	210
4032405	217HSTN	387	-1388	-1459	-1561		71	
4032501	217HSTN	445	-1585	-1650	-1799	-2050	65	251
4032502	217HSTN	445	-1615	-1685	-1799		70	
4032507	217HSTN	385	-1606	-1646	-1772	-2084	40	312
4032813	217HSTN	385	-1593	-1638	-1816	-2026	45	210
4037501	218HNSL	739	-231	-291			60	
4037601	218HNSL	690	-260	-310			50	
4037602	217HSTN	690	-280	-345			65	
4037603	218HNSL	720	-248	-298			50	
4037604	218HNSL	745	-216	-270			54	
4037606	218HNSL	685	-275	-335			60	

4037607	218HNSL	722	-203	-274			71	
4037608	218HNSL	745	-223	-268			45	
4037801	218HNSL	755	-216	-267			51	
4037802	218HNSL	774	-186	-245			59	
4037803	218HNSL	781	-181	-229			48	
4037804	218HNSL	800	-157	-257			100	
4037805	218HNSL	780	-204	-269			65	
4037806	218HNSL	725	-218	-285			67	
4037901	217HSTN	710	-265	-335	-425	-435	70	10*
4038101	218HNSL	637	-374	-429			55	
4038102	218HNSL	620						
4038201	218HNSL	595	-447	-518			71	
4038202	218HNHS	548	-469	-520	-667		51	
4038203	217HSTN	538	-534	-587	-728		53	
4038302	218HNSL	570						
4038303	217HSTN	535	-625	-700	-785		75	
4038304	218HNSL	504	-561	-696			135	
4038502	218HNSL	617						
4038601	218HNSL	712	-700	-768			68	
4038602	217HSTN	710	-696	-735	-820		39	
4038801	218HNHS	695	-460		-733			
4039101	217HSTN	635	-925	-977	-1059	-1127	52	68
4039102	218HNSL	633						
4039103	218HNSL	663	-847	-907			60	
4039104	217HSTN	670	-865	-910	-1032	-1250	45	218
4039105	218HNSL	717						
4039106	217HSTN	655						
4039107	217HSTN	681			-862			
4039108	218HNSL	725						
4039109	217HSTN	725	-695	-765	-861	-1065	70	204
4039201	217HSTN	639						
4039203	217HSTN	585	-1055	-1120	-1225	-1440	65	215
4039204	217HSTN	655	-933	-995	-1083		62	
4039205	217HSTN	550	-1040	-1110	-1200	-1457	70	257
4039206	218HNSL	640	-952	-1025			73	
4039301	217HSTN	595	-1095	-1160	-1294	-1590	65	296
4039302	217HSTN	558	-1097	-1202	-1342	-1610	105	268
4039304	217HSTN	529				-1706		
4039305	217HSTN	485						
4039306	217HSTN	535						
4039402	217HSTN	690	-760	-820	-934	-1110	60	176
4039403	217HSTN	671	-891	-980	-1049	-1245	89	196
4039404	217HSTN	679		-941	-1021	-1201		180

4039501	218HNSL	620						
4039502	218HNSL	645						
4039503	217HSTN	615	-965		-1280			
4039504	217HSTN	670	-1010	-1055			45	
4039701	217HSTN	604						
4039702	217HSTN	579	-851	-901	-1076	-1235	50	159
4039802	217HSTN	635						
4039803	217HSTN	592	-938	-998	-1158	-1378	60	220
4039901	217HSTN	500	-1340	-1400	-1510		60	
4040101	217HSTN	468	-1572	-1642	-1717	-2050	70	333
4040103	217HSTN	475	-1552	-1612	-1742		60	
4040104	217HSTN	488	-1537	-1597	-1672		60	
4040105	217HSTN	482	-1648	-1698	-1788		50	
4040401	217HSTN	460	-1478		-1725			
4040517	217HSTN	392	-1638	-1708	-1878	-2288	70	410
4040701	217HSTN	483			-1755	-2190		435
4040702	217HSTN	523						
4040703	217HSTN	499	-1606	-1661	-1831		55	
4040804	217HSTN	385						
4045601	217HSTN	800	-342	-400	-510		58	
4046101	217HSTN	815	-450		-685			
4046402	217HSTN	776						
4046403	217HSTN	767	-448		-728			
4046501	217HSTN	840	-546	-605	-695	-875	59	180
4046601	218HNSL	685						
4046602	218HNSL	690						
4046801	217HSTN	830	-525	-595	-760		70	
4047102	218HNSL	612						
4047401	218HNSL	600						
4047403	218HNSL	600	-875	-920			45	
3909901	217HSTN	610	-1908	-2105	-2323		197	
3909903	217HSTN	623	-2463	-2527		-2646	64	
3910201	217HSTN	638	-2507	-2622	-2852		115	
3909201	217HSTN	570	-2181		-2395	-2480		85
4008801	217HSTN	712			-1198	-1378		180
4008802	217HSTN	703	-1067	-1107	-1257	-1367	40	110
4015201	217HSTN	604	-746	-796	-966		50	
4015101	218TRNT	535	-637	-713	-780	-937	76	157
4014903	218HNSL	522	-658	-704			46	
4022203	217HSTN	566	-359	-454	-569		95	
4022103	217HSTN	626	-354	-396	-490	-582	42	92
4021601	218HNSL	680	-280					
4021603	218HNSL	693	-217	-317			100	

4021605	217HSTN	639	-269	-331	-421	-536	62	115
4021705	217HSTN	612	-88	-135	-259	-342	47	83
4020602	218HNSL	638	-37					
4020704	217HSTN	918	115	62	-13	-98	53	85
4020703	218HNSL	925	128	75			53	
4019901	218HNSL	990	230	198			32	
4028404	217HSTN	990	132		19	-60		79
4044902	217HSTN	800	-85	-120	-260	-320	35	60
4053201	217HSTN	665	-289		-430			
4053302	218HNSL	698	-316	-382			66	
4053301	218HNSL	698	-311	-378			67	
4054503	217HSTN	697			-978	-1115		137
4047703	217HSTN	640	-1120	-1180	-1370		60	
4048201	217HSTN	486	-1833					
3933901	217HSTN	465	-2665	-2797	-2986		132	
3933305	217HSTN	566	-2598	-2657	-2862	-3274	59	412
3933605	217HSTN	550	-2313	-2383	-2497		70	
4043603	217HSTN	870	82	-3	-100		85	

*= indicates possible McGregor high well

GE= ground elevation

THLelev= top of the Hensell elevation, BHLelev= bottom of the Hensell elevation, THNelev=bottom of the Hosston elevation, BHNelev= bottom of the Hosston elevation

APPENDIX B

Geophysical Logs used and Percent Sand calculated

State Well Number	Top	Bottom	aquifer	hnsl_psand	hstn_psand
40-37-601	0	1005	218HNSL		
40-45-601	45	1402	217HSTN	83	89
40-40-703	1297	2496	217HSTN	83	82
39-25-201	103	3140	217HSTN	70	85
40-40-104	50	2536	217HSTN	83	80
40-15-904	62	1950	217HSTN	84	72
40-16-802	1300	2368	217HSTN	67	73
40-22-812	50	1294	218HNSL	60	
40-23-907	1052	2113	217HSTN	70	80
40-23-104	462	1378	218HNSL	87	
40-24-803	85	2436	217HSTN	85	80
40-22-502	2	1063	218HNSL		
40-31-802	2	2040	217HSTN		
40-24-705	40	2349	217HSTN	60	81
40-30-502	20	1300	217HSTN	86	86
40-39-504	0	1971	217HSTN		
40-39-803	20	1995	217HSTN	83	83
40-39-901	35	2310	217HSTN	83	83
40-31-805	990	2024	217HSTN	65	70
40-30-802	75	1294	218HNSL	70	75
40-37-607	50	1127	218HNSL		
40-24-201	1784	2603	217HSTN		
40-39-402_BU6	23	1900	217HSTN	93	88
39-25-401	80	3042	217HSTN	60	75
39-25-402	100	2960	217HSTN	67	60
40-31-708	30	1817	217HSTN	86	80
39-25-801	100	3370	217HSTN	82	81
39-33-102	95	2900	217HSTN	93	86
39-33-101	90	2824	217HSTN	70	62

BIBLIOGRAPHY

Bain, J.S., 1973, The Nature of the Cretaceous-Precretaceous Contact, North-Central Texas, Baylor Geological Studies, Bulletin No. 25: Baylor University, p. 1–22

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. 1-1 – 17-7

Bené, J., Hardin, B., O'Rourke, D., Donnelly, A., and Yelderman, J., 2007, North Trinity/Woodbine Aquifer Groundwater Availability Model prepared for the Texas Water Development Board, 391 p. 1-1 – 17-7

Boone, P.A., 1968, Stratigraphy of the Basal Trinity (Lower Cretaceous) Sands of Central Texas: Baylor Geological Studies, Bulletin No. 15, p. 37

Chebotarev, I. J., 1955, Metamorphism of natural waters in the crust of weathering, Geochemica Cosmica Acta 8, pt. 1., p22-32.

Cutter, Charles, 1894, Cutters Guide to the City of Waco, S.N., 1894

Davis, K.W., 1974, Stratigraphy and Depositional Environments of the Glen Rose Formation North-Central Texas: Baylor Geological Studies, Bulletin 26, p. 1-43.

ESRI, 2010, Arcmap 10, ESRI International Distributors, Redlands, California.

Flawn, Peter T., and Burkett, J.M., 1965, Urban Geology of Greater Waco Part 1: Geology, Baylor Geological Studies, Bulletin No. 8

Hayward, C., 1978, Structural Evolution of the Waco Region: Baylor Geological Studies, Bulletin 34, p. 1-39.

Henningsen, R.E., 1962, Water Diagenesis in Lower Cretaceous Trinity Aquifers of Central Texas: University at Austin, Baylor Geographical Studies, Bulletin No. 3.

Hill, R.T., 1901, Geography and Geology of the Black and the Cretaceous Formations and Special Reference to Artesian Waters: U.S. Geological Survey, 21st Annual Report, pt. 2, 1899-1900, p, 1-666.

Holloway, H.D., 1961, The Lower Cretaceous Trinity Aquifers, McLennan County, Texas: Baylor University, Baylor Geographical Studies Bulletin No. 1.

Kaiser, R., (oral commun., 2002), cited in Bené, J., Hardin, B., O'Rourke, D., Donnelly, A., and Yelderman, J., 2007, North Trinity/Woodbine Aquifer Groundwater Availability Model prepared for the Texas Water Development Board, 391 p. 1-1 – 17-7

Klemt, W., Perkins, R., and Alvarez, H., 1975, Ground Water Resources of Part of Central Texas with Emphasis on the Antlers and Travis Peak Formations: Austin, Texas, Texas Water Development Board, Report 195, v. 1, p. 7-61

Mace, R.E., Dutton, A.R., and Nance, H.S., 1994, Water-Level Declines in the Woodbine, Paluxy, and Trinity Aquifers of North-Central Texas: Gulf Coast Assoc. Geolog. Soc. Trans, v. 44, p. 413.

Nordstrom, P.L., 1982, Occurrence, Availability, and Chemical Quality of the Ground Water in the Cretaceous Aquifers of North-Central Texas: Texas Department of Water Resources, Report 269, v. 1, p. 15-54.

Rapp, K., 1986, Groundwater Recharge in the Trinity Aquifer, Central Texas: Waco, Texas, Baylor University, M.S. Thesis

Rupp, Siegfried, 1974. Urban geology of greater Waco PART III: WATER, Subsurface Waters of Waco. Baylor bachelor thesis

Sokol, Daniel (1963) Position and fluctuations of water levels in wells perforated in more than one aquifer, Journal of Geophysical Research, Volume 68, no. 4, p. 1079-1080.

Southern Trinity Groundwater Conservation District, 2010, Management Plan, p. 1-163

Southern Trinity Groundwater Conservation District, 2007, District Rules, Initially Adopted and Effective December 6, 2007; Revised February 28, 2008; Amended and Effective January 7, 2010; p. 1-111

Texas Administrative Code, Title 31, Chapter 356, Subchapter A, rule §356.3 relating to Required Management Plan

Texas Administrative Code, Title 31, Chapter 356, Subchapter A, rules §§356.5 and 356.6, relating to Management Plan and Plan Submittal, respectively

Texas Commission on Environmental Quality, 2008, An Order: Designating the Central Texas Trinity Aquifer Priority Groundwater Management Area and Approving the Executive Director's Recommendations Regarding Groundwater Conservation Districts in the PGMA, TCEQ Docket No. 2008-0099-MIS; State Office of Administrative Hearings Docket No. 582-08-1502

Texas Legislature, Act of May 26, 2007, 80th Leg., R.S., Senate Bill 1985 chapter 1345, 2007 Tex. Gen. Laws 4594 (then the "McLennan County Groundwater Conservation District"), Texas Legislature, Act of May 31, 2009, 81st Leg., R.S., Senate Bill 2513, chapter 1248, 2009 Tex. Gen. Laws 3976, and codified in Texas Special District Local Laws Code, Chapter 8821 ("Act")

Texas Water Development Board, 2010 text file data: http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWDatabaseReports/GWdatabaserpt.asp#M

Texas Water Code, 2009, Title 2. Water Administration, Chapter 36 Groundwater Conservation Districts, Subchapter A. General Provisions, rule §36.0015. Purpose

Texas Water Code, 2009, Title 2. Water Administration, Chapter 36: Groundwater Conservation Districts, Subchapter B. Creation of District, rule §36.011. Method of Creating District

Theis, C.V., 1935, The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Ground-Water Storage: Am. Geophys. Union Trans., Pt. 2, p. 519-524.

Thomas, C.D., 1997, The Geochemical Transition of the Deep Trinity Aquifer Across the Balcones Fault Zone, Central Texas: Waco, Texas, Baylor University, M.S. Thesis

Wade, Shirley C., 2009, Texas Water Development Board, GAM Run 08-84mag, p. 1-37.