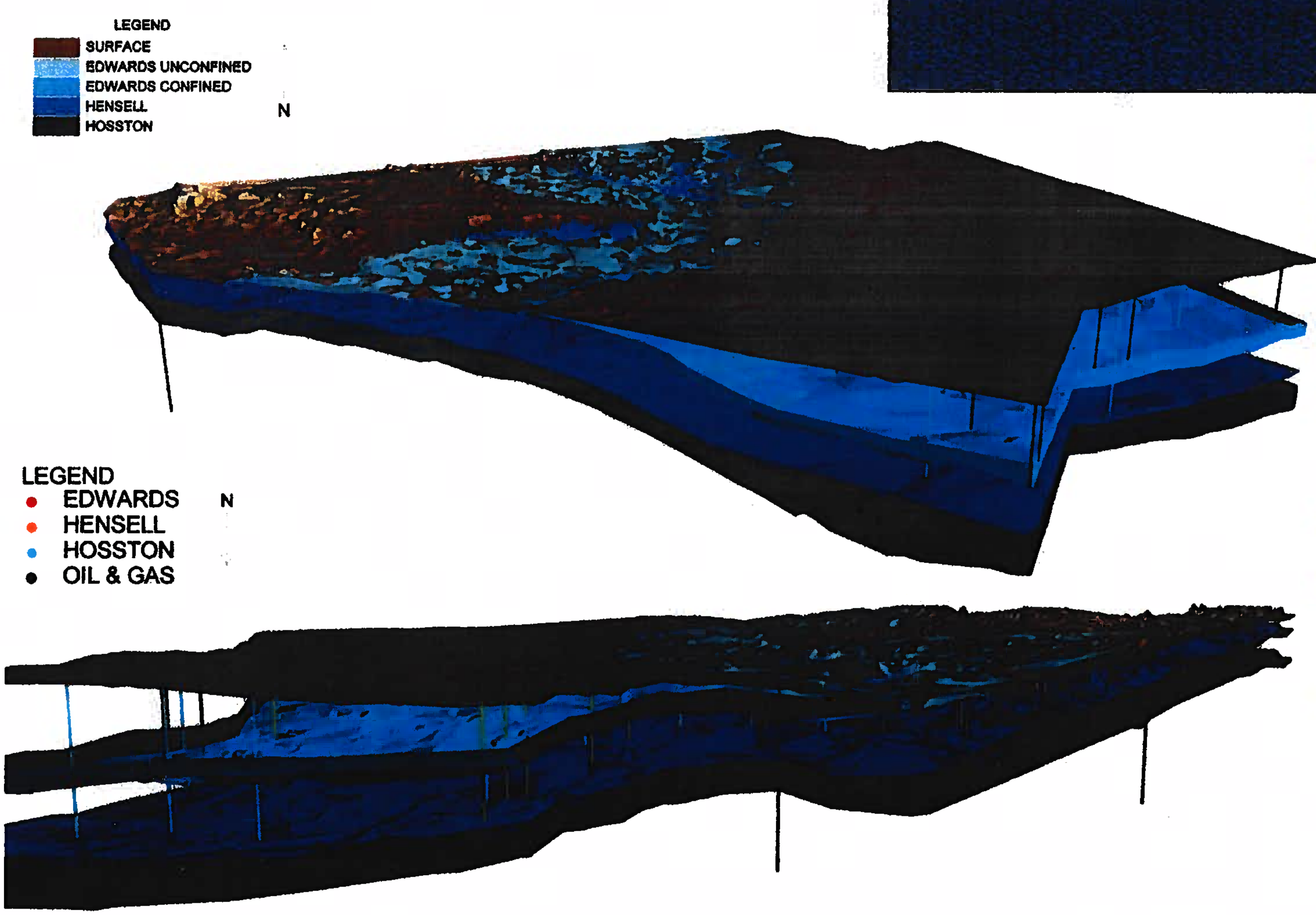
January 2002

Groundwater Resources Management Information

Prepared For

The Clearwater Underground Water Conservation District



Prepared by:
Turner Collie & Braden Inc.
Engineers • Planners • Project Managers

In association with
LBG-Guyton Associates

GROUNDWATER RESOURCES MANAGEMENT INFORMATION

ACKNOWLEDGEMENTS

The project team would like to extend its appreciation to Cheryl Maxwell, administrative manager, and to the Directors of the Clearwater Underground Water Conservation District (CUWCD) for the opportunity to assist them in developing the foundation for the management of groundwater resources in Bell County.

We would also like to thank the Barton Springs Edwards Aquifer Conservation District and General Manager Stovy Bowlin as well as Paul Tybor, General Manager of the Hill County Underground Water Conservation District for their assistance with the development of the management tools necessary to properly and adequately manage the groundwater resources.

Turner Collie and Braden Inc. (TCB) appreciates the technical information developed by LBG-Guyton and Associates (Guyton), Bruce Darling, Project Manager and Kristen Persky, Hydrogeologist. Thanks are also extended to Ed Copeland, Senior GIS Specialist, Brian McCaig, Graduate Engineer, Bruce Davidson, Project Manager for Technology Services, Doug Zarker, Geologist, Mark Lowry, P.E., Project Director of QA/QC and all with TCB.

A very special thanks and notice of appreciation is extended to all the members of the Clearwater Underground Water Conservation District for their assistance and willingness to serve the District as representatives of the varied and diverse citizens of the region and the state of Texas.

This report was prepared under the guidance and direction of the Board of Directors of the Clearwater Underground Water Conservation District. We would like to dedicate this report to the memory of Board President Don Mackie for the leadership he provided to the District from August 1999 to September 2001.

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EXECUTIVE SUMMARY

The "Groundwater Resources Management Information" report prepared by Turner Collie and Braden Incorporated (TCB) and LBG-Guyton and Associates (Guyton) describes the location and geography of the Clearwater Underground Water Conservation District (CUWCD), summarizes the projected population growth of the District based on the findings of the Region G Water Plan approved in 2001, defines and describes the geology of the District and the hydrology of the underlying Edwards Balcones Fault Zone (BFZ) and Trinity aquifers, and explains the need for a monitoring program that assists the District with its management goals.

The CUWCD currently comprises Bell County in central Texas and encompasses a range of geographic features. The region varies in elevation from 1,200 feet in the west to 450 feet in the east. The vegetation cover in the west is primarily Live Oak and Ashe Juniper while Silver Bluestem, Texas Wintergrass, and Post Oak grasslands dominate the sandy soils in the central and eastern portions of the county. Due to extensive erosion of the hills in the west, the soil thickness increases from west to east within the District. The climate is sub-humid with long, hot summers and short, mild winters.

The primary cities based on population within the CUWCD are Killeen and Temple. Belton is the county seat of Bell County. Other significant communities within the District include Bartlett, Holland, Salado, Morgan's Point and Fort Hood.

The major water resources within the District are provided either by surface water from Belton Lake and Lake Stillhouse Hollow which are operated by the United States Corp of Engineers or by groundwater from the Edwards (BFZ) and Trinity aquifers. Major rivers within the District draining into Lake Belton and Lake Stillhouse Hollow include the Lampasas River, the Little River, the Leon River, Rockhouse Creek and Owl Creek.

The population of Bell County resides mainly within cities and other unincorporated communities. In 2000 the population of Bell County was 247,000 residents, and the cities of Killeen and Temple accounted for 60% of the population. By 2050 the population is expected to increase to 414,000 residents, a 68% increase, with little change in the population distribution.

Municipal water demand within the District is expected to increase 72 percent between 2000 and 2050. Approximately 70% of groundwater pumpage is for municipal water user groups. From 1980 to 1996, the quantity of groundwater pumped from the Trinity aquifer has been about 50% greater than the quantity pumped from the Edwards (BFZ) aquifer. The availability of groundwater over the next fifty years from both aquifers ranges from 95,162 to 119,659 acre-feet of water.

There are two important stratigraphic groups within the CUWCD. The first is the Fredericksburg group which encompasses the Edwards (BFZ) aquifer and the Trinity group which encompasses the Trinity aquifer. The aquifers increase in depth from the northwestern end of Bell County to the southeast. Due to erosion, the older stratigraphic layers are exposed at the surface in the western part of the county, and the younger stratigraphic layers are exposed at the surface in the east.

The availability of water in the aquifers is determined by the regional geology. The Edwards (BFZ) aquifer is considered an unconfined aquifer for purposes of calculating groundwater storage while the Trinity aquifer is considered to be confined. As a result of the geology and differences in the physical properties of the aquifers, the method of calculating storage in the Edwards (BFZ) aquifer differs from the method for the Trinity aquifer. The total volume of available water in the Edwards (BFZ) aquifer is measured as the actual volume released from storage by lowering the water table. The volume of available water in the Edwards (BFZ) aquifer ranges from 50,697 to 101,394 acre-feet of water depending upon the specific yield of the aquifer. The volume of available water in the Trinity aquifer is the volume of water released from the aquifer as a result of a reduction in aquifer pressure in the form of water expansion or compaction of the aquifer. The volume of available water in the Trinity aquifer is approximately 44,500 acre-feet of water. However, the total volume of water stored in the Trinity aquifer is estimated to be 32,000,000 acre-feet.

The United States Environmental Protection Agency has stipulated a limit of 500 milligrams/liter as the safe-drinking water standard for long-term human consumption of total dissolved solids (TDS). Within the outcrop areas of the Edwards (BFZ) aquifer, wells produce water with levels typically lower than the standard. However, wells pumping from the Edwards (BFZ) aquifer in other areas of Bell County and wells pumping from the Trinity aquifer typically produce water in excess of the standard. Perchlorate levels in groundwater are also a concern in the western part of Bell County but the determination of existing contamination or the potential for future contamination is outside the scope of this study.

TCB created a graphical user interface (GUI) incorporating the capabilities of ArcView GIS and Microsoft Access in order to assist the District with its groundwater monitoring and management program. The graphical user interface permits well applications and registrations, water quality, and other well information to be geo-referenced. All the well and aquifer data can be stored and queried based on location within the CUWCD. Existing wells and new wells can be identified, and attributes of the well or aquifer can be stored, referenced and analyzed based on a variety of characteristics. In addition, as new data on existing wells is collected, the database can be updated allowing the district to identify trends and evaluate aquifer characteristics based on a comprehensive review of the data. The information and analysis can then be quickly accessed through reports prepared by the database component of the GUI in Microsoft Access and through maps prepared in the geographic information system (GIS) in ArcView GIS.

Table of Contents

List of Figures

List of Tables

1.0 INTRODUCTION

The Clearwater Underground Water Conservation District recognized that any program designed to promote efficient and equitable development and management of groundwater must be based on a sound understanding of the hydrogeological systems on which the municipal, industrial, and agricultural sectors of the local economy rely for water. It is reasonable to infer that the ability of a Water Conservation District to fulfill its statutorily designated responsibility to promulgate management plans, rules, practices, and procedures to ensure that adequate water is available for all users within its jurisdiction is directly related to the degree to which sources of groundwater are known, and hydrogeological processes are understood by managers. The CUWCD chose TCB and Guyton to conduct a study of the groundwater resources which include the Edwards (BFZ) and Trinity aquifers within Bell County, Texas in response to the CUWCD's request for proposals.

The Directors of the CUWCD have expressed their interest in understanding the hydrogeology of the Edwards (BFZ) and Trinity aquifers, along with the many factors that affect the long-term availability of the groundwater resources of the county as a prelude to their efforts to develop a program to monitor groundwater conditions in the county and to promulgate rules, practices, and procedures to guide the orderly development and management of the aquifers. The Scope of Work developed and the information resulting from the investigations and research will provide the CUWCD with the technical information needed to understand the many hydrogeological factors that form the foundation of a sound groundwater management plan and the tools necessary to manage the data and produce reports regarding the groundwater resources in the CUWCD.

The following report includes various maps, graphics, and discussion of the aquifer characteristics and groundwater use along with recommendations that address a number of engineering and planning issues that are an outgrowth of the technical information developed as a part of the aquifer study.

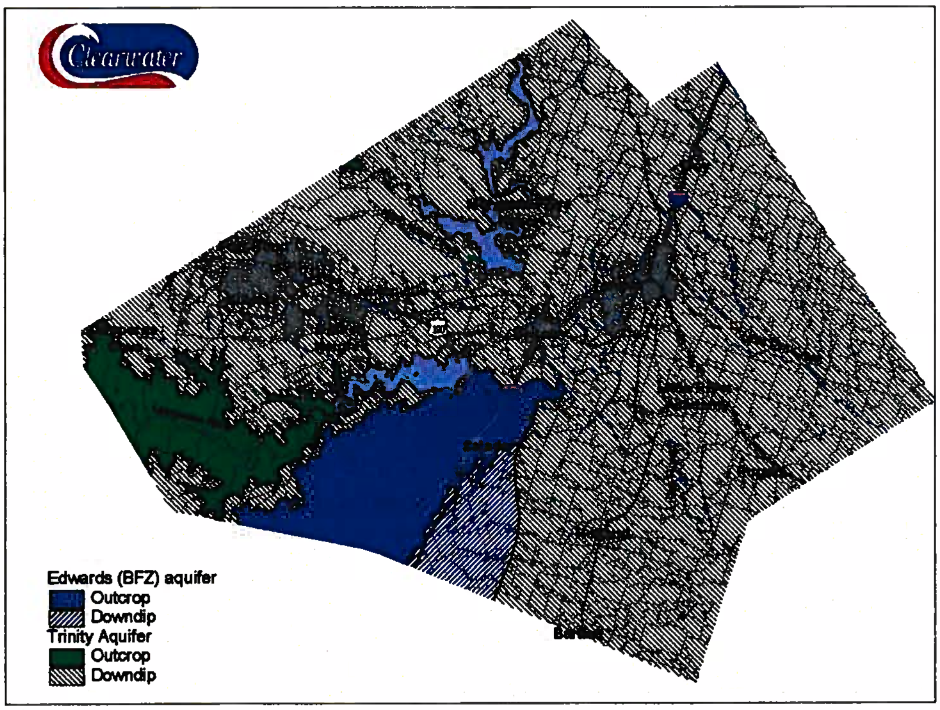
2.0 GEOGRAPHIC AND WATER DEMAND DESCRIPTION

2.1 Location

The Clearwater Underground Water Conservation District (CUWCD) is located inside the Region G Water Planning Group and encompasses all of Bell County, Texas. The City of Belton is the county seat. Killeen, Temple and Harker Heights are the other major cities located within the county. There are also several large communities located within the county such as Bartlett, Holland, Salado, Morgan's Point Resort, and portions of Fort Hood. The District is surrounded by Williamson and Milam Counties to the south, Falls County to the east, McLennan and Coryell Counties to the north, and Lampasas and Burnet Counties to the west.

Numerous rivers such as the Lampasas River, Nolan Creek, Little Elm Creek and the Little River traverse the county, their paths following the general southeastward slope of the land surface. Bell County is also the location of two artificial lakes, Lake Stillhouse Hollow and Belton Lake. The lakes, which are owned by the U.S. Corp of Engineers, provide flood control and drinking water to the cities and unincorporated communities of the county. *Figure 1* is a map depicting the major water resources and cities of Bell County.

Figure 1. Map of Water Resources and Cities within Bell County and the CUWCD.



The topography of Bell County varies greatly between the western and eastern boundaries of the county as illustrated in *Figure 2*. The westernmost areas of the county consist of limestone and sandstone hills that reach elevations of 1,200 feet above mean sea level (MSL). Surface elevations decrease toward the east and southeast, where relatively flat-lying coastal plain sediments are located at elevations ranging between 430 and 450 feet above MSL.

The vegetation cover of Bell County ranges from open cropland to juniper forests and can be seen in *Figure 3*. The native vegetation is dominated by the following:

- Live Oak and Ashe Juniper woods occurring primarily on shallow limestone soils and on the hills and escarpments of the Edwards Plateau in northwestern Bell County;
- Live Oak, Mesquite, and Ashe Juniper parks occurring chiefly on level to gently rolling uplands and ridge tops of the Edwards Plateau in western Bell County;
- Oak-Mesquite and Juniper Parks/Woods occurring as associations or as a mixture of individual woody species standing on the uplands and prairies of central and western Bell County;
- Post Oak Woods, Forests, and Grasslands occurring mostly on sandy soils; and
- Silver Bluestem and Texas Wintergrass Grasslands occurring primarily in prairies in southern and northern Bell County.

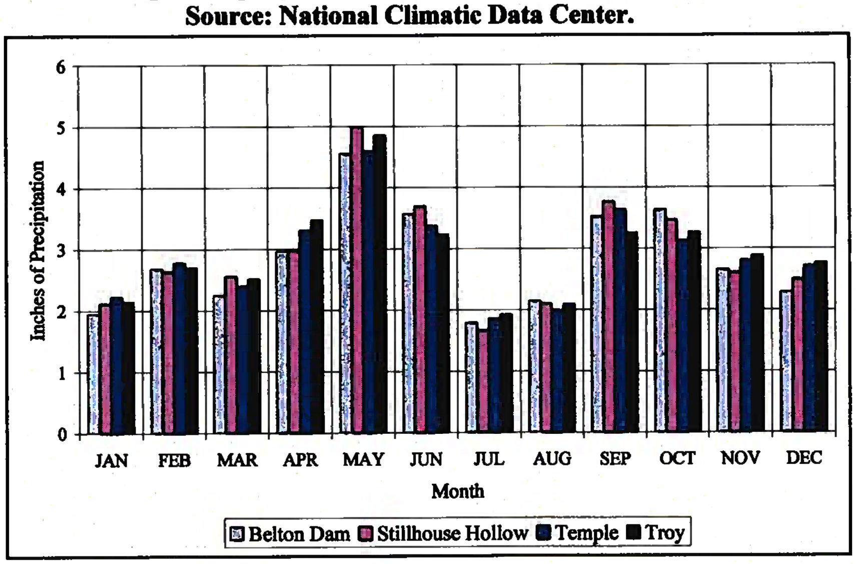
The soil thickness of Bell County (*Figure 4*) varies according to the lithology of the underlying weathered material. The eastern half of the county is in the Texas Blackland Prairie. The soils in this area are deep and are underlain by marl, marly clay, and soft limestone. The western half of the county is in the Grand Prairie. The soils in this area are on a limestone plain, and most are deep to shallow over soft or hard limestone. The permeability of topsoil is generally five inches or less per hour (*Figure 5*). Permeability is the property that allows a soil to transmit a fluid such as water. Terms used to describe permeability are: *very slow, slow, moderately slow, moderate, moderately rapid, rapid, and very rapid.* The permeability of Bell County soils is typically moderate to moderately slow (SSURGO Database, United States Department of Agriculture).

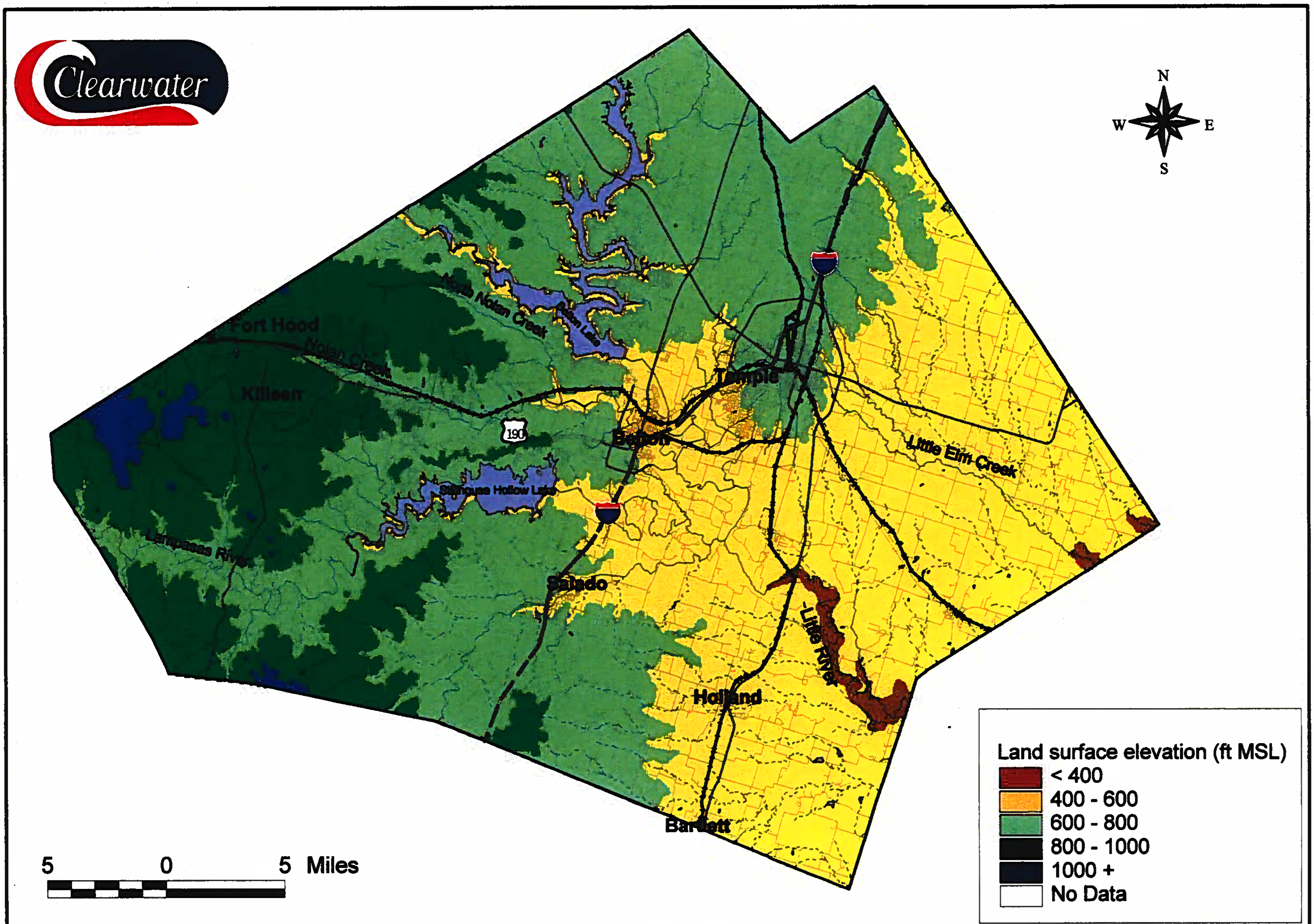
The climate of Bell County is sub-humid. The summers are long and hot, and the winters are short and mild. In the winter, the average temperature is 49° Fahrenheit (F). The average summer temperature is 83°F. Mean annual precipitation in Bell County is approximately 36 inches (National Climatic Data Center). The greatest amounts of precipitation occur in the southern and western areas of the county (*Figure 6*). Average monthly precipitation recorded at Belton Lake Dam, Stillhouse Hollow Dam, Temple, and Troy ranges from two inches or less during winter and summer to as much as 5 inches in spring and 4.5 inches in fall. Average annual precipitation of each of these locations is listed as follows:

- Belton Lake Dam, 33.9 inches (based on records from July 1953 to December 1992);
- Stillhouse Hollow Dam, 35.1 inches (based on records from July 1963 to September 2000);
- Temple, 34.7 inches (based on records from July 1931 to September 2000); and
- Troy, 35.1 inches (based on records from January 1949 to September 2000).

Precipitation at the locations listed above is highest during spring and autumn as illustrated in *Figure 7*.

Figure 7. Average Precipitation by Month at Weather Stations in Bell County.
Source: National Climatic Data Center.





THE TOPOGRAPHY OF BELL COUNTY

Figure 2

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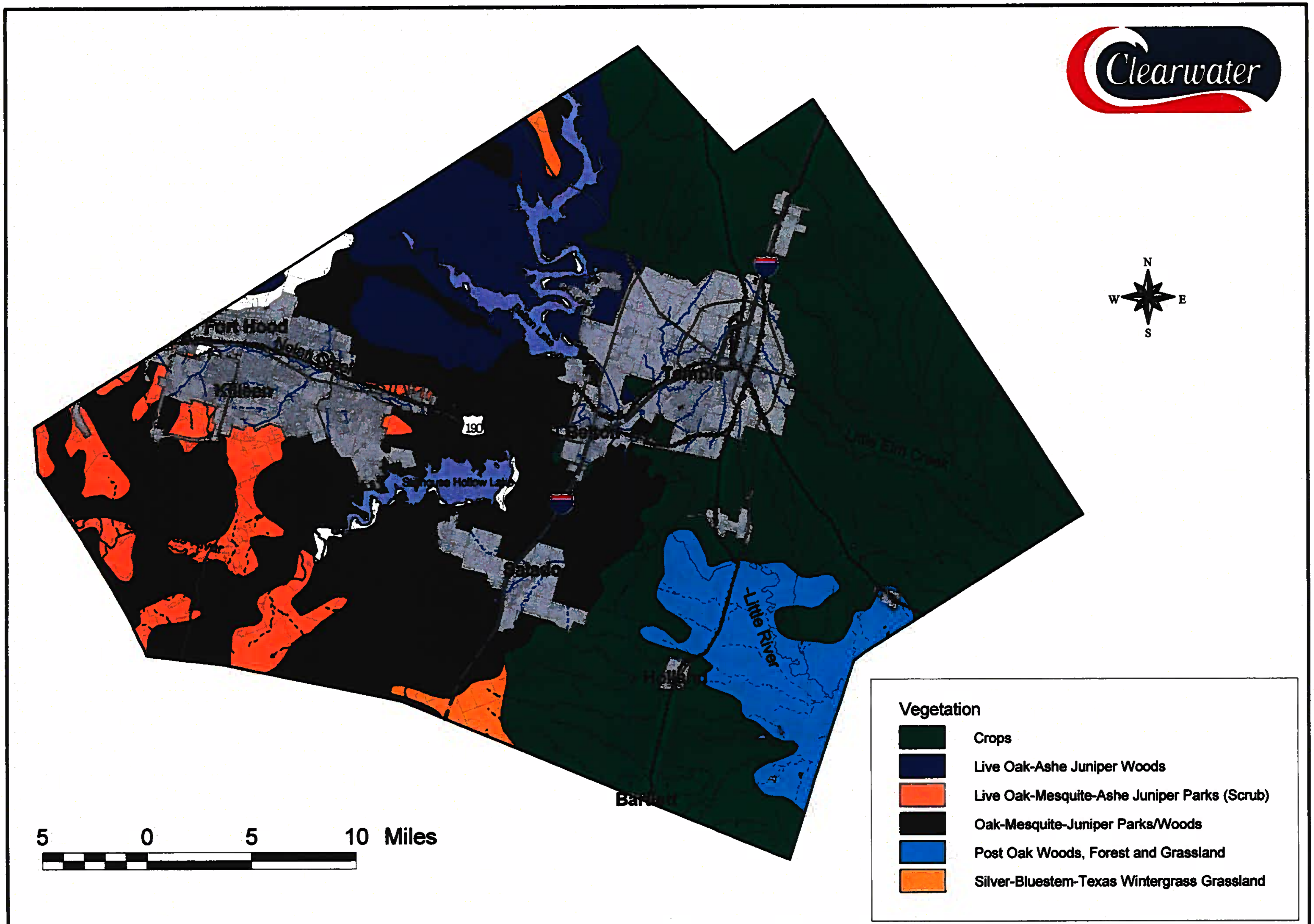

VEGETATION OF BELL COUNTY

Figure 3

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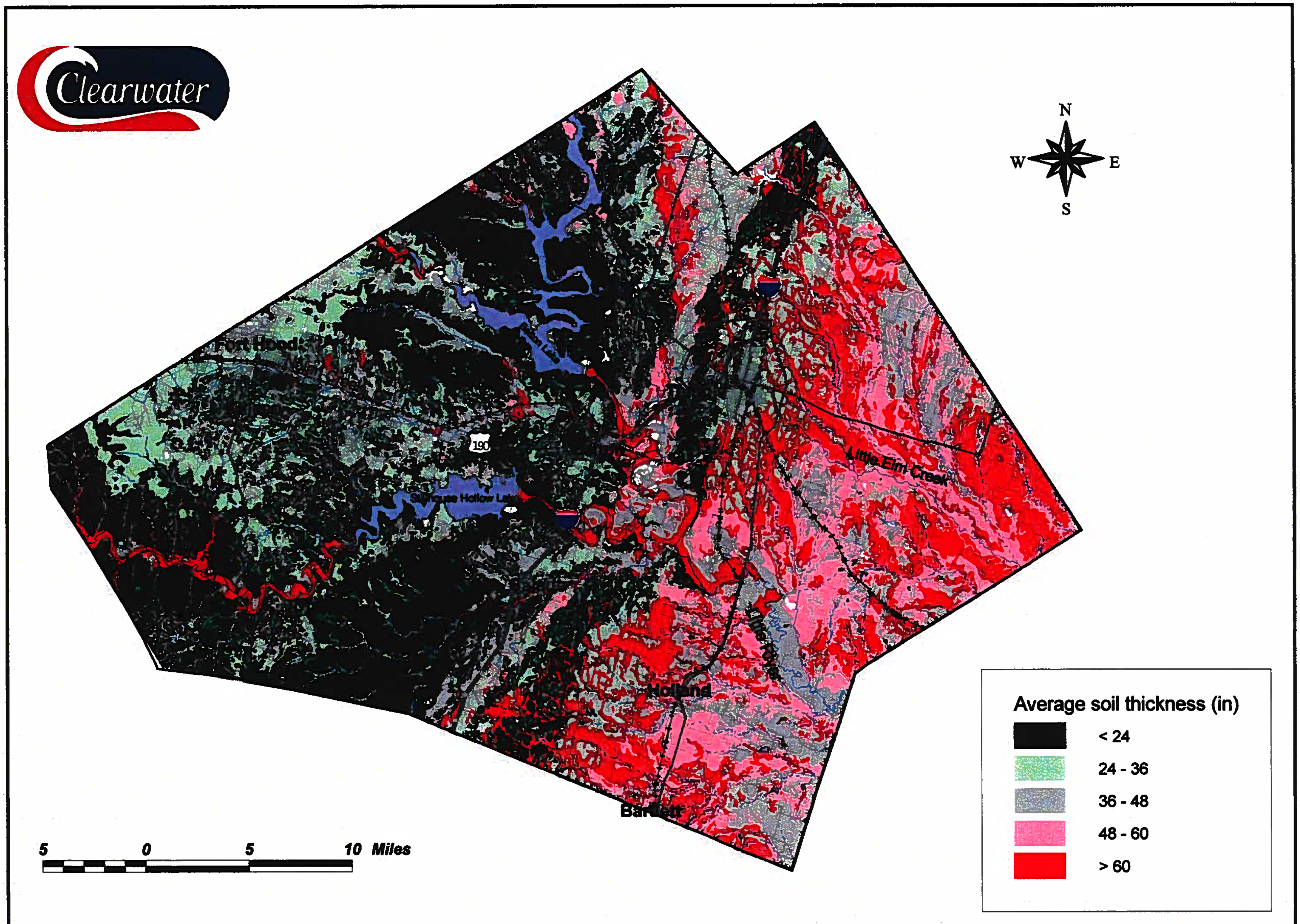

BELL COUNTY SOIL THICKNESS

Figure 4

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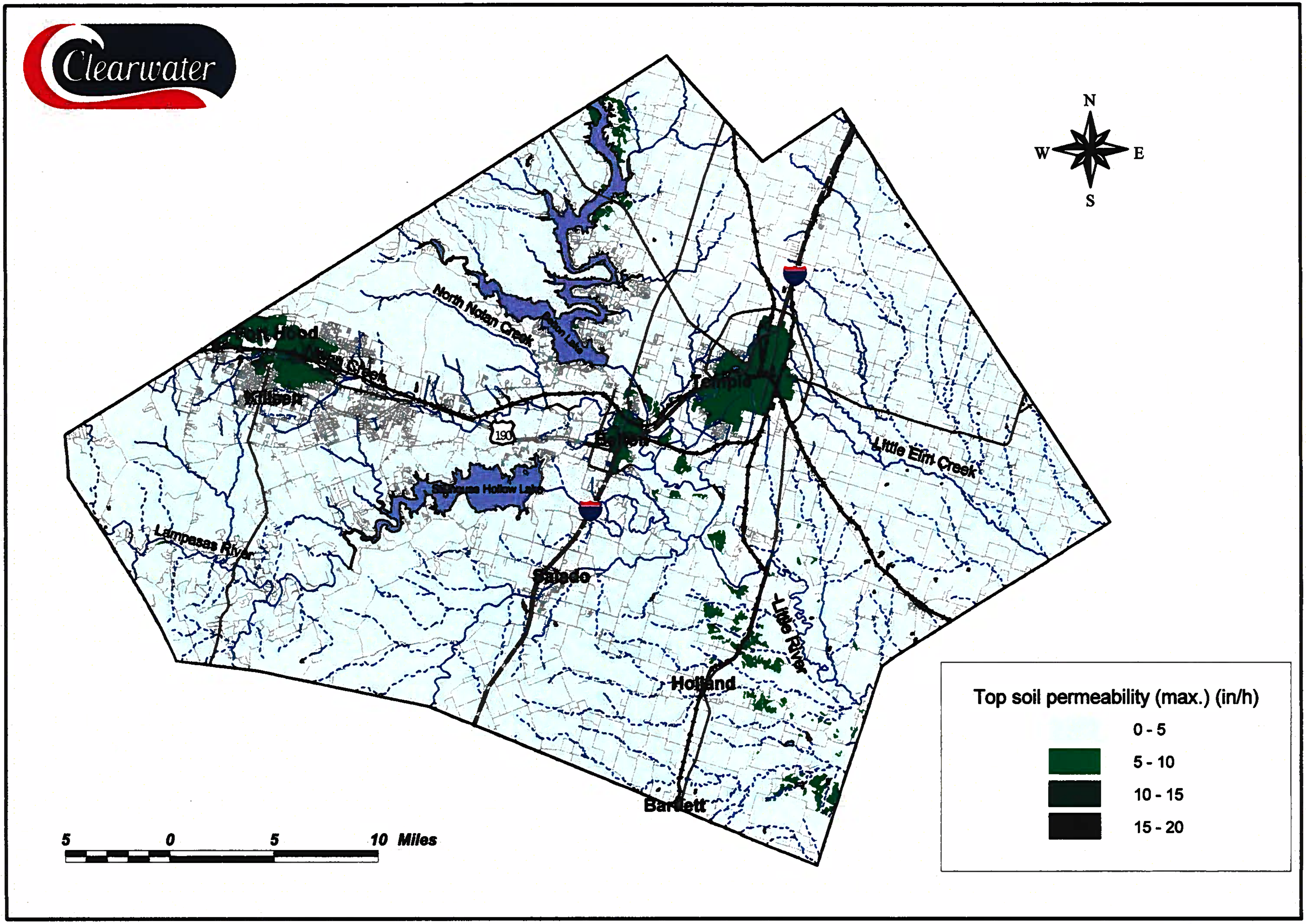

BELL COUNTY TOP SOIL PERMEABILITY

Figure 5

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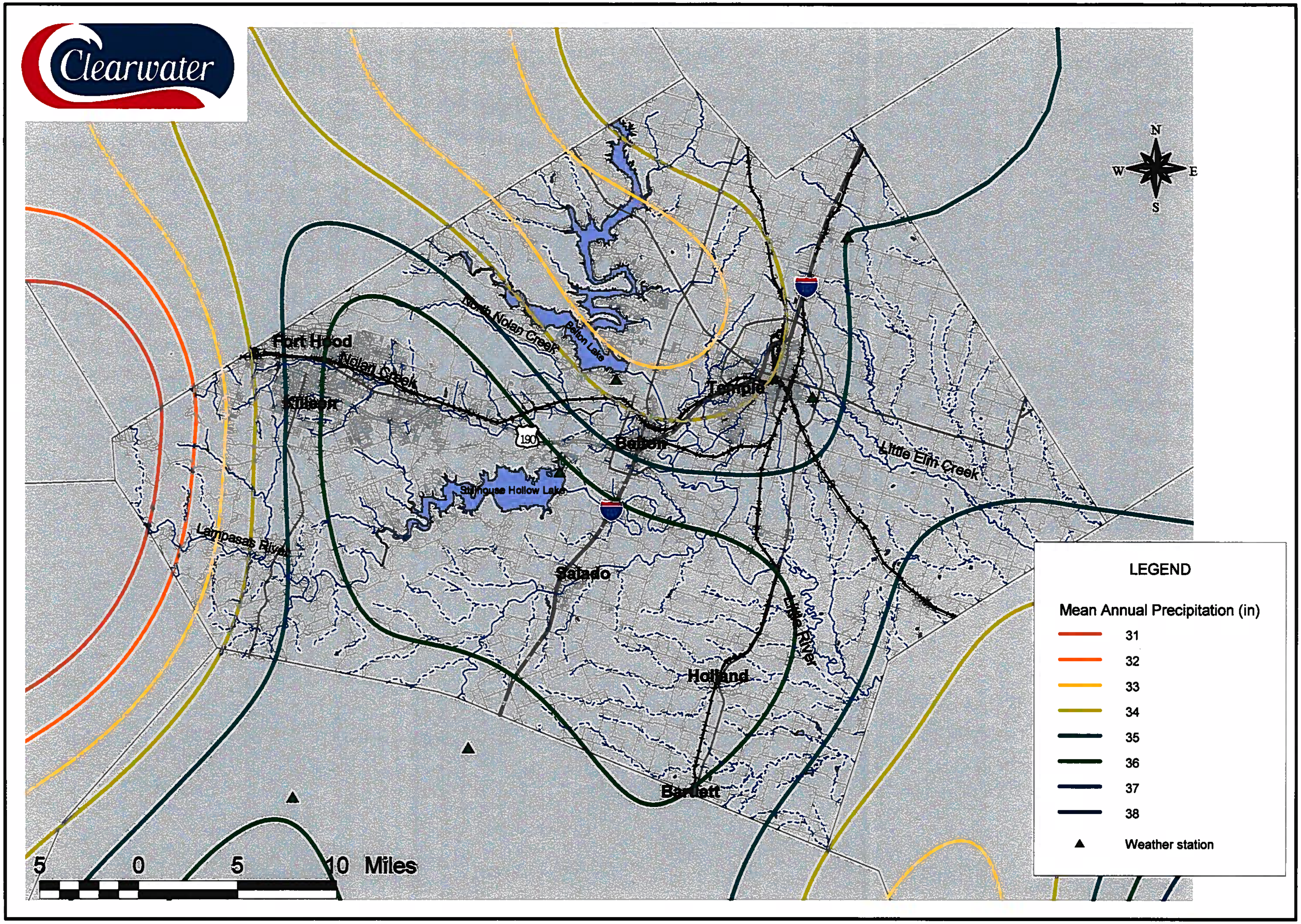

MEAN ANNUAL PRECIPITATION IN BELL COUNTY AND SURROUNDING COUNTIES

Figure 6

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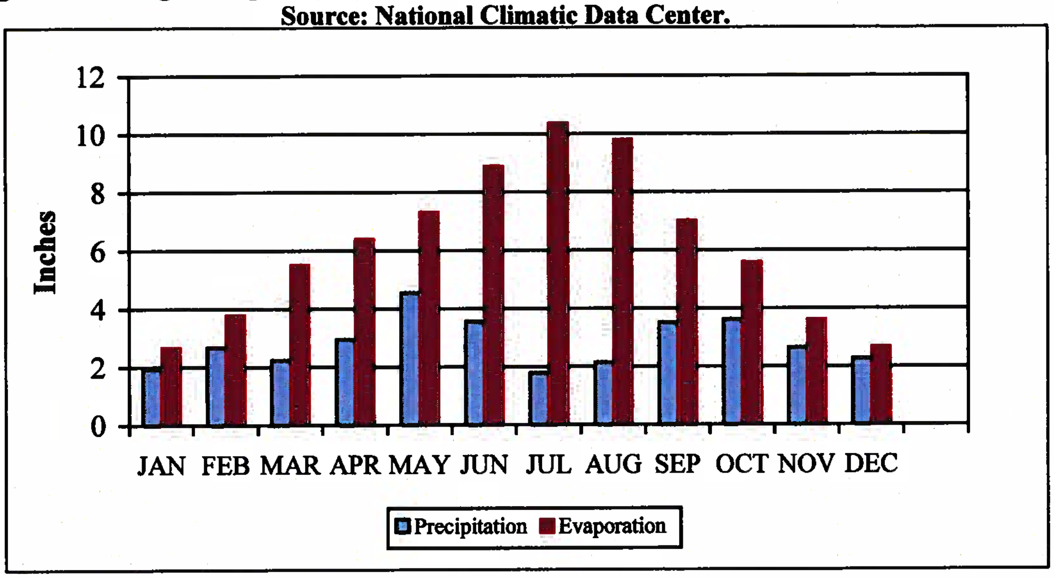
Despite the sub-humid climate, evaporation exceeds precipitation every month of the year as illustrated in *Figure 8*. The greatest excesses of evaporation over precipitation occur during summer, when monthly precipitation is typically two inches or less and evaporation is as much as ten inches.

Figure 8. Average Precipitation and Evaporation at Belton Lake Dam by Month (1966-1992). Source: National Climatic Data Center.



2.2 Population

Over the 50-year planning period from 2000 to 2050 specified by Senate Bill 1, the population of Bell County is expected to increase by 68%, from approximately 247,000 to 414,000 residents. This is equivalent to an average yearly increase of 1.04%. The cities of Killeen and Temple are expected to account for most of the growth. *Figure 9* illustrates the projected population growth of several municipalities within the county as well as the total projected population of Bell County.

Figure 9. Projected Population Growth of Bell County from 2000 to 2050. Source: Region G Water Plan, 2001.

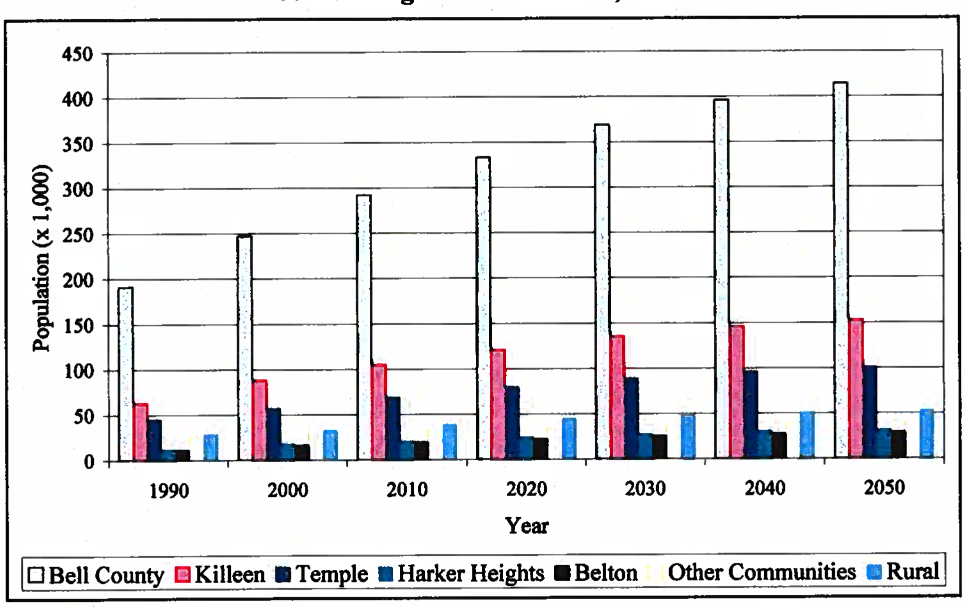


Table 1 below lists the population growth by location or municipality as projected by the Texas Water Development Board (TWDB). The column entitled "Bell County" lists the population for the entire county while the other columns list the projected population growth for their respective municipalities.

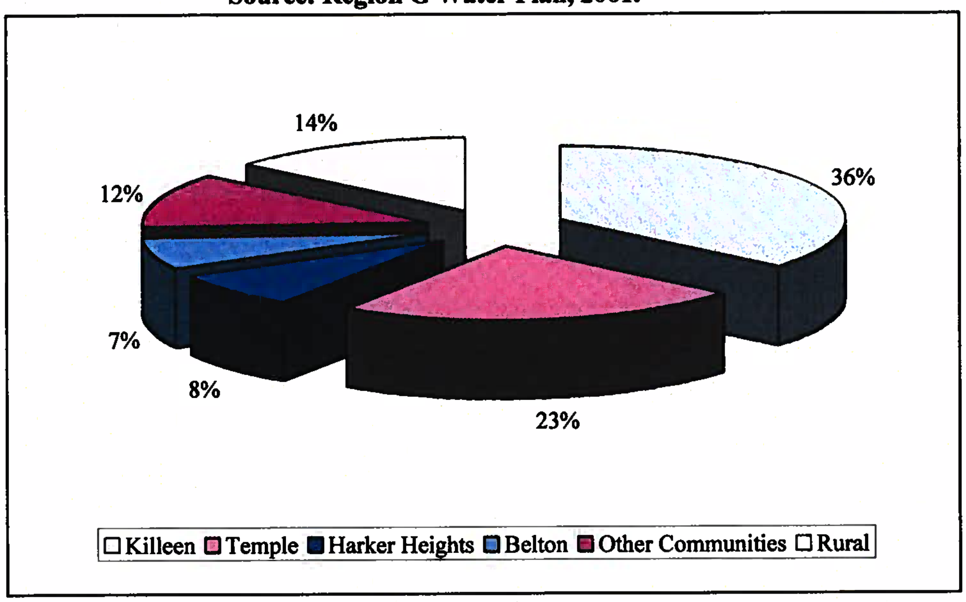
Table 1. Projected Population (x 1000) in Bell County, 2000 to 2050

Year	Bell County	Killeen	Temple	Harker Heights	Belton	Other Communties	Rural
2000	247	89	58	19	17	30	34
2010	292	106	70	22	20	34	40
2020	333	122	81	26	23	35	46
2030	369	136	90	29	26	39	49
2040	396	147	97	32	28	40	52
2050	414	154	102	33	30	41	54

Source: Table 2-1 Region G Water Plan (Historical and Projected Population by City/Community).

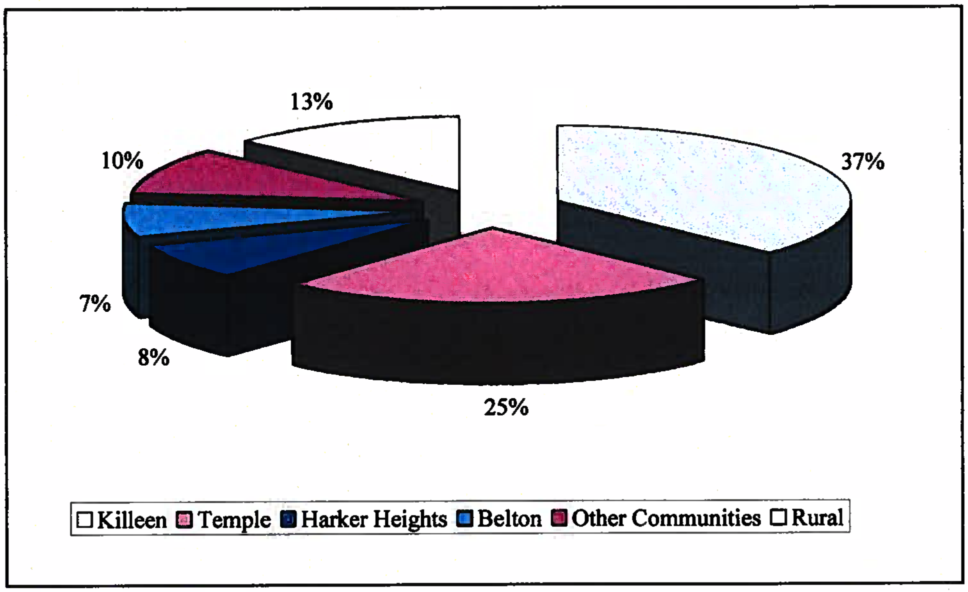
Based on estimates from the Region G Water Plan, Killeen and Temple account for nearly 60 percent of the population of Bell County in 2000. Killeen and Temple account for 36 percent and 23 percent of the population, respectively, while the remaining 41 percent of the population are located in rural areas (14 percent), other communities (e.g. Holland, Morgans Point Resort, Nolanville, and Salado all of which account for 12 percent), Harker Heights (8 percent), and Belton (7 percent). *Figure 10* below illustrates the estimated population distribution within the county in 2000.

Figure 10. Bell County Population Distribution in 2000.
Source: Region G Water Plan, 2001.



Even with the expected growth in population, the distribution of residents is not expected to change significantly by the year 2050 (*Figure 11*). Killeen and Temple will account for 37 percent and 25 percent, respectively, of county residents. The other 38 percent will live in: rural areas (13 percent), other cities (10 percent), Harker Heights (8 percent), and Belton (7 percent).

Figure 11. Bell County Population Distribution in 2050.
Source: Region G Water Plan, 2001.



2.3 Projected Water Demand

Projections for each category of water demand are presented in this section as identified in the Region G Water Plan. A discussion of factors that constitute demand for each user group is included. The projections, provided by the TWDB to the Region G Water Planning Group, were based on data series compiled through the year 1996. The TWDB generated projections of population and demand for each decade, beginning with the year 2000. The projections discussed in this report will be revised during the next round of regional water planning, based on new census and pumpage data collected over the period 1997 to 2000.

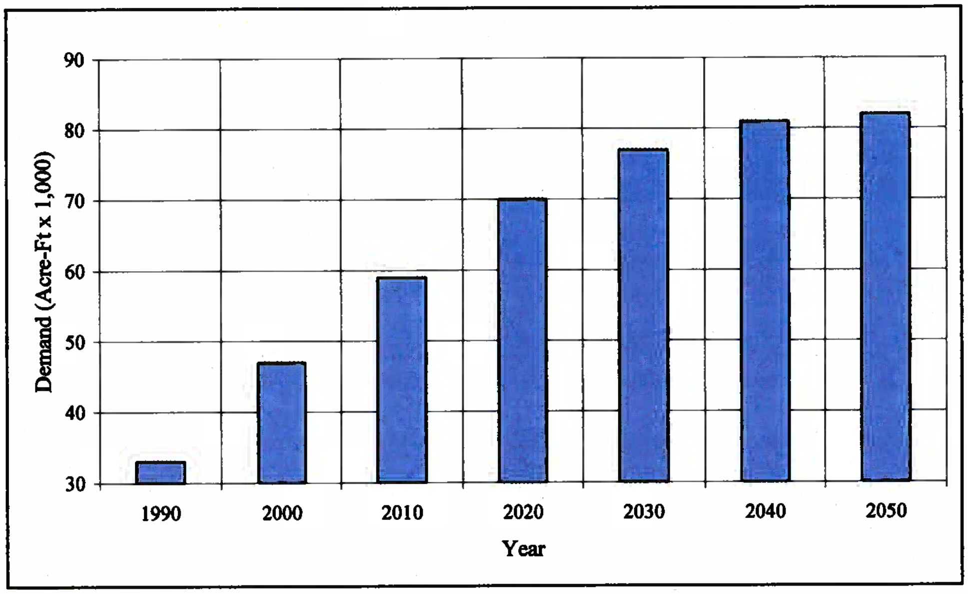
2.3.1 Municipal

All water used by households (e.g., drinking, bathing, food preparation, dishwashing, laundry, flushing toilets, lawn watering and landscaping, swimming pools), by commercial establishments, (e.g., restaurants, car washes, hotels, laundromats, and office buildings) and for fire protection, public recreation and sanitation fall under the category of "municipal" demand. All municipal water must meet safe drinking water standards as specified by Federal and State laws and regulations.

Municipal water demand projections are computed by multiplying the projected population of an entity by the entity's projected per capita water use and adjusted for "expected" water conservation savings (Region G Water Plan, 2001). The projected per capita water use takes into account current plumbing, appliances, and other conservation technology. Per capita water use is projected to decline from 180 gallons per day in 2010 to 176 gallons per day in 2050 due to water conservation strategies such as installation of water-efficient plumbing fixtures and landscaping techniques, public education, and the effects of the 1991 State Water-Efficient Plumbing Act. Expected water conservation represents feasible strategies for economically sound water conservation savings.

Municipal water use for Bell County is projected to increase by 72 percent between 2000 and 2050, or from 47,389 acre-feet to 81,663 acre-feet. Compared with 1990 figures, the increase is projected to be 48,500 acre-feet, or 142 percent. The relation between population growth and expected municipal demand in the form of groundwater and surface water is illustrated by *Figure 12* below which has been adapted from data in the Region G Water Plan. Since the population of Bell County is expected to increase at a linear rate for the next 30 years, demand is expected to increase in a nearly linear fashion through 2020, and then level off over the remaining 30 years of the 50-year planning period.

Figure 12. Projected Municipal Water Demand in Bell County by Decade.
Source: Region G Water Plan, 2001.



2.3.2 Steam-Electric

The projections for steam-electric water demand are based on power generation projections—determined by population and manufacturing growth—and on power generation capacity and fresh water use. The steam-electric generation process uses water in boilers and for cooling. Steam-electric water demand is currently zero, but demand is expected to hit 11,200 acre-feet per year from 2010 to 2050 because of new power generating plants proposed to be built in Bell County (*Figure 13*). This will be the largest non-municipal category of water demand in Bell County.

2.3.3 Manufacturing

Water is used in a large number of manufacturing processes. It can be used as a component of the final product, as a cooling agent during the manufacturing process, or for cleaning/wash-down of parts and/or products. Manufacturing water demand is projected by applying industry-specific water demand coefficients, adjusted for water-use efficiencies (recycling/reuse), to growth trends for each industry. These growth trends assume expansion of existing capacity and building of new facilities, continuation of historical trends of interaction between oil price changes, and industrial activity. It is also assumed that a county's manufacturing base remains constant throughout the 50-year planning horizon. For Bell County, the manufacturing demand for water is projected to increase by 115 percent, from 4,040 acre-feet in 2000 to 8,700 acre-feet in 2050 (*Figure 13*).

2.3.4 Livestock

Projections of livestock water demand are based on estimates of the maximum carrying capacity of the rangeland and the estimated number of gallons of water per head of livestock per day. Additionally, the economics of milk production and the environmental impacts of the operation are major factors in the projections of the water demands for this category of livestock. Livestock drinking water in Bell County is obtained from wells, stock watering ponds, and streams. Livestock water demand is projected to remain constant at 1,119 acre-feet for the 50-year planning period (*Figure 13*).

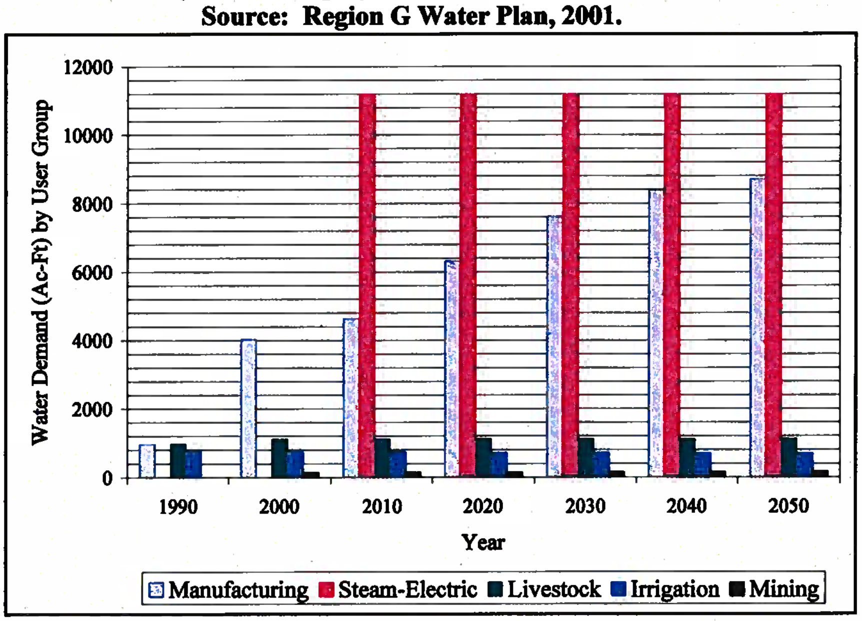
2.3.5 Irrigation

Irrigation water demand projections are based on assumptions regarding resource constraints, crop prices, crop yields, agricultural policy, and technological improvement in irrigation systems. The projections were last updated in 1993 using 1990 data. The projections do not reflect the changes in farm policy that resulted from passage of the 1996 Farm Bill. According to the Region G Water Plan, irrigation demand in Bell County is expected to decrease by 49 acre-feet over the 50-year planning period, from 745 acre-feet in 2000 to 696 acre-feet in 2050 (*Figure 13*). This represents a decrease of nearly 7 percent.

2.3.6 Mining

Projections for mining water demand are based on projected production of mineral commodities, and historic rates of water use, moderated by water requirements of technological processes used in mining. Mining use in Bell County is expected to increase 21 percent between 2000 and 2050, from 155 acre-feet to 176 acre-feet (*Figure 13*).

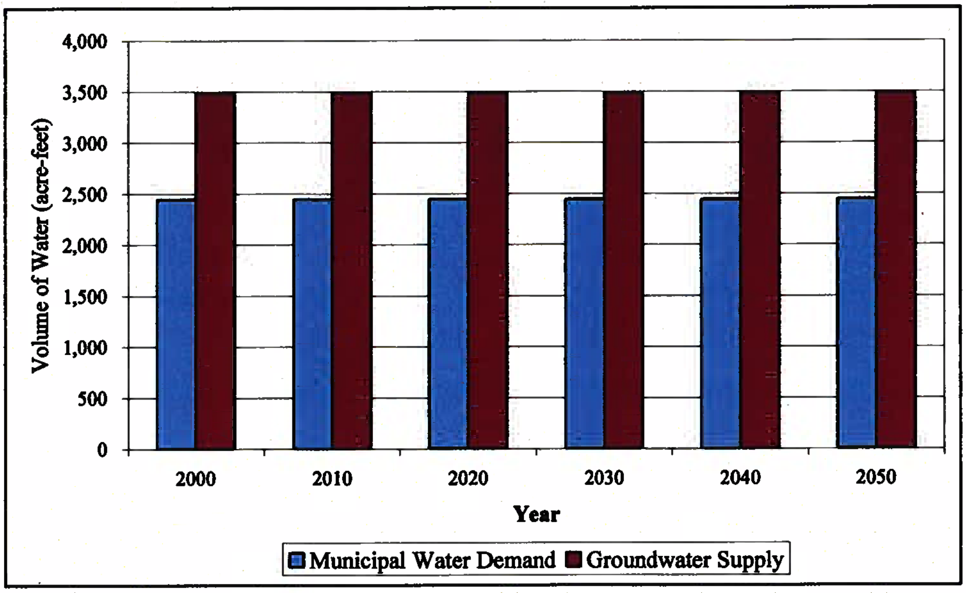
Figure 13: Water Demand by User Group by Decade (both Edwards (BFZ) and Trinity aquifers). Source: Region G Water Plan, 2001.



2.4 Projected Water Supply

A comparison of the total amount of groundwater supplied versus the municipal water demand for Bell County from 2000 to 2050 is provided in *Figure 14* below. Municipal water user groups utilize most of the groundwater, over 70%. The Brazos G Regional Water Plan indicates that this will continue to be the case through 2050.

Figure 14. Municipal Water Demand Versus Groundwater Supply for Bell County by Decade. Source: Region G Water Plan, 2001.



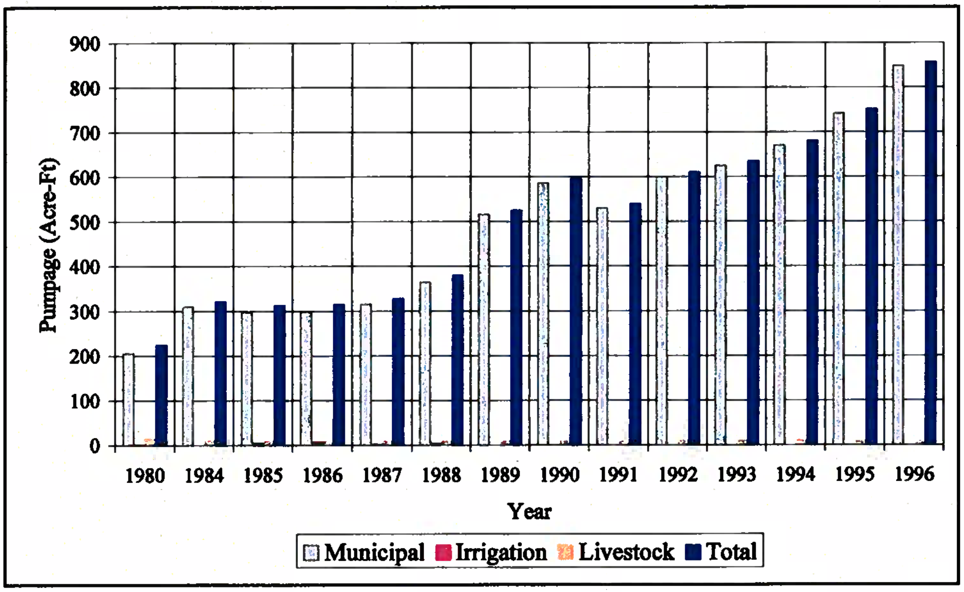
2.4.1 Edwards (BFZ) Aquifer

Table 2 below lists the historic pumping rates of groundwater from the Edwards(BFZ) aquifer from 1980 to 1996 by water user group. As the table indicates, the primary water user group of groundwater has been municipalities. A graphical display of the table is provided in *Figure 15*.

Table 2. Annual Pumpage (Acre-Feet) from Edwards (BFZ) Aquifer

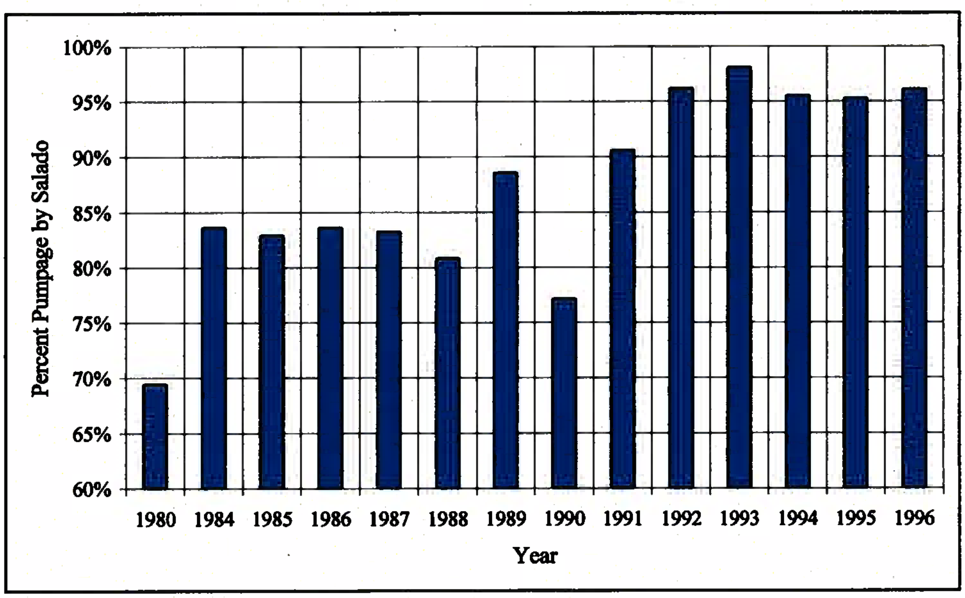
Year	Municipal	Irrigation	Livestock	Total
1980	206	3	16	225
1984	311	0	11	322
1985	298	6	10	314
1986	299	8	9	316
1987	316	3	10	329
1988	365	5	10	380
1989	516	0	10	526
1990	586	0	10	596
1991	530	0	10	540
1992	600	0	11	611
1993	625	0	11	636
1994	670	0	11	681
1995	742	0	10	752
1996	848	0	9	857

Figure 15. Pumpage from Edwards (BFZ) Aquifer from 1980 to 1996.
Source: Texas Water Development Board.



Over the 17-year reporting interval, the total annual pumpage from the Edwards (BFZ) aquifer increased from 225 acre-feet in 1980 to 857 acre-feet in 1996. Most of the pumpage from the aquifer was for municipal use (Figure 9). There was no reported use of Edwards (BFZ) groundwater by the manufacturing, steam-electric, or mining water-user groups. Of the total amount of pumpage by the municipal water-use group, the community of Salado accounted for 69 percent to as much as 96 percent of municipal groundwater use (Figure 10).

Figure 16. Percentage of Groundwater Pumpage Attributable to Community of Salado from 1980 to 1996.
Source: Texas Water Development Board.



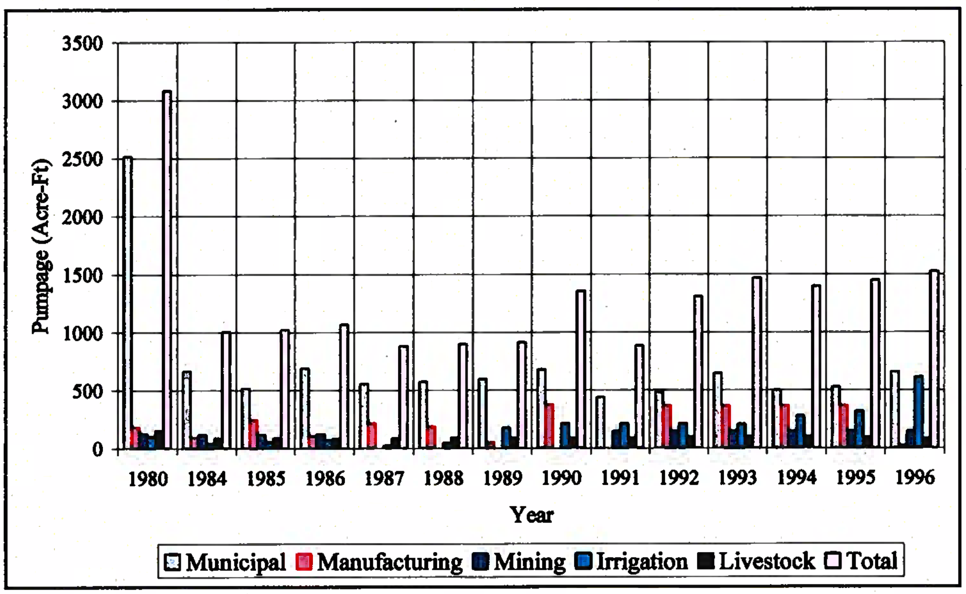
2.4.2 Trinity Aquifer

Table 3 below lists the historic pumping rates of groundwater from the Trinity aquifer from 1980 to 1996 by water user group. *Figure 17* illustrates graphically the data in *Table 3*.

Table 3. Annual Pumpage (Acre-Feet) from Trinity Aquifer

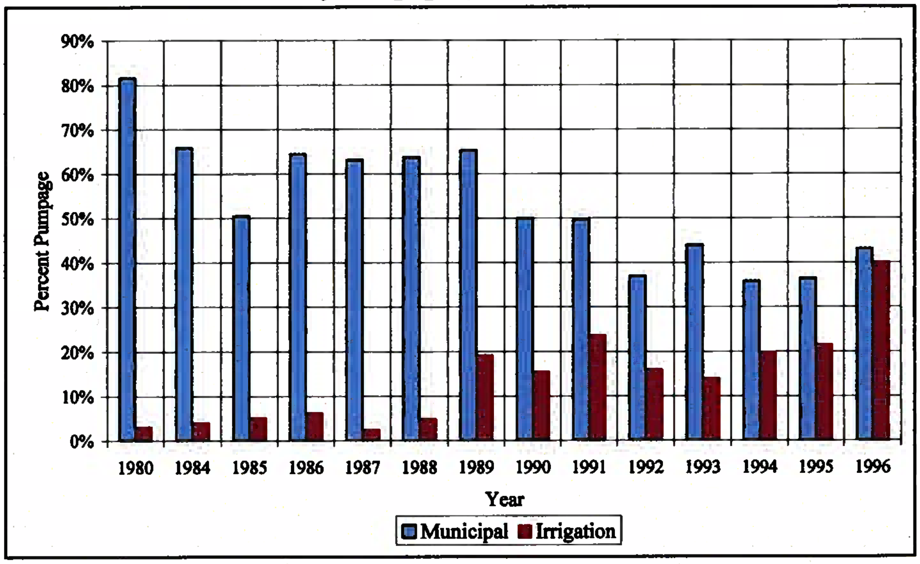
Year	Municipal	Manufacturing	Mining	Irrigation	Livestock	Total
1980	2,516	183	126	100	157	3,082
1984	663	94	117	42	90	1,006
1985	516	245	117	54	88	1,020
1986	689	106	122	68	83	1,068
1987	557	215	0	23	87	882
1988	573	187	0	45	94	899
1989	597	51	0	177	89	914
1990	677	377	0	211	88	1,353
1991	439	0	145	211	90	885
1992	484	368	145	211	101	1,309
1993	646	368	145	207	102	1,468
1994	500	368	145	279	102	1,394
1995	528	368	145	315	92	1,448
1996	657	27	145	612	83	1,524

Figure 17. Pumpage from Trinity Aquifer from 1980 to 1996.
Source: Texas Water Development Board.



Over the 17-year reporting interval, the total annual pumpage from the Trinity aquifer has fluctuated from a maximum of 3,082 acre-feet in 1980 to a low of 882 acre-feet in 1987. During the 1990's, total pumpage was between 885 and 1,550 acre-feet per year. Most of the pumpage from the aquifer has been for municipal use, but irrigation pumpage increased during the 1990's (*Figure 18*).

Figure 18. Percent of Total Trinity Pumpage Attributable to Municipal and Irrigation Uses.



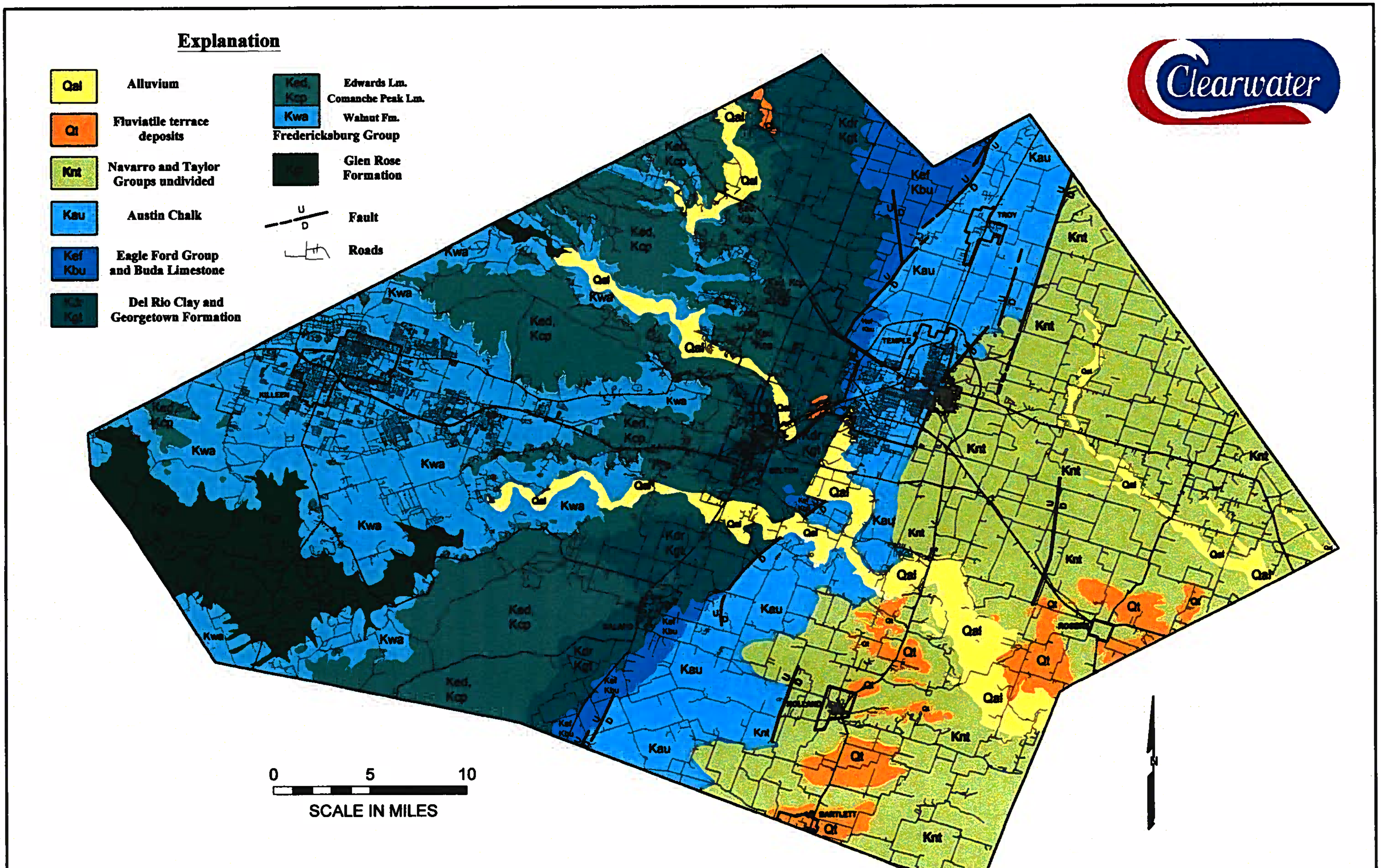
3.0 GENERAL GROUNDWATER RESOURCES

3.1 Regional Geology

An understanding of the geology of Bell County is fundamental to any program intended to manage the groundwater resources of the county. The geology of the county is represented in graphic form by a "geologic map" (*Figure 19*). This color-coded figure shows the areal extent of formations that are exposed at the surface in Bell County, along with major structural features such as faults. The legend in the upper-left corner of the map lists the formations of Bell County, beginning at the top with the youngest (Qal, or Quaternary Alluvium) and ending at the bottom with the oldest (Kgr, or Cretaceous Glen Rose Formation). This list of formations illustrates the sequence in which the formations occur from the surface downward, without stratigraphic displacements caused by faulting.

The Balcones Fault Zone runs along a north-northeastward path through the central area of Bell County. The faulting, which occurred approximately 10 million years ago, and subsequent erosion displaced the formations of Bell County in a downward stair-step fashion toward the east-southeast. As a result of the faulting, older rocks, that is, rocks that are at the bottom of the stratigraphic column, are exposed at the surface in western Bell County. The younger rocks in eastern Bell County were removed by erosion in the structurally higher western and central areas of the county to the topographically lower elevations in the easternmost areas of the county. Rocks that lie within the middle of the stratigraphic column are exposed in a narrow band of outcrops within the central area of the fault zone. The faults are delineated on the map by narrow black lines with "upthrown" and "downthrown" sides listed, respectively, by the letters "u" and "d".

There are two important stratigraphic groups within the boundaries of the CUWCD, the Fredericksburg group and the Trinity group. Within the Fredericksburg group are several geologic formations. These geologic formations include the Navarro and Taylor formations, the Austin Chalk formation, the Eagle Ford and Buda Limestone formations, the Georgetown and Del Rio formations, the Edwards Limestone formation, the Comanche Peak Limestone formation, and the Walnut formation. Within the Trinity group are two geologic formations, the Glen Rose formation and the Travis Peak formation. Within the Travis Peak formation are several members of hydrogeologic importance. The members are the Hensell, Cow Creek, Hammett, Sligo, and Hosston. It is within this geologic framework of the Fredericksburg and Trinity groups that the Edwards (BFZ) and Trinity aquifers exist.



Source: Geology adapted from Barnes (1970, 1981) and Adkins (1930).

GEOLOGIC OUTCROPPINGS OF BELL COUNTY, TEXAS

FIGURE 19

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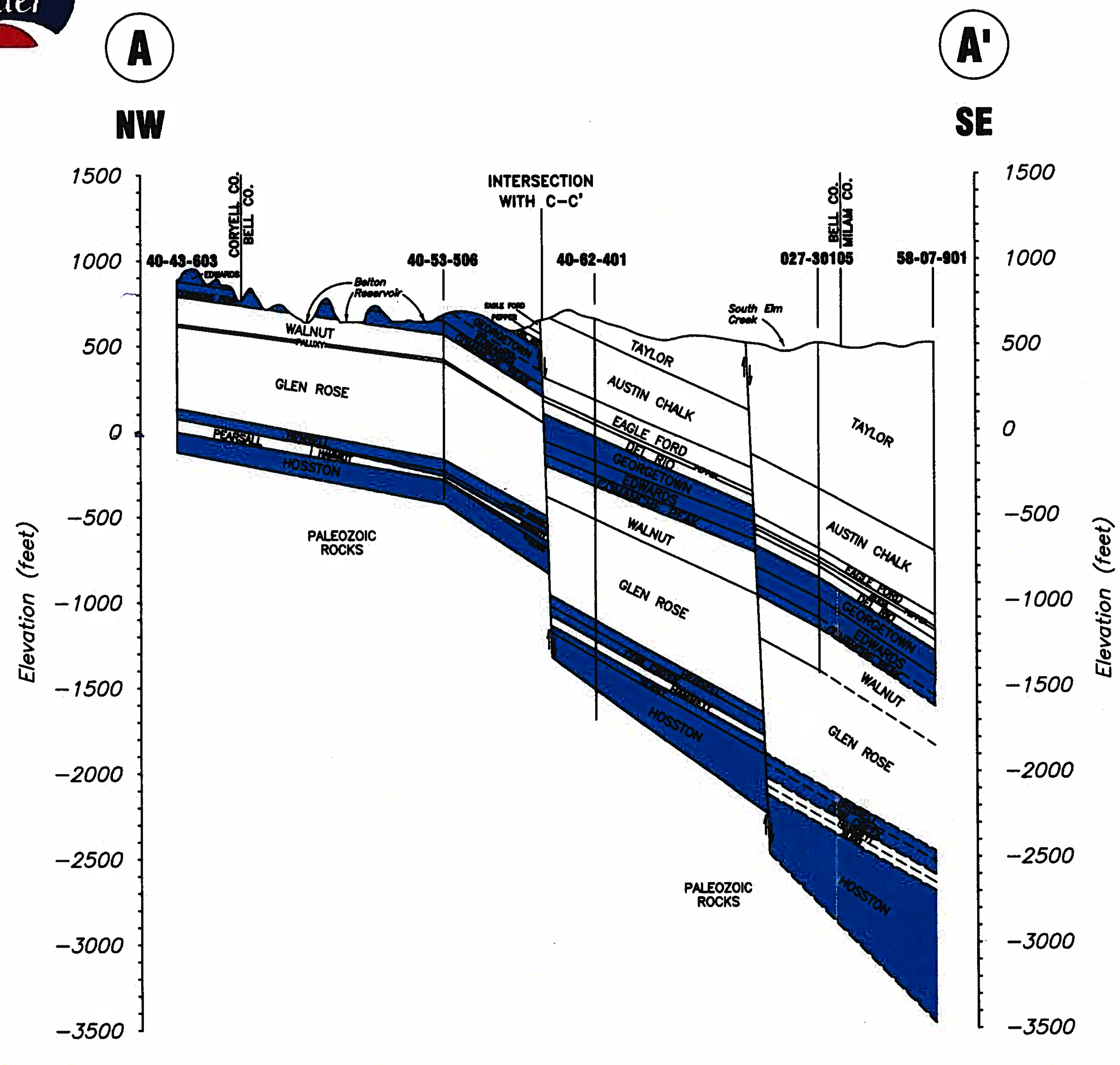
The thickness and transmissivity of each of the geologic formations in the Edwards (BFZ) and Trinity aquifers determine the quantity of water that can be held in storage, released from storage, and allowed to flow through the aquifers. The following is a brief description of each of the formations comprising the Edwards (BFZ) and Trinity aquifers:

- The Austin Chalk formation consists of thin and thick-bedded chalk, marl and limestone that is generally characteristic of low hydraulic conductivities and low transmissivities. The group, which is exposed in the central area of Bell County, ranges in thickness from 360 to 425 feet.
- The Eagle Ford formation consists of alternating layers of calcareous shale bounding a layer of silty limestone. The formation ranges in thickness from 23 to 65 feet and is located in the south central area of Bell County.
- The Buda formation, also located in the south central area of Bell County, consists primarily of limestone and ranges in thickness from 3 to 30 feet.
- The Del Rio Clay formation is composed of calcareous, fossiliferous clay containing pyrite and gypsum. This formation is the uppermost boundary of the Edwards (BFZ) aquifer due to its low permeability. It has a relatively constant thickness of 65 feet within the central area of Bell County.
- The Georgetown formation is composed of fossiliferous limestone imbedded with marls. This formation represents the uppermost strata of the Edwards (BFZ) aquifer and ranges in thickness from 65 to 110 feet in the central area of Bell County.
- The Edwards Limestone formation consists of thin-bedded limestone and dolomite forming a honeycomb texture which accounts for the porosity of the formation. The formation is the lowermost strata of the Edwards (BFZ) aquifer and has a thickness of approximately 100 feet in the CUWCD. It is located west of Belton and Salado in Bell County.
- The Comanche Peak formation consists of limestone and marl and represents the lowest strata of the Edwards (BFZ) aquifer within the CUWCD. The formation ranges in thickness from 40 to 70 feet and is located west of Belton and Salado in Bell County.
- The Walnut formation is composed of limestone and marl and crops out near the western corner of Bell County along its boundary with Coryell County. The formation ranges in thickness from 30 to 50 feet. The Walnut formation represents the lowermost confining strata of the Edwards (BFZ) aquifer.
- The Glen Rose formation is the uppermost stratigraphic formation of the Trinity group. The formation consists of alternating beds of hard to soft fossiliferous limestone, porous dolomite and marl. The thickness is approximately 500 feet within the CUWCD. This formation as well as those discussed above have outcroppings in Bell County.
- The Travis Peak formation consists of a number of water bearing stratigraphic members and consists of a conglomerate of clay, silt, sand, sandstone, dolomitic limestone and shale. This formation contains the water-bearing geologic members of the Trinity aquifer in Bell County. Thickness varies from 200 to 500 feet. However, the formation does not outcrop in the CUWCD.

The geology of Bell County is also illustrated by a series of cross-sections (*Figures 20* to *22*), which were constructed from logs of oil and gas wells and water wells drilled in Bell County and surrounding counties. The logs provided a basis for identifying the tops of formations within the subsurface. Two "dip" sections and one "strike" section were developed for this report. The dip sections (*Figure 20*, or A-A' and *Figure 21*, or B-B') illustrate structural and stratigraphic relationships along transects that follow the formations from northwest to southeast. The formations plunge deeper into the subsurface along sections A-A' and B-B'. The strike section (*Figure 22*, or C-C') shows structural and stratigraphic relationships along a line of section that is orthogonal to the two dip sections.

The dip sections clearly show the eastward stair-step displacement of formations attributable to faulting. For example, the Walnut formation, which is exposed at the surface along the northwestern end of A-A', is



STRATIGRAPHY

NAVARRO AND TAYLOR GROUPS
- Taylor marl undivided

AUSTIN GROUP
- Austin chalk

EAGLE FORD GROUP
- Eagle Ford shale

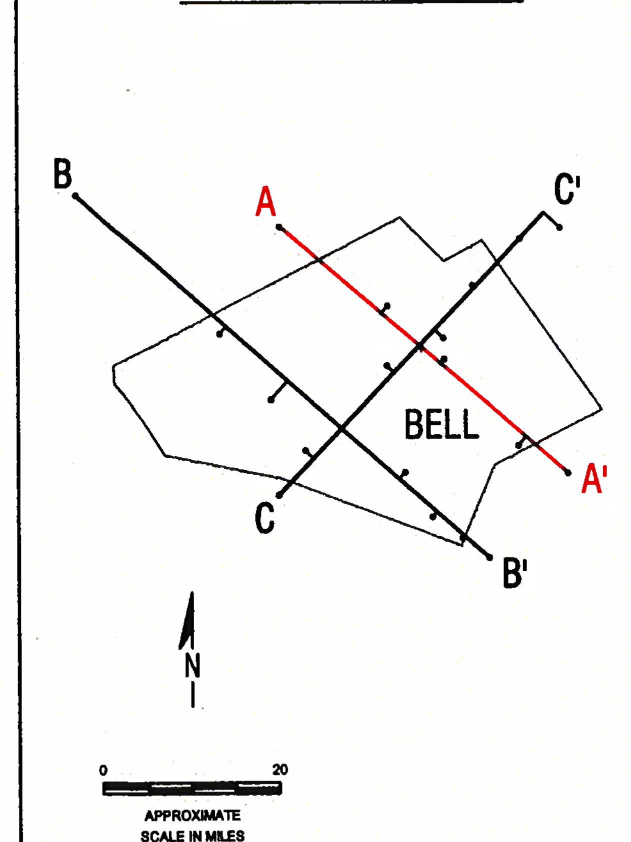
WOODBINE GROUP
- Pepper shale

WASHITA GROUP
- Buda limestone
- Del Rio clay
- Georgetown limestone

FREDERICKSBURG GROUP
- Edwards limestone
- Comanche Peak limestone
- Walnut marl/limestone

TRINITY GROUP
- Paluxy sand
- Glen Rose limestone
- Travis Peak Formation
  - Hensell sand
  - Cow Creek limestone
  - Hammett shale
  - Sligo limestone
  - Hosston sand

CROSS SECTION LOCATION MAP

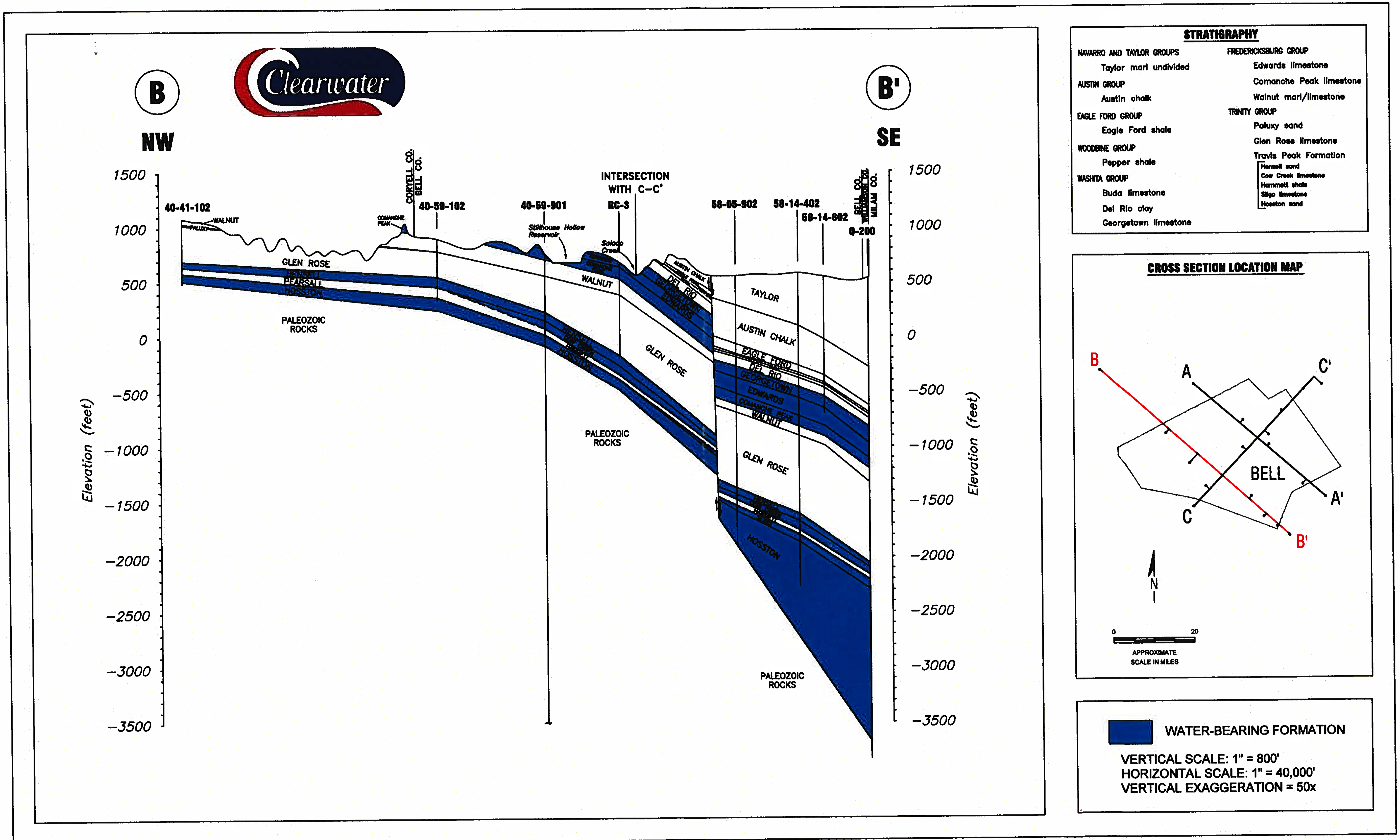


WATER-BEARING FORMATION

VERTICAL SCALE: 1" = 800'
HORIZONTAL SCALE: 1" = 40,000'
VERTICAL EXAGGERATION = 50x

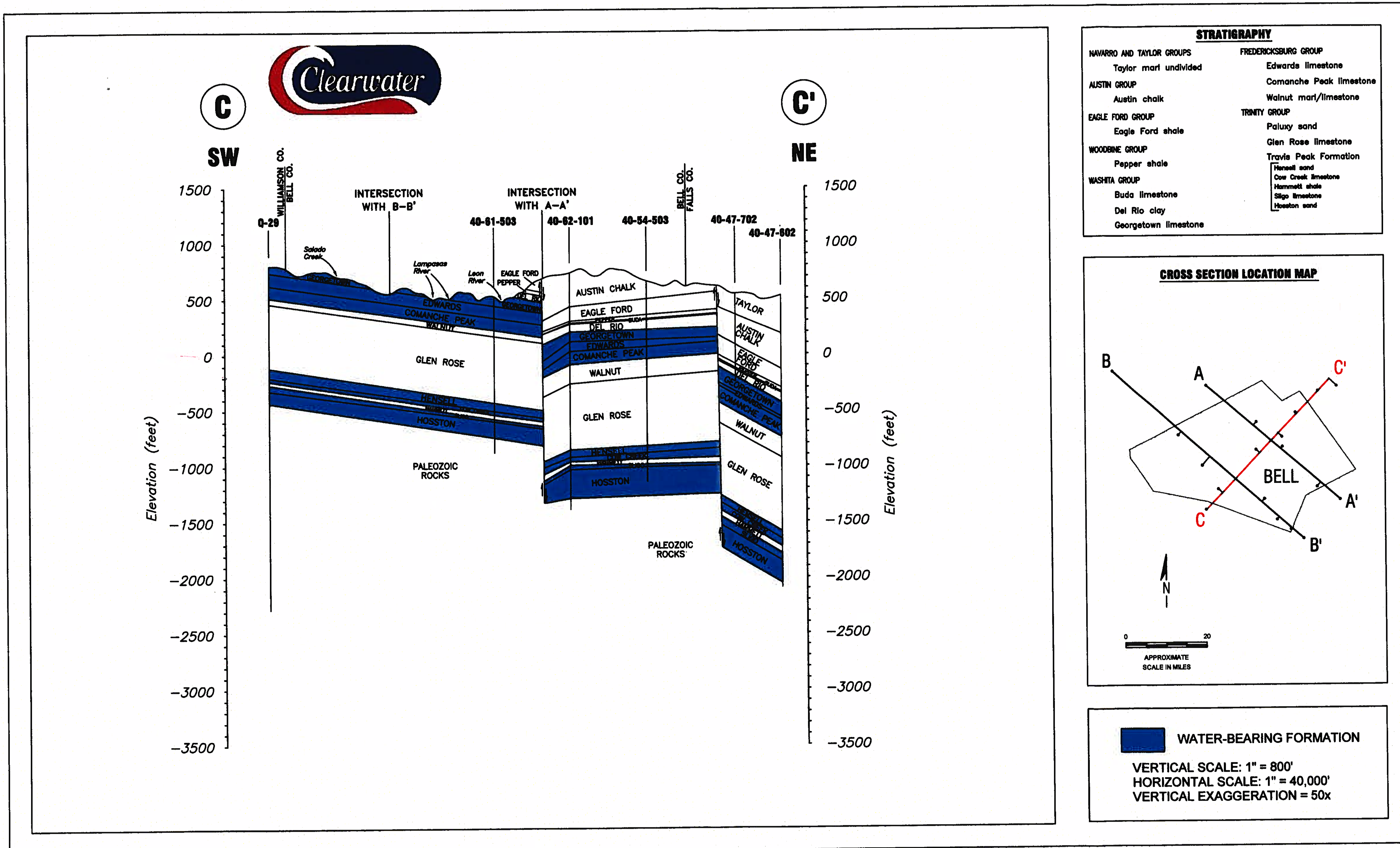
CROSS SECTION A-A'
BELL COUNTY, TEXAS

FIGURE 20



CROSS SECTION B-B'
BELL COUNTY, TEXAS

FIGURE 21



CROSS SECTION C-C'
BELL COUNTY, TEXAS

FIGURE 22

downthrown more than 700 feet into the subsurface at the location of well 40-62-401, located approximately in the middle of the cross-section. Further to the southeast, the Walnut is again displaced several hundred feet downward by another fault. Along the strike section, the formations do not plunge into the subsurface as sharply as along the two dip sections. Nevertheless, a general stair-step pattern can be seen along the northwest-oriented section C-C'. The Walnut formation, which occurs at about 500 feet above MSL along the southwestern end of the cross-section, is displaced 1,000 feet downward by two major faults, so that in Milam County, the formation is at least 500 feet below MSL.

3.2 Regional Hydrogeology

There are two significant aquifers within the boundaries of the CUWCD, the Edwards (BFZ) and Trinity aquifers. The major water-bearing formations of the Edwards (BFZ) aquifer are the Georgetown and Edwards formations. For the Trinity aquifer, the major water-bearing formations are the Hensell, Cow Creek, Sligo, and Hosston. The Cow Creek is hydrogeologically integrated with the Hensell, and the Sligo is integrated with the Hosston. For the purposes of this report, the references to the Hensell aquifer include the Cow Creek member and references to the Hosston aquifer include the Sligo member. Only the Hensell and the Hosston aquifers (subsets of the Trinity aquifer) are referenced in later discussions of this report.

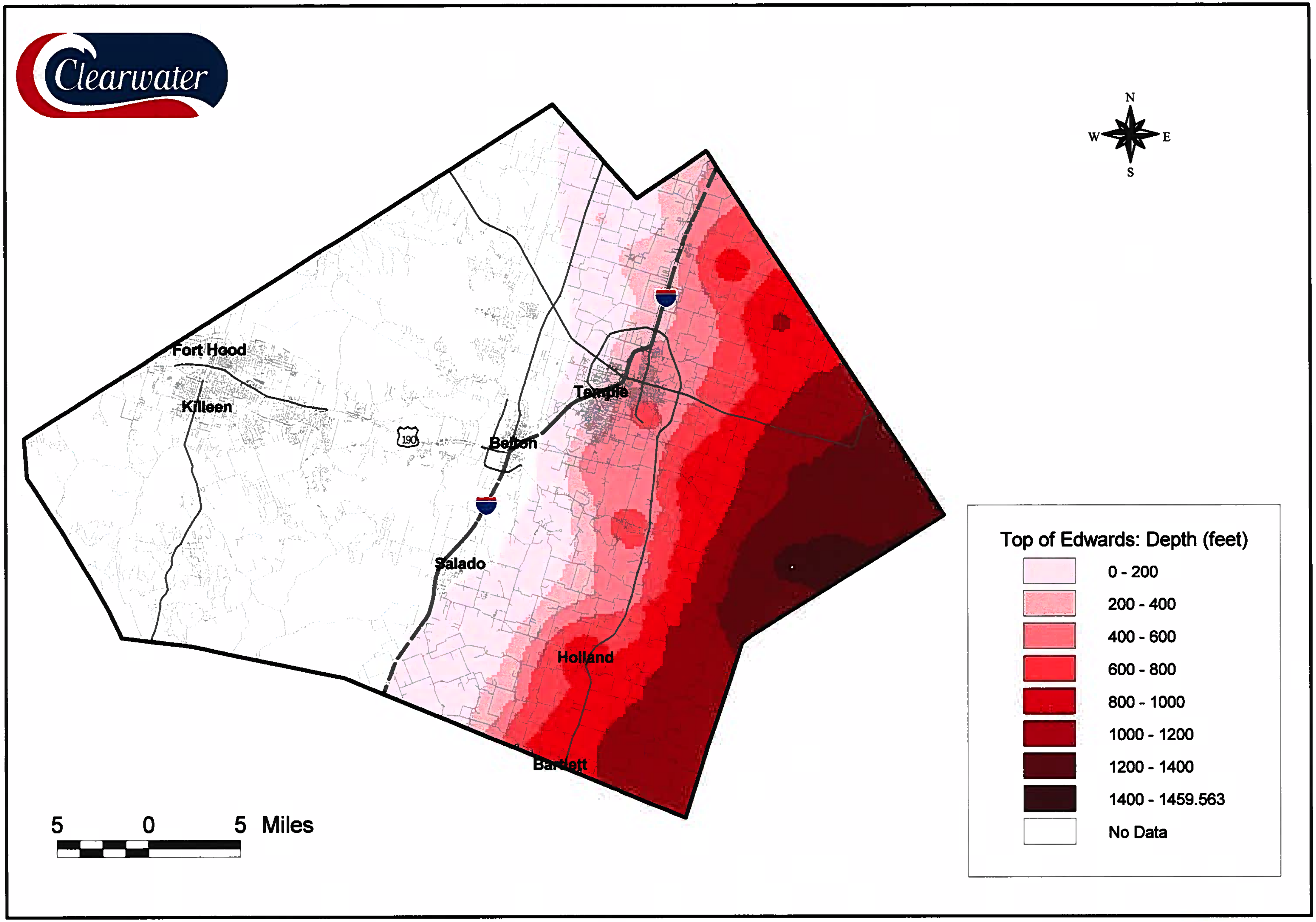
The Edwards and equivalent formations are exposed at the surface in central Bell County, but occur at depths greater than 1,400 feet in eastern Bell County (*Figures 20, 21,* and *23*). The base of the aquifer ranges from 250 feet or less in the outcrop areas to 1,600 and 1,800 feet in the easternmost sections of the county (*Figure 24*). The Edwards and equivalent formations are divided into unconfined and confined sections (*Figure 25*). The unconfined sections are exposed at the surface along a narrow band of northwest-trending outcrops in central Bell County. The confined sections of the Edwards and equivalent formations occur in the subsurface in the eastern half of Bell County. The thickness of the unconfined sections is generally less than 200 feet.

In the Trinity group, the depth to the top of the Hensell ranges from less than 500 feet in westernmost Bell County to 2,500 feet or more in eastern Bell County (*Figure 26*). The formation is not exposed anywhere within the county. The thickness of the formation is typically less than 70 feet, the thickest sections occurring in the central and northern sections of Bell County (*Figure 27*).

The depth to the top of the Hosston is approximately 800 to 1,000 feet in western Bell County, and as much as 3,000 feet in the easternmost sections of the county (*Figures 20, 21,* and *28*). The thickness of the formation increases from 250 feet or less in the western half of the county to between 750 feet and 1,000 feet along the eastern boundary of the county (*Figure 29*).

3.2.1 Recharge of the Edwards (BFZ) and Trinity Aquifers

The predecessor of the TWDB (the Texas Department of Water Resources) published Report 238 (Ground-Water Availability in Texas: Estimates and Projections Through 2030) in 1979. Recharge and availability estimates for the Edwards (BFZ) Aquifer were based on measurements of base-flow and spring-flow at Salado Springs and were estimated from groundwater withdrawals in 1956 from the Brazos River basin. The base-flow and spring-flow method assumes that inflow (recharge) is equal to outflow (discharge). For any aquifer, stream base-flow and spring-flow may be used to estimate these quantities. The components of pumpage from the aquifer and water losses, such as evaporation along streams and transpiration by crops and phreatophytes, must be included as outflow. The assumptions may be applied to the aquifer outcrop areas to determine the percentage of mean annual precipitation that becomes recharge. This factor may be projected to nearby aquifer outcrop areas where data are lacking, provided that hydrogeological conditions are sufficiently similar to those in areas where properties are known to warrant the projection. The recharge areas of the Edwards (BFZ) are delineated in *Figure 30*, which shows the outcrop areas of the unconfined sections of the aquifer. *For the Edwards (BFZ) aquifer, annual effective recharge (the amount of water that enters an aquifer and is available for development) is estimated to be 1,315 acre-feet.*



DEPTH TO TOP OF EDWARDS OR EDWARDS EQUIVALENTS

Figure 23

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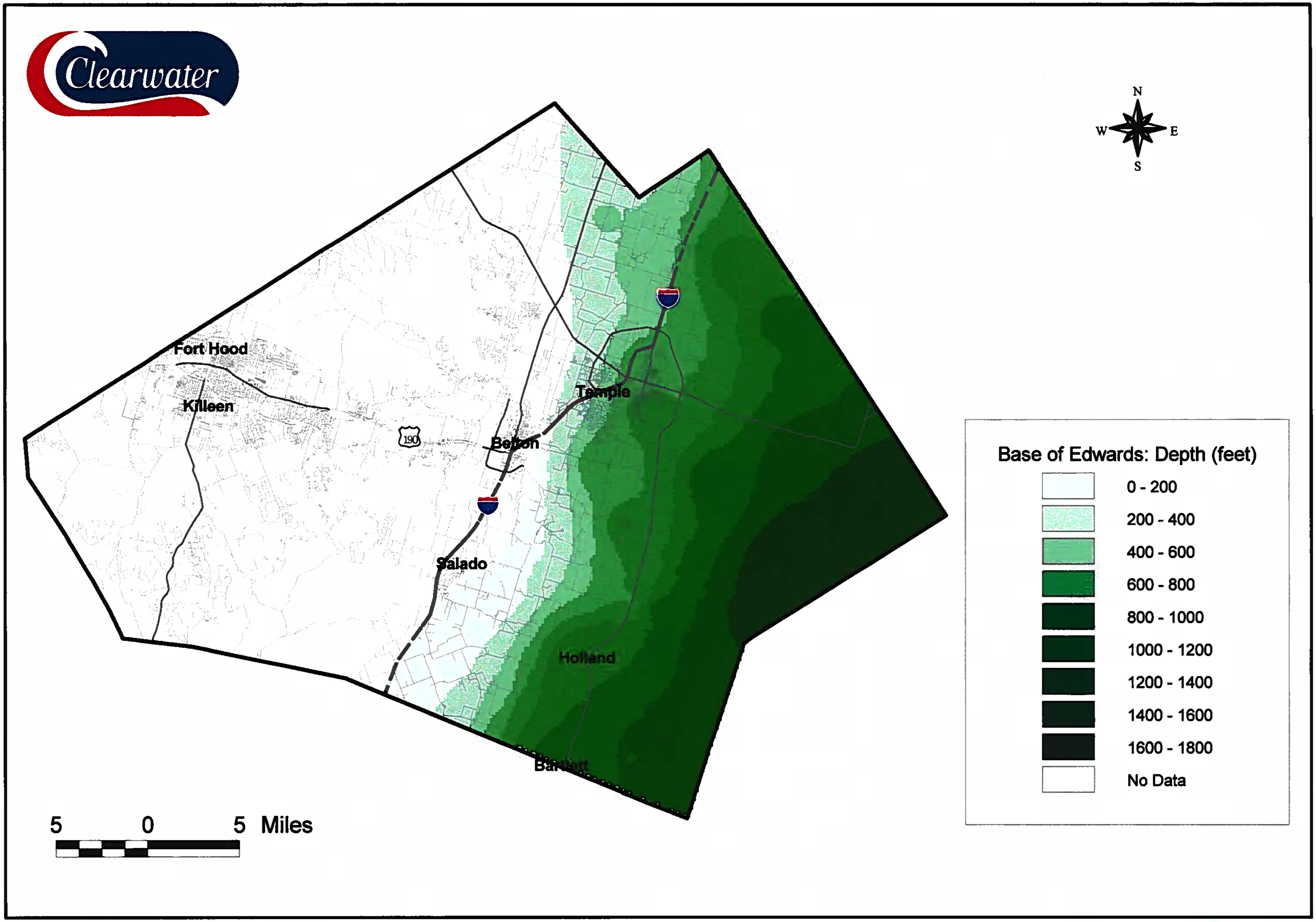
25



DEPTH OF BASE OF EDWARDS OR EDWARDS EQUIVALENTS

Figure 24

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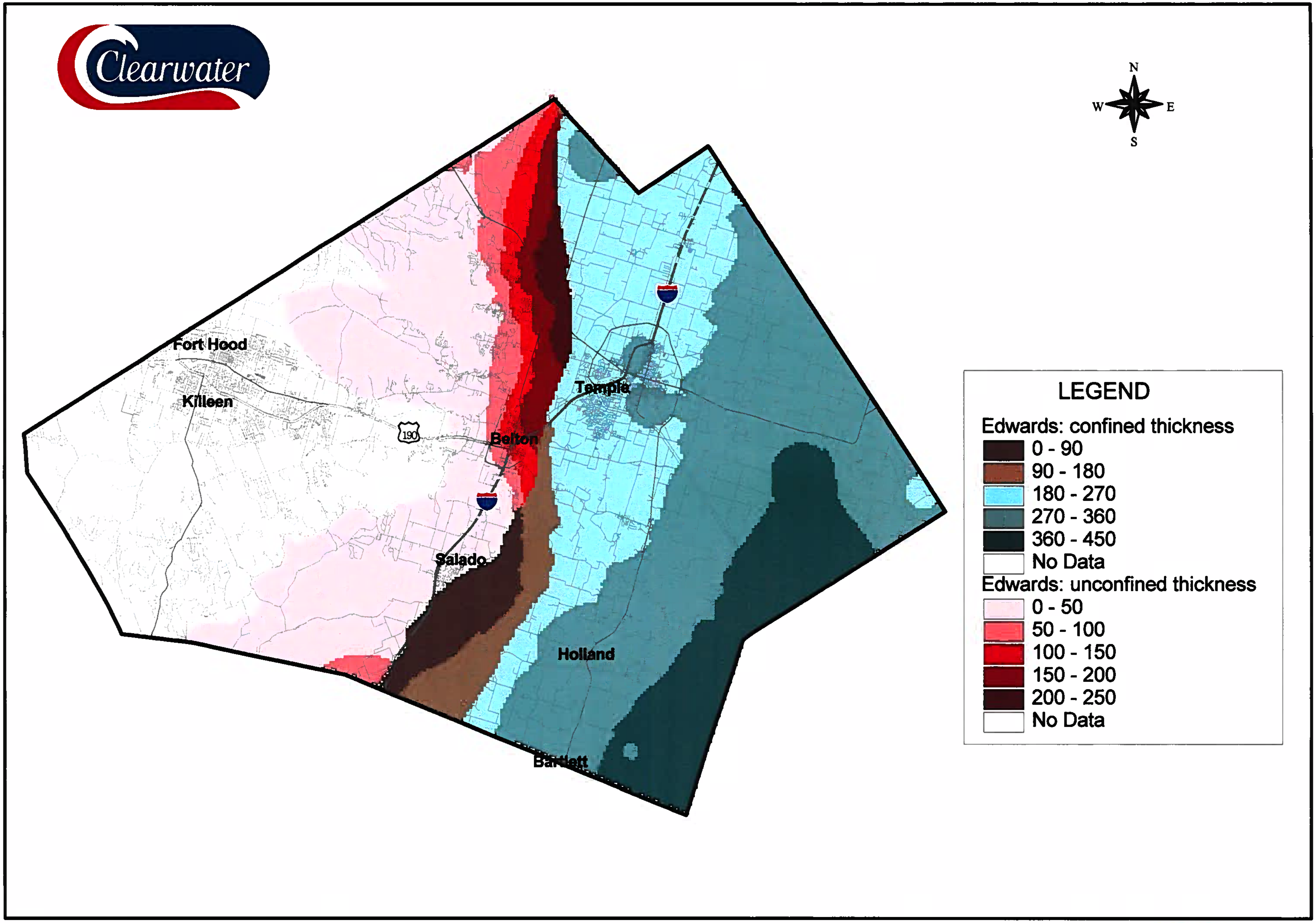

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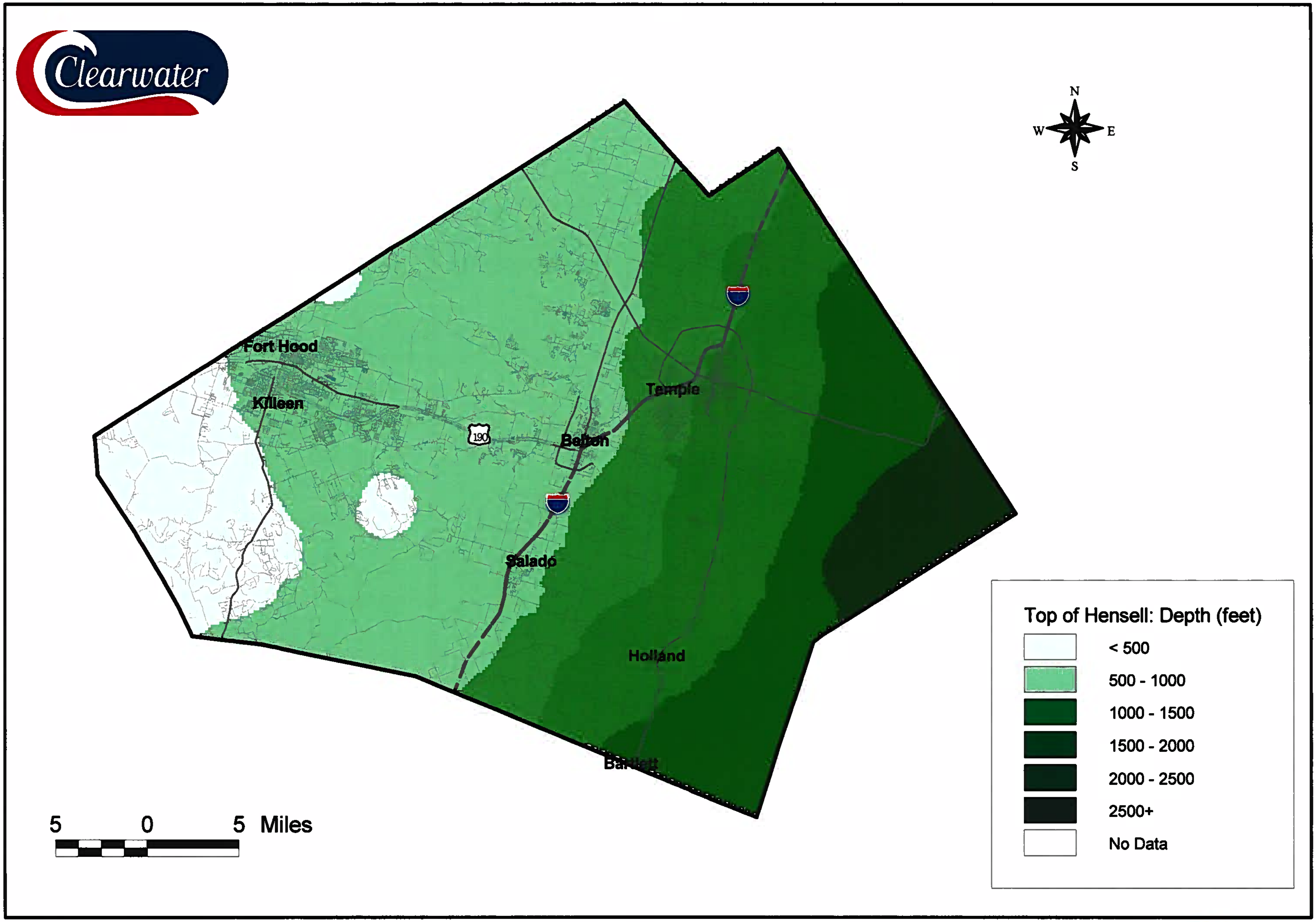
EDWARDS AND EDWARDS EQUIVALENT THICKNESS

Figure 25



DEPTH TO TOP OF HENSELL

Figure 26

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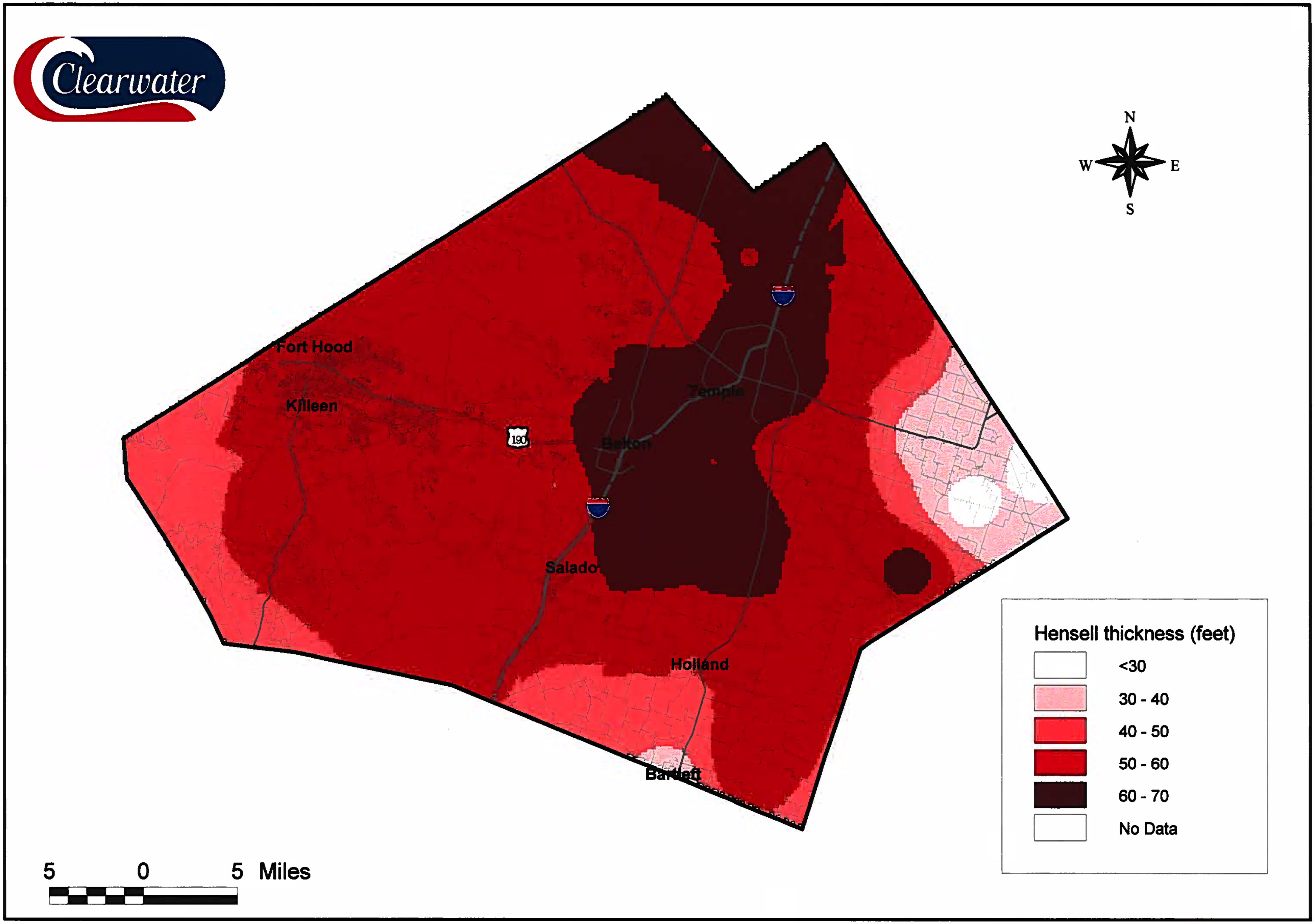

THICKNESS OF HENSELL IN BELL COUNTY

Figure 27

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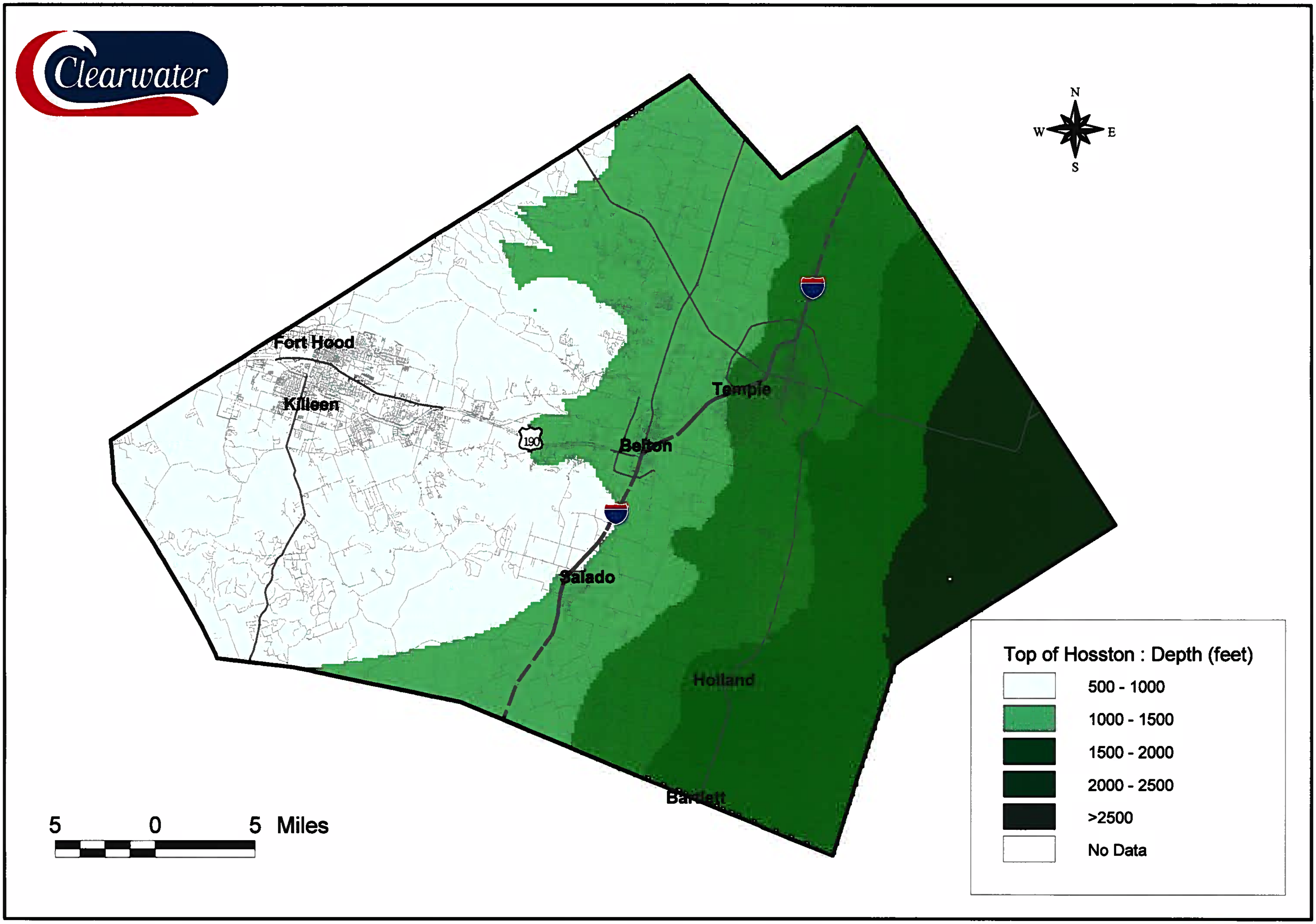

DEPTH TO TOP OF HOSSTON

Figure 28

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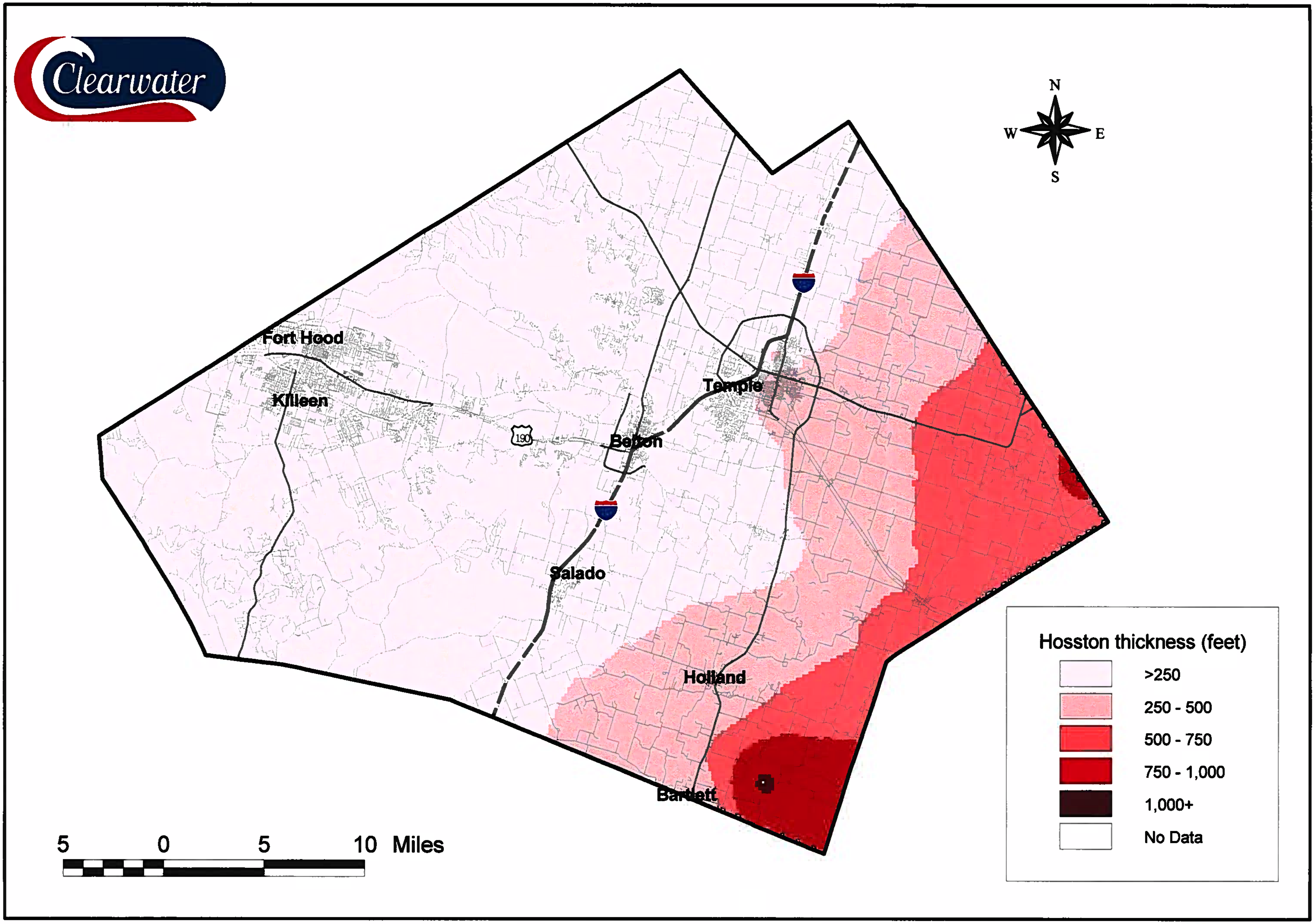

THICKNESS OF HOSSTON IN BELL COUNTY

Figure 29

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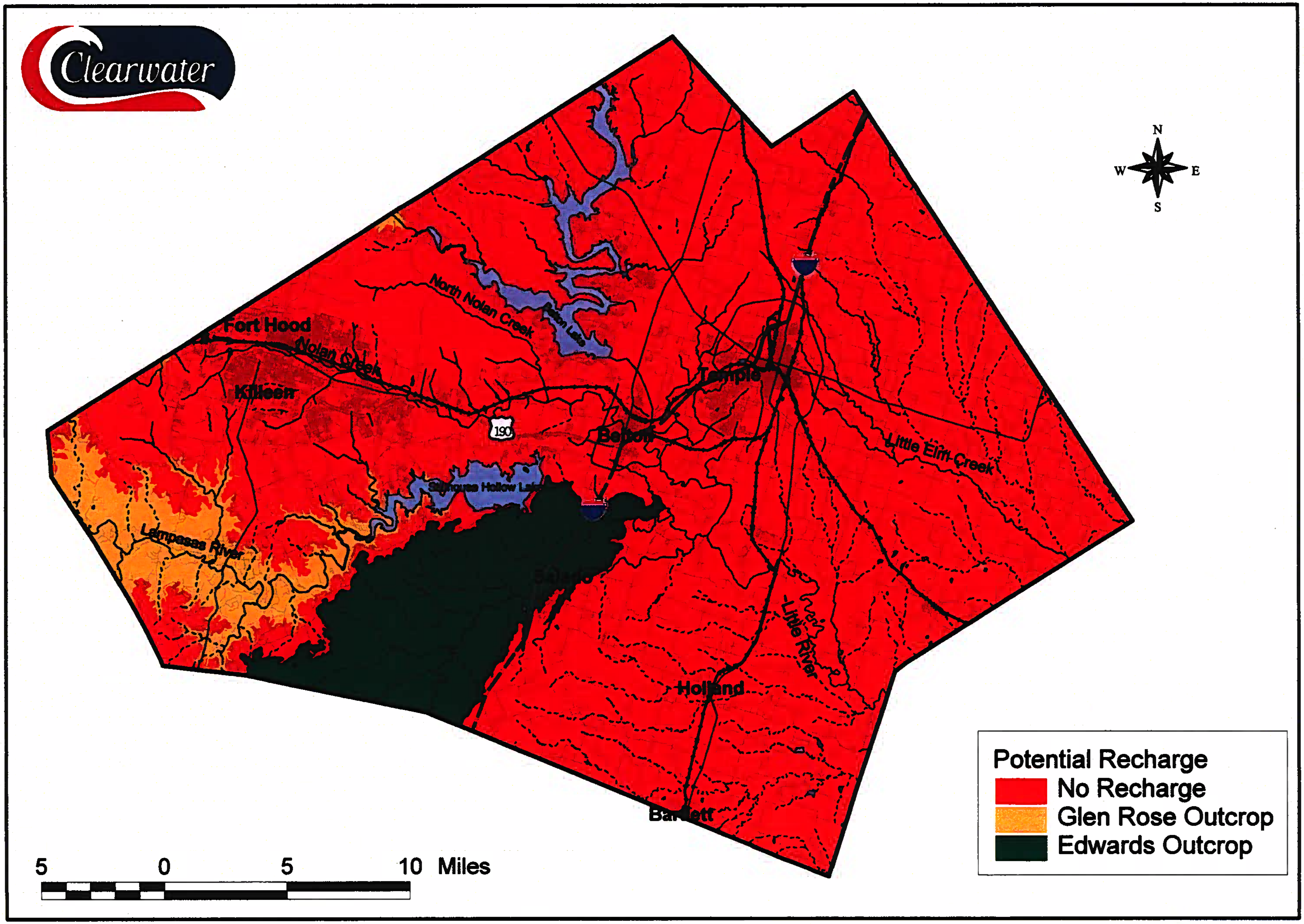

RECHARGE AREAS WITHIN BELL COUNTY

Figure 30

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Based on current research, the only recharge area for the Trinity aquifer within the CUWCD is the Glen Rose outcrop in the western portion of Bell County. However, the Glen Rose outcrop has low permeability and is not conducive to groundwater flow within the current boundaries of the District. Therefore, groundwater enters the Trinity aquifer in Bell County by the following two pathways: 1) seepage of water from overlying formations and 2) lateral subsurface inflow from counties to the west of the CUWCD. The TWDB based estimates of lateral subsurface inflow for the Trinity aquifer on the trough method, a geometric application of Darcy's law. The transmission capacity of the Trinity aquifer was calculated based on the assumption that water levels were lowered 400 feet below the land surface along a line approximately parallel to the hydraulic gradient of the aquifer. Using these limitations and the average values for the transmissivity of the aquifer, the TWDB estimated that 2,645 acre-feet of water entered the Trinity aquifer in Bell County per year as subsurface flow or approximately 1.5 percent of average annual precipitation falling on the outcrop areas of the Trinity aquifer outside Bell County. These calculations were made based on the hydraulic gradient of the aquifer that existed at the time of the study and may not accurately reflect current conditions of the aquifer. The model that predicted the amount of subsurface flow also did not account for losses from the Trinity aquifer due to subsurface flow from the District to surrounding counties down-gradient from Bell County. The assumptions made in the model are that subsurface flow equals the maximum amount of pumpage capable by lowering water levels 400 feet. Therefore, the effects to the groundwater supply of the District due to pumping outside of Bell County are unknown. Future work needs to be done on the Trinity aquifer to determine the effects of pumpage and the quantity, if it exists, of recharge within the District.

3.2.1.1 Augmenting Recharge

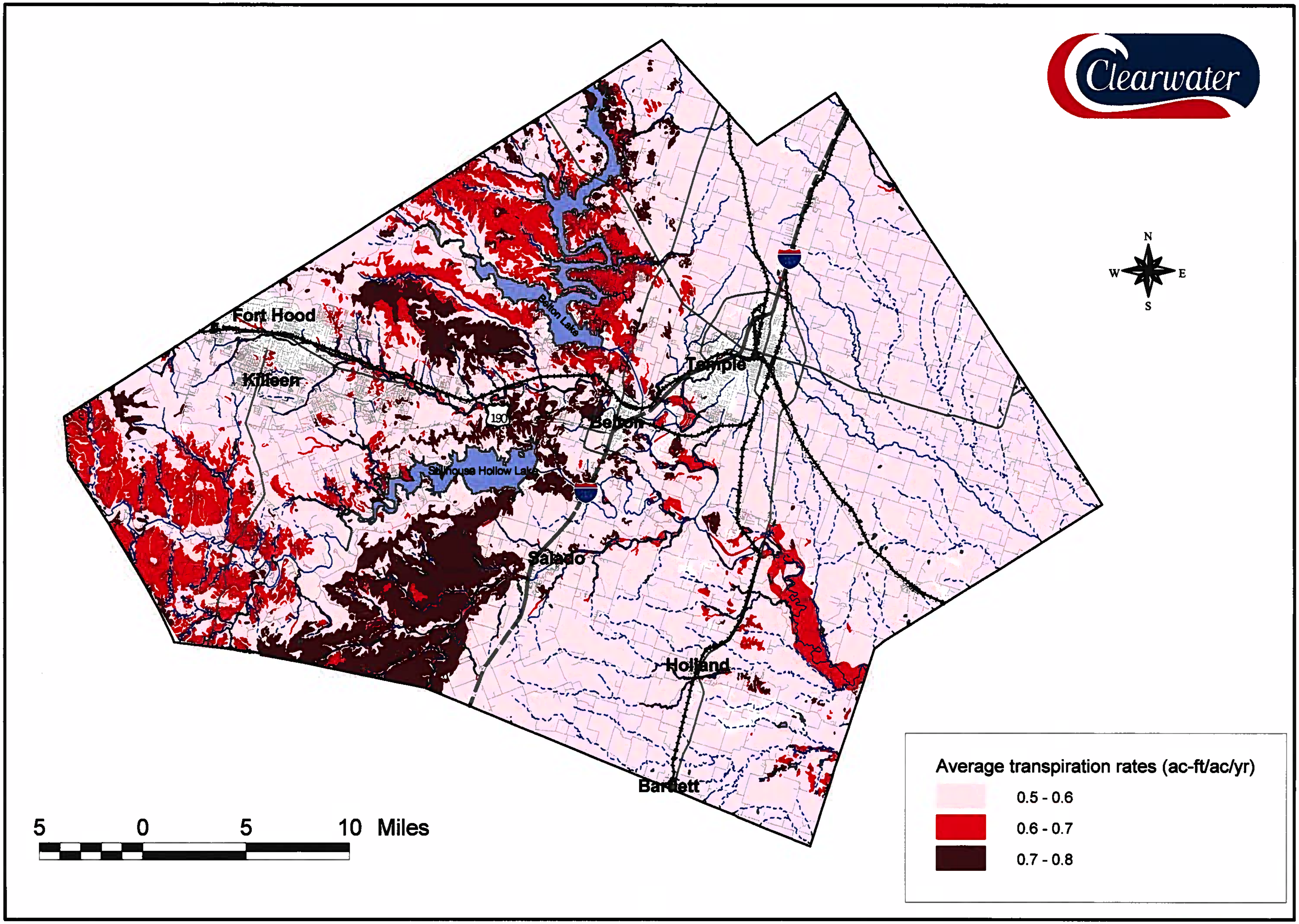
It is possible to augment natural recharge processes by a combination of recharge dams and brush control. The effectiveness of each method depends on the degree to which water that would ordinarily be lost by runoff or evapotranspiration can be retained long enough to percolate to the saturated zone. Both methods are more effective for unconfined aquifers than for confined aquifers. Hence, the Edwards (BFZ) aquifer is likely to benefit more from the construction of dams and the clearing of brush. There is little that can be done to augment recharge significantly for the Trinity aquifer, as the major recharge areas for the aquifer lie to the west of Bell County, well outside of the jurisdiction of the CUWCD.

Estimating the amount of runoff water that can be impounded by dams on streams that traverse the outcrop areas of the Edwards (BFZ) aquifer presupposes the construction of rainfall-runoff models that are beyond the scope of this project. Nonetheless, the construction of dams is an option that warrants further examination. Brush clearing would reduce the amount of water lost by transpiration. An effective brush control program might reduce transpiration losses over the Edwards (BFZ) aquifer recharge zone by as much as 0.01 to 0.05 acre-feet/acre/year. This would increase the potential recharge by 575 acre-feet to as much as 2,800 acre-feet per year.

3.2.2 Groundwater Discharge

Groundwater discharges from an aquifer by one of the following four methods: 1) evapotranspiration, 2) springflow, 3) water wells , or 4) lateral or vertical movement to other formations. Evapotranspiration is a combination of the evaporation of water from the soil and the transpiration of water by plants that capture groundwater in their root zones. The highest evapotranspiration rates in Bell County occur over outcrops of the Edwards formation in the southwestern and western areas of the county (*Figure 31*). In recharge areas, plants with high evapotranspiration potential limit the replenishment of aquifers by capturing soil water before it can percolate to the saturated zone. Estimates of recharge should factor in evapotranspiration losses as a component of a regional water-balance analysis.

Springs occur where the land surface intercepts the water table or perched water zones. Most of the springs of Bell County discharge within exposures of the unconfined zones of the Edwards (BFZ) aquifer (*Figure 32*). The volume of water discharging from Edwards (BFZ) springs ranges from less than 20 gallons per



ESTIMATED EVAPOTRANSPIRATION RATES FOR BELL COUNTY

Figure 31

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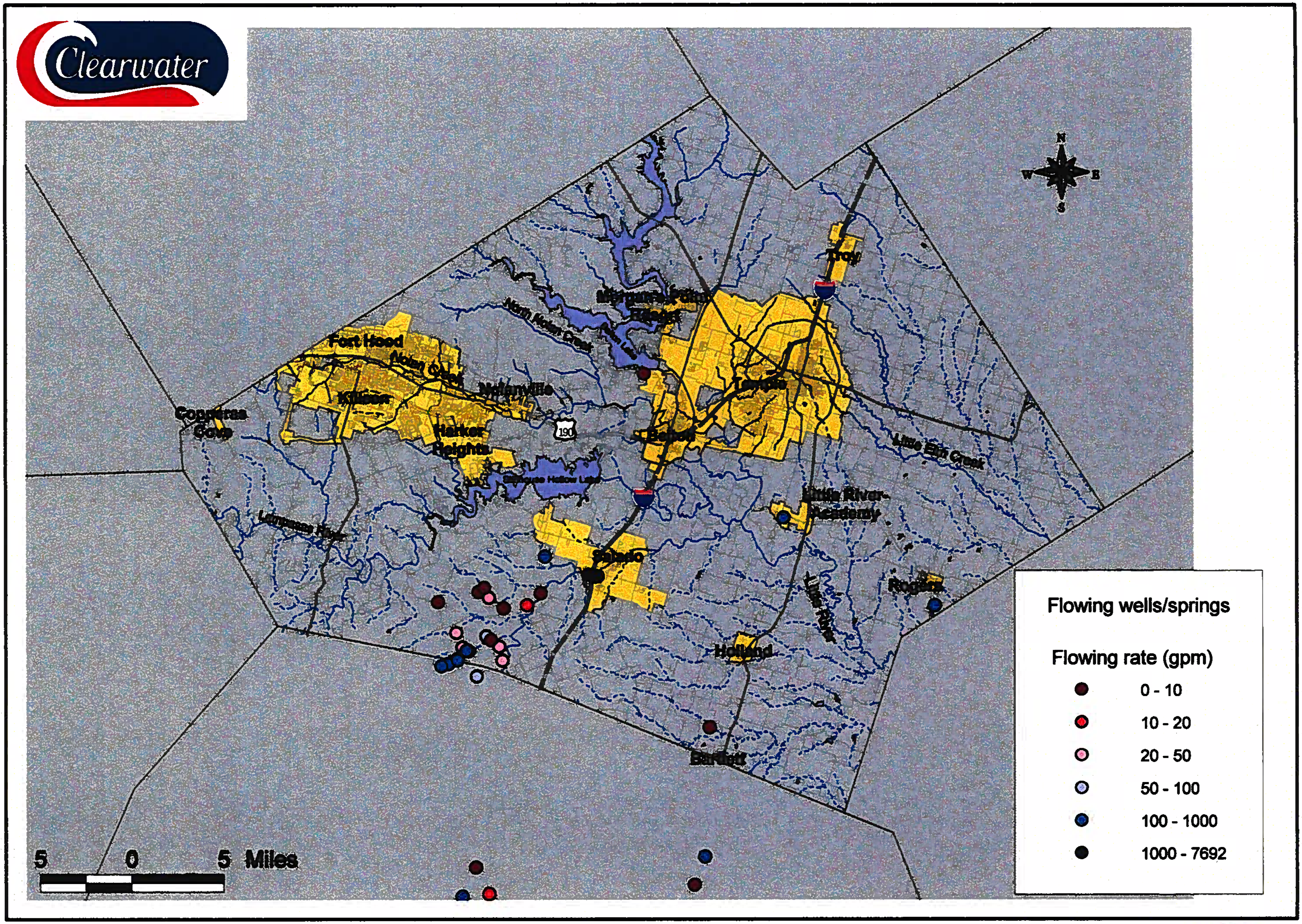

HISTORIC FLOWING WELL/SPRING DISCHARGE RATES

Figure 32

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minute (gpm) in areas south of Salado to more than 1,000 gpm at Salado Springs. Groundwater does not discharge to the surface by springflow from the Trinity aquifer.

Groundwater produced from wells is the most widespread form of discharge from the aquifers of Bell County (*Figure 33*). Within the CUWCD, water is produced from small domestic and livestock wells pumping less than 10 gallons per minute (gpm) to larger capacity wells capable of pumping enough water to supply municipal demands. Wells that produce from the Edwards (BFZ) aquifer are located primarily in the south-central area of Bell County, where the Edwards (BFZ) aquifer is exposed between Salado and the Williamson County line. The trend of Edwards (BFZ) production continues southward into Williamson County, where the Edwards (BFZ) is also a major aquifer. In other areas of Bell County, most other wells produce water primarily from the Trinity aquifer.

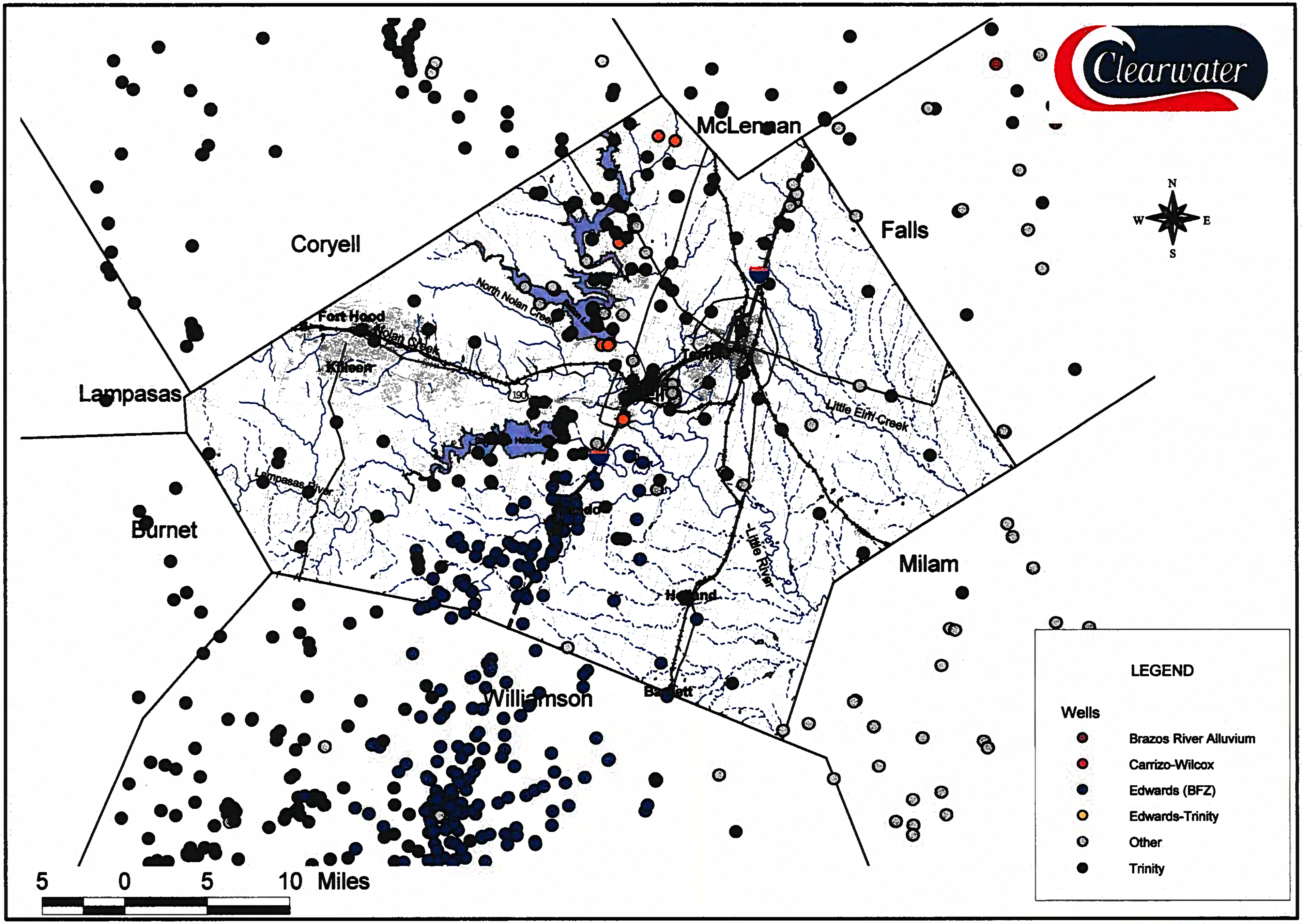
The TWDB and its predecessor agencies have measured groundwater levels in Bell County since the 1940's. The water-level measurements establish a basis for tracing changes in the depth of water over time, especially in areas where heavy pumpage is reported. *Figures 34* through *39* show the locations of wells and associated average water levels of the Edwards (BFZ) aquifer for each decade beginning with the 1940's. *Figure 40* shows the locations of wells and the ranges of water level measurements for the years 1999 to 2000. All water level measurements are reported relative to MSL. *Figures 41* through *45* and *Figures 46* through *50* trace the same series for the Hensell and Hosston formations, beginning with the 1960's.

Figures 34 through *40* indicate that water-level measurements for the Edwards (BFZ) aquifer have been relatively stable over the last 60 years. In areas of the outcrop area, the depths to water for most wells producing from the Edwards (BFZ) aquifer have fluctuated between 600 and 700 feet above MSL in the 1990's. In areas to the east of the outcrop area, water-level measurements range between 500 and 600 feet above MSL. The differences in water-level measurements indicate that water-level elevations decrease toward the east. Hence, the flow of groundwater is also eastward.

Measurement points in the Hensell and Hosston are more widely dispersed than are those of the Edwards (BFZ) aquifer. The pattern for each formation, however, indicates decreasing water levels for both aquifers throughout the last 40 years. Water-level measurements of wells producing from the Hensell show decreases of 200 to 400 feet or more, primarily in northern Bell County and surrounding areas of McLennan and Coryell counties. Hensell water-level measurements in southern Bell County have remained relatively constant. The Hosston has exhibited the largest decrease in water-level measurements of the two water-bearing formations of the Trinity aquifer. Since the 1960's, Hosston water-level measurements have decreased by 200 feet or more in all areas of Bell County.

3.2.3 Storage

Effective management of the Edwards (BFZ) and Trinity aquifers presupposes an understanding of the groundwater storage and availability within each aquifer. The availability of water within an aquifer differs depending upon whether the aquifer is confined or unconfined. A confined aquifer is one that is bounded from above and below by impervious geologic formations. An unconfined aquifer (also known as a phreatic aquifer) is one in which the water table (phreatic surface) serves as its upper boundary and, therefore, is directly recharged from the ground surface above. The availability of water for unconfined aquifers is based on the specific yield of an aquifer, where specific yield is defined as the yield of an aquifer per unit area per unit drop of the depth of the water table. The availability of water for a confined aquifer is based on the storativity of the aquifer. The storativity is the volume of water released from storage per unit area per unit decrease in piezometric head. Piezometric head is the sum of the potential energy resulting from the gravitational force of the aquifer above a datum point and the static pressure force exerted on the aquifer by the confining bed and the water column.



WELLS IN BELL COUNTY AND SURROUNDING COUNTIES

Figure 33

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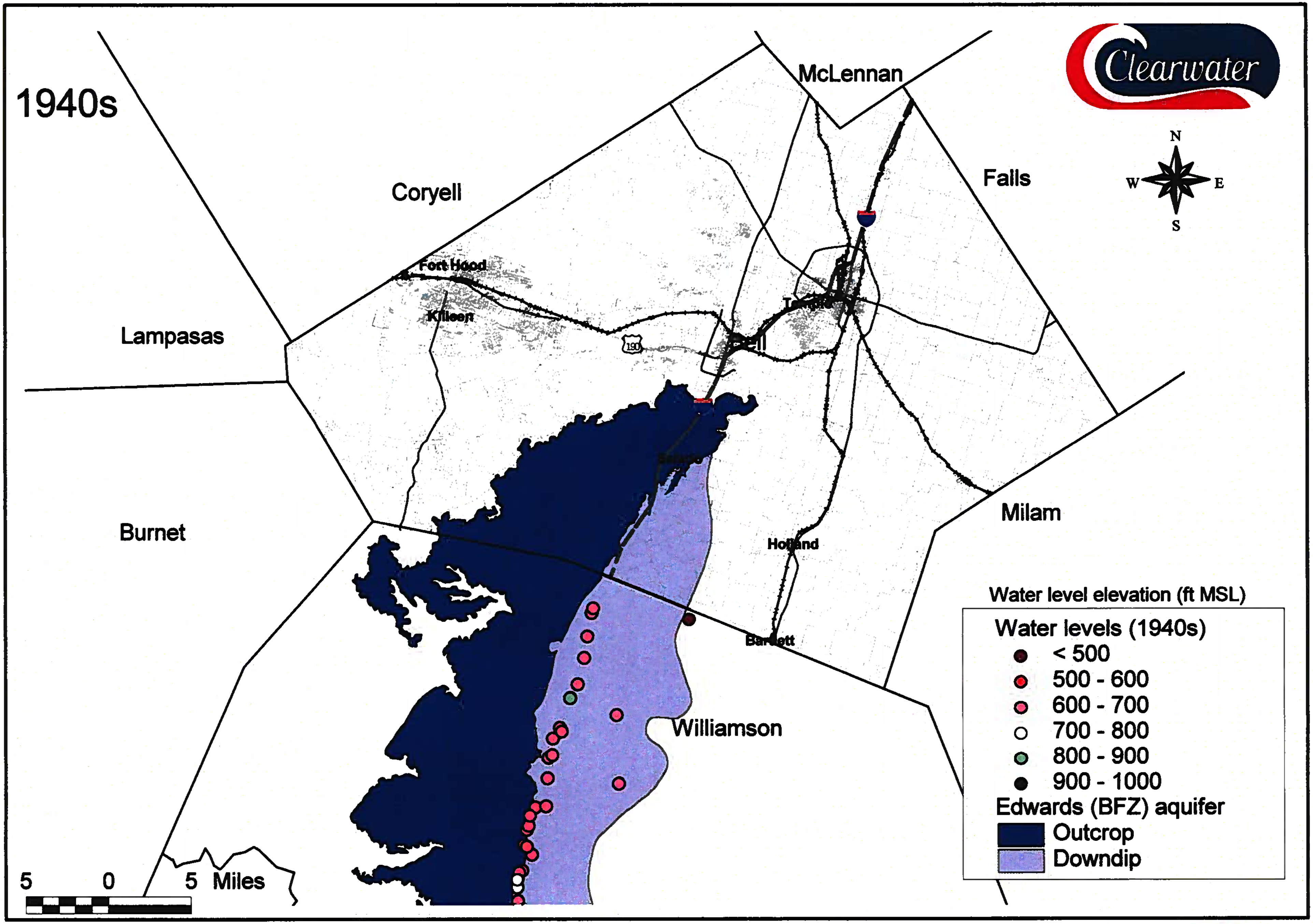

WATER-LEVEL ELEVATIONS IN EDWARDS (BFZ) AQUIFER AND EDWARDS EQUIVALENTS

Figure 34

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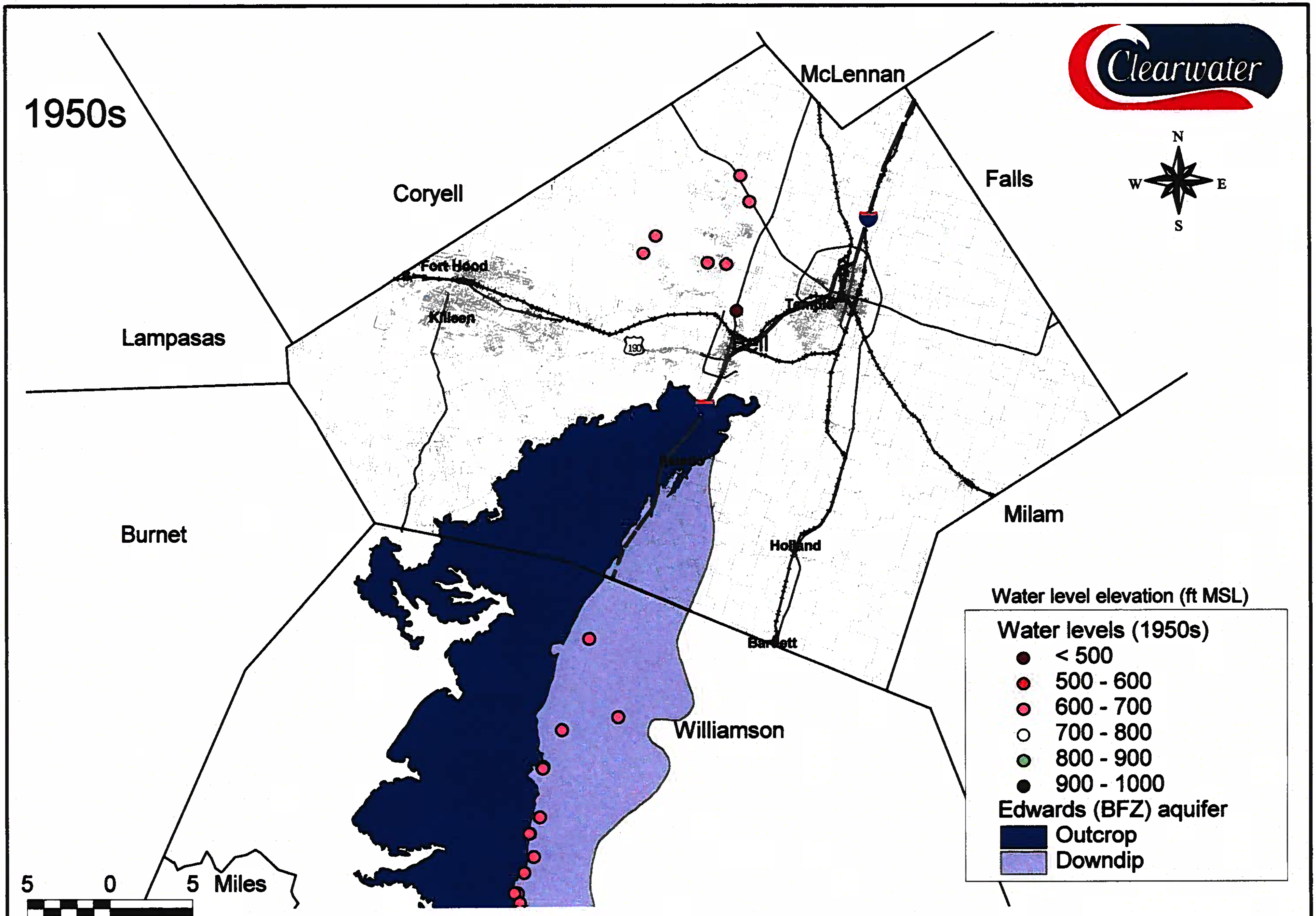

WATER-LEVEL ELEVATIONS IN EDWARDS (BFZ) AQUIFER AND EDWARDS EQUIVALENTS

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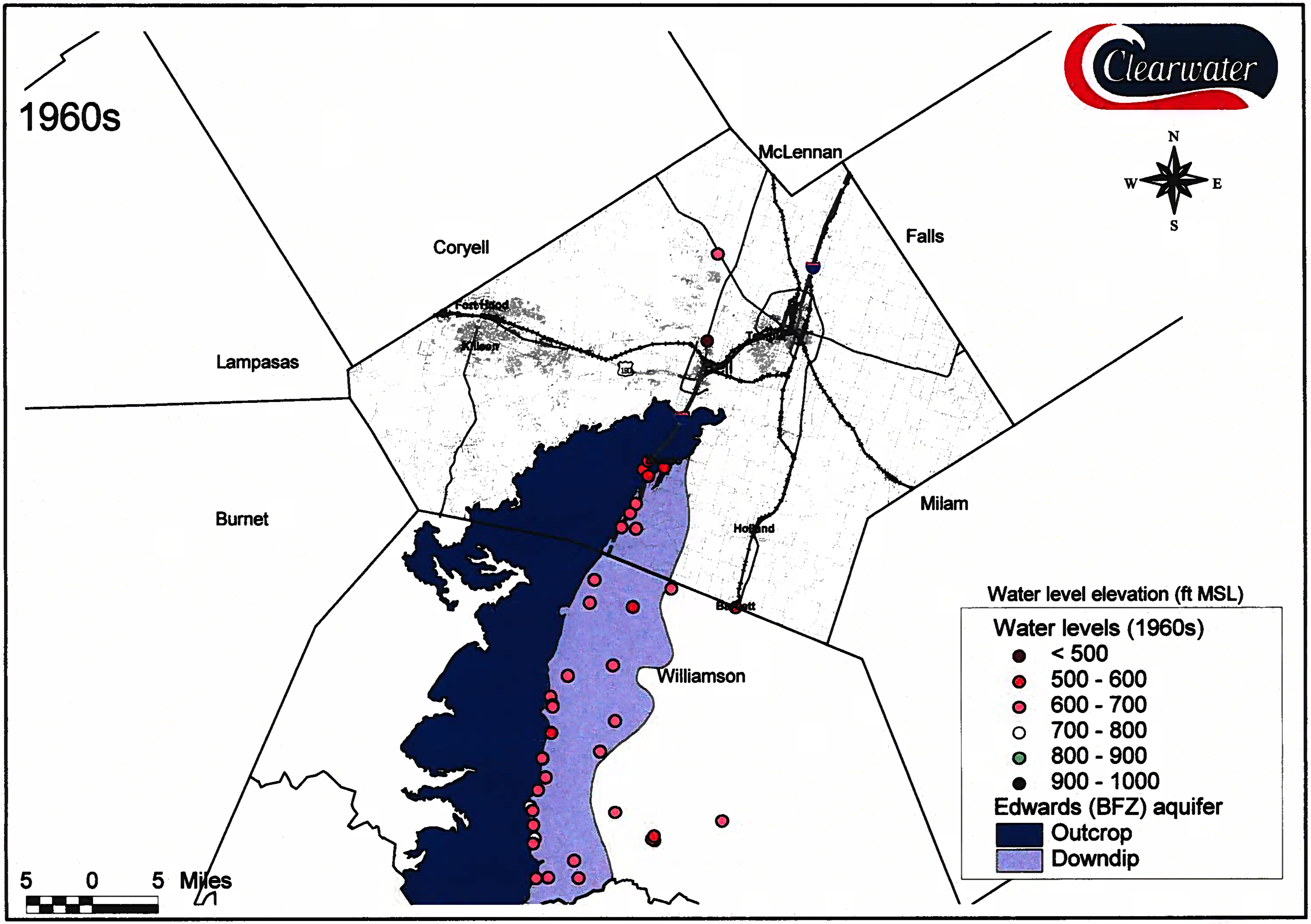
Figure 35



WATER-LEVEL ELEVATIONS IN EDWARDS (BFZ) AQUIFER AND EDWARDS EQUIVALENTS

Figure 36

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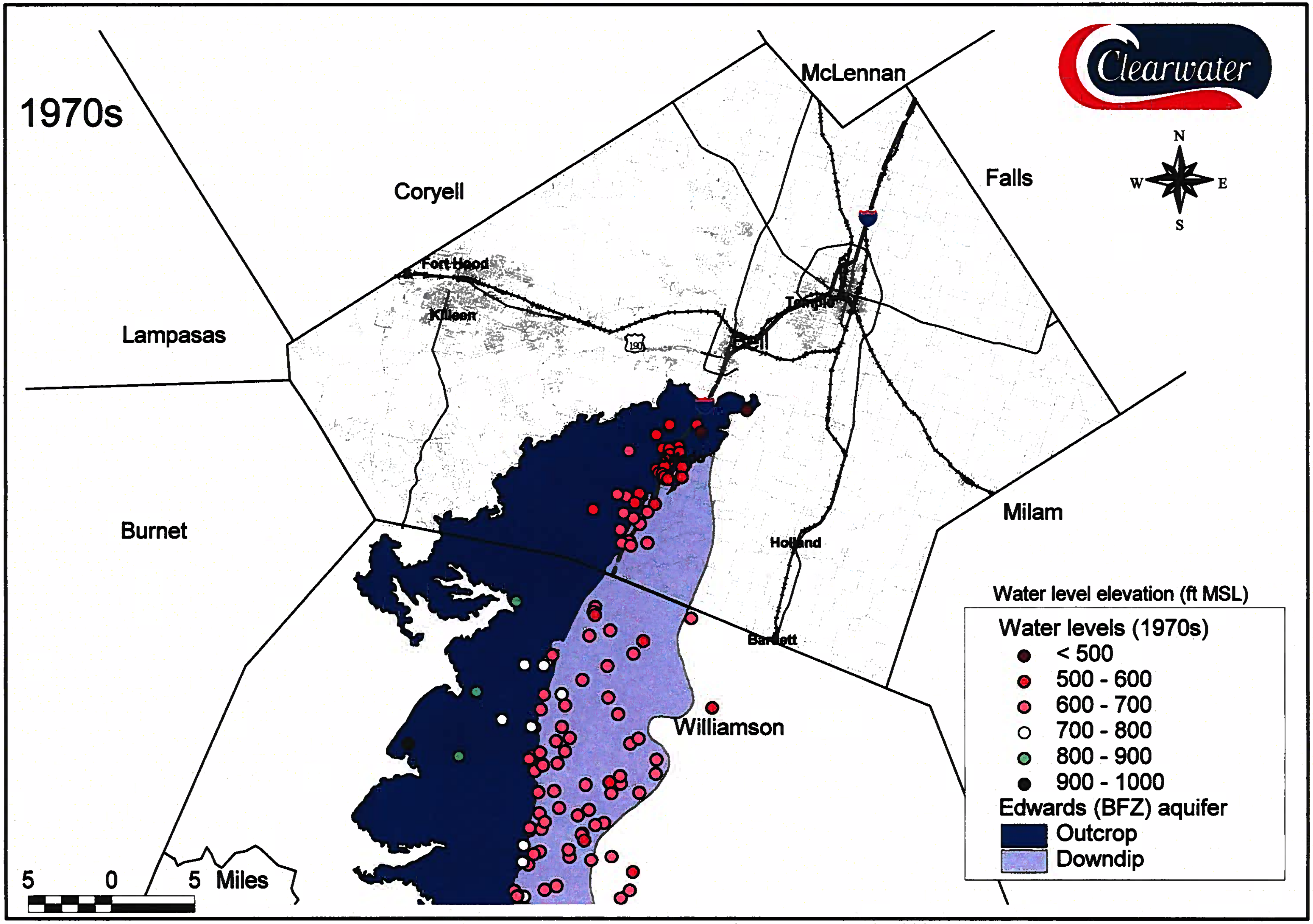
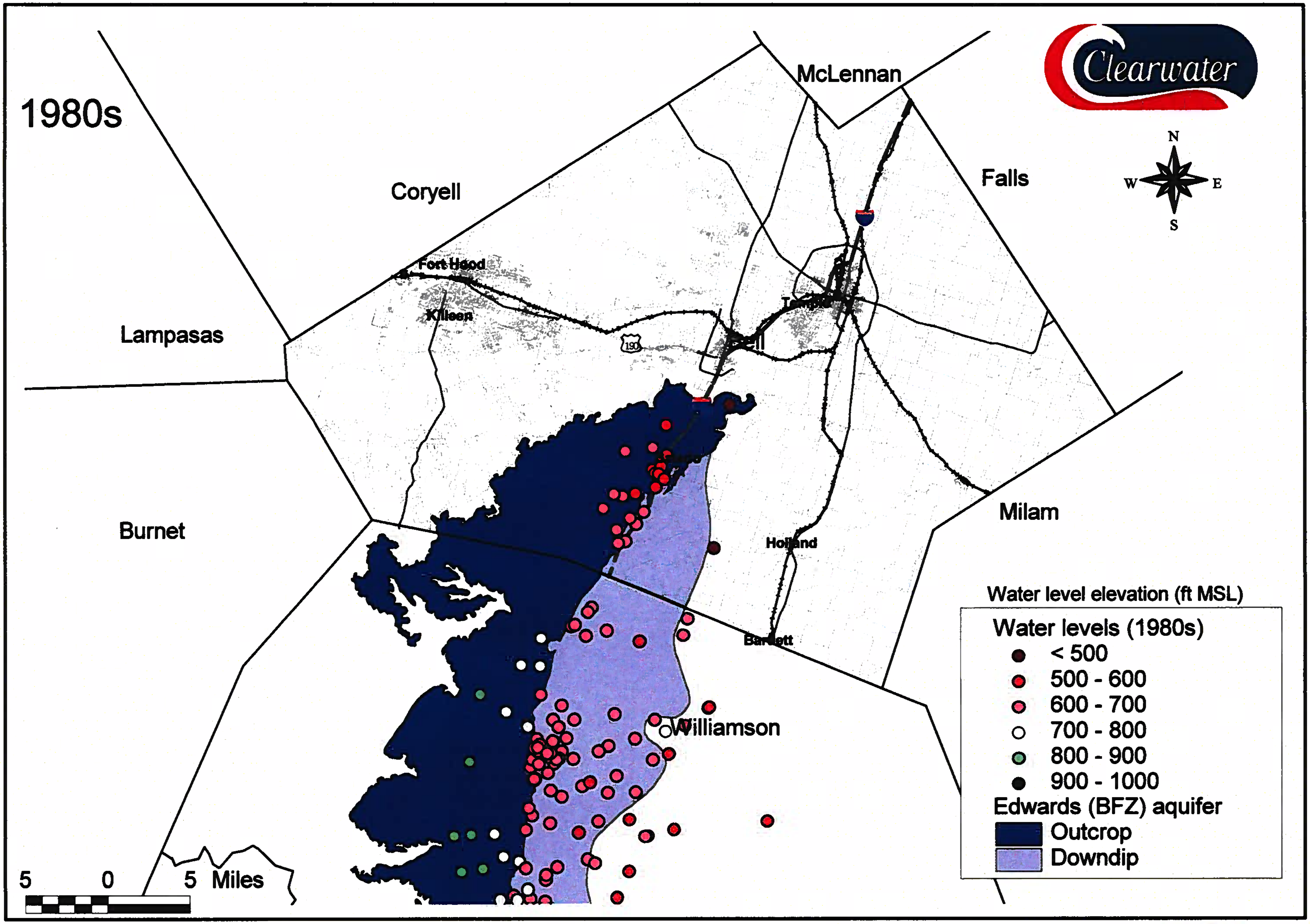


WATER-LEVEL ELEVATIONS IN EDWARDS (BFZ) AQUIFER AND EDWARDS EQUIVALENTS

Figure 37



WATER-LEVEL ELEVATIONS IN EDWARDS (BFZ) AQUIFER AND EDWARDS EQUIVALENTS

Turner Collie & Braden Inc.
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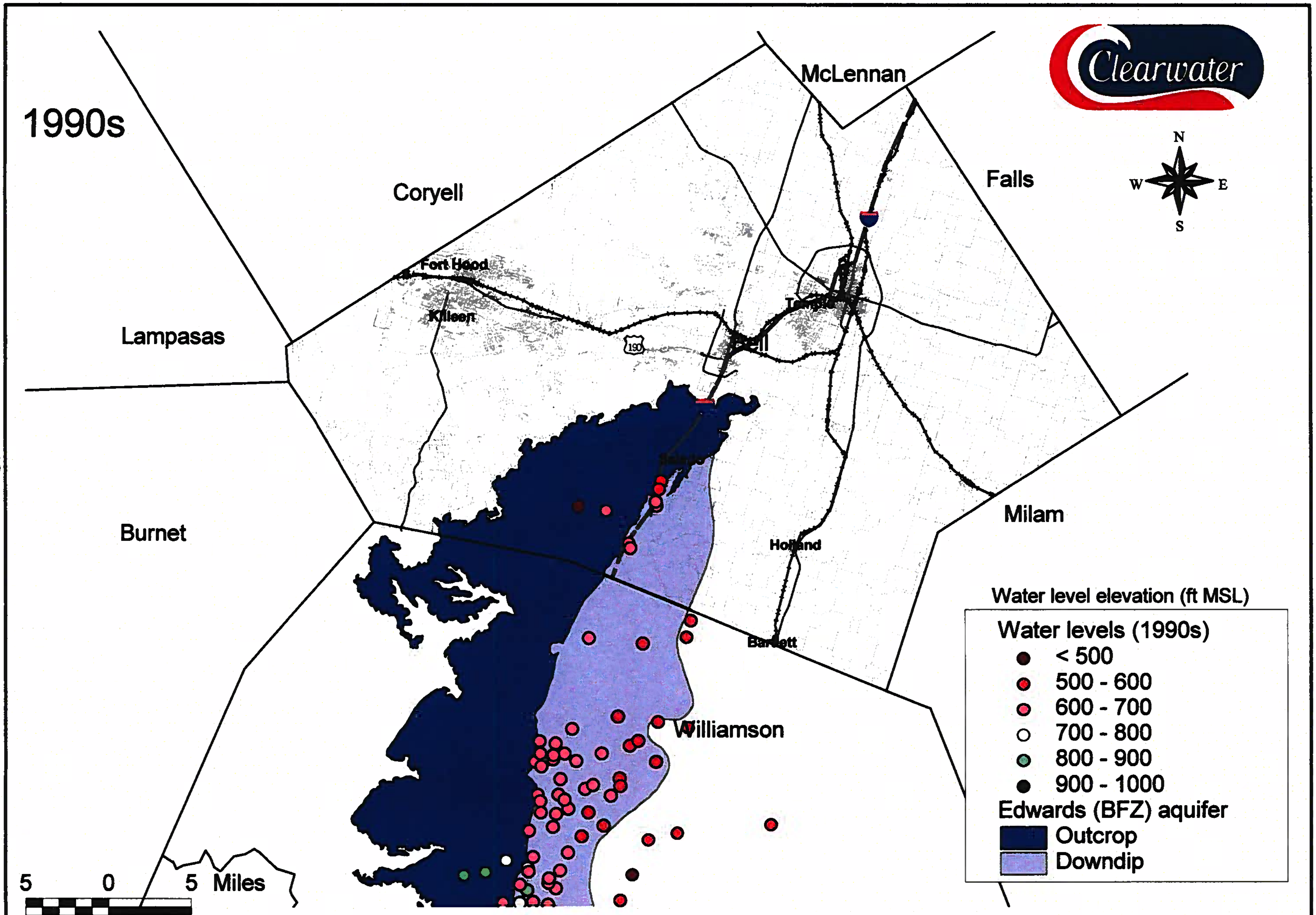
Figure 38



WATER-LEVEL ELEVATIONS IN EDWARDS (BFZ) AQUIFER AND EDWARDS EQUIVALENTS

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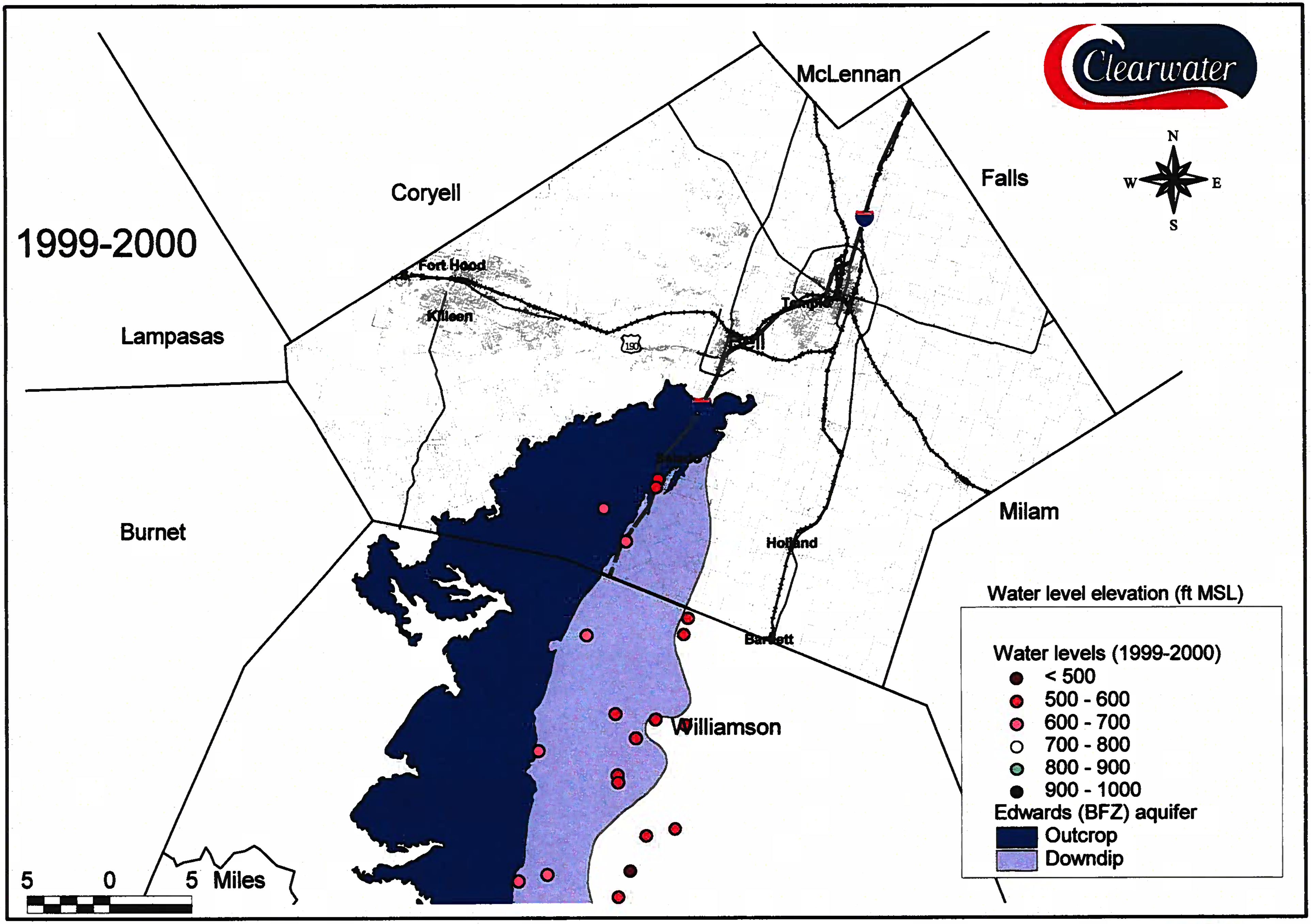
Figure 39



WATER-LEVEL ELEVATIONS IN EDWARDS (BFZ) AQUIFER AND EDWARDS EQUIVALENTS

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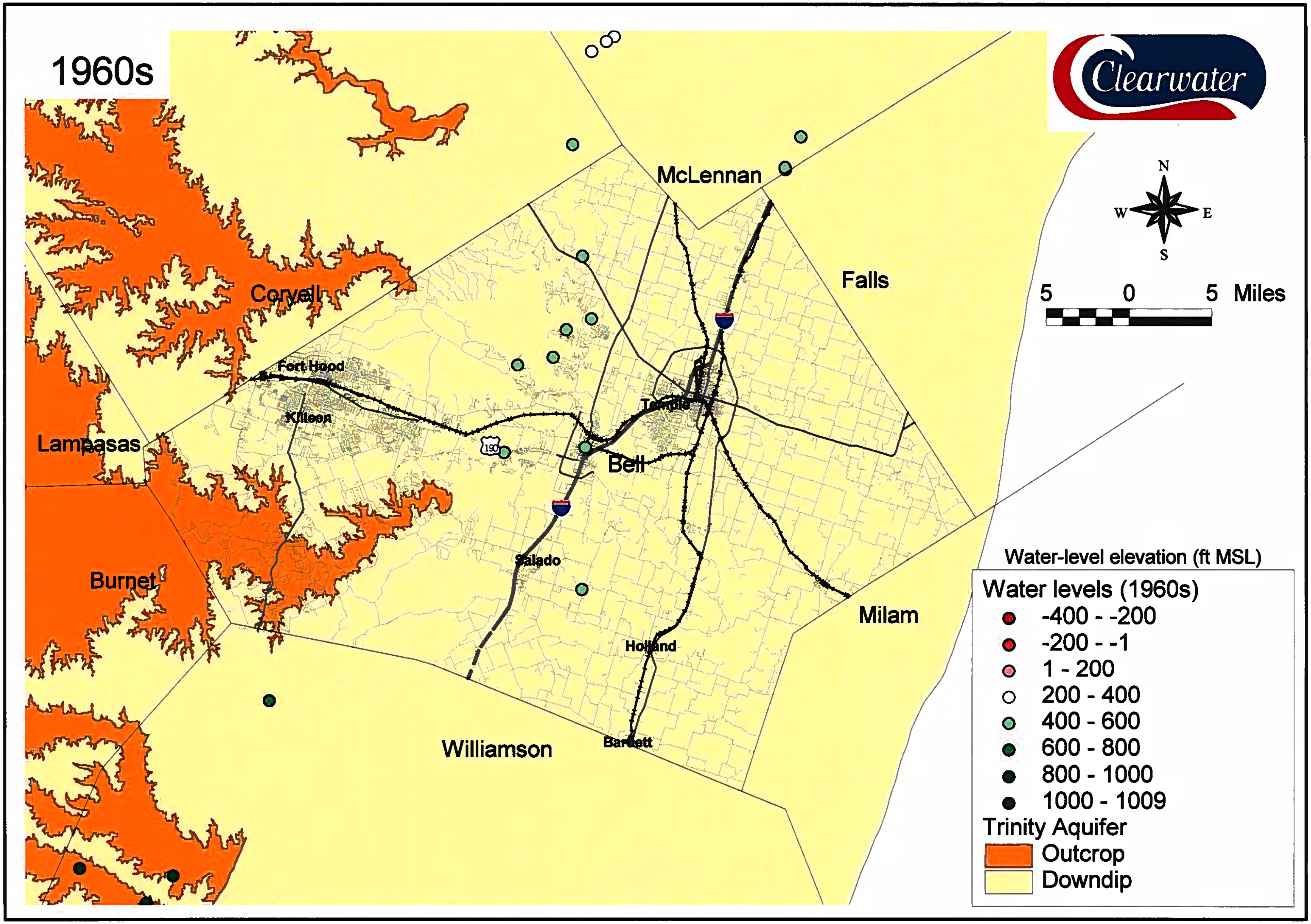
Figure 40



WATER-LEVEL ELEVATIONS IN HENSELL AQUIFER

Figure 41

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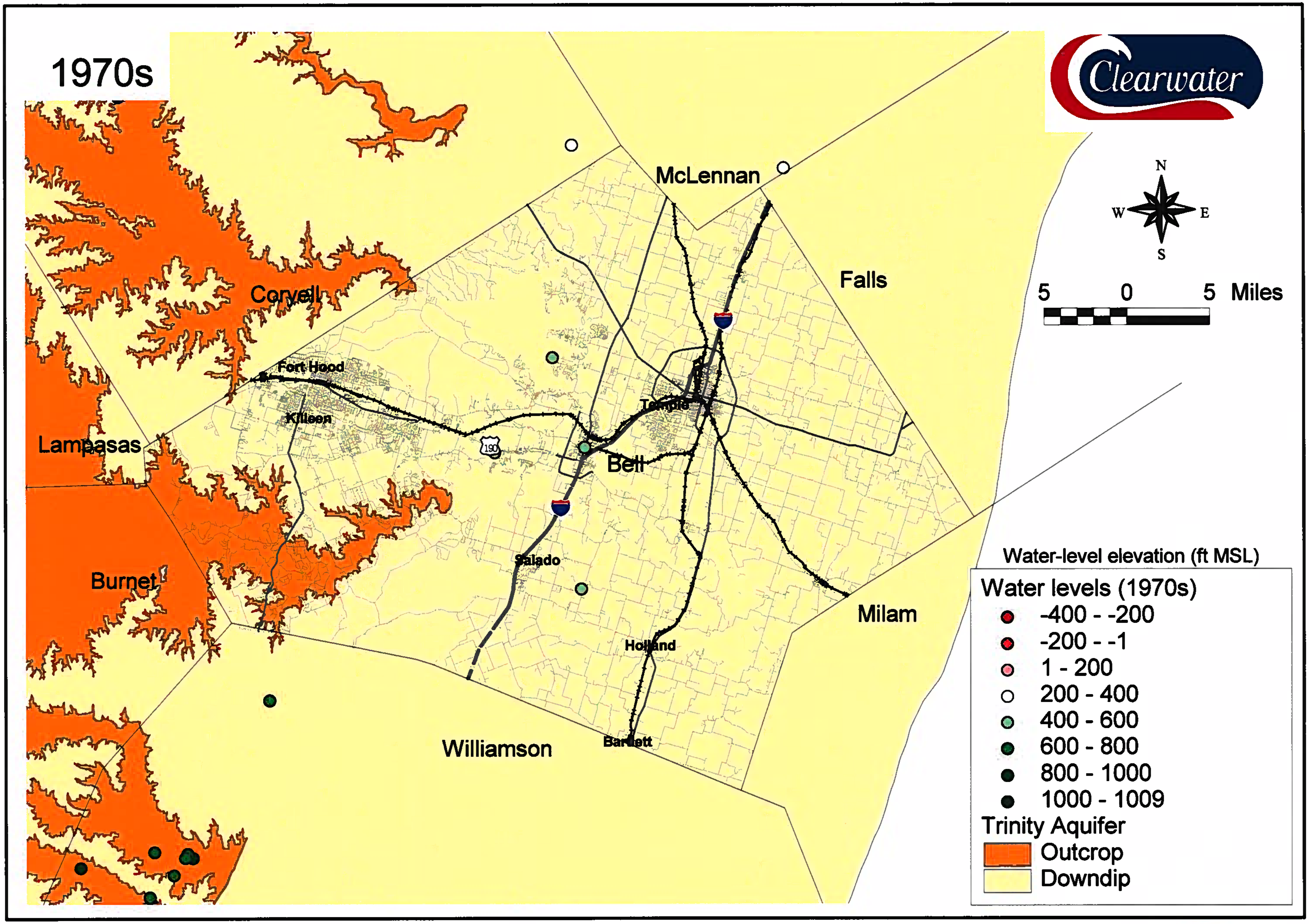

WATER-LEVEL ELEVATIONS IN HENSELL AQUIFER

Figure 42

Turner Collie & Braden Inc.
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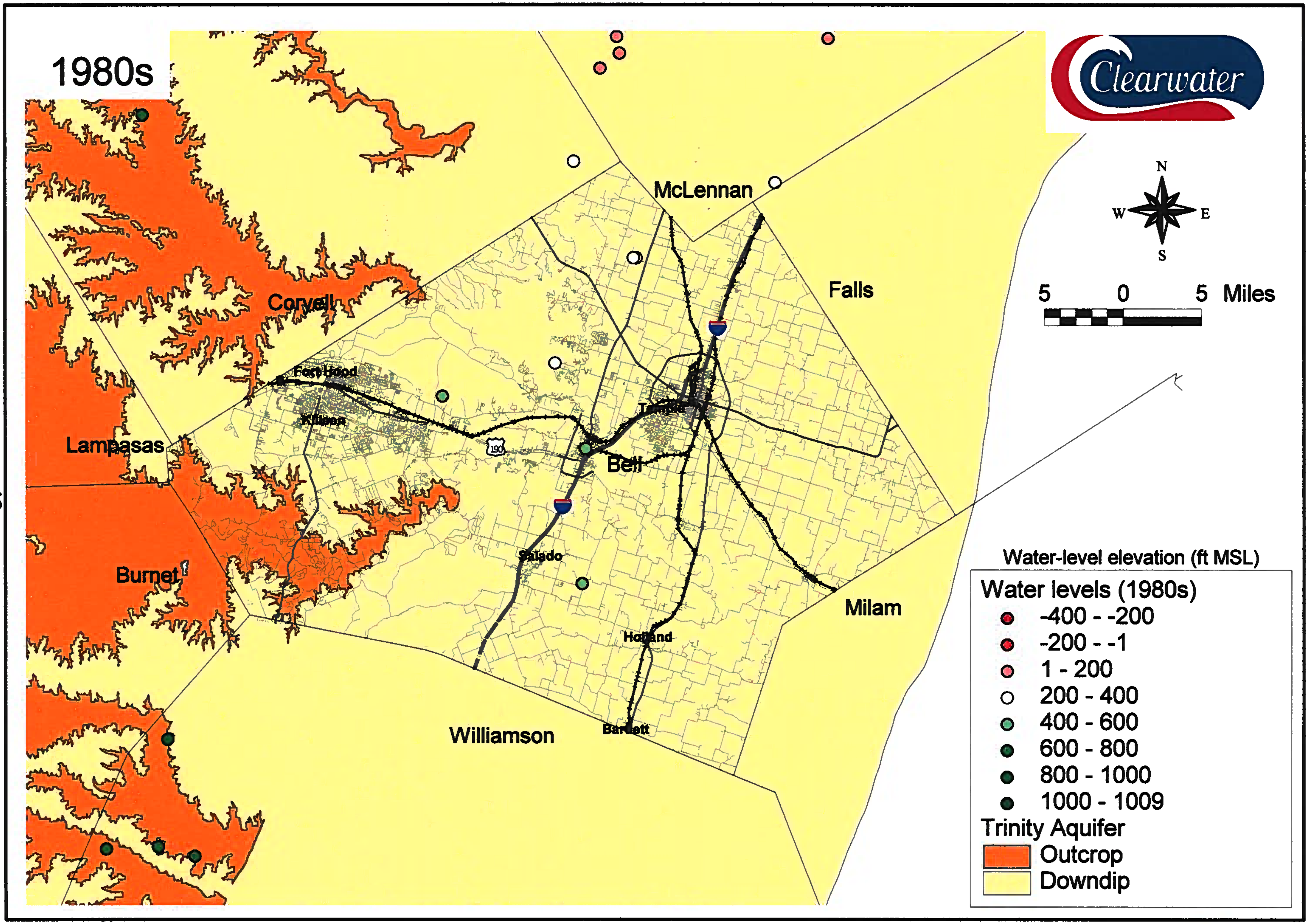

WATER-LEVEL ELEVATIONS IN HENSELL AQUIFER

Figure 43

Turner Collie & Braden Inc.
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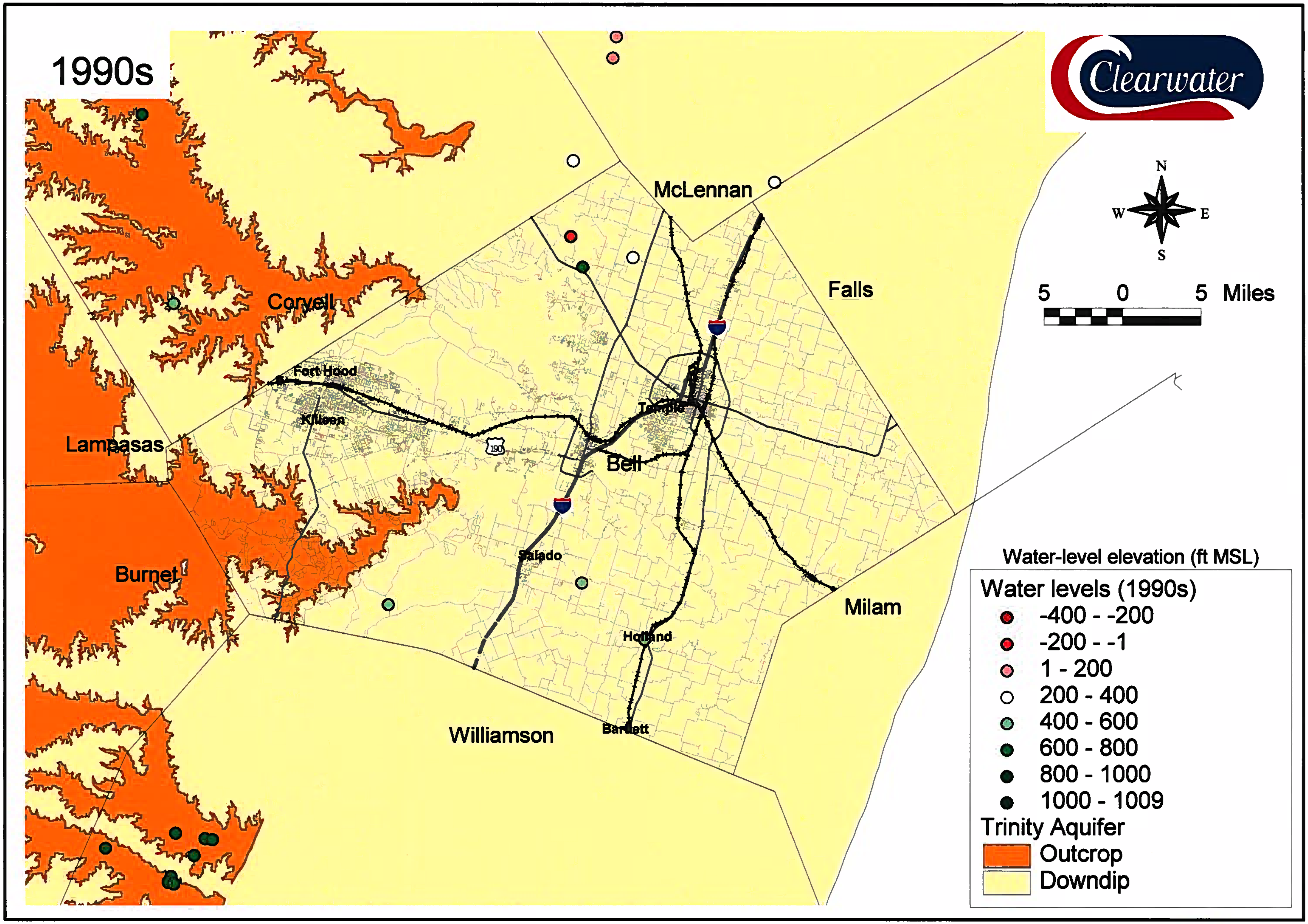
LBG



WATER-LEVEL ELEVATIONS IN HENSELL AQUIFER

Figure 44

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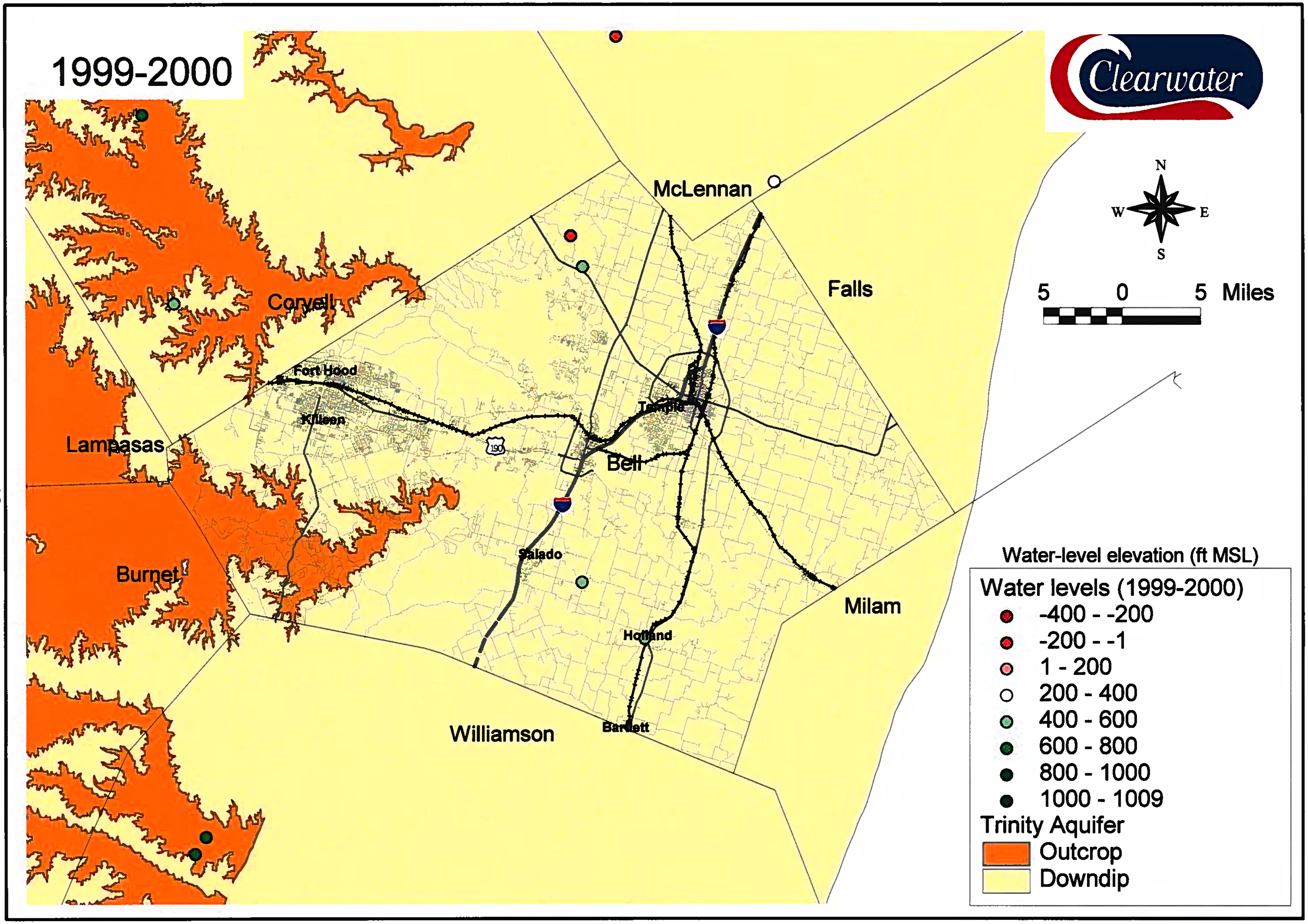
LBG



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WATER-LEVEL ELEVATIONS IN HENSELL AQUIFER

Figure 45

Turner Collie & Braden Inc.
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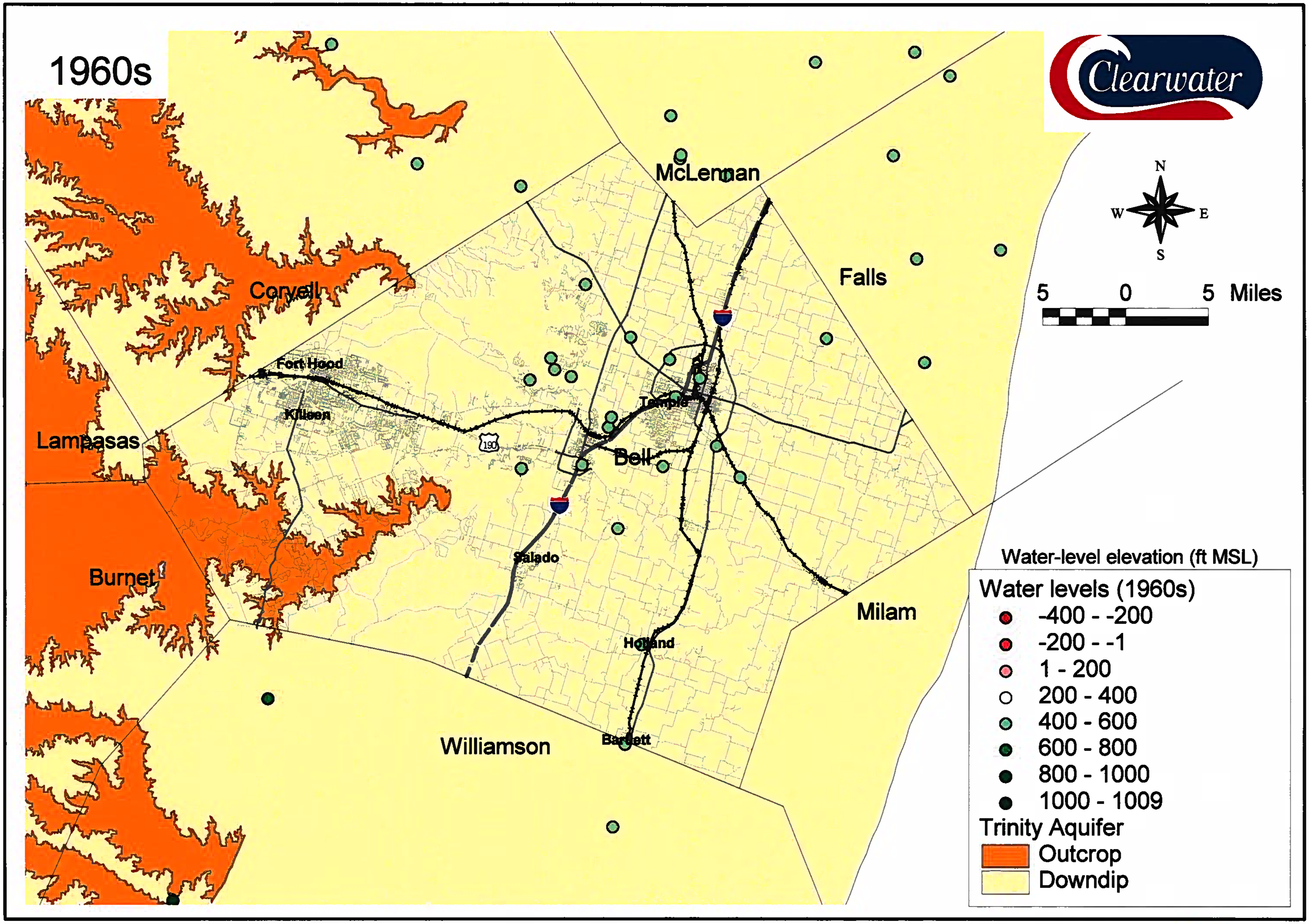
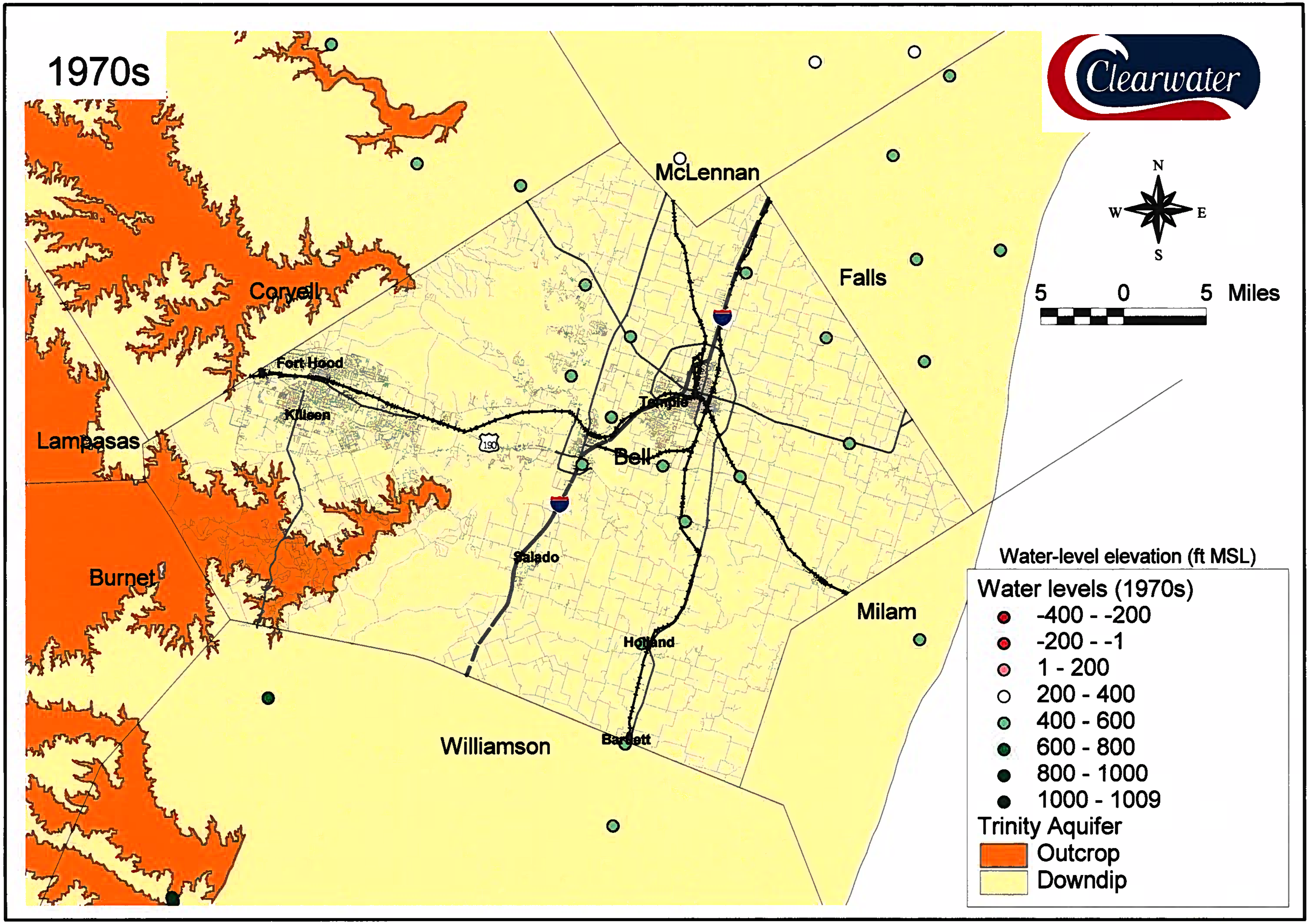


WATER-LEVEL ELEVATIONS IN HOSSTON AQUIFER

Figure 46

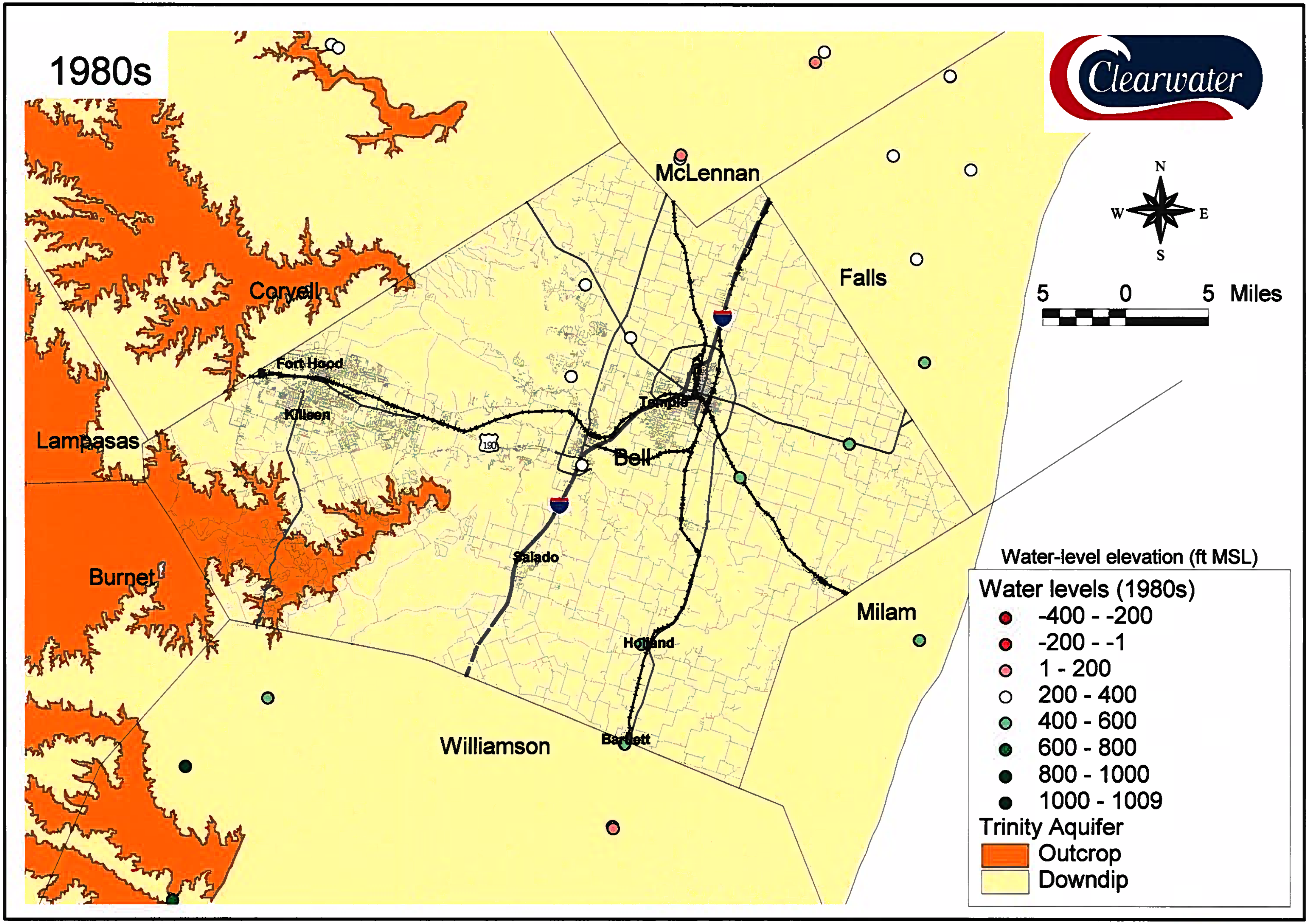
Turner Collie & Braden Inc.
Engineers • Planners • Project Managers



WATER-LEVEL ELEVATIONS IN HOSSTON AQUIFER

Turner Collie & Braden Inc.
Engineers • Planners • Project Managers

Figure 47



WATER-LEVEL ELEVATIONS IN HOSSTON AQUIFER

Figure 48

Turner Collie & Braden Inc.
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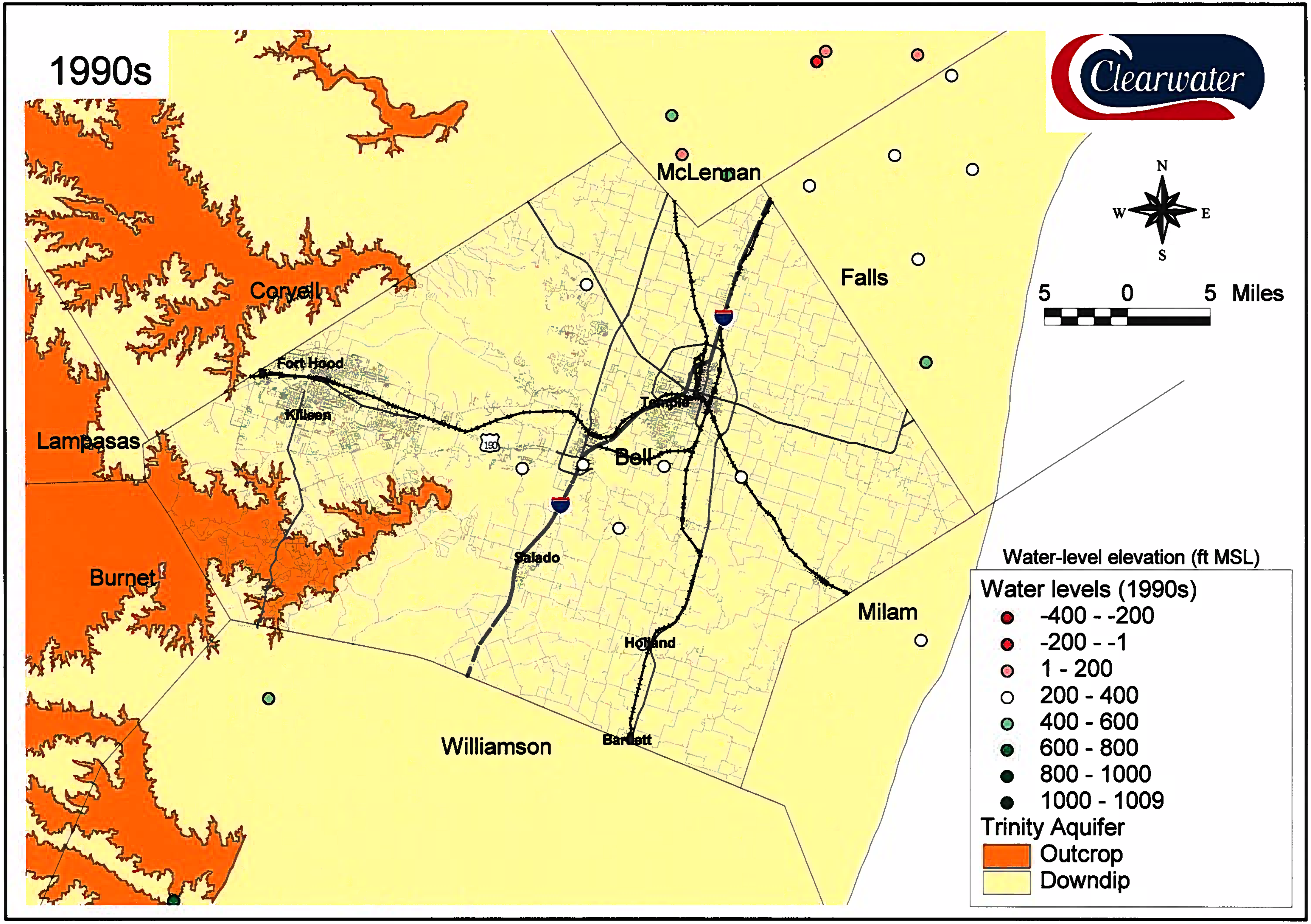

WATER-LEVEL ELEVATIONS IN HOSSTON AQUIFER

Figure 49

TurnerCollie&Braden Inc.
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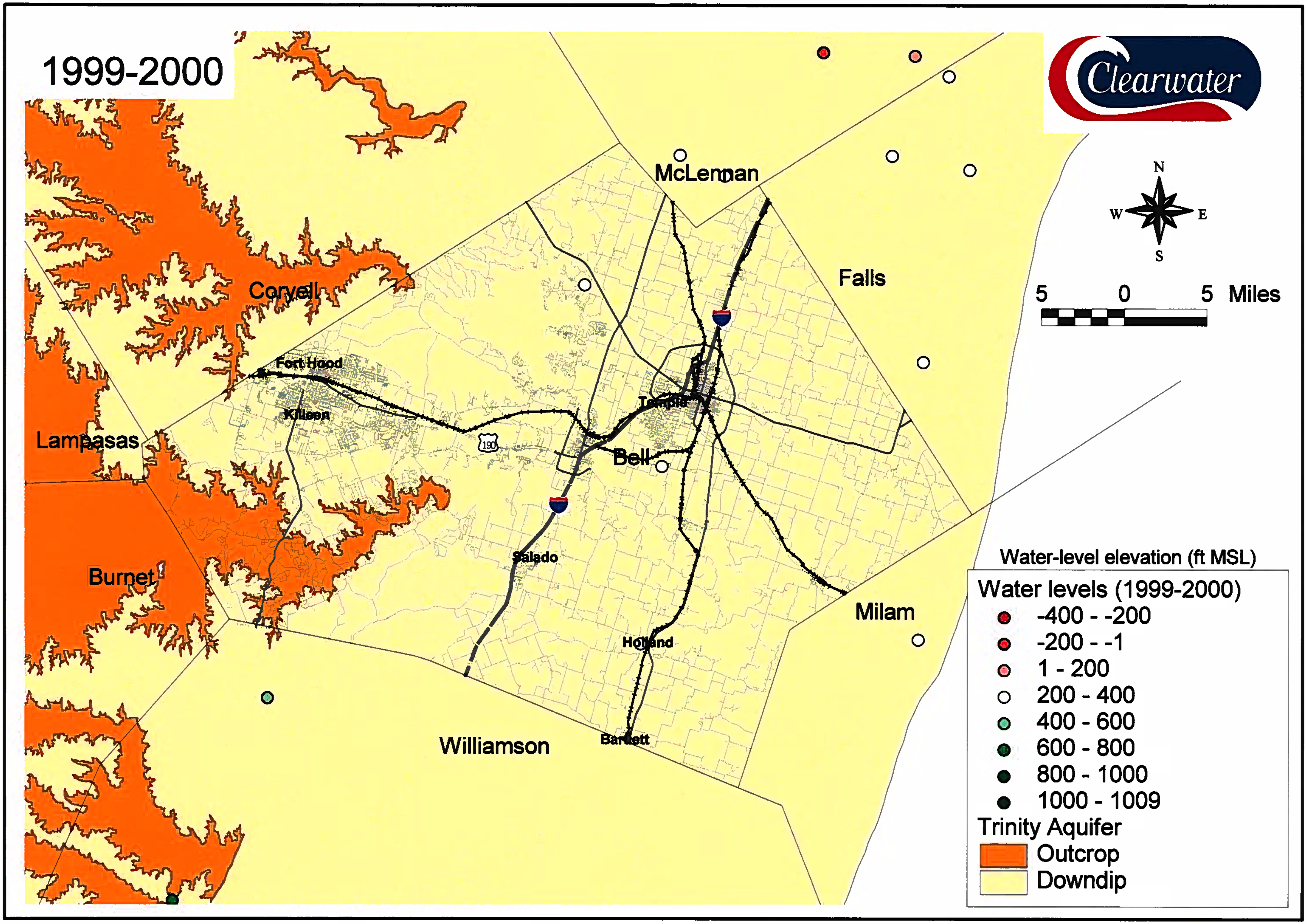

WATER-LEVEL ELEVATIONS IN HOSSTON AQUIFER

Figure 50

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The definitions of storativity and specific yield are similar yet indicate different processes taking place within the aquifer. Specific yield, used in connection with unconfined aquifers, represents the actual volume of water drained from an aquifer by lowering the water table and is a function of the quantity and size of interconnected void spaces in the soil matrix. Values for specific yield range from 0.01 (1%) to 0.4 (40%) with typical values ranging from 0.1 (10%) to 0.3 (30%). The less uniform, fine-grained and dense the material, the lower the value of specific yield. On the other hand, storativity represents the volume of water released due to expansion of water or compaction of the aquifer resulting from a reduction in pressure. The value of storativity is independent of the void content of the aquifer material and ranges from 0.00001 to 0.001.

The storage estimate for the Edwards (BFZ) aquifer assumed unconfined conditions. The area overlying the aquifer was divided into 18 cells. The area of each cell was calculated and then multiplied by the average saturated thickness of the cell and a porosity of 0.15 (based on TWDB Report 339) to determine the volume. The groundwater storage volume is the product of the specific yield and the volume. Two values are used for specific yield, 0.15 (or 15%) and 0.3 (or 30%) (based on TWDB Report 339). *Based on a specific yield of 0.15, the storage volume of the Edwards(BFZ) aquifer is 50,697 acre-feet. Based on a specific yield of 0.3, the storage volume is 101,394 acre-feet.* This method is based upon the following sources of data: estimates of saturated thickness extracted from well logs, published estimates of the porosity of the formation, and estimates of specific yield.

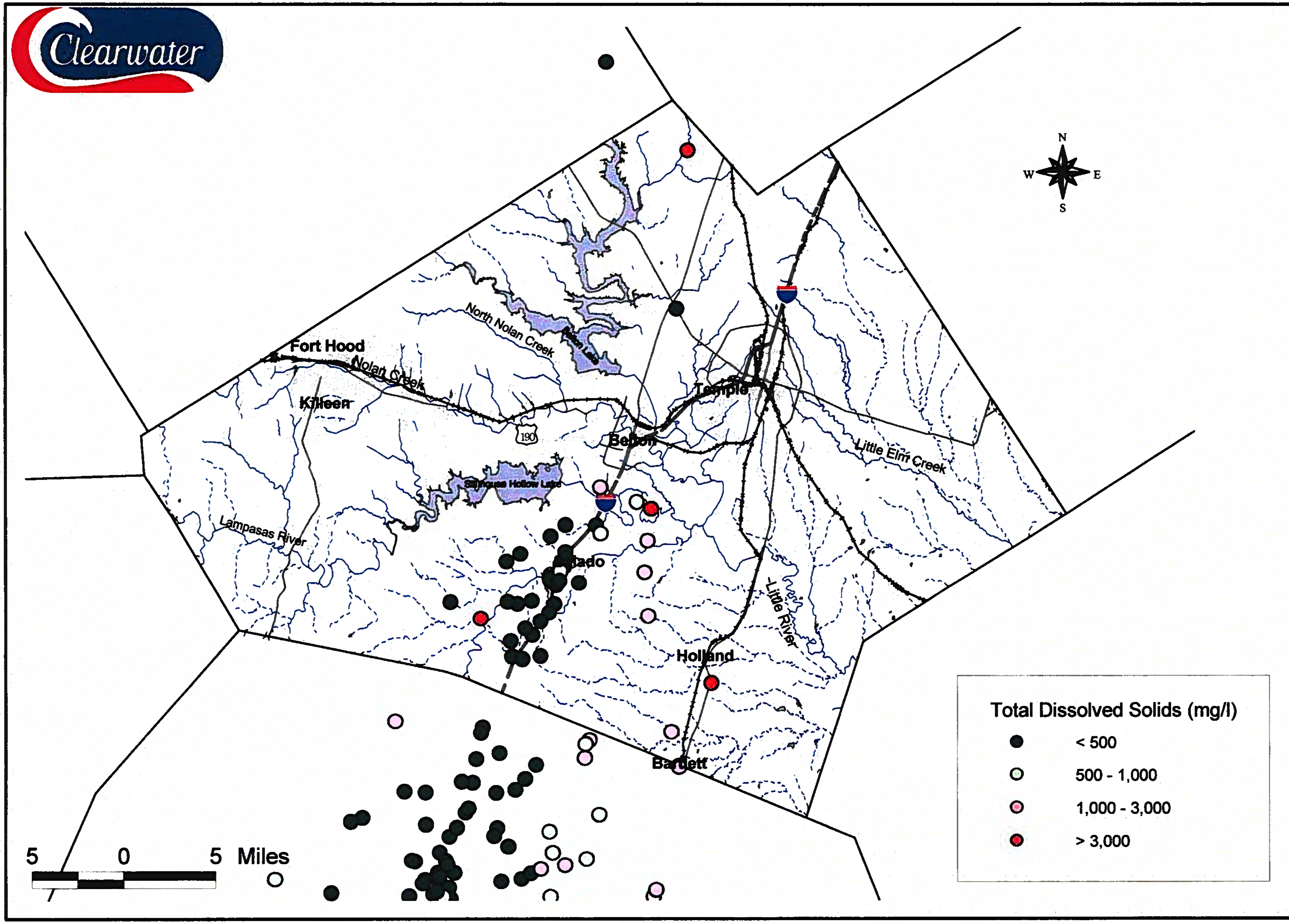
The storage estimate of the Trinity aquifer was calculated for the two economically significant water-bearing strata, the Hensell and Hosston members, which are both confined. In this case the storage volume of the aquifer is calculated as the product of the storativity of the aquifer, the area of the cell, and the total head above the top of the aquifer as measured in wells and estimated from well logs. The values of storativity, obtained from TWDB Report 339, are 0.000025 (or 0.0025%) for the Hensell and 0.000035 (or 0.0035%) for the Hosston. *For the Hensell, the volume of available water is 15,350 acre-feet. For the Hosston, the volume of available water is 29,115 acre-feet.*

The lower storage estimates for the Hensell and Hosston formations, compared with the Edwards (BFZ) aquifer, represent total availability and not the total amount of water in storage. Despite the lower volume of available water in the Hensell and Hosston formations, the storage volume is 32,000,000 acre-feet. Although this component of storage is much larger than the estimated availability calculated from storativity and total artesian head, it cannot be tapped without significantly affecting conditions in the aquifer. For example, lowering the potentiometric surface below the top of a confined stratum causes a change to unconfined conditions. This may cause rapid dewatering of the formation, increasing rates of drawdown, and diminished well efficiency.

3.2.4 Water Quality

The most basic measurement of water quality is total dissolved solids (TDS). The United States Environmental Protection Agency (USEPA) has determined that water with a TDS concentration greater than 500 milligrams per liter (mg/l) is not acceptable for long-term consumption by humans, without blending with lower-TDS water or water treatments such as reverse osmosis. Therefore, water from the Trinity aquifer and some wells of the Edwards (BFZ) aquifer may not be suitable for human consumption without some form of water treatment.

Within the outcrop areas of the Edwards (BFZ) aquifer in Bell County, wells produce groundwater with TDS typically less than 500 mg/l (*Figure 51*). Further to the east, in areas where the Edwards is buried deep within the subsurface, the TDS concentration increases to more than 3,000 mg/l. A "bad-water line" may be drawn where the TDS reaches 1,000 mg/l along a path a few miles east of Salado southward into Williamson County, approximately midway between State Highway 95 and Interstate 35. This "bad-water line" represents the downdip limit of useable Edwards (BFZ) groundwater.



TOTAL DISSOLVED SOLIDS OF EDWARDS (BFZ) AQUIFER

Figure 51

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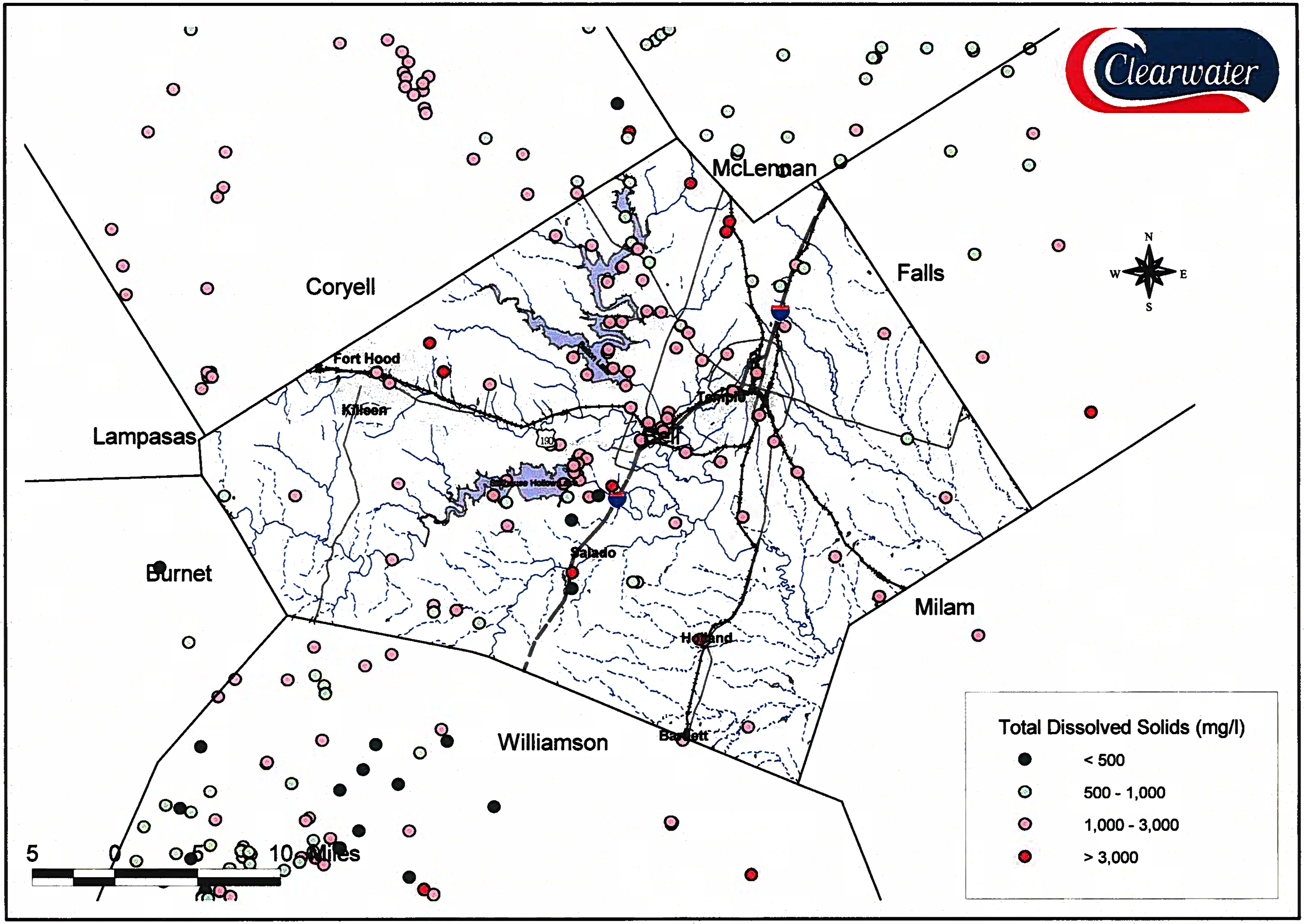

TOTAL DISSOLVED SOLIDS OF TRINITY AQUIFER

Figure 52

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With few exceptions, the TDS of Trinity groundwater is greater than 500 mg/l (*Figure 52*). Most groundwater samples analyzed by the TWDB are within the range of 1,000 to 3,000 mg/l. A smaller number of wells that produce groundwater with TDS concentrations greater than 3,000 mg/l are scattered across the county. The high TDS concentrations are attributable to the slow dissolution of minerals by groundwater and not to manmade sources of contamination. Although not generally acceptable for consumption by humans, the higher TDS water of the Trinity aquifer is acceptable for watering of livestock and wild game. However, the high TDS content may limit the use of Trinity groundwater for irrigation.

3.2.5 Potential Sources of Contamination

There are numerous potential sources of groundwater contamination within the boundaries of the CUWCD. A short list includes the following: active and inactive landfills, toxic release sites, leaking underground storage tanks (LUSTs), Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) sites, hazardous solid waste sites, industrial discharge sites, and oil and gas pipelines. The multitude and variety of contamination sources becomes even more important when the topography and geology of the District is considered. Since, the soil layer throughout the District is relatively thin, especially in the western portion of the county, there is little opportunity for volatile and non-volatile pollutants that are typically found in LUSTs and landfill sites to adsorb to the soil before leaching to the water table. This is especially true since the large outcrop areas of the Edwards (BFZ) aquifer located in southern Bell County provide numerous pathways in the form of fractures and karst features for the transport of point-source and nonpoint source contaminants from the surface to the saturated zone. However, the identification and transport of particular contaminants such as perchlorate are beyond the scope of this project and require further study. *Figure 53* graphically illustrates the location of potential sources of groundwater pollution located within the boundaries of the CUWCD.

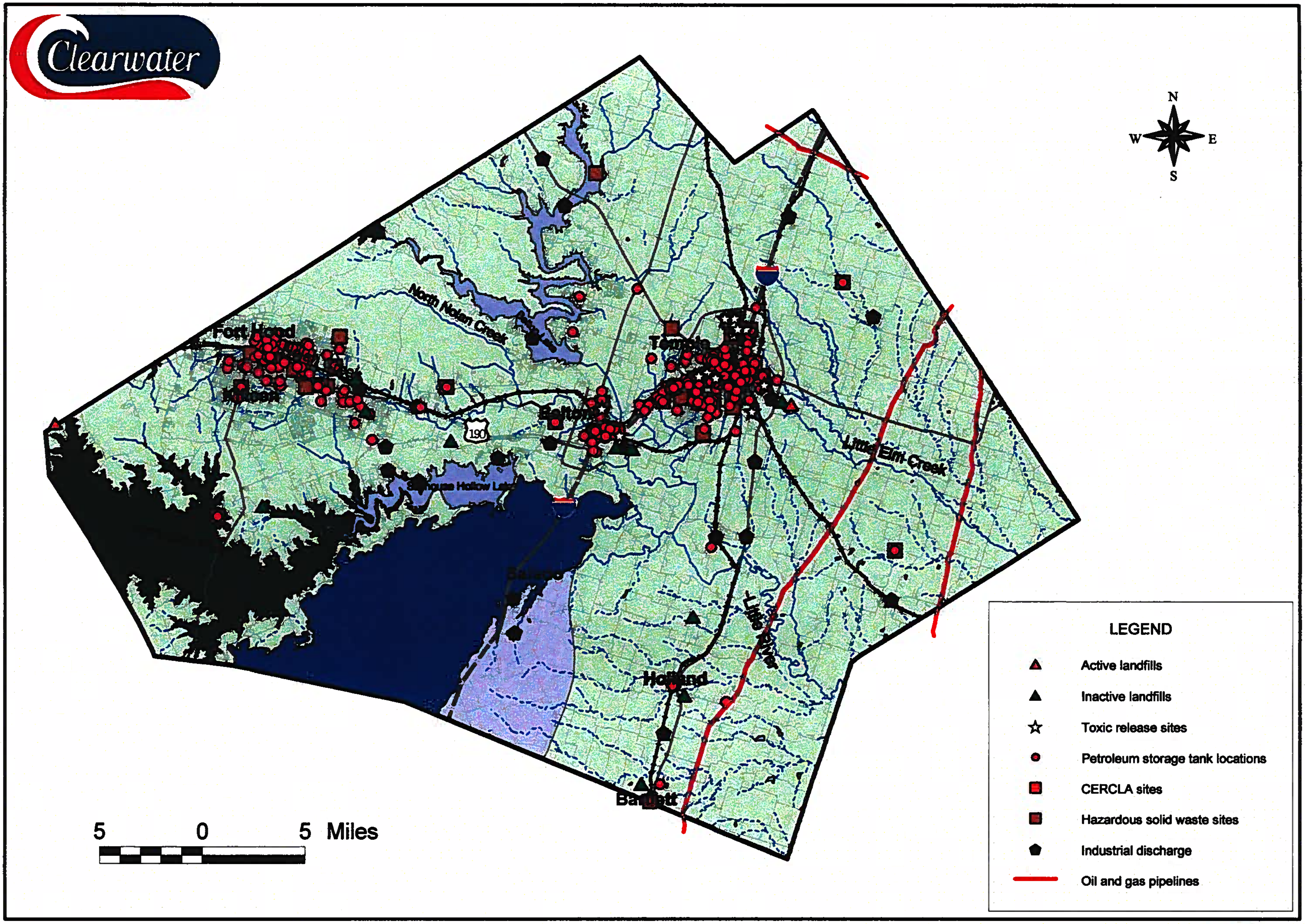
The Edwards (BFZ) aquifer is more vulnerable to contamination than the Hensell and Hosston formations. Most of the features shown in *Figure 53* are not immediate threats to the Hensell and Hosston formations of the Trinity Aquifer. Both of these formations are buried deep enough within the subsurface that there is less potential for direct contact with sources of contamination that are either on the surface or buried within the uppermost soil zones in Bell County. These aquifers are susceptible to contamination occurring in their recharge zones, but a determination of the those potentials is beyond the scope of this study.

4.0 MANAGEMENT OF GROUNDWATER RESOURCES

As previously discussed, the demand for water within the CUWCD is projected to increase significantly by 2050. This includes water demand by all water user groups, municipal, industrial, and agricultural. Since groundwater is a significant portion of the water supply for municipalities such as the community of Salado, initiating and maintaining good groundwater management practices is essential to providing adequate water quality and supply.

Vital to management of groundwater resources is accurate and comprehensive monitoring. Monitoring allows managers to determine direction of groundwater flow, storage of groundwater, areas of groundwater recharge, use of groundwater, and sources and rates of groundwater contamination. As a result, TCB and Guyton have considered a number of automated groundwater monitoring devices that would be suitable for long-term use by the CUWCD. Our objective was to identify recording devices that not only would be economic to purchase and operate, but also would make the collection of water-level measurements relatively quick and easy to obtain. The recommendations for the monitoring instrumentation are listed in Appendix A.

The CUWCD should seek to establish a groundwater monitoring program, based on the selection of wells that have been part of the TWDB's monitoring program in Bell County. This will ensure that data from a specific location can be tied to measurements made over many years. Eighteen wells for which water-level



POTENTIAL SOURCE OF WATER CONTAMINATION IN BELL COUNTY

Figure 53

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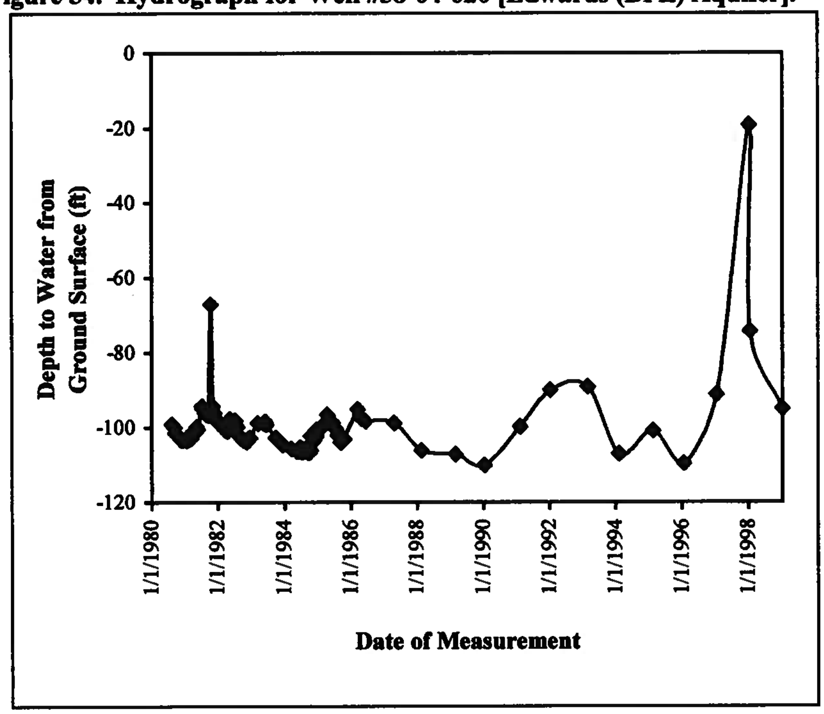
measurements have been collected over time by the TWDB have been identified. Nine of the wells produce water from the Edwards (BFZ) aquifer, and nine are completed in the Trinity Aquifer. Of the nine Trinity wells, two are listed as Hensell wells. The other seven are screened in the Hosston. *Table 4* on page 61 lists the wells by their respective state well numbers. Also included are periods for which water-level measurements have been made, the year the well was drilled, the depth of the well, the primary use of the well, and latitude and longitude in decimal degrees. The list provides reasonable coverage in the southern, central, and eastern sections of Bell County. Hydrographs of the potentiometric surface relative to the ground surface of one Edwards (BFZ) well (58-04-620; *Figure 54*), one Hensell well (58-05-403; *Figure 55*), and two Hosston wells (58-05-902; *Figure 56* and 40-61-901; *Figure 57*) are provided to illustrate expected trends for each water-bearing stratum.

It is important to note that the wells listed in *Table 4* are recommendations only. Before the wells can be integrated into a effective monitoring program, it will be necessary to secure the consent of the owner, and to evaluate the condition of the well to determine how easily water-level measurements may be taken and periodic samples collected for analysis of water quality.

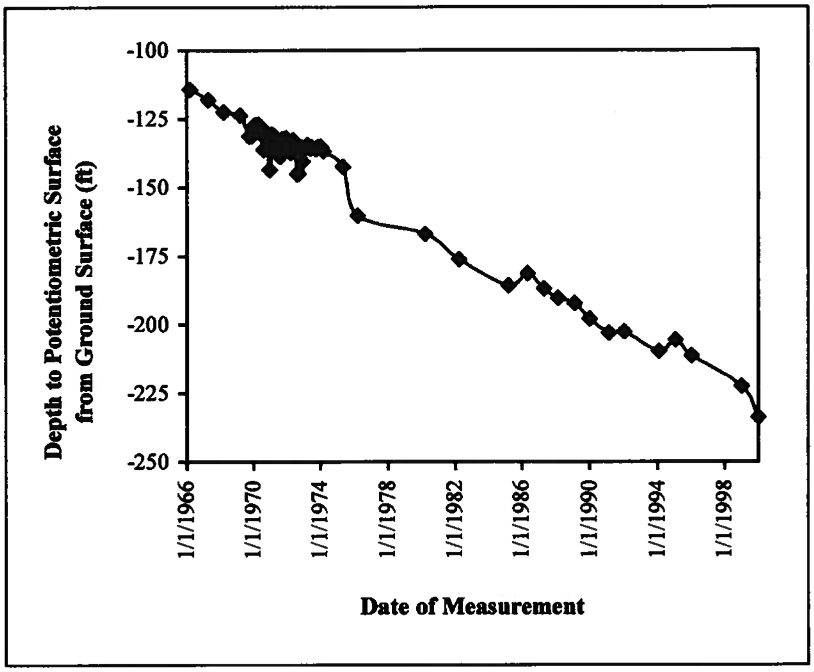
The data for Edwards (BFZ) well 58-04-620 represents data collected over a period of nearly 19 years. Located in southern Bell County, east of Interstate 35, the well was drilled in 1980. The TWDB lists it use as "recreation." The first measurement was recorded on August 6, 1980; and the lastest was made on January 13, 1999. Except for two sharp spikes in the hydrograph, the depth to water has remained approximately 100 feet below the surface. The pattern of relatively constant water levels is characteristic of other Edwards (BFZ) aquifer wells in Bell County. Water levels of these wells appear to respond quickly to rainfall, indicating that the Edwards (BFZ) aquifer recharges rapidly.

Figure 54. Hydrograph for Well #58-04-620 [Edwards (BFZ) Aquifer].



The data collected for Hensell well 58-05-403 covers a 34-year period. Completed in 1965, the well was drilled to a depth of 1,630 feet. The well is located in southern Bell County, approximately six miles northwest of Holland. The well provides water for livestock. The first measurement was recorded on March 15, 1966; and the last was made on January 11, 2000. The potentiometric surface has decreased 120 feet over the 34-year measurement period. The trend of lower water-level measurements is characteristic of many other Hensell wells in Bell County. Although the potentiometric surface at this location is still 1,000 feet or more above the top of the Hensell, falling water levels require increasing amounts of energy to lift water to the surface.

Figure 55. Hydrograph for Well #58-05-403 (Hensell Aquifer).



The data series for Hosston well 58-05-902 covers a 33-year period. Completed in 1957, the well was drilled to a depth of 2,420 ft. Located at the community of Holland, the well is used for "public supply". The first measurement was recorded on March 16, 1966; and the last was made on August 5, 1999. The potentiometric surface has decreased 158 ft over the 34-year measurement period.

Figure 56. Hydrograph for Well #58-05-902 (Hosston Aquifer).

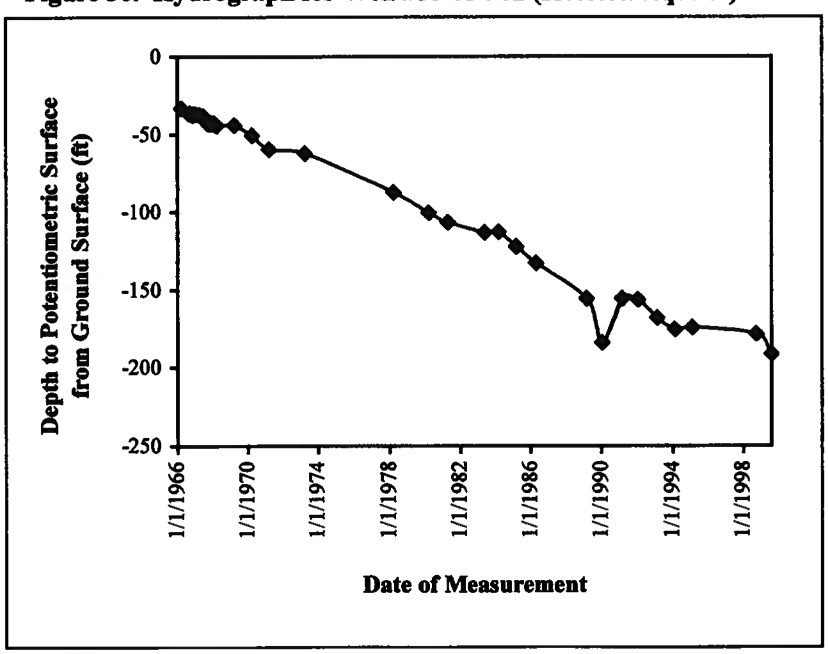
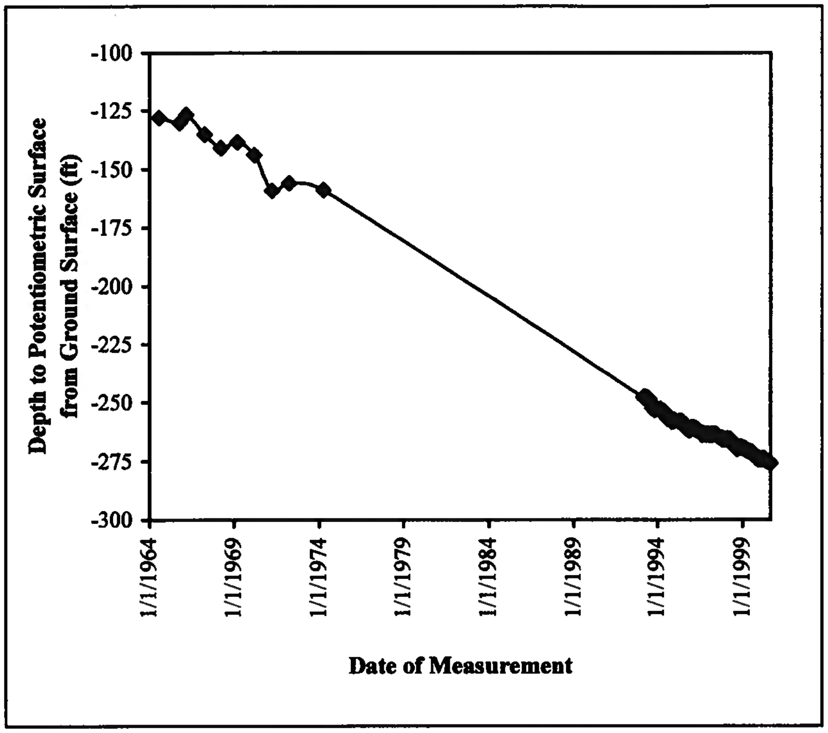


Table 4. List of Recommended Monitoring Wells for Edwards (BFZ) and Trinity Aquifers

Well #	Begin	End	Year Drilled	Depth below Ground Surface (ft)	USE	Latitude (North)	Longitude (West)
Edwards (BFZ)							
58-04-202	1973	1985	1973	102	Domestic	30.9658	97.5694
58-04-302	1981	1985	1973	148	Domestic	30.9878	97.5272
58-04-311	1982	1985	1980	107	Unused	30.9683	97.5414
58-04-502	1967	1985	1967	90	Public	30.9489	97.5422
58-04-620	1980	1999	1980	199	Recreation	30.9333	97.5397
58-04-702	1980	2000	1980	95	Unused	30.9158	97.5933
58-04-801	1966	2000	1966	175	Stock	30.8867	97.5717
58-04-802	1967	1985	1987	180	Public	30.9119	97.5525
58-04-803	1967	1985	1967	180	Public	30.9014	97.5603
Trinity-Hensell							
Well #	**Begin**	**End**	**Year Drilled**	**Depth below Ground Surface (ft)**	**USE**	**Latitude (North)**	**Longitude (West)**
40-61-404	1965	1984	1965	890	Unused	31.0564	97.4642
58-05-403	1966	2000	1965	1630	Stock	30.9322	97.4717
Trinity-Hosston							
Well #	**Begin**	**End**	**Year Drilled**	**Depth below Ground Surface (ft)**	**USE**	**Latitude (North)**	**Longitude (West)**
40-55-701	1961	1974	1961	2652	Public	31.1436	97.2142
40-61-105	1965	1989	1961	1080	Public	31.1161	97.4750
40-61-703	1952	1990	1952	1293	Unused	31.0386	97.4664
40-61-901	1964	2000	1964	1850	Unused	31.0353	97.3842
40-62-101	1951	1969	1951	2136	Unused	31.1119	97.3444
40-62-801	1965	1990	1960	2366	Public	31.0242	97.3061
58-05-902	1966	1999	1957	2420	Public	30.8803	97.4108

The data series for Hosston well 40-61-901 covers a 36-year period. Completed in 1964, the well was drilled to a depth of 1,850 ft. Located south of the City of Temple, the well is listed as "unused", according to the TWDB. The first water-level measurement was recorded on July 31, 1964; and the last was made on August 15, 2000. The potentiometric surface has decreased 147 ft over the 36-year measurement period.

Figure 57. Hydrograph for Well #40-61-901 (Hosston Aquifer).



Most water-level measurements are made either with an electric-line (e-line) or a steel tape (tape). Although both are reliable data-gathering tools, e-lines and tapes can be cumbersome to use in small-diameter wells equipped with submersible pumps. For example, it is common for e-lines to become tangled with wires. The use of e-lines and tapes can be improved by adding an access port at the wellhead and an access tube to keep the measuring devices from becoming snagged by wires. Depending on the number of wells established for the monitoring program, the amount of data that can be gathered with e-lines and tapes is a function of manpower, and the frequency of desired measurements. However, District rules should require that all new wells and reworked wells have access ports in place in order to measure water-levels.

Pressure transducers provide an effective means of collecting nearly continuous water-level measurements from wells. Transducers can be installed in wells for years, without harm to the devices. In addition, transducers can be programmed to collect data at any desired time interval. This is especially helpful if managers are interested in gauging the responsiveness of aquifers to rainstorms over recharge areas.

Our recommendation is to equip as many as eight wells with transducers at different locations in county. The field staff can download data from each transducer once a month. Water-level measurements at other wells can be made with an e-line or a tape. It is recommended that measurements be collected at least once a month.

Monitoring water quality should be an integral component of the CUWCD's monitoring program. Senate Bill 1 has appropriated funds for water quality testing by groundwater districts who enter into a contractual agreement with the TWDB. The TWDB has substantial resources to assist districts in the collection and analysis of water samples. The TWDB's Geohydrologic Unit supplies sampling equipment to the groundwater districts and trains field staff in proper sampling protocol. However, groundwater districts must agree to transport the samples to the Lower Colorado River Authority's (LCRA) laboratory in Austin. Typically, the number of samples analyzed during a year ranges from 20 to 50 and is determined by the TWDB. The length of the contract with the TWDB is generally five years.

The TWDB offers assistance to the groundwater districts to set up and maintain the groundwater monitoring program. Through the Texas Water Information Network (TWIN), the TWDB will provide the CUWCD with a laptop computer and other equipment, if the CUWCD agrees to develop a website linked to TWIN's website.

Just as important as accurate and comprehensive monitoring is maintenance of groundwater data in the form of a database. This permits records to be kept on groundwater use, water quality, water availability, and groundwater recharge rates. As a result the CUWCD can make proper decisions to prevent the overpumping of groundwater, ensure the proper spacing and construction standards of new water wells, develop programs and policies for the registration and permitting of wells, and transport of water outside of the District, and any considerations to establish a program for the assessment and collection of fees based on groundwater consumption.

In order to facilitate the management of the groundwater resources within the CUWCD, TCB developed a graphical user interface (GUI) that permits application, registration, water quality, and well information to be geo-referenced. In other words, all the well and aquifer data can be stored and queried based on location within the CUWCD. Existing wells and new wells can be identified, and attributes of the well or aquifer can be stored, referenced and analyzed based on a variety of characteristics. In addition, as new data on existing wells is collected, the database can be updated allowing the district to identify trends and evaluate aquifer characteristics based on a comprehensive review of the data. The information and analysis can then be quickly accessed through reports prepared by the database component of the GUI in Microsoft Access and through maps prepared in the geographic information system (GIS) in ArcViewGIS.

The database portion of the GUI is focused around the Main Switchboard, a user form that permits the user to navigate through the database. From the Main Switchboard, the user has the option to enter data for a new or existing well, to edit data for an existing well, to make reports based on current data for the existing wells, or to apply for a permit and register a well with the CUWCD. *Figure 58* is a reproduction of the Main Switchboard and illustrates the options available to the user.

To enter data for a new well, proceed from the Main Switchboard, by pushing the Data Entry button followed by the New Well button. The user has the ability to input data for the well by data type, permanent well data or well equipment. Examples of permanent data are the state well number, the well location, the owner of the well, the driller of the well, the date the well was drilled, the well depth and bore, and the surface geology at the location of the well. Examples of well equipment are pump size, pump rate, pump setting, storage capacity, etc. *Figure 59* is a reproduction of the permanent well data input form. *Figure 60* is a reproduction of the well equipment data form.

New data for existing wells can be entered by selecting the Data Entry button from the Main Switchboard. The user then has the option of entering water quality data, water metering data, well casing data, or water depth information. The water quality option permits the user to track contaminants in groundwater by storing data for parameters such as pH, alkalinity, conductivity, concentration of coliform, and dissolved oxygen. The well casing data form permits the user to track wells by casing material and state well number. *Figures 61* through *63* are reproductions of the input forms for each of the data entry options for existing wells.

Figure 58. Reproduction of Main Switchboard of Graphical User Interface

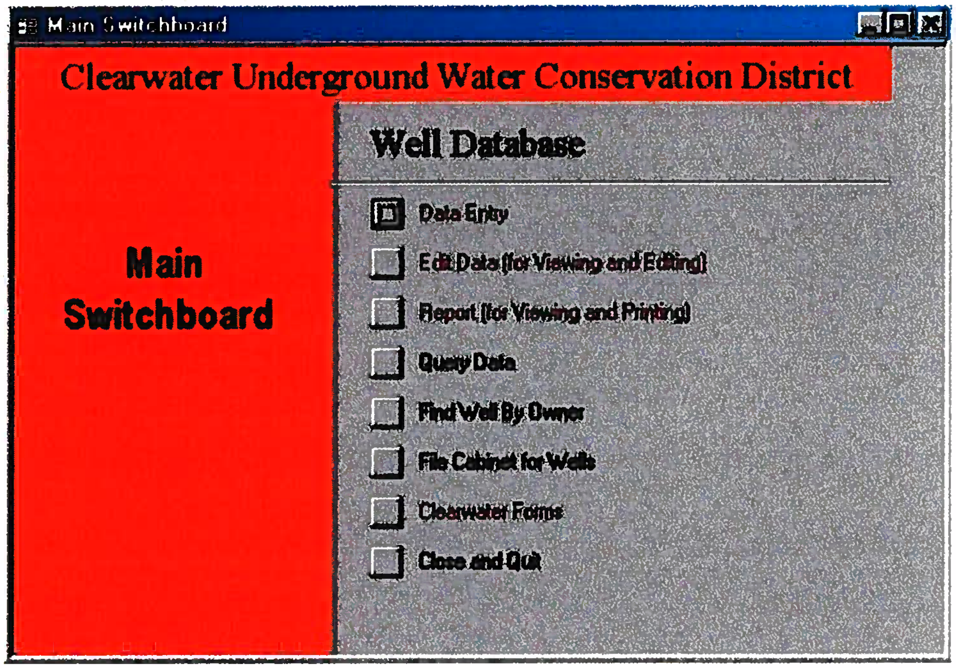


Figure 59. Reproduction of Permanent Well Data Form in the Graphical User Interface

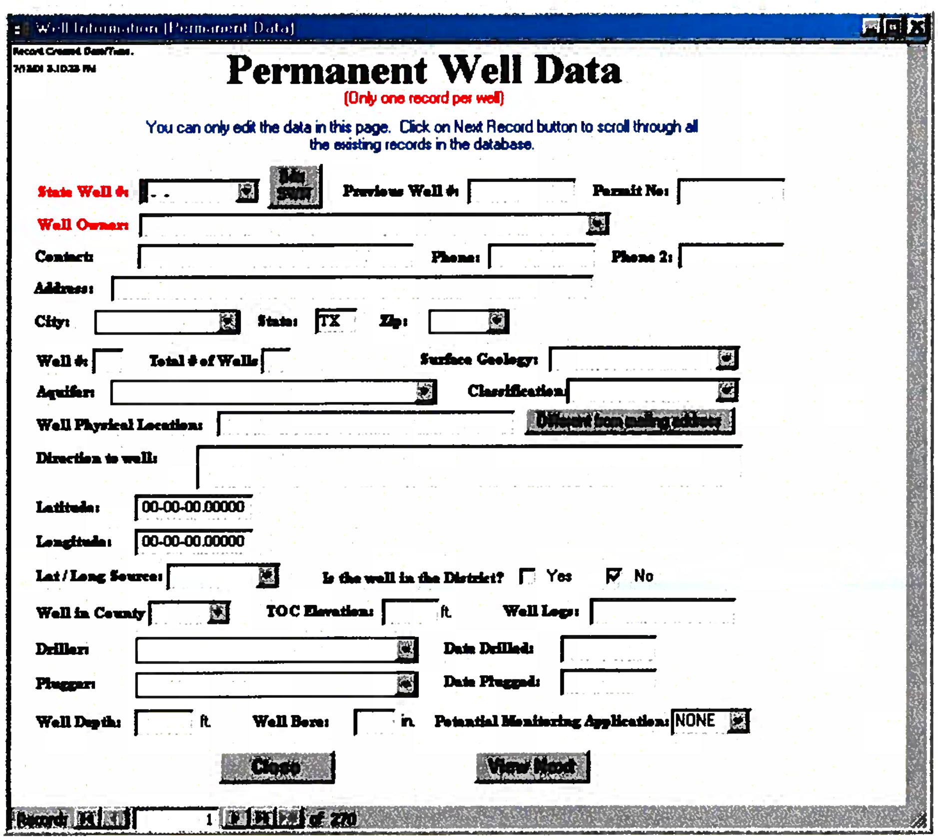


Figure 60. Reproduction of Permanent Well Equipment Form in the Graphical User Interface

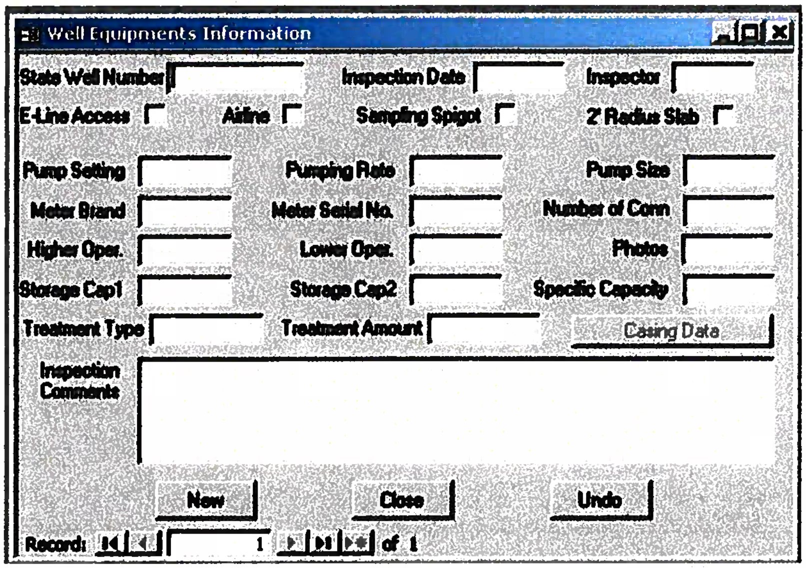


Figure 61. Reproduction of Permanent Well Sampling Form in the Graphical User Interface

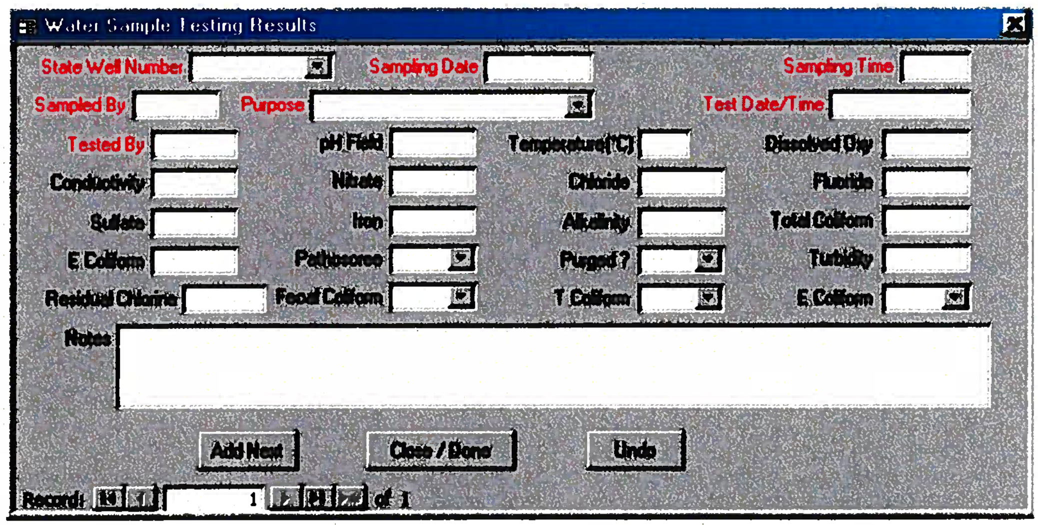


Figure 62. Reproduction of Meter Reading Form in the Graphical User Interface

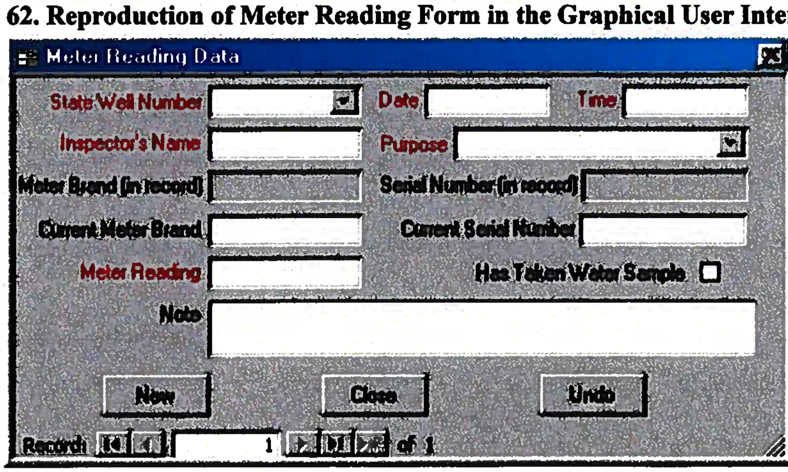
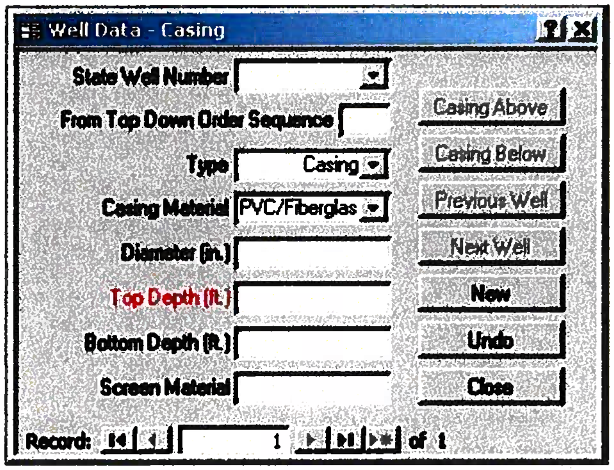


Figure 63. Reproduction of Well Casing Form in the Graphical User Interface



Editing data for existing wells can be performed by selecting Edit Data from the Main Switchboard. The user has the same choices for editing data as he does for entering new data. The following options are available under the Edit Data selection: 1) edit owner information, 2) edit permanent well information, 3) edit well equipment data, 4) edit meter reading data, 5) edit water level data, 6) edit water quality data, and 7) edit well casing data.

The Reports option on the Main Switchboard allows the user to make reports based on multiple criteria. Under this option, the user can make reports based upon well inspections, water quality in the water wells, well application data, or well registration data. An example of the output for a report based on well registration data can be found in Appendix B.

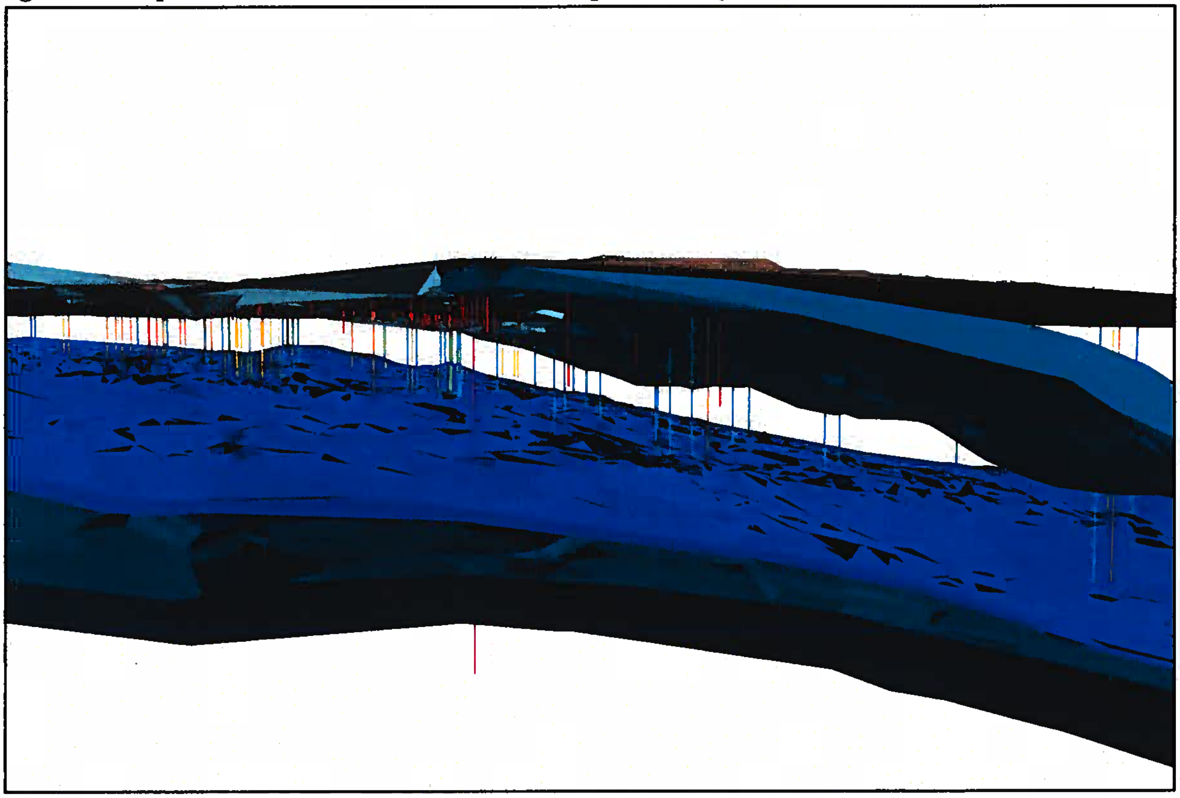
The Clearwater option button on the Main Switchboard allows the user to apply for permits or register a water well within the CUWCD. Reproductions of the Permit Application form and the Registration Form can be found in Appendix B.

The data stored in the database can then be accessed through ArcView GIS. This allows the data to be seen graphically throughout the CUWCD. For example, *Figure 33* is a reproduction of a view within ArcView GIS illustrating the location of wells throughout Bell County and their location with respect to the Edwards (BFZ), Trinity, or other aquifers. Clicking on the location of one of the wells in the GUI instantly accesses all the data regarding that particular well. This data ranges from the state identification number and well owner to water quality data and well casing data as it has been entered in the database.

The combination of all the well data stored in the database then allows for a three dimensional view of the aquifers to be viewed. As new data is added, the impacts on the aquifer can be seen graphically in the three dimensional model. This makes analyzing trends and impacts to the aquifer simple for the user. *Figure 64* is a reproduction in ArcView GIS of a three dimensional view of the Edwards (BFZ) and Trinity aquifers in the CUWCD.

The District will be able to better develop and implement its rules as a result of the developed data, analyzed resources, and the established methods to input and update well information. Sources of data provided to the CUWCD include electric well logs, catalogued well logs, well plugging reports, and reports and theses discussing groundwater resources in Bell County.

Figure 64. Reproduction of three-dimensional view produced by the GUI of wells within the CUWCD.



Electric logs record the electrical properties of the formations and fluids within a well. These logs are used to determine the structure of geologic formations and can help determine the location of groundwater resources. Electric logs were collected in preparation of the study of the Edwards (BFZ) and Trinity aquifers and for development of the GUI. Copies of the electric logs for Bell County have been provided to the CUWCD.

Catalogued well logs are records of the stratigraphic layers logged from a particular well. These records indicate the hydraulic conductivity of the geologic formations and aid in the determination of groundwater flow. These logs were also collected in preparation of the study of Bell County's groundwater resources and for development of the GUI. Copies of these records also have been provided to the CUWCD.

Other sources of data such as well plugging reports give information on the use of wells and a summary of the well dimensions. Dissertations, theses and other technical reports relate information regarding geologic and hydrogeologic properties and studies at locations throughout the District. A list of representative theses and dissertations discussing groundwater resources and copies of well plugging reports also have been provided to the CUWCD.

APPENDIX A: MONITORING RECOMMENDATIONS

As specified the Scope-of-Work for the CUWCD, TCB and Guyton have considered a number of automated groundwater monitoring devices that would be suitable for long-term use by the CUWCD. The objective was to identify recording devices that not only would be economic to purchase and operate, but also would make the collection of water-level measurements quick and easy to obtain. Based on our experience with these instruments and their manufacturers, we submit the following recommendations:

(1) The In-Situ Standard MiniTROLL: a battery-operated transducer with barometric adjustment. The Standard MiniTROLL sells for $999, software included. The cost of the required cable is $195, plus $2.25 per foot. (For example, 200 ft of cable would run $195 + 200*$2.25, or $450.) The Standard MiniTROLL stores up to 32,000 water-level measurements, and data can be downloaded either to a laptop or to a Compaq iPAQ pocket pc. The cost of the iPAQ is about $500. Additional information can be obtained from In-Situ, Inc.'s website: http://www.in-situ.com. The sales representative may be contacted at 800-446-7488.

(2) The Hydrolab Diver: a battery-operated transducer. An attachment to compensate for barometric pressure (the Baro Diver) is recommended. The cost of the Baro Diver is $325. The Diver stores up to 48,000 data points. An optical reader is required to download data from the Diver. Additional information can be obtained from Hydrolab's website: http://www.hydrolab.com. A Hydrolab representative may be contacted at 800-949-3766.

Either one of the above transducers will be sufficient to handle all of CUWCD's water level monitoring requirements.

Below is a list of companies and their respective websites that sell groundwater monitoring equipment. Most of the websites contain a price list for the products they sell. The Barton Springs Edwards Aquifer Conservation District (BSEACD) has used the products sold by many of these companies with various degrees of satisfaction.

(1) Instrumentation Northwest, Inc.
The BSEACD uses the PS9105 pressure transducer to measure water levels and the 247 conductivity and temperature probe. The PS9105 probes are sensitive and need external calibration by the company approximately once every nine months. The website address is http://www.inwusa.com and the phone number is 800-776-9355.

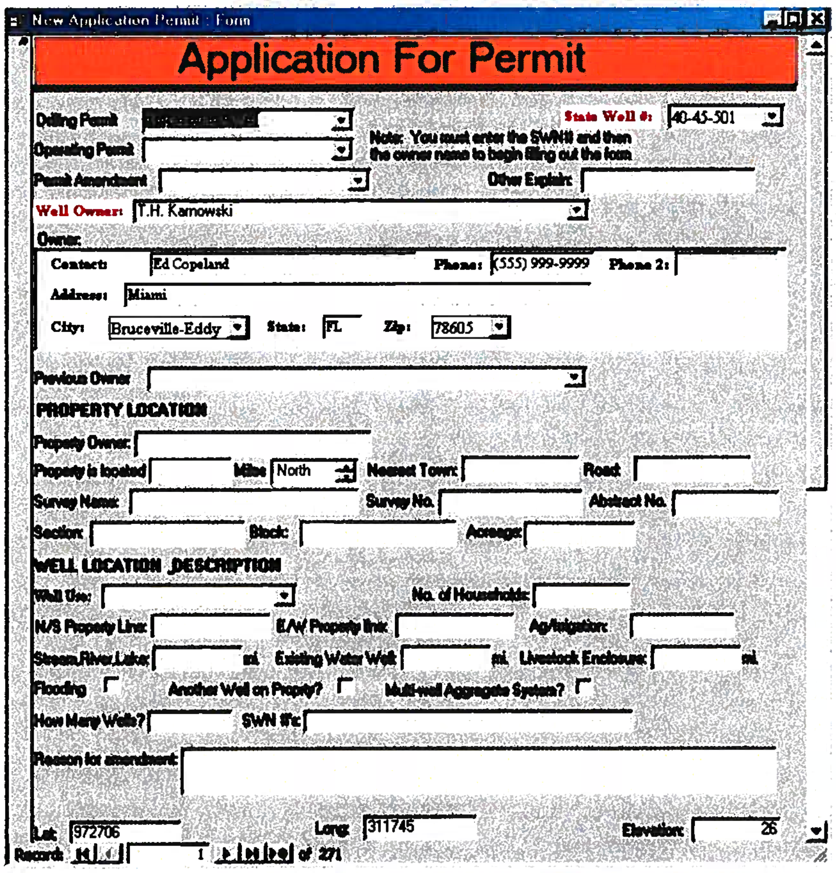
(2) Campbell Scientific, Inc.
The BSEACD uses the CR10X datalogger. The datalogger is reliable and easy to operate. However, diagnosing hardware problems is difficult. The website address for this company is http://www.campbellsci.com and the phone number is 435-753-2342.

(3) Wescor, Inc.
The BSEACD has used the Easy Logger 900 Series. Wescor may have discontinued production of these dataloggers; however, they also sell other dataloggers and sensors. The website address for Wescor is http://www.wescor.com and their phone number is 435-752-6011.

(4) In-Situ
Insitu produces the highly regarded miniTROLL sensor and datalogger. The website address for In-Situ is http://www.in-situ.com and their phone number is 800-446-7488.

(5) Solinst Canada Ltd.
Solinst sells a number of water-level meters, groundwater samplers, pumps, and dataloggers. Their website is http://www.solinst.com and their phone number is 800-661-2023.

APPENDIX B: GRAPHICAL USER INTERFACE FORMS


New Application Permit : Form

Application For Permit

Drilling Permit [redacted]

State Well #: 40-45-501

Operating Permit

Note: You must enter the SWN# and then the owner name to begin filling out the form

Permit Amendment

Other Explain:

Well Owner: T.H. Karnowski

Owner:

Contact: Ed Copeland

Phone: (555) 999-9999

Phone 2:

Address: Miami

City: Bruceville-Eddy

State: FL

Zip: 78605

Previous Owner

PROPERTY LOCATION

Property Owner:

Property is located

Miles North

Nearest Town:

Road

Survey Name:

Survey No.

Abstract No.

Section:

Block:

Acreage:

WELL LOCATION DESCRIPTION

Well Use:

No. of Households:

N/S Property Line:

E/W Property line:

Ag/Irrigation:

Stream,River,Lake: mi.

Existing Water Well: mi.

Livestock Enclosure: mi.

Flooding

Another Well on Property?

Multi-well Aggregate System?

How Many Wells?

SWN #'s:

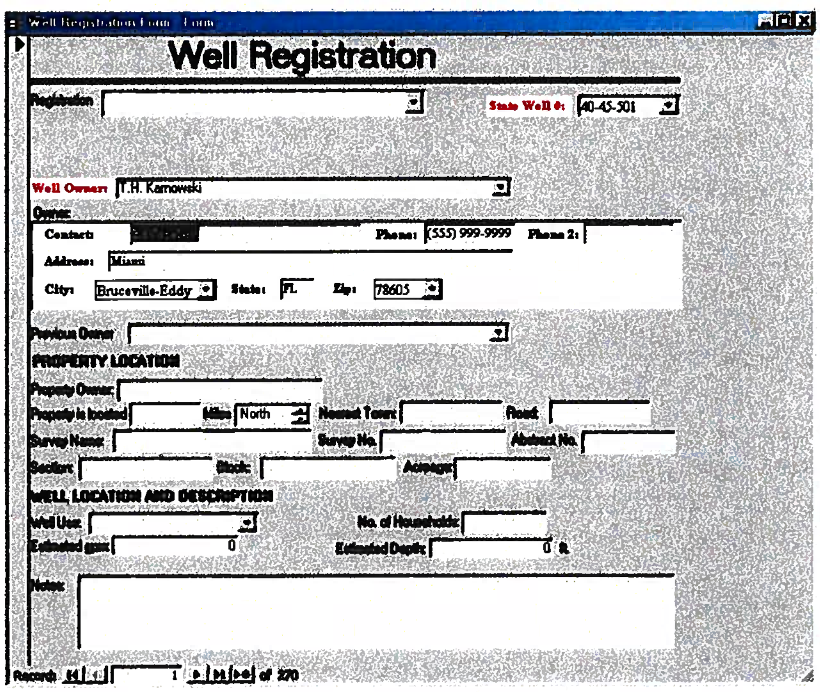
Reason for amendment:

Lat: 972706

Long: 311745

Elevation: 26

Record: 1 of 271


Well Registration Form : Form

Well Registration

Registration

State Well #: 40-45-501

Well Owner: T.H. Karnowski

Owner:

Contact: [redacted]

Phone: (555) 999-9999

Phone 2:

Address: Miami

City: Bruceville-Eddy

State: FL

Zip: 78605

Previous Owner

PROPERTY LOCATION

Property Owner:

Property is located

Miles North

Nearest Town:

Road

Survey Name:

Survey No.

Abstract No.

Section:

Block:

Acreage:

WELL LOCATION AND DESCRIPTION

Well Use:

No. of Households:

Estimated gpm: 0

Estimated Depth: 0 ft.

Notes:

Record: 1 of 270

APPENDIX C: LIST OF REPRESENTATIVE THESES AND DISSERTATIONS

Records of Water-Level Measurements in Bell, McLennan, and Somervell Counties, Texas, 1930 through 1957, by F.A. Rayner, February 1959. B5902.

Results of Pumping Tests of Wells at Camp Hood, Texas, by W.F. Guyton, January 1943. M031.

Ground-Water Resources of Part of Central Texas with Emphasis on the Antlers and Travis Peak Formations, by William B. Klemt, Robert D. Perkins, and Henry J. Alvarez. November 1975. R195 V. 1.

Ground-Water Resources of Part of Central Texas with Emphasis on the Antlers and Travis Peak Formations, by William B. Klemt, Robert D. Perkins, and Henry J. Alvarez. January 1976. R195 V. 2.

Groundwater Availability in Texas: Estimates and Projections Through 2030 by Daniel Muller and Robert D. Price, September 1979. R238.

Geohydrology of the Edwards Aquifer in the Austin Area, Texas, by E.T. Baker, R.M. Slade, M.E. Dorsey, G.L. Duffin. March 1986. R293.

Evaluation of Water Resources in Part of Central Texas, by Bernard Baker, Gail Duffin, Robert Flores, Tad Lynch. January 1990. R319.

Test Well Drilling Investigation to Delineate the Downdip Limits of Usable-Quality Ground Water in the Edwards Aquifer in the Austin Region, Texas, by Robert Flores. April 1990. R325.

Evaluation of Water Resources in Bell, Burnet, Travis, Williamson and Parts of Adjacent Counties, Texas, by Gail Duffin and Steven P. Musick, January 1991. R326.

Aquifers of Texas, by John B. Ashworth and Janie Hopkins. November 1995. R345.

Changes in Groundwater Conditions in the Edwards and Trinity Aquifers, 1987-1997, for Portions of Bastrop, Bell, Burnet, Lee, Milam, Travis, and Williamson Counties, Texas, by Cindy Ridgeway and Harald Petrini. November 1999. R350.

Hydrochemical Facies in the Badwater Zone of the Edwards Aquifer, Central Texas, by Tonia Judith Clement. M.A. thesis in Geology, The University of Texas at Austin.

Hydrogeology of the Northern Segment of the Edwards Aquifer, Ausin Region, by Rainer K. Senger, Edward W. Collins, and Charles W. Kreitler, 1990. Bureau of Economic Geology, University of Texas at Austin.

GLOSSARY

confined aquifer: an aquifer that is overlain by a confining layer (aquitard)

dip: the angle that a stratum or similar geological feature makes with a horizontal plane

elevation head: the potential energy per unit weight of water due to gravitational force

evapotranspiration: loss of water from the soil both by evaporation and by transpiration from the plants growing thereon

fault: a fracture or fracture system that has experienced movement along opposite sides of a fracture

groundwater: water within the earth that supplies wells and springs

hydraulic conductivity: measure of the ability of a particular material to allow water to move through it. Units are length per time

lithology: the study of rocks

marl: a loose or crumbling earthy deposit (as of sand, silt, or clay) that contains a substantial amount of calcium carbonate and is used especially as a fertilizer for soils deficient in lime

orthogonal: intersecting or lying at right angles

permeability: a measure of the ability of an earth material to transmit fluids such as water or oil

phreatophytes: a deep-rooted plant that obtains its water from the water table or the layer of soil just above it

piezometric head: sum of pressure head and elevation head

potentiometric surface: an imaginary surface representing the level to which underground water confined in pores and conduits would rise if intersected by a borehole

pressure head: pressure energy per unit weight of water due to gravitational force

saturated zone: see *zone of saturation*

specific yield: the volume of water released from storage per unit area per unit drop of the water table, usually used in reference to unconfined aquifers

storativity: the volume of water released from storage per unit horizontal area per unit drop of piezometric head, usually used in reference to confined aquifers

stratigraphy: geology that deals with the origin, composition, distribution, and succession of strata

stratum: a sheetlike mass of sedimentary rock or earth of one kind lying between beds of other kinds *strike*: the direction of the line of intersection of a horizontal plane with an uptilted geological stratum

topography: the configuration of a surface including its relief and the position of its natural and man-made features

transducer: a device that is actuated by power from one system and supplies power usually in another form to a second system

transmissivity: the rate of flow per unit width through the entire thickness of an aquifer per unit hydraulic gradient; the product of hydraulic conductivity and aquifer thickness

unconfined aquifer: aquifer in which there is no impermeable layer restricting the upper surface of the zone of saturation

zone of saturation: zone or layer below the water table in which all the pore space of rock or soil is saturated