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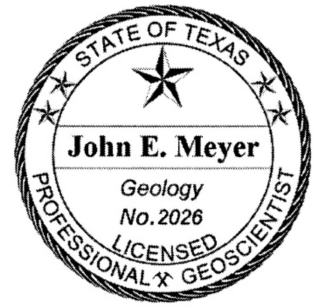

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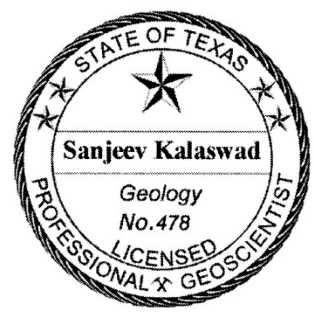

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1. Executive summary

Estimated at more than 2.7 billion acre-feet, brackish groundwater (water with total dissolved solids concentration of 1,000 to 10,000 milligrams per liter) constitutes an important desalination water supply option in Texas. However, one of the more challenging issues—and a potential roadblock to more widespread implementation of desalination—is the lack of detailed information on parameters important to desalination for the brackish sections of Texas Water Development Board (TWDB) designated aquifers.

In 2009 TWDB established the Brackish Resources Aquifer Characterization System (BRACS) program to map and characterize brackish groundwater in the state and facilitate the planning of desalination projects.

We selected the Lower Rio Grande Valley as a study area because of the anticipated need for additional water in the region. Most of the groundwater in the Lower Rio Grande Valley has concentrations of total dissolved solids greater than 1,000 milligrams per liter and does not meet drinking water quality standards. Rio Grande (Region M) Regional Water Planning Area projected population is expected to more than double in the fifty years between 2010 and 2060, from 1.7 million to 3.9 million. The municipal water demand is estimated to increase from 259,524 to 581,043 acre-feet per year in the same time period. Brackish groundwater desalination is expected to provide 92,212 acre-feet per year (13.7 percent of the recommended water management strategies) of water in 2060.

The study area encompasses parts of Cameron, Hidalgo, Starr, and Willacy counties. It lies entirely within the Rio Grande (Region M) Regional Water Planning Area. Parts of the study area lie within four groundwater conservation districts. The Gulf Coast Aquifer and overlying Quaternary geologic units underlie an area of about 3,900 square miles in the study area. It is the primary source of groundwater in the area.

Seven desalination plants treat brackish groundwater for municipal use in the study area, and an additional 23 desalination projects have been recommended by the Rio Grande (Region M) Regional Water Planning Group in the 2012 State Water Plan.

For the study, we collected thousands of water well and geophysical well logs for geologic, water chemistry, water level, and aquifer test data from a wide variety of sources to characterize groundwater in the Gulf Coast Aquifer. From this information, we mapped salinity zones that are three-dimensional regions within the aquifer containing groundwater of a similar salinity range: slightly saline groundwater (1,000 to 3,000 milligrams per liter total dissolved solids), moderately saline groundwater (3,000 to 10,000 milligrams per liter total dissolved solids), very saline groundwater (10,000 to 35,000 milligrams per liter total dissolved solids), and brine (greater than 35,000 milligrams per liter total dissolved solids). The study area contains 21 geographic areas that have a unique salinity zone profile from ground surface to the base of the Gulf Coast Aquifer.

We estimate the Gulf Coast Aquifer in the Lower Rio Grande Valley contains a significant volume of brackish groundwater: more than 40 million acre-feet of slightly saline groundwater, 112 million acre-feet of moderately saline groundwater, and 123 million acre-feet of very saline groundwater. Not all of the brackish groundwater can be produced or be economical, but the estimates provide an indication of the potential availability of this important resource.

Study deliverables include a peer-reviewed, published report, Geographic Information System (GIS) map files, BRACS Database and data dictionary, and water well and geophysical well log files. The real value of this study is the GIS and BRACS Database information. These can be used by stakeholders to map potential groundwater development areas. Information contained in the report is not intended to serve as a substitute for site-specific studies that are required to evaluate local aquifer characteristics and groundwater conditions for a desalination plant.

2. Introduction

A 2003 TWDB-funded study (LBG-Guyton, 2003) estimated brackish groundwater volumes in the state. However, the study was, by design regional in scope, limited in areal extent, and narrow in its assessment of groundwater quality. To improve on the 2003 study, TWDB requested and received funding from the 81st Texas Legislature (2009) to implement the Brackish Resources Aquifer Characterization System program to more thoroughly characterize the brackish aquifers. The 83rd Texas Legislature in 2013 provided additional funding to increase the number of TWDB staff assigned to this program.

The goals of the Brackish Resources Aquifer Characterization System program are to (1) map and characterize the brackish parts of the major and minor aquifers of the state in greater detail using existing water well reports, geophysical well logs, and available aquifer data and (2) build datasets that can be used for groundwater exploration and replicable numerical groundwater flow models to estimate aquifer productivity.

We selected the Lower Rio Grande Valley as a study area because of the anticipated need for additional water supplies. Most of the groundwater in the Lower Rio Grande Valley has concentrations of total dissolved solids greater than 1,000 milligrams per liter and does not meet secondary drinking water quality standards. Population in the Rio Grande (Region M) Regional Water Planning Area is expected to more than double in the 50 years between 2010 and 2060, from 1,628,278 to 3,935,223 (TWDB, 2012). The municipal water demand is estimated to increase from 259,524 to 581,043 acre-feet per year and the municipal water need is expected to increase from 20,889 to 292,700 acre-feet per year in the same time period (TWDB, 2012).

The bulk of the water used in the study area to meet municipal, industrial, and agricultural demands is from surface water. Irrigation water rights are junior to municipal and industrial users in the study area. However, drought can also result in surface-water curtailment to municipal and industrial users (Bureau of Reclamation, 2013). The water supply issues in the study area are complex, encompassing local and international challenges that are explained in great detail in a study by the Bureau of Reclamation (2013).

In 2060, brackish groundwater desalination is expected to provide 92,212 acre-feet per year (13.7 percent of the recommended water management strategies) of new water to that region (Figure M.4, TWDB, 2012). The Bureau of Reclamation (2013) recommended brackish groundwater desalination for preliminary engineering and affordability analysis. Their strategy recommends three generalized locations for future desalination plants (Bureau of Reclamation, 2013).

The study area encompasses parts of Cameron, Hidalgo, Starr, and Willacy counties (Figure 2-1). It lies entirely within the Rio Grande (Region M) Regional Water Planning Area. Parts of four groundwater conservation districts and part of Groundwater Management Area 16 are present within the study area (Figure 2-2).

Presently, seven desalination plants treat brackish groundwater for municipal use in the study area (Figure 2-3). An additional 23 desalination projects (Figure 2-4) have been recommended by the Rio Grande (Region M) Regional Water Planning Group in the 2012 State Water Plan.

The Gulf Coast Aquifer underlies an area of about 3,900 square miles in the study area and is the primary source of groundwater in the region. We used the stratigraphic framework of the Gulf Coast Aquifer developed by Young and others (2010) that included overlying Quaternary deposits such as the Rio Grande Alluvium. The stratigraphic framework extended into the Gulf of Mexico, east of the TWDB-designated Gulf Coast Aquifer boundary based on an upper limit of 3,000 milligrams per liter of total dissolved solids.

Groundwater can contain total dissolved solids (dissolved minerals) which is measured in units of milligrams per liter and is classified in five categories by Winslow and Kister (1956) (Table 2-1). The same groundwater salinity classification was used in the LBG-Guyton (2003) study and in previous studies completed in the TWDB's BRACS program (Meyer and others, 2012; Wise, 2014). For comparison, 1,000 milligrams per liter of total dissolved solids is the secondary limit set by the Texas Commission on Environmental Quality for public water systems (TCEQ, 2013). Seawater has approximately 35,000 milligrams per liter of total dissolved solids (Hem, 1985).

For the study, we collected thousands of water well and geophysical well logs for geologic, water chemistry, water level, and aquifer test data from a wide variety of sources to characterize groundwater in the Gulf Coast Aquifer. From this information, we mapped salinity zones that are three-dimensional regions within the aquifer containing groundwater of a similar salinity range: slightly saline groundwater (1,000 to 3,000 milligrams per liter total dissolved solids), moderately saline groundwater (3,000 to 10,000 milligrams per liter total dissolved solids), very saline groundwater (10,000 to 35,000 milligrams per liter total dissolved solids), and brine (greater than 35,000 milligrams per liter total dissolved solids).

The study area contains 21 geographic areas (Figure 2-5) that have a unique salinity zone profile from ground surface to the base of the Gulf Coast Aquifer (Tables 2-2 through 2-4). Some of the salinity zones are quite complex, with intermingled groundwater of different salinity ranges that could not be classified into unique, mapped zones. The vertical and lateral salinity zone boundaries are often complex, usually occurring in areas with little or limited well control. Placement of these boundaries represents best professional judgment, and can undoubtedly be refined with more data from future drilling and testing. The user is cautioned accordingly when evaluating future well fields near one of these boundaries.

We calculated the volume of groundwater in the Gulf Coast Aquifer based on the three-dimensional salinity zones, using net sand volume and an estimated specific yield of 15 percent. We did not attempt to determine the volume of confined storage; the amount of water derived from confined storage would represent less than one percent of the total volume as estimated by LBG-Guyton (2003).

We estimate that the Gulf Coast Aquifer in the Lower Rio Grande Valley contains a significant volume of brackish groundwater: more than 40 million acre-feet of slightly saline groundwater, 112 million acre-feet of moderately saline groundwater, and 123 million acre-feet of very saline groundwater. However, not all of the brackish groundwater can be produced or will be economical.

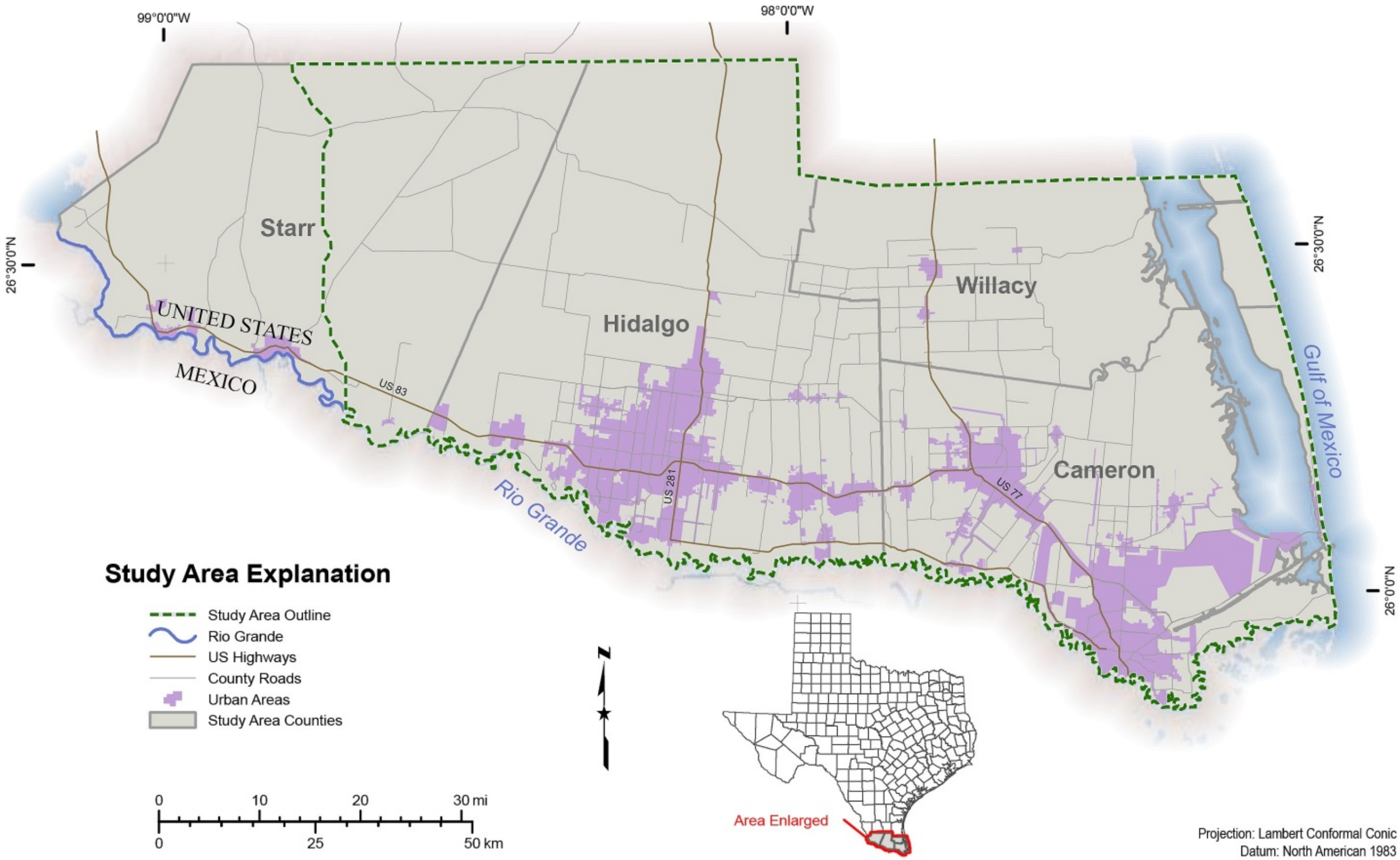


Figure 2-1. **Study area boundary.**

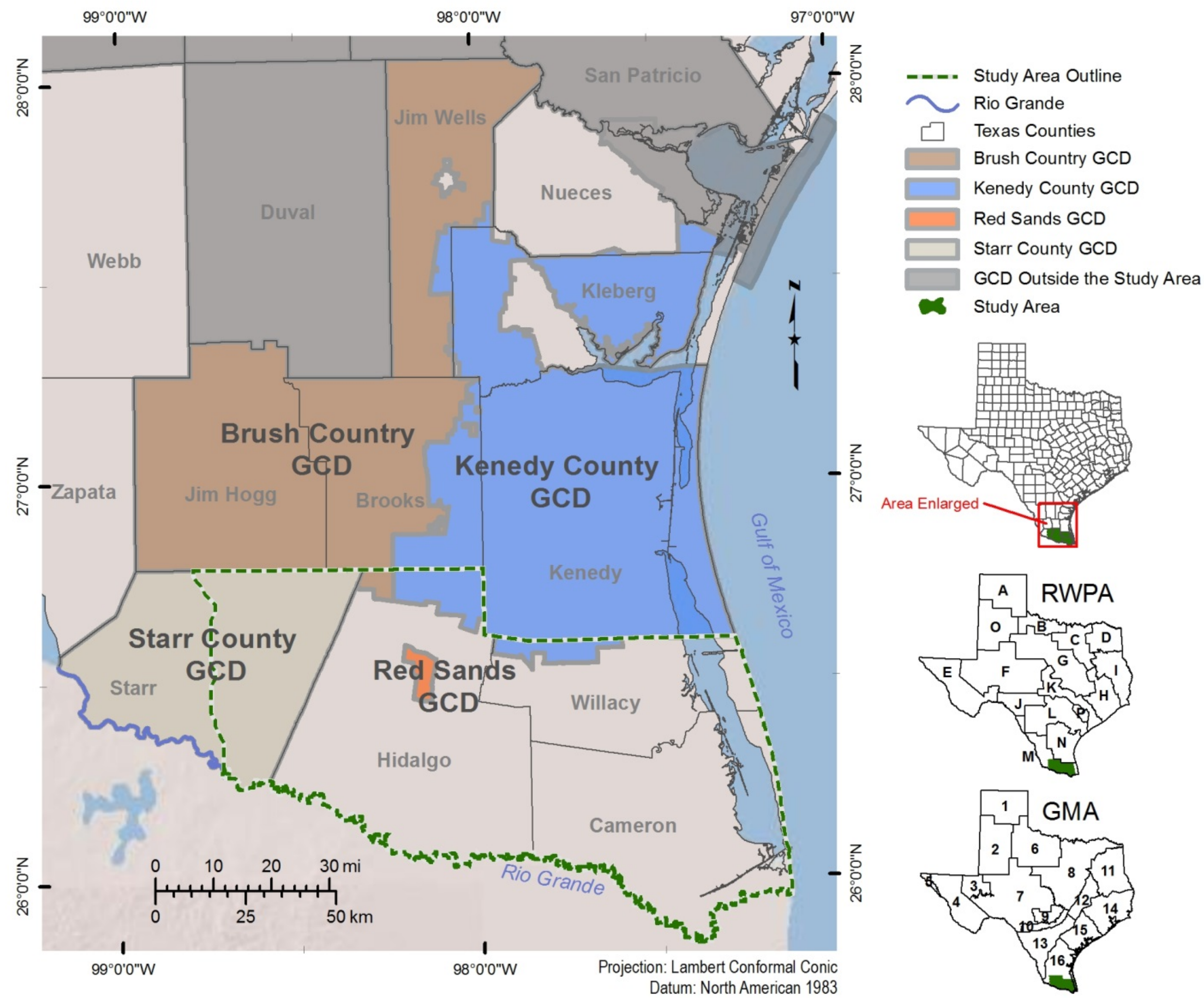
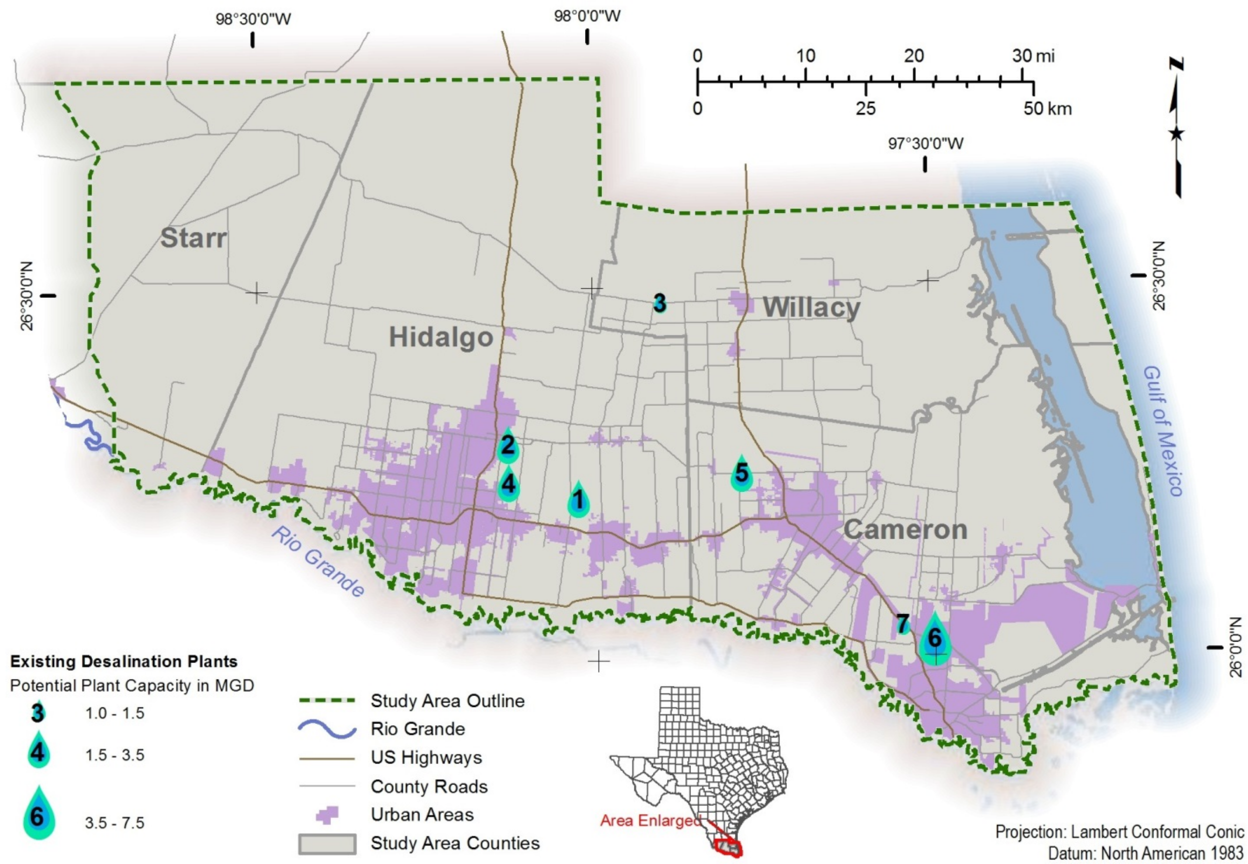
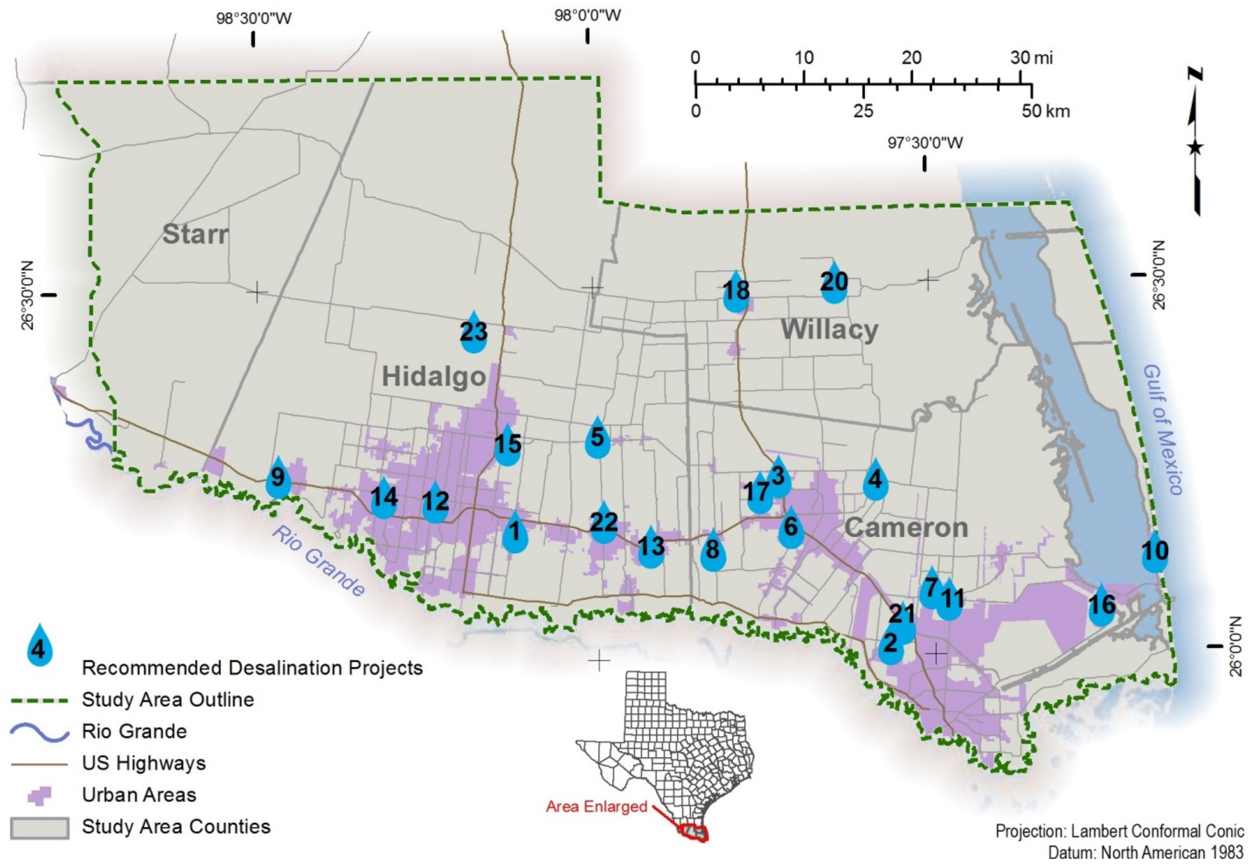


Figure 2-2. **Administrative boundaries within and adjacent to the study area. Acronyms used: GCD = groundwater conservation district; GMA = groundwater management area; RWPA = regional water planning area.**



Map ID	Plant Name	Plant Capacity (million gallons per day)
1	North Alamo Water Supply Corporation (Donna)	2.25
2	North Alamo Water Supply Corporation (Doolittle)	3.5
3	North Alamo Water Supply Corporation (Lasara)	1.2
4	North Alamo Water Supply Corporation (Owassa)	2.0
5	North Cameron / Hidalgo Water Authority	2.5
6	Southmost Regional Water Authority	7.5
7	Valley Municipal Utility District 2	1

Figure 2-3. Existing brackish groundwater desalination plants used for public water supply in the study area. Source of data: TWDB Desalination Database. MGD = millions of gallons per day.



Map ID	Recommended Plant
1	Alamo
2	Brownsville
3	Combes
4	East Rio Hondo
5	Elsa
6	Harlingen
7	Indian Lake
8	La Feria
9	La Joya
10	Laguna Madre Water District
11	Los Fresnos
12	McAllen

Map ID	Recommended Plant
13	Mercedes
14	Mission
15	North Alamo Water Supply Corporation
16	Port Isabel
17	Primera
18	Raymondville
19	Rio Grande City
20	San Perlita
21	Valley Municipal Utility District 2
22	Weslaco
23	County - other

Figure 2-4. Estimated location of brackish groundwater desalination projects recommended by the Rio Grande (Region M) Regional Water Planning Group in the 2012 State Water Plan (TWDB, 2012).

Table 2-1. Groundwater salinity classification used in the study (Winslow and Kister, 1956). Salinity zone codes are used in report tables, the BRACS Database, and the GIS file-naming scheme (Section 21.2). Colors used in this table for each salinity classification are consistent throughout the report and GIS datasets.

Groundwater salinity classification	Salinity zone code	Total dissolved solids concentration (units: milligrams per liter)
Fresh	FR	0 to 1,000
Slightly saline	SS	1,000 to 3,000
Moderately saline	MS	3,000 to 10,000
Very saline	VS	10,000 to 35,000
Brine	BR	Greater than 35,000

Information contained in the report is not intended to serve as a substitute for site-specific studies that are required to evaluate local aquifer characteristics and groundwater conditions for a desalination plant. Sustainability of the brackish aquifers in the study area will need to be determined during well field design and development using monitor and production wells and groundwater modeling. Existing TWDB groundwater models are designed for regional assessment and are not applicable to well field analysis. The models were not constructed to analyze the effect of salinity on groundwater flow and in general should not be used for estimating withdrawal of saline water. Groundwater quantity and quality changes, potential subsidence, and sustainability are significant factors that must be evaluated before developing brackish groundwater.

3. Project deliverables

This peer-reviewed report contains a discussion of the methodology used and conclusions and is available for download from the TWDB website. In addition, this report contains sections describing data collection, previous investigations, 2012 State Water Plan information, hydrogeologic setting, aquifer determination, aquifer hydraulic properties, groundwater chemistry, net sand analysis, geophysical well log investigation, groundwater salinity zones, groundwater volume methodology, electromagnetic data, desalination concentrate disposal, BRACS Database tables, GIS datasets, RWA Minimum Methodology, and Gulf Coast Aquifer formation maps.

Another equally important objective is to make the information and datasets gathered for the study readily available to the public. Thus, all of the information collected is non-confidential. The information includes raw data such as water well reports and digital geophysical well logs, processed data such as lithology, simplified lithologic descriptions, stratigraphic picks, water chemistry, and interpreted results in the form of GIS datasets. The BRACS Database and BRACS Database Data Dictionary (Meyer, 2014) and all GIS datasets are available for download from the TWDB website. Geophysical well logs are available upon request.

Many of the TWDB reports, contracted reports, and databases with supporting data dictionaries mentioned in this report are available on the TWDB website.

4. Study area

The study area encompasses parts of Cameron, Hidalgo, Starr, and Willacy counties that are underlain by the Gulf Coast Aquifer (Figure 2-1). Cities and the boundaries of the larger public water supply systems in the study area are presented in Figures 4-1 through 4-5. A cross-reference between the city name and map identification number used on the figures is provided in Table 4-1. A cross-reference between the public water supply system name, map identification number, and public water supply identification number assigned by the Texas Commission on Environmental Quality is provided in Table 4-2. The public water supply name or identification number can be used to query public water system data from the TCEQ website using the Water Utilities Database (also known as WUD).

The study area lies entirely within the Rio Grande (Region M) Regional Water Planning Area, and contains parts of four groundwater conservation districts and part of Groundwater Management Area 16 (Figure 2-2).

The largest concentration of existing and recommended desalination projects in Texas is present in the study area. Presently, seven desalination plants treat brackish groundwater for municipal use in the study area (Figure 2-3) and 23 additional desalination projects (Figure 2-4) have been recommended in the 2012 State Water Plan. Estimated combined desalination plant capacity in the study area presently is 19.95 million gallons per day, not including ongoing plant expansions. Six of the plants each have one or two production wells and the largest of these plants produces 3.5 million gallons per day of treated water. The Southmost Regional Water Utility has 20 production wells, produces 7.5 million gallons per day of desalinated water (being expanded at the time of writing this report), and provides water to the Brownsville Public Utilities Board, Brownsville Navigation District, City of Los Fresnos, Town of Indian Lake, and Valley Municipal Utility District 2 (Norris, 2006).

Although recommendations have been made for 23 additional desalination projects for the study area, a water user group may not build its own plant. The Southmost Regional Water Utility serves as an example of multiple water systems using a larger regional facility creating an economy of scale that results in significant cost savings (Norris, 2004).

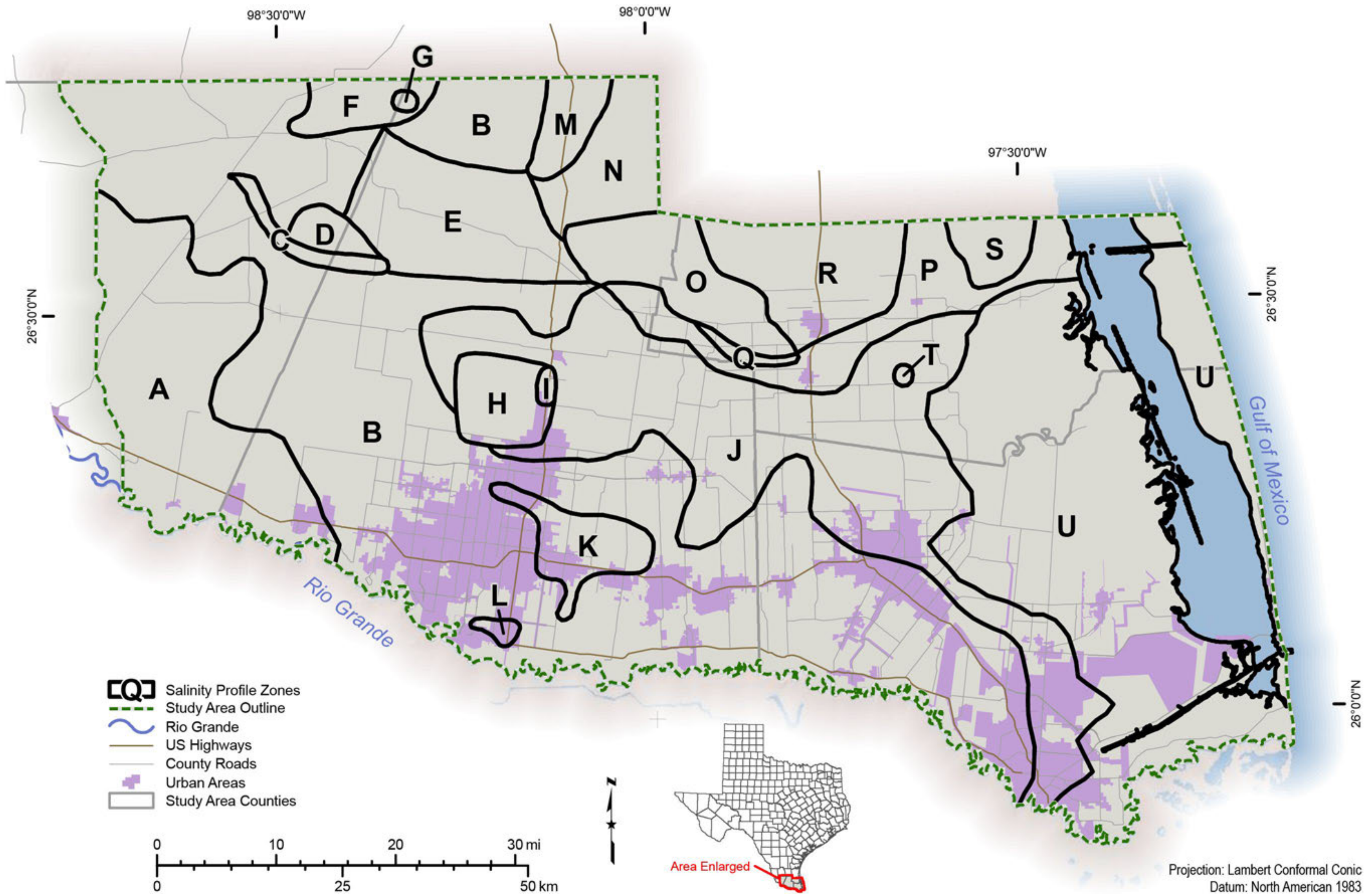


Figure 2-5. **Twenty-one mapped areas labeled A through U represent unique vertical salinity profiles in the Gulf Coast Aquifer. Refer to Tables 2-2 through 2-4 for diagrammatic salinity profiles.**

Table 2-2. **Diagrammatic vertical salinity profiles for salinity areas A through G. Refer to Figure 2-5 for map of salinity areas in the study. Each salinity zone name has a salinity type (SS = slightly saline, MS = moderately saline, VS = very saline, BR = brine), reference to its depth below ground surface (deep, intermediate, shallow), and in some cases a number. Refer to Section 7 for salinity zone horizontal extent, depth to top surface of salinity zone, thickness, and net sand content. Refer to Section 21.2 for GIS file names of each salinity zone.**

A	B	C	D	E	F	G
				SS Shallow 2		VS Shallow 1
		MS Shallow 5		MS Intermediate 1	MS Shallow 4	MS Shallow 4
	SS Deep	SS Deep		SS Deep	SS Deep	SS Deep
MS Deep	MS Deep	MS Deep	MS Deep	MS Deep	MS Deep	MS Deep
VS Deep	VS Deep	VS Deep	VS Deep	VS Deep	VS Deep	VS Deep
BR Deep	BR Deep	BR Deep	BR Deep	BR Deep	BR Deep	BR Deep

Table 2-3. **Diagrammatic vertical salinity profiles for salinity areas H through N. Refer to Figure 2-5 for map of salinity areas in the study. Each salinity zone name has a salinity type (SS = slightly saline, MS = moderately saline, VS = very saline, BR = brine), reference to its depth below ground surface (deep, intermediate, shallow), and in some cases a number. Refer to Section 7 for salinity zone horizontal extent, depth to top surface of salinity zone, thickness, and net sand content. Refer to Section 21.2 for GIS file names of each salinity zone.**

H	I	J	K	L	M	N
	VS Shallow 3			SS Shallow 1	VS Shallow 2	
MS Shallow 2	MS Shallow 2		MS Shallow 1	MS Intermediate 2	MS Intermediate 1	MS Intermediate 1
SS Intermediate	SS Intermediate		SS Deep	SS Deep	SS Deep	SS Deep
MS Deep	MS Deep	MS Deep	MS Deep	MS Deep	MS Deep	MS Deep
VS Deep	VS Deep	VS Deep	VS Deep	VS Deep	VS Deep	VS Deep
BR Deep	BR Deep	BR Deep	BR Deep	BR Deep	BR Deep	BR Deep

Table 2-4. **Diagrammatic vertical salinity profiles for salinity areas O through U. Refer to Figure 2-5 for map of salinity areas in the study. Each salinity zone name has a salinity type (SS = slightly saline, MS = moderately saline, VS = very saline, BR = brine), reference to its depth below ground surface (deep, intermediate, shallow), and in some cases a number. Refer to Section 7 for salinity zone horizontal extent, depth to top surface of salinity zone, thickness, and net sand content. Refer to Section 21.2 for GIS file names of each salinity zone.**

O	P	Q	R	S	T	U
VS Shallow 4			VS Shallow 4			
MS Intermediate 1			MS Intermediate 1	MS Shallow 3	Brine Shallow	
SS Deep	VS Shallow 4		SS Deep	VS Shallow 4	VS Intermediate	
MS Deep	MS Deep	MS Deep	MS Deep	MS Deep	MS Deep	
VS Deep	VS Deep	VS Deep	VS Deep	VS Deep	VS Deep	VS Deep
BR Deep	BR Deep	BR Deep	BR Deep	BR Deep	BR Deep	BR Deep

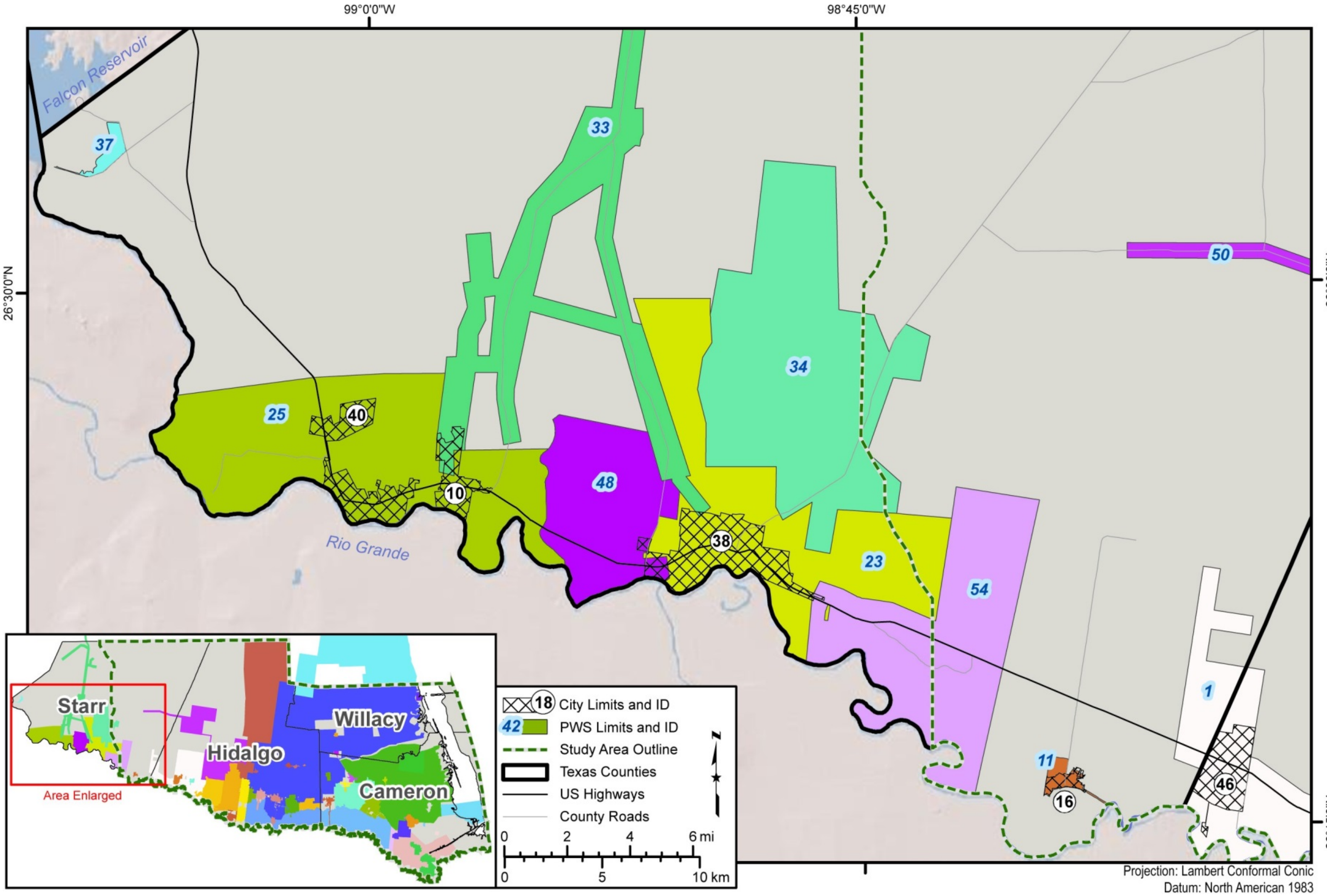


Figure 4-1. **City and public water supply system limits in the western part of the study area. Table 4-1 is a cross-reference of city map numbers and names. Table 4-2 is a cross-reference of public water system map numbers and names. City limits are from Texas Natural Resource Information System geographic information system file. Public water system limits are from HDR (2011). Acronyms used: ID = identification, refers to map number used; PWS = public water system.**

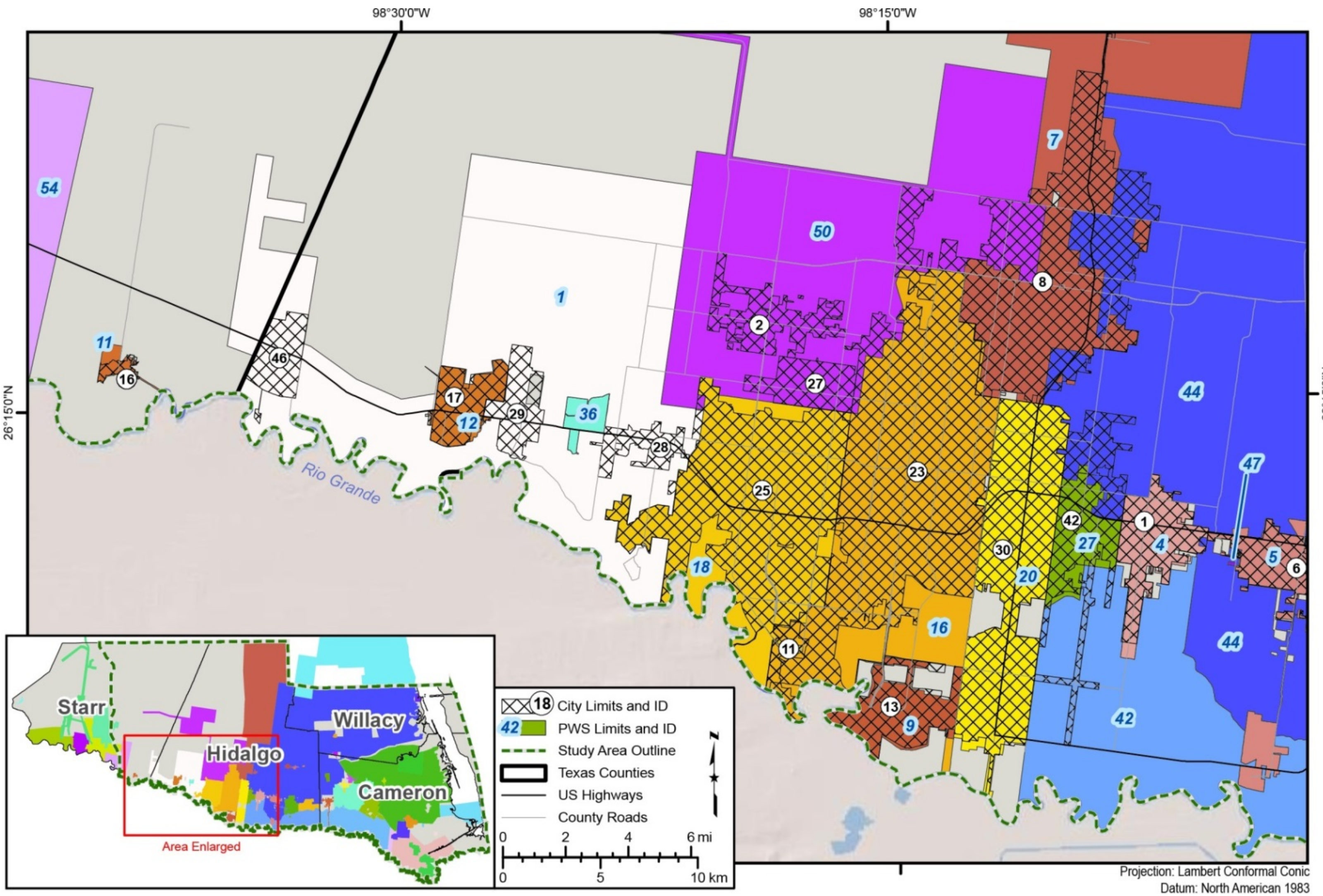


Figure 4-2. **City and public water supply system limits in the central part of the study area. Table 4-1 is a cross-reference of city map numbers and names. Table 4-2 is a cross-reference of public water system map numbers and names. City limits are from Texas Natural Resource Information System geographic information system file. Public water system limits are from HDR (2011). Acronyms used: ID = identification, refers to map number used; PWS = public water system.**

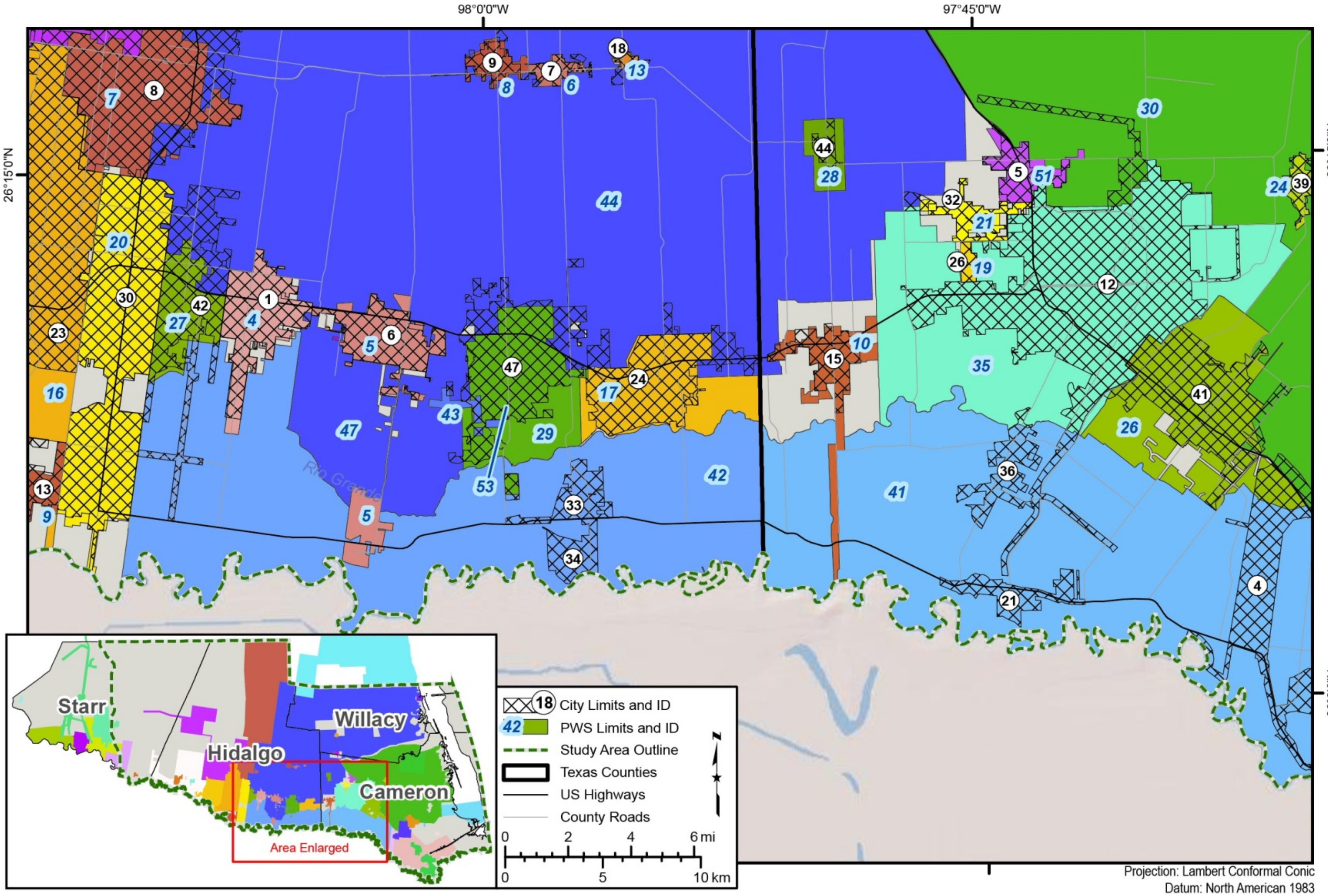


Figure 4-3. City and public water supply system limits in the east-central part of the study area. Table 4-1 is a cross-reference of city map numbers and names. Table 4-2 is a cross-reference of public water system map numbers and names. City limits are from Texas Natural Resource Information System geographic information system file. Public water system limits are from HDR (2011). Acronyms used: ID = identification, refers to map number used; PWS = public water system.

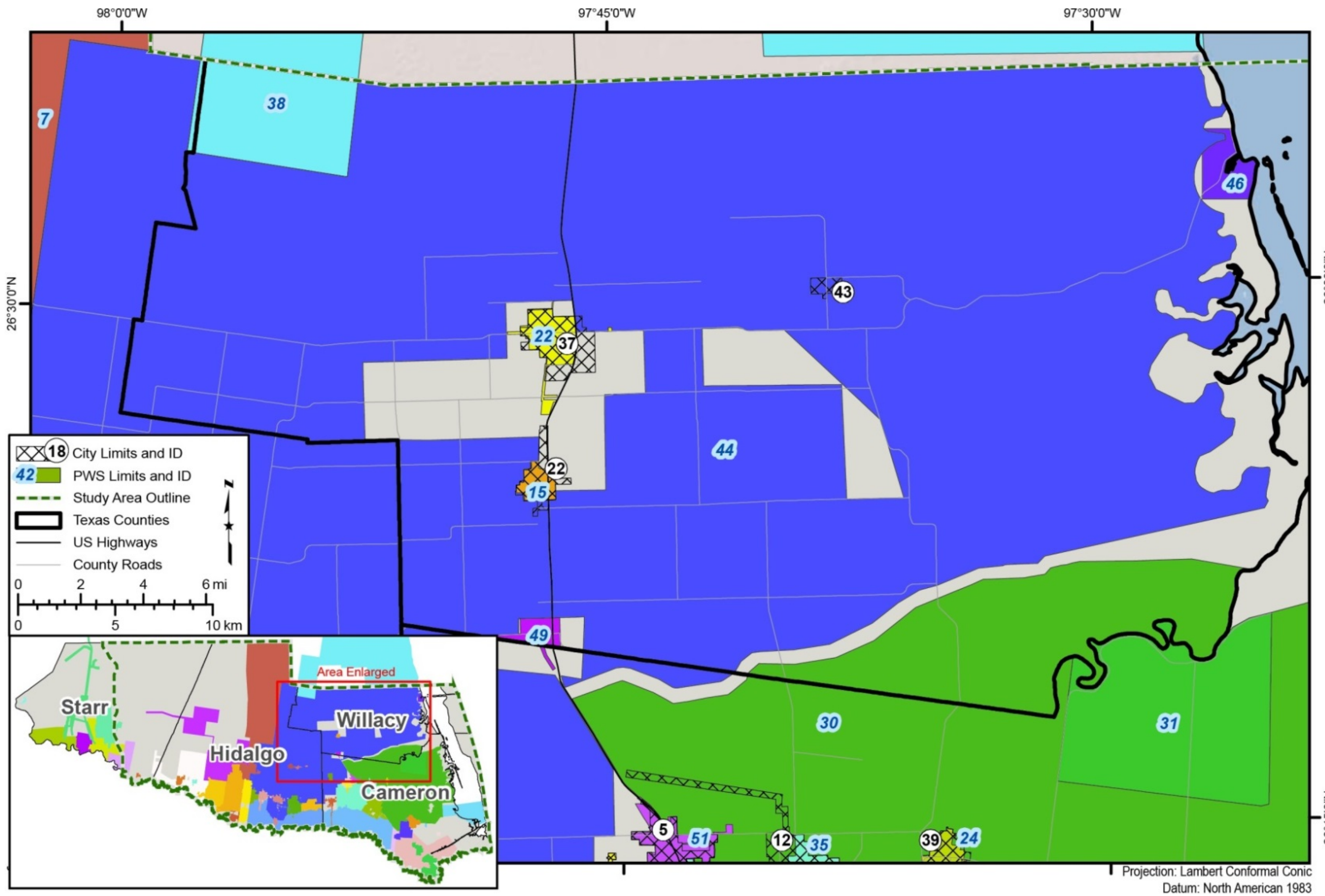


Figure 4-4. **City and public water supply system limits in the northern part of the study area. Table 4-1 is a cross-reference of city map numbers and names. Table 4-2 is a cross-reference of public water system map numbers and names. City limits are from Texas Natural Resource Information System geographic information system file. Public water system limits are from HDR (2011). Acronyms used: ID = identification, refers to map number used; PWS = public water system.**

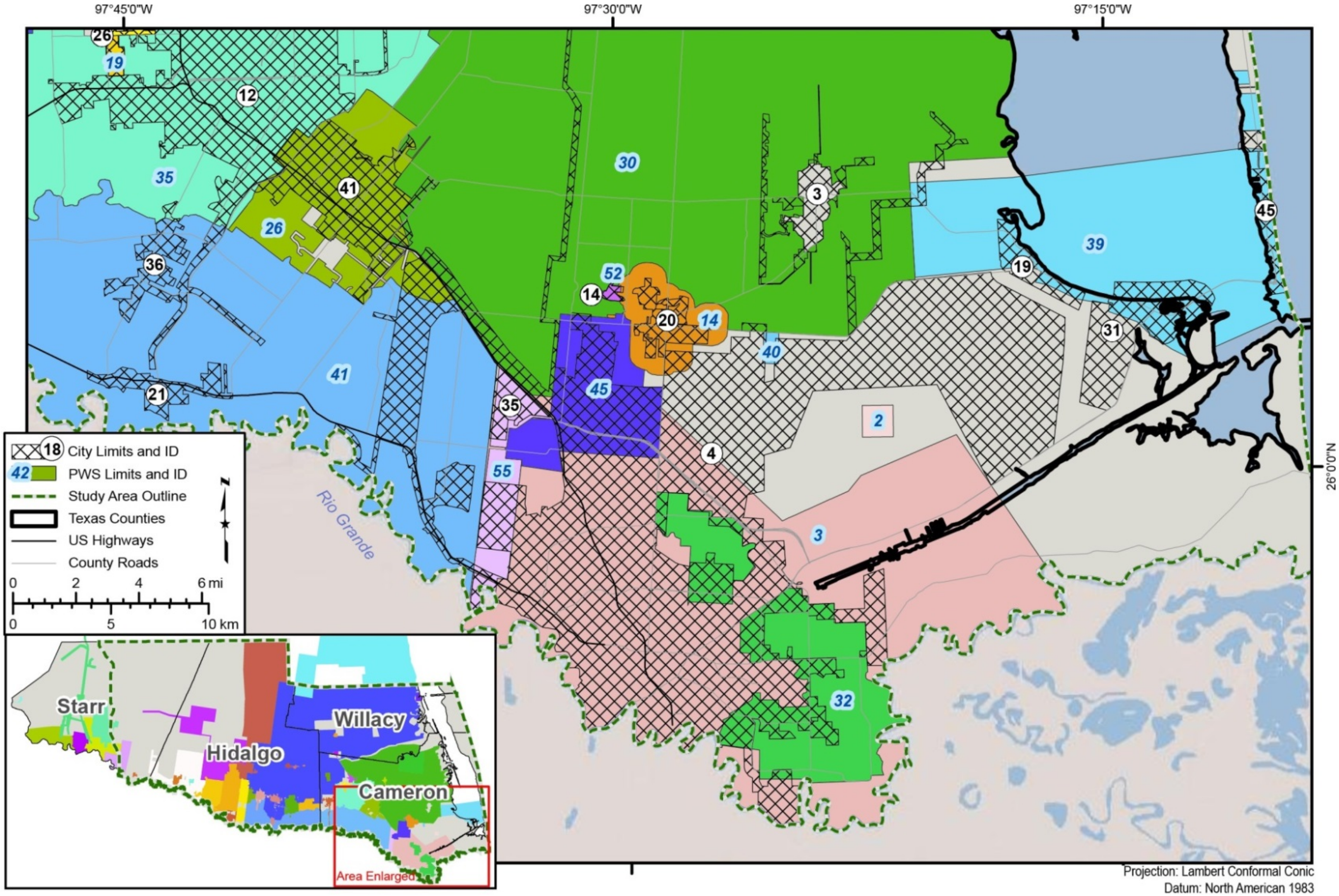


Figure 4-5. **City and public water supply system limits in the eastern part of the study area. Table 4-1 is a cross-reference of city map numbers and names. Table 4-2 is a cross-reference of public water system map numbers and names. City limits are from Texas Natural Resource Information System geographic information system file. Public water system limits are from HDR (2011). Acronyms used: ID = identification, refers to map number used; PWS = public water system.**

Table 4-1. **Cross-reference between the map ID number and city name used in Figures 4-1 through 4-5. ID = identification.**

Map ID	City Name	Map ID	City Name	Map ID	City Name
1	Alamo	17	La Joya	33	Progreso
2	Alton	18	La Villa	34	Progreso Lakes
3	Bayview	19	Laguna Vista	35	Rancho Viejo
4	Brownsville	20	Los Fresnos	36	Rangerville
5	Combes	21	Los Indios	37	Raymondville
6	Donna	22	Lyford	38	Rio Grande City
7	Edcouch	23	McAllen	39	Rio Hondo
8	Edinburg	24	Mercedes	40	Roma
9	Elsa	25	Mission	41	San Benito
10	Escobares	26	Palm Valley	42	San Juan
11	Granjeno	27	Palmhurst	43	San Perlita
12	Harlingen	28	Palmview	44	Santa Rosa
13	Hidalgo	29	Penitas	45	South Padre Island
14	Indian Lake	30	Pharr	46	Sullivan City
15	La Feria	31	Port Isabel	47	Weslaco
16	La Grulla	32	Primera		

Table 4-2. Cross-reference between the map ID number and the public water supply system name and identification number (PWD ID) used in Figures 4-1 through 4-5. The Texas Commission on Environmental Quality official public water supply systems names and assigned ID numbers are used in this table. ID = identification; SUD = Special Utility District; WSC = Water Supply Corporation; MUD = Municipal Utility District; WTP = Water Treatment Plant; PUD = Public Utility District. Source of the water system boundaries is from a 2011 study contracted by the TWDB (HDR, 2011) using 2010 data; not all public water supply systems are present in this dataset, and water system boundaries may have changed since this project was completed.

Symbol	Map ID Number	PWS ID	PWS System Name	Symbol	Map ID Number	PWS ID	PWS Name
	1	1080022	Agua SUD		29	1080011	City of Weslaco
	2	0310028	Brownsville Navigation District		30	0310096	East Rio Hondo WSC
	3	0310001	Brownsville Public Utilities Board		31	0310031	East Rio Hondo WSC Arroyo City
	4	1080001	City of Alamo		32	0310022	El Jardin WSC
	5	1080002	City of Donna		33	2140028	El Sauz WSC
	6	1080003	City of Edcouch		34	2140029	El Tanque WSC
	7	1080004	City of Edinburg		35	0310002	Harlingen Water Works System
	8	1080005	City of Elsa		36	1080088	Hidalgo County MUD 1
	9	1080021	City of Hidalgo		37	2140002	IBWC Falcon Village
	10	0310003	City of La Feria		38	1310003	King Ranch Norias
	11	2140006	City of La Grulla		39	0310005	Laguna Madre Water District
	12	1080213	City of La Joya		40	0310147	Military Hwy WSC Del Mar Heights
	13	1080023	City of La Villa		41	1080067	Military Hwy WSC Las Rusias WTP
	14	0310004	City of Los Fresnos		42	1080234	Military Hwy WSC Progreso
	15	2450003	City of Lyford		43	1080235	Military Hwy WSC Weslaco
	16	1080006	City of McAllen		44	1080029	North Alamo WSC
	17	1080007	City of Mercedes		45	0310026	Olmito WSC
	18	1080008	City of Mission		46	2450004	Port Mansfield PUD
	19	0310027	City of Palm Valley		47	1080221	Quiet Village II
	20	1080009	City of Pharr		48	2140016	Rio WSC
	21	0310094	City of Primera		49	2450006	Sebastian MUD
	22	2450001	City of Raymondville		50	1080033	Sharyland WSC
	23	2140018	City of Rio Grande City		51	0310021	Town of Combes
	24	0310006	City of Rio Hondo		52	0310008	Town of Indian Lake
	25	2140007	City of Roma		53	1080223	Trails End Mobile Home Park
	26	0310007	City of San Benito		54	2140004	Union WSC
	27	1080010	City of San Juan		55	0310059	Valley MUD 2 Rancho Viejo
	28	0310009	City of Santa Rosa				

5. Rio Grande Regional Water Planning Area summary, 2012 State Water Plan information

The following description of existing water supplies, needs, and recommended water strategies are excerpted from the 2012 State Water Plan representing the entire Rio Grande (Region M) Regional Water Planning Area:

> *Existing water supplies:*
> *Surface water provides over 90 percent of the region's water supply. The principal surface water source is the Rio Grande, its tributaries, and two major international reservoirs, one of which is located upstream above the planning area's northern boundary. The United States' share of the firm yield of these reservoirs is over 1 million acre-feet; however, sedimentation will reduce that yield by 3 percent (about 31,000 acre-feet of existing supply) over the planning period. About 87 percent of the United States' surface water rights in the international reservoirs go to the lower two counties in the planning area, Cameron and Hidalgo. There are two major aquifers in the region: the Carrizo-Wilcox and Gulf Coast. A large portion of the groundwater found in Region M's portion of the Gulf Coast Aquifer is brackish. By 2060, the total surface water and groundwater supply is projected to decline 2 percent.*
>
> *Needs:*
> *The region's surface water supplies from the Rio Grande depend on an operating system that guarantees municipal and industrial users' supplies over other categories (particularly agriculture). Thus, the total water supply volume is not accessible to all water users throughout the region, resulting in significant water needs occurring during drought across the region. In the event of drought conditions, total water needs of 435,922 acre-feet could have occurred across the region as early as 2010, and by 2060 these water needs are projected to increase to 609,906 acre-feet. The majority of the Rio Grande Region water needs are associated with irrigation and municipal uses. Irrigation accounted for 93 percent of the Rio Grande Region's total water needs in 2010 and is projected to decrease to 42 percent by 2060. During the same time period, municipal water needs increase from 6 percent to 54 percent of the region's total water needs.*
>
> *Recommended Water Management Strategies and Cost:*
> *The Rio Grande Planning Group recommended a variety of water management strategies to meet future needs including municipal and irrigation conservation, reuse, groundwater development, desalination, and surface water reallocation. The total needs for Region M are projected to decrease between 2010 and 2030 due to the rate of irrigation demand decrease being larger than the rate of municipal demand increase. However, after the year 2030 the rate of change for increasing municipal demand surpasses that of the decreasing irrigation demand resulting in the steady increase of total needs through the year 2060. Implementation of the recommended strategies will meet all regional needs (including all the needs associated with municipalities) for water users identified in the plan except for a significant portion of the region's irrigation needs, for which no economically feasible strategies were identified. This is estimated to be up to 394,896 acre-feet of unmet irrigation needs in 2010. In all, the recommended strategies would*

provide over 673,846 acre-feet of additional water supply by the year 2060 at a total capital cost of $2.2 billion.

Brackish groundwater desalination is expected to provide up to 92,212 acre-feet per year (13.7 percent of the recommended water management strategies) of water in 2060 with a capital cost of $267 million (TWDB, 2012). The region's population, water supply, demands, and needs are summarized in Table 5-1.

Table 5-1. Rio Grande (Region M) Regional Water Planning Area population, water supply, demand, and needs, listed for each decade from 2010 through 2060 (TWDB, 2012).

	2010	2020	2030	2040	2050	2060
Projected population	1,628,278	2,030,994	2,470,814	2,936,748	3,433,188	3,935,223
Existing supplies (acre-feet per year)						
Surface water	1,008,597	1,002,180	996,295	990,244	983,767	977,867
Groundwater	81,302	84,650	86,965	87,534	87,438	87,292
Reuse	24,677	24,677	24,677	24,677	24,677	24,677
Total water supplies	1,114,576	1,111,507	1,107,937	1,102,455	1,095,882	1,089,836
Demands (acre-feet per year)						
Municipal	259,524	314,153	374,224	438,453	508,331	581,043
County-other	28,799	35,257	42,172	49,405	57,144	64,963
Manufacturing	7,509	8,274	8,966	9,654	10,256	11,059
Mining	4,186	4,341	4,433	4,523	4,612	4,692
Irrigation	1,163,634	1,082,232	981,748	981,748	981,748	981,748
Steam-electric	13,463	16,864	19,716	23,192	27,430	32,598
Livestock	5,817	5,817	5,817	5,817	5,817	5,817
Total water demands	1,482,932	1,466,938	1,437,076	1,512,792	1,595,338	1,681,920
Needs (acre-feet per year)						
Municipal	20,889	53,849	98,933	154,514	221,595	292,700
County-other	5,590	10,428	16,786	23,491	30,698	37,925
Manufacturing	1,921	2,355	2,748	3,137	3,729	4,524
Irrigation	407,522	333,246	239,408	245,896	252,386	258,375
Steam-electric	0	1,980	4,374	7,291	11,214	16,382
Total water needs	435,922	401,858	362,249	434,329	519,622	609,906

6. Hydrogeologic setting

The study area is located over the Gulf Coast Aquifer, a regional aquifer that extends from the Texas-Republic of Mexico border in the south to Louisiana and beyond in the north. Sediments of the Gulf Coast Aquifer are Cenozoic in age and were deposited in fluvial-deltaic or shallow marine depositional environments influenced by sediment input, basin subsidence, erosion, sediment compaction and movement, and sea-level fluctuations. Brown and Loucks (2009) have identified 31 sequences (sequences 19 through 49) within formations of the Gulf Coast Aquifer containing multiple unconformities. Sedimentary sequences consist of discontinuous sand, silt, clay, and gravel deposits influenced by syn- and post-depositional growth faults and, in parts of the Gulf Coast, by movement of salt domes. Formations within the study area were deposited within the Rio Grande embayment, a broad structural depression that is present south of the San Marcos Arch. The Rio Grande embayment focused accumulation of sediment from one of five persistent extrabasinal fluvial axes in the Gulf Coast that extended the coastal margin seaward during the Cenozoic Era (Galloway and others, 2000).

While a detailed description of the hydrostratigraphy of the study area is beyond the scope of this report, excellent information on the subject is presented in reports (for example, Young and others, 2010) that are available on the TWDB website.

For our study, we used the stratigraphic picks defined by Young and others (2010) for the Gulf Coast Aquifer. The hydrostratigraphy forms the basis for subdividing the lithology, water quality, and hydraulic properties information into consistent formations/aquifers for comparison purposes. The relationship between the geologic formations, their age, and individual aquifers that comprise the Gulf Coast Aquifer is shown in Table 6-1.

We estimated the regional structural dip of the Gulf Coast Aquifer along a 100-mile-long, northwest-southeast line that bisects the study area. The regional structural dip is approximately 44 feet per mile at the base of the Chicot Aquifer, 91 feet per mile at the base of the Evangeline Aquifer, and 114 feet per mile at the base of the Jasper Aquifer. The increase in dip with depth of the aquifer across the study area is the result of the increasing thickness of formations coastward.

Major growth faults in eastern Willacy and Cameron counties extend into the base of the Gulf Coast Aquifer (Ewing, 1991), directly below saline areas U and adjacent areas B, J, P, and S (Figure 6-1). Brine overlies very saline groundwater in area T. Areas J and B have shallow layers of moderately and slightly saline water overlying the very saline groundwater. Growth faults to the west penetrate deeper formations and their potential connection to the Gulf Coast Aquifer is unknown (Figure 6-1).

Table 6-1. **Stratigraphic column showing relationship between geologic epoch and age, formation, and aquifer. The Gulf Coast Aquifer comprises the Chicot, Evangeline, and Jasper aquifers. Modified from Young and others (2010). Formation assignment to epoch and age still in debate among geologists.**

<table>
<tr><th>Epoch and age (millions of years before present)</th><th>Geologic formation</th><th colspan="2">Hydrogeologic unit</th></tr>
<tr><td rowspan="2">Pleistocene (1.8-present)</td><td>Beaumont</td><td rowspan="3">Chicot Aquifer</td><td rowspan="11">Gulf Coast Aquifer</td></tr>
<tr><td>Lissie</td></tr>
<tr><td rowspan="2">Pliocene (5.6-1.8)</td><td>Willis</td></tr>
<tr><td rowspan="2">Upper Goliad</td><td rowspan="4">Evangeline Aquifer</td></tr>
<tr><td rowspan="6">Miocene (23.8-5.6)</td></tr>
<tr><td>Lower Goliad</td></tr>
<tr><td>Upper Lagarto</td></tr>
<tr><td>Middle Lagarto</td><td>Burkeville Confining Unit</td></tr>
<tr><td>Lower Lagarto</td><td rowspan="3">Jasper Aquifer</td></tr>
<tr><td>Oakville</td></tr>
<tr><td>Oligocene</td><td>(upper) Catahoula</td></tr>
</table>

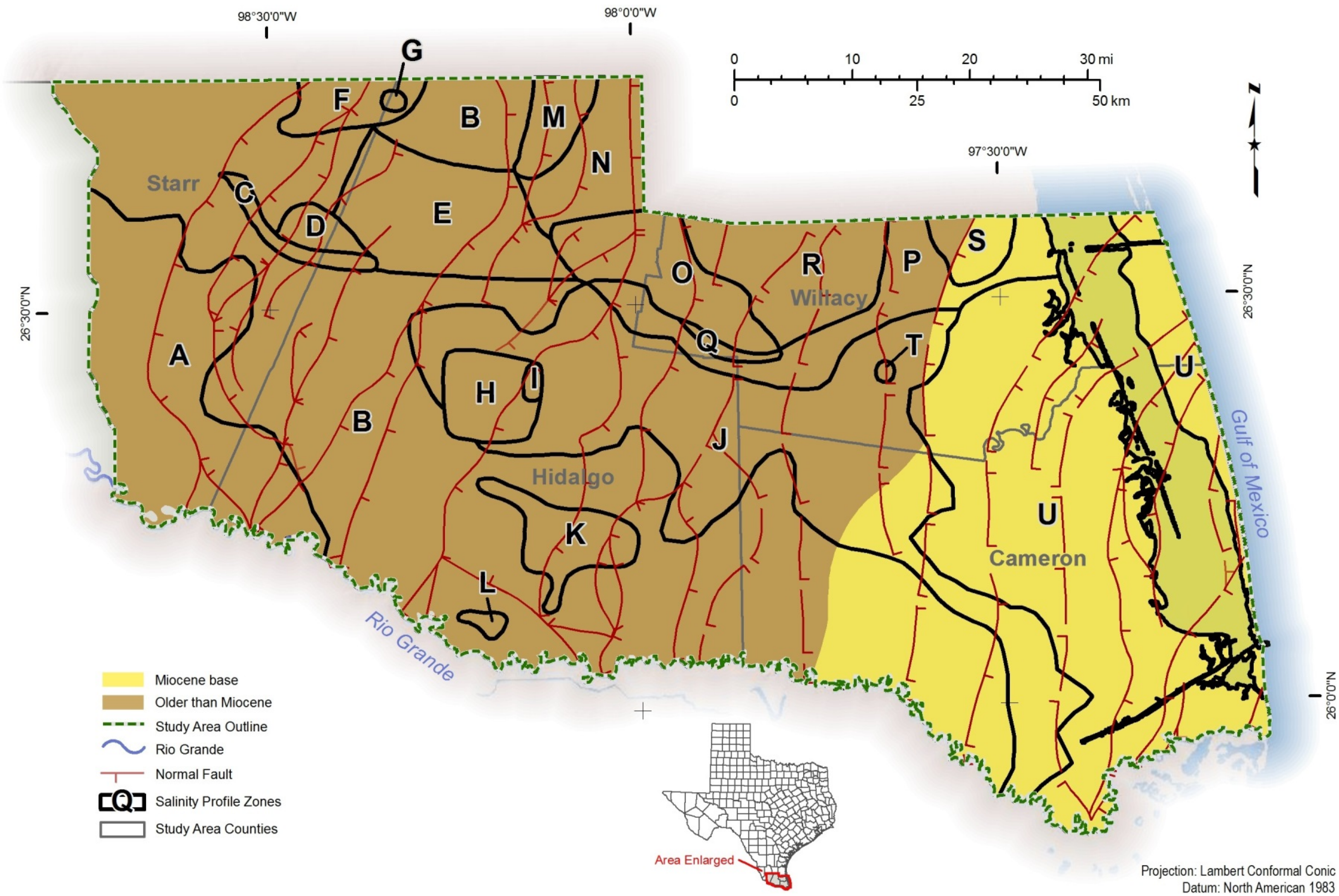


Figure 6-1. **Salinity profile areas and major growth faults in the study area mapped by Ewing (1991). Growth faults in the eastern part of the study area may intersect Miocene-age formations of the lower Gulf Coast Aquifer. Growth faults west of this zone affect formations older than the Gulf Coast Aquifer formations, however their impact on the Gulf Coast Aquifer is not known. We prepared this figure with a GIS version (Breton, 2013) of Ewing (1991).**

7. Groundwater salinity zones

We interpreted 114 geophysical well logs in this study to estimate the concentration of total dissolved solids across the entire depth range of the Gulf Coast Aquifer. We used geophysical well logs because groundwater quality data is limited both laterally and especially vertically within the Gulf Coast Aquifer. Where possible, groundwater quality samples were used to calibrate the geophysical well log interpretation for a limited, shallow portion of the Gulf Coast Aquifer. For formations without nearby water quality samples, we used formation groundwater correction factors derived from an analysis of the complete water quality dataset. Methodology used to interpret the geophysical well logs in this study is provided in Section 21.3.

We investigated each formation of the Gulf Coast Aquifer, if present, on each geophysical well log using the RWA Minimum Method (Estepp, 1998). We determined an interpreted concentration of total dissolved solids for each formation, and assigned a salinity zone with top and bottom depths based on the groundwater salinity classification (Table 2-1). If a formation contained more than one salinity zone, the top and bottom depths of the salinity zones were interpreted from multiple zones in the formation. We appended the results to the geology table (tblWell_Geology) in the BRACS Database as a hydrochemical record.

We used the results of geophysical well log interpretation and groundwater quality samples from wells with screen information to prepare three-dimensional salinity zones based on the groundwater salinity classification (Table 2-1). The horizontal and vertical boundaries of the three-dimensional salinity zone represent a transition from one salinity zone to another. The geophysical well logs provide better control on the vertical transition. The lateral transition from one salinity zone to another is less well understood because of the limited number of geophysical well logs and water quality samples in the study area. Thus, the salinity zone boundaries are based on best professional judgment of existing data and are subject to change with the availability of more data in the future. Users of this study are advised accordingly.

We developed a naming scheme for each of the salinity zones consisting of the groundwater salinity classification system, a qualitative depth term (deep, intermediate, and shallow), and an integer if more than one zone of this type was present in the study area. An example of this naming scheme would be: Slightly Saline Shallow 1.

We created three-dimensional salinity zones by extracting well points from the BRACS Database with attributes including latitude and longitude coordinates to a table, exporting to ArcGIS®, and converting to a point shape file using a Lambert Conformal Conic projection with a 1983 North American Datum horizontal datum. We extracted a subset of points representing each salinity classification and water quality data points sorted by salinity zone classification for each salinity zone for analysis. We deleted data points from each point file if they were not applicable or contained only partial information at that well point. Two examples of partial information include the cased section of a well or a shallow water well that partially penetrated the zone of interest. We addressed conflicts between water quality samples and geophysical well logs, with water quality data generally being given more importance. Wells with water quality data often only partially penetrate a salinity zone. In these cases, we estimated the salinity zone bottom depth value as total well depth plus 25 feet. We added dummy points representing a zero value to some point files to force the ArcGIS® Spatial Analyst® Topo to Raster tool to thin along the edges of a salinity zone. We added results from qualitative analysis of geophysical well logs as well points for some salinity zones to better define top, bottom, and lateral boundaries.

Salinity zone point files were interpolated using the ArcGIS® Spatial Analyst® Topo to Raster tool and saved as raster grid files snapped to the project snap raster grid. Each raster has a Lambert Conformal Conic projection with a 1983 North American Datum horizontal datum. Several data processing steps were required to prepare a final integer raster grid with each well point depth value copied into the corresponding grid cell. We corrected the top and bottom surfaces of the salinity zones with overlying and underlying surfaces to ensure that overlaps and gaps did not exist. We created a top depth, bottom depth, and thickness file for each salinity zone. Methodology to prepare GIS files and tables listing file names are presented in Section 21.2.

Twenty-one geographic areas are defined by a unique salinity profile from ground surface to the base of the Gulf Coast Aquifer. Each salinity profile is represented by letters A through U on Figure 2-5. Diagrammatic salinity profiles are presented in Tables 2-2 through 2-4.

We assigned each well in the study area (all BRACS Database wells and all Groundwater Database wells) salinity zone top and bottom depths based on the GIS surfaces. Each well was also assigned the one-character salinity area profile letter. The BRACS Database table tblSalinityZoneDetermination_GulfCoast was designed for this task and contains all of the information, including well screen and depth data. The BRACS Database form frmSalinityZone_GulfCoast was designed to display this information, along with links to water quality samples. Each well in the study area can be queried to view these relationships. For example, this information was used to determine the net sand values per salinity zone used for volumetric calculations. The information can also be used to assign wells with hydraulic properties to different salinity zones.

A discussion of each salinity zone is presented with tables referencing applicable figures and tables.

7.1 Slightly saline zones

We identified four slightly saline zones in this study: two shallow zones (ss_s1, ss_s2), an intermediate zone (ss_i), and a deep zone (ss_d). The slightly saline deep zone extends from the ground surface to depths of approximately 2,075 feet. As a result, it underlies shallower zones of differing water quality. The slightly saline deep zone (ss_d) overlies the moderately saline deep zone (ms_d). Two slightly saline shallow zones (ss_s1, ss_s2) and one slightly saline intermediate zone (ss_i) overlie moderately saline water in the study area.

To add to the complexity, pockets of fresh groundwater and moderately saline groundwater are intermingled within the slightly saline deep zone. These pockets are identified by water quality samples from water wells completed in the Gulf Coast Aquifer and, in rare cases, geophysical well logs. These pockets are small and complex, precluding definition as individual three-dimensional salinity zones but are mapped on Figure 7.1-1 as polygons showing water wells with symbols colored according to the salinity classification.

The following desalination plants produce brackish groundwater from the slightly saline deep zone: Southmost Regional Water Authority, North Alamo Water Supply Corporation Lasara, Owassa, and Doolittle (shallow well).

Reference figures, tables, and appendices for each of the slightly saline salinity zones is presented in Tables 7.1-1 through 7.1-4.

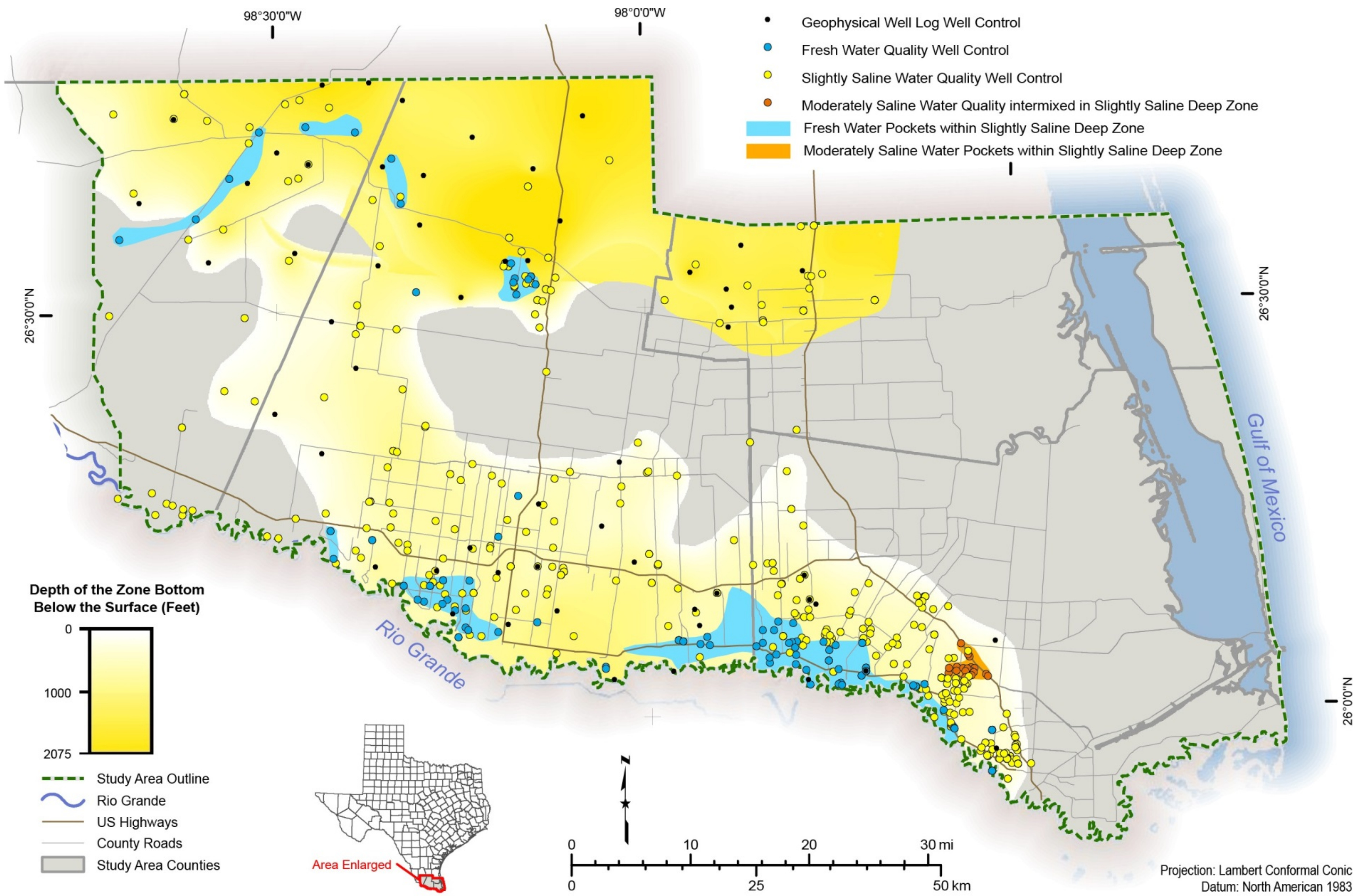


Figure 7.1-1. **Slightly saline deep zone well control consisting of interpreted geophysical well logs and water well water quality data. Pockets of fresh water and moderately saline water intermingled with slightly saline water are shown as blue and orange polygons on this map.**

Table 7.1-1. Slightly saline deep zone (ss_d) figures and tables.

Salinity area(s)	B, C, E, F, G,K, L, M, N, O, R
Salinity area map	Figure 2-5
Salinity profile(s)	Tables 2-2 through 2-4
Top depth map	Figure 7.1-2
Thickness map	Figure 7.1-3
Well control map	Figure 7.1-1
Net sand map	Figure 7.1-4
Groundwater volume	Table 14-1
GIS files	Section 21.2, Table 21.2.4-1

Table 7.1-2. Slightly saline shallow 1 zone (ss_s1) figures and tables.

Salinity area(s)	L
Salinity area map	Figure 2-5
Salinity profile(s)	Table 2-3
Top depth map	Figure 7.1-5
Thickness map	Figure 7.1-6
Well control map	No map, refer to GIS file
Net sand map	No map, manual calculation from wells
Groundwater volume	Table 14-1
GIS files	Section 21.2, Table 21.2.4-1

Table 7.1-3. Slightly saline shallow 2 zone (ss_s2) figures and tables.

Salinity area(s)	E
Salinity area map	Figure 2-5
Salinity profile(s)	Table 2-2
Top depth map	Figure 7.1-5
Thickness map	Figure 7.1-6
Well control map	No map, refer to GIS file
Net sand map	Figure 7.1-7
Groundwater volume	Table 14-1
GIS files	Section 21.2, Table 21.2.4-1

Table 7.1-4. Slightly saline intermediate zone (ss_i) figures and tables.

Salinity area(s)	H, I
Salinity area map	Figure 2-5
Salinity profile(s)	Table 2-3
Top depth map	Figure 7.1-5
Thickness map	Figure 7.1-6
Well control map	No map, refer to GIS file
Net sand map	No map, manual calculation from wells
Groundwater volume	Table 14-1
GIS files	Section 21.2, Table 21.2.4-1

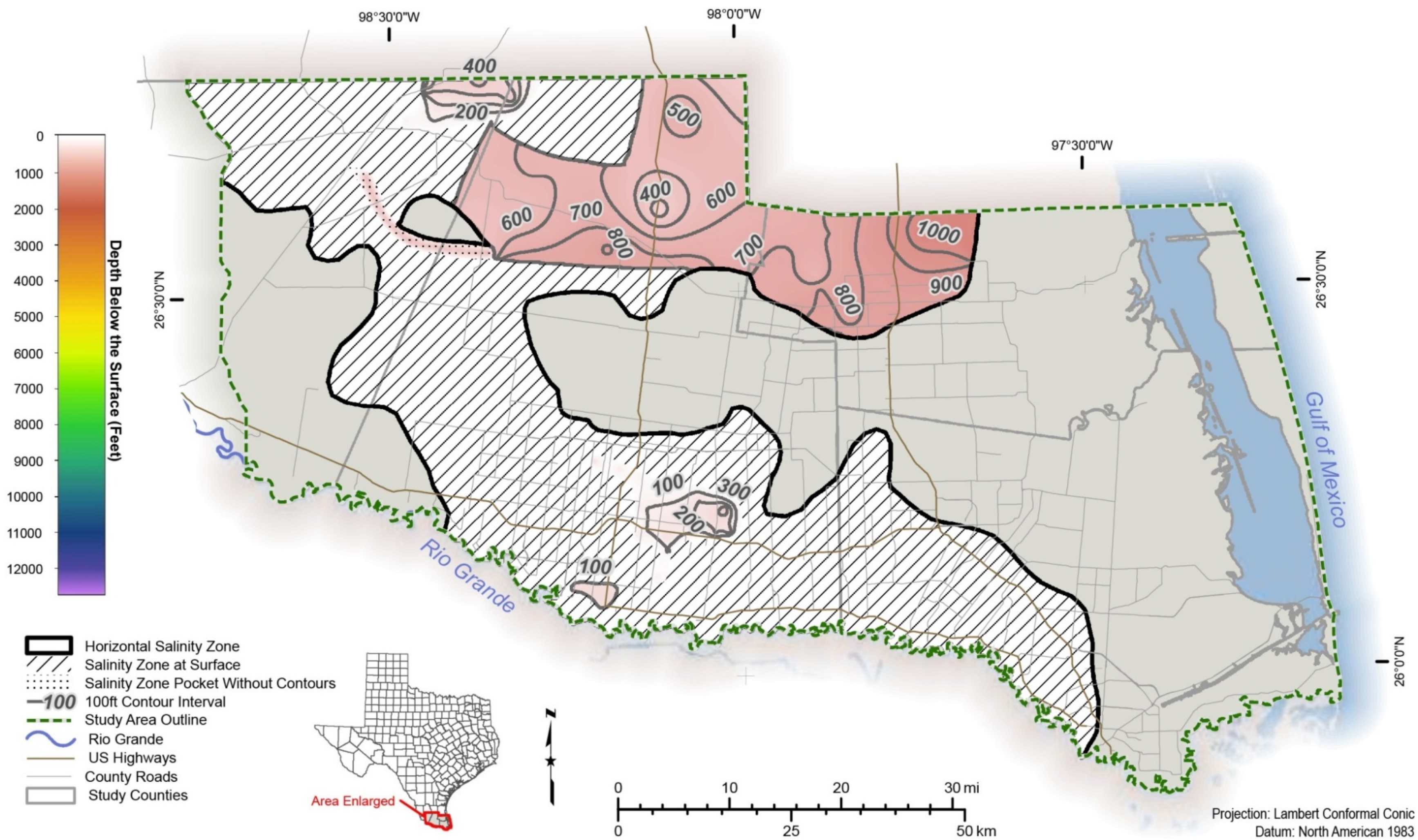


Figure 7.1-2. Depth (below ground surface) to the top of the slightly saline deep zone.

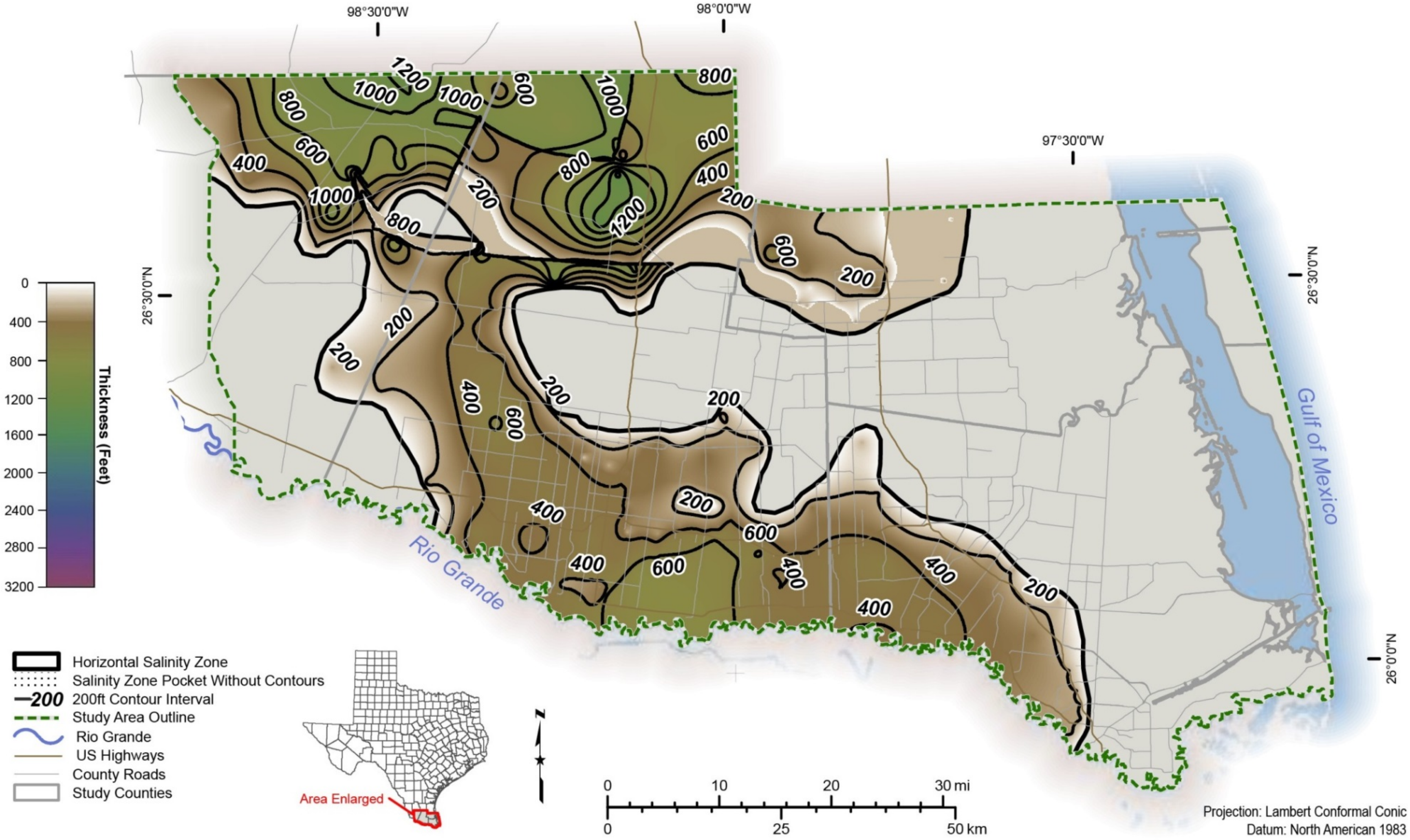


Figure 7.1-3. Thickness of the slightly saline deep zone.

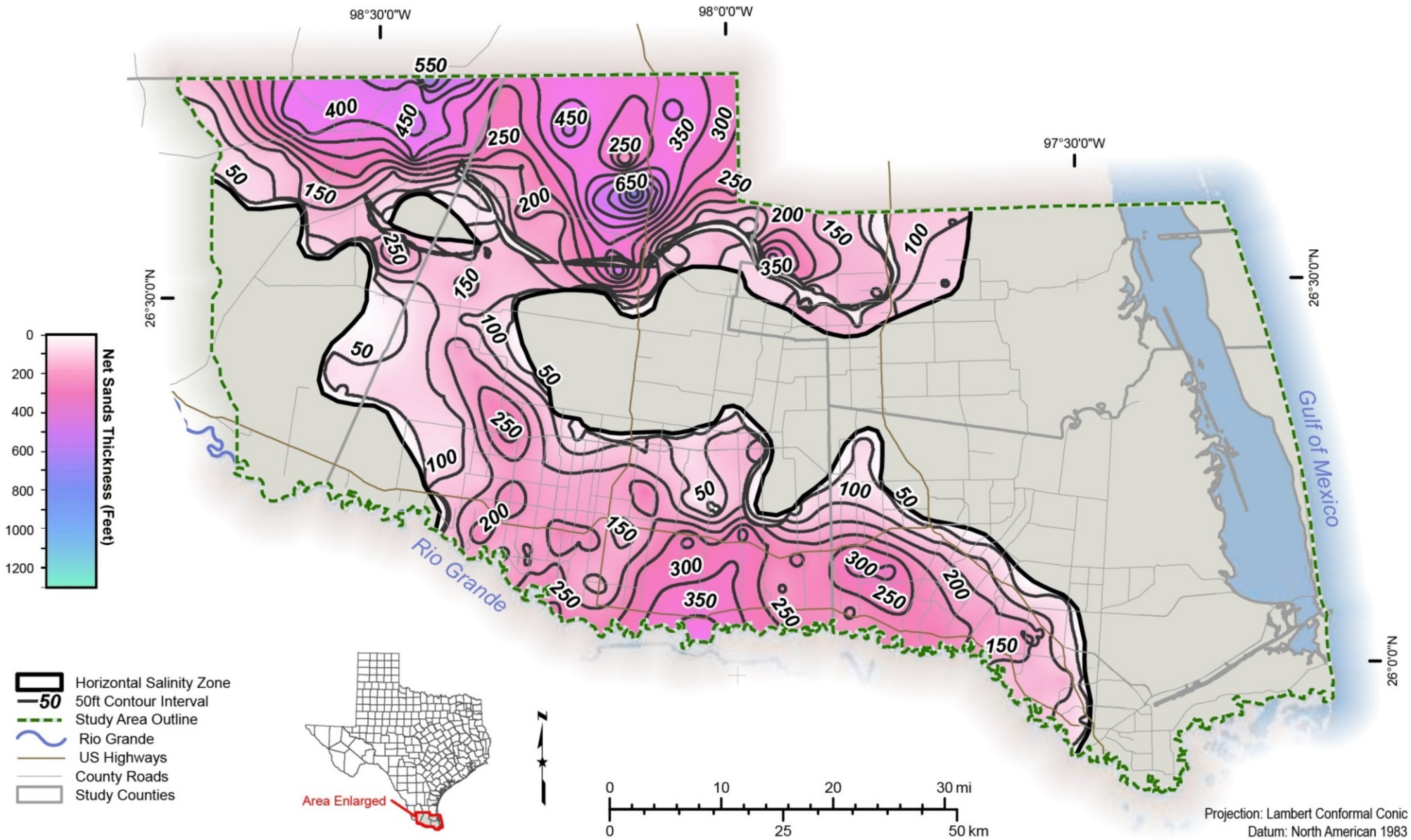


Figure 7.1-4. Net sand thickness of the slightly saline deep zone.

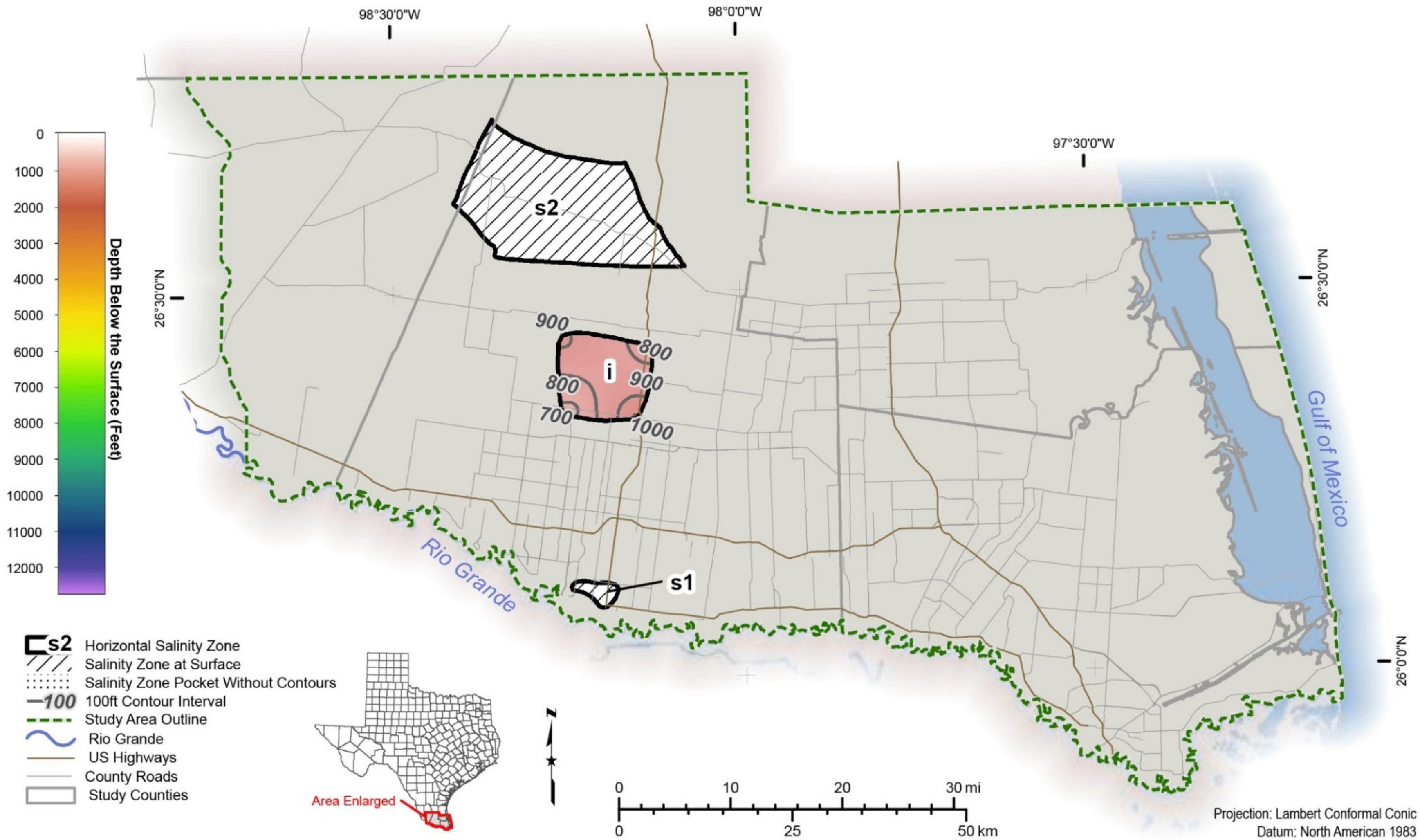


Figure 7.1-5. **Depth (below ground surface) to the top of the slightly saline shallow 1, shallow 2, and intermediate zones.**

Figure 7.1-6. Thickness of the slightly saline shallow 1, shallow 2, and intermediate zones.

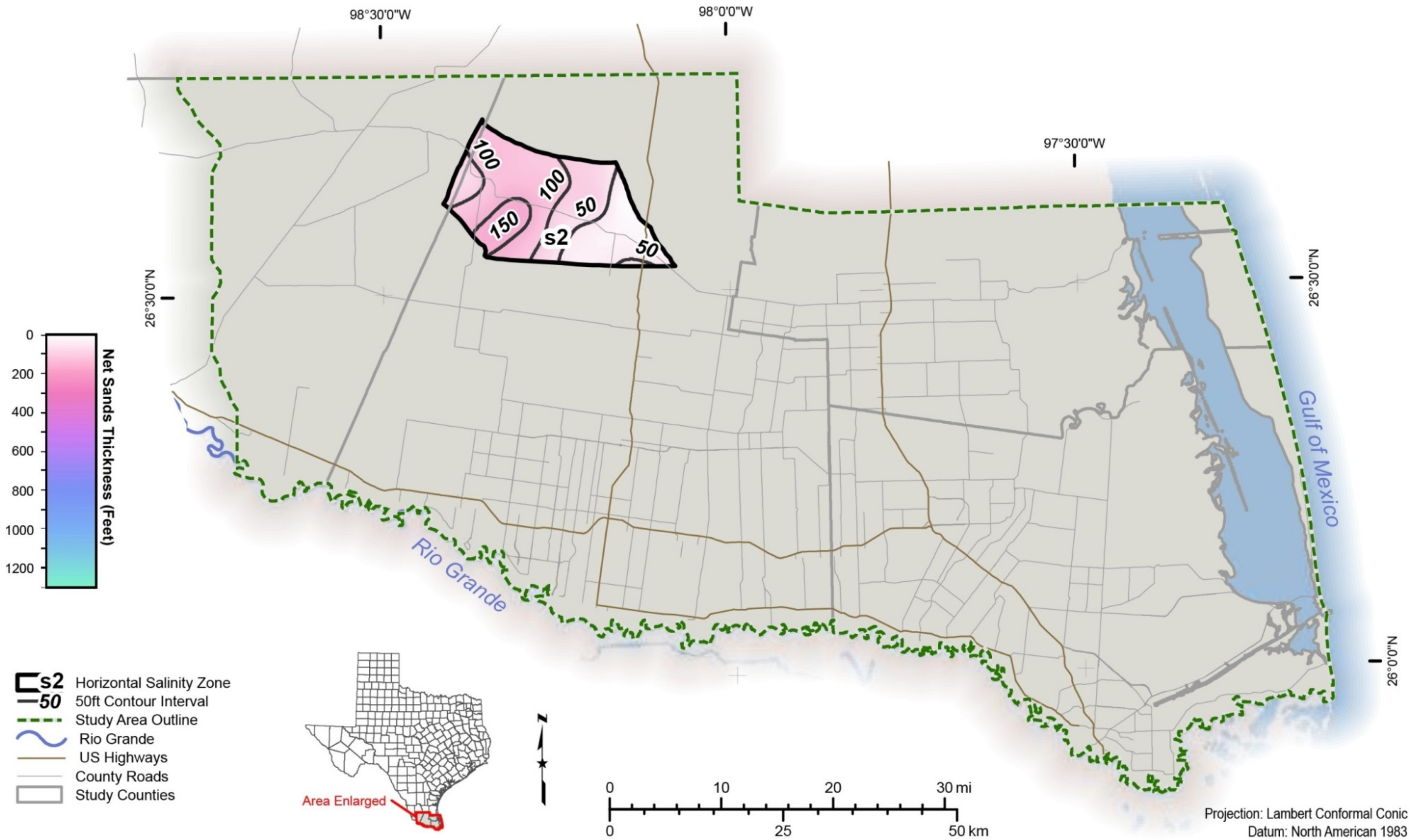


Figure 7.1-7. Net sand thickness of the slightly saline shallow 2 zone.

7.2 Moderately saline zones

A moderately saline deep zone underlies the slightly saline deep zone and overlies the very saline deep zone across most of the study area except eastern Willacy and eastern Cameron counties (Figure 7.2-1). Four moderately saline shallow zones (ms_s1, ms_s2, ms_s4, and ms_s5) overlie slightly saline water in the study area and one moderately saline shallow zone (ms_s3) overlies very saline water. Two moderately saline intermediate zones (ms_i1, ms_i2) overlie slightly saline water (Figure 7.2-5).

Pockets of slightly saline water intermingle with moderately saline water along the Rio Grande in Starr County (Figure 7.1-1). These pockets are identified by water quality samples from water wells completed in the Gulf Coast Aquifer. The pockets are small and complex, precluding definition as individual three-dimensional salinity zones.

The following desalination plants produce brackish groundwater from the moderately saline deep zone: North Cameron/Hidalgo Water Authority, Valley Municipal Utility District 2, and North Alamo Water Supply Corporation Donna and Doolittle (deep well).

Reference figures, tables, and appendices for each of the moderately saline salinity zones are presented in Tables 7.2-1 through 7.2-8.

Table 7.2-1. Moderately saline deep zone (ms_d) figures and tables.

Salinity area(s)	A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T
Salinity area map	Figure 2-5
Salinity profile(s)	Tables 2-2 through 2-4
Top depth map	Figure 7.2-2
Thickness map	Figure 7.2-3
Well control map	Figure 7.2-1
Net sand map	Figure 7.2-4
Groundwater volume	Table 14-1
GIS files	Section 21.2, Table 21.2.4-2

Table 7.2-2. Moderately saline shallow 1 zone (ms_s1) figures and tables.

Salinity area(s)	K
Salinity area map	Figure 2-5
Salinity profile(s)	Table 2-3
Top depth map	Figure 7.2-5
Thickness map	Figure 7.2-6
Well control map	No map, refer to GIS file
Net sand map	No map, manual calculation from wells
Groundwater volume	Table 14-1
GIS files	Section 21.2, Table 21.2.4-2

Table 7.2-3. Moderately saline shallow 2 zone (ms_s2) figures and tables.

Salinity area(s)	H, I
Salinity area map	Figure 2-5
Salinity profile(s)	Table 2-3
Top depth map	Figure 7.2-5
Thickness map	Figure 7.2-6
Well control map	No map, refer to GIS file
Net sand map	No map, manual calculation from wells
Groundwater volume	Table 14-1
GIS files	Section 21.2, Table 21.2.4-2

Table 7.2-4. Moderately saline shallow 3 zone (ms_s3) figures and tables.

Salinity area(s)	S
Salinity area map	Figure 2-5
Salinity profile(s)	Table 2-4
Top depth map	Figure 7.2-5
Thickness map	Figure 7.2-6
Well control map	No map, refer to GIS file
Net sand map	No map, manual calculation from wells
Groundwater volume	Table 14-1
GIS files	Section 21.2, Table 21.2.4-2

Table 7.2-5. Moderately saline shallow 4 zone (ms_s4) figures and tables.

Salinity area(s)	F, G
Salinity area map	Figure 2-5
Salinity profile(s)	Table 2-2
Top depth map	Figure 7.2-5
Thickness map	Figure 7.2-6
Well control map	No map, refer to GIS file
Net sand map	No map, manual calculation from wells
Groundwater volume	Table 14-1
GIS files	Section 21.2, Table 21.2.4-2

Table 7.2-6. Moderately saline shallow 5 zone (ms_s5) figures and tables.

Salinity area(s)	C
Salinity area map	Figure 2-5
Salinity profile(s)	Table 2-2
Top depth map	Figure 7.2-5
Thickness map	Figure 7.2-6
Well control map	No map, refer to GIS file
Net sand map	No map, manual calculation from wells
Groundwater volume	Table 14-1
GIS files	Section 21.2, Table 21.2.4-2

Table 7.2-7. Moderately saline intermediate 1 zone (ms_i1) figures and tables.

Salinity area(s)	E, M, N, O, R
Salinity area map	Figure 2-5
Salinity profile(s)	Tables 2-2 through 2-4
Top depth map	Figure 7.2-5
Thickness map	Figure 7.2-6
Well control map	No map, refer to GIS file
Net sand map	Figure 7.2-7
Groundwater volume	Table 14-1
GIS files	Section 21.2, Table 21.2.4-2

Table 7.2-8. Moderately saline intermediate 2 zone (ms_i2) figures and tables.

Salinity area(s)	L
Salinity area map	Figure 2-5
Salinity profile(s)	Table 2-3
Top depth map	Figure 7.2-5
Thickness map	Figure 7.2-6
Well control map	No map, refer to GIS file
Net sand map	No map, manual calculation from wells
Groundwater volume	Table 14-1
GIS files	Section 21.2, Table 21.2.4-2

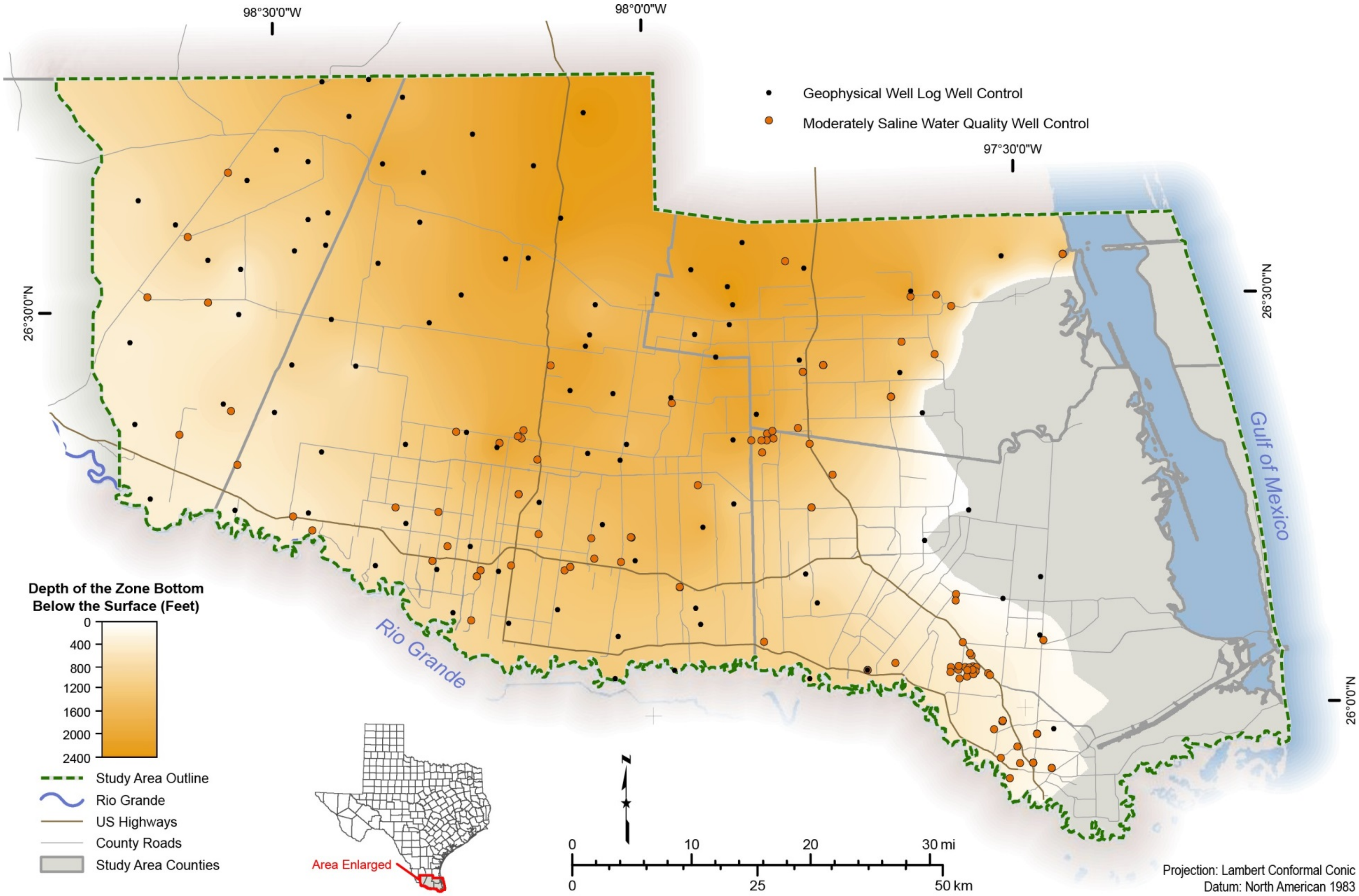


Figure 7.2-1. Moderately saline deep zone well control consisting of interpreted geophysical well logs and water well water quality data.

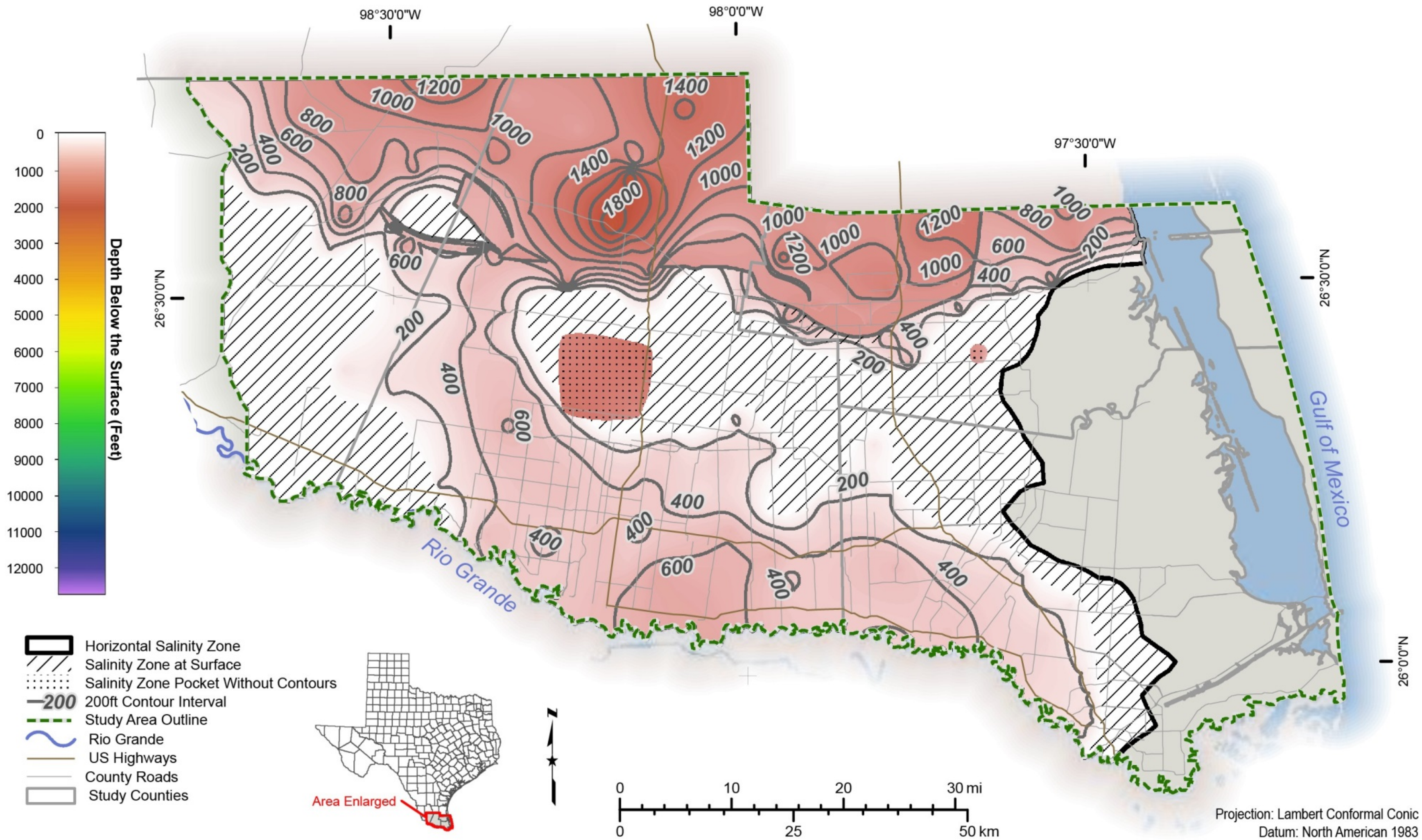


Figure 7.2-2. **Depth (below ground surface) to the top of the moderately saline deep zone.**

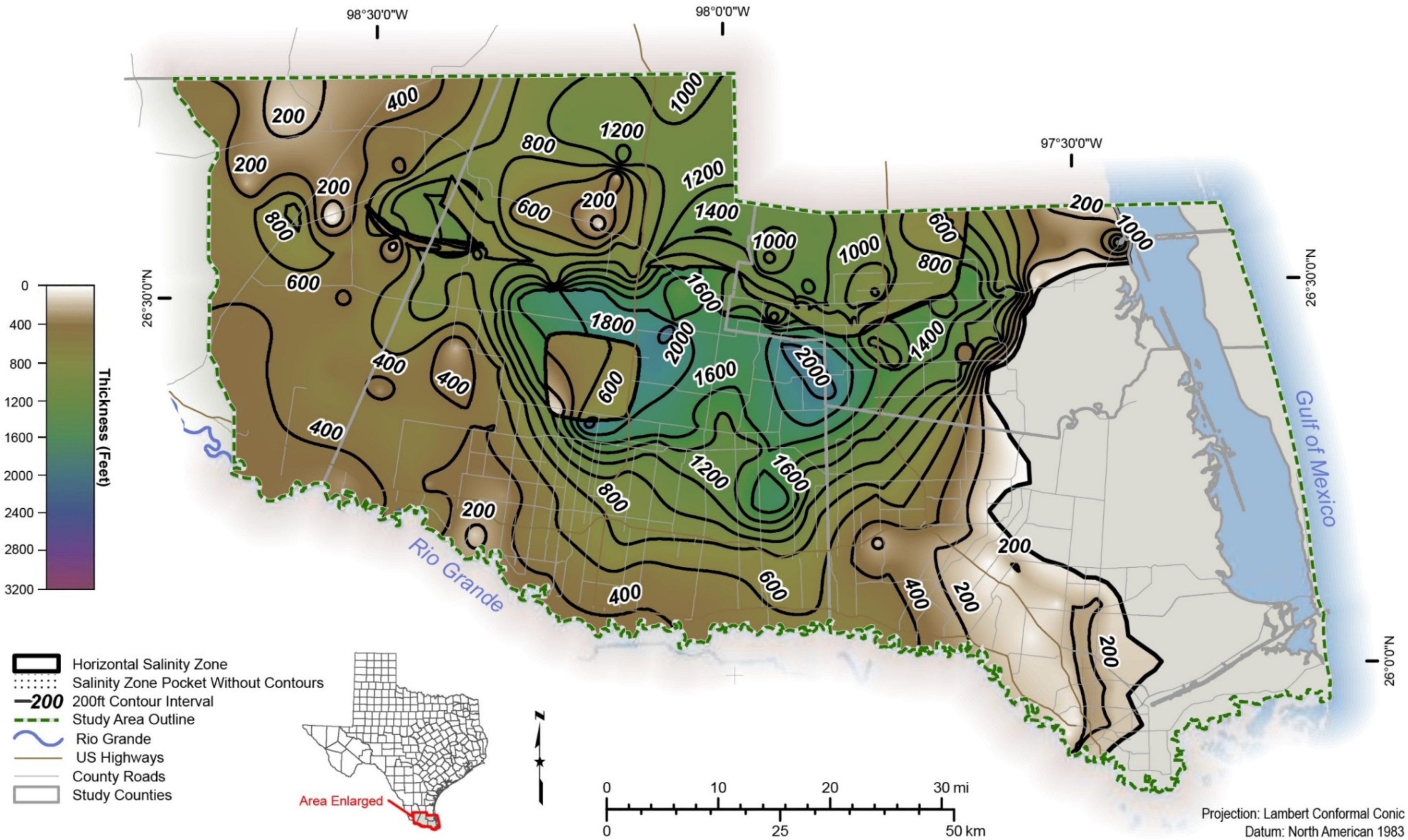


Figure 7.2-3. Thickness of the moderately saline deep zone.

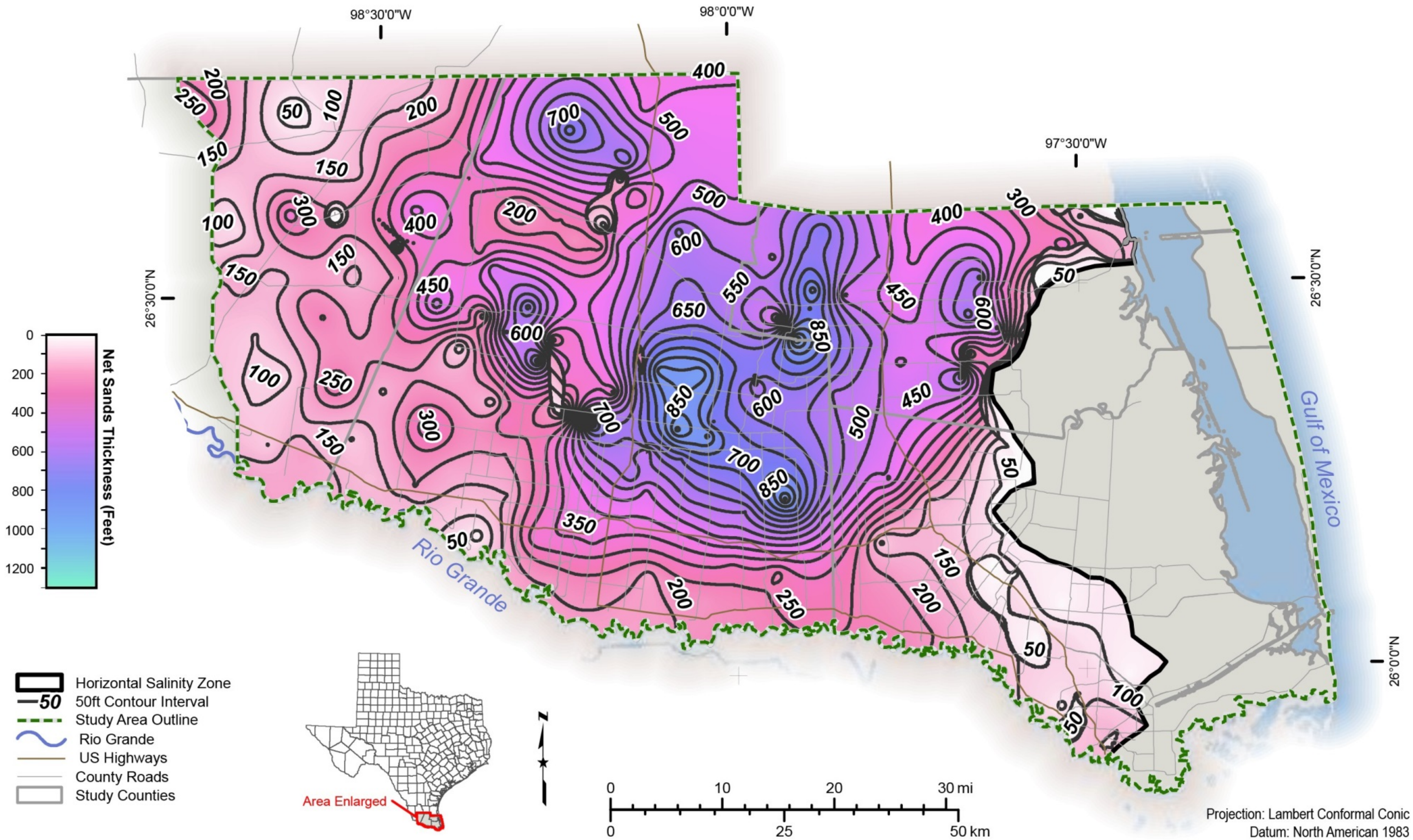


Figure 7.2-4. Net sand thickness of the moderately saline deep zone.

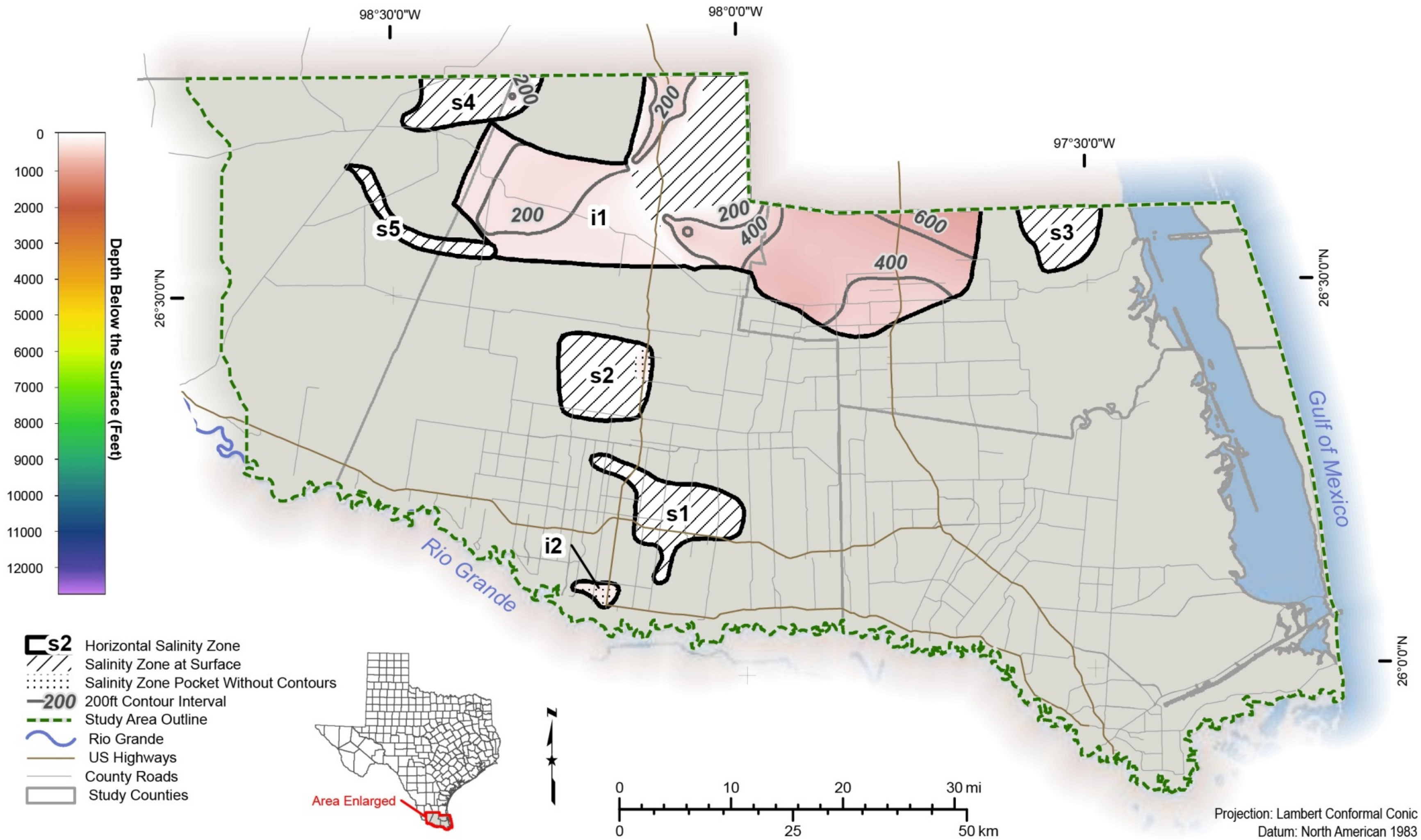


Figure 7.2-5. Depth (below ground surface) to the top of the moderately saline shallow 1, 2, 3, 4, and 5 zones and intermediate 1 and 2 zones.

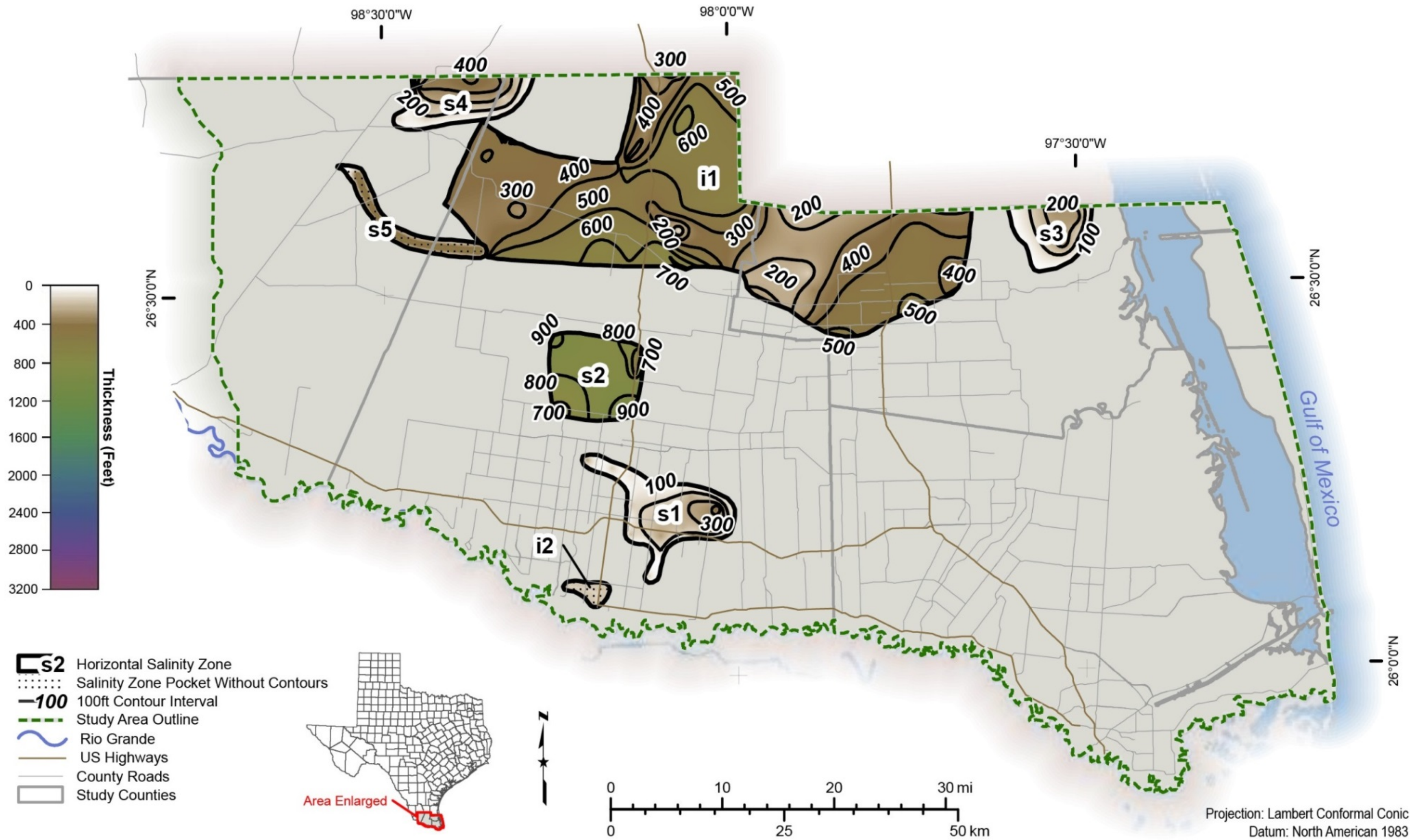


Figure 7.2-6. Thickness of the moderately saline shallow 1, 2, 3, 4, and 5 zones and intermediate 1 and 2 zones.

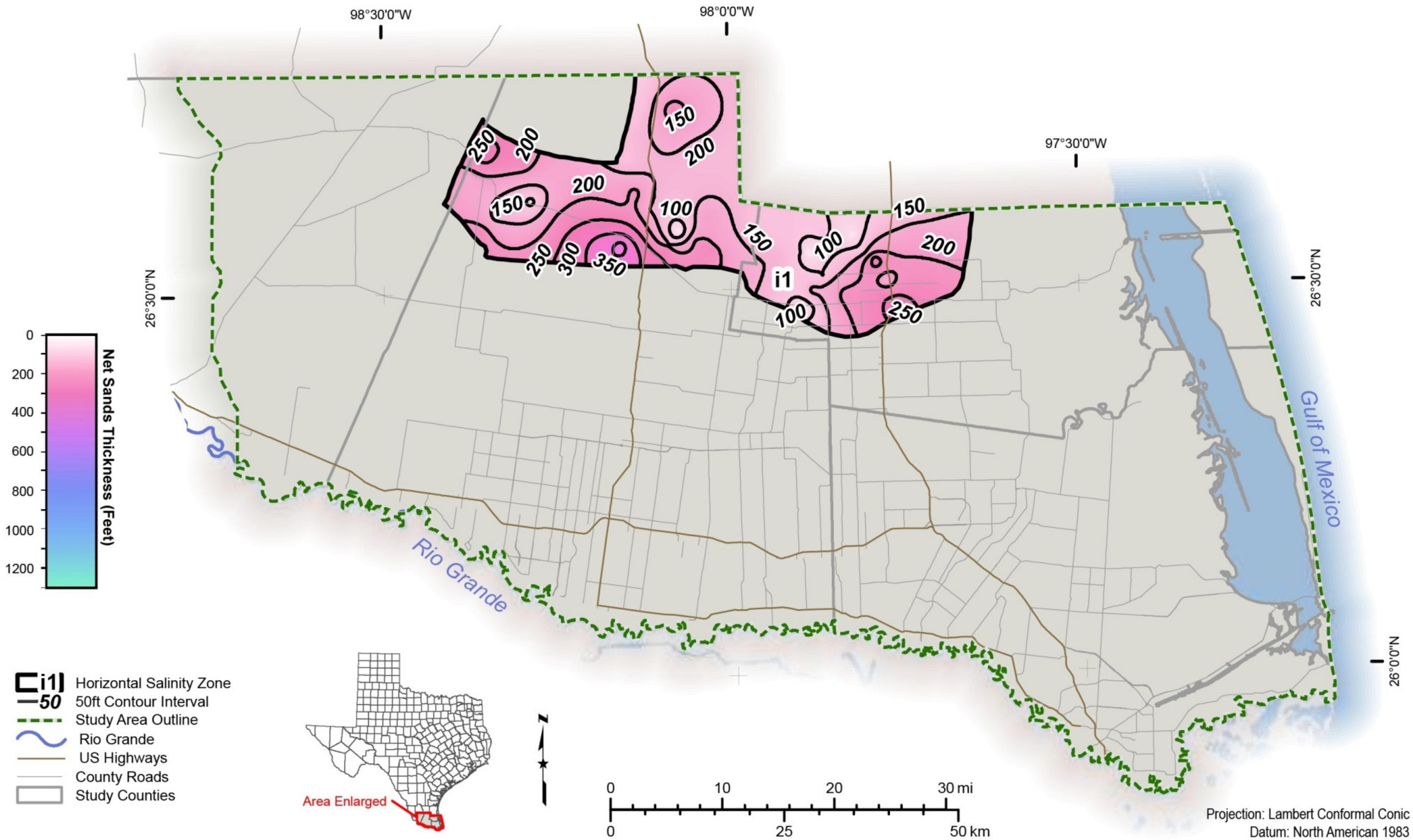


Figure 7.2-7. Net sand thickness of the moderately saline intermediate 1 zone.

7.3 Very saline zones

A very saline deep zone underlies the moderately saline deep zone and overlies the brine deep zone across the entire study area. The very saline deep zone is exposed on the ground surface in eastern Cameron and Willacy counties. Four very saline shallow zones (vs_s1, vs_s2, vs_s3, and vs_s4) overlie moderately saline water in the study area. One very saline intermediate zone (vs_i) overlies moderately saline water and underlies brine in salinity area T (Figure 7.3-4).

Isolated pockets of shallow, fresher groundwater occur in eastern Cameron and Willacy counties intermingled with the very saline groundwater. These are represented by water well water quality samples from individual wells, are too small and complex to map as individual three-dimensional salinity zones, and may not provide a significant volume of water.

Three natural saline lakes, La Sal Vieja and East Lake in Willacy County and Sal del Rey in adjacent Hidalgo County, occur in the very saline shallow 4 zone. Sal del Rey has been mined for halite (salt) for centuries (Mattei, 2006).

Reference figures, tables, and appendices for each of the very saline salinity zones are presented in Tables 7.3-1 through 7.3-6.

Table 7.3-1. Very saline deep zone (vs_d) figures and tables.

Salinity area(s)	A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U
Salinity area map	Figure 2-5
Salinity profile(s)	Tables 2-2 through 2-4
Top depth map	Figure 7.3-1
Thickness map	Figure 7.3-2
Well control map	No map, refer to GIS file
Net sand map	Figure 7.3-3
Groundwater volume	Table 14-1
GIS files	Section 21.2, Table 21.2.4-3

Table 7.3-2. Very saline shallow 1 zone (vs_s1) figures and tables.

Salinity area(s)	G
Salinity area map	Figure 2-5
Salinity profile(s)	Table 2-2
Top depth map	Figure 7.3-4
Thickness map	Figure 7.3-5
Well control map	No map, refer to GIS file
Net sand map	No map, manual calculation from wells
Groundwater volume	Table 14-1
GIS files	Section 21.2, Table 21.2.4-3

Table 7.3-3. Very saline shallow 2 zone (vs_s2) figures and tables.

Salinity area(s)	M
Salinity area map	Figure 2-5
Salinity profile(s)	Table 2-3
Top depth map	Figure 7.3-4
Thickness map	Figure 7.3-5
Well control map	No map, refer to GIS file
Net sand map	No map, manual calculation from wells
Groundwater volume	Table 14-1
GIS files	Section 21.2, Table 21.2.4-3

Table 7.3-4. Very saline shallow 3 zone (vs_s3) figures and tables.

Salinity area(s)	I
Salinity area map	Figure 2-5
Salinity profile(s)	Table 2-3
Top depth map	Figure 7.3-4
Thickness map	Figure 7.3-5
Well control map	No map, refer to GIS file
Net sand map	No map, manual calculation from wells
Groundwater volume	Table 14-1
GIS files	Section 21.2, Table 21.2.4-3

Table 7.3-5. Very saline shallow 4 zone (vs_s4) figures and tables.

Salinity area(s)	O, P, Q, R, S
Salinity area map	Figure 2-5
Salinity profile(s)	Table 2-4
Top depth map	Figure 7.3-4
Thickness map	Figure 7.3-5
Well control map	No map, refer to GIS file
Net sand map	Figure 7.3-6
Groundwater volume	Table 14-1
GIS files	Section 21.2, Table 21.2.4-3

Table 7.3-6. Very saline intermediate zone (vs_i) figures and tables.

Salinity area(s)	T
Salinity area map	Figure 2-5
Salinity profile(s)	Table 2-4
Top depth map	Figure 7.3-4
Thickness map	Figure 7.3-5
Well control map	No map (used BRACS well 22713)
Net sand map	No map, manual calculation from wells
Groundwater volume	Table 14-1
GIS files	Section 21.2, Table 21.2.4-3

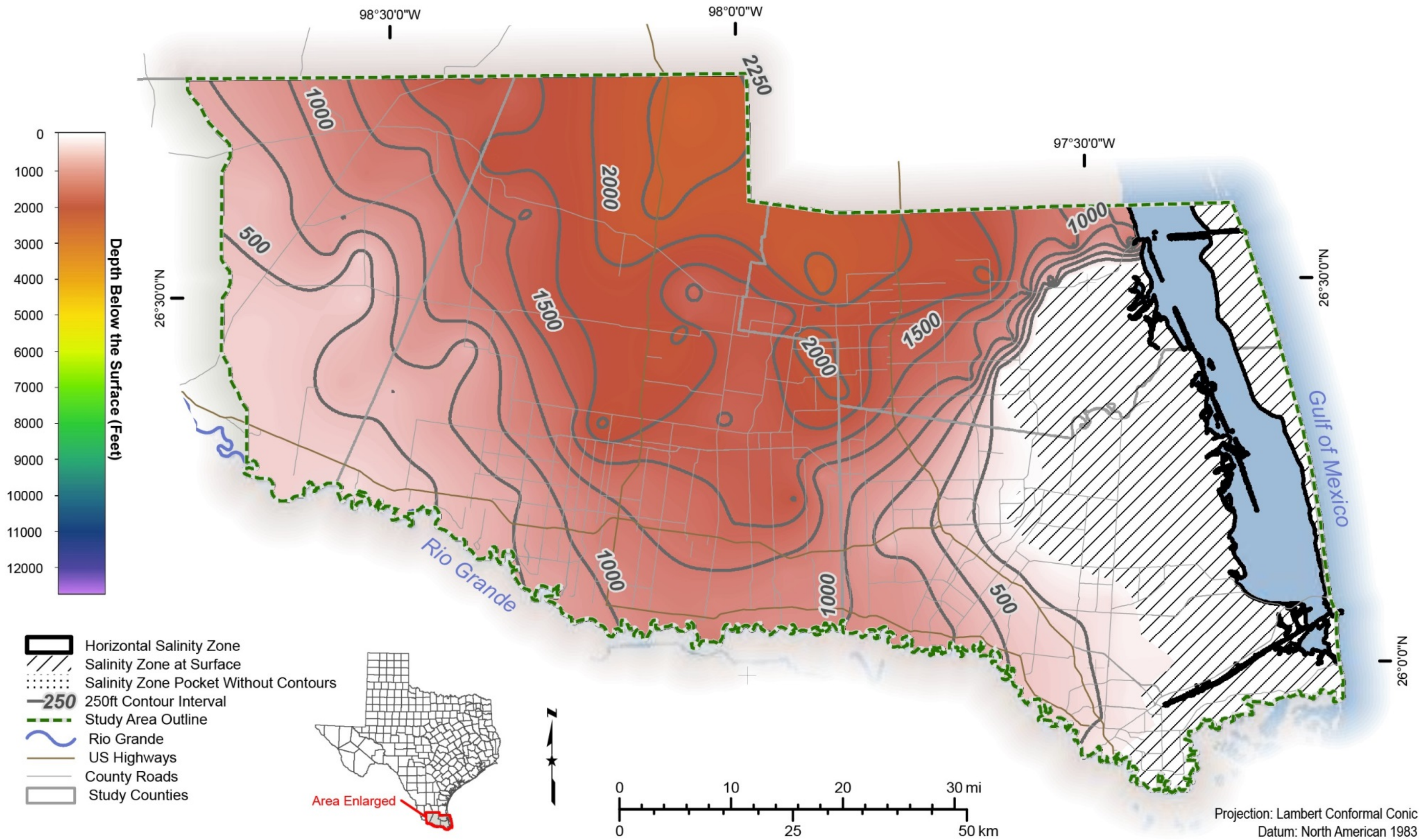


Figure 7.3-1. **Depth (below ground surface) to the top of the very saline deep zone.**

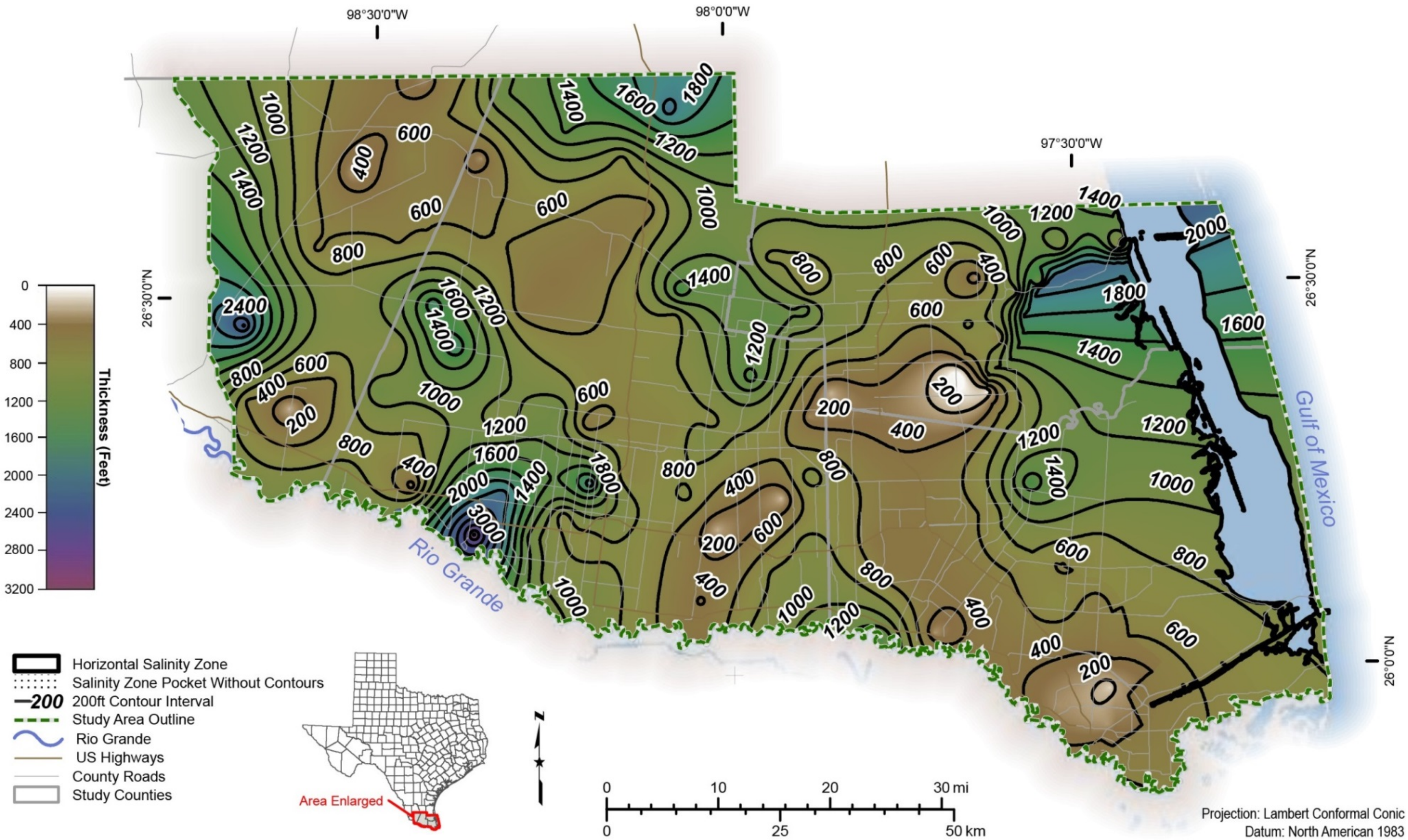


Figure 7.3-2. Thickness of the very saline deep zone.

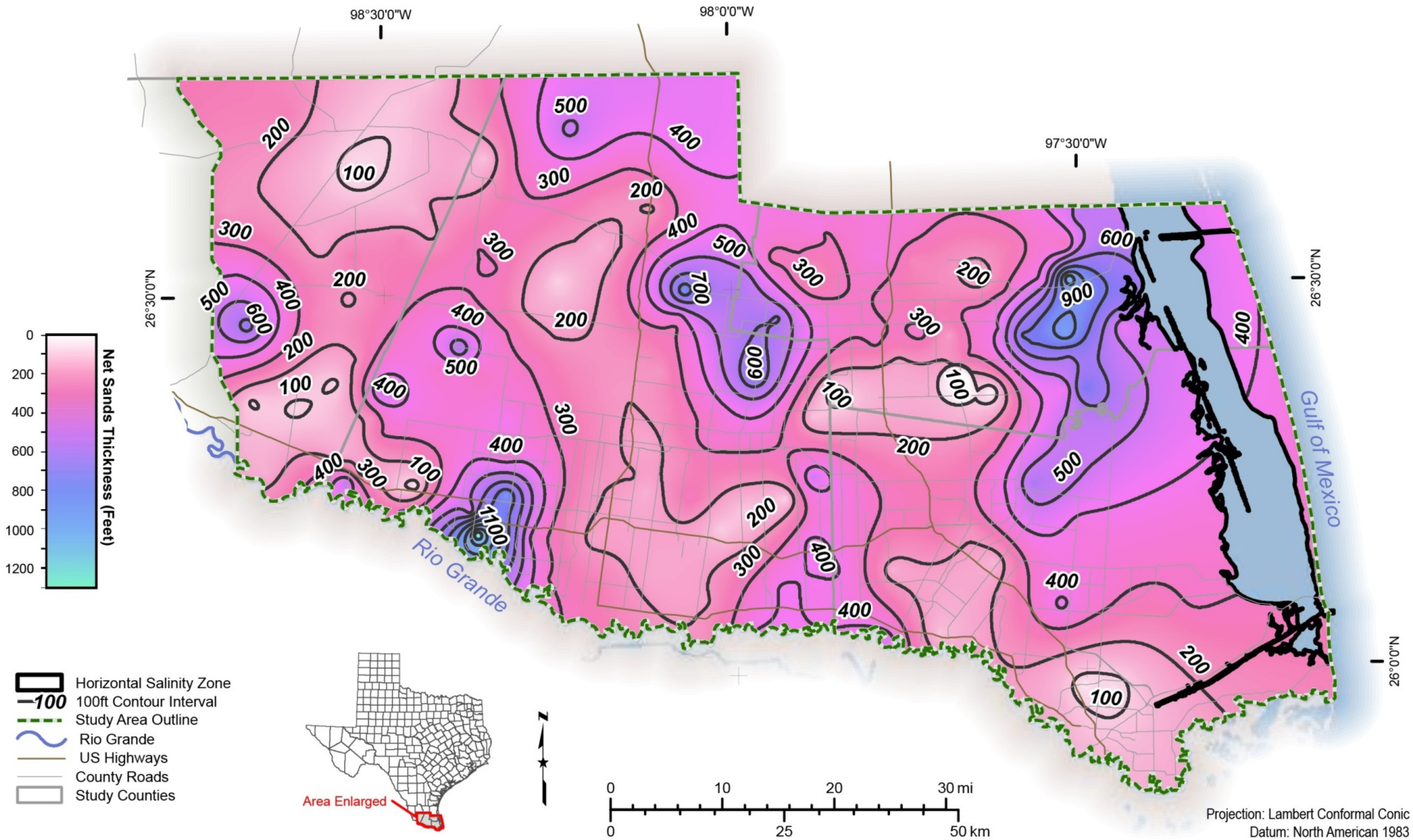


Figure 7.3-3. Net sand thickness of the very saline deep zone.

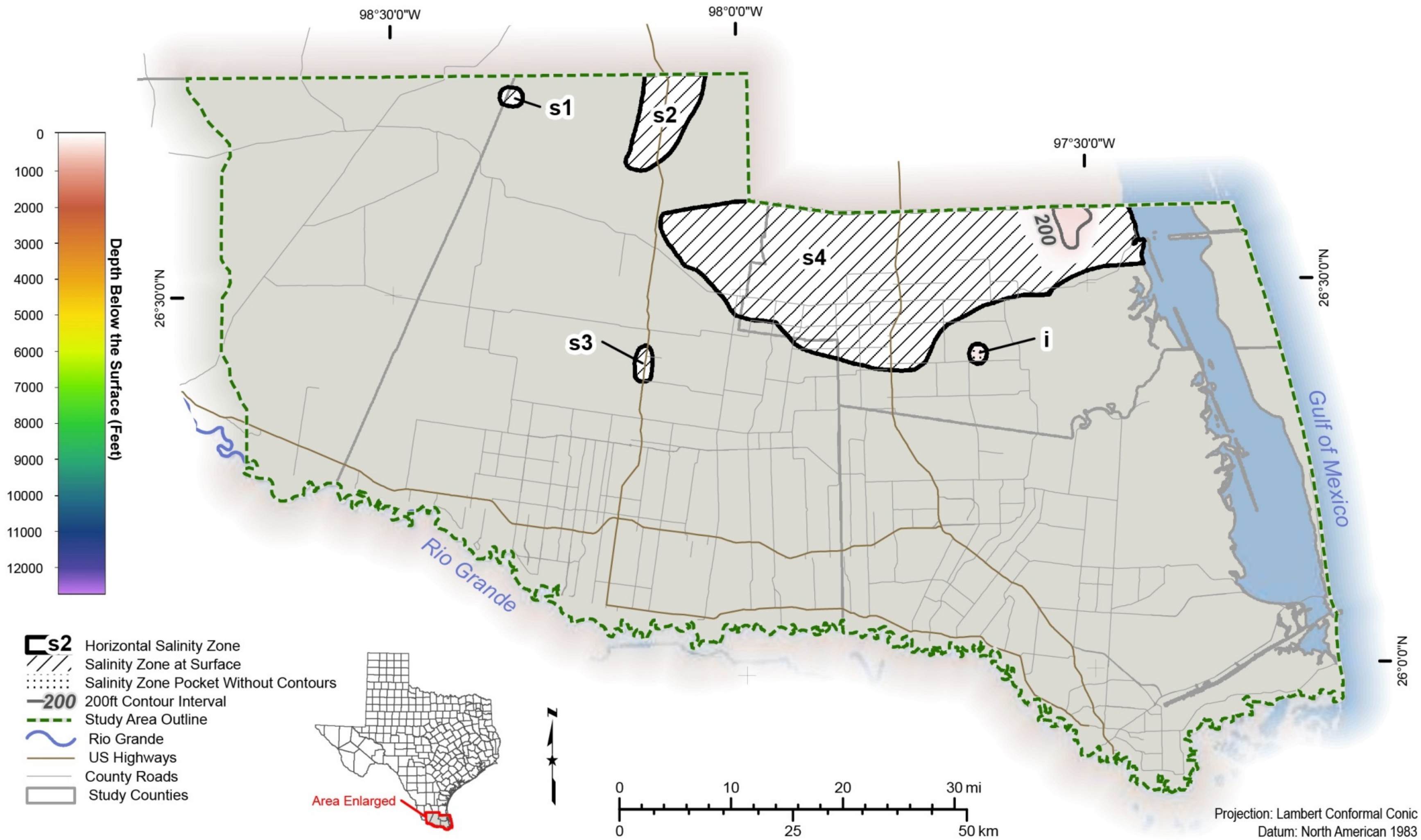


Figure 7.3-4. **Depth (below ground surface) to the top of the very saline shallow 1, 2, 3, and 4 zones and the intermediate zone.**

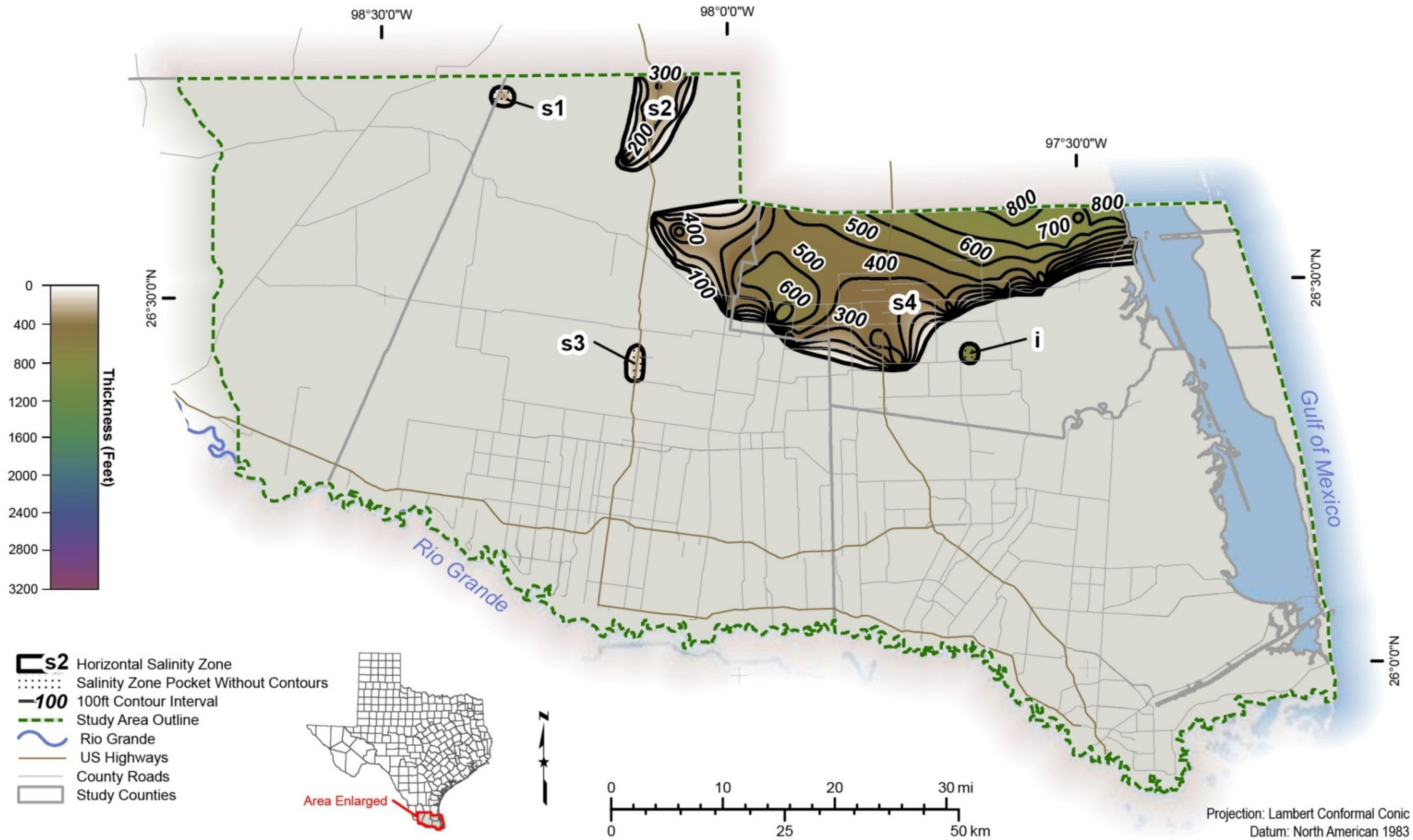


Figure 7.3-5. Thickness of the very saline shallow 1, 2, 3, and 4 zones and intermediate zone.

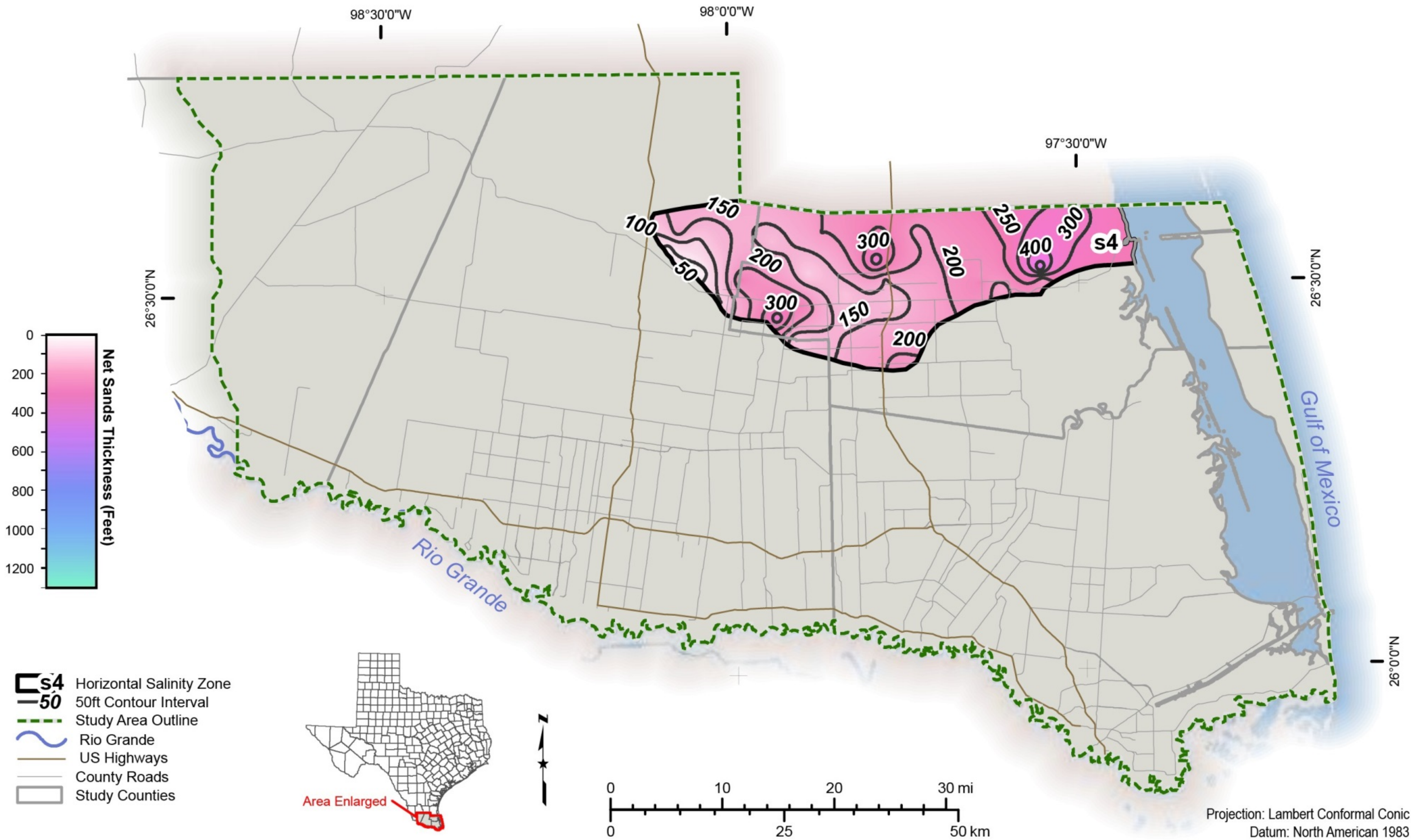


Figure 7.3-6. Net sand thickness of the very saline shallow 4 zone.

7.4 Brine zones

The entire study area is underlain by a deep brine zone. We did not evaluate the bottom depth, thickness, net sand, and groundwater volume of the brine deep zone. We mapped a brine shallow zone in salinity area T (Figure 2-5) overlying very saline water (Table 2-4). This zone is represented on one geophysical well log (BRACS well ID 22713).

Reference figures, tables, and appendices for each of the brine salinity zones are presented in Tables 7.4-1 and 7.4-2.

Table 7.4-1. Brine deep zone (br_d) figures and tables.

Salinity area(s)	A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U
Salinity area map	Figure 2-5
Salinity profile(s)	Tables 2-2 through 2-4
Top depth map	Figure 7.4-1
Thickness map	No thickness
Well control map	No map, refer to GIS file
Net sand map	No net sand calculations
Groundwater volume	No groundwater volume calculations
GIS files	Section 21.2, Table 21.2.4-4

Table 7.4-2. Brine shallow zone (br_s) figures and tables.

Salinity area(s)	T
Salinity area map	Figure 2-5
Salinity profile(s)	Table 2-4
Top depth map	No map
Thickness map	No thickness
Well control map	No map, refer to GIS file
Net sand map	No net sand calculations
Groundwater volume	No groundwater volume calculations
GIS files	Section 21.2, Table 21.2.4-4

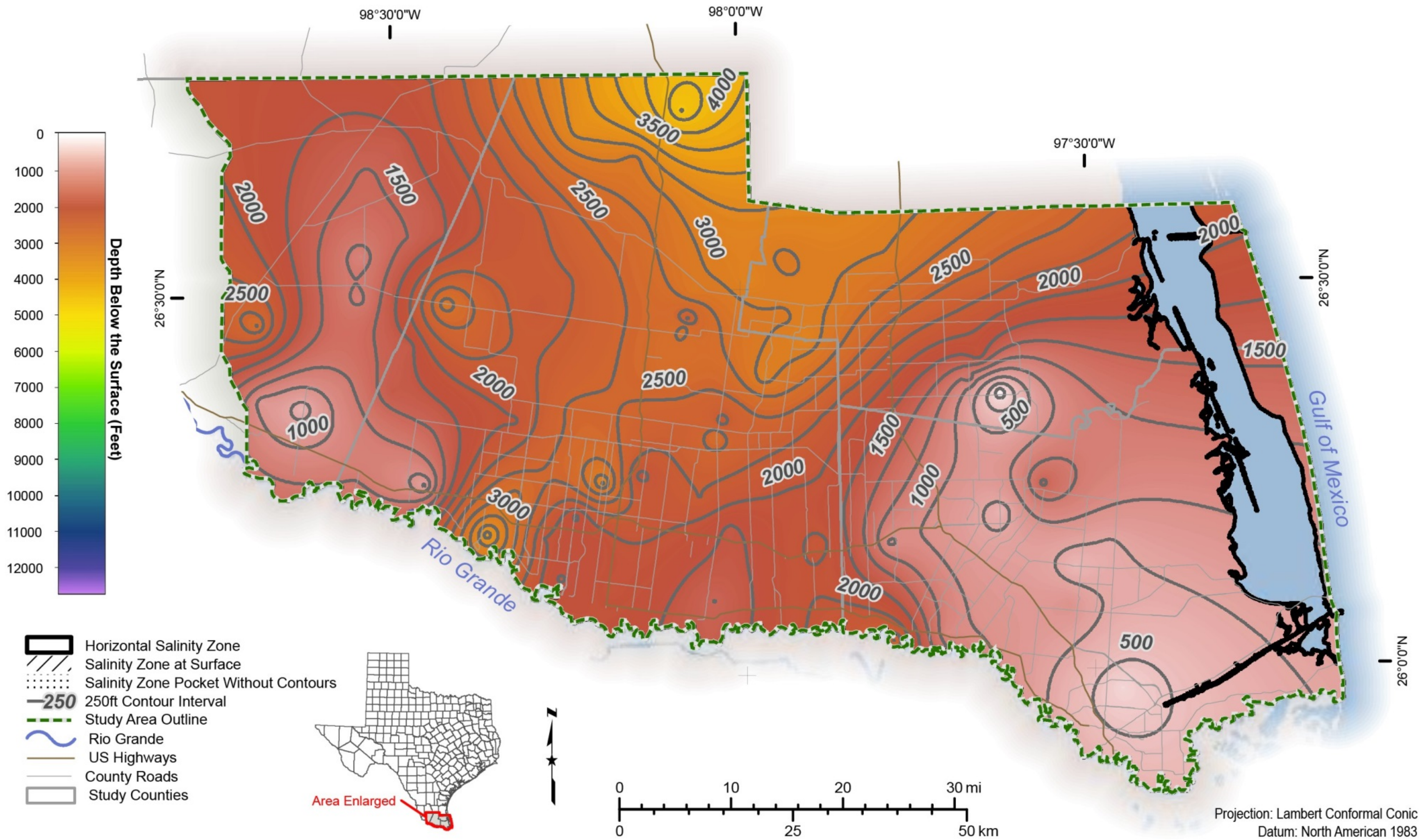


Figure 7.4-1. **Depth (below ground surface) to the top of the brine zone.**

8. Previous investigations

County-wide hydrological studies by TWDB (and predecessor agencies), the U.S. Geological Survey, and other agencies began in the 1930s for the Gulf Coast Aquifer (Baker, 1965; Baker, 1971; Baker, 1979; Baker, 1986; Baker and Dale, 1961; Dale, 1952; Dale and George, 1954; Deussen, 1924; Follett and others, 1949; Galloway, 1977; Galloway, 1982; George, 1947; McCoy, 1990; Molofsky, 1985; Paine, 2000; Peckham, 1963; Preston, 1983; Rose, 1954; Ryder, 1988; Sellards and others, 1932; Sellards and Baker, 1934; Wood and others, 1963). Chowdhury and others (2006) and Young and others (2014) evaluated the geochemistry of the Gulf Coast Aquifer. Scanlon and others (2012) evaluated recharge to the Gulf Coast Aquifer. Mace and others (2006) compiled a number of articles on the aquifers of the Gulf Coast of Texas.

The hydrostratigraphy of the Gulf Coast Aquifer was evaluated by Young and others (2010). The formation top, bottom, and thickness GIS datasets used in our study were derived from datasets provided in Young and others (2010). These datasets form the basis for the stratigraphic segregation of the sand and clay units that were mapped in greater detail in our study. It is likely that future Gulf Coast Aquifer Groundwater Availability Model(s) may be based on this hydrostratigraphy. We formatted the information in this study in a manner that will allow seamless integration into future studies.

Surface geologic mapping conducted by The University of Texas at Austin at a scale of 1:250,000 (Bureau of Economic Geology, 1976) was subsequently processed into a statewide digital geologic map in a geodatabase format. The surface geology in the study area derived from that work is presented in Figure 8-1.

The development of computer-based groundwater models of the Gulf Coast Aquifer in Texas began in 1985 and continues to this day. Chowdhury and Mace (2006) provide a summary of Gulf Coast Aquifer models. Chowdhury and Mace (2003, 2007), Chowdhury and others (2004), and Hutchison and others (2011) developed groundwater models for the Gulf Coast Aquifer. Carr and others (1985) evaluated the Chicot and Evangeline aquifers in a groundwater model north of the study area. As described in Young and others (2006), other entities have also developed groundwater models within areas of the Gulf Coast Aquifer to meet their own specific needs. Several site-specific groundwater studies were conducted for water purveyors in the study area (Harden and Associates, 1991, 2002).

Geologic cross-sections for the Gulf Coast Aquifer and underlying formations were prepared by a number of agencies starting in the 1960s (Baker, 1979; Baker and Dale, 1961; CH2M Hill, 1996; Dodge and Posey, 1981; Knox and others, 2007; Young and others, 2010). The well control points and cross-section lines from these studies were appended to GIS files in the study area (Figure 8-2) and, where possible, the well logs were added to the BRACS Database.

Examples of studies that address the development of brackish groundwater in the study area include an assessment of the future of desalination in Texas (Arroyo, 2004), a guidance manual for brackish groundwater desalination (NRS Consulting Engineers, 1996, 2008), the use of fiberglass casing in public supply wells (Harden and Associates, 2013), the use of oil fields to dispose concentrate from desalination plants (Mace and others, 2006; CDM Smith, 2014), and an assessment of groundwater using airborne electromagnetic induction (Paine, 2000).

The Bureau of Reclamation in conjunction with the Rio Grande Regional Water Authority and other parties completed a water supply and demand project in the study area (Bureau of Reclamation, 2013).

9. Data collection and analysis

One of the primary objectives of the study is to gather available well data from existing water well reports, geophysical well logs, water chemistry samples, and aquifer tests. This information augmented existing well information contained in the TWDB Groundwater Database. No single agency has complete information on all water wells or oil and gas wells in Texas. Therefore, we evaluated a number of existing collections that contain publicly available paper and digital information. Because many of the datasets and analysis features did not fit into the structure of the existing TWDB Groundwater Database, the information was loaded into the BRACS Database. Each well that was added to the BRACS Database shows the source of the information and all applicable well identification numbers.

Another equally important objective is to make the information and datasets gathered for the study readily available to the public. Thus, all of the information collected is non-confidential. The information includes raw data such as water well reports and digital geophysical well logs, processed data such as lithology, simplified lithologic descriptions, stratigraphic picks, water chemistry, and interpreted results in the form of GIS datasets.

With these goals in mind, we appended to the BRACS Database information from 1,418 wells located in Cameron, Hidalgo, Starr, and Willacy counties; 591 of these well records have a state well number with additional information in the TWDB Groundwater Database. An additional 1,489 well records are present in the TWDB Groundwater Database, making a total of 2,907 well records within the study area (Figure 9-1). Oil and gas wells account for 585 wells, water wells account for 2,192 wells, and other types of wells (test holes, geothermal, waste disposal, and injection) account for 130 wells in the study area. This represents only a fraction of all the wells installed in the study area. Information about many other wells was either unavailable, incomplete, limited in scope, of poor quality, confidential, or did not meet the requirements of the study. Additional information in the study area is available from public and private sources: Volume II of Baker and Dale (1961), additional water quality data in the TWDB Groundwater Database, Submitted Driller's Report Database for well reports younger than 2001, Water Well Report Viewer on the Texas Commission on Environmental Quality website for well reports older than 2001, digital geophysical well logs available on the Railroad Commission of Texas website, paper and digital geophysical well logs and miscellaneous records at the Bureau of Economic Geology.

Geophysical well logs, stratigraphic picks, and interpreted lithology from Young and others (2010) were added to the BRACS Database.

We obtained 480 wells (Q-logs) from the Groundwater Advisory Unit of the Railroad Commission of Texas and added this information to the Brackish Resources Aquifer Characterization System geophysical well log collection and to the BRACS Database.

We did not verify the location of every well that was obtained from other agency datasets unless there appeared to be a problem, such as a mismatch in the geology. When locations had to be verified or digital locations were not available, the Original Texas Land Survey linen maps from the Railroad Commission of Texas, Groundwater Advisory Unit, were used as a base map. The location legal description noted on the log header was used to plot the wells in GIS to determine the latitude and longitude coordinates. Users of our study data should be aware that well locations may need verification.

We used the following sources of well data in this study:

- Bureau of Economic Geology Geophysical Log Facility;
- Texas Commission on Environmental Quality water well image files and public drinking water files;
- Texas Department of Licensing and Regulation Submitted Driller's Report Database;
- Railroad Commission of Texas paper and digital geophysical well logs, and the Underground Injection Control Database;
- Texas Water Development Board Groundwater Database, BRACS Database, paper well reports, paper geophysical log collection, groundwater availability model studies, and written reports; and
- U.S. Geological Survey written reports and the Produced Water Database.

Each well in the BRACS Database contains a source reference for the information.

We made the decision to include all of the wells contained in the TWDB Groundwater Database and some wells of the Texas Department of Licensing and Regulation Submitted Driller's Report Database into the BRACS Database. These wells contain information that is essential to understanding the geology of the region. Because the TWDB Groundwater and the Texas Department of Licensing and Regulation water well databases are updated on a daily basis, users should be aware that in the future there may be information available in these databases in addition to that present in the BRACS Database.

Based on information obtained from the Railroad Commission of Texas Oil and Gas Well Database, the study area contains approximately 13,673 oil and gas wells and 504 Class II injection wells.

10. Aquifer determination

We employed a technique to consistently assign the correct aquifer(s) to wells drilled in the study area so that information from these wells, specifically hydraulic properties, lithology, and water quality, could be meaningfully compared and extrapolated across the study area. The BRACS Database table tblAquiferDetermination_GulfCoast was designed for this task and contains all of the information. The hydrostratigraphic framework of the Gulf Coast Aquifer by Young and others (2010) was used to meet this objective. Each well in the study area (all BRACS Database wells and all Groundwater Database wells) was assigned a stratigraphic top and bottom depth based on the GIS surfaces created for the nine geological formations within the Gulf Coast Aquifer. Each well was also assigned a one-digit region code, with each region representing a unique stratigraphic column of geologic formations in the study area (Table 10-1). The surficial geographic area for each region represents the outcrop area of a formation and overlying Quaternary age sedimentary deposits (Figure 8-1).

The region code permitted automated aquifer determination analysis within the BRACS Database. Well-screen information was compared with formation top and bottom depths to determine the aquifer(s) used by the water well. If well-screen information was not available, the total depth of the well or borehole was used and all aquifers present at the well site were selected from the total depth to surface. Wells screened 100 feet or less below the base of the Oakville Formation with at least 20 feet of screen in the Oakville were coded as Oakville. The aquifer determination technique also facilitated the assignment of sand layers to specific geologic formations, allowing the tabulation and mapping of net sand and sand percent information.

Water wells in the TWDB Groundwater Database have aquifer codes assigned to them. Over the 25 years that the database has been in existence, different staff using a variety of information has been assigning aquifer codes in the database. The complex stratigraphic nomenclature, changes in stratigraphic interpretation by different authors, and discontinuity of lithologic units within formations in the Gulf Coast Aquifer have led to inconsistencies in the application of aquifer codes. Wells appended to the BRACS Database from sources other than the TWDB Groundwater Database do not have aquifers assigned to them. The aquifer determination step solves these problems.

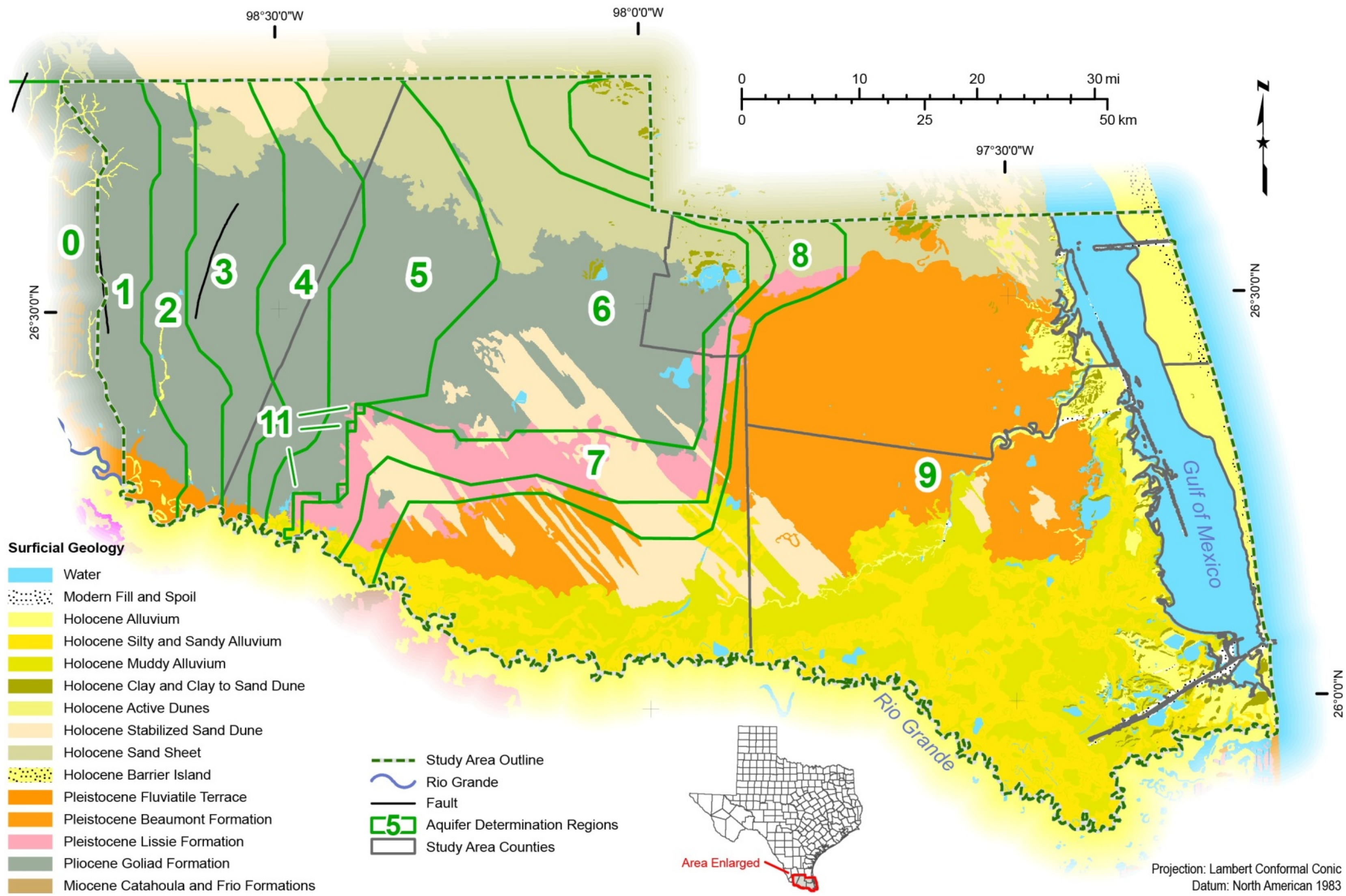


Figure 8-1. **Surface geology in the study area (digital dataset from Texas Natural Resources Information System, based on Bureau of Economic Geology, 1976). Region numbers (0 through 11) refer to the outcrop areas of each formation. Each region has a unique stratigraphic sequence (Table 10-1), used for the aquifer determination task.**

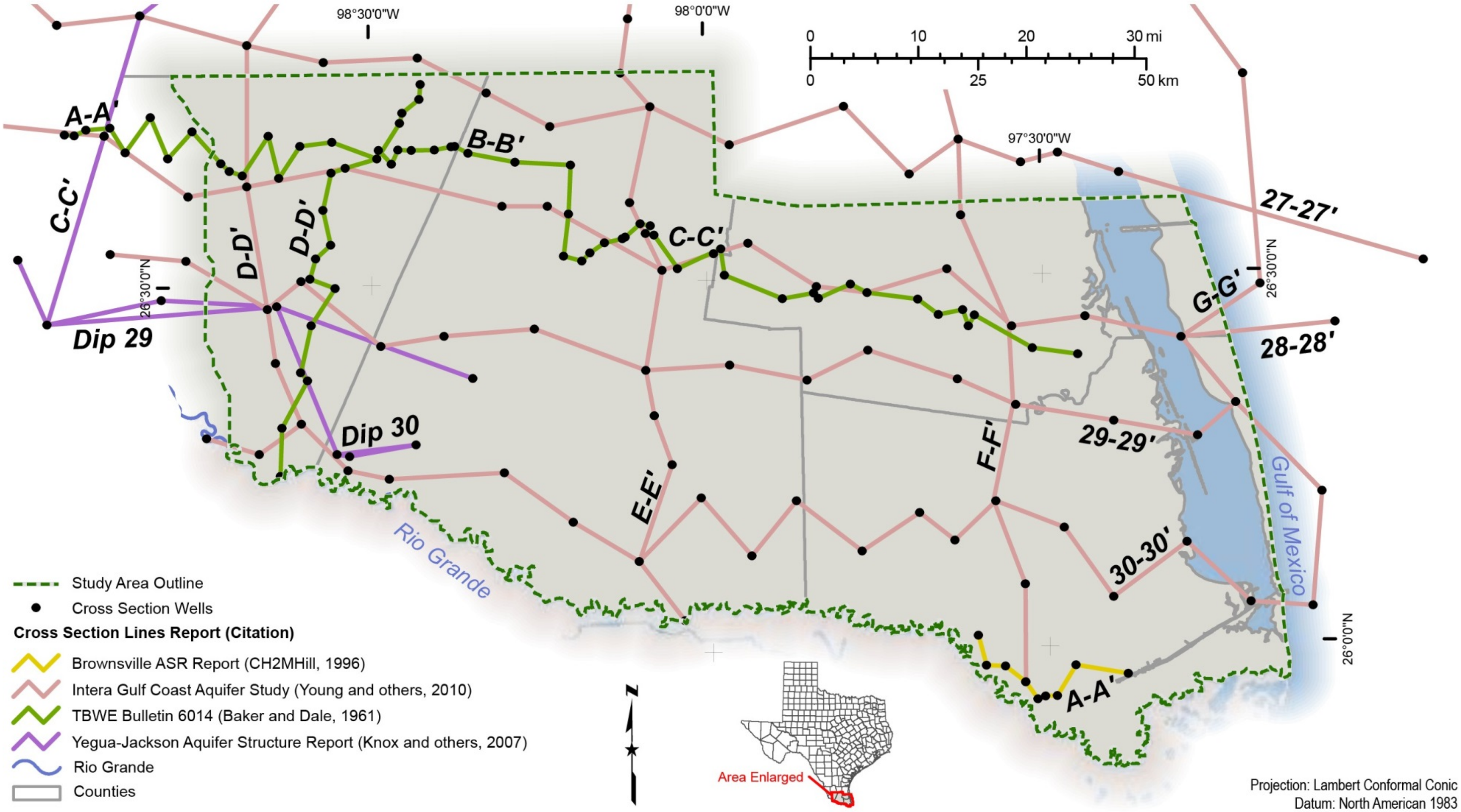


Figure 8-2. Geologic cross-sections in the study area. Letter and number designations refer to studies and authors referenced in the legend.

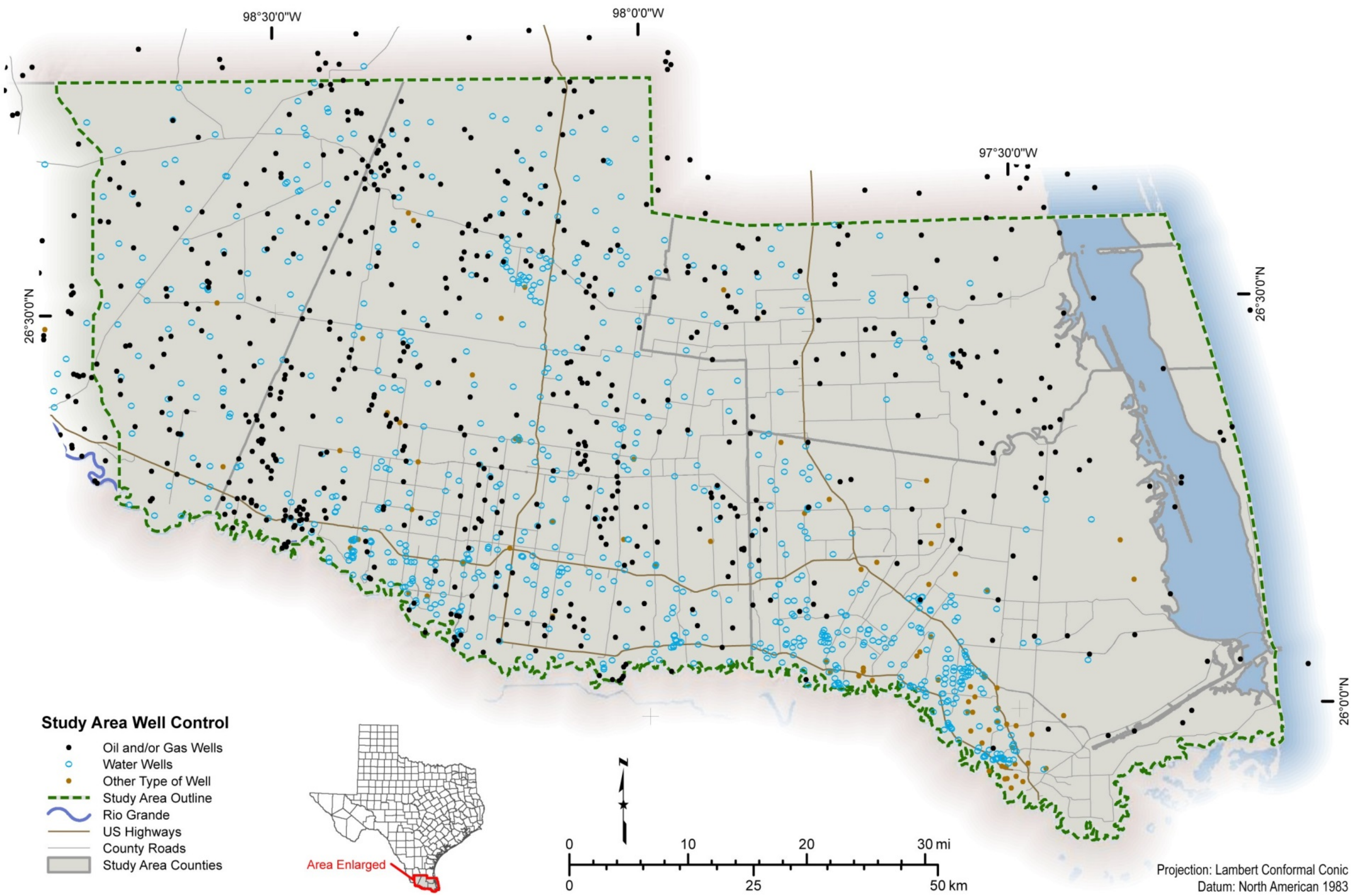


Figure 9-1. **Study area well control consists of 2,907 data points: 585 oil and gas wells, 2,192 water wells, and 130 classified as other. A total of 2,080 wells have been assigned a State Well Number in the TWDB Groundwater Database, and 1,418 have been assigned a well ID in the TWDB BRACS Database (591 of these wells occur in both databases).**

Table 10-1. **Stratigraphic sequence (youngest to oldest) within each region of the study area. Refer to Figure 8-1 for a map of the regions. The geologic formation at the top of each region indicates that it outcrops at or is close to the ground surface. Quaternary-age deposits are not shown in this table. In Region 7, the Willis Formation is absent either because it was not deposited or was eroded before the deposition of the overlying Lissie Formation. The Willis and Upper Goliad formations are not present in Region 11 for a similar reason. The Willis Formation subcrop limit is in Region 8. Geologic formations of the Gulf Coast Aquifer are not present in Region 0.**

Region 0	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Region 7	Region 11	Region 8	Region 9	Gulf Coast Aquifers
										Beaumont	
							Lissie	Lissie	Lissie	Lissie	Chicot
									Willis	Willis	
						Upper Goliad	Upper Goliad		Upper Goliad	Upper Goliad	
					Lower Goliad	Lower Goliad	Lower Goliad	Lower Goliad	Lower Goliad	Lower Goliad	Evangeline
				Upper Lagarto	Upper Lagarto	Upper Lagarto	Upper Lagarto	Upper Lagarto	Upper Lagarto	Upper Lagarto	
			Middle Lagarto	Middle Lagarto	Middle Lagarto	Middle Lagarto	Middle Lagarto	Middle Lagarto	Middle Lagarto	Middle Lagarto	Burkeville Confining
		Lower Lagarto	Lower Lagarto	Lower Lagarto	Lower Lagarto	Lower Lagarto	Lower Lagarto	Lower Lagarto	Lower Lagarto	Lower Lagarto	Jasper
	Oakville	Oakville	Oakville	Oakville	Oakville	Oakville	Oakville	Oakville	Oakville	Oakville	

11. Aquifer hydraulic properties

The hydraulic properties of an aquifer refer to characteristics that allow water to flow through the aquifer. Hydraulic properties include transmissivity, hydraulic conductivity, specific yield, specific capacity, drawdown, pumping rate (well yield), and storage coefficient. Lithology, cementation, fracturing, structural framework, and juxtaposition of adjacent formations all influence the flow of water within and between aquifers.

We compiled hydraulic properties for 606 wells containing 630 analyses completed in the Gulf Coast Aquifer (Table 11-1). We added this information to the BRACS Database table tblBRACS_AquiferTestInformation. Locations of aquifer tests are presented in Figures 11-1 and 11-2.

The sources of aquifer test information include TWDB aquifer test spreadsheet and the remarks table in the TWDB Groundwater Database, published reports (Baker and Dale, 1961; Christian and Wuerch, 2012; Myers, 1969), Texas Commission on Environmental Quality water well reports, and Texas Department of Licensing and Regulation Submitted Driller's Report Database. Additional information is available in the TWDB paper well reports. Specific yield data for wells located within the study area was not available.

Users of the hydraulic property data presented in our study should evaluate the data in the proper context. We obtained many of the well yields from tests conducted decades ago and many well yields are from domestic, small capacity wells that may not be indicative of what a properly designed, large capacity well may be capable of producing.

A three-dimensional, finite difference groundwater flow model for the Gulf Coast Aquifer in the Lower Rio Grande Valley was developed by Chowdhury and Mace (2007). This model included the study area and the southern half of Jim Hogg, Brooks, and Kleberg counties. The Gulf Coast Aquifer structure differed from that used in this study, which is based on Young and others (2010). Chowdhury and Mace (2007) determined a recharge rate of 0.52 percent of average annual rainfall for the period including 1930 through 1980 which equaled 0.08 to 0.14 inches per year. They assumed that 47 percent of the recharge was derived from rainfall and 53 percent from seepage from the Rio Grande, the Arroyo Colorado, and irrigation return flow. Seepage from irrigation canals and distribution pipes could also be a source of recharge (McCoy, 1990).

Scanlon and others (2012) estimated recharge using the chloride mass balance approach for the Gulf Coast Aquifer. Study area recharge rates are varied: less than 0.1 inches per year in Starr and central Hidalgo counties; 0.1 to 0.25 inches per year in northeastern Starr, northern and southern Hidalgo, western Willacy, and western Cameron counties; 0.25 to 0.5 inches per year in extreme southeastern Hidalgo and southwestern Cameron, and along the Rio Grande (Scanlon and others, 2012; Figure 17). Eastern Willacy and Cameron counties, outside of the TWDB mapped Gulf Coast Aquifer, were not evaluated.

Cross-formational flow between aquifers is a significant component of total flow for each aquifer (Chowdhury and Mace, 2007). Deeper Evangeline Aquifer groundwater was found to flow upward near the coast, resulting in greater salinity in the overlying Chicot Aquifer.

Table 11-1. Hydraulic properties of aquifers within the study area. Refer to the BRACS Database table tblBRACS_AquiferTestInformation for detailed information about each well and data. N/A = not available.

Hydraulic property	Chicot Aquifer	Evangeline Aquifer	Burkeville confining unit	Jasper Aquifer
Transmissivity	**Units: gallons per day per foot**			
Number of values	11	2	N/A	N/A
Low	7,201	1,279	N/A	N/A
High	100,000	7,500	N/A	N/A
Average	47,094	4,390	N/A	N/A
Hydraulic conductivity	**Units: feet per day**			
Number of values	8	N/A	N/A	N/A
Low	10	N/A	N/A	N/A
High	1,003	N/A	N/A	N/A
Average	489	N/A	N/A	N/A
Storage coefficient	**Units: dimensionless**			
Number of values	8	N/A	N/A	N/A
Low	0.000025	N/A	N/A	N/A
High	0.00868	N/A	N/A	N/A
Average	0.0015	N/A	N/A	N/A
Specific capacity	**Units: gallons per minute per foot**			
Number of values	141	65	5	31
Low	0.2	0.1	0.1	0.01
High	46	25	2	10
Average	9	2	0.5	0.5
Well yield	**Units: gallons per minute**			
Number of values	332	158	16	39
Low	3	1	5	3
High	2,900	2,220	100	1,200
Average	651	271	46	85

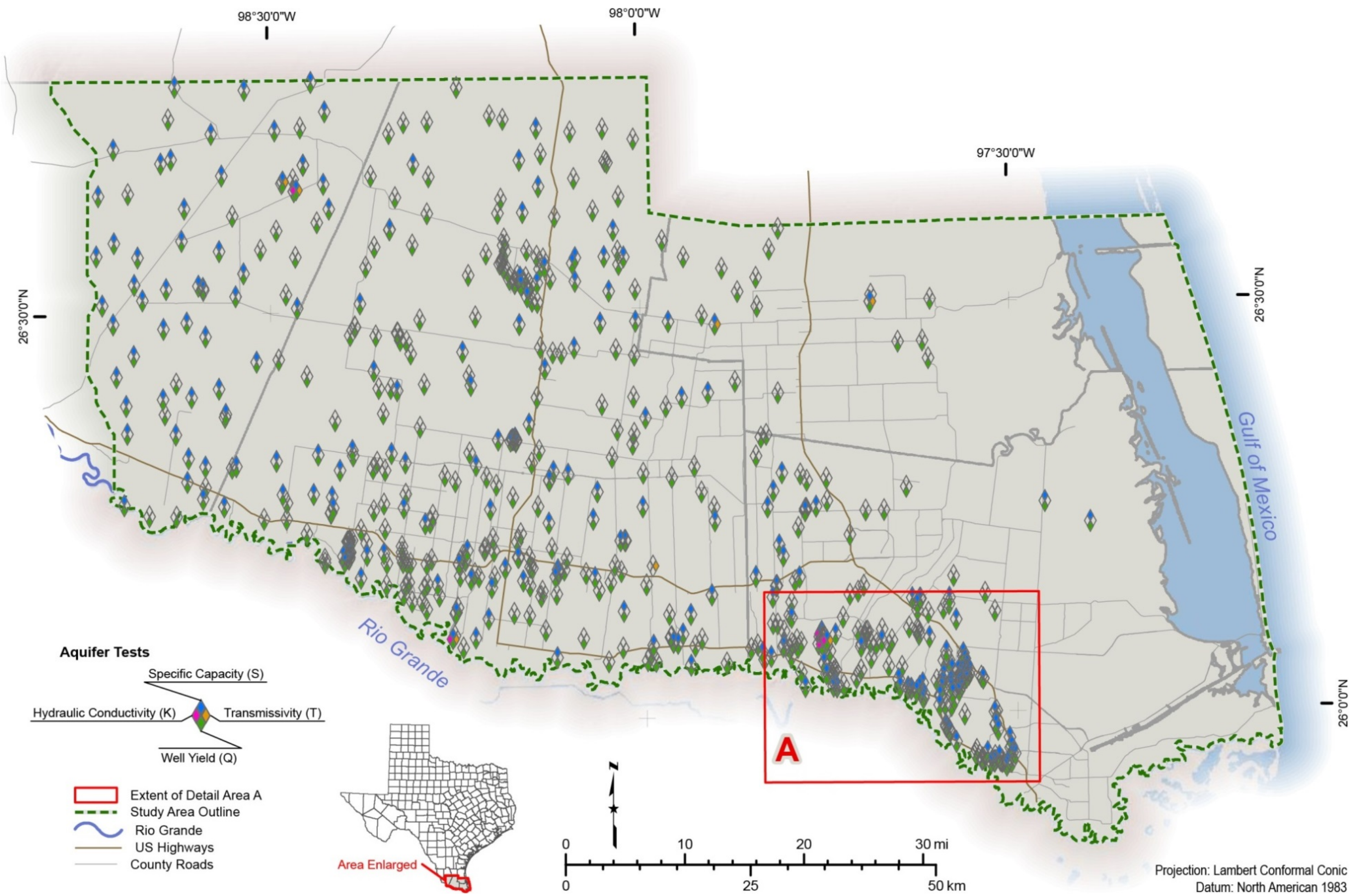


Figure 11-1. **Distribution of wells with the following hydraulic property data: hydraulic conductivity, specific capacity, transmissivity, and well yield. Refer to Table 11-1 for a summary of this data.**

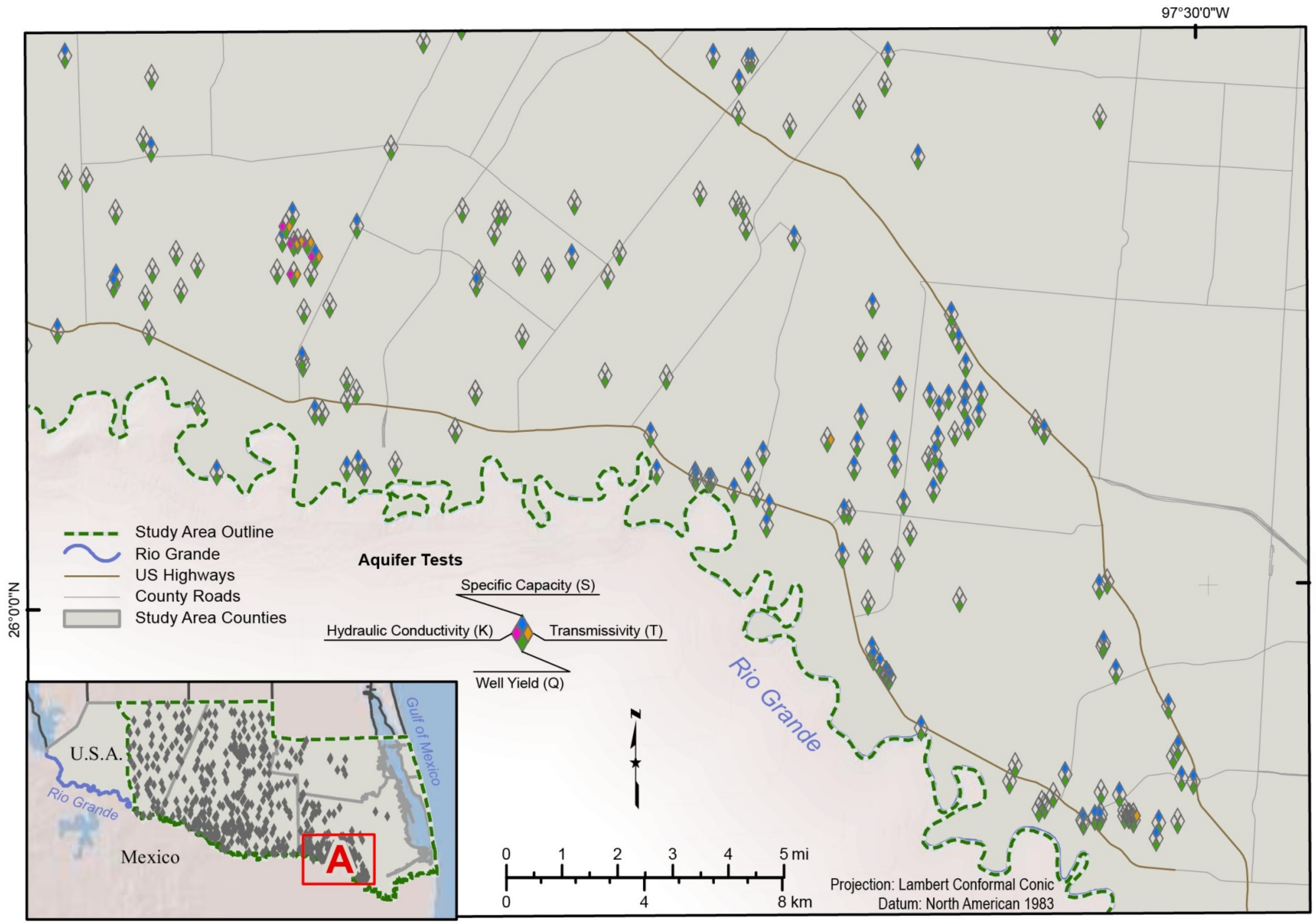


Figure 11-2. **Detail map of Figure 11-1. Distribution of wells with the following hydraulic property data: hydraulic conductivity, specific capacity, transmissivity, and well yield. Refer to Table 11-1 for a summary of this data.**

12. Water quality data

We obtained water quality data from the TWDB Groundwater Database and a limited number of raw-water sample reports from the Texas Commission on Environmental Quality public drinking water system paper file collection. We did not use results from Safe Drinking Water Act compliance samples for public water supply systems for this study. These samples are taken from the distribution system after treatment and disinfection and do not provide an accurate assessment of native water quality in the aquifer. Comparison of raw-water quality sample results with Safe Drinking Water Act maximum contaminant levels in this section does not imply that public water systems are providing water exceeding health limits.

TWDB staff conducted a limited water quality sampling program in the study area during the summer of 2013, collecting 38 samples for chemical analysis.

We combined all water quality data obtained for the study into one master water quality dataset consisting of dissolved minerals and physical parameters such as pH and specific conductance. One thousand six hundred and eleven water quality samples from 1,091 wells were assembled into the master water quality table. Radionuclide sample data were combined into a separate table. One hundred sixty-nine water quality samples from 113 wells were assembled into the radionuclide table. Additional water quality data (for example, metals) is present in the TWDB Groundwater Database. We assigned an updated aquifer assignment for each well based on the aquifer determination task described in Section 10, allowing us to produce GIS maps of several important parameters.

12.1 Parameters of concern for desalination

If used for potable purposes, brackish groundwater needs to be treated (desalinated). Without treatment, brackish water can cause scaling and corrosion problems in water wells and treatment equipment and cannot be used in many industrial processes. The Texas Commission on Environmental Quality has established a secondary standard of 1,000 milligrams per liter of total dissolved solids for public water supply systems (TCEQ, 2013). Groundwater containing total dissolved solids at concentrations greater than 3,000 milligrams per liter is not suitable for irrigation without dilution or desalination and, although considered satisfactory for most poultry and livestock watering, can cause health problems at increasingly higher concentrations (Kalaswad and Arroyo, 2006).

The physical and chemical parameters of concern to desalination facilities that use reverse osmosis—the predominant desalination technology in Texas—are listed in Table 12-1. While the TWDB Groundwater Database contains sample results in two tables for most of these parameters, the amount of information available from a well can vary greatly. For example, TWDB does not maintain information on silt density index or turbidity from groundwater samples. If the turbidity or silt density index is high, pre–treatment of the feedwater is required to avoid plugging the membranes in a reverse osmosis treatment system.

Groundwater quality in an aquifer can vary greatly due to factors such as mineral composition of aquifer materials, recharge rates, spatial distribution, chemical composition of recharge waters, and historical changes with time, geochemical processes, natural and man–made discharge rates and spatial distribution, residence time, and groundwater flow velocity. A review of published literature and comparison with GIS mapping of chemical parameters shows that groundwater geochemistry in the Gulf Coast Aquifer is extremely complex.

Mapping groundwater quality data also depends on the number and spatial distribution of samples, types of samples collected, and the dates the samples were collected. We present a series of maps (Table 12-2 cross-references parameters with figures) for the Gulf Coast Aquifer showing the distribution of some of the parameters of concern to desalination. The lack of significant numbers of samples in any one recent sampling year meant that we had to extract data from a multi-year period. While these maps display the spatial distribution of chemical parameters, they do not necessarily show current water quality conditions. Users interested in a specific region are encouraged to use the available database, GIS datasets, and GIS software to construct site-specific maps to meet project needs.

Table 12-1. Parameters of concern for desalination. The integers with a positive or negative sign indicate the valence of the ion.

Physical parameters	Chemical parameters			
	Cations		**Anions**	**Other**
Conductivity	Al^{+3}	K^{+1}	Cl^{-1}	Alkalinity
pH	As^{+3}	Mg^{+2}	CO_3^{-2}	Boron
Silt density index	As^{+5}	Mn^{+2}	F^{-1}	Dissolved oxygen
Temperature	Ba^{+2}	Na^{+1}	HCO_3^{-1}	H_2S
Turbidity	Ca^{+2}	NH_4^{+1}	NO_2^{-1}	Hardness
	Cu^{+2}	Ni^{+2}	NO_3^{-1}	Pesticides
	Fe^{+2}	Sr^{+2}	OH^{-1}	Radionuclides
	Fe^{+3}	Zn^{+2}	SO_4^{-2}	Silica
				Total dissolved solids

Table 12-2. Mapped chemical parameter data.

Chemical parameter	Figure number
Total dissolved solids	Figure 12.2-1
Arsenic	Figure 12.2-2
Boron	Figure 12.2-3
Chloride	Figure 12.2-4
Iron	Figure 12.2-5
Silica	Figure 12.2-6
Sulfate	Figure 12.2-7
Selenium	Figure 12.2-8
Barium	Figure 12.2-9
Radionuclides: combined radium	Figure 12.3-1
Radionuclides: gross alpha	Figure 12.3-2
Uranium	Figure 12.3-3
Radionuclide: wells with sample data	Figure 12.3-4

12.2 Dissolved minerals

Total dissolved solids concentration is a measure of the mineral content in water and is an important parameter for designing a reverse osmosis plant. Salinity is the term used to describe the concentration of dissolved, inorganic salts in groundwater. The common unit of measurement for total dissolved solids concentration is milligrams per liter. Eight hundred and ninety-four wells containing 1,322 water quality samples of total dissolved solids are available in the study area. The total dissolved solids concentrations ranged from 198 to 37,752 milligrams per liter. One thousand one hundred and thirteen of the 1,332 (84 percent) samples in the study area analyzed for total dissolved minerals (Figure 12.2-1) exceeded the Safe Drinking Water Limit secondary maximum contaminant level of 1,000 milligrams per liter (TCEQ, 2013).

Two hundred ninety-nine wells containing 318 water quality samples analyzed for dissolved arsenic are available in the study area (Figure 12.2-2). Arsenic concentrations ranged from 0.001 to 0.0994 milligrams per liter in the study area. Ninety-one of the 318 (29 percent) water quality samples exceeded the Safe Drinking Water Act maximum contaminant level for arsenic of 0.010 milligrams per liter (TCEQ, 2013).

Five hundred sixty-six wells containing 780 water quality samples analyzed for dissolved boron are available in the study area (Figure 12.2-3). Boron concentrations ranged from 0.00004 to 25.2 milligrams per liter. There is no maximum contaminant level for boron in public drinking water (TCEQ, 2013). Boron is listed on the Environmental Protection Agency Contaminant Candidate List 2 developed in 2005. In natural environments, boron exists as boric acid (H_3BO_3), a weak acid that does not dissociate readily (Hem, 1985). Boron concentrations in seawater average 4.6 milligrams per liter (Hem, 1985). Boron rejection by reverse osmosis membranes was studied by Kim and others (2009).

One-thousand eighty-three wells containing 1,563 water quality samples analyzed for chloride are available in the study area (Figure 12.2-4). Chloride concentrations ranged from 14 to 17,900 milligrams per liter. One thousand one hundred and forty-three of the 1,563 (73 percent) samples exceeded the Safe Drinking Water Act secondary maximum contaminant level for chloride of 300 milligrams per liter (TCEQ, 2013).

Eighty-seven wells containing 136 water quality samples analyzed for total iron concentration are available in the study area (Figure 12.2-5). An additional 1,007 samples analyzed for dissolved iron are present in the TWDB Groundwater Database (concentrations range from 0.014 to 0.8 milligrams per liter). Iron concentrations ranged from 0.003 to 6.19 milligrams per liter. Eighty-nine of the 136 (65 percent) samples exceeded the Safe Drinking Water Act secondary maximum contaminant level for iron of 0.3 milligrams per liter (TCEQ, 2013). Iron in groundwater can become oxidized and will precipitate when it reaches ground surface. To avoid fouling reverse osmosis membranes, water with elevated levels of iron must be pre-treated.

Seven hundred and sixteen wells containing 1,119 water quality samples analyzed for silica are available in the study area (Figure 12.2-6). Silica concentrations ranged from less than 1 to 245 milligrams per liter. There is no maximum contaminant level for silica in public drinking water (TCEQ, 2013). However, silica is an important desalination parameter because at elevated concentrations it can foul reverse osmosis membranes. The term silica is widely used to refer to dissolved silicon in natural water but the actual form is hydrated and should be represented as

H_4SiO_4 (Hem, 1985). The SiO_4^{-4} tetrahedron is the building block of most igneous and metamorphic rocks and is present in some form in most soils and groundwater.

One thousand sixty-six wells containing 1,514 water quality samples analyzed for sulfate are available in the study area (Figure 12.2-7). Sulfate concentrations ranged from 6.8 to 6,687 milligrams per liter. Nine hundred and forty-two of the 1,514 (62 percent) samples exceeded the Safe Drinking Water Act secondary maximum contaminant level for sulfate of 300 milligrams per liter (TCEQ, 2013). Sulfate in groundwater can cause scaling and fouling of reverse osmosis membranes, requiring the source water to be pre-treated.

Ninety-five wells containing 134 water quality samples analyzed for dissolved selenium are available in the study area (Figure 12.2-8). Selenium concentrations ranged from 0.001 to 0.06 milligrams per liter. Four of the 134 (3 percent) samples exceeded the Safe Drinking Water Act secondary maximum contaminant level for selenium of 0.05 milligrams per liter (TCEQ, 2013). Selenium can be a problem with concentrate surface discharge permits issued by the Texas Commission on Environmental Quality.

One hundred and sixty-eight wells containing 281 water quality samples analyzed for dissolved barium are available in the study area (Figure 12.2-9). Barium concentrations ranged from 0.0053 to 0.352 milligrams per liter. None of the samples exceeded the Safe Drinking Water Act secondary maximum contaminant level for barium of 2 milligrams per liter (TCEQ, 2013). Barium in groundwater can cause scaling and fouling of reverse osmosis membranes.

12.3 Radionuclides

The TWDB Groundwater Database includes 113 Gulf Coast Aquifer wells that have a total of 498 sample results for radionuclides. The samples were analyzed for uranium, radium, beta radiation, and alpha radiation. Wells in which radionuclides were detected are shown in Figure 12.3-4.

The presence of radionuclides in groundwater is important when selecting screen zone(s) for a well. Elevated naturally occurring radioactive material waste in the concentrate will impact the method of waste disposal and, thus, cost. Future test wells should always be logged with a gamma ray tool; elevated radionuclides in formation materials will be discovered using these logs.

Results of 32 samples from the study area analyzed for dissolved radium-226 (and 33 samples of dissolved radium-226 using the radon method) are available in the TWDB Groundwater Database. Sixty-one samples contained dissolved radium-228. None of the samples tested for combined radium-226 and radium-228 (Figure 12.3-1) exceeded the Safe Drinking Water Limit maximum contaminant level of 5 picoCuries per liter (TCEQ, 2013) as calculated by the summation of the results for radium-226 and radium-228.

The TWDB Groundwater Database contains 131 water quality sample results from the study area (Figure 12.3-2) for dissolved alpha radiation (and 26 samples of gross alpha radiation, produced water). Forty-four of the 131 samples (34 percent) exceeded the Safe Drinking Water Limit maximum contaminant level of 15 picoCuries per liter (TCEQ, 2013).

Ninety-eight water quality sample results of dissolved beta radiation (and 26 samples of gross beta radiation, produced water) are available in the TWDB Groundwater Database for the study area.

Sixty-two wells containing 91 water quality samples analyzed for dissolved natural uranium are available in the TWDB Groundwater Database (Figure 12.3-3). Thirteen samples (14 percent) exceeded the Safe Drinking Water Limit maximum contaminant level for uranium of 30 micrograms per liter (TCEQ, 2013).

12.4 Sources of dissolved minerals

Salinity in the Gulf Coast Aquifer in the study area can be traced to numerous natural causes based on time-scales of thousands to millions of years and also to anthropogenic conditions since the development of urbanization, agriculture, and oil and gas development in the study area.

Young and others (2014) provide a good discussion of salinity sources that may have caused or increased the concentration of total dissolved solids in the waters of the Gulf Coast Aquifer. Salinity sources can include salt domes (to the north of the study area), brine upwelling from geopressured zones (along growth faults), sea salt spray, connate water (water incorporated into sediments at the time of deposition or from marine inundation of sediments thereafter), natural deposits of evaporite minerals (salts derived from evaporation of sea water), salt water intrusion, and oil and gas development. Recharge to the Gulf Coast Aquifer can result from infiltration of surface water from the Rio Grande, agricultural watering, tailwater disposal wells (Knape, 1984), and leakage from irrigation canals and pipes.

Groundwater flow between wells is much more complicated than expected (Young and others, 2014). Young and others (2014) conclude that multiple potential scenarios can cause variations in measured chemical concentrations in the Gulf Coast Aquifer that cannot be explained by geochemical modeling alone. They believe that groundwater flow through the geological units is not characterized by the bulk movement of large regional slugs of water but rather is largely controlled by sand rich sections that finger through lower permeability deposits.

The Gulf Coast Aquifer has two primary types of groundwater: meteoric and connate water. Meteoric water is sourced from precipitation and connate water is water that was trapped in the sediments as they were being deposited. Saline water has been assumed to represent original connate water or seawater flooding during marine transgressions, and may be several thousand years old. A deep geopressured regime has greater than hydrostatic pressure due to compartmentalized coarser sediments encased in low-permeability clay. Faults are likely pathways for migration of deep basin brines into overlying aquifers, providing a significant source of sodium and chloride in groundwater (Young and others, 2014). Young and others (2014) estimate that 1.5 percent to 3 percent mixture of brine (40,000 to 80,000 milligrams per liter total dissolved solids concentration) is sufficient to produce groundwater of total dissolved solids concentrations of 1,000 to 1,500 milligrams per liter that commonly exist in down-gradient Chicot and Evangeline aquifers.

Young and others (2014) evaluated groundwater age and concluded that the current groundwater flow regime is based on hydrogeological conditions that have existed for the past 7,000 to 10,000 years. They summarize the paleohistory of the Gulf Coast aquifer in the following three 10,000 year periods (Young and others, 2014, p. xxviii):

> *(1) 30,000 to 20,000 years ago – Groundwater was part of a larger regional flow system than it is today because of a lower ocean level and more distant shore line. Also the base of the meteoric water was deeper than it is currently. Much of the*

Chicot footprint currently above sea level was being actively recharged and groundwater typically has a large vertical downward flow component.

(2) *20,000 to 10,000 years ago – As ocean levels rose 400 feet and the shoreline moved inland from about 50 miles in Groundwater Management Area 16 and about 100 miles in Groundwater Management Area 14, the base of the meteoric water rose. Beneath the Chicot footprint that is above sea level today, the downward hydraulic gradients gradually lessen and even reversed as movement in the deep Gulf Coast Aquifer System began to slow as the regional flow system shrunk in response to the transgression of the coastline caused by a rise in sea level.*

(3) *10,000 years ago to present – The ocean level reached stability about 7,000 years before present and the Gulf Coast Aquifer regional flow system achieved the current equilibrium with the current shore line, sea level and recharge condition. Groundwater with an age greater than 10,000 years is a mixture of waters that has been a part of regional flow systems that have changed with changes in sea levels and recharge conditions.*

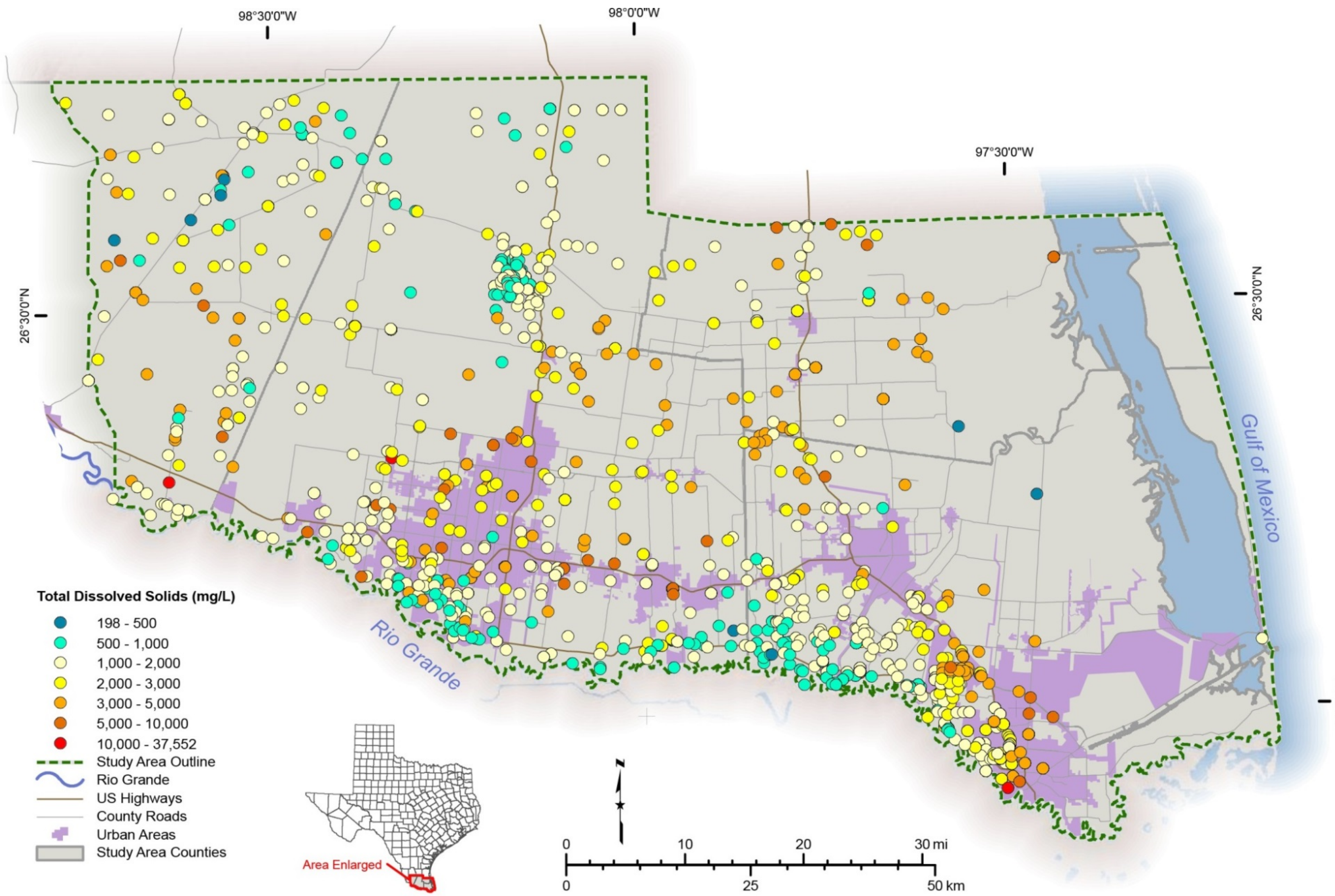


Figure 12.2-1. Distribution of wells sampled for total dissolved solids. mg/L = milligrams per liter.

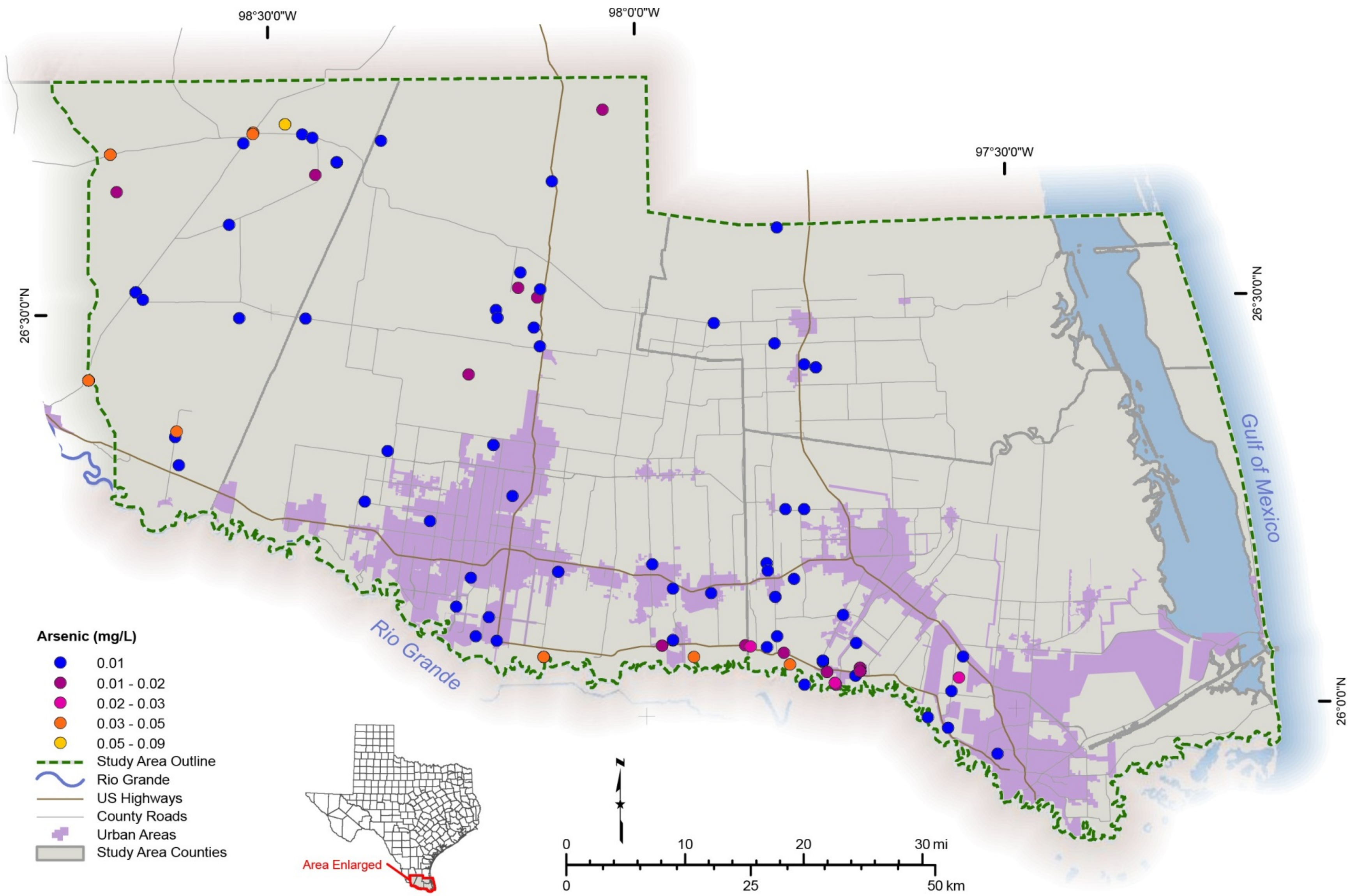


Figure 12.2-2. Distribution of wells sampled for dissolved arsenic. mg/L = milligrams per liter.

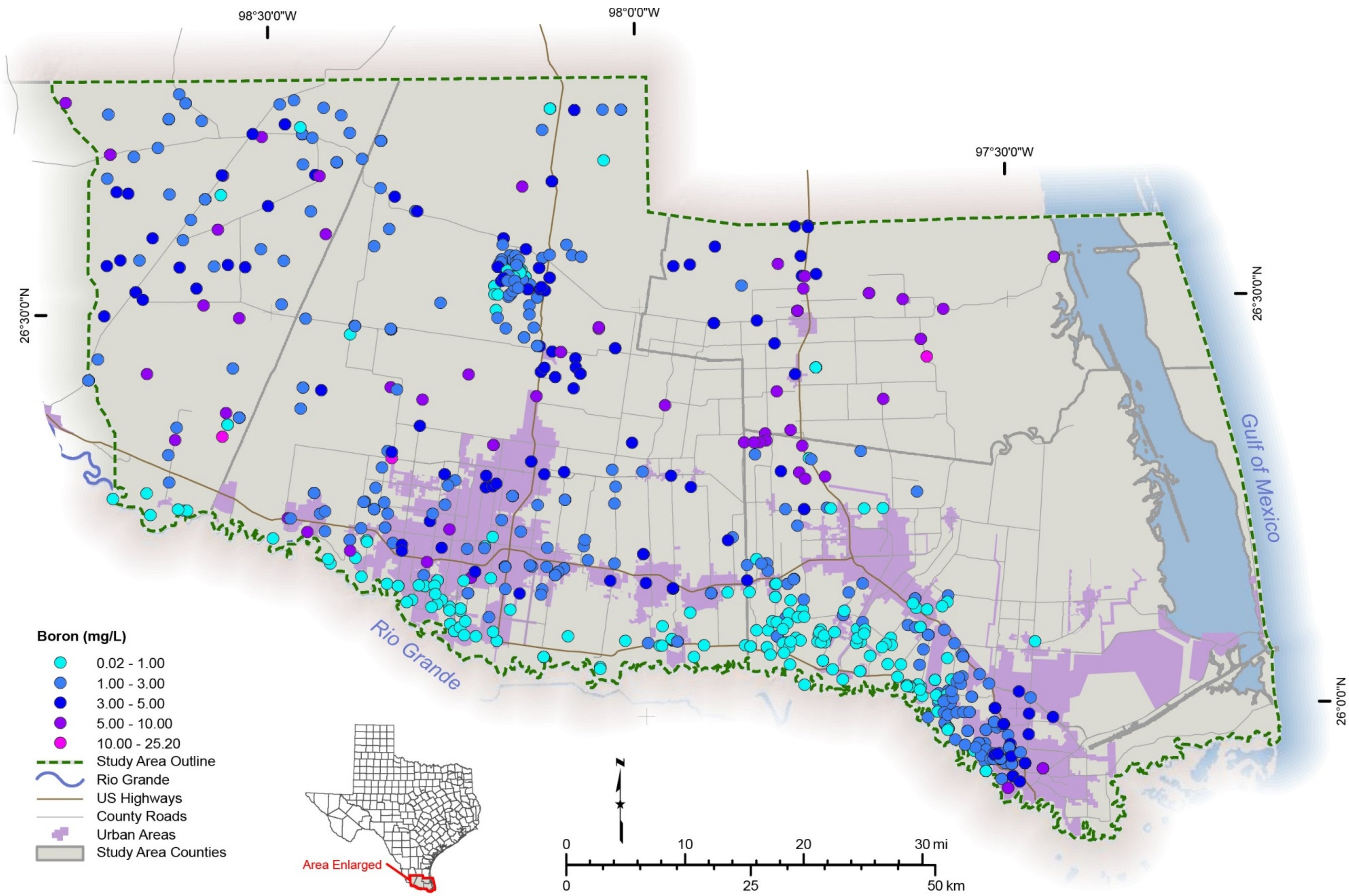


Figure 12.2-3. Distribution of wells sampled for dissolved boron. mg/L = milligrams per liter.

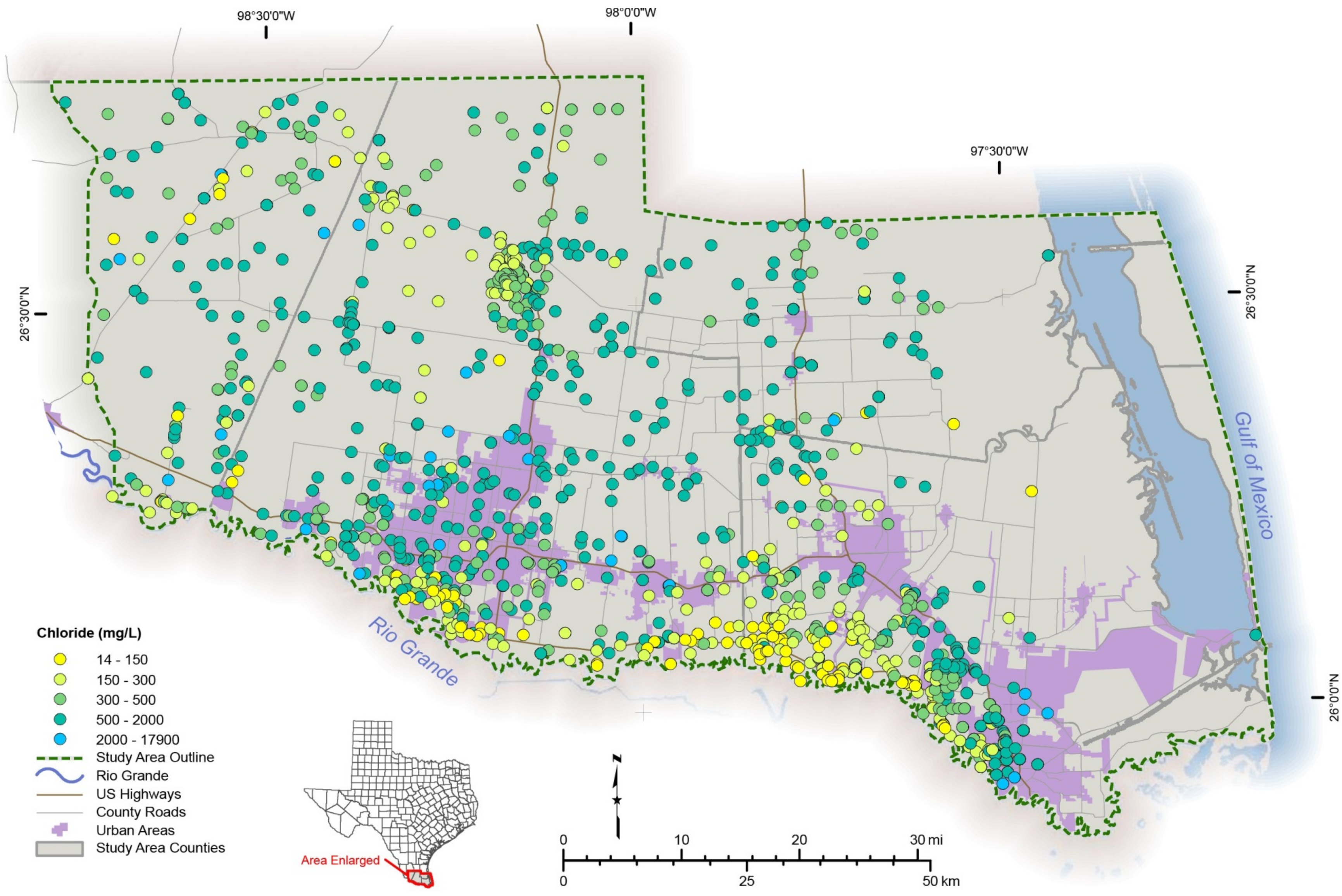


Figure 12.2-4. Distribution of wells sampled for chloride. mg/L = milligrams per liter.

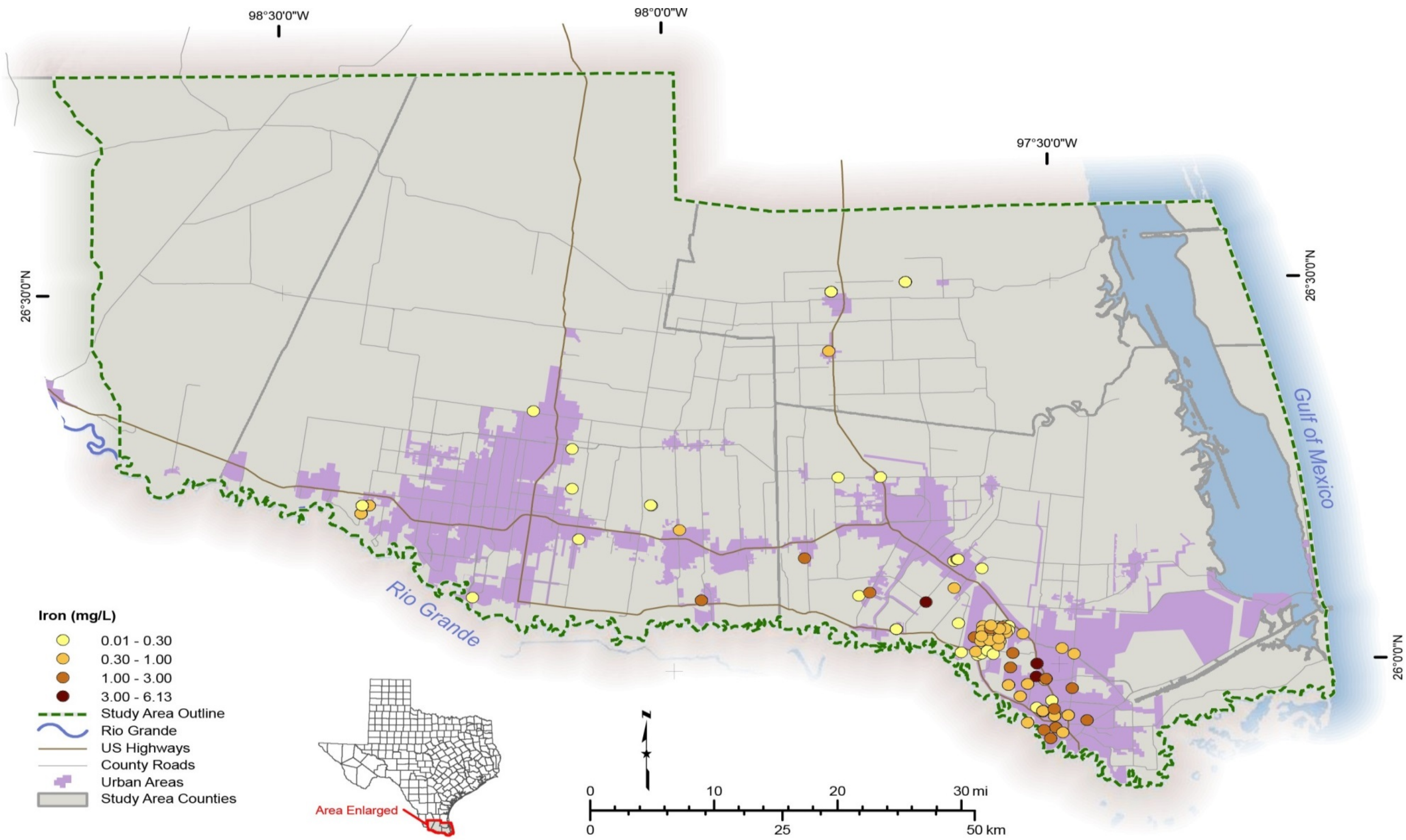


Figure 12.2-5. Distribution of wells sampled for total iron. mg/L = milligrams per liter.

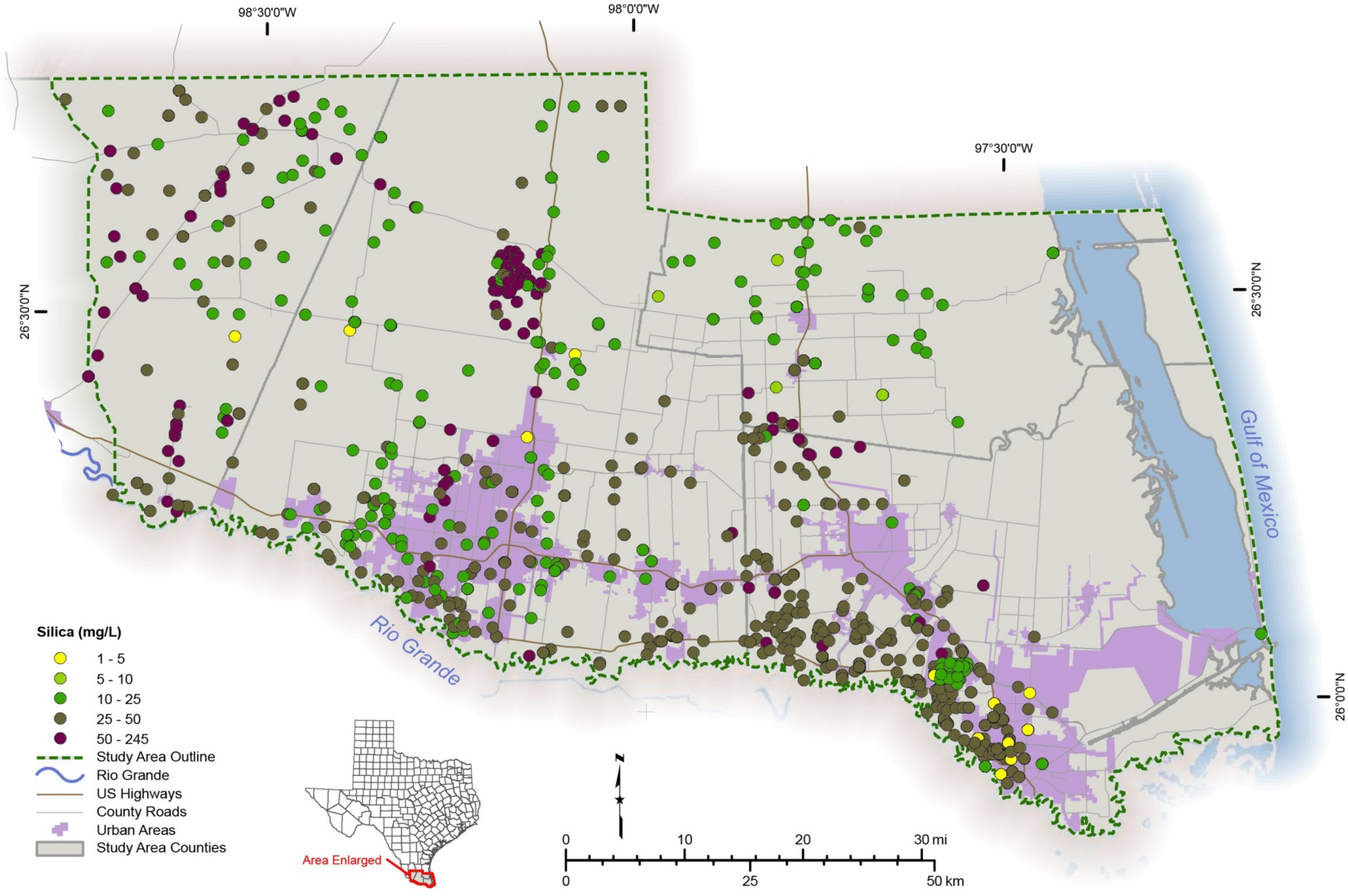


Figure 12.2-6. Distribution of wells sampled for silica. mg/L = milligrams per liter.

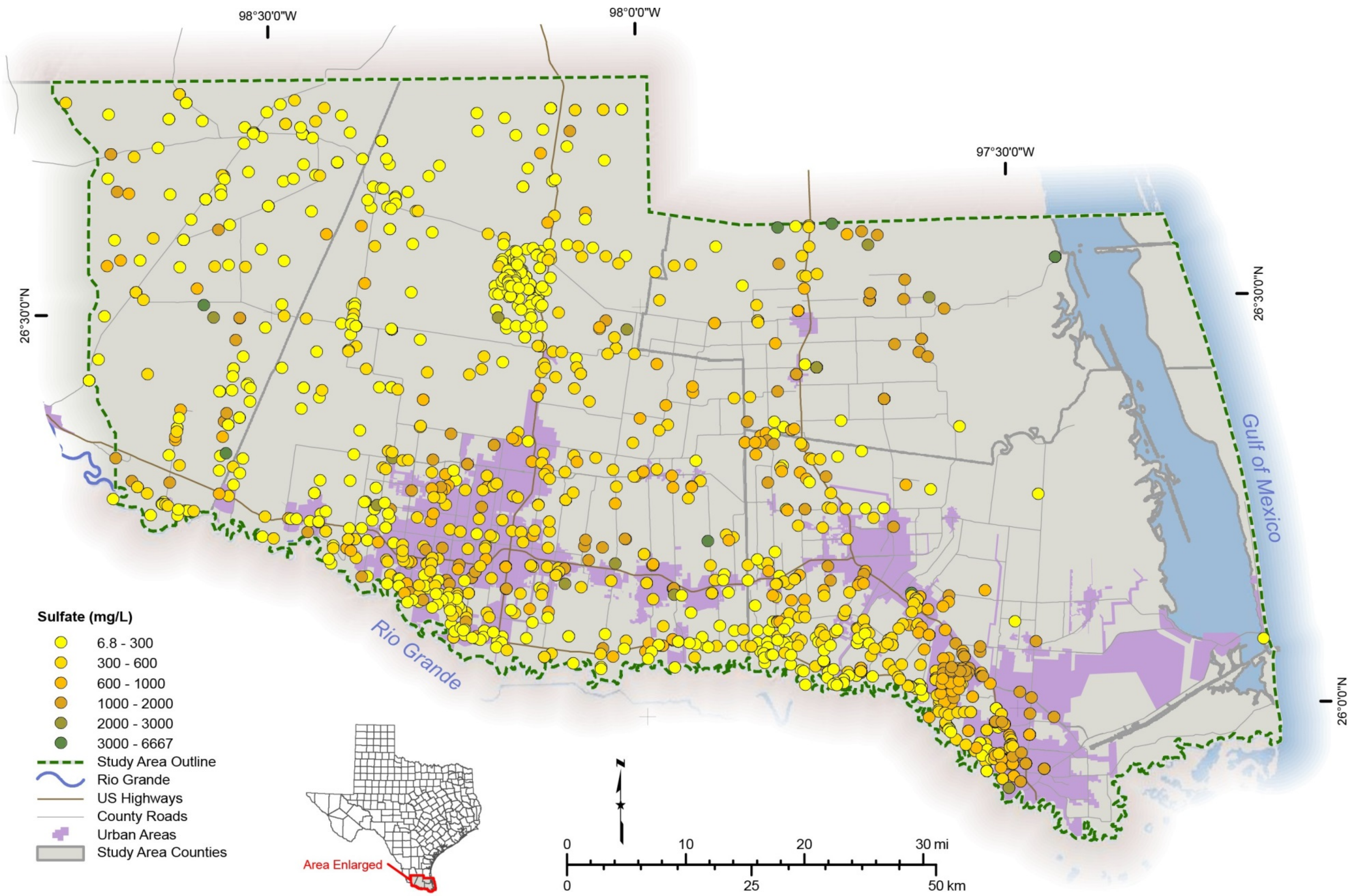


Figure 12.2-7. Distribution of wells sampled for sulfate. mg/L = milligrams per liter.

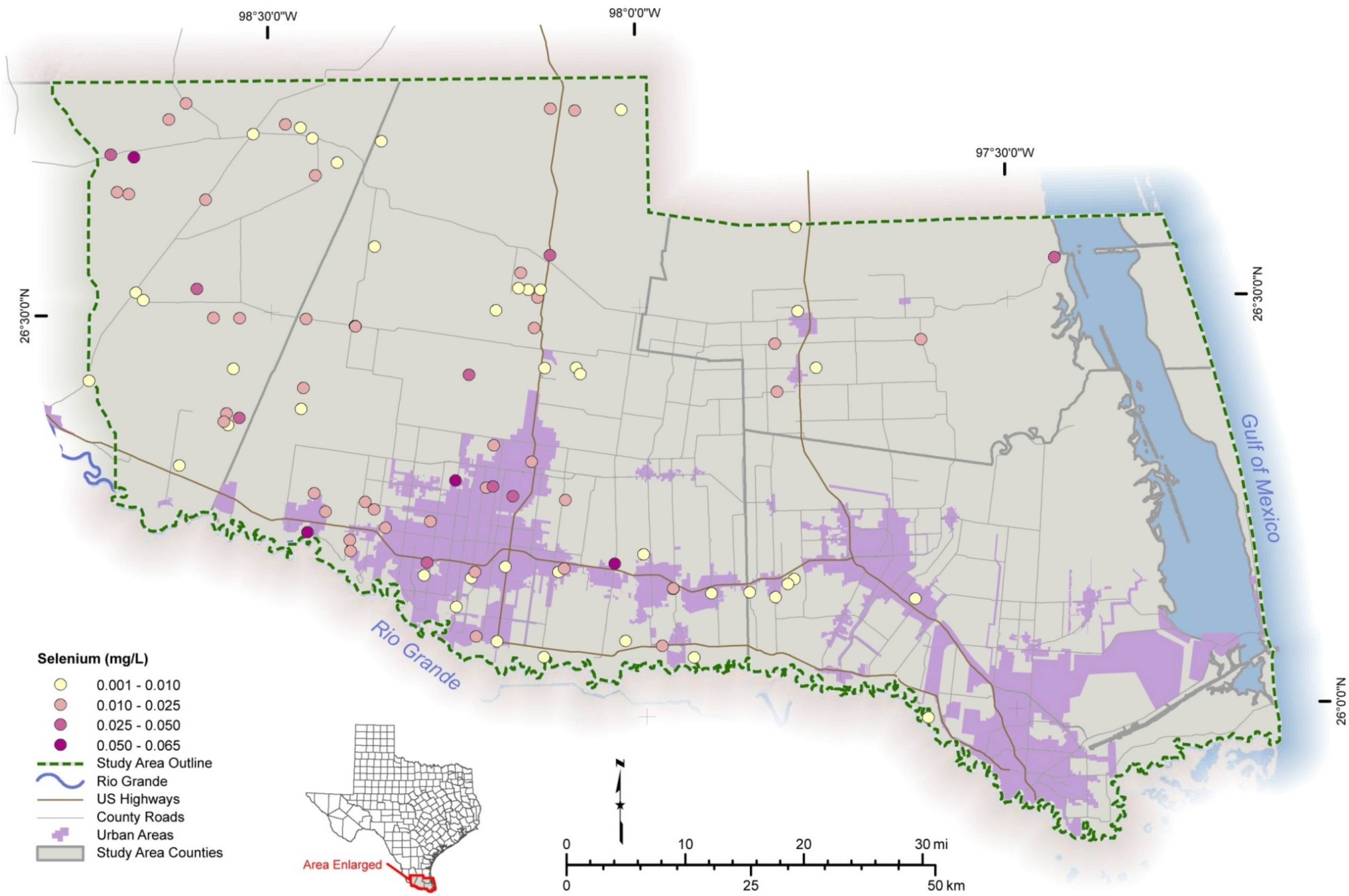


Figure 12.2-8. Distribution of wells sampled for dissolved selenium. mg/L = milligrams per liter.

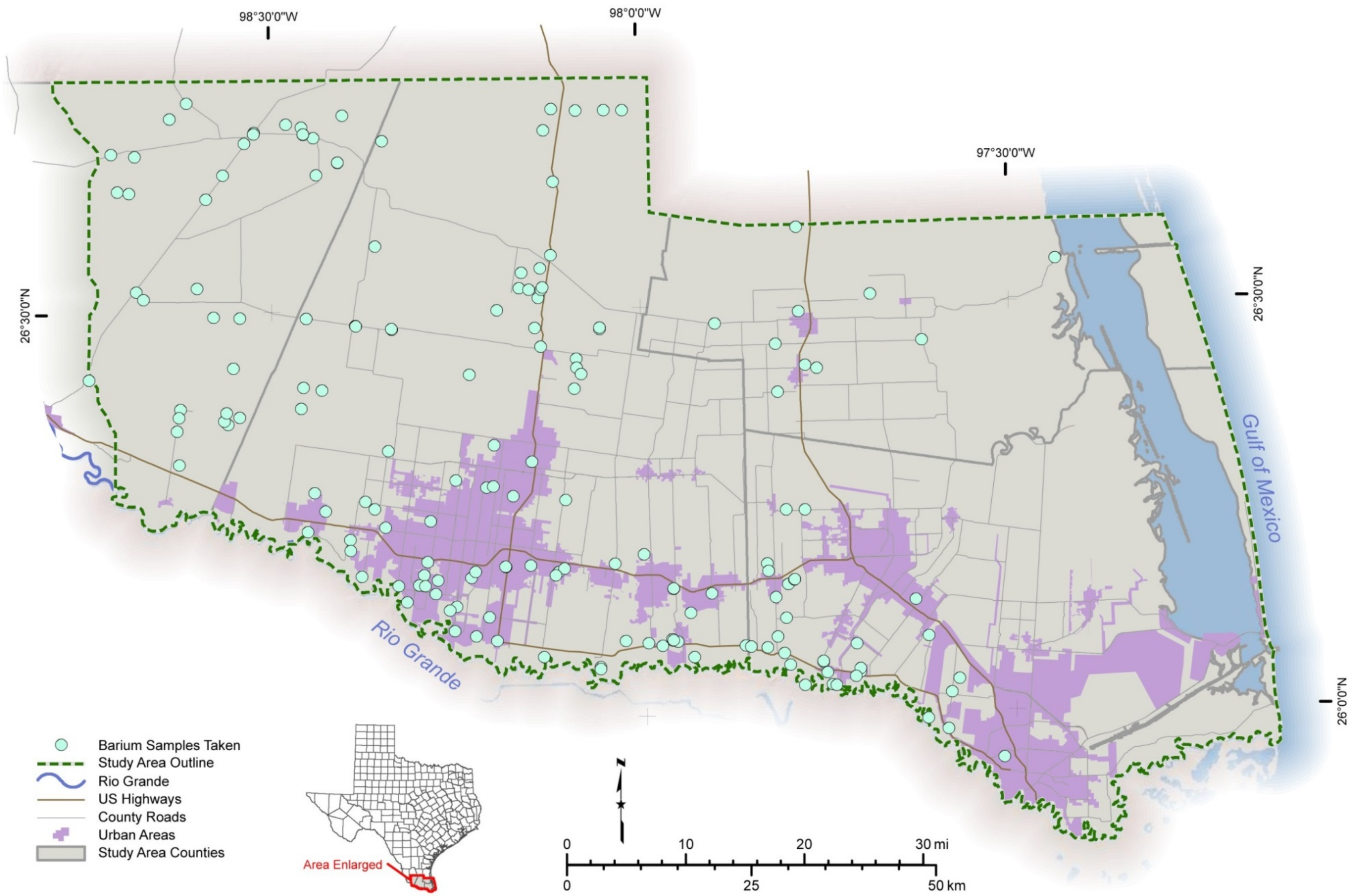


Figure 12.2-9. Distribution of wells sampled for dissolved barium. mg/L = milligrams per liter.

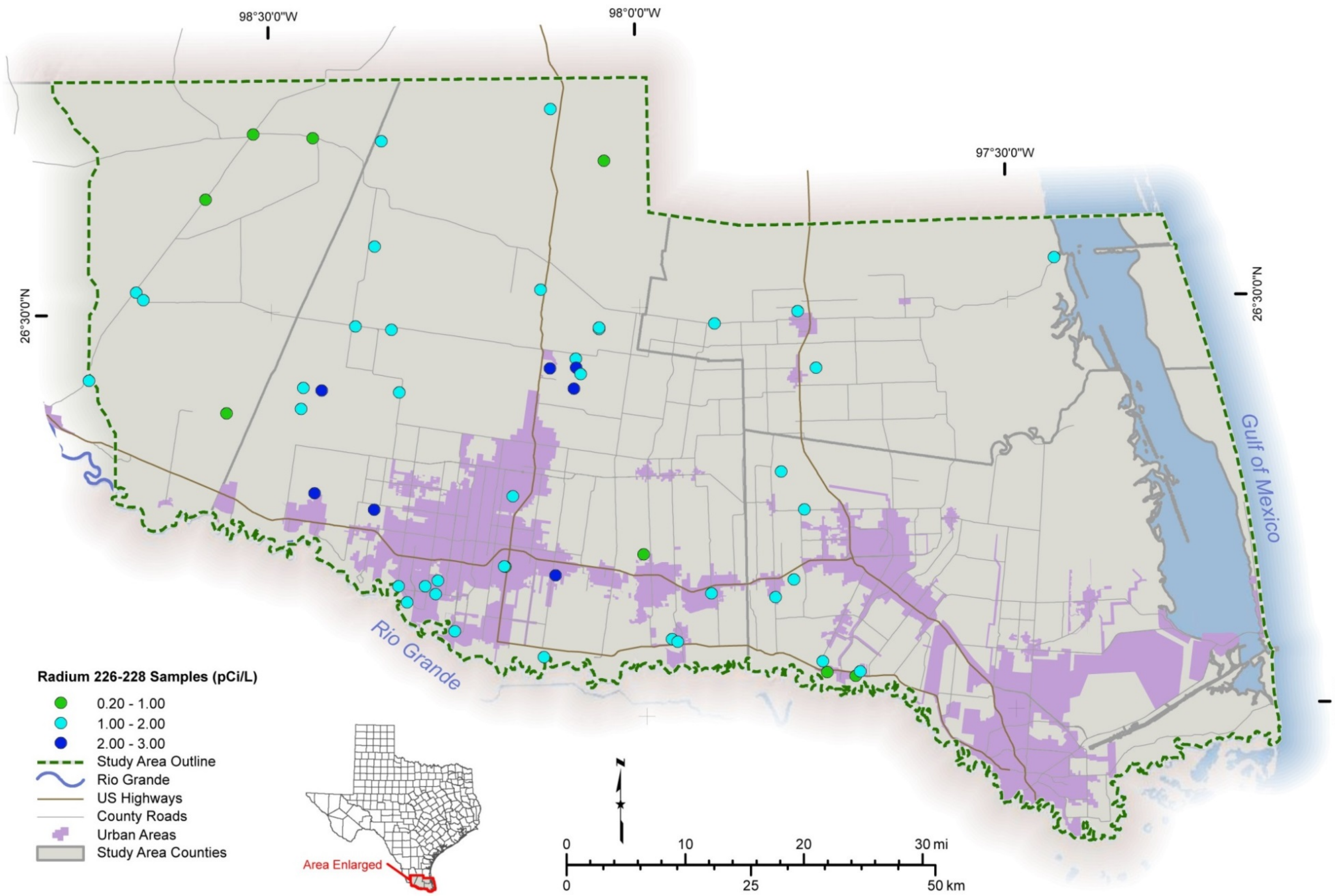


Figure 12.3-1. Distribution of wells sampled for combined radium-226 and radium-228. pCi/L = picoCuries per liter.

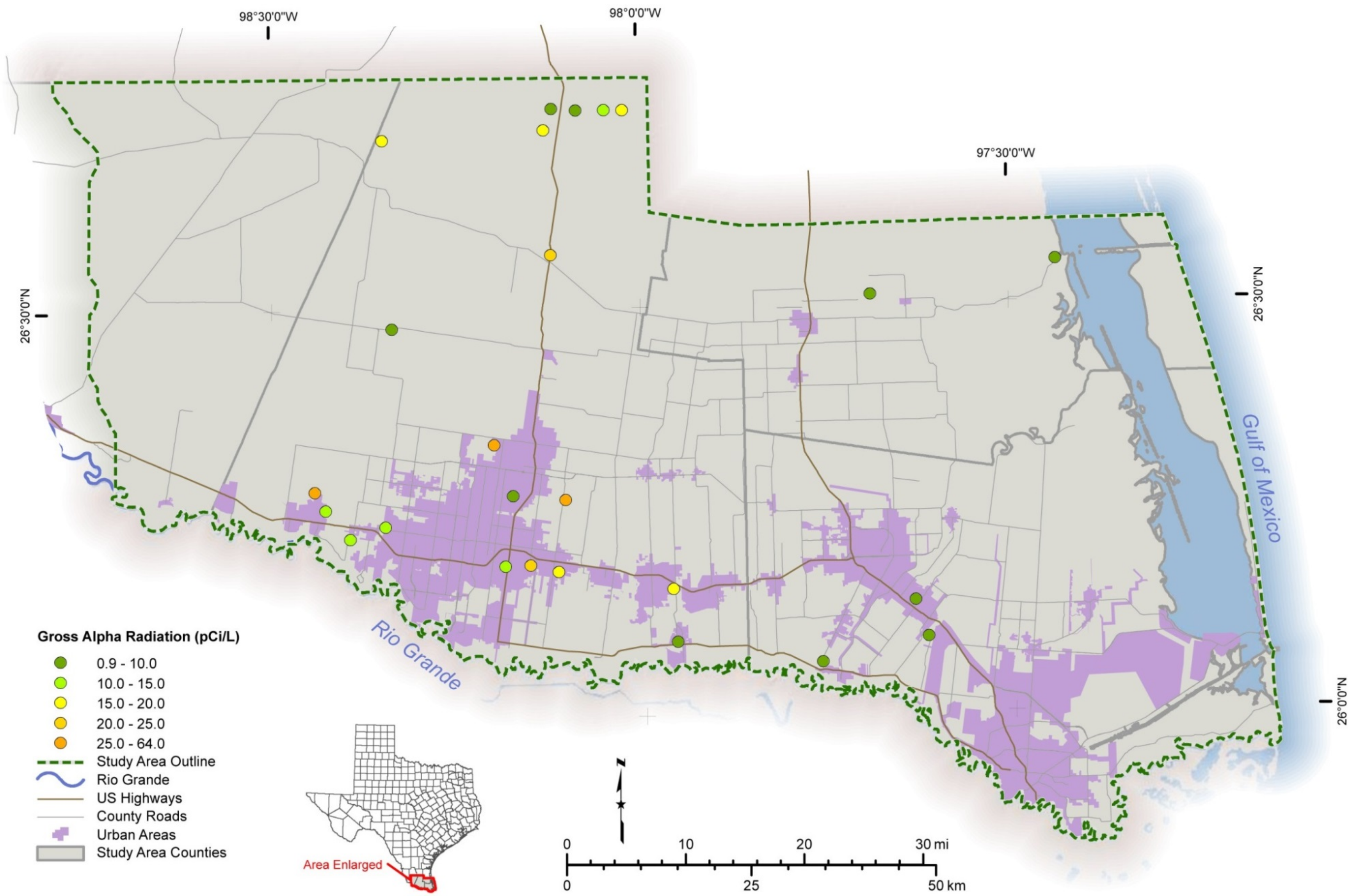


Figure 12.3-2. Distribution of wells sampled for gross alpha radiation. pCi/L = picoCuries per liter.

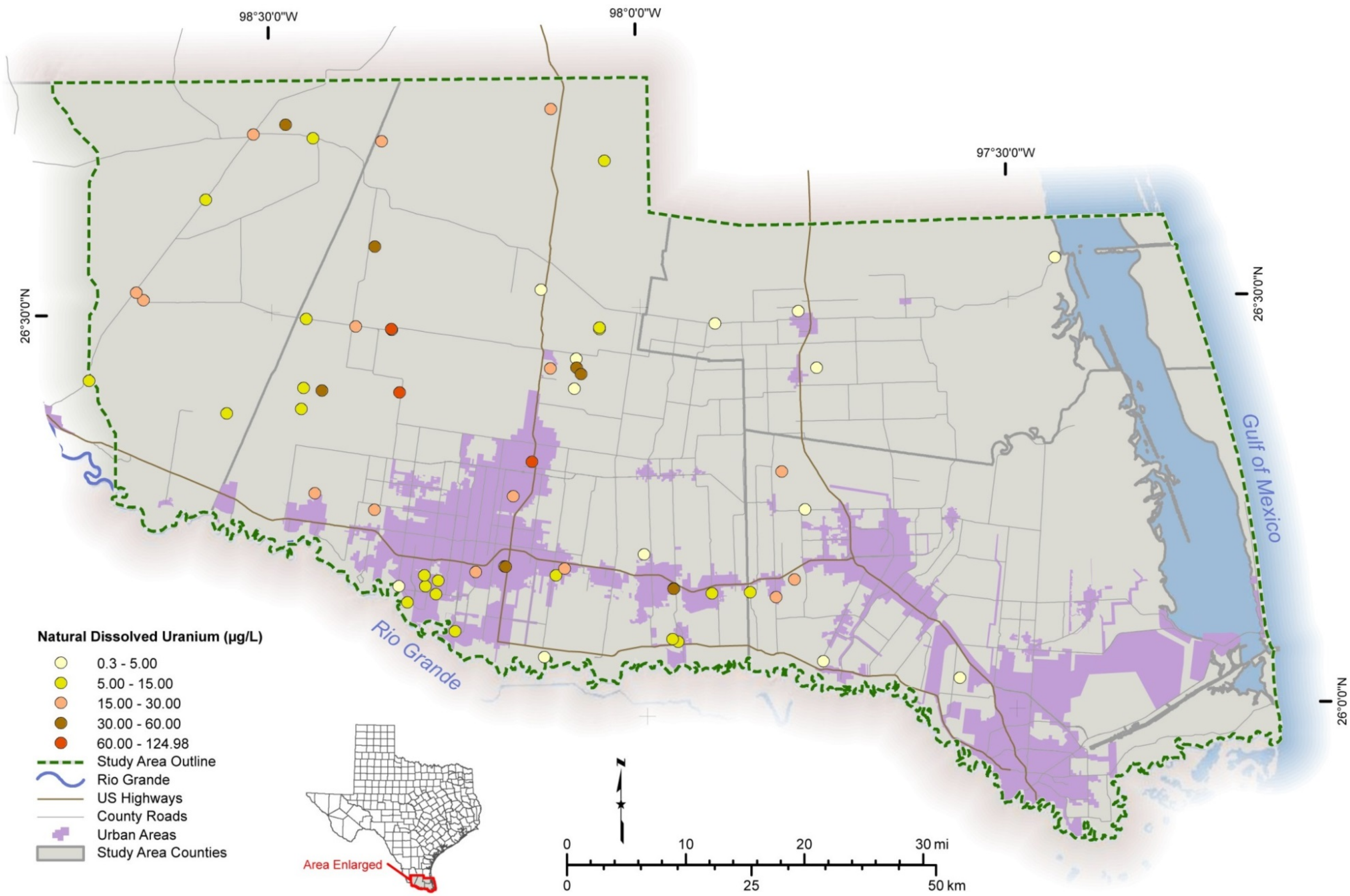


Figure 12.3-3. Distribution of wells sampled for uranium. µg/L = micrograms per liter.

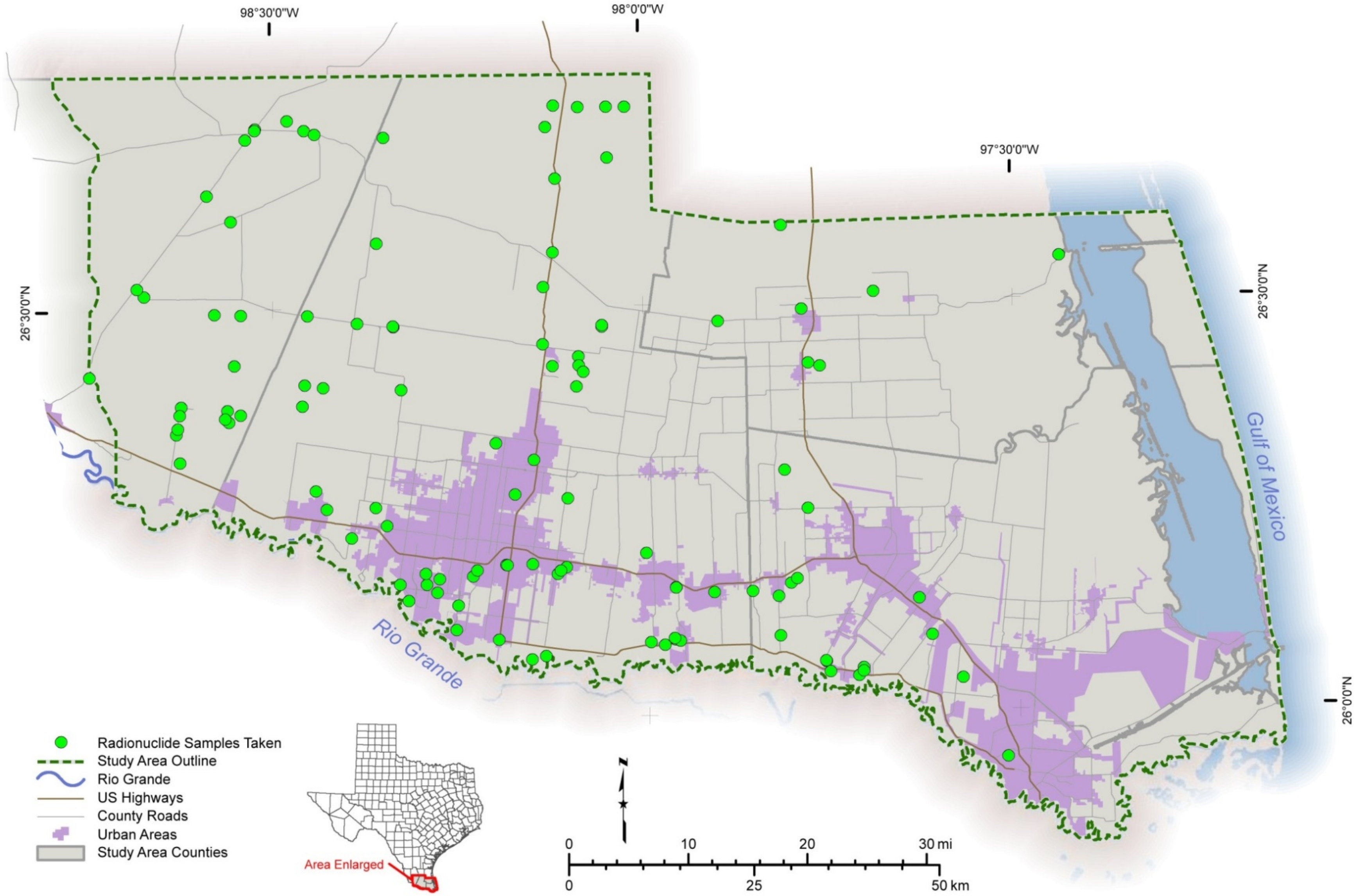


Figure 12.3-4. Distribution of wells sampled for radionuclides.

13. Net sand analysis

The geological formations within the study area contain interbedded layers of sand and clay. Although both types of formations contain groundwater, only sands can produce groundwater economically. However, clay layers can allow water to leak into adjacent sands. We prepared maps of net sand (the cumulative thickness of sand) for each geologic formation and selected salinity zones within the study area to estimate the volume of brackish groundwater and to show areas that are favorable for developing brackish groundwater. The net sand maps are generated from two sets of information: existing description of rocks by water well drillers and our interpretation of geophysical well logs. We evaluated 593 wells (Figure 13-1) of which 356 are water wells, 201 are oil and gas wells, and 36 are wells classified as other (primarily test holes for water wells). We used geophysical well logs for 244 wells and drillers' descriptions of lithology for the remaining 349 wells. The sections that follow describe the methods used to identify and describe the rocks.

We added the descriptions of rocks recorded by water well drillers on water well reports to the well geology table in the BRACS Database either manually or by digital parsing techniques (for wells in the Submitted Driller's Report Database of the Texas Department of Licensing and Regulation). The well geology table includes the following information for each lithologic unit: top and bottom depths, thickness, lithologic description, a simplified lithologic description, and the source of information.

Because well drillers frequently use non-geological terms (for example, gumbo), misapply terms (for example, talc in an alluvial deposit), and almost never describe the rocks and geological formations in a uniform and systematic manner, we developed a process to systematically translate the drillers' descriptions of rocks into a simple and consistent terminology. Our description consists of a short list of terms based on mineralogy and grain size. We prepared a database lookup table relating the drillers' lithologic name to the simplified lithologic description to accommodate the numerous variations present on well reports. Presently, the database lookup table contains more than 7,700 records and 94 simplified lithologic names.

The simplified lithologic names represent either one predominant type of material (for example, sand), or a mixture of two materials (for example, sand and gravel). Each term representing a mixture assumes that each component of the mixture approximates a 50-50 mix. The creation of the database table relating lithologic name to simplified lithologic name presented challenges and also necessitated some simplifications. Formation descriptions that contained more than two terms as part of a mixture (for example, sand, clay, and limestone) were converted to only the first two terms or the two most important terms based on percentage (if provided by the driller). Formation descriptions that included percentages of material within the 35-65 percent range were categorized as a 50-50 mixture. The simplified lithologic description was applied from ground surface to the total depth of the hole for water wells.

We evaluated geophysical well log lithology using the four-tier method used by Young and others (2010). The four-tier method includes the terms sand, clay, sand with clay, and clay with sand. The log was interpreted from the bottom of the surface casing to the very saline – brine interface or to the bottom of the logged interval, whichever was encountered first.

We used deep investigative resistivity tools in the shallow sections (fresher aquifer sections) because the spontaneous potential tool may be ineffective in this zone. In the deeper portions of the aquifers, where the resistivity of the drilling mud filtrate is greater than the resistivity of groundwater, we used spontaneous potential tools rather than deep resistivity tools. These zones produce a negative (or left) shift of the spontaneous potential log with respect to the shale baseline within permeable sands. The spontaneous potential and resistivity logs are affected by the presence of hydrocarbons; the spontaneous potential log is suppressed and the resistivity is increased (Hilchie, 1978).

Where available, gamma ray tools were interpreted because of its suitability for discriminating sand and clay sequences and, where present, were used in conjunction with the spontaneous potential and resistivity tools to identify lithology.

The well geology table contains all well lithology, including clay units. Although we did not prepare net clay or clay percent maps, the clay data can be reviewed in the BRACS Database or extracted to GIS. The presence of clay units and their thickness should be considered when locating groundwater wells for a desalination plant, especially if a well screen is going to be placed in an aquifer that is adjacent to a boundary between zones of different salinity.

If the water well report or geophysical well log is missing information because of the presence of well casing or lost circulation (no drill cuttings returned to surface), the term "No Record" is listed in the geology table for this depth interval. If a portion of the well report or geophysical well log is missing because the log is incomplete (only part of the log was scanned as a digital image), the term "Geology not processed–Log image cut off" is listed in the geology table for this depth interval. If a portion of the geophysical log was not interpreted, the term "Geology Not Described, But Available on Log" is listed in the geology table for this depth interval. Recording missing information with these terms is required during subsequent evaluation of net sand and sand percent.

Net sand and sand percent values for wells penetrating the geological formations in the Gulf Coast Aquifer and the different salinity zones were generated from the simplified lithologic description using structured query language in the BRACS Database. If a well only partially penetrated a geological formation, a net sand value was calculated, but not the sand percent.

The table listing all simplified lithologic names contains a field for sand percent. Values of 0, 35, 50, 65, or 100 were chosen based on the presence of sand or coarser material. For example, a value of 50 would be applied to a lithologic unit containing a mixture of sand and clay. This table is used in subsequent database queries to process well records.

Because database queries must address lithologic units that are not completely contained within one formation (the unit may straddle the formation top, bottom, or both), specific queries were written to evaluate each of these scenarios to assign the correct thickness of a lithologic unit to the correct formation. A separate query was run to assemble the information into a table for export into GIS for spatial display.

We created two tables in the BRACS Database containing net sand information for the study area; one table contains individual records for each layer with sand and the other table with one record per well and is a summary of net sand and sand percent for each formation encountered. These tables can be exported into GIS for display and analysis. The two database tables can also be queried in a number of ways to develop custom approaches to analysis. The design of the geology and net sand tables and the methods used to capture this data afford the user a tremendous degree of flexibility in data analysis.

We prepared net sand maps for 6 of 18 salinity zones (Figures 7.1-4, 7.1-7, 7.2-4, 7.2-7, 7.3-3, and 7.3-6). The remaining 12 salinity zones were of limited lateral and vertical extent defined by a limited number of data points; these zones were calculated manually. As described in Section 14, we used the net sand to calculate the volume of brackish groundwater volume in the study area.

We prepared a series of net sand maps for each formation in the study area (Section 21.4.2). These maps can serve as a good reference for future work on the individual formations that comprise the Gulf Coast Aquifer. This study used 593 data points compared to the 29 data points used by Young and others (2010).

We prepared the net sand maps using ArcGIS® 10.0 software with the Spatial Analyst® extension. Each of the 593 data points were compared to formation top and bottom depths and to salinity zone top and bottom depths to determine the net sand value. The points were exported to ArcGIS® as a point file using a Lambert Conformal Conic projection with a 1983 North American Datum horizontal datum. We extracted a subset of data points for each formation and each salinity zone for analysis. Data points from each point file were deleted if they did not apply or contained partial information at that well point. Two examples of partial information include the cased section of a well or a shallow water well that partially penetrated the zone of interest. Net sand maps of formations and salinity zones present at the ground surface generally reflect a lower value of net sand than probably exists due to the presence of surface casing, which precluded evaluation with geophysical well logs.

Point files of each formation and salinity zone were interpolated using the ArcGIS® Spatial Analyst® Topo to Raster tool and saved as raster grid files that were snapped to the project snap raster grid. Each raster has a Lambert Conformal Conic projection with a 1983 North American Datum horizontal datum. Several data processing steps were required to prepare a final integer raster grid with each data point net sand value copied into the corresponding grid cell. In areas lacking sufficient well control where the interpolation tool created a net sand cell value greater than the thickness of the formation or salinity zone, the cell was corrected to 50 percent of the thickness. Dummy points representing a zero net sand value were added to some point files to force the Topo to Raster tool to thin along the edges of a salinity zone.

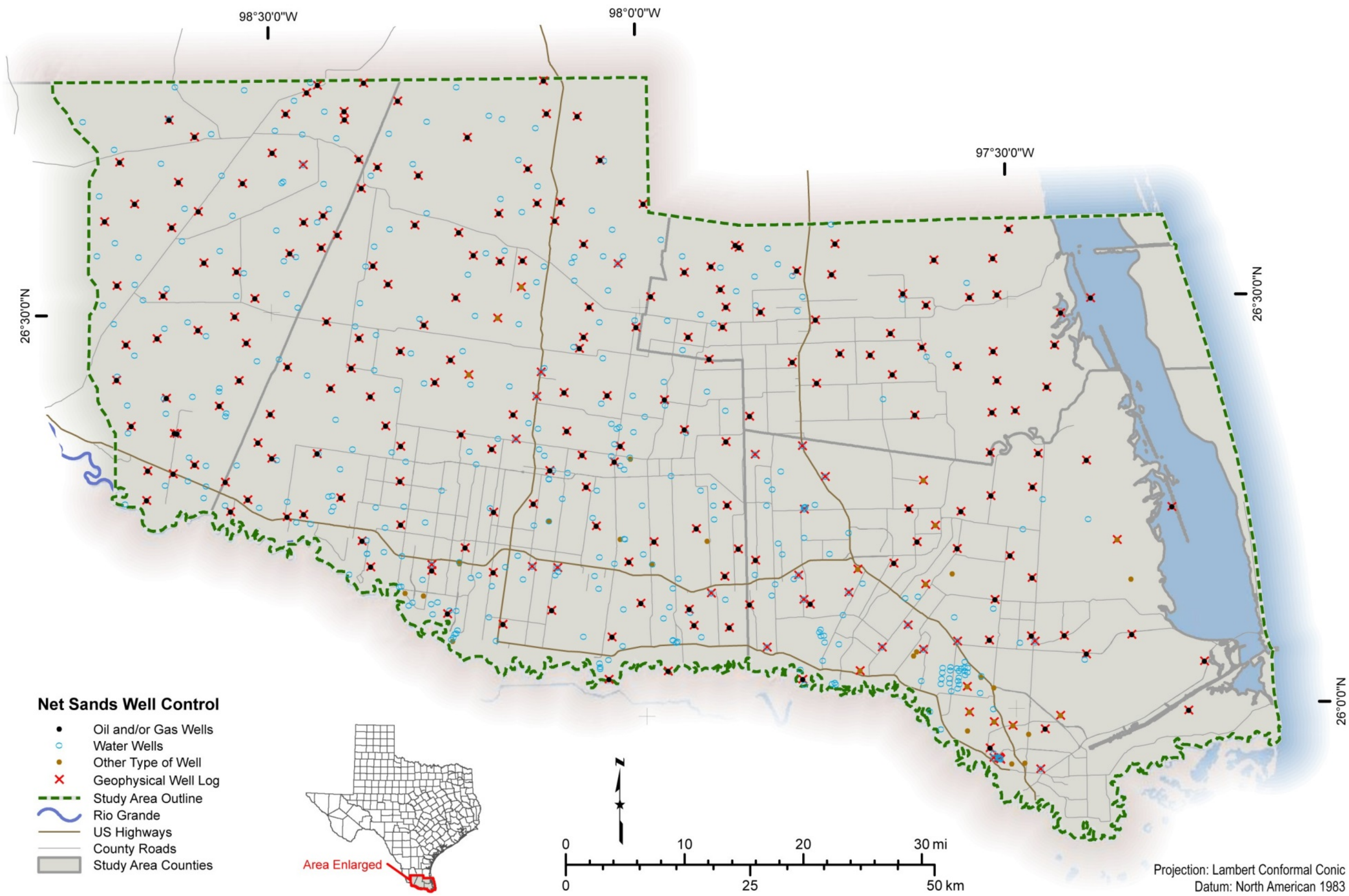


Figure 13-1. **Well control (593 wells) in the study area used for net sand analysis. The wells consisted of 244 geophysical logs and 349 water well driller lithology reports.**

14. Groundwater volume methodology

We estimated the volume of groundwater in the Gulf Coast Aquifer using the three-dimensional salinity zones. We prepared groundwater volumes for slightly saline (1,000 to 3,000 milligrams per liter of total dissolved solids), moderately saline (3,000 to 10,000 milligrams per liter of total dissolved solids), and very saline (10,000 to 35,000 milligrams per liter of total dissolved solids) zones. We did not prepare a volumetric estimate for brine. We also did not prepare a volumetric estimate for fresh water; areas containing fresh water were included in the slightly saline zone.

For the estimate we used a specific yield of 15 percent, consistent with used by LBG-Guyton (2003) and Chowdhury and Mace (2007). Measured specific yield data for the study area were not available. We did not calculate the volume of groundwater from confined storage for the following reasons: (1) the volume was assumed to represent less than one percent of total groundwater volume for the study area (LBG-Guyton, 2003), (2) the task would have been extremely complicated because each salinity zone would require analysis of confined versus unconfined extent, and (3) the only storativity values available for the study area are for the Chicot Aquifer, not for the Evangeline, Burkeville, or Jasper aquifers (Table 11-1).

Net sand volume GIS data were available for six salinity zones (Table 14-1). Groundwater volume was calculated by: Net Sand Volume (cubic feet) · Specific Yield · Conversion Factor (cubic feet to acre-feet).

Twelve of the salinity zones had sparse well control, so net sand maps were not prepared. For these zones, wells were reviewed manually and a sand percent value was obtained. Groundwater volume was calculated by: Volume of Salinity Zone (cubic feet) · Sand Percent · Specific Yield · Conversion Factor (cubic feet to acre-feet).

We estimate that the Gulf Coast Aquifer in the Lower Rio Grande Valley contains a significant volume of brackish groundwater: more than 40 million acre-feet of slightly saline groundwater, 112 million acre-feet of moderately saline groundwater, and 123 million acre-feet of very saline groundwater (Table 14-1). Not all of the brackish groundwater can be produced economically or even be produced.

TWDB Groundwater Resources Division staff calculated the total estimated recoverable storage of groundwater within the Gulf Coast Aquifer in the study area (Jigmond and Wade, 2013). These calculations were based on groundwater modeling and did not include a breakdown of volumes on the basis of salinity. Also, the assessment included both confined and unconfined storage, was limited to the TWDB-designated boundaries of the Gulf Coast Aquifer, and did not include the Catahoula Formation.

As estimated by Jigmond and Wade (2013), total storage in the study area was: 49 million acre-feet in Cameron County, 160 million acre-feet in Hidalgo County, 15 million acre-feet in Starr County, and 45 million acre-feet in Willacy County. These estimates (269 million acre-feet) compare favorably with the results of our study (275 million acre-feet of slightly saline to very saline groundwater.

Table 14-1. Groundwater volume estimates per salinity zone. We calculated volume with the volume of net sand per salinity zone using GIS techniques or an estimated sand percent multiplied by the volume of the salinity zone using a manual method. We used a value of 15 percent for specific yield.

Groundwater salinity classification	Salinity zone GIS File	Salinity zone letter(s)	GIS/Manual calculation	Volume water (acre-feet)
Slightly saline	SS S1	L	Manual	32,200
	SS S2	E	GIS	1,392,100
	SS i	H, I	Manual	1,256,000
	SS D	B, C, E, F, G, K, L, M, N, O, R	GIS	37,760,200
			Total Volume	40,440,500
Moderately saline	MS S1	K	Manual	275,400
	MS S2	H, I	Manual	1,920,600
	MS S3	S	Manual	172,500
	MS S4	F, G	Manual	290,400
	MS S5	C	Manual	227,400
	MS i1	E, M, N, O, R	GIS	8,456,400
	MS i2	L	Manual	33,900
	MS D	A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T	GIS	100,825,800
			Total Volume	112,202,400
Very saline	VS S1	G	Manual	5,000
	VS S2	M	Manual	232,900
	VS S3	I	Manual	10,100
	VS S4	O, P, R, S	GIS	7,679,200
	VS i	T	Manual	83,400
	VS D	A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U	GIS	115,286,000
			Total Volume	123,296,600

The LBG-Guyton (2003, Table 5) estimate for Gulf Coast Aquifer brackish groundwater volume in the study area includes more than 104 million acre-feet of slightly saline groundwater and more than 33 million acre-feet of moderately saline groundwater. They also estimated an additional one-half million acre-feet of slightly and moderately saline water from confined storage assuming a drawdown of 200 feet. Compared with the results from our study, it appears that they significantly over-estimated the volume of slightly saline groundwater and underestimated the volume of moderately saline groundwater. Another possible explanation could be that in the LBG-Guyton (2003, Table 5) study the values of the slightly and moderately saline water may have been inadvertently switched.

15. Electromagnetic data

Paine (2000) conducted a study of groundwater in the study area using airborne electromagnetic induction. The goal of this study was to assess the feasibility of this technique to select sites favorable for groundwater development. Two areas were investigated, Faysville and Stockholm (Figure 15-1). The data collected and processed during this study included conductivity data acquired from the ground surface to 656 feet (200 meters) below the ground surface. The gridded data was processed and smoothed with a 164 foot (50 meter) cell size. Data were collected in a much greater density than available geophysical well logs and water quality data for our study.

Ground conductivity is a function of the geological materials and groundwater. Variations in ground conductivity with groundwater containing low concentration of total dissolved solids is related to changes in minerals present in the rocks, and the porosity and permeability of the rocks. Ground conductivity with groundwater containing high concentrations of total dissolved solids is mostly a function of groundwater with relatively little effect from the formation. Geological formations containing a large amount of clay are more conductive than sand or gravel deposits assuming groundwater quality is constant.

A series of ground conductivity maps representing horizontal depth slices at approximately 30 feet (10 meter) depth intervals from approximately 30 to 600 feet (10 through 200 meters) were prepared for the Faysville and Stockholm areas. Users of these maps are cautioned that the ground conductivity color range scale of each depth slice is different, making direct comparisons difficult. Paine (2000) reasonably attributed sinuous features to ancient river or other fluvial/deltaic channel deposits within the Gulf Coast formations. Channel thickness, channel orientation, and the structural dip of the formation need to be considered when interpreting the data. The maps provided in his report represent a depth slice, but channels may dip into a different depth zone. Generally, the structural dip of the formations increases with increasing depth within the Gulf Coast Aquifer.

Paine (2000) compared the airborne electromagnetic data with ground-based measurements in addition to water quality and driller log lithology for calibration. He presented several low conductivity groundwater exploration targets within the Faysville and Stockholm areas. Paine (2000) did not prepare maps showing interpreted total dissolved solids content of groundwater or net sand maps. The report is available on the TWDB website and GIS data is available on request from the TWDB Contracts Division.

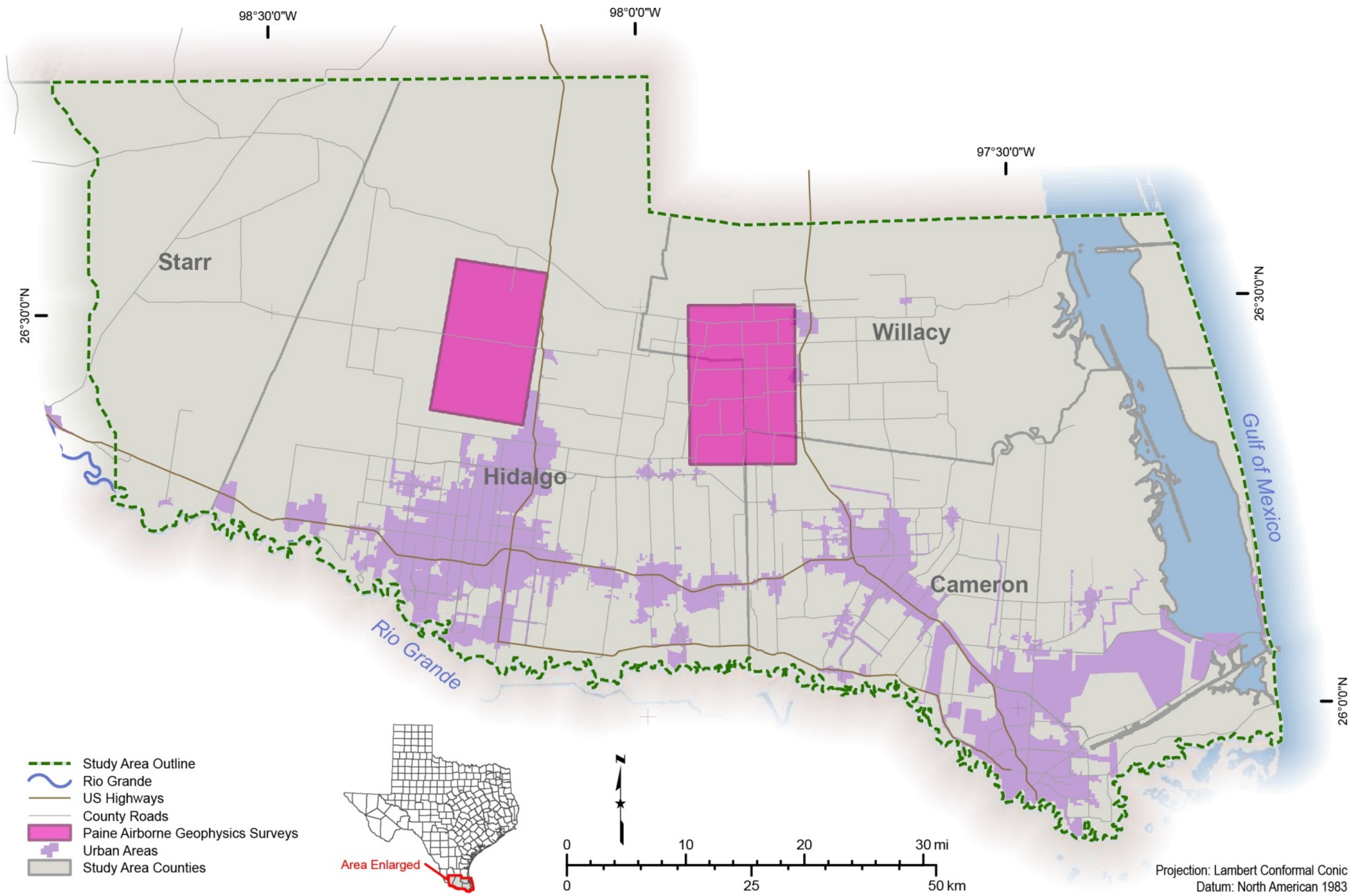


Figure 15-1. **Airborne electromagnetic surveys conducted in the study area by Paine (2000). The Faysville survey is to the west, and the Stockholm survey is to the east.**

16. Desalination concentrate disposal

All seven existing brackish groundwater desalination plants in the study area (Southmost Regional Water Authority; Valley Municipal Utility District 2; North Alamo Water Supply Corporation: Donna, Doolittle, Lasara, and Owassa; North Cameron/Hidalgo Water Authority) discharge the concentrate (wastewater from the reverse osmosis process) to a surface-water ditch under permit conditions established by the Texas Commission on Environmental Quality. This method of concentrate disposal is less expensive than disposal by injection well.

Class II injection wells dispose produced water, obtained from oil and gas wells, into subsurface zones where groundwater is greater than 10,000 milligrams per liter total dissolved solids (except in very specific circumstances). Class II injection wells can be used for disposal of nonhazardous desalination concentrate or nonhazardous drinking water treatment residuals if the following well types and conditions apply (CDM Smith, 2014):

Class II Type 1:	*Disposal injection well into a nonproductive oil and gas zone or interval. The well can be dually permitted as a Class I injection well under the Texas Commission of Environmental Quality General Permit. The well must meet all applicable construction standards of a Class I well under 30 Texas Administrative Code Section 331.62.*
Class II Type 2:	*Injection well into a productive oil and gas zone or interval. The well can be dually permitted as a Class I injection well under the Texas Commission of Environmental Quality General Permit. The well must meet all applicable construction standards of a Class I well under 30 Texas Administrative Code Section 331.62.*
Class II Type 3:	*Enhanced recovery injection well. This type of well can receive a permit amendment under the Railroad Commission of Texas.*

For future desalination plants that may be built in the study area, if disposal of desalination concentrate using a Class II injection well is considered as a potential option, a considerable amount of research must be undertaken to ensure that the well meets construction requirements, appropriate permits are obtained, and a contract with the owner of the injection well can be obtained for the lifetime of the project (Mace and others, 2006; CDM Smith, 2014).

We mapped the location of Class II injection wells in the study area using data obtained in 2012 from the Railroad Commission of Texas Underground Injection Control Database. We did this to identify: (1) potential sites for desalination concentrate waste disposal, and (2) sites where produced water may have been disposed within the Gulf Coast Aquifer. The latter helps us better understand and explain at least some of elevated salinity zones identified during our study.

We prepared two maps of Class II injection wells: wells that have not been plugged (Figure 16-1), and wells that have been plugged (Figure 16-2). Each map has symbols showing use of the actual injection and if the well had injected fluids into formations of the Gulf Coast Aquifer. We compared injection zone top and bottom depths with top and bottom depths of the Gulf Coast Aquifer formations to determine if the injection zone intersects the Gulf Coast Aquifer. Well information is summarized in Table 16-1. The Class II injection well GIS shape file will be included in the study deliverables and is described in Section 21.2.

There are a number of discrepancies with the data obtained from the Railroad Commission of Texas. For example, one set of data indicates that a well is plugged whereas another set of data for the same well indicates it has not been plugged. Therefore, users of this information should conduct a thorough investigation of a well should a Class II well be considered for concentrate disposal or if groundwater development is considered near an existing Class II well.

Another option for concentrate disposal is using a Class I injection well permitted under the Texas Commission on Environmental Quality General Permit. The Class I General Permit only applies to wells disposing of nonhazardous desalination concentrate or nonhazardous drinking water treatment residuals.

Table 16-1. Class II injection wells in the study area. Data obtained in 2012 from the Railroad Commission of Texas, Underground Injection Control Database.

Class II well type	Plugged status	Injection activity status	Total well count	Total well count: Injection into Gulf Coast Aquifer
1	Not plugged	Active	85	25
1	Not plugged	Not active	22	6
2	Not plugged	Active	43	2
2	Not plugged	Not active	13	1
3	Not plugged	Active	60	1
3	Not plugged	Not active	10	0
1	Plugged	Active	82	32
1	Plugged	Not Active	37	8
2	Plugged	Active	31	1
2	Plugged	Not Active	7	1
3	Plugged	Active	57	0
3	Plugged	Not Active	57	0

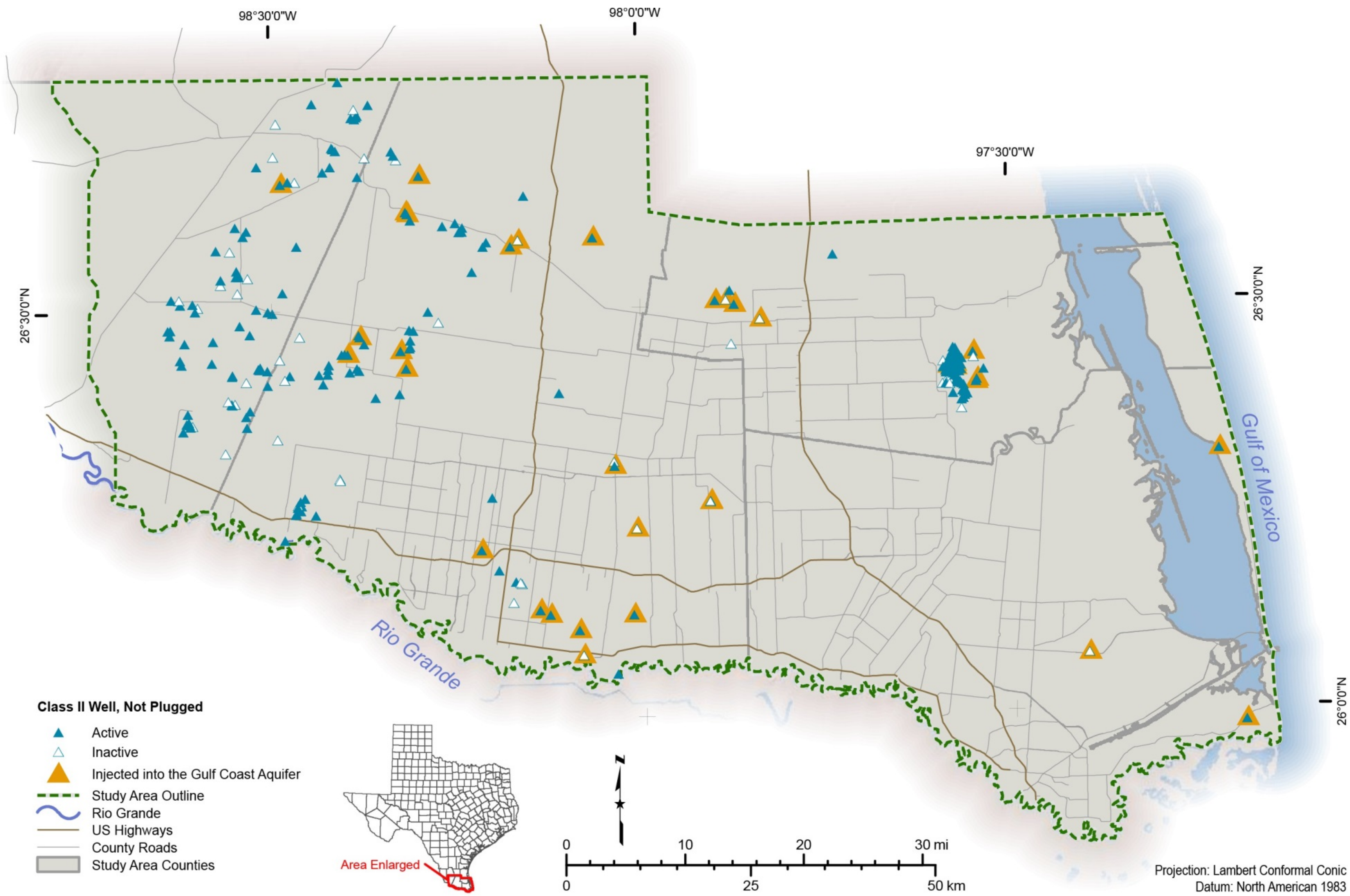


Figure 16-1. **Distribution of Class II injection wells in the study area that have not been plugged. Data obtained in 2012 from the Railroad Commission of Texas, Underground Injection Control Database.**

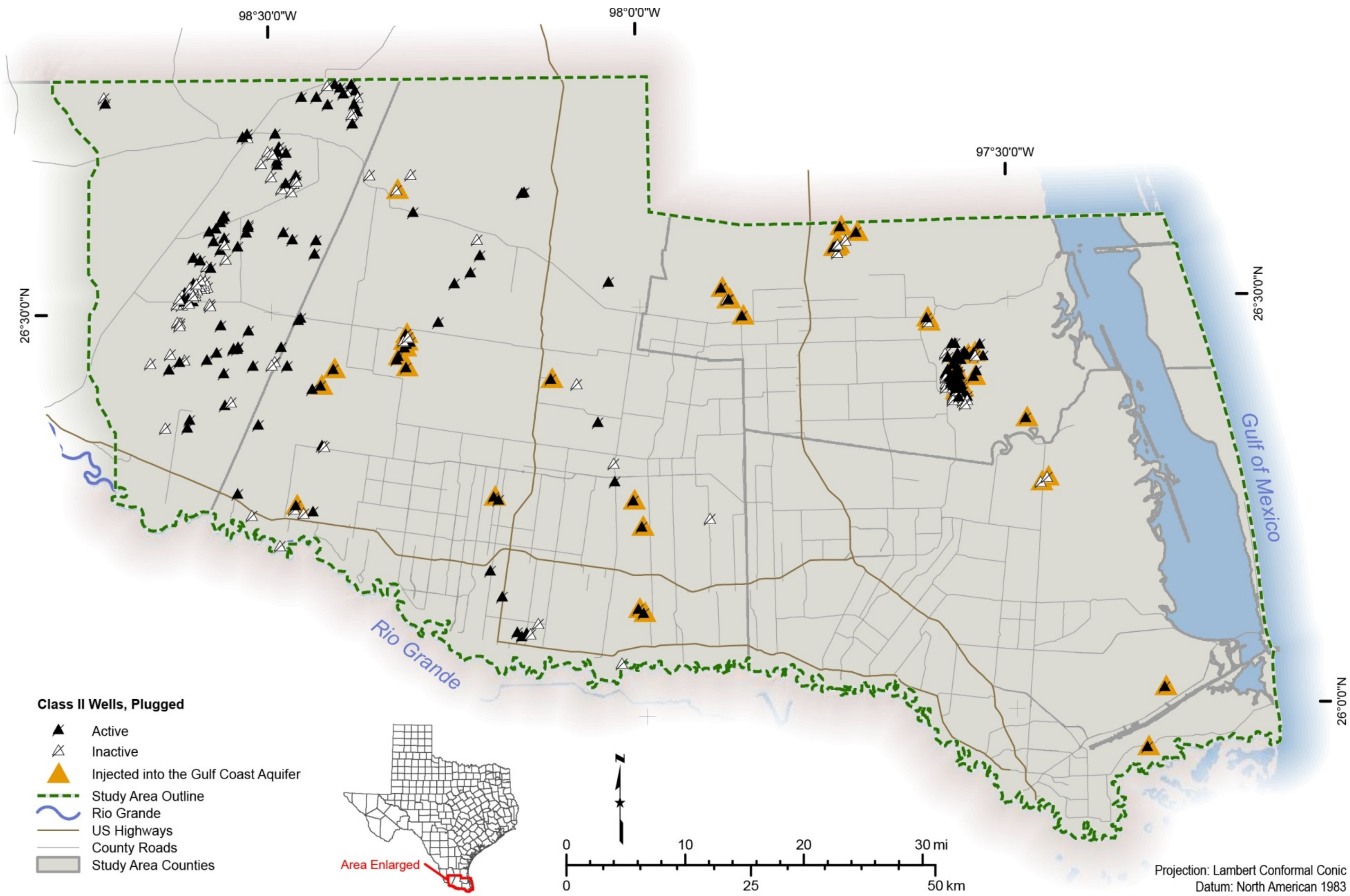


Figure 16-2. Distribution of plugged Class II injection wells in the study area. Data obtained in 2012 from the Railroad Commission of Texas, Underground Injection Control Database.

17. Future improvements

One of TWDB's many missions is to collect and disseminate groundwater data. The TWDB is interested in obtaining data on future development of brackish groundwater in the study area. Collection of pumping tests in brackish portions of the Gulf Coast Aquifer is very important because we do not presently have a sufficient number of data points. We are still interested in obtaining existing well and well-field data that we have not been able to acquire for this study.

One of the questions frequently posed is how development of brackish groundwater will impact fresh-water resources. A corollary to this question is how development of slightly saline water may be impacted by more saline sources during long-term development. Groundwater modeling, perhaps using variable-density tools, may be able to answer some of these questions.

Continued development of brackish groundwater will improve the accuracy of the numerous mapped salinity zones in the study area.

18. Conclusions

We selected the Lower Rio Grande Valley as a brackish groundwater study area because of the anticipated need for additional water in the region. Most of the groundwater in the Lower Rio Grande Valley has concentrations of total dissolved solids greater than 1,000 milligrams per liter and does not meet drinking water quality standards and. Population in the Rio Grande (Region M) Regional Water Planning Area is expected to more than double in the next fifty years from about 1.7 million to 3.9 million. The municipal water demand is estimated to increase from 259,524 to 581,043 acre-feet per year in the same time period. Brackish groundwater desalination is expected to provide 92,212 acre-feet per year (13.7 percent of the recommended water management strategies) of water in 2060.

The study area contains the largest density of existing and recommended desalination plants in Texas. Seven existing plants currently produce 20 million gallons per day of desalinated drinking water. An additional 23 desalination plants have been recommended by the Rio Grande (Region M) Regional Water Planning Group, although regionalization may limit the actual number of plants built.

For the study, we collected thousands of water well and geophysical well logs for geologic, water chemistry, water level, and aquifer test data from a wide variety of sources to characterize groundwater in the Gulf Coast Aquifer. From this information, we mapped salinity zones that are three-dimensional regions within the aquifer containing groundwater of a similar salinity: slightly saline groundwater (1,000 to 3,000 milligrams per liter total dissolved solids), moderately saline groundwater (3,000 to 10,000 milligrams per liter total dissolved solids), very saline groundwater (10,000 to 35,000 milligrams per liter total dissolved solids), and brine (greater than 35,000 milligrams per liter total dissolved solids).

The study area contains 21 geographic areas that have a unique salinity zone profile from ground surface to the base of the Gulf Coast Aquifer.

We estimate that the Gulf Coast Aquifer in the Lower Rio Grande Valley contains a significant volume of brackish groundwater: more than 40 million acre-feet of slightly saline groundwater, 112 million acre-feet of moderately saline groundwater, and 123 million acre-feet of very saline groundwater. Not all of the brackish groundwater can be economically produced or even be produced. Nevertheless, these estimates provide indications of the potential availability of this important resource.

Study deliverables include: a peer-reviewed published report, Geographic Information System (GIS) map files, BRACS Database and data dictionary, and water well and geophysical well log files. The real value of this study is the GIS and BRACS Database information. This can be used by stakeholders to map areas for potential groundwater development. Finally, information contained in the report is not intended to serve as a substitute for site-specific studies that are required to evaluate local aquifer characteristics and groundwater conditions for a desalination plant.

19. Acknowledgments

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21. Appendices

21.1 BRACS Database

All water well and geophysical well log information and supporting databases for the Lower Rio Grande Valley study are managed in the BRACS Database using Microsoft® Access® 2007. When spatial analysis is required, copies of information are exported into ArcGIS®. Information developed in ArcGIS® is then exported back into Microsoft® Access® and the tables are updated accordingly. Although this approach may be cumbersome, it takes advantage of the strengths of the software. The project also relied on other software for specific tasks, including Microsoft® Excel®, and Schlumberger Blueview® (for geophysical well log analysis).

For the study, we assembled information from external agencies and updated these databases frequently. All of these databases are maintained in Microsoft® Access® and GIS files were developed for spatial analysis and well selection. Many of the databases were built from scratch or were redesigned to meet project objectives. Data from external agencies or projects were available in many different data designs, so establishing a common design structure proved beneficial in leveraging information compiled by other groups.

The BRACS and supporting databases are fully relational. Data fields common to multiple datasets have been standardized in data type and name with lookup tables shared between all databases. Database object names use a self-documenting style that follows the Hungarian naming convention (Novalis, 1999). The volume of project information required us to develop comprehensive data entry and analysis procedures (coded as tools) that were embedded on forms used to display information. Visual Basic for Applications® is the programming language used in Microsoft® Access®, and all code was written at the Microsoft® ActiveX® Data Objects level with full code annotation. The code for geophysical well log resistivity analysis was specifically written with class objects to support a rapid analysis of information with the benefit of only having data appended when the user approved the results.

The BRACS Database is documented in a data dictionary (Meyer, 2014), which is available with the BRACS Database from the TWDB website. The following two sections will briefly describe the BRACS Database table relationships and the supporting databases developed to date.

21.1.1 Table relationships

The BRACS Database contains 16 primary tables of information (Figure 21.1-1), 39 lookup tables, tables designed for GIS export, and many supporting tables for analysis purposes. A brief description of each of the primary tables is provided in this section. Lookup tables provide control on data entry codes or values for specific data fields (for example, a county lookup table with all 254 county names in Texas). The tables for GIS export are copies of information obtained from one or more tables and in some cases are reformatted to meet GIS analysis needs. These tables can be custom tailored to meet project needs and will not be discussed further.

A fully relational database design has information organized into tables based on a common theme. Information must be segregated into separate tables for each one-to-many data relationship. For example, one well may have many well screens with unique top and bottom depth values; each well screen constitutes one record. Tables are linked by key fields. The field well_id is the primary key field for every table in the BRACS Database. For each one-to-many relationship at least one additional key field is required.

Well locations

The table tblWell_Location contains one record for each well record in the BRACS Database and is assigned a unique well_id as the key field. The well_id field links all the tables together. This table contains information such as well owner, well depth(s), location attributes (such as latitude, longitude, and elevation), source of well information, county name, and date drilled.

Foreign keys

The table tblBracs_ForeignKey has zero to many unique well identification names or numbers assigned to it (for example, state well number and American Petroleum Institute number). These identifiers, also known as foreign keys, permit database linkage to the supporting databases developed from external agencies and other TWDB project databases with geophysical well logs and stratigraphic pick information.

Digital well reports

The table tblBracsWaterWellReports contains zero to many records for digital copies of water well reports and miscellaneous records including oil and gas well scout tickets. The purpose of this table is to track the digital file names, file types, and hyperlinks to the documents.

Geophysical well logs

Information on the digital geophysical well logs is recorded in the table tblGeophysicalLog_Header. This includes the type of digital file, digital file name, data hyperlink to the log image, and well log parameters such as depth, temperature of the bottom hole, and resistivity of the mud filtrate. The well log parameters are only recorded if the well log is to be used for resistivity analysis for interpreted total dissolved solids.

Each geophysical well log may have one or more tools used to record subsurface parameters. This information is recorded in the table tblGeophysicalLog_Suite. Each tool name and its start and bottom depth values in units of feet below ground surface are recorded in this table.

The results from resistivity analysis for interpreted total dissolved solids are recorded in two tables. Evaluating more than one depth interval per well necessitated designing the table, tblGeophysicalLog_WQ, to hold the depth of formation, temperature, and resistivity of the mud filtrate values for that interval. Evaluating more than one resistivity technique per depth interval dictated designing one table, tblGeophysicalLog_WQ_Method, to hold the analysis results including interpreted total dissolved solids, log correction values, method used, geophysical well log used, and a multitude of intermediate values.

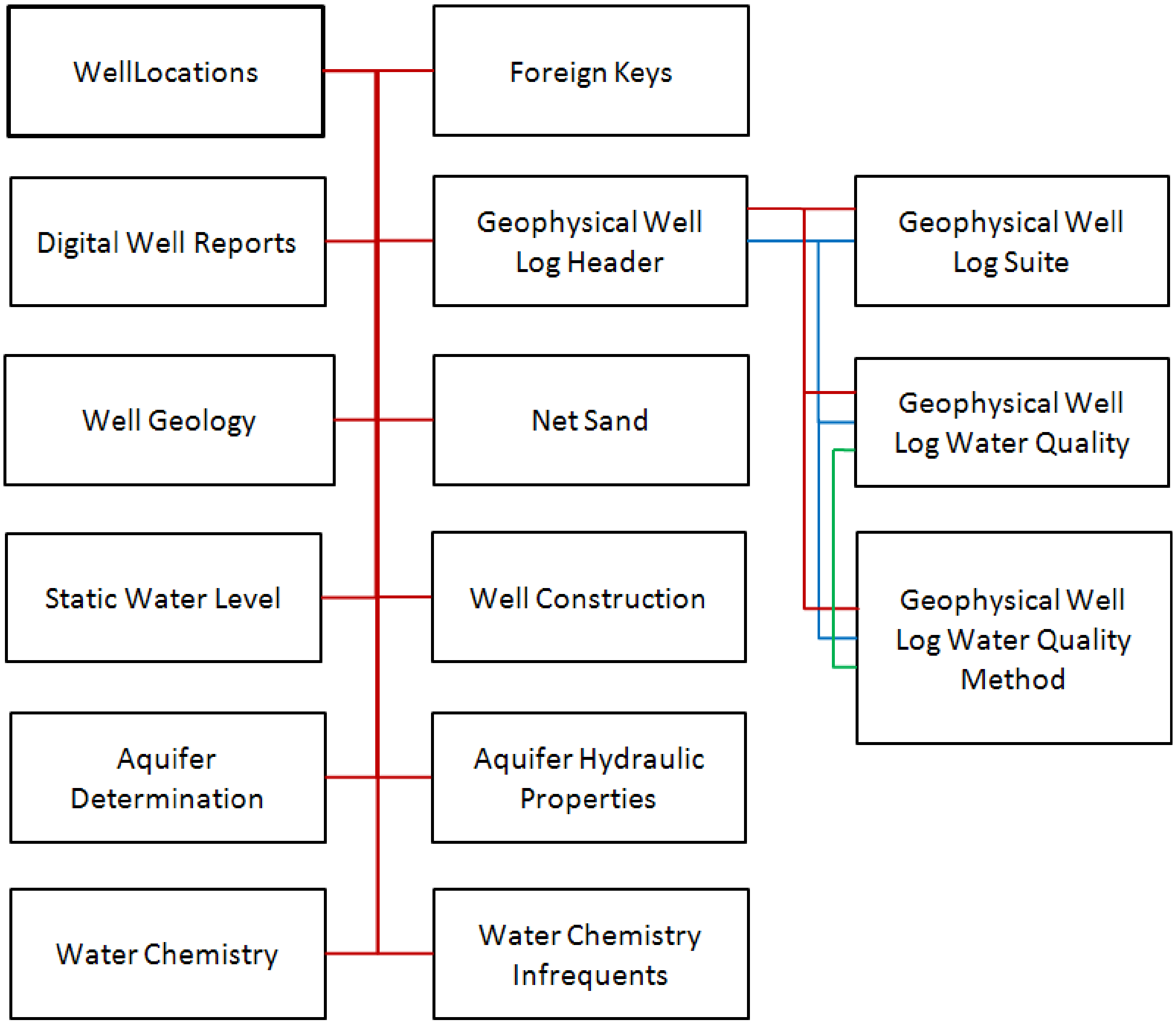

Figure 21.1-1. BRACS Database table relationships. Each rectangle represents a primary data table. The lines connecting the tables represent key fields: red represents the primary key well_id, blue represents the second key, and green represents the third key. New well records must be appended to the well locations table to set the unique well_id.

Well geology

The descriptions of rock types reported on drillers' well logs, simplified lithologic descriptions, stratigraphic picks, and hydrochemical zones are all contained in the table tblWell_Geology. Each record contains a top and bottom depth, thickness of the unit, top and bottom elevations, source of data, and a value for type of geologic pick (for example, lithologic, stratigraphic, or hydrogeologic). The latter field permits the storage of all this information in one table and the ability to view the information in one form.

The analysis of net sand, maximum sand thickness, and sand percent for each well record is contained in the table tblWell_Geology_NetSand_GulfCoast. The table is custom-designed for this study.

Well construction

Well casing and screen information is contained in the table tblBracs_Casing. This table design is similar to the well-casing table in the TWDB Groundwater Database and contains top and bottom depths for casing and screen.

Water quality

Two tables contain the results of water quality analyses recorded for wells that are not in the TWDB Groundwater Database: tblBracsWaterQuality and tblBracsInfrequentConstituents. The table designs are similar to those in the TWDB Groundwater Database.

All water quality records for wells in the study area were appended to the tables tblBRACS_GC_MasterWaterQuality and tblBRACS_GC_WQ_Radionuclide. These include records obtained from the TWDB Groundwater Database and records obtained from research for wells in the BRACS Database.

Static water level

Static water level information is contained in the table tblBRACS_SWL. The table is similar to its equivalent in the TWDB Groundwater Database. Information on dates, water levels, and source of measurement are recorded in the table. Static water levels for all wells in the study area were compiled into table tblLRGV_M_SWL along with new aquifer determinations.

Aquifer hydraulic properties

Information from existing aquifer tests conducted in the study area is contained in the table tblBRACS_AquiferTestInformation. The table contains fields for hydraulic conductivity, transmissivity, specific yield, storage coefficient, drawdown, pumping rate, specific capacity, the types of units for each measurement, date of analysis, source of information, and remarks. If an analysis included the top and bottom depths of the screen, well depth, and static water level, it was captured in this table in case the values differed from what is presented in the casing table (test may have been performed before total depth of the well was reached). The length of aquifer tests, values for drawdown versus recovery, pumping and static water levels, and two analysis remarks fields complete the table design. Because many results are from Myers (1969), a page reference to that report for each test is recorded and references to other published reports and table numbers are also included.

Aquifer determination

The results of the aquifer determination for well records described in Section 10 are presented in table tblAquiferDetermination_GulfCoast. This table includes fields for the aquifer region, new aquifer decision, TWDB Groundwater Database aquifer code assigned to the well (if any), well and screen depths, whether the well has multiple screens, aquifer decision codes, well owner, and latitude/longitude coordinates. Fields for geologic formation top and bottom depths derived from GIS geologic formation datasets are listed.

21.2 Geographic information system datasets

Many GIS datasets were created during the course of this study. The GIS techniques used to build the files are explained in the following sections and noted in the GIS file metadata. ArcGIS® 10.0 and the Spatial Analyst® extension software by Environmental Systems Research Institute, Inc. (ESRI) were used to create the GIS files. Each of the GIS files prepared for this BRACS study is available for download from the Texas Water Development Board website.

Each point file is in the ArcGIS® shape file format. Point files of well control used for general purposes have a geographic projection and the North American Datum 1983 as the horizontal datum. Point files used for GIS surface (raster) creation have a Lambert Conformal Conic projection and the North American Datum 1983 as the horizontal datum.

All surface files are in the ArcGIS® raster integer grid file format with a Lambert Conformal Conic projection and the North American Datum 1983 as the horizontal datum. All raster files are snapped to the project snap grid raster with a cell size of 250 by 250 feet.

Polygon and polyline files are in the ArcGIS® shape file format with a Lambert Conformal Conic projection and the North American Datum 1983 as the horizontal datum.

All well records are managed in Microsoft® Access® databases. Well records are queried from the database and imported into ArcGIS® for spatial analysis. When new attributes are added to a well using ArcGIS®, the information is imported into Microsoft® Access®, and the well records updated.

Every well record in each database used for this project contains latitude and longitude coordinates in the format of decimal degrees with a North American Datum of 1983. All of these well records are imported into ArcGIS® and georeferenced in a geographic coordinate system, North America, North American Datum 1983 projection. A point shapefile was then saved in a working directory. Every well record then had an elevation assigned from the U.S. Geological Survey seamless 30 meter digital elevation model using the ArcGIS® ArcToolbox (Spatial Analyst® Tools, Extraction, and Extract Values to Points). The dbase file from each shapefile was then imported into Microsoft® Access® and the elevation data updated to each well record, along with date, method, vertical datum, and agency attributes. Each well record also recorded the kelly bushing height when available. GIS point files subsequently created for each geologic formation and salinity zone were corrected for kelly bushing height and elevation.

In many cases, new wells were plotted in ArcGIS® and the latitude, longitude, and elevation were determined and appended to the database tables manually. The Original Texas Land Survey obtained from the Railroad Commission of Texas was the principal base map used to plot well locations; county highway maps and topographic maps were used on occasion.

GIS file name codes

ArcGIS® raster files are limited to 12 characters, necessitating the development of a file naming scheme for all GIS files created for BRACS studies. The full list of naming codes can be found in BRACS Database table tblGisFile_NamingConventions and a shortened list of codes is presented in Table 21.2.1-1.

Each code is separated from the next code with an underscore character. For example, the code ss_d_bd_trim refers to the slightly saline deep zone bottom depth created by the topo to raster surface interpolation as an integer value and masked.

Table 21.2.1-1. GIS file naming codes applied to the Lower Rio Grande Valley BRACS study.

Code	Code type	Code position	Code description
LRGV	BRACS Project	1	Lower Rio Grande Valley project acronym
b	Stratigraphic	1	Beaumont Formation
l	Stratigraphic	1	Lissie Formation
w	Stratigraphic	1	Willis Formation
ug	Stratigraphic	1	Upper Goliad Formation
lg	Stratigraphic	1	Lower Goliad Formation
ul	Stratigraphic	1	Upper Lagarto Formation
ml	Stratigraphic	1	Middle Lagarto Formation
ll	Stratigraphic	1	Lower Lagarto Formation
ok	Stratigraphic	1	Oakville Formation
fr	Salinity zone	1	Fresh water
ss	Salinity zone	1	Slightly saline water
ms	Salinity zone	1	Moderately saline water
vs	Salinity zone	1	Very saline water
br	Salinity zone	1	Brine
s	Salinity zone depth interval	2	Shallow
i	Salinity zone depth interval	2	Intermediate
d	Salinity zone depth interval	2	Deep
ns	Sand analysis	2	Net sand (units: feet)
ps	Sand analysis	2	Sand percent (units: dimensionless)
t	Surface position	2	Top
b	Surface position	2	Bottom
d	Value	3	Depth below ground surface (units: feet)
e, elev	Value	3	Elevation above mean sea level (units: feet)
tk	Value	3	Thickness (units: feet)
swl	Value	3	Static water level, below ground surface (units: feet)
sat	Value	3	Saturated thickness (units: feet)
fm	Value	3	Formation (geologic)
tds	Value	3	Total dissolved solids (units: milligrams per liter)
vgw	Groundwater volume	3	Volume groundwater (Units: cubic feet)
tr	Interpolation method	3	Topo to raster
idw	Interpolation method	3	Inverse distance weighted
k	Interpolation method	3	Kriging
nn	Interpolation method	3	Natural neighbor

Code	Code type	Code position	Code description
25	Contour interval	6	Contour interval of 25 feet (units: feet)
50	Contour interval	6	Contour interval of 50 feet (units: feet)
100	Contour interval	6	Contour interval of 100 feet (units: feet)
250	Contour interval	6	Contour interval of 250 feet (units: feet)
i	Raster data value	8	Integer
fp	Raster data value	8	Floating point
snap	Snap raster	10	Snap raster file used to snap all project cells into conformable alignment
250	Snap raster cell size	11	Raster cell size 250 feet by 250 feet (units: feet)
500	Snap raster cell size	11	Raster cell size 500 feet by 500 feet (units: feet)
m	mask	7	Raster file setting the lateral limits of another raster. Value: 1 = real data cell; 9 = no data cell.
con	Data type	4	contour
ext	Data type	4	Extent
pt	Data type	4	Point
pl	Data type	4	Polyline
pg	Data type	4	Polygon
s, sur	Data type	4	Raster surface
st	Data type	4	Stratigraphic pick
lcc	Map projection	12	Lambert Conformal Conic (North American Datum 1983)
aea	Map projection	12	Albers Equal Area (North American Datum 1983)
geog	Map projection	12	Geographic (North American Datum 1983)

Table 21.2.1-2. Project support GIS files.

Folder structure: BRACS_LRGV_GIS_Data\StudyAreaData.

File type	Point file name	Polyline file name	Polygon file name	Raster file name
Project snap grid				lrgv_snap250
Project elevation				dem_i_250
Project boundary		StudyArea_pl	StudyArea_pg	lrgvprojpoly
Aquifer determination			LRGV_AD_Regions_simple_pg	
Project well control	Lrgv_ad_wellcontrol			
Net sand well control	Lrgv-ns_wellcontrol			
Master water quality	LRGV_MWQ_all			
Master water quality radiochemical	LRGV_WQ_Radiochem LRGV_WQ_radiochem_radium_sum_diss			
Paine (2000) geophysics study areas			Paine_Airborne_Geophysics	
LRGV existing desalination plants	desal_plants_lrgv_existing			
LRGV recommended desalination plants	Desal_plants_lrgv_recommended			
LRGV public water supply boundary			lrgv_pws_pg	
Texas counties			Tx_counties_pg	
Texas groundwater conservation dist.			gcd	
Texas groundwater management areas			Gma_2011	
Texas regional water planning area			Rwpa_2008	
LRGV tectonics **		lrgv_tectonic_faults		
Geologic cross sections **	lrgv_cross_sections_pt	lrgv_cross_sections_pl		
Project area clip file			Universe	
Rio Grande River clipped			Rio_Grande_clip	
Figure feathering			Study_Area_Feathering	
Counties feathering			StudyAreaCounties_Feathering	
Aquifer test data	LRGV_Bracs_AT			

Geologic formation GIS files

Table 21.2.3-1. Geologic formation GIS files.

Folder structure: BRACS_LRGV_GIS_Data\Hydrostratigraphy.

Formation name	Raster surface file name	Polygon file name	Raster extent file name
Beaumont	b_t_d_i	b_ext_pg	b_ext
	b_b_d_i		
	b_tk_i		
Lissie	l_t_d_i	l_ext_pg	l_ext
	l_b_d_i		
	l_tk_i		
Willis	w_t_d_i	w_ext_pg	w_ext
	w_b_d_i		
	w_tk_i		
Upper Goliad	ug_t_d_i	ug_ext_pg	ug_ext
	ug_b_d_i		
	ug_tk_i		
Lower Goliad	lg_t_d_i	lg_ext_pg	lg_ext
	lg_b_d_i		
	lg_tk_i		
Upper Lagarto	ul_t_d_i	ul_ext_pg	ul_ext
	ul_b_d_i		
	ul_tk_i		
Middle Lagarto	ml_t_d_i	ml_ext_pg	ml_ext
	ml_b_d_i		
	ml_tk_i		
Lower Lagarto	ll_t_d_i	ll_ext_pg	ll_ext
	ll_b_d_i		
	ll_tk_i		
Oakville	ok_t_d_i	ok_ext_pg	ok_ext
	ok_b_d_i		
	ok_tk_i		

Table 21.2.3-2. Geologic formation net sand GIS files.

Folder structure: BRACS_LRGV_GIS_Data\Hydrostratigraphy.

Formation name	**Raster surface file name**	**Point file name**	**Raster extent file name**
Beaumont	b_ns_trim	b_ns_pts_lcc	b_ext
Lissie	l_ns_trim	l_ns_pts_lcc	l_ext
Willis	w_ns_trim	w_ns_pts_lcc	w_ext
Upper Goliad	ug_ns_trim	ug_ns_pts_lcc	ug_ext
Lower Goliad	lg_ns_trim	lg_ns_pts_lcc	lg_ext
Upper Lagarto	ul_ns_trim	ul_ns_pts_lcc	ul_ext
Middle Lagarto	ml_ns_trim	ml_ns_pts_lcc	ml_ext
Lower Lagarto	ll_ns_trim	ll_ns_pts_lcc	ll_ext
Oakville	ok_ns_trim	ok_ ns_pts_lcc	ok_ext

Salinity zone GIS files

Table 21.2.4-1. Slightly saline zone GIS files.

Folder structure: BRACS_LRGV_GIS_Data\SalinityZones.

Zone names	**Raster surface file name**	**Point file name**	**Polygon file name**	**Raster extent file name**
Shallow zone 1	ss_s1_td_trim	**	ss_s1_pg	ss_s1
	ss_s1_bd_trim			
	ss_s1_tk			
Shallow zone 2	ss_s2_td_trim	ss_s2_pt_lcc	ss_s2_pg	ss_s2
	ss_s2_bd_trim			
	ss_s2_tk			
Intermediate zone	ss_i_td_trim	ss_i_td_pt_lcc	ss_i_pg	ss_i
	ss_i_bd_trim	ss_i_bd_pt_lcc		
	ss_i_tk			
Deep zone	ss_d_td_trim	ss_d_bd_pt_lcc	ss_d_pg	ss_d
	ss_d_bd_trim			
	ss_d_tk			

** point file not prepared. Surfaces based on ms_i2 data and BRACS well 25298

Table 21.2.4-2. Moderately saline zone GIS files.

Folder structure: BRACS_LRGV_GIS_Data\SalinityZones.

Zone names	Raster surface file name	Point file name	Polygon file name	Raster extent file name
Shallow zone 1	ms_s1_td_trim	ms_s1_bd_pt_lcc	ms_s1_pg	ms_s1
	ms_s1_bd_trim			
	ms_s1_tk			
Shallow zone 2	ms_s2_td_trim	**	ms_s2_pg	ms_s2
	ms_s2_bd_trim			
	ms_s2_tk			
Shallow zone 3	ms_s3_td_trim	ms_s3_bd_pt_lcc	ms_s3_pg	ms_s3
	ms_s3_bd_trim			
	ms_s3_tk			
Shallow zone 4	ms_s4_td_trim	ms_s4_pt_lcc	ms_s4_pg	ms_s4
	ms_s4_bd_trim			
	ms_s4_tk			
Shallow zone 5	ms_s5_td_trim	ms_s5_pt_lcc	ms_s5_pg	ms_s5
	ms_s5_bd_trim			
	ms_s5_tk			
Intermediate zone 1	ms_i1_td_trim	ms_i1_pt_lcc	ms_i1_pg	ms_i1
	ms_i1_bd_trim			
	ms_i1_tk			
Intermediate zone 2	ms_i2_td_trim	ms_i2_pt_lcc	ms_i2_pg	ms_i2
	ms_i2_bd_trim			
	ms_i2_tk			
Deep zone	ms_d_td_trim	ms_d_bd_pt_lcc	ms_d_pg	ms_d
	ms_d_bd_trim		ms_d_zero_pg	ms_d_zero
	ms_d_tk			

** point file not prepared. Surfaces based on BRACS wells 39988, 42434, and 42466 and local water well water quality data.

Table 21.2.4-3. Very saline zone GIS files.

Folder structure: BRACS_LRGV_GIS_Data\SalinityZones.

Zone names	Raster surface file name	Point file name	Polygon file name	Raster extent file name
Shallow zone 1	vs_s1_td_trim	vs_s1_pt_lcc	vs_s1_pg	vs_s1
	vs_s1_bd_trim			
	vs_s1_tk			
Shallow zone 2	vs_s2_td_trim	vs_s2_pt_lcc	vs_s2_pg	vs_s2
	vs_s2_bd_trim			
	vs_s2_tk			
Shallow zone 3	vs_s3_td_trim	vs_s3_pt_lcc	vs_s3_pg	vs_s3
	vs_s3_bd_trim			
	vs_s3_tk			
Shallow zone 4	vs_s4_td_trim	vs_s4_pt_lcc	vs_s4_pg	vs_s4
	vs_s4_bd_trim			
	vs_s4_tk			
Intermediate zone	vs_i_td_trim	**	vs_i_pg	vs_i
	vs_i_bd_trim			
	vs_i_tk			
Deep zone	vs_d_td_trim	vs_d_bd_pt_lcc	vs_d_pg	vs_d
	vs_d_bd_trim			
	vs_d_tk			

** Point file not prepared. Based on BRACS well 22713

Table 21.2.4-4. Brine zone GIS files.

Folder structure: BRACS_LRGV_GIS_Data\SalinityZones.

Zone names	Raster surface file name	Point file name	Polygon file name	Raster extent file name
Shallow zone	br_s_td_trim	br_s_pt_lcc	br_s_pg	br_s
	br_s_bd_trim			
	br_s_tk			
Deep zone	br_d_td_trim	br_d_pt_lcc	br_d_pg	br_d
	**			
	**			

**The base of the brine zone was not mapped. No thickness map prepared.

Table 21.2.4-5. Salinity zone net sand GIS files.

Folder structure: BRACS_LRGV_GIS_Data\SalinityZones.

Salinity zone	Zone names	Raster surface file name	Point file name
Slightly saline	ss_s2	ss_s2_ns_trim	ss_s2_ns_pt_lcc
Slightly saline	ss_d	ss_d_ns_trim	ss_d_ns_pt_lcc
Moderately saline	ms_i1	ms_i1_ns_trim	ms_i1_ns_ pt_lcc
Moderately saline	ms_d	ms_d_ns_trim	ms_d_ns_ pt_lcc
Very saline	vs_s4	vs_s4_ns_trim	vs_s4_ns_ pt_lcc
Very saline	vs_d	vs_d_ns_trim	vs_d_ns_ pt_lcc

Table 21.2.4-6. Salinity zone project support GIS files.

Folder structure: BRACS_LRGV_GIS_Data\SalinityZones.

File type	Point file name	Polyline file name	Polygon file name	Raster file name
Fresh wells within slightly saline deep zone			fr_well_pg	
Moderately saline wells within slightly saline deep zone	ms_d_gl_pts		ms_well_in_ss_d_pg	
Salinity zones			salinity_zones_pg	
Well control used for slightly saline deep zone	ss_d_gl_pts			

Class II injection wells

We created a GIS file from data from: Railroad Commission of Texas, Underground Injection Control Database; Railroad Commission of Texas oil and gas well county shape files; Gulf Coast Aquifer formation top and bottom depth values. The name of this GIS file is: lrgv_rrc_uic_classII_1_2_3.shp.

This shape file contains several important fields listed in Table 21.2.5-1. Additional data may be found at the Railroad Commission of Texas.

Table 21.2.5-1. Class II injection well table. Significant field names and description of GIS file: lrgv_rrc_uic_classII_1_2_3.shp.

Folder structure: BRACS_LRGV_GIS_Data\WellData.

Field name	**Description**
API_Number	American Petroleum Institute unique number for each oil/gas/injection well
UIC_Type	Type of class II injection well: • Disposal into a nonproductive zone (W-14) • Disposal into a productive zone (H-1) • Secondary or tertiary recovery
T_INJ_ZONE	Top depth of the injection zone, units feet below ground surface
B_INJ_ZONE	Bottom depth of the injection zone, units feet below ground surface
B_D_BUQ	Bottom depth of the base of useable quality water, approximately 3,000 milligrams per liter total dissolved solids
T_D_SPL_BU	Top depth of a split zone, base of useable quality water, approximately 3,000 milligrams per liter total dissolved solids
B_D_SPL_BU	Bottom depth of a split zone, base of useable quality water, approximately 3,000 milligrams per liter total dissolved solids
ACTIVE	Activity status of well, Y = yes; N = No
UIC_APPR	Underground Injection Control approval letter date
UIC_CANCEL	Underground Injection Control cancel letter date
UIC_PLUG	Underground Injection Control plugging date
LATDD	Latitude in decimal degrees with a North American Datum of 1983
LONGDD	Longitude in decimal degrees with a North American Datum of 1983
WELL_TYPE	Well type, obtained from Railroad Commission of Texas oil and gas well county shape file
PLUG_DATE	Well plug date, obtained from Railroad Commission of Texas oil and gas well county shape file
INJECTION	Injection fluid: FW = fresh water; SW = salt water; GAS = gas; LPG = liquid petroleum gas
AQUIFER_NE	Aquifer or multiple aquifers in which injection well zone overlaps Gulf Coast Aquifer formations. Pre-Oakville = injection below Oakville Formation OK = Oakville Formation LL = Lower Lagarto Formation ML =Middle Lagarto Formation UL = Upper Lagarto Formation LG = Lower Goliad Formation UG = Upper Goliad Formation W = Willis Formation L = Lissie Formation B = Beaumont Formation ? = uncertain because top and or bottom of injection zone was not specified
AQUIFER_DECISIO	Note on how the aquifer decision was made
B_T_D	Fields with this coding refer to the top and bottom depths of Gulf Coast Aquifer formations using GIS analysis Refer to Table 21.2.1-1 for a list of these codes

21.3 Geophysical well log interpretation

We used geophysical well logs to calculate an interpreted total dissolved solids concentration across the entire depth range of the Gulf Coast Aquifer in the study area. We used existing groundwater quality data to calibrate the interpretations for a limited, shallow portion of the Gulf Coast Aquifer where possible.

Estepp (1998, 2010) provided six methods for interpreting total dissolved solids concentration in a formation using geophysical well logs. Each of the methods has advantages and disadvantages with respect to the type of logging tool, input parameters, assumptions, geological formations being assessed, and expected range of groundwater salinity. Calculating groundwater total dissolved solids concentration is complicated because the geologic environment is complex and the majority of the existing geophysical well logs were developed for petroleum exploration and production where the groundwater is dominated by sodium and chloride ions. Application of these logging tools and techniques for fresh and brackish aquifers pose problems that are addressed in different ways by each of the six methods. We selected the RWA (resistivity water apparent) Minimum Method for this project because it performed reasonably well with the available data and assumptions.

The RWA Minimum Method is based on Archie's (1942) equation in a 100 percent water saturated formation where:

$$Ro = F \cdot Rw$$

$$F = a/\Phi^m$$

Where:	Ro	=	Resistivity of the formation (units: ohm-meter)
	F	=	Formation resistivity factor (units: dimensionless)
	Rw	=	Resistivity of water (units: ohm-meter)
	a	=	Tortuosity factor (units: dimensionless)
	Φ	=	Porosity (units: percent)
	m	=	Cementation factor (units: dimensionless)

The resistivity of the formation is determined with a deep investigation resistivity logging tool and is a combination of formation rock matrix resistivity and groundwater resistivity. The formation resistivity is determined by reading a deep resistivity geophysical tool in a thick layer of shale-free sand that is not affected by hydrocarbons. The resistivity of the formation is the result of several parameters: resistivity of the formation minerals, resistivity of groundwater and its composition, porosity, cementation of sediment grains, sediment grain size, and surface conductance on mineral grains (Alger, 1966). Obtaining some of these parameters is not possible using only a geophysical well log. Hence, some information for the parameters, such as porosity, were not available in the study area. To solve the calculations, we estimated some of these parameters based on similar geologic conditions existing elsewhere or using best professional judgment.

Relatively thick sand units that are free of clay and hydrocarbons can be used for interpretation. Most formation rock matrix, when dry, will have infinitely high resistivity (this does not include formations containing metal ore deposits). Clay, however, contributes to lower resistivity because it contains interstitial fluid and ion-exchange sites on the clay lattice. The effect of clay on a resistivity log is often disproportionately large compared to the amount of clay in a geologic formation, as well as the amount, type, and distribution within the geologic formation (Schlumberger, 1987). Hydrocarbons do not conduct electrical current. The presence of hydrocarbons in sand will show elevated resistivity and a decrease in spontaneous potential response (Hilchie, 1978; Schlumberger, 1987).

Electric current will only flow through the interstitial water within the connected pore structure, and then only if the water contains dissolved minerals (Schlumberger, 1987). To conduct a current the ion must move through the solution to transfer the charge (Hem, 1985). Groundwater resistivity is a function of ion concentration, charge, size, interaction and interference, mobility, and the way it interacts with the solvent (Hem, 1985; Jones and Buford, 1951). Ionic mobility is decreased as the concentration increases due to interference and interaction among the ions (Hem, 1985). Groundwater resistivity varies inversely with dissolved minerals concentration but this is not a straight line relationship when graphed. Resistivity increases with increasing ion concentrations although the change in resistivity varies between the ions (Hem, 1985).

The RWA Minimum Method requires several input parameters in order to calculate an interpreted total dissolved solids value (Table 21.3-1).

Table 21.3-1. Input parameters for the RWA Minimum Method.

Parameter	Symbol	Units
Depth total	Dt	Feet
Depth formation	Df	Feet
Temperature surface	Ts	Degrees Fahrenheit
Temperature bottom hole	Tbh	Degrees Fahrenheit
Deep resistivity	Ro	Ohm-meter
Porosity	Φ	Percent
CT conversion factor	ct	dimensionless
Cementation factor	m	dimensionless
Water quality correction factor	Rwe_Rw_cor	dimensionless

RWA Minimum Method parameters are described in detail in the following sections. If a parameter could not be measured, we made a reasonable assumption based on the geology of the formation being investigated.

21.3.1 Depth total

The total depth of the well is required to calculate the formation temperature at the depth of investigation. If a well was logged during multiple runs, with each run representing a different depth range, the total depth of the logging run applicable to the depth of investigation must be used.

21.3.2 Depth formation

The depth of the formation that is being investigated is required to calculate the formation temperature. The depth of the middle of the sand unit is obtained from the geophysical well log and recorded in the BRACS Database table. The depth is not corrected for kelly bushing height (kelly bushing depth corrections are made prior to GIS analysis of well points when mapping the three-dimensional limits of the salinity zones).

The thickness of the sand unit being investigated and geologic formation are also recorded in the BRACS Database.

21.3.3 Temperature surface

Surface temperature is required to calculate the formation temperature at the depth of investigation. This is often not listed on the geophysical well log header. Forrest and others (2005) state that mean annual surface temperature data is used for geothermal gradient calculations, and a value of 68 to 70 degrees Fahrenheit is often used for the Texas Gulf Coast. Temperature records from 1951-1980 compiled by Larkin and Bomar (1983) indicate mean annual surface temperature in the study area ranged from 73 to 74 degrees Fahrenheit. Interpreted total dissolved solids calculations in this study used a surface temperature value of 73 degrees Fahrenheit.

21.3.4 Temperature bottom hole

Bottom hole temperature is required to calculate the formation temperature at the depth of investigation. Bottom hole temperature is found on the geophysical well log header. If a well was logged during multiple runs, with each run representing a different depth range, the bottom hole temperature of the logging run applicable to the depth of investigation must be used. Bottom hole temperatures are valid if the temperature was recorded after the drilling fluids in the bottom of the hole have equilibrated with the deepest formation (Forrest and others, 2005). Since there is no way to verify if this situation occurred, one must assume the bottom hole temperature is correct.

If the bottom hole temperature is missing from the log header, a bottom hole temperature can be calculated using the well's surface temperature and well depth (or depth of logging run) with a geothermal gradient calculated from the log of a nearby well with complete information. Calculated bottom hole temperatures are noted in the database table with supporting information.

21.3.5 Deep resistivity

The resistivity of the formation being investigated is determined from a deep investigative logging tool. Two logging tools were utilized for deep resistivity measurement: the induction log and the deep normal resistivity log. The type of tool used is recorded in the BRACS Database.

Care must be exercised in determining the resistivity by checking the tool scale, over-range scale, and line symbol(s) for the appropriate tool. Older logs and logs of poor quality present particular challenges.

21.3.6 Porosity

Porosity data from geophysical well logs or core tests is extremely limited in the study area for the formations of interest. A value of 30 percent porosity was used for all shale-free formation sands evaluated between ground surface and approximately 1,000 feet in depth. A value of 25 percent porosity was used for formations deeper than 1,000 feet below ground surface. In some cases a different porosity value was used to calibrate a geophysical well log with nearby water quality data. The porosity variable has a significant impact on the interpreted total dissolved solids calculations.

21.3.7 CT conversion factor

The conversion factor ct represents total dissolved solids concentration divided by specific conductance and is determined empirically from water quality samples. The ct factor is used in the RWA Minimum Method to convert conductivity to interpreted total dissolved solids concentration. The ct factor has a range of 0.55 to 0.75 for waters of ordinary composition up to total dissolved solids concentration of a few thousand milligrams per liter (Hem, 1985). Water with anions dominated by bicarbonate and chloride will be near the lower end of this range and water with anions dominated by sulfate will have water near the high end of or even beyond this range (Hem, 1985). Waters saturated with gypsum or having high concentrations of silica may have a ct factor as high as 1 (Hem, 1985). Because groundwater quality can vary between aquifers and within an aquifer as the ion concentrations evolve, the ct factor should be considered valid for a specific aquifer in a specific area. The ct factor used for interpreting geophysical well logs can be derived with three different approaches. First, ct factors for a given formation in a specific area (for example, a county) can be collected and averaged for a representative ct. Second, water quality samples can be averaged and organized per geologic formation, per area, per range of total dissolved solids concentration to develop representative water quality parameters. We used this approach to extrapolate water quality parameters for geologic formations without a nearby water quality sample. Third, one can use the ct factor from the nearest well with water quality data for a given formation. We used this approach to calibrate geophysical well logs with water quality data for a specific geologic formation.

21.3.8 Cementation factor

The cementation exponent (m) is a dimensionless parameter that can only be determined empirically if all the other parameters are known with certainty (Estepp, 1998). This condition does not exist within the study area. The cementation exponent is related to formation matrix cementation and its effect upon the tortuosity of pore paths an ion would take conducting an electric current. Cemented sands have a higher cementation exponent relative to unconsolidated sands. Tables of cementation factors have been produced in studies across the country (Carothers, 1968; Carothers and Porter, 1970; Kwader, 1986), and the range of values for clean sand is quite large. Estepp (1998) provides an equation (1.18) where the cementation exponent changes with depth for Texas Gulf Coast sand aquifers where: m = 1.75 + ((depth of formation investigation – 1,500)/10,000) where the units for depth of formation investigation is in feet below ground surface. We used this equation for the study.

21.3.9 Water quality correction factor

Groundwater ions have different resistivity values. For example, bicarbonate contributes more resistivity than an equal weight of chloride in a solution (Alger, 1966; Jones and Buford, 1951; Schlumberger, 1979, 1985). This means that sand containing groundwater with a high bicarbonate concentration will have a large deep resistivity value on a geophysical well log that indicates a lower total dissolved solids concentration than actually occurs. This sand would need to have a correction factor applied to lower the resistivity value in order to provide a more realistic interpreted total dissolved solids concentration. Estepp (1998) proposed a correction factor of 1.75 for high bicarbonate groundwater using the RWA Minimum Method, based on a value obtained from Alger (1966). There are two problems with using a single correction factor for groundwater interpretation. First, this may work satisfactorily for water with high bicarbonate concentration but does not address groundwater with intermediate bicarbonate concentration or waters with mixed constituents, including sulfate. Second, Alger (1966) did not provide supporting documentation of how the value of 1.75 was determined:

"The HCO_3 ion contributes only 27% as much conductivity as an equal weight of Cl^- ion. Or, in other words, the R_w of an $NaHCO_3$ solution is 1.75 times greater than R_w of an Cl^- solution having the same Na^+ concentration".

We investigated another approach for this study using a correction factor based on multiple constituents. A method to adjust cation and anion concentrations to obtain an equivalent sodium chloride concentration has been used in oilfield log analysis applications. Cation and anion concentrations are multiplied with a weighting multiplier specific to the ion and total dissolved solids concentration of the water sample and added together to obtain equivalent sodium chloride concentration. Weighting multipliers are from Chart Gen-8, Resistivities of Solutions (Schlumberger, 1979; 1985). The water quality sample total dissolved solids concentration is divided by the equivalent sodium chloride concentration to equal the sodium chloride correction factor (equation parameter is Rwe_Rw_cor) presented in Tables 21.3-3 through 21.3-11. This method has three drawbacks. First, weighting multipliers are not available for fluoride, silica, strontium, and nitrate which are used to calculate total dissolved solids concentration. Therefore, the equivalent sodium chloride concentration is lower than it should be if all the constituents are present and corrected, and the resulting resistivity correction factor ends up slightly larger than it should be. Second, many older water quality analyses have a combined sodium and potassium concentration so the correction for potassium is not possible. Potassium tends to have a very small concentration in groundwater (except for groundwater containing dissolved potassium-bearing evaporite), so this should not pose a significant problem. Many water quality analyses prior to 1960 had sodium and potassium calculated rather than measured (Hem, 1985). This can cause errors if other species were not identified or inaccuracies of other analyses were made. Third, Chart Gen-8 consists of separate, complex curves for each constituent. To support automated processing in this study, the weighting multipliers were manually extracted using Chart Gen-8 from the midpoint between distinct ranges of total dissolved solids concentration and loaded into a BRACS Database table (tblLkCf_NaClWeightingMultiplier). This simplification may introduce slight errors in the calculations, however manually determining values from the chart and calculating a correction factor for each chemical sample was considered impractical.

Fresh and brackish groundwater formations must have a correction factor. We developed a method to assign these correction factors based on the assumption that individual constituent concentrations will vary with increased total dissolved solids concentration within a geologic formation. All water quality samples within the project area were grouped by Gulf Coast Aquifer geologic formation and each chemical constituent is averaged within defined ranges of total dissolved solids concentration (Tables 21.3-3 through 21.3-11). During analysis of geophysical well logs, the formation deep resistivity value serves as a guide to selecting appropriate ct and equivalent sodium chloride correction factors based on an iterative approach. Since groundwater resistivity and total dissolved solids concentration are inversely related, a low deep resistivity value requires input parameters from a high total dissolved solids range and vice versa. If the calculated interpreted total dissolved solids concentration does not match the input parameter total dissolved solids range, input parameters of a lower or higher range are tested until satisfactory results are obtained. Because the tables are based on actual water quality data in the study area, each range of total dissolved solids concentration may not have data. If a defined total dissolved solids concentration range is lacking values, the next appropriate range of values may be selected. This method is assumed to be reasonable since water quality changes as groundwater flows from outcrop to downdip and the concentrations of different constituents may be different for each geologic formation.

Limitations of this method include: lack of water quality data for many geologic formations with elevated total dissolved solids concentration; some ranges of total dissolved solids are represented by one to a few samples, some of which may not occur in the same geologic setting being investigated; water quality samples with elevated salinity are difficult to analyze in the lab; water quality data from many wells may lack well screen information, making it difficult to determine the correct aquifer.

If high-salinity water quality data for geologic formation zones with extremely low formation resistivity in the very saline to brine ranges was not present, we assigned the default parameter 0.56 for ct and 1 for sodium chloride equivalent correction factor. The use of 1 for the sodium chloride correction factor at high total dissolved solids concentrations assumes the cations and anions area dominated by sodium and chloride (Schlumberger, 1985, Chart GEN-8).

Table 21.3-2. List of abbreviations used in Tables 21.3-3 through 21.3-11.

Abbreviation	Term	Units of measure
TDS range	Range of total dissolved solids	Milligrams per liter
TDS low	Total dissolved solids low range value	Milligrams per liter
TDS high	Total dissolved solids high range value	Milligrams per liter
Num. rec.	Number of water quality sample records	N/A
TDS	Total dissolved solids	Milligrams per liter
ct	ct factor (total dissolved solids / specific conductance)	dimensionless
NaCl cf	Sodium chloride equivalent correction factor	dimensionless
Ca	Calcium	Milligrams per liter
Mg	Magnesium	Milligrams per liter
Na	Sodium	Milligrams per liter
K	Potassium	Milligrams per liter
HCO_3	Bicarbonate	Milligrams per liter
CO_3	Carbonate	Milligrams per liter
SO_4	Sulfate	Milligrams per liter
Cl	Chloride	Milligrams per liter

Table 21.3-3. **Beaumont Formation groundwater quality data organized by selected ranges of total dissolved solids concentration and each chemical constituent averaged from all samples within this range. Refer to Table 21.3-2 for a list of abbreviations used in this table and units of measure per constituent. N/A = not available.**

TDS range	TDS low	TDS high	Num. rec.	TDS	ct	NaCl cf	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl
0 - 999														
	0	249	1	198	0.59	1.5	32	6	31	N/A	177	0	7	14
	250	449	2	334	0.5	1.12	19	7	98	N/A	98	0	34	122
	500	749	4	648	0.6	1.32	52	20	150	5	313	0	140	94
	750	999	16	912	0.6	1.3	80	26	202	6	396	1	201	159
1000 - 2999														
	1000	1999	53	1446	0.69	1.25	110	40	340	7	403	0	382	323
	2000	2999	15	2345	0.65	1.23	147	60	583	8	459	1	647	620
3000 - 9999														
	3000	3999	11	3400	0.58	1.2	165	72	951	16	351	0	962	1026
	4000	4999	7	4344	0.64	1.2	319	109	1053	15	442	0	1141	1422
	5000	5999	5	5510	1.9	1.2	263	157	1429	12	423	0	1526	1852
	6000	6999	1	6296	0.7	1.22	283	204	1500	8	389	0	1970	2070
	7000	7999	4	7196	0.52	1.23	230	167	2099	N/A	434	0	2319	2138
	8000	8999	2	8568	0.59	1.15	616	316	1882	18	278	0	1892	3662
	9000	9999	1	9072	0.49	1.11	410	302	2427	23	364	0	1468	4229
10000 - 34999														
	10000	14999	4	12032	0.51	1.21	471	322	3352	N/A	441	0	3402	4232
	15000	19999	1	18123	0.51	1.21	533	571	5167	N/A	647	0	5177	6313
	20000	24999	1	20319	0.51	1.26	630	487	5776	N/A	635	0	6667	6413
	25000	29999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	30000	34999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 21.3-4. Lissie Formation groundwater quality data organized by selected ranges of total dissolved solids concentration and each chemical constituent averaged from all samples within this range. Refer to Table 21.3-2 for a list of abbreviations used in this table and units of measure per constituent. N/A = not available.

TDS range	TDS low	TDS high	Num. rec.	TDS	ct	NaCl cf	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl
0 - 999														
	0	249	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	250	449	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	500	749	1	629	0.61	1.17	70	21	117	5	126	0	216	126
	750	999	4	860	0.64	1.26	126	28	126	4	333	0	198	176
1000 - 2999														
	1000	1999	5	1534	0.6	1.23	143	33	340	6	309	0	463	357
	2000	2999	3	2153	0.59	1.2	143	36	547	8	249	0	672	602
3000 - 9999														
	3000	3999	5	3295	0.63	1.19	245	90	757	18	363	0	813	1137
	4000	4999	1	4216	0.69	1.2	298	114	925	11	360	0	1080	1500
	5000	5999	2	5547	0.6	1.24	147	86	1590	55	498	0	1711	1610
	6000	6999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	7000	7999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	8000	8999	1	8141	0.64	1.12	1090	341	1250	18	283	0	1200	4050
	9000	9999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
10000 - 34999														
	10000	14999	1	14679	0.5	1.14	836	456	3822	94	509	0	2867	6328
	15000	19999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	20000	24999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	25000	29999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	30000	34999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 21.3-5. **Willis Formation groundwater quality data organized by selected ranges of total dissolved solids concentration and each chemical constituent averaged from all samples within this range. Refer to Table 21.3-2 for a list of abbreviations used in this table and units of measure per constituent. N/A = not available.**

TDS range	TDS low	TDS high	Num. rec.	TDS	ct	NaCl cf	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl
0 - 999														
	0	249	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	250	449	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	500	749	1	677	0.59	1.28	37	14	172	5	279	0	162	126
	750	999	1	755	0.59	1.27	44	16	207	5	292	0	178	135
1000 - 2999														
	1000	1999	6	1502	0.66	1.2	70	28	426	10	298	0	394	397
	2000	2999	1	2210	0.61	1.21	111	43	596	7	289	0	682	598
3000 - 9999														
	3000	3999	1	3651	0.48	1.1	219	87	970	28	301	0	483	1680
	4000	4999	1	4465	0.68	1.22	130	52	1360	17	126	0	1660	1170
	5000	5999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	6000	6999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	7000	7999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	8000	8999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	9000	9999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
10000 - 34999														
	10000	14999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	15000	19999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	20000	24999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	25000	29999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	30000	34999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 21.3-6. Upper Goliad Formation groundwater quality data organized by selected ranges of total dissolved solids concentration and each chemical constituent averaged from all samples within this range. Refer to Table 21.3-2 for a list of abbreviations used in this table and units of measure per constituent. N/A = not available.

TDS range	TDS low	TDS high	Num. rec.	TDS	ct	NaCl cf	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl
0 - 999														
	0	249	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	250	449	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	500	749	2	714	0.58	1.31	38	24	171	N/A	248	0	56	209
	750	999	5	866	0.55	1.32	52	28	200	8	326	0	79	238
1000 - 2999														
	1000	1999	19	1446	0.56	1.18	56	25	424	10	280	0	218	514
	2000	2999	10	2493	0.6	1.18	74	36	756	10	273	0	644	802
3000 - 9999														
	3000	3999	1	3577	0.72	1.31	86	24	1060	10	132	0	1860	450
	4000	4999	5	4287	0.61	1.31	149	26	1239	9	83	3	2172	629
	5000	5999	3	5563	0.63	1.21	220	105	1549	18	242	5	1714	1806
	6000	6999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	7000	7999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	8000	8999	1	8483	0.52	1.16	309	164	2509	21	420	0	1792	3338
	9000	9999	3*	9511	0.89	1.39	480	131	2410	33	80	0	5160	1236
10000 - 34999														
	10000	14999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	15000	19999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	20000	24999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	25000	29999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	30000	34999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

* Three samples from state well number 88-29-501, 1580 feet deep

Table 21.3-7. Lower Goliad Formation groundwater quality data organized by selected ranges of total dissolved solids concentration and each chemical constituent averaged from all samples within this range. Refer to Table 21.3-2 for a list of abbreviations used in this table and units of measure per constituent. N/A = not available.

TDS range	TDS low	TDS high	Num. rec.	TDS	ct	NaCl cf	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl
0 - 999														
	0	249	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	250	449	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	500	749	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	750	999	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1000 - 2999														
	1000	1999	1	1931	0.67	1.09	83	34	578	17	242	0	194	877
	2000	2999	5	2293	0.55	1.11	97	46	678	15	248	0	332	969
3000 - 9999														
	3000	3999	1	3434	0.59	1.11	202	107	911	N/A	220	0	536	1500
	4000	4999	1	4275	0.63	1.16	202	78	1240	N/A	335	0	834	1650
	5000	5999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	6000	6999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	7000	7999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	8000	8999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	9000	9999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
10000 - 34999														
	10000	14999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	15000	19999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	20000	24999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	25000	29999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	30000	34999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 21.3-8. **Upper Lagarto Formation groundwater quality data organized by selected ranges of total dissolved solids concentration and each chemical constituent averaged from all samples within this range. Refer to Table 21.3-2 for a list of abbreviations used in this table and units of measure per constituent. N/A = not available.**

TDS range	TDS low	TDS high	Num. rec.	TDS	ct	NaCl cf	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl
0 - 999														
	0	249	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	250	449	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	500	749	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	750	999	3	823	0.64	1.47	46	21	200	8	342	0	109	139
1000 - 2999														
	1000	1999	7	1275	0.59	1.19	38	12	418	7	348	1	179	409
	2000	2999	1	2924	0.64	1.2	39	33	1000	14	632	0	327	1032
3000 - 9999														
	3000	3999	1	3641	0.63	1.2	84	75	1060	19	637	0	483	1400
	4000	4999	1	4472	0.59	1.09	150	107	1360	N/A	200	0	655	2080
	5000	5999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	6000	6999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	7000	7999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	8000	8999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	9000	9999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
10000 - 34999														
	10000	14999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	15000	19999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	20000	24999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	25000	29999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	30000	34999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 21.3-9. Middle Lagarto Formation groundwater quality data organized by selected ranges of total dissolved solids concentration and each chemical constituent averaged from all samples within this range. Refer to Table 21.3-2 for a list of abbreviations used in this table and units of measure per constituent. N/A = not available.

TDS range	TDS low	TDS high	Num. rec.	TDS	ct	NaCl cf	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl
0 - 999														
	0	249	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	250	449	2	320	0.66	1.83	39	14	32	N/A	197	0	12	29
	500	749	1	609	0.55	1.22	64	24	119	N/A	235	0	47	193
	750	999	1	853	0.54	1.15	11	3	295	5	210	0	75	342
1000 - 2999														
	1000	1999	3	1375	0.62	1.35	45	20	427	16	569	0	115	333
	2000	2999	4	2312	0.56	1.1	163	50	592	23	261	0	160	1121
3000 - 9999														
	3000	3999	2	3248	0.67	1.2	110	27	941	23	162	0	996	1000
	4000	4999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	5000	5999	1	5172	0.66	1.17	322	107	1370	N/A	230	0	1270	1910
	6000	6999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	7000	7999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	8000	8999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	9000	9999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
10000 - 34999														
	10000	14999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	15000	19999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	20000	24999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	25000	29999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	30000	34999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	

Table 21.3-10. Lower Lagarto Formation groundwater quality data organized by selected ranges of total dissolved solids concentration and each chemical constituent averaged from all samples within this range. Refer to Table 21.3-2 for a list of abbreviations used in this table and units of measure per constituent. N/A = not available.

TDS range	TDS low	TDS high	Num. rec.	TDS	ct	NaCl cf	Ca	Mg	Na	K	HCO_3	CO_3	SO_4	Cl
0 - 999														
	0	249	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	250	449	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	500	749	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	750	999	1	961	0.59	1.31	168	39	130	N/A	614	0	93	188
1000 - 2999														
	1000	1999	2	1544	0.59	1.18	80	26	434	14	333	0	198	563
	2000	2999	2	2916	0.48	1.1	208	67	766	23	310	0	308	1340
3000 - 9999														
	3000	3999	2	3321	0.66	1.2	140	35	988	22	358	0	838	1044
	4000	4999	1	4070	0.48	1.12	338	90	1019	26	343	0	543	1842
	5000	5999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	6000	6999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	7000	7999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	8000	8999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	9000	9999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
10000 - 34999														
	10000	14999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	15000	19999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	20000	24999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	25000	29999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	30000	34999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 21.3-11. **Oakville Formation groundwater quality data organized by selected ranges of total dissolved solids concentration and each chemical constituent averaged from all samples within this range. Refer to Table 21.3-2 for a list of abbreviations used in this table and units of measure per constituent. N/A = not available.**

TDS range	**TDS low**	**TDS high**	**Num. rec.**	**TDS**	**ct**	**NaCl cf**	**Ca**	**Mg**	**Na**	**K**	**HCO_3**	**CO_3**	**SO_4**	**Cl**
0 - 999														
	0	249	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	250	449	1	401	0.73	1.8	22	17	70	N/A	226	0	44	28
	500	749	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	750	999	1	906	0.65	1.43	38	10	265	8	381	0	90	179
1000 - 2999														
	1000	1999	6	1181	0.64	1.33	94	24	272	11	417	0	190	283
	2000	2999	2	2520	0.68	1.23	144	32	676	27	307	0	774	650
3000 - 9999														
	3000	3999	2	3432	0.7	1.24	222	37	910	42	245	0	840	1100
	4000	4999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	5000	5999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	6000	6999	1	6173	0.62	1.14	452	108	1630	N/A	252	0	818	2790
	7000	7999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	8000	8999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	9000	9999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
10000 - 34999														
	10000	14999	1	10564	0.48	1.09	340	97	3486	33	150	0	1420	5050
	15000	19999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	20000	24999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	25000	29999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	30000	34999	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

21.3.10 RWA Minimum Method formulas

We used equations from Estepp (1998) to calculate interpreted total dissolved solids. We standardized the equations with similar parameter names and coded them in Visual Basic for Applications® as a class object within the BRACS Database for automated calculation. We entered parameters into a series of data entry forms linked to tables. We select the type of method, the calculations are performed, and output is written to tables. There are many advantages in performing this work in Microsoft® Access®. First, parameter performance can be evaluated when calibrating existing groundwater chemistry samples. Second, calculations are performed quickly and consistently. Third, all parameters, correction factors, intermediate, and final results are recorded allowing staff to open an existing record and modify the output, if necessary.

Steps to perform the RWA Minimum Method for interpreted total dissolved solids:

Determine each parameter listed in Table 21.3-1.

1. Determine the temperature of the formation being investigated

$$\mathbf{T_f = (G_g \cdot D_f) + T_s}$$

$\mathbf{T_f}$	=	Temperature formation (units: degrees Fahrenheit)
$\mathbf{D_f}$	=	Depth formation (units: feet)
$\mathbf{G_g}$	=	Geothermal gradient (units: degrees Fahrenheit/foot)
$\mathbf{T_s}$	=	Temperature surface (units: degrees Fahrenheit)

$$\mathbf{G_g = (T_{bh} - T_s) / D_t}$$

$\mathbf{G_g}$	=	Geothermal gradient (units: degrees Fahrenheit/foot)
$\mathbf{T_{bh}}$	=	Temperature bottom hole (units: degrees Fahrenheit)
$\mathbf{T_s}$	=	Temperature surface (units: degrees Fahrenheit)
$\mathbf{D_t}$	=	Depth total (units: feet)

2. Determine resistivity of water equivalent

$$\mathbf{R_{we} = \Phi^m \cdot R_o}$$

$\mathbf{R_{we}}$	=	Resistivity of water equivalent (units: ohm-meter)
$\mathbf{\Phi}$	=	Porosity of the formation evaluated (units: dimensionless)
$\mathbf{m}$	=	Cementation exponent (units: dimensionless)
$\mathbf{R_o}$	=	Resistivity of water from geophysical log (units: ohm-meter)

3. Correct resistivity water based on groundwater type correction factor

$$\mathbf{R_w = R_{we}/R_{we}R_{w}\_cor}$$

$\mathbf{R_{we}\_R_{w}\_cor}$	=	Sodium chloride equivalent correction factor (units: dimensionless)
$\mathbf{R_w}$	=	Resistivity water (units: ohm-meter)
$\mathbf{R_{we}}$	=	Resistivity water equivalent (units: ohm-meter)

4. Convert resistivity water at formation temperature to 75^0F

$$\mathbf{R_{w75} = R_w \cdot (T_f/75)}$$

$\mathbf{T_f}$	=	Temperature formation (units: degrees Fahrenheit)
$\mathbf{R_w}$	=	Resistivity water (units: ohm-meter)
$\mathbf{R_{w75}}$	=	Resistivity water at 75^0F (units: ohm-meter)

5. Convert resistivity water at 75^0F to conductivity water at 75^0F

$$\mathbf{C_w = 10000/R_{w75}}$$

$\mathbf{C_w}$	=	Conductivity water at 75^0F (units: microsiemens-centimeter)
$\mathbf{R_{w75}}$	=	Resistivity water at 75^0F (units: ohm-meter)

6. Calculate interpreted total dissolved solids

$$\mathbf{TDS = ct \cdot C_w}$$

TDS	=	interpreted total dissolved solids (units: milligrams per liter)
ct	=	ct conversion factor
$\mathbf{C_w}$	=	conductivity water at 75^0F (units: microsiemens centimeter)

21.3.11 Geophysical well log tools

The objective of geophysical log interpretation used in this study is twofold: calculate interpreted total dissolved solids content of groundwater at different depth zones and determine the top and bottom of sand and clay layers.

Geophysical well logs are produced from tools that are lowered into a well bore with a wireline and retrieved back to the ground surface at a specific rate. Combinations of different tools can be assembled in standard "packages" to measure specific formation, fluid, borehole, casing, and cement properties. Tools are selected based on a number of factors including anticipated geology, information required from logging, cased or uncased bore holes, and the composition of the well bore fluid (air or drilling mud). The tools have progressively improved since they were first applied to oil field investigations in the 1930s. The geophysical well logs collected for this study were produced between 1935 and 2008. Interpretation of logs that were produced over such a long time span and presumably with varying designs and accuracies presents challenges. Obviously, some of the older logs simply could not be used in all aspects of the study. The digital image quality of some logs also presented challenges. Geophysical well log tools available in the study area varied in age, type, and vertical depth ranges. Oil field wells are generally logged after a section of surface casing is installed. With the exception of the gamma ray tool, the section of the wellbore containing surface casing cannot be logged. The amount of information that can be collected from ground surface to the bottom of the casing is limited, which can be several hundred or thousand feet. Older wells generally had a shallower bottom depth of surface casing, making these important for near-surface interpretations.

The resistivity of a formation can be measured from geophysical logging tools that pass electricity into the formation and record voltages between measuring electrodes. The resistivity of dry rock is a good electrical insulator (with the exception of metallic ores), so the only way electricity can pass through a formation is if the rock contains groundwater. The groundwater is contained either in the pores between mineral grains or adsorbed in interstitial clay. Tools with deep depths of investigation are needed to minimize the influence of borehole fluid, mud filter cake, and the groundwater invasion zone.

A normal resistivity log usually consists of multiple tools used to measure the resistivity of rocks and water surrounding the borehole at different depths of investigation. The spacing between the electrodes is directly proportional to the depth of investigation, with larger spacing offering deeper depth of investigation. Resistivity measurements are affected by the borehole, drilling fluids, mud filter cake, borehole fluid invasion zone, formation being investigated, surrounding formations, and formation groundwater. Resistivity tool measurements are presented on the right track of a geophysical well log in units of ohm-meter. A conductivity track may be present and is calculated from the inverse of a resistivity tool measurement.

The induction log is a deep investigation tool used to measure the resistivity of rocks and water surrounding the borehole. This type of log uses focusing coils to direct the electricity into the formation and minimize the influence of the borehole, drilling fluids, surrounding formations, mud filter cake, and the invaded zone (Schlumberger, 1987). Induction tool measurements are presented on the right track of a geophysical well log in units of ohm-meter.

The spontaneous potential log is a record of the direct current reading between a fixed electrode at the ground surface and a movable electrode (spontaneous potential tool) in the well bore. The tool must be run in an open borehole with a conductive drilling mud. Spontaneous potential is measured in millivolts, with a negative or positive value depending on the curve deflection of the measurement in a left or right direction, respectively, within a porous unit. The electrochemical factors that create the spontaneous potential response are based on the salinity difference between the borehole mud filtrate and the groundwater within permeable beds (Asquith, 1982). A negative deflection of the spontaneous potential response occurs when the mud filtrate is more resistive than groundwater. A positive deflection occurs when mud filtrate is less resistive than groundwater. When mud filtrate equals groundwater resistivity there is no deflection of the spontaneous potential response from the shale baseline. The spontaneous potential response of shale is relatively constant and is referred to as the shale baseline. The permeable bed boundaries are detected at the point of inflection of spontaneous potential response.

Spontaneous potential deflection is affected by the type of cation species (positive ions such as calcium, magnesium, potassium, or sodium) present in water. Oilfield analysis equations assume that the groundwater is dominated by sodium and chloride. Divalent cations (with a plus two charge, such as calcium and magnesium) in dilute groundwater have a larger impact on spontaneous potential deflection than sodium (Alger, 1966). The spontaneous potential response of high calcium or magnesium waters indicates that the water is more saline than an analysis using resistivity tools. Alger (1966) described a method for correcting this effect; however, a complete water quality analysis is needed to apply the correction. Alger indicated that once a well is calibrated, the analysis can be extrapolated from one well to another assuming that water quality remains relatively constant.

The spontaneous potential response is affected by bed thickness; thin beds do not allow a full spontaneous potential response and must be corrected (Asquith, 1982; Estepp, 1998; Schlumberger, 1972). If a sand unit is less than 10 feet thick, the response curve tends to have a pointed shape, and requires a thickness correction. Spontaneous potential response is also affected by bed resistivity, borehole invasion of drilling fluid, hydrocarbons, and shale content. Shale content reduces the spontaneous potential response. Spontaneous potential tools run in freshwater wells commonly use native mud when, prior to logging, the borehole fluid is essentially groundwater. In this situation, the resistivity of groundwater and borehole fluid is almost equal and the spontaneous potential tool cannot be used to estimate total dissolved solids concentration (Keys, 1990).

Gamma ray logs normally reflect the clay content in sedimentary formations (Schlumberger, 1972). Clays such as illite and mica contain the radioactive potassium-40 isotope that produces gamma rays in clay or shale lithologies. Gamma ray tools encountering natural uranium or thorium will record the zone as an elevated measurement much higher than background clay response. Units exhibiting these spikes in gamma ray measurements are recorded in the well geology table with the top and bottom depths and the gamma ray measurement in American Petroleum Institute units.

Advantages of using a gamma ray log include: it is present on most logging runs, it can be recorded in cased holes, it is generally started near ground surface, and, in many situations, the clay content can be used to recognize the boundaries of geologic units and facilitate the interpretation of depositional environments.

Disadvantages of using a gamma ray log include: attenuation of the overall log signature in cased holes, masking of the more subtle changes in log response with transition from uncemented to cemented formations, inability to evaluate borehole washouts because of the absence of caliper logs prior to casing the well, lack of tool calibration or complete casing records on the log header, which precludes accurate interpretation, presence of older gamma tool types where documentation of tool parameters is limited or impossible to acquire, older gamma ray logs may have different units of measure compared with the modern standard of American Petroleum Institute units, comparison of measurements between tools with different units is problematic, and inability to differentiate clay-free sand, silt, and gravel.

21.4 Gulf Coast Aquifer formation maps

21.4.1 Formation maps

We re-processed study area GIS files for the nine formations of the Gulf Coast Aquifer from GIS data provided by Young and others (2010). Young and others (2010) formation bottom elevation maps with a grid cell size of 4,000 feet were clipped to the study area and re-sampled to the study area project grid cell size of 250 feet. We converted their formation elevation data to depth below ground surface in units of feet using the U.S. Geological Survey 30 meter digital elevation model for Texas. The U.S. Geological Survey 30 meter digital elevation model lacked data in the northeast part of the study area. This caused an artifact of no data when we used ArcGIS® Spatial Analyst® software to create the formation top depth, bottom depth, and thickness maps. We decided not to correct this artifact, since we did not have sufficient brackish groundwater resources and water wells in this part of the study area. The original data from Young and others (2010) is available from the TWDB.

We created formation top depth and thickness maps for each of the nine formations of the Gulf Coast Aquifer (Figures 21.4.1-1 through 21.4.1-18). The GIS files are a part of the study deliverables.

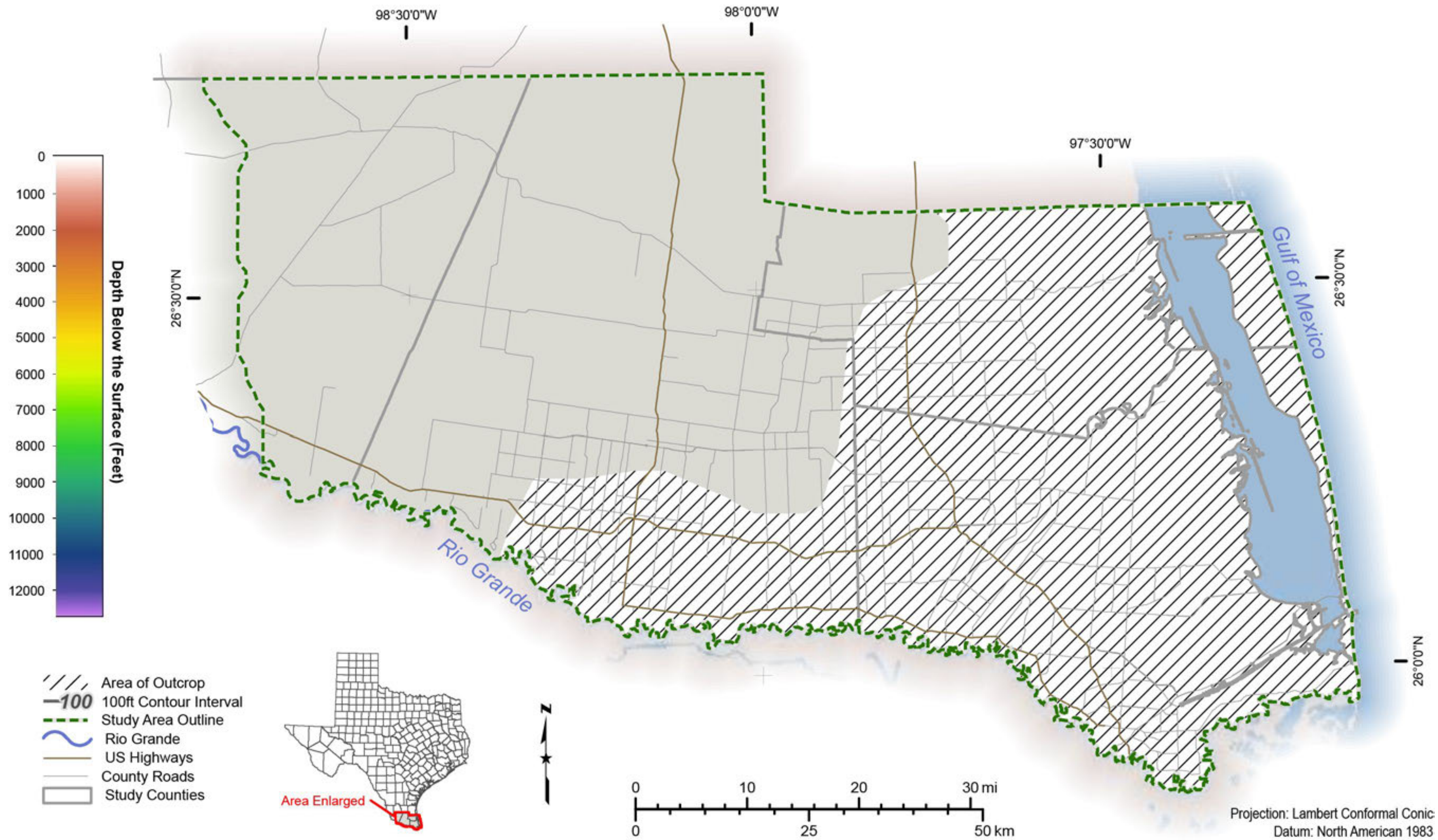

Figure 21.4.1-1. Depth (below ground surface) to the top of the Beaumont Formation.

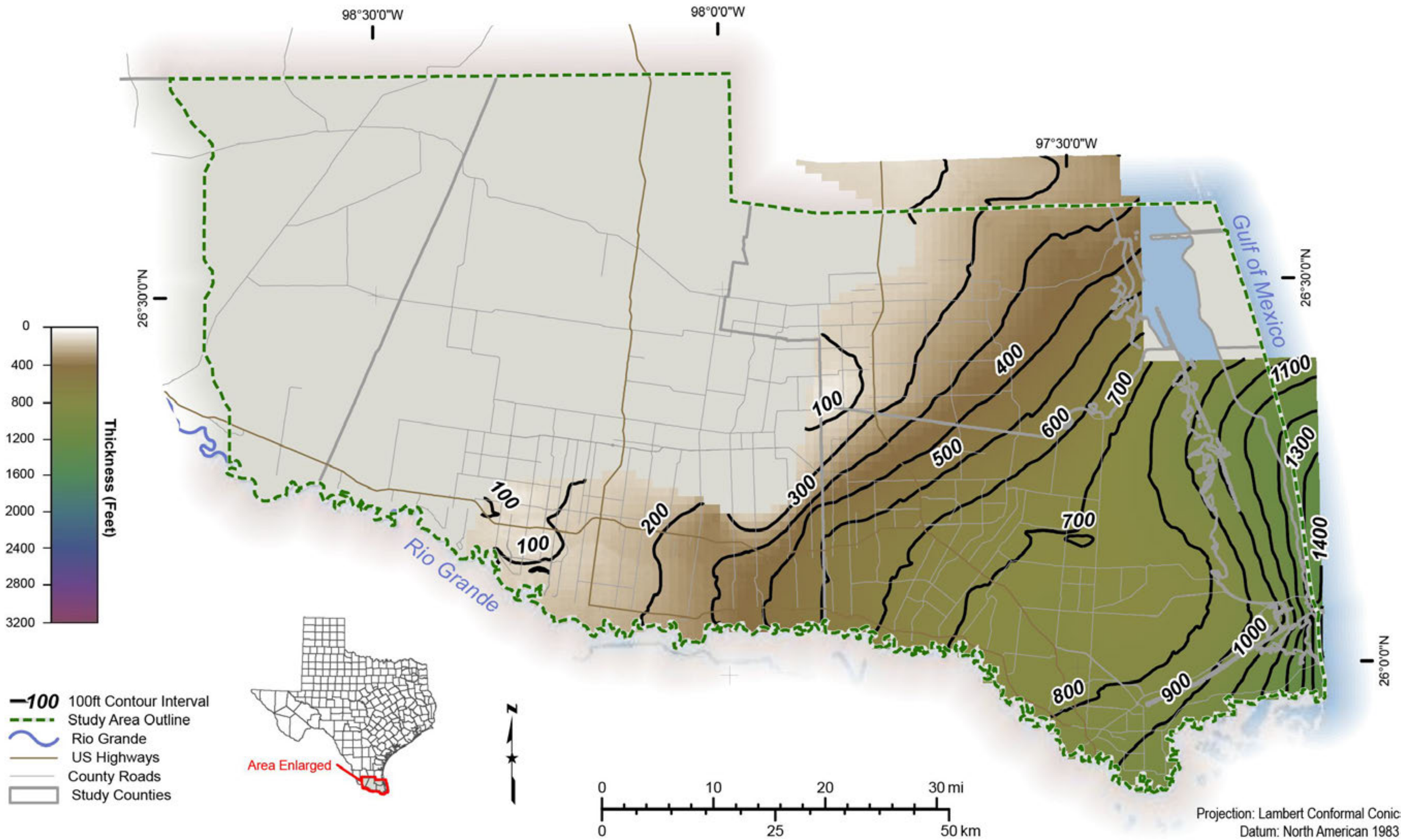

Figure 21.4.1-2. Thickness of the Beaumont Formation.

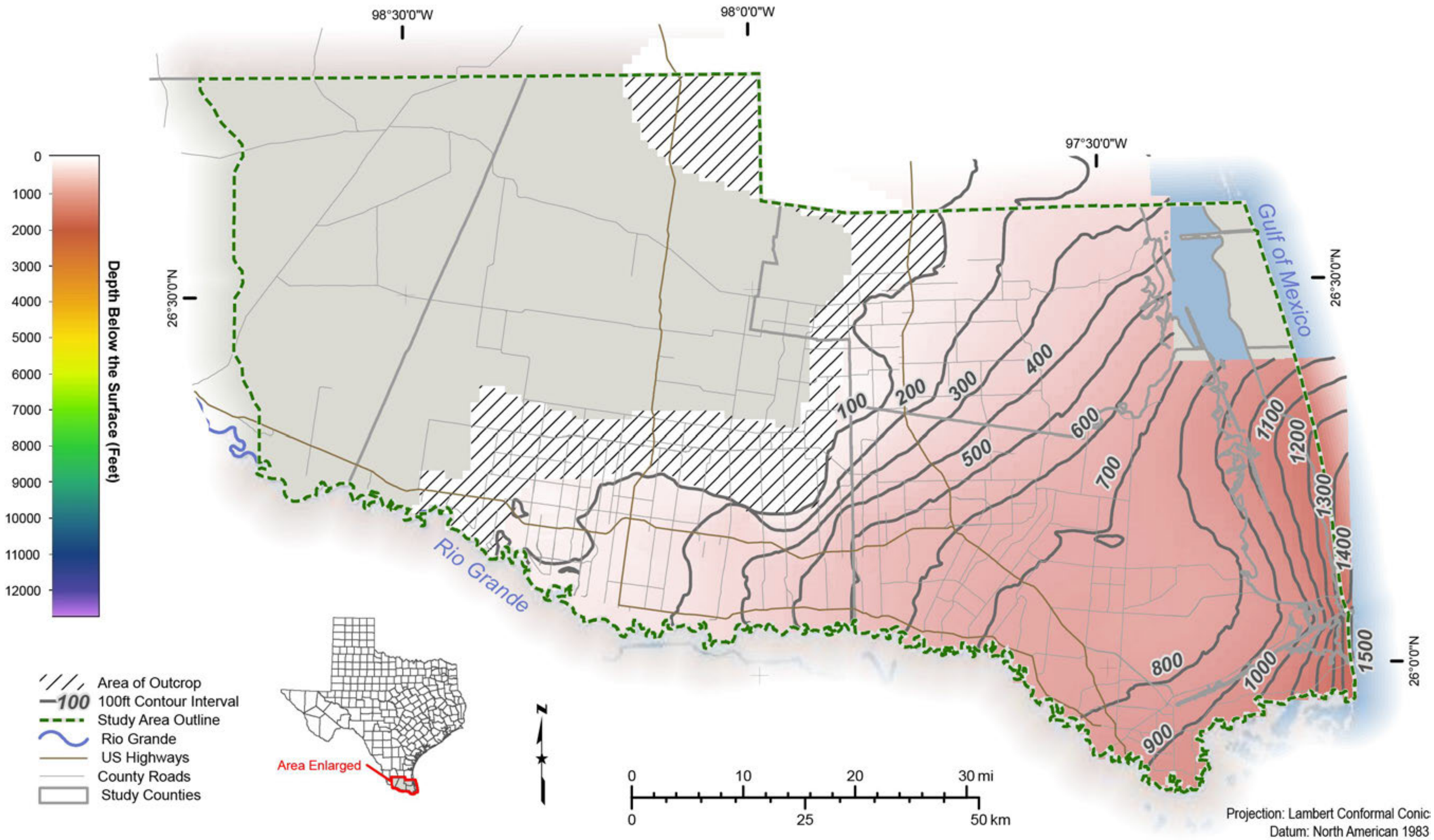

Figure 21.4.1-3. Depth (below ground surface) to the top of the Lissie Formation.

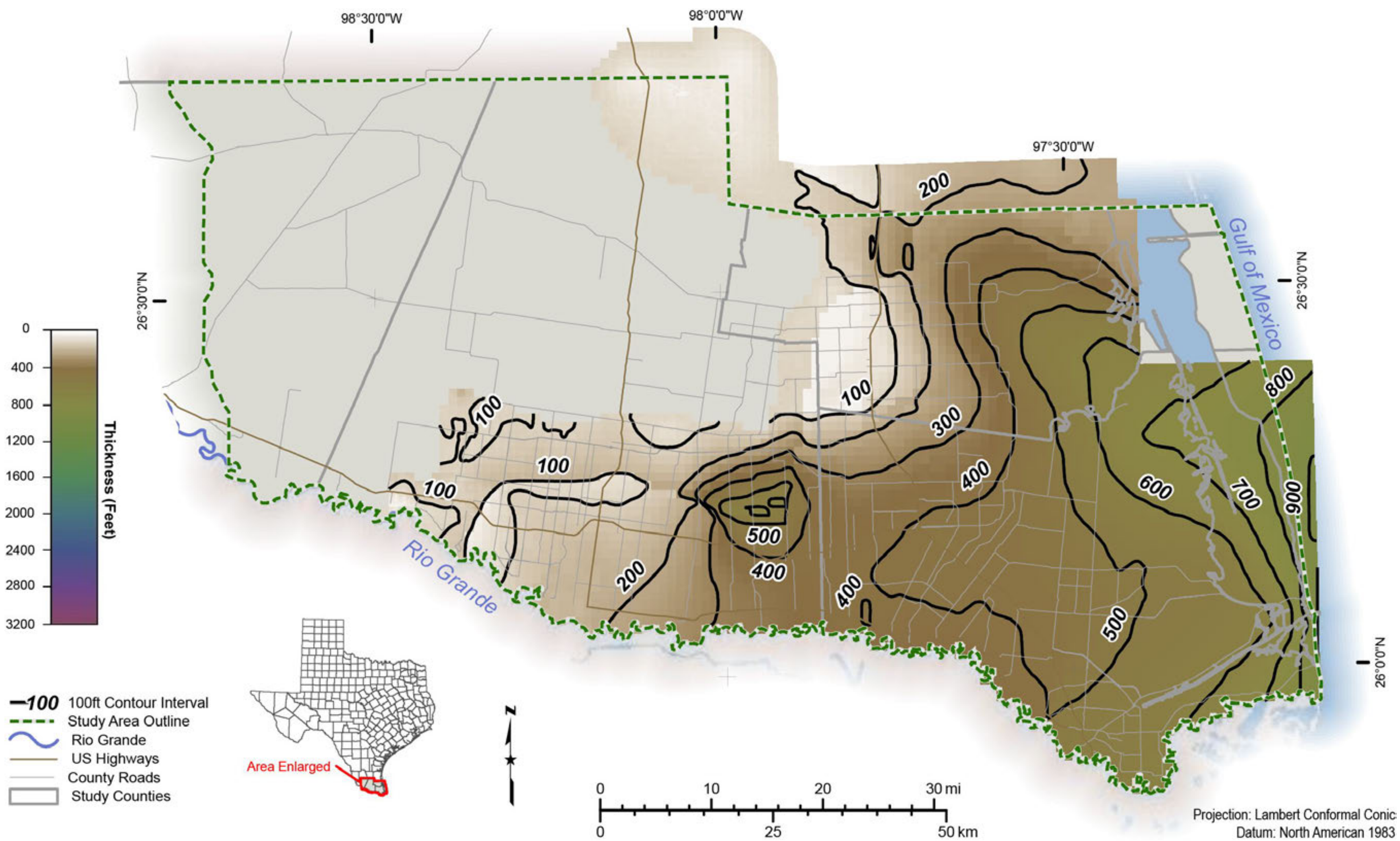

Figure 21.4.1-4. Thickness of the Lissie Formation.

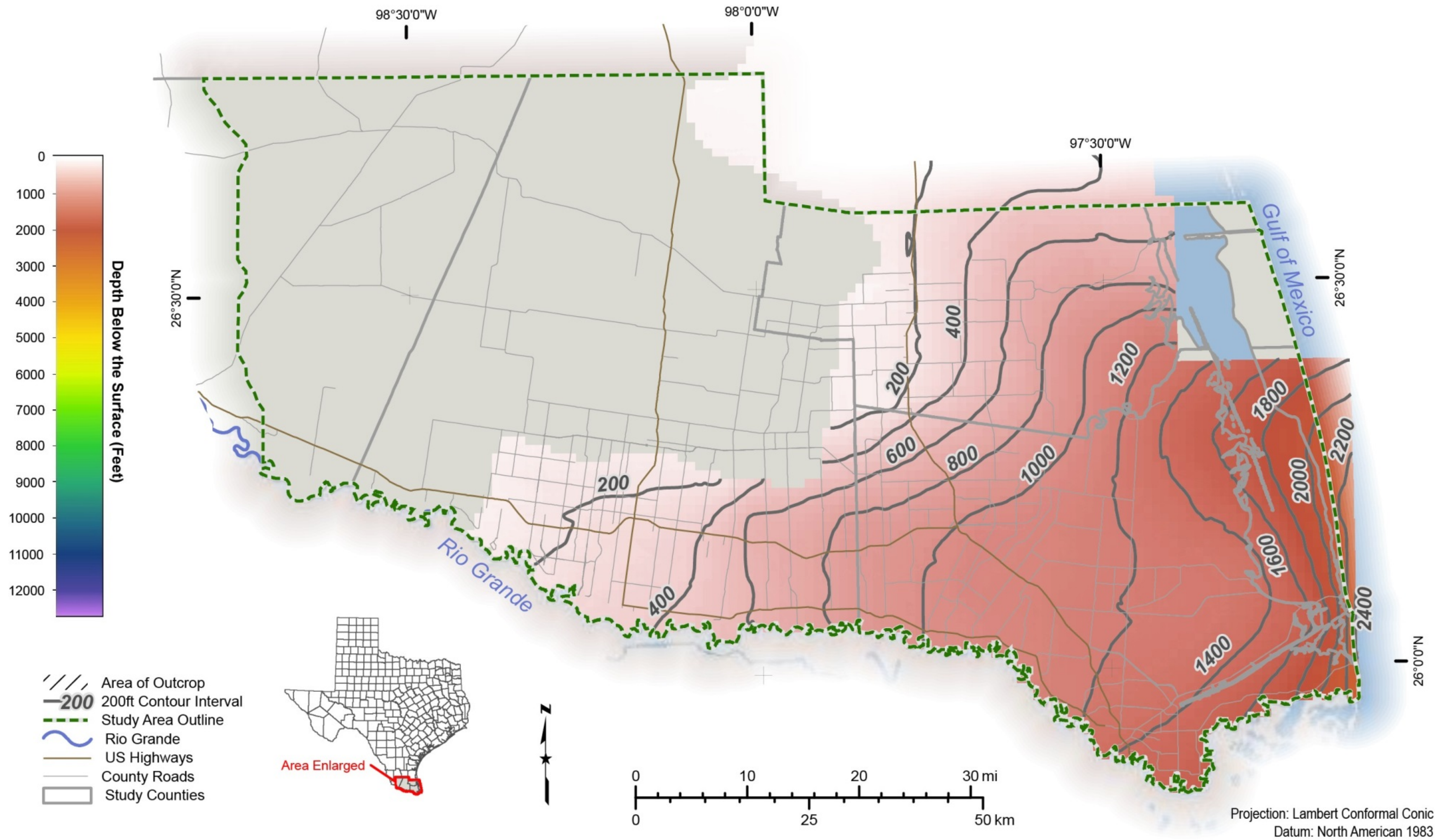

Figure 21.4.1-5. Depth (below ground surface) to the top of the Willis Formation.

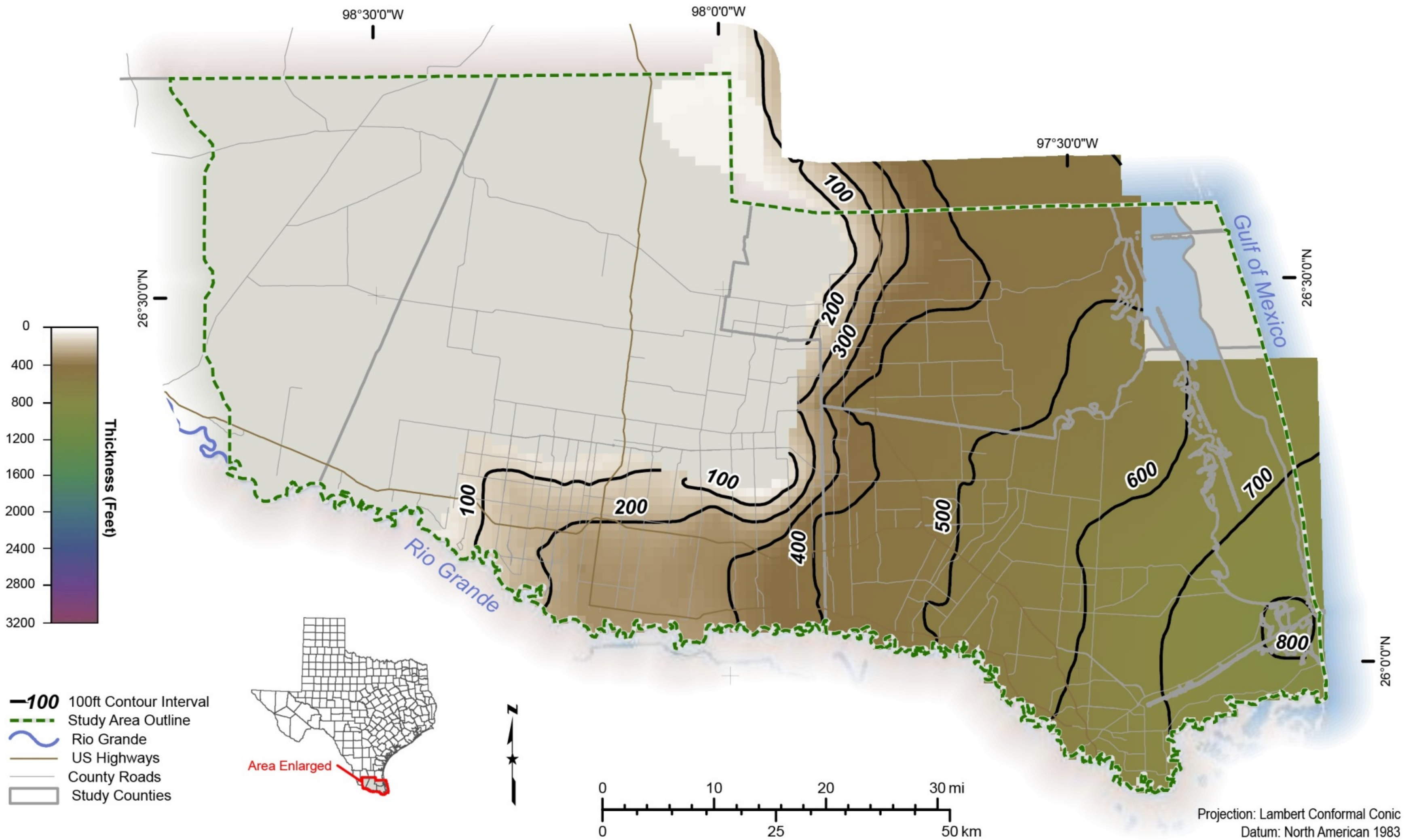

Figure 21.4.1-6. Thickness of the Willis Formation.

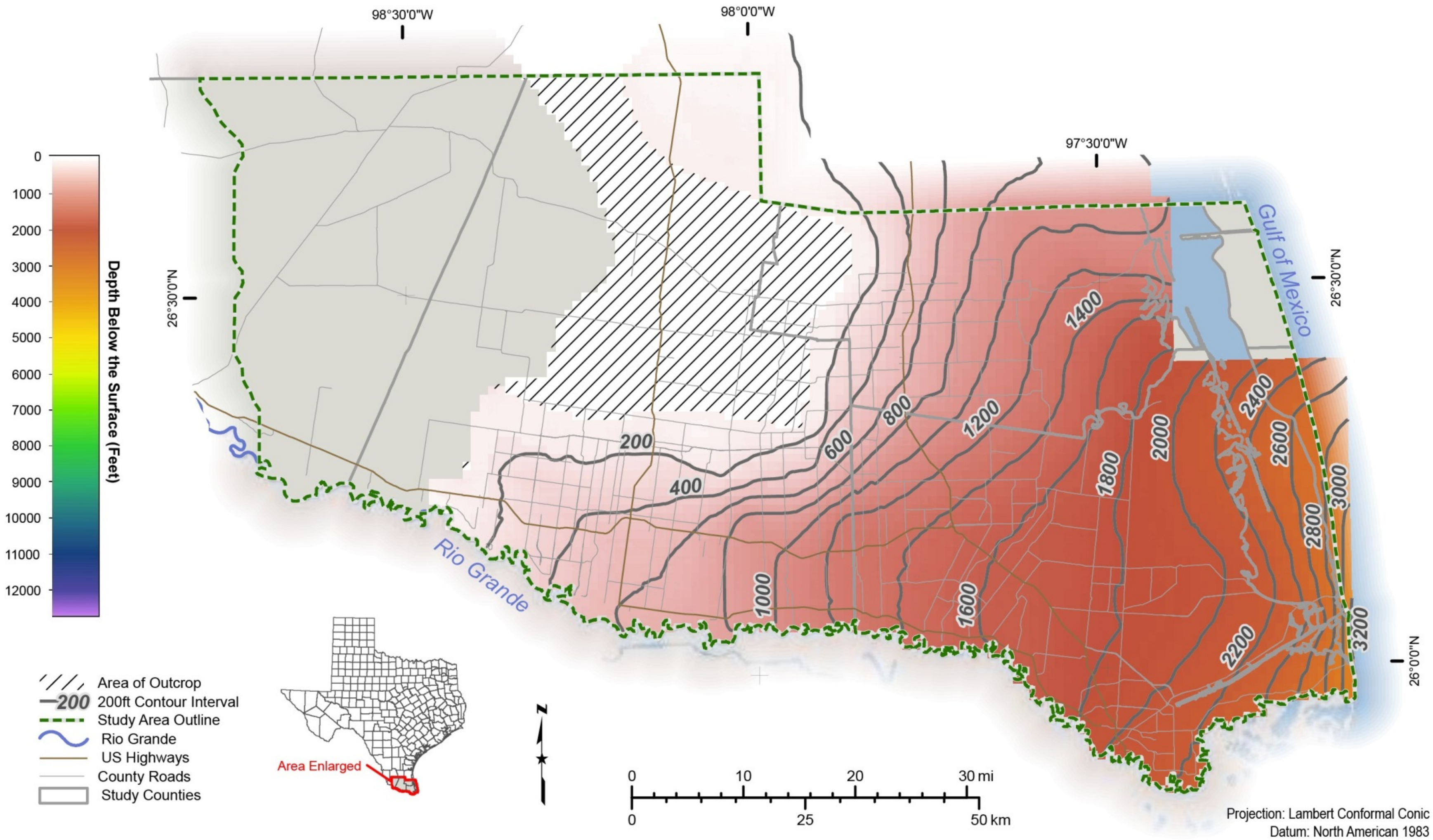

Figure 21.4.1-7. Depth (below ground surface) to the top of the Upper Goliad Formation.

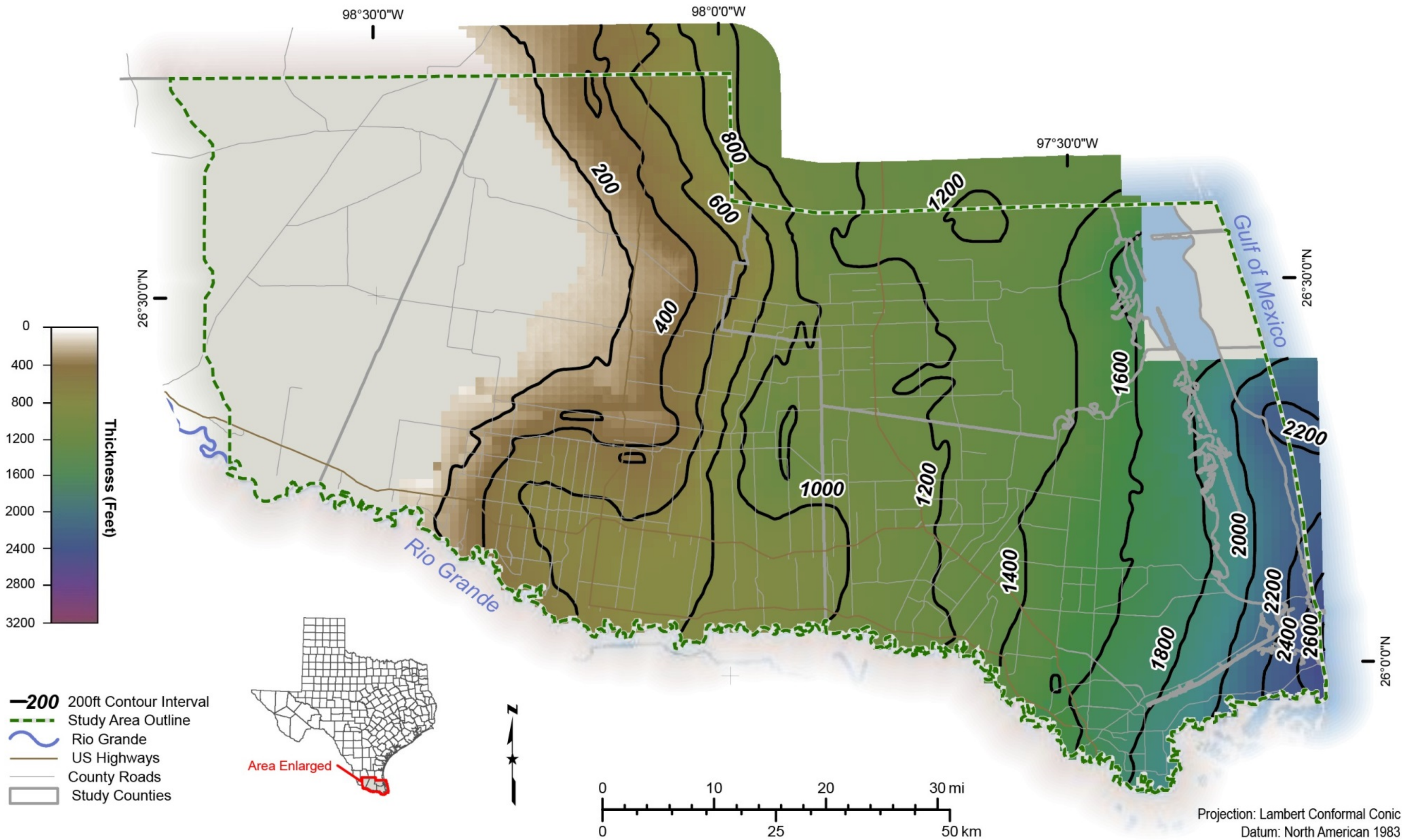

Figure 21.4.1-8. Thickness of the Upper Goliad Formation.

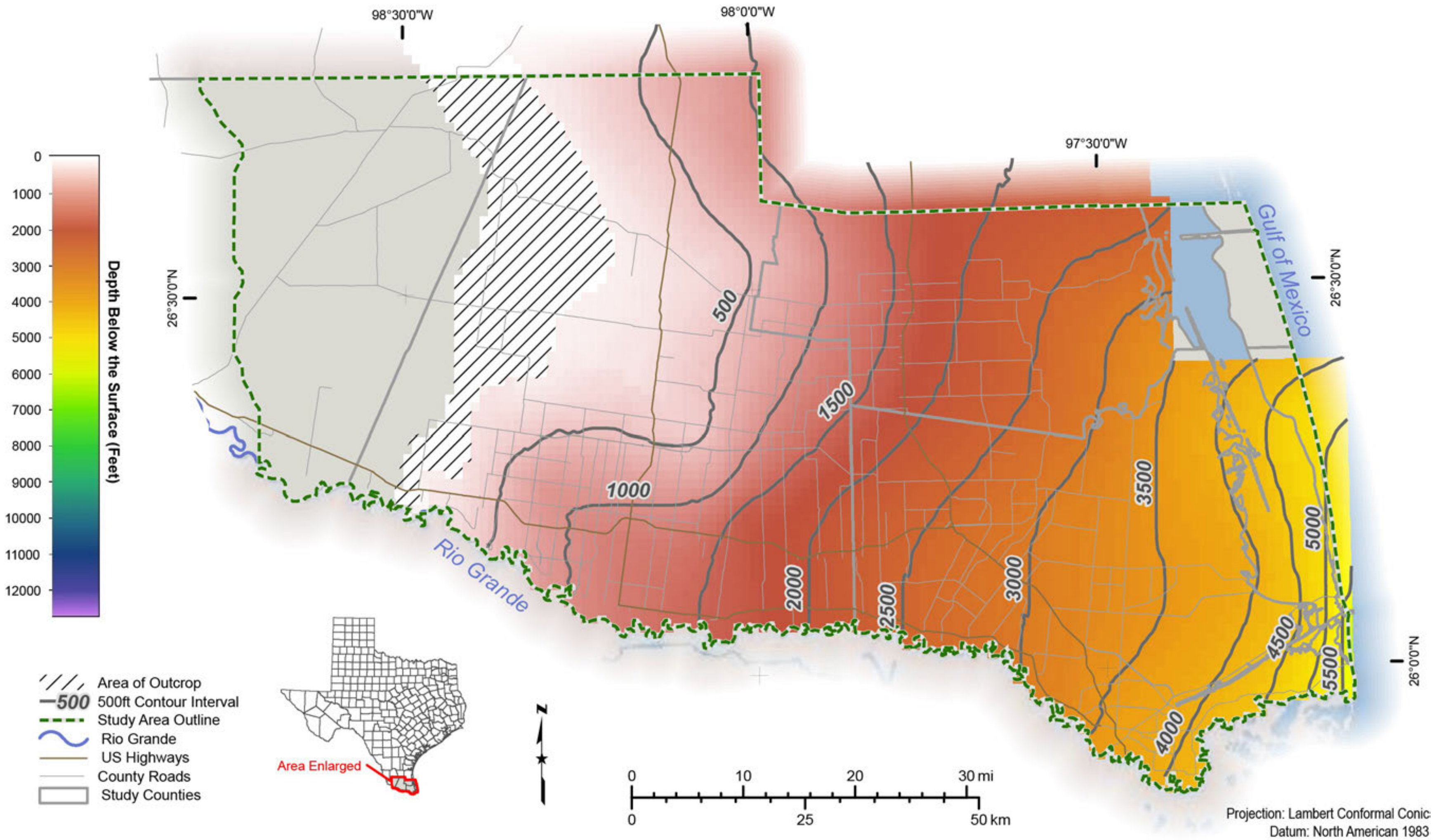

Figure 21.4.1-9. Depth (below ground surface) to the top of the Lower Goliad Formation.

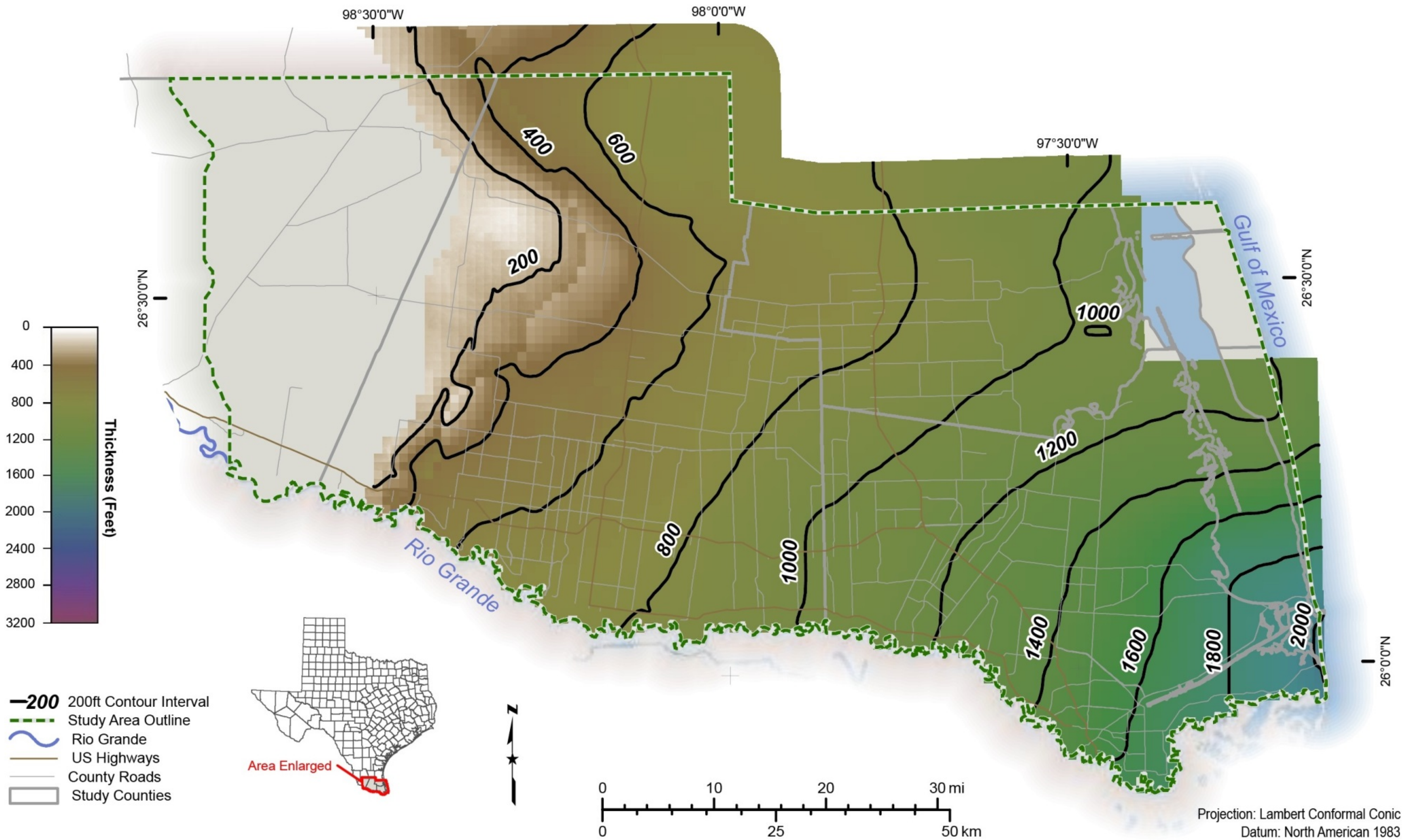

Figure 21.4.1-10. Thickness of the Lower Goliad Formation.

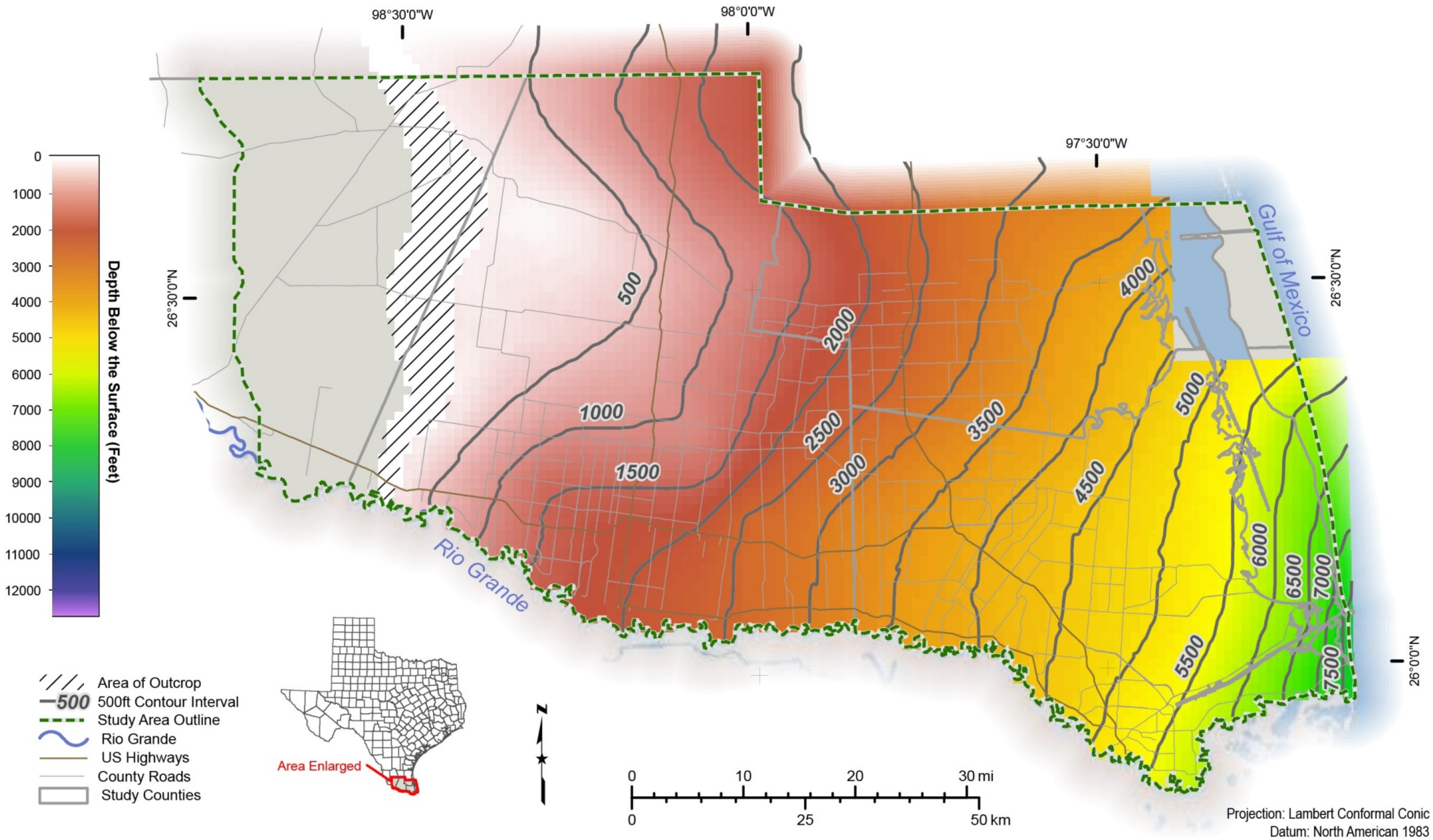

Figure 21.4.1-11. Depth (below ground surface) to the top of the Upper Lagarto Formation.

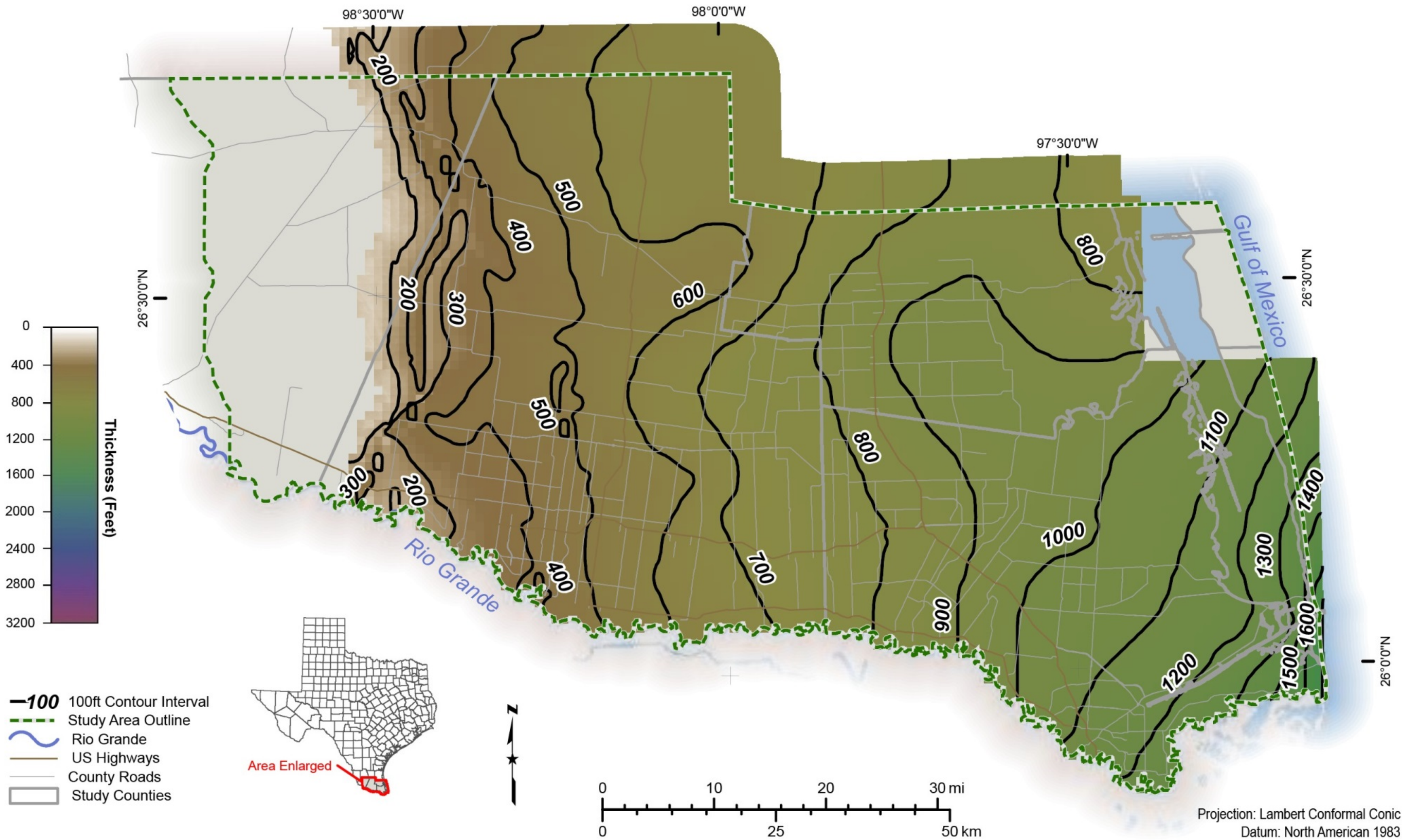

Figure 21.4.1-12. Thickness of the Upper Lagarto Formation.

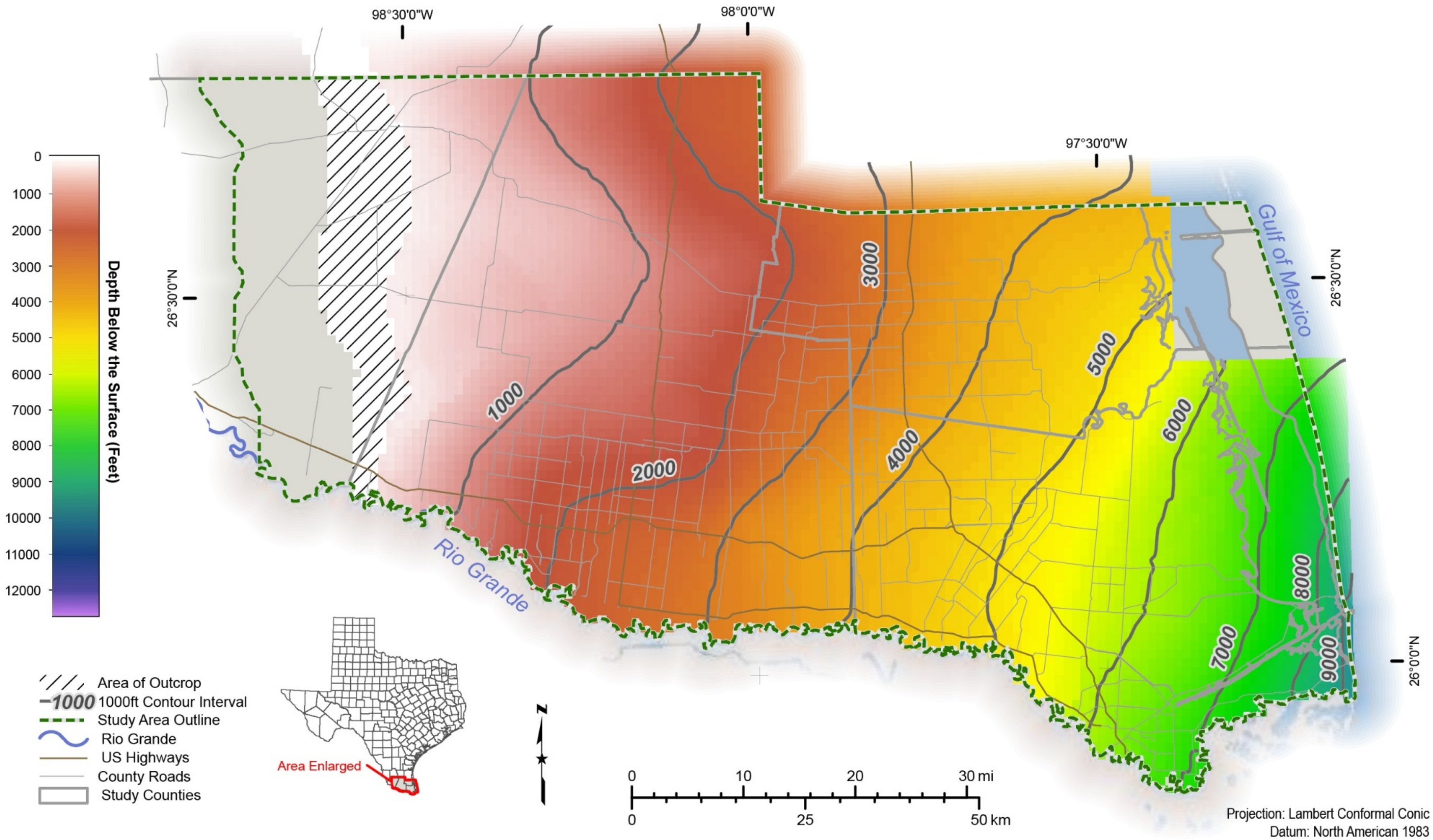

Figure 21.4.1-13. Depth (below ground surface) to the top of the Middle Lagarto Formation.

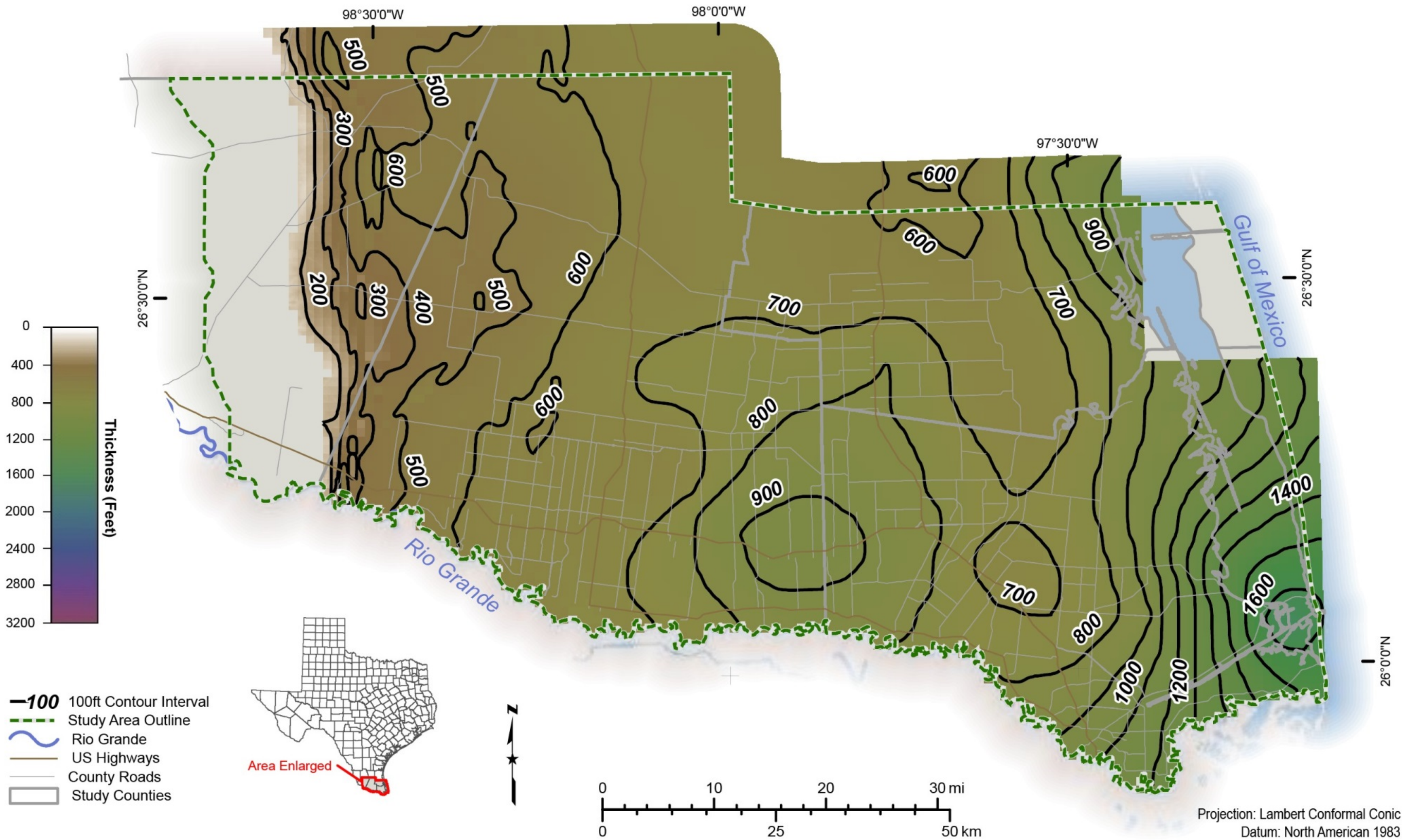

Figure 21.4.1-14. Thickness of the Middle Lagarto Formation.

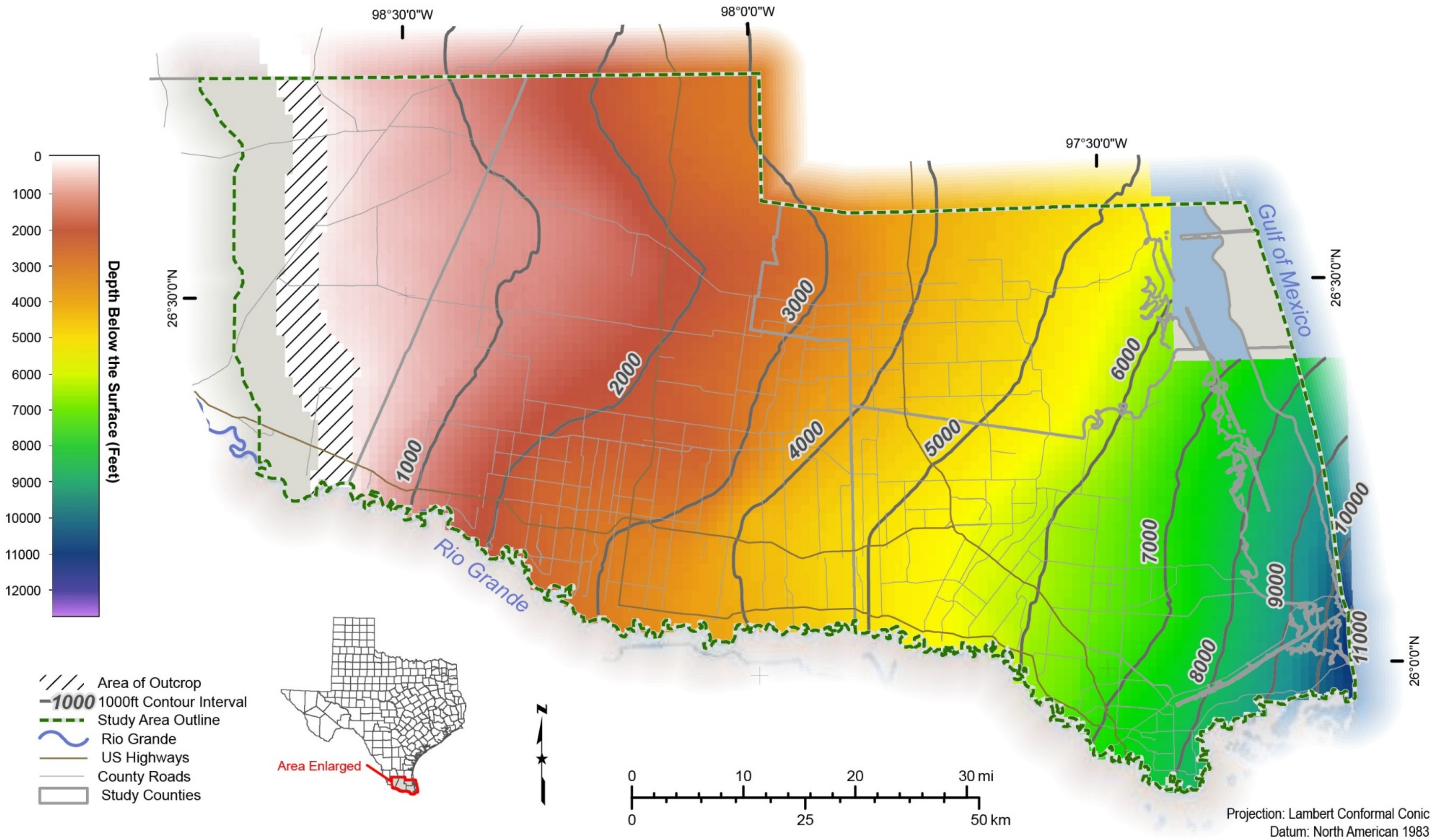

Figure 21.4.1-15. Depth (below ground surface) to the top of the Lower Lagarto Formation.

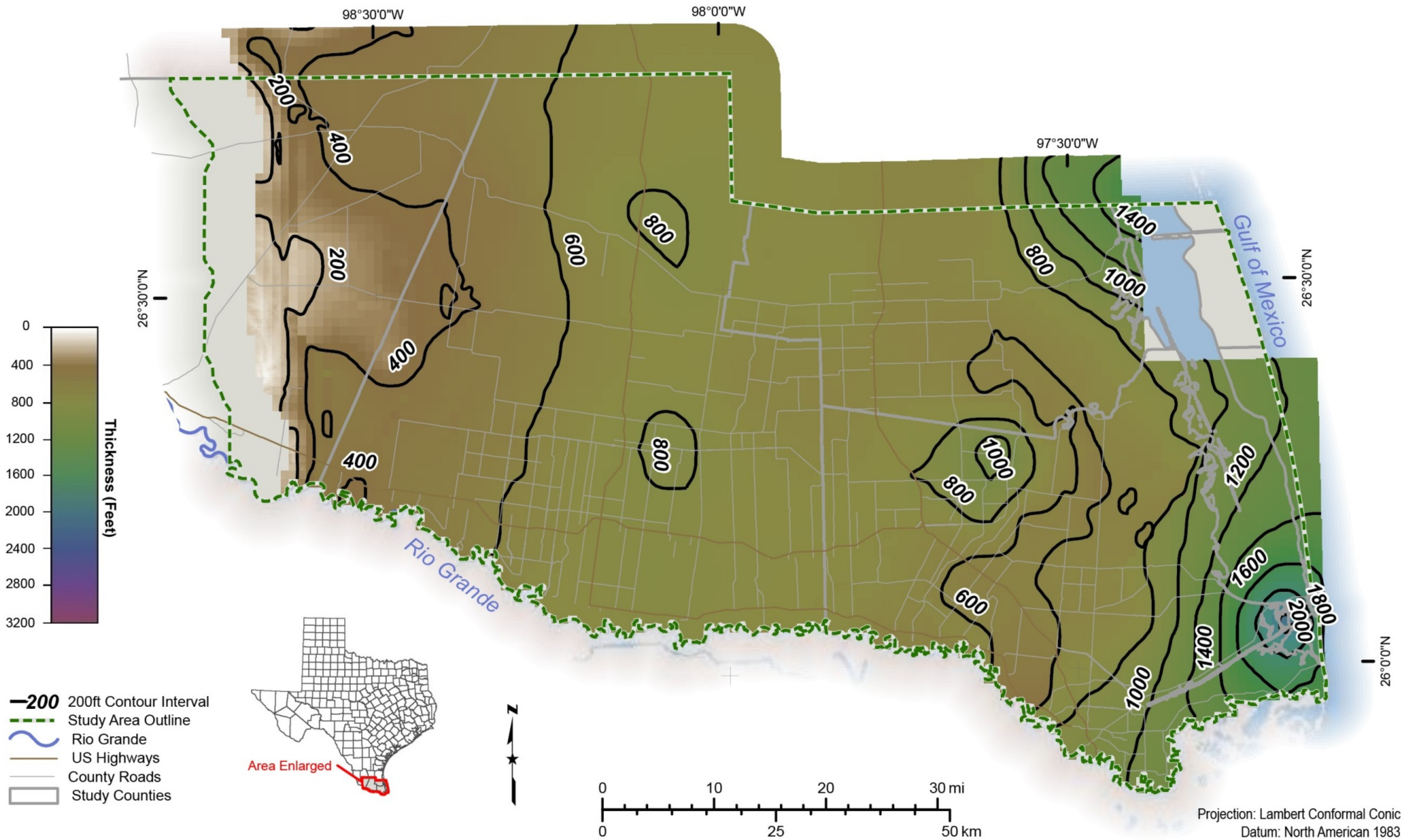

Figure 21.4.1-16. Thickness of the Lower Lagarto Formation.

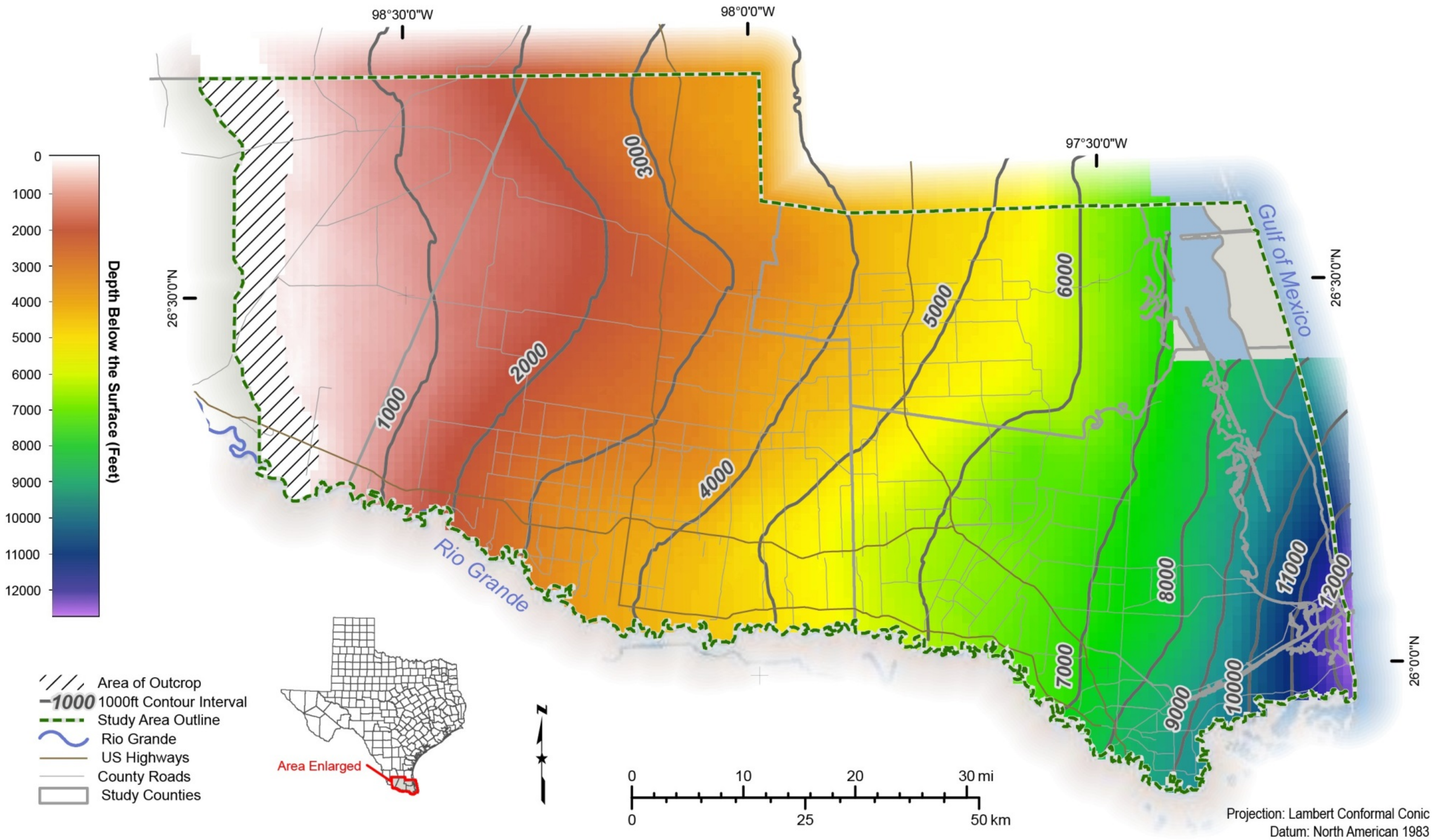

Figure 21.4.1-17. Depth (below ground surface) to the top of the Oakville Formation.

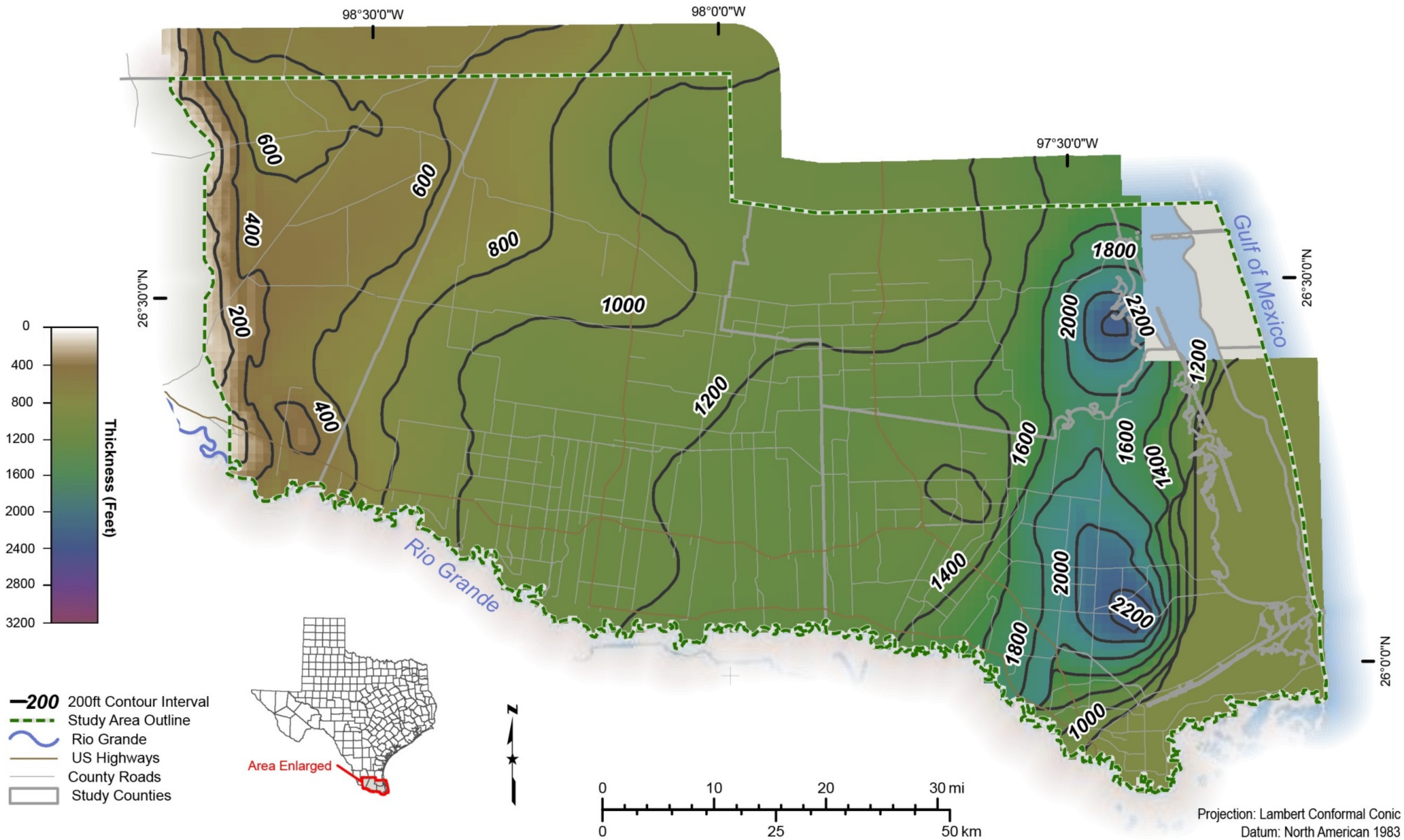

Figure 21.4.1-18. Thickness of the Oakville Formation.

21.4.2 Net sand maps

Net sand methodology is described in Section 13. We used data from 593 wells (Figure 13-1) to prepare the net sand maps for the nine formations of the Gulf Coast Aquifer (Figures 21.4.2-1 through 21.4.2-9). The BRACS Database contains two tables of net sand data that were used to prepare the well control point file. We calculated sand percent data for these wells in the table, but we did not prepare sand percent maps.

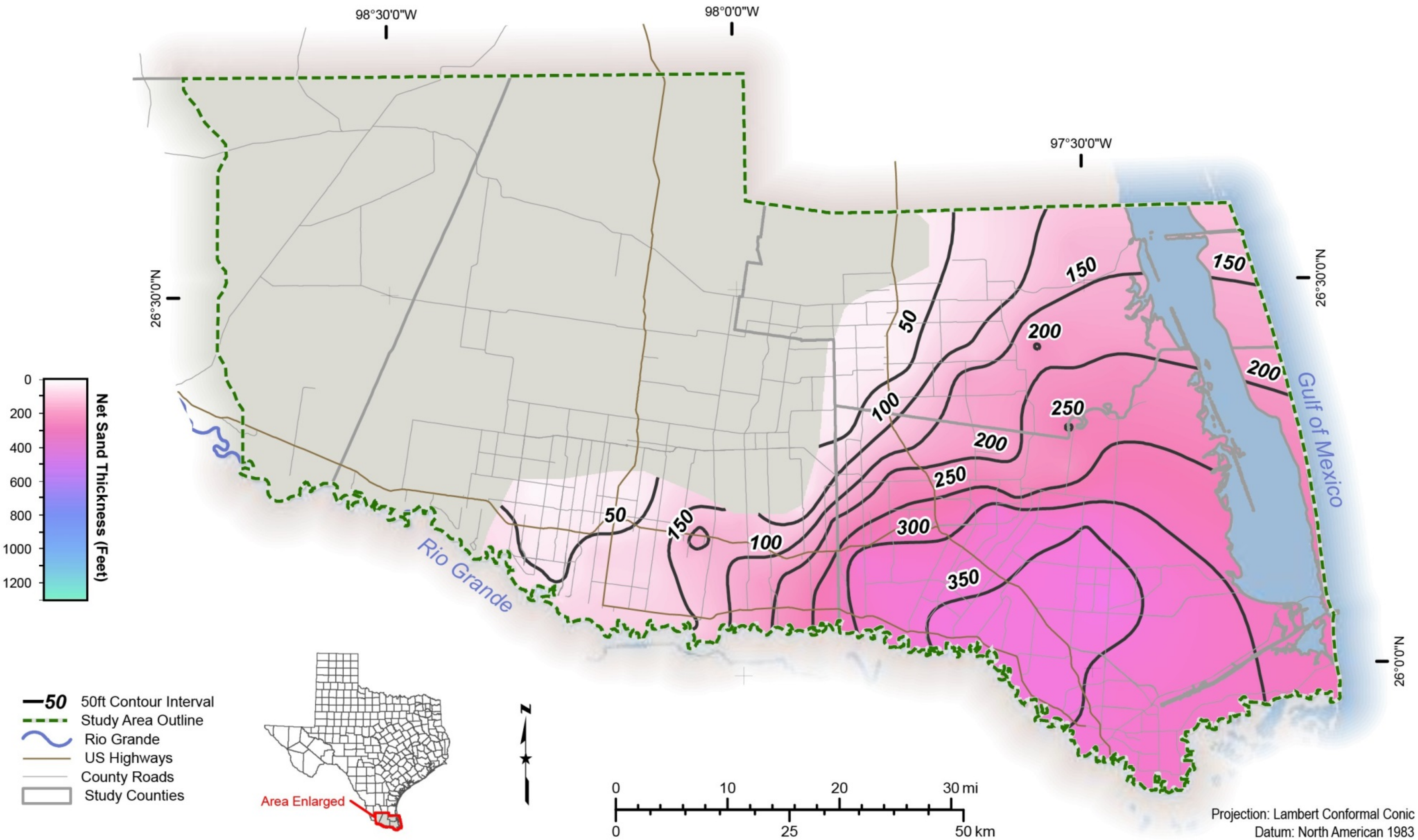

Figure 21.4.2-1. Net sand thickness of the Beaumont Formation.

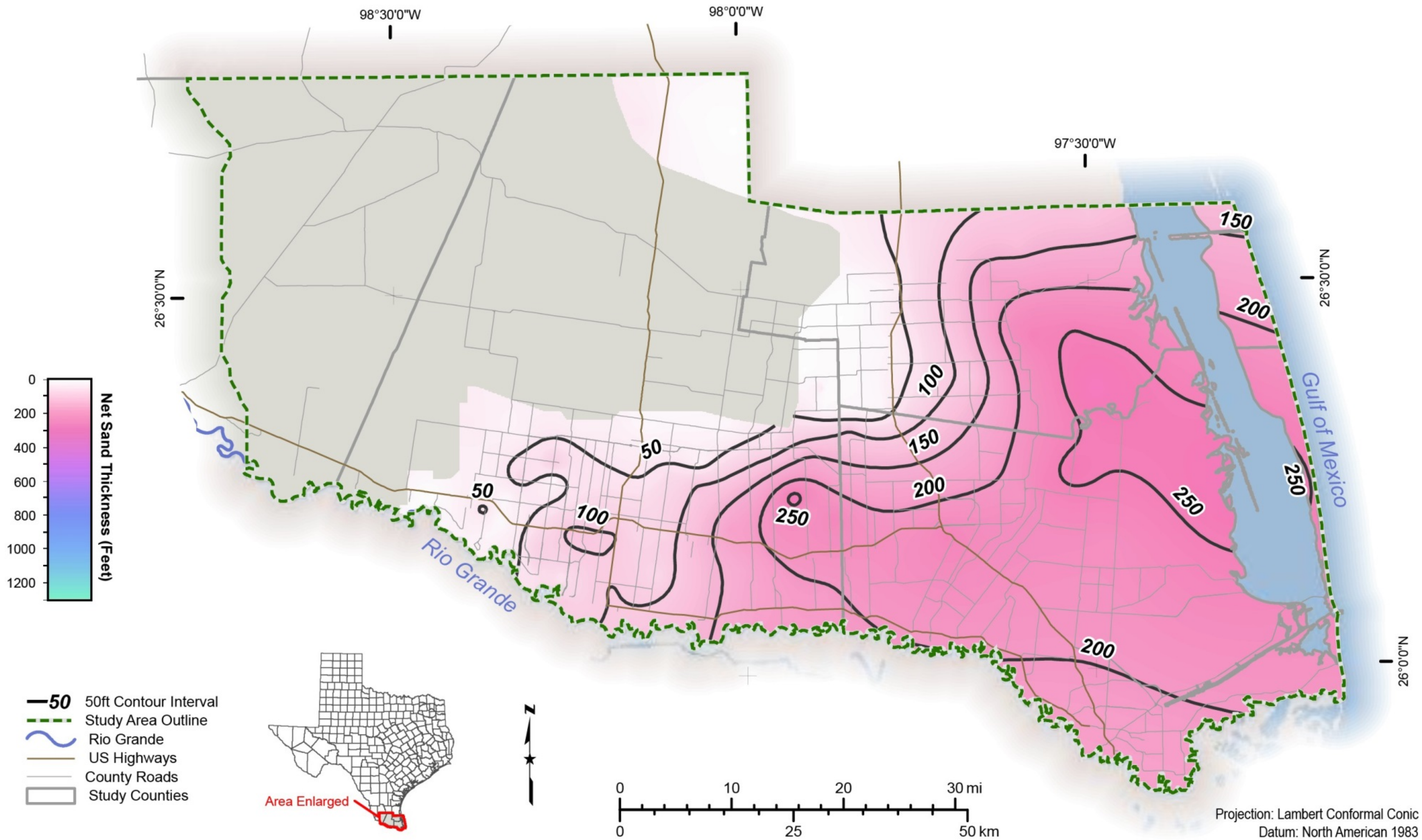

Figure 21.4.2-2. Net sand thickness of the Lissie Formation.

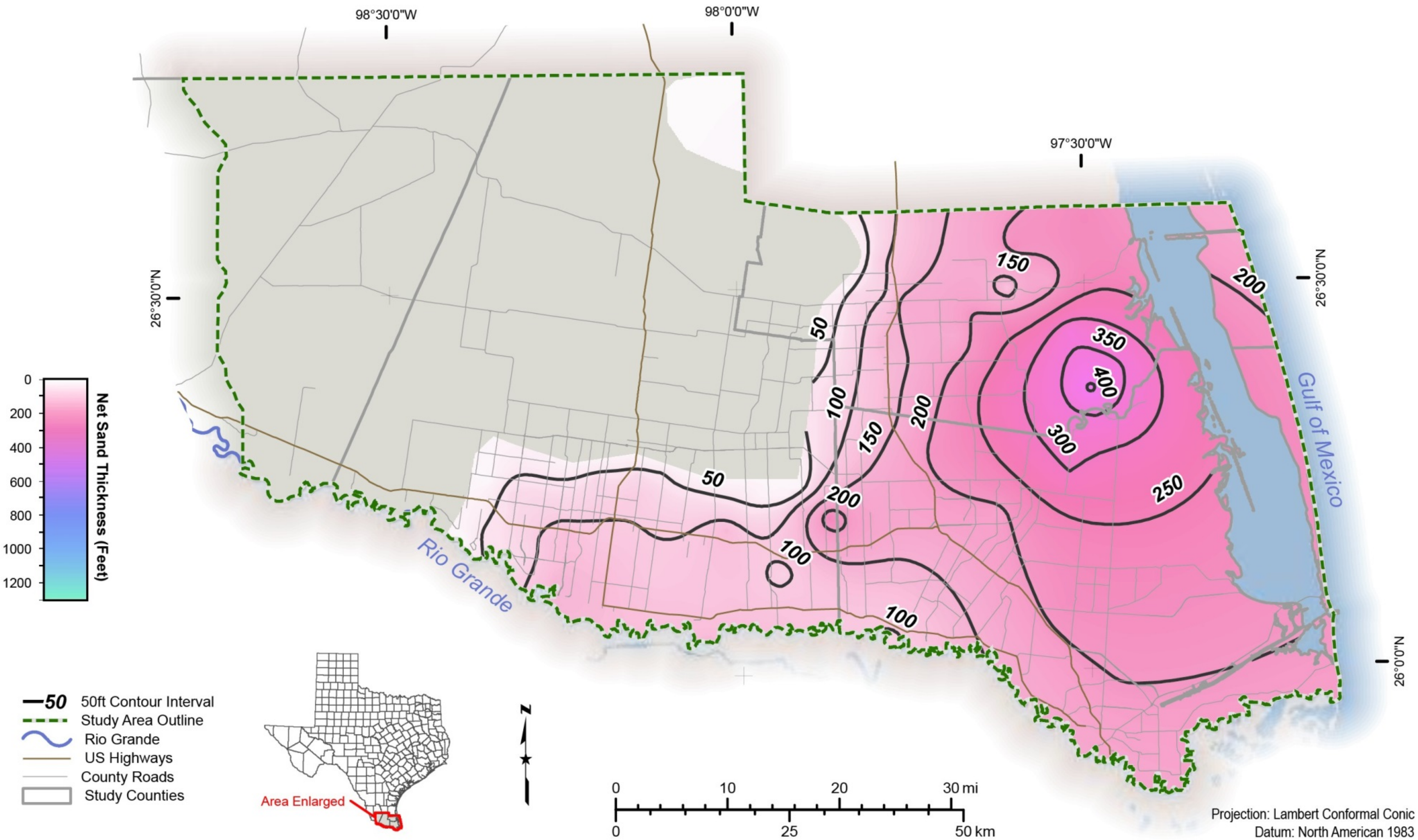

Figure 21.4.2-3. Net sand thickness of the Willis Formation.

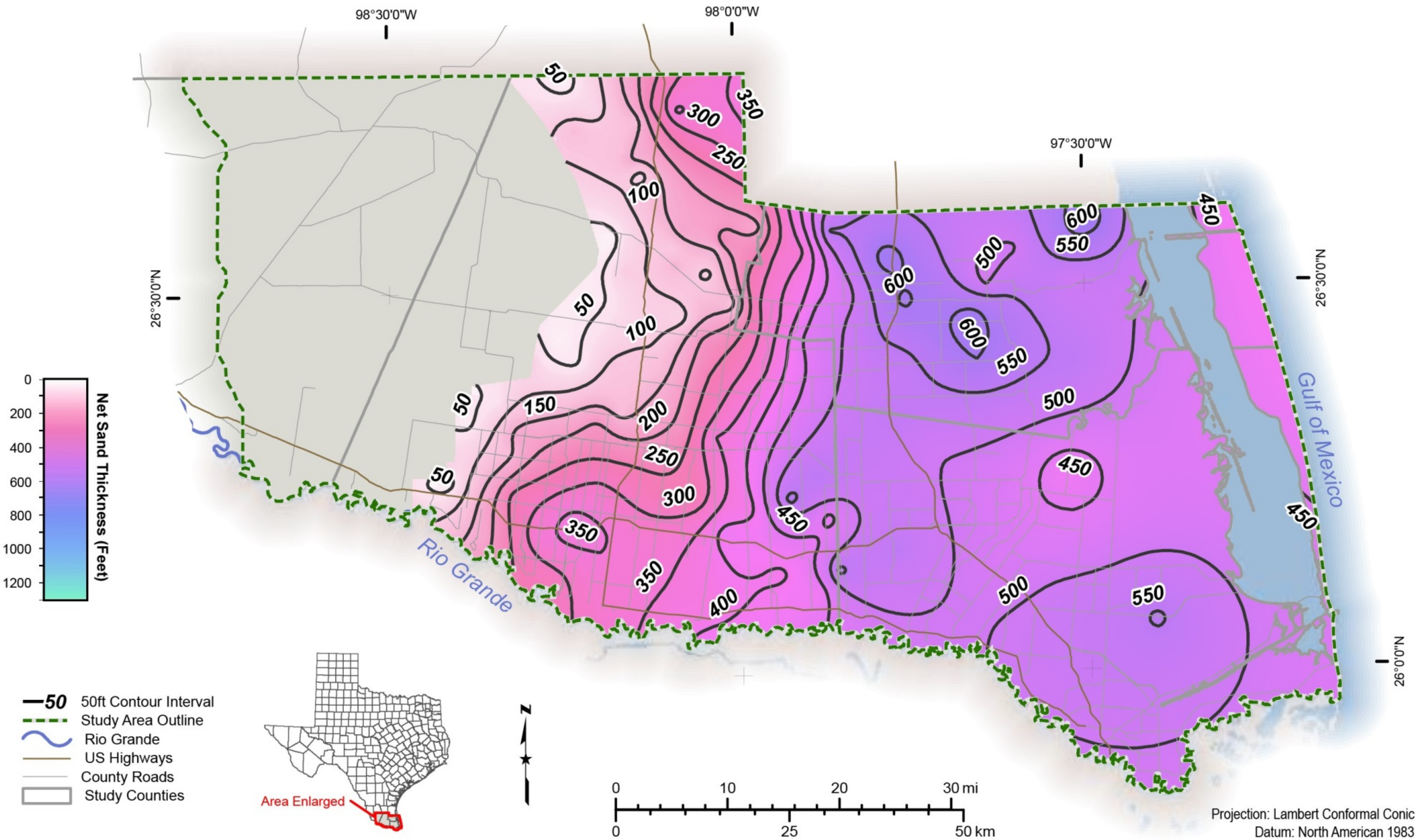

Figure 21.4.2-4. Net sand thickness of the Upper Goliad Formation.

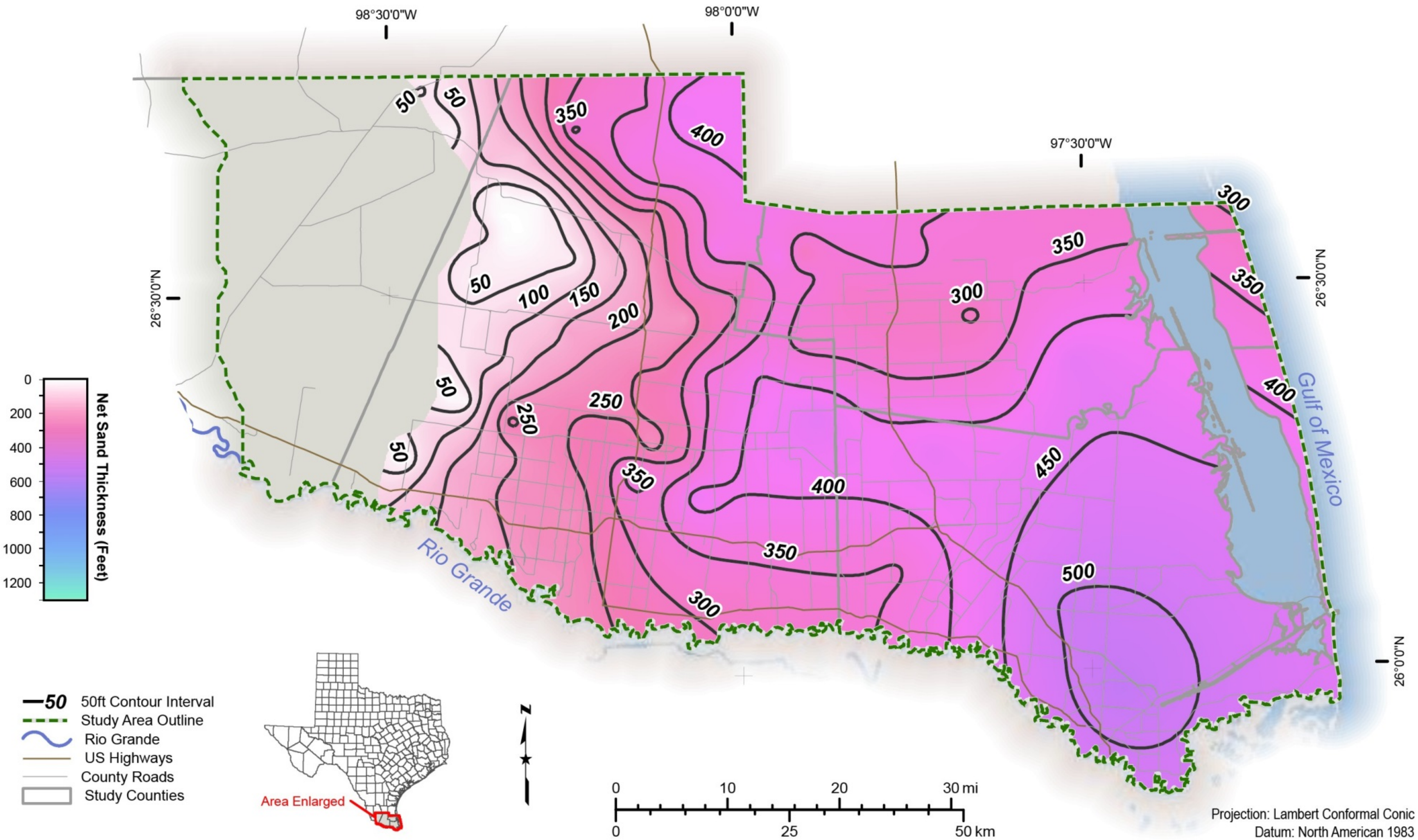

Figure 21.4.2-5. Net sand thickness of the Lower Goliad Formation.

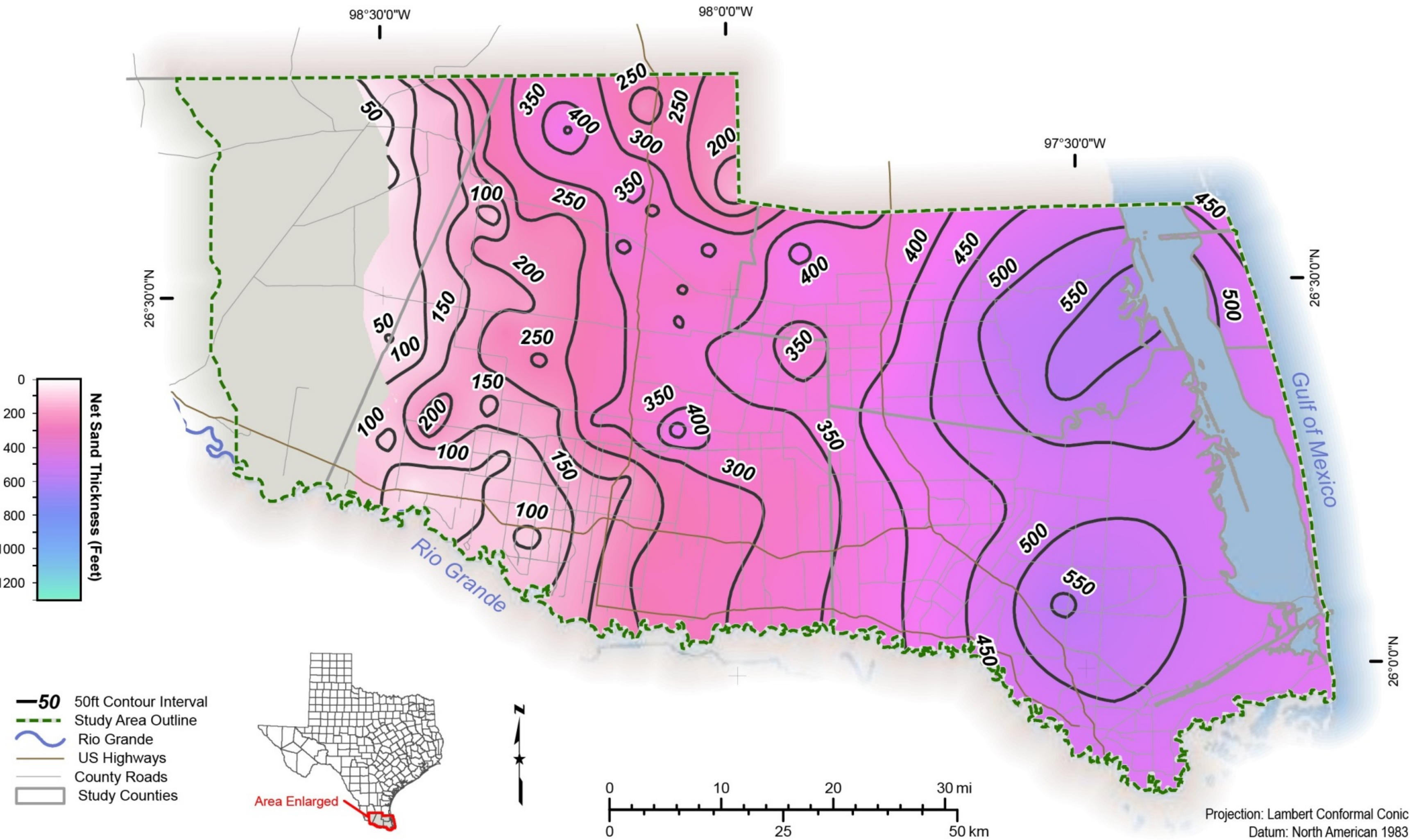

Figure 21.4.2-6. Net sand thickness of the Upper Lagarto Formation.

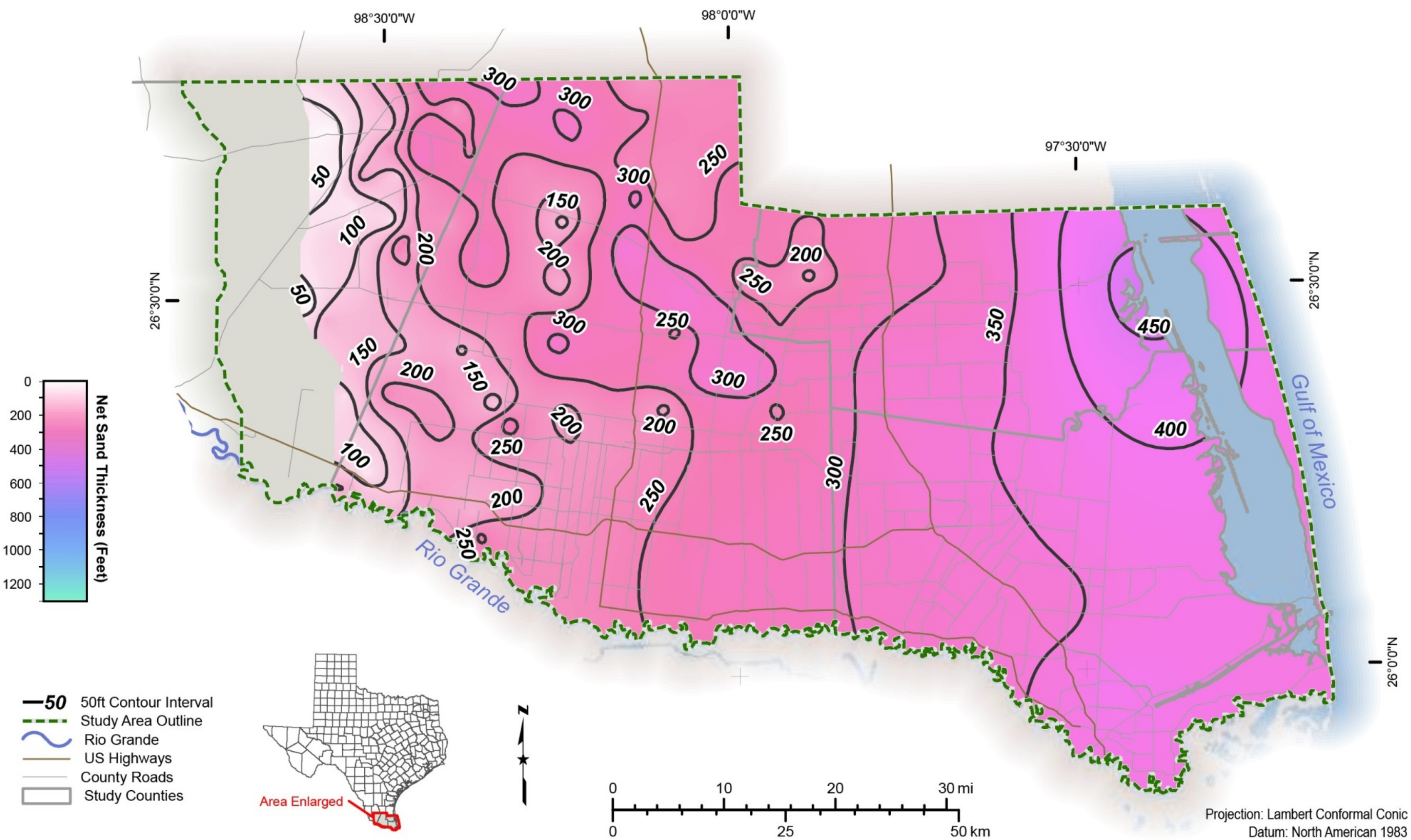

Figure 21.4.2-7. Net sand thickness of the Middle Lagarto Formation.

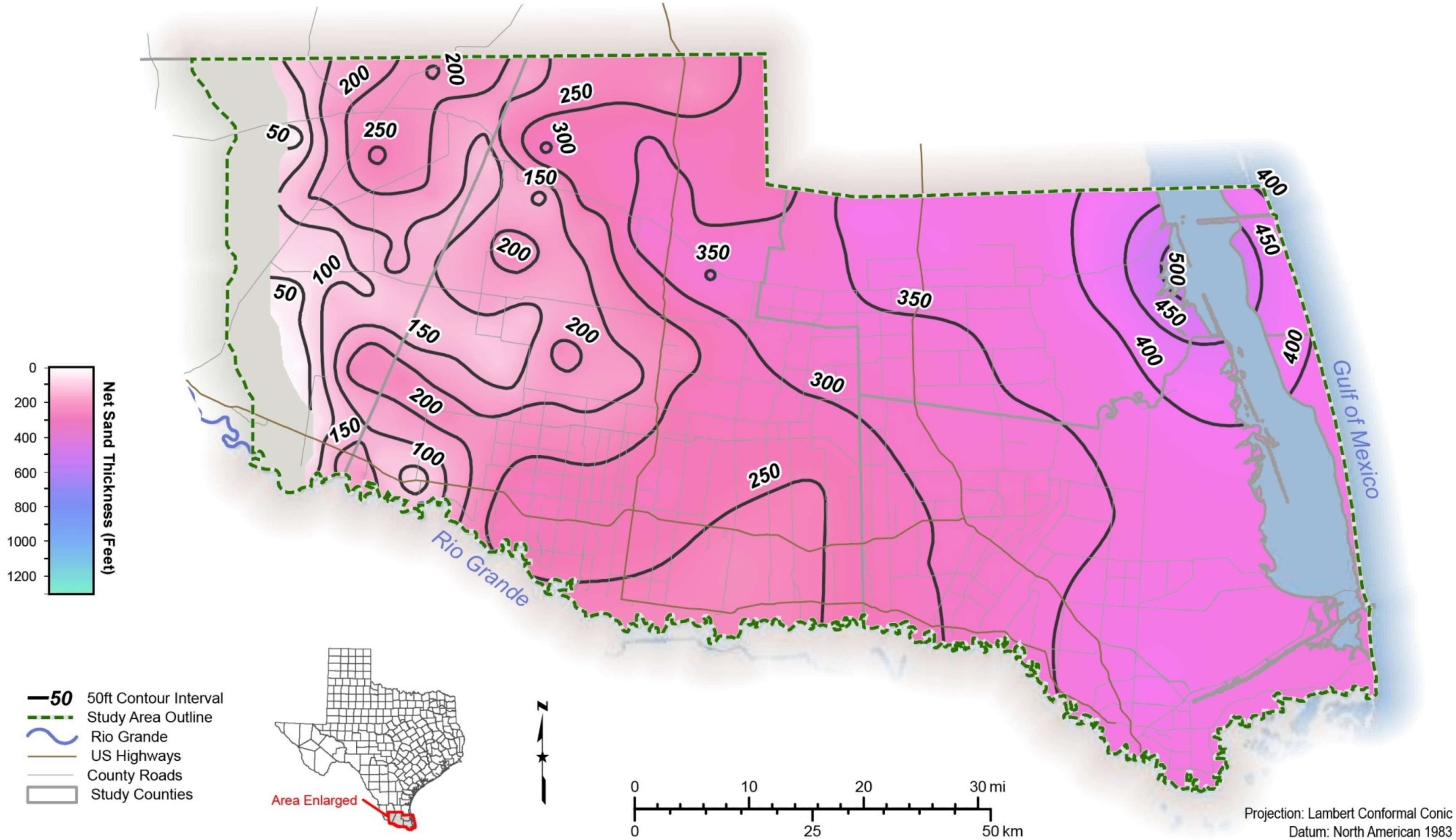

Figure 21.4.2-8. Net sand thickness of the Lower Lagarto Formation.

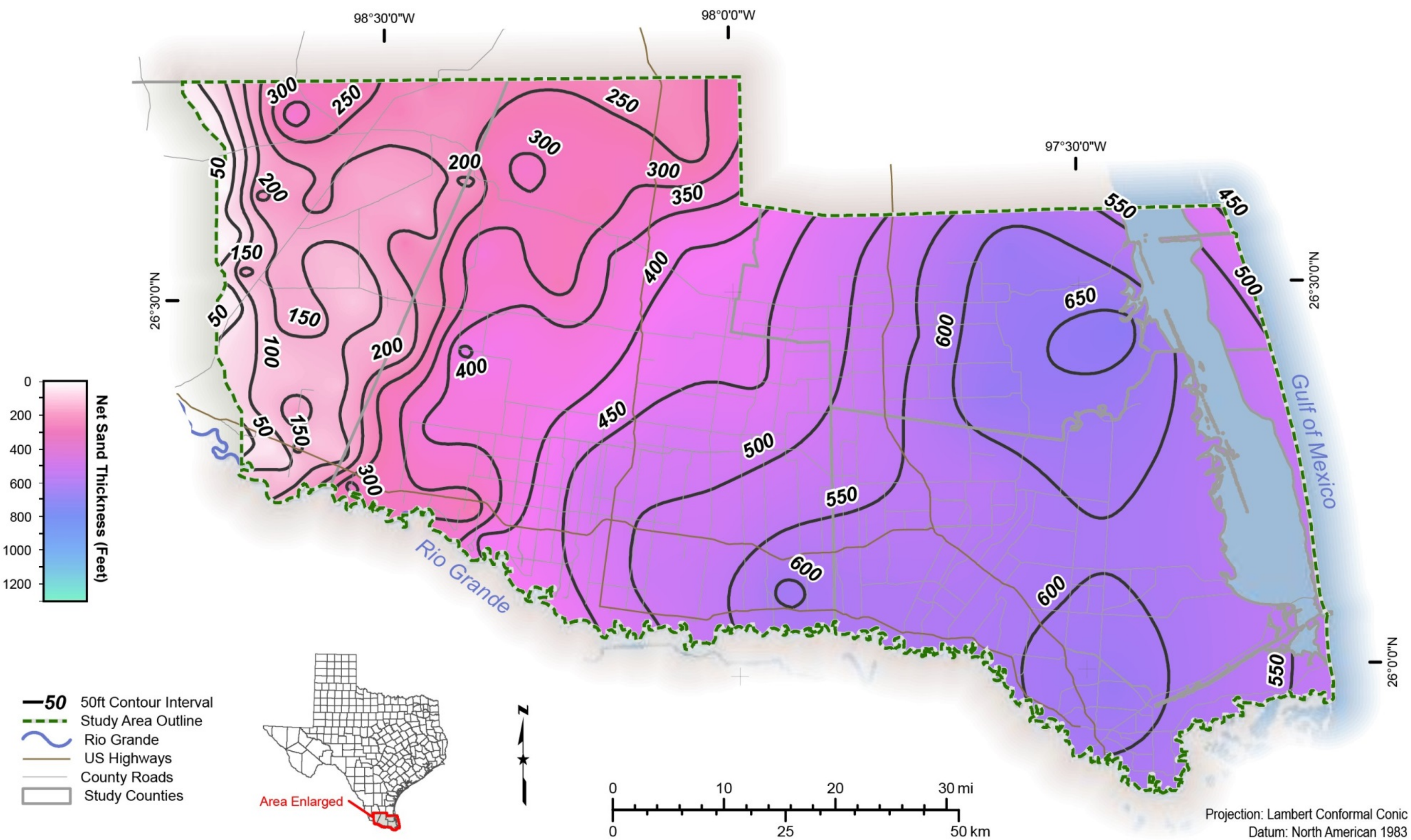

Figure 21.4.2-9. Net sand thickness of the Oakville Formation.