Identification of Geographic Areas in Texas Suitable for Groundwater Banking

Prepared for

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Executive Summary

The population in Texas is expected to double in the next 50 years, increasing from approximately 21 million in 2000 to approximately 40 million by 2050. During this same period, water demand is projected to increase by 18 percent, from nearly 17 to 20 million acre-feet. Texas' water supplies are also diminishing as a result of droughts, historical and ongoing overdrafts of aquifers in excess of natural recharge rates, pollution of available supplies, and limitations on use that result from environmental regulation such as total maximum daily load requirements and requirements of the Endangered Species Act. Despite increasing demand and dwindling supply, only eight surface water reservoirs with conservation storage greater than 5,000 acre-feet are expected to be built in the next 50 years. Consequently, alternative approaches will be required to meet future water demand, particularly during periods of drought.

One approach to meet the increasing water demand is to artificially recharge groundwater supplies with excess surface water. Artificial recharge of groundwater, or "groundwater banking," is becoming more common in the U.S., particularly in semiarid states such as California and Arizona, as a means to manage water resources and meet water demands during periods of extended droughts. The storage volume available in aquifers is generally much greater than that available in surface reservoirs.

This report documents a study performed by Daniel B. Stephens & Associates, Inc. and the Bureau of Economic Geology on behalf of the Texas Water Development Board. The goal for this project was to identify regions in Texas that are potentially suitable for groundwater banking. Although there are a variety of methods for artificially recharging aquifers with surface water, this study only considered recharge from spreading (or infiltration) basins on the land surface, although an overview of other techniques and examples of their application in Texas is provided.

Methodology

Identification of appropriate target areas for this project consisted of two tasks. Task 1 was a screening analysis performed at a statewide level. The overall purpose of this task was to show

how a geographic information system (GIS) can be used to identify broad regions that may be suitable for artificial recharge through the use of spreading basins. Once these regions were identified, we performed further analysis at a more site-specific level to identify potential sites suitable for banking (Task 2). Each of these tasks is described below.

Task 1: Statewide Screening Analysis

Initially, a statewide screening procedure was conducted that included water quality, regional water demand, aquifer characteristics (recharge areas and depth to water), distance from surface water, and topographic slope. However, once available data sets were evaluated, it was concluded that the water quality, distance from surface water, and topographic slope screens were more appropriately applied at the site rather than the statewide level.

The final statewide screening analysis yielded 48 counties that fit the criteria for preliminary site-specific evaluation of recharge basin suitability (Table ES-1). These counties are all projected to have water deficits by 2050 and include areas that (1) overlie the outcrop area of one or more major aquifers and (2) have depths to water in the major aquifers between 40 and 500 feet below land surface. The 48 counties were grouped into six general regions based on their Regional Water Planning Area, the major aquifers that they overlie, and their proximity to other selected counties. One county from each region was selected for more detailed, site-specific analysis. Because the statewide screen for high-demand regions was performed at the county level, potentially suitable sites in counties with lower demand were excluded from further analysis.

A GIS Screening Analysis Tool was also developed as part of this project for general application. The GIS tool can be applied to assist users with application of custom screening criteria for groundwater banking site selection.

Table ES-1. Counties Selected for Site-Specific Analysis Grouped by Region

Site-Specific Region	Counties	
South Central	Atascosa Bandera Bexar Comal Dimmit Guadalupe	Hays Kendall Maverick Medina Uvalde Zavala
Brazos G	Comanche Coryell	Williamson
Region C	Parker	Wise
Region F	Crockett Ector Glasscock Kimble Loving Midland	Reagan Reeves Tom Green Upton Ward
Ogallala (includes Region A Panhandle and Region O Llano Estacado Regional Water Planning Areas)	Bailey Briscoe Castro Cochran Dallam Deaf Smith Floyd Gaines Hale Lamb	Moore Oldham Parmer Potter Randall Sherman Swisher Terry Yoakum
Far West Texas	El Paso	

Task 2: Site-Specific Analysis

Counties within each of the six identified regions were evaluated and further screened for suitability for groundwater banking using recharge or spreading basins. For each of the regions, an analysis was performed that included:

- A general overview of water resources
- Identification of water storage and conveyance systems
- Discussion of infiltration rate, area, and time period for infiltration

Specific areas potentially suitable for groundwater banking were determined by screening for suitable soil permeability, topographic slope, and proximity to potential source water for infiltration, as described below.

- Relatively high soil permeability is required so that captured surface water can be infiltrated at a reasonable rate. Soil permeability data were derived from two online databases (SSURGO and STATSGO) published by the United States Department of Agriculture. Soils with a permeability greater than or equal to 2 inches per hour were selected as suitable for this analysis. SSURGO data are more detailed than STATSGO data and are required for detailed site evaluation at the county scale.

- The topographic slope of an area is also an important consideration when locating a potential recharge facility. A recharge basin generally needs to be located on a relatively flat area to eliminate the need for major excavation. A slope of 5 degrees or less was determined to be acceptable for this level of analysis. Topographic slopes were derived from the U.S. Geological Survey 1:250,000 digital elevation model.

- Another important consideration regarding a site's suitability for basin recharge is distance from the surface water source. Higher costs associated with moving water long distances reduce the economic benefits of recharge basins located far from their source of recharge water. For this analysis, sites within 3 miles of a designated first-, second-, or third-order stream were identified (a lower stream order indicates a larger stream).

Other factors, including surface water quality, water availability, availability of existing water storage and conveyance infrastructure, and time period in which recharge could occur, were considered in the site-specific analysis but were not applied directly to include or exclude potential water banking sites.

For each example county, infiltration was calculated for one or two hypothetical basins in the county. The total volume of water that can be infiltrated into the subsurface is equal to the rate of infiltration times the infiltration area times the time period during which infiltration occurs; each of these factors can be locally limiting. The purpose of these calculations is to provide a general idea as to the potential volumes of water that might be banked within different regions of the state. Site-specific infiltration calculations were conducted as outlined below.

Water availability at potential banking sites was determined using hydrograph data and Texas Commission on Environmental Quality (TCEQ) Water Availability Modeling (WAM) results. The modeling results provide estimates of average available water (non-appropriated water) at various locations in a given stream system. Because the source of banked water would most likely come from large streamflows of short duration, an estimate of water volume available from large storm flows is more appropriate than average annual estimates of available water. For this reason, water availability for infiltration calculations at specific sites was estimated using hydrograph data rather than modeling results for example counties within each region.

For each example site, one or two hydrograph records were used to estimate water availability over a period of approximately 6 to 10 years. Recent data (1990s) were available for 5 of the 9 selected gauges; older periods of record were used at other gauge locations. For each hydrograph, a flow threshold was selected to separate storm flows from base flows and typical annual flows. One half of the volume of water above the selected threshold value for each hydrograph was assumed to be available for banking at a given site. This approach assumes that observed flow at the selected gauge provides a reasonable estimate of available water for the drainage area upstream of the gauge and is sufficient for the example infiltration calculations conducted.

Results

Results of the infiltration calculations for the selected counties are summarized in Table ES-2. Other results for each of the six regions are summarized below.

Table ES-2. Summary of Site-Specific Infiltration Calculations for Selected Counties

Region	Example County	Gauge	Available Time Period for Infiltration (days)	Sample Infiltration Calculations [a]		
				Threshold Flow (cfs) [b]	Period	Cumulative Volume (ac-ft)
South Central Texas	Uvalde	Nueces River	5	850	1990-1999	50,000
		Frio River	8	450	1990-1999	75,000
Brazos	Coryell	Leon River	5	2,000	1991-2001	34,000
Region C	Parker	Brazos River	6	3,250	1991-2001	225,000
		Clear Fork of the Trinity River	6	100	1991-2000	22,500
Region F	Reeves	San Solomon Springs	57	35	1956-1966	1,150
		Barilla Draw	2	0	1976-1984	5,000
Ogallala	Randall	Prairie Dog Town Fork of the Red River	3	250	1940-1950	15,800
Far West Texas	El Paso	Rio Grande	9	600	1970-1975	60,000

[a] Infiltration calculations assumed a basin area of 100 acres except for Coryell County where 50 acres was used.
[b] Water available for infiltration assumed to be one-half the streamflow above the threshold value.

cfs = Cubic feet per second
ac-ft = Acre-feet

South Central Texas Region

The South Central Texas region is perhaps the most suitable region in Texas for groundwater banking. Water deficits are projected to occur by 2050 for a large number of counties in the region. The unconfined sections of the Edwards and Edwards-Trinity Aquifers are well suited in many areas as potential recharge sites. Due to the dynamic nature of groundwater flow in the Edwards Aquifer, recharge to this aquifer is likely not recoverable near the source, but should be viewed as an additional recharge component to the regional aquifer system. A number of potential recharge sites also overlie the Carrizo-Wilcox aquifer outcrop area.

Bandera, Medina, and Bexar Counties all have potential banking locations along stretches of the Medina and San Antonio Rivers. However, because stretches of both these Rivers are impaired, potential water quality impacts should be evaluated as part of any further consideration of these sites for groundwater banking. Zavala and Dimmit Counties, both of which have projected water deficits, have several small potential sites along the headwaters of the Nueces River including El Morro, Comanche, and Capote Creeks. WAM data show significant water availability along these streams.

Uvalde County, which was selected for more in-depth screening because of the available SSURGO soil and streamflow hydrograph data, has many potential recharge locations along the river valleys and tributary reaches of the Nueces and Frio Rivers, as well as a lesser number of areas along the Sabinal River. These locations are primarily upstream from Uvalde and Sabinal, the major towns in the county.

Recharge computations were conducted using two observed hydrographs, one from a gauge on the Nueces River in the southern part of the county and the other from a gauge on the Frio River in the northern part of the county. Both gauges are close to potentially suitable recharge sites. Results of these computations are provided in Table ES-2

Brazos Region

The site-specific analysis identified only one potential recharge location in the three counties in the Brazos region selected by the statewide screening. This 80-acre site is in Coryell County, on the Leon River upstream from Gatesville. Infiltration calculations using a hydrograph from the gauge at Gatesville are summarized in Table ES-2.

This location could be ideal for groundwater banking as it is upstream from the major population center of the county and it meets all initial screening criteria. Because of the limited available acreage, such a site might be reserved as a future recharge facility. However, since this stretch of the Leon River has been designated as an impaired stream, potential water quality impacts should be evaluated as part of any further consideration of this site for groundwater banking.

Williamson County should be analyzed further, as it is one of the fastest growing counties in the nation. In our analysis, no suitable locations were identified because of the criteria for distance from streams and rate of infiltration. However, the rate of infiltration should be evaluated in greater detail, because some of the sites excluded on this basis might be acceptable recharge locations if the uppermost layers of soil are excavated.

Region C

Of the two counties selected for site-specific analysis in Region C, high-resolution SSURGO soil data are available for only one, Parker County. While the site-specific analysis identified many potential groundwater banking locations in Parker County, the soil infiltration characteristics derived from the STATSGO data in Wise County did not meet the screening criteria.

Parker County recharge sites are scattered along the Brazos River in the southwestern portion of the county, along Rock Creek in the northwestern portion of the county, and along Willow Creek and the Clear Fork of the Trinity River in the central and north-central portions of the county. Many of the potential banking sites identified in Parker County are well situated because they are near and upstream of population centers; however, the availability of good-quality recharge water limits the usefulness of some of these sites.

WAM model data indicate that up to 8,500 acre-feet per year (ac-ft/yr) of available water may be available on Rock Creek in the vicinity of the town of Mineral Wells. The WAM model data show excess flows of more than 400,000 ac-ft/yr along the Brazos River in the southwestern portion of Parker County. Site-specific recharge analysis using a Brazos River hydrograph in the southwestern portion of the county indicated large volumes of potential infiltration over a 10-year period (Table ES-2).

Sites along Willow Creek could be potentially viable recharge sites for meeting the future needs of Weatherford, Texas. Willow Creek WAM data indicate excess flows of about 1,800 ac-ft/yr. Recharge sites along the Clear Fork of the Trinity River are likely unsuitable for banking due to the amount and water quality of flows in the Clear Fork of the Trinity River above Lake Weatherford.

Region F

The primary need for future water development in Region F will be near the population centers of Midland, Odessa, Pecos, and San Angelo in Midland, Ector, Reeves, and Tom Green Counties, respectively. Potentially suitable locations exist in three of these counties as well as in some of the rural agricultural counties in the region.

Based on our site-specific screening, significant areas in Midland and Tom Green counties may be suitable for groundwater banking, but available source water is very small (based on the WAM model data in Midland, Ector, and Tom Green Counties, less than 100 ac-ft/yr on average). Kimble County has several potential locations along the Llano River and its tributaries. WAM model data from the Llano River show excess surface water of more than 46,000 ac-ft/yr on the river and more than 1,000 ac-ft/yr on some of the river's smaller tributaries.

Reeves County was the only selected county in the region with both high resolution soil data available and U.S. Geological Survey stream gauge locations from which surface water flow can be analyzed. Our site-specific analysis identified only a few small potential recharge areas throughout the central and southeastern portions of the county. As illustrated by the Barilla

Draw gauge, water available for banking along most of the streams in this area would come from short-duration, infrequent storm events, which may be difficult to capture for banking.

There could be opportunities for efficient banking of water from springs in the region, particularly following wet periods when spring flows are higher than normal. This water would be ideal for banking because it is potentially available over extended time periods and, unlike tributary storm flows, would not be laden with suspended sediment. However, volumes of water available for banking from springs are likely to be small, as indicated by analysis of the San Solomon Springs gauge data (Table ES-2). Additional suitable locations may exist in this region along the northern side of the Pecos River that were not identified because only low-resolution STATSGO data are available for Loving and Ward Counties.

Ogallala Region

The primary use of water in counties that overlie the Ogallala Aquifer is for irrigated agriculture. Most of the region that overlies the Ogallala Aquifer drains internally to thousands of playas, each of which has its own drainage area. Therefore, any large-scale recharge program should incorporate some type of playa modification or enhancement within or adjacent to irrigated areas, the benefits of which could be significant.

The site-specific screening analysis indicates that potentially suitable recharge sites are present along several of the draws that cross the High Plains. However, these draws flow only during large storm events, and the volume of water that can be practically captured for banking is small compared to demand in the region. In addition, previous studies have indicated that a significant portion of storm flows along the draws infiltrates and recharges the Ogallala Aquifer naturally. Therefore, groundwater banking of water from stream courses on the High Plains that overlie the Ogallala Aquifer is probably not an efficient approach to take in general, although there could be local applications, such as municipal use.

Far West Texas Region

El Paso County, which was the only county selected for site-specific analysis in the Far West Texas Region, is the most populous in the region. The TCEQ has not yet completed the water availability study for the Rio Grande Basin, so WAM results were not available for review as part of this study. Although the Rio Grande is a first-order stream, probably very little if any water is currently available that is not already appropriated. Irrigation structures in the Rio Grande Valley, from the New Mexico-Texas state line to El Paso and from El Paso into Hudspeth County, could potentially serve as conveyance for groundwater banking projects.

Site-specific analysis indicates that a substantial area, primarily within and immediately adjacent to the Rio Grande Valley, is potentially suitable for groundwater banking if water is made available. Example infiltration calculations for a Rio Grande hydrograph record several miles upstream of El Paso are provided in Table ES-2.

Because of the 3-mile distance from surface water used as a criterion in the site-specific analysis, the only sites identified in El Paso County were along the Rio Grande. However, very permeable soil exists throughout the Far West Texas Region, and various methods for moving water longer distances should be explored before totally excluding an area for groundwater banking.

Recommendations and Additional Research

The methods applied and the associated results documented in this report highlight (1) the effects of the various types of screening criteria applied to determine suitable regions for groundwater banking and (2) the utility of the GIS tool for conducting alternative queries and screens of the data. Clearly, users from different geographic areas will have different priorities regarding screening criteria. The methodology presented in this report is useful not only for the screening results documented herein, but also for its flexibility in allowing other users to manipulate the screens according to their own needs. Thus the report can be used as a template for identifying suitable sites for groundwater banking and a guide in determining some of the key factors that should be considered.

Prior to implementation of an actual recharge basin or series of basins, a formal feasibility study should be conducted that addresses, at a minimum, the following factors:

- Evaluation of site-specific stream hydrographs (observed or synthetic) to determine water availability, including the frequency and duration of peak (storm) flows

- Evaluation of the amount of prior appropriations on a given stream course and other water requirements, such as requirements for in-stream flows and freshwater inflows to bays and estuaries

- Detailed characterization of site-specific permeability of near-surface soils and deeper geologic units

- Evaluation of topographic slope and potential pathways for conveying surface water to the recharge basin (for off-channel facilities)

- Evaluation of sediment load and surface water quality as a function of stream discharge

Consideration of the above factors was outside the scope of work for this project. Acquisition of such data would facilitate better recharge facility design and better predictions of long-term facility performance. However, lack of such data should not unduly impede pilot projects. Stream gauges can provide data useful for evaluation of available water at particular stream locations and for scaling up pilot projects. Periodic sampling under changing flow conditions can provide useful background information on water quality.

High-resolution soil data such as the SSURGO soil database will be required, at a minimum, to analyze the rate of infiltration. However, soil survey data pertain only to near-surface soils, and more in-depth data from soil borings would be necessary for a site feasibility study. If more in-depth soil analysis determines that near-surface permeability adequate for recharge is available at depths slightly deeper than those analyzed in the SSURGO data, excavation of the top layer of soil is an option.

The environmental effects of recharge basin development must also be considered. The Texas Parks and Wildlife's Biological and Conservation Database provides tracking information on federally listed endangered and threatened species and most plants and vertebrate animals considered rare in Texas, as well as many non-rare biological features and plant communities.

Finally, those involved in water planning should keep an open mind and attempt to be as creative as possible in formulating solutions to existing or pending supply problems. Each region or county is unique in terms of its water availability, and workable solutions will likely be highly customized to individual regions. With creative approaches to managing each region's particular resources, groundwater banking can play an important role in comprehensive water plans developed in many regions of Texas over the coming years.

1. Introduction

The population in Texas is expected to double in the next 50 years, increasing from approximately 21 million in 2000 to approximately 40 million by 2050. During this same period, water demand is projected to increase by 18 percent, from nearly 17 to 20 million acre-feet (ac-ft) (TWDB, 2002a). Texas' water supplies are also diminishing as a result of droughts, historical and ongoing overdrafts of aquifers in excess of natural recharge rates, pollution of available supplies, and limitations on use that result from environmental regulation such as total maximum daily load requirements and requirements of the Endangered Species Act. Despite increasing demand and dwindling supply, only eight surface water reservoirs with conservation storage greater than 5,000 ac-ft are expected to be built in the next 50 years (TWDB, 2002a). Consequently, alternative approaches will be required to meet future water demand, particularly during periods of drought.

One approach to meet the increasing water demand is to artificially recharge groundwater supplies with excess surface water. Artificial recharge of groundwater, or "groundwater banking," is becoming more common in the U.S., particularly in semiarid states such as California and Arizona, as a means to manage water resources and meet water demands during periods of extended droughts. The storage volume available in aquifers is generally much greater than that available in surface reservoirs, with the depth of storage zones ranging from around 200 to 3,000 feet below ground surface (ft bgs).

This report documents a study performed by Daniel B. Stephens & Associates, Inc. (DBS&A) and the Bureau of Economic Geology (BEG) on behalf of the Texas Water Development Board (TWDB). The purpose of this study is discussed in more detail in Section 1.3, following brief descriptions of the types of artificial recharge and historical and current use of these systems in Texas.

1.1 Types of Artificial Recharge Systems

Artificial recharge has been described by various researchers (Asano, 1985; Johnson and Pyne, 1994; Pettyjohn, 1981; Pyne, 1995) and addressed in a number of international recharge symposia held in California (1988), Florida (1994), Amsterdam (1998) (Peters, 1998), and Adelaide (2002). Bouwer (2002) provides a comprehensive overview of many aspects of artificial recharge and defines artificial recharge systems as engineered systems that recharge excess surface water either on the ground surface, in the unsaturated zone, or directly into an aquifer. The primary objective of an artificial recharge system is to store water during times of water surplus and provide water during times of water shortage (droughts). Traditionally, this objective has been met through the impoundment of water by surface water dams. However, several disadvantages are associated with the use of dams including high evaporation losses, sedimentation, and adverse ecological impacts. In contrast, artificial recharge results in little or no evaporation and sedimentation, leads to increased storage volumes, and incurs negligible ecological impacts.

Sources of water for artificial recharge include streams, aqueducts, and treatment plants for drinking water and sewage (Bouwer, 2002). Water can be recharged (1) at the ground surface through either in-channel or off-channel (spreading basins) systems, (2) in the unsaturated zone through trenches or dry wells, or (3) directly into groundwater through wells.

1.1.1 Artificial Recharge at the Ground Surface

Recharge through infiltration at the ground surface can be achieved through in-channel systems such as inflatable dams, T-shaped dykes, levees, gated structures, and basins. These structures impound channelized water and allow it to spread over a larger area of the streambed or floodplain to increase infiltration. Typically, in-channel systems have fewer permitting and land acquisition issues and higher infiltration rates than do off-channel systems. One of the disadvantages of in-channel systems, however, is their inherent susceptibility to damage from seasonal flows. In-channel techniques are used in Arizona to recharge water from the Central Arizona Project, which conveys Colorado River water to the Phoenix and Tucson areas in Arizona.

Surface infiltration using off-channel techniques includes specially constructed spreading or infiltration basins. Some spreading basins are constructed of earthen berms; in other situations old gravel pits are used for surface infiltration. Requirements for off-channel surface infiltration systems include:

- An unconfined aquifer (that is, an aquifer under water table conditions) beneath the infiltration location
- Sufficient aquifer transmissivity to minimize development of groundwater mounds
- Sufficient permeability in the unsaturated zone to transmit water to the aquifer (in this report the terms permeability and hydraulic conductivity are used interchangeably)

Spreading basins have been used to recharge Central Arizona Project water in Pima County, Arizona for supplying water to the City of Tucson (Meyer et al., 1999). Spreading basins are also widely used in California; a commonly cited example is the Montebello Forebay Project in Los Angeles, which has operated since 1962.

The surface area of a spreading basin can range from several acres to tens of acres, and the depth to groundwater beneath a basin can be up to several hundred ft bgs. Ponding depth in spreading basins is generally less than 3 to 5 feet; however, gravel pits and quarries may pond water to greater depths. In some cases, surficial soil layers with low permeability are removed to increase infiltration rates, provided these layers are not too deep.

Infiltration rates in spreading basins generally decrease over time, as the basin becomes clogged with suspended sediment from diverted surface water and from algal growth. Typically, basin infiltration rates decline from initial rates of several feet per day to several inches per day after many weeks or months of recharge operations. One management strategy to minimize clogging is to periodically dry out the spreading basin and disk the surface to restore infiltration rates. Because suspended sediment loads in surface waters increase with increased discharge, sedimentation problems can also be alleviated by diverting river water only after sediment loads have decreased below a site-specific criterion. However, this may mean that diversions are delayed for days or weeks, which affects the technical and economic viability of the spreading basin. Less commonly, water is treated with a flocculate-forming chemical to reduce suspended load content in the water before it reaches the spreading basin. Finally, gravel pits or other facilities can be used to reduce the suspended sediment load from river water by allowing it to settle out before the water is routed to a spreading basin.

The source of water for artificial recharge in spreading basins is an important consideration. The availability of surface water for artificial recharge is typically lowest in semiarid and arid regions, where artificial recharge is most needed. To deal with this supply problem, states such as Arizona and California have large conveyance structures that pipe water from higher precipitation regions within the state or from large reservoirs to more arid settings, thus allowing infiltration systems to be operated over time at optimal infiltration rates. Such infrastructure is generally lacking in Texas; therefore, excess surface water in the eastern portion of the state cannot readily be recharged in semiarid and arid regions in the western half of the state.

1.1.2 Artificial Recharge in the Unsaturated Zone

If low-permeability materials extend to significant depths or there is limited space available for recharge structures, trenches or boreholes (dry wells) can be developed in the unsaturated zone for artificial recharge. Typically, recharge trenches are approximately 3 feet wide and up to 15 feet deep and are backfilled with sand or fine gravel (Bouwer, 2002). A perforated pipe is generally used to supply water and the system is covered with topsoil. Dry wells are generally about 3 feet in diameter, up to 200 feet deep, and backfilled with coarse sand or fine gravel (Bouwer, 2002). Dry wells generally have a limited lifespan because they clog up as a result of suspended sediments and/or biofilms, and because they are located in the unsaturated zone, these wells cannot be cleaned or redeveloped like traditional water wells.

1.1.3 Artificial Recharge in the Saturated Zone

Artificial recharge using water wells, known as aquifer storage and recovery (ASR), is currently used at approximately 50 sites in the U.S. This approach is described in Pyne (1995, 2002), which was used as a basis for the following overview.

The advantages of ASR relative to surface and unsaturated zone infiltration techniques include:

- Independence of the permeability of the materials in the unsaturated zone
- Low land requirements
- Ability to be conducted in unconfined and confined aquifers

Water quality in aquifers used for storage ranges from fresh to brackish (total dissolved solids [TDS] less than or equal to 5,000 milligrams per liter [mg/L]). Sites used for ASR generally have one or more groundwater constituents that preclude direct potable use without treatment (e.g., iron, manganese, fluoride, hydrogen sulfide, chloride, or radium). Water injected into an ASR well displaces existing water in the aquifer and creates a reservoir of injected water adjacent to the well that can have a storage volume ranging form 13 million gallons in individual wells to 2.5 billion gallons in large well fields. Water is generally treated prior to injection and may be stored in the subsurface seasonally or over a period of years. Water is recovered from the same well that was used to inject it.

1.2 Historical Use of Artificial Recharge in Texas

Artificial recharge has been of interest in various parts of Texas for many decades. Areas where studies or projects have been performed include the following:

- High Plains area (recharge to the Ogallala Aquifer)
- El Paso area (recharge to the Hueco-Mesilla Bolson)
- Central Texas (recharge to the Edwards Aquifer)

1.2.1 Use of Spreading Basins in Texas

Studies have been conducted to evaluate the use of spreading basins to provide recharge to the Ogallala Aquifer and to recharge treated wastewater in the El Paso area.

1.2.1.1 Recharge to the Ogallala Aquifer

The potential for using water ponding in playas to enhance recharge to the Ogallala Aquifer has been considered since it became clear that more groundwater was being removed from this aquifer than was being returned through natural recharge. Numerous field experiments, dating from at least 1955, have been undertaken to test the feasibility of artificial recharge of the Ogallala Aquifer. The most popular methods of artificial recharge to the Ogallala Aquifer have been spreading basins.

The most common problem encountered with the use of playa water in spreading basins to recharge the Ogallala Aquifer has been clogging of the recharge basins by sediments suspended in the water. Dvoracek and Peterson (1971) achieved recharge rates of as much as 1.5 feet per day (ft/d) from pits located on the outer perimeter of a playa near Lubbock. However, continued infiltration of water with high sediment content reduced this rate to only 0.1 ft/d. Consequently, Dvoracek and Peterson (1971) concluded that "some clarification of water is required for economical and efficient artificial recharge." Aronovici et al. (1972) conducted several tests on recharge basins excavated beneath Pullman clay soils (to a depth of approximately 4 ft bgs) adjacent to a playa near Amarillo, Texas. Flooding depths in these basins ranged from 1 to 1.5 feet, and the total percolation for two separate basins ranged from 147 feet over 65 days (where turbid water was used) to 196 feet over 46 days (where clear water was used). Eventually, however, percolation rates decreased to a minimum of 1 ft/d in the basin filled with turbid water because of surface sealing, while percolation rates in the basin filled with clear water increased to a maximum of 7 ft/d.

A 1-acre prototype basin (660 by 66 feet) studied by Schneider and Jones (1988) had an average recharge rate of 0.37 ft/d between 1971 and 1978. Various basin management techniques were investigated at this site, including scraping the surface and using organic mats. Corrugations up and down the slopes combined with a drain allowed the basin to recharge over the seven-year period without any other type of invasive management. In contrast, another study documented a recharge basin in a playa where recharge rates decreased to 0.125 ft/d because of low-permeability sediments (Signor and Hauser, 1968). The results from these studies indicate that recharge beneath low-permeability sediments adjacent to playas may provide a valuable water management strategy in the High Plains; however, proper management of these basins is critical for optimal recharge efficiency.

1.2.1.2 Artificial Recharge in El Paso Area

The use of spreading basins is also being investigated in El Paso, Texas. A research project conducted by DBS&A and Boyle Engineering Corporation for the City of El Paso, the American Water Works Association Research Foundation, and the U.S. Bureau of Reclamation (Hahn et al., 2002) aims to evaluate the use of recharging treated wastewater currently being piped from the Fred Hervey Wastewater Treatment Plant to a nearby power station. The 0.5-acre recharge basin (150 by 150 feet) was excavated below a surface caliche layer to increase infiltration. Water is pumped into the basin at rates between 0 and 1,500 gallons per day (gpd). Recharge rates have averaged about 8 ft/d since the basin was put into operation in July 2001.

1.2.2 Use of In-Channel Infiltration Techniques in Texas

Artificial recharge to the Edwards Aquifer has been accomplished through the use of four concrete in-channel dams in Parkers, Seco, Verdy, and San Geronimo Creeks. These in-channel dams have been operational since the 1960s and 1970s (Johnson et al., 2002). The Edwards Aquifer Authority has developed rules to give recharge credit to individuals installing retention structures.

1.2.3 Use of Aquifer Storage and Recovery in Texas

There are two operational ASR systems in Texas, one near El Paso and the other near Kerrville. The El Paso site consists of 11 injection wells that are also used for backflushing and are therefore termed ASR wells. The Kerrville site consists of 2 ASR wells that are used to recharge water from the Guadalupe River. The Kerrville system has been operational since 1996.

ASR is one of several techniques being considered by Regional Water Planning Groups (RWPGs) for future groundwater management. Three RWPGs (Regions K, L, and N) have included ASR in their regional water plans (TWDB, 2002a). Region L has planned an ASR system for Bexar County to store water from the Edwards Aquifer in the Carrizo Wilcox Aquifer during periods when excess water is available for use during periods of peak demand (summer). Region K has planned a retention structure in Onion Creek and an ASR system in

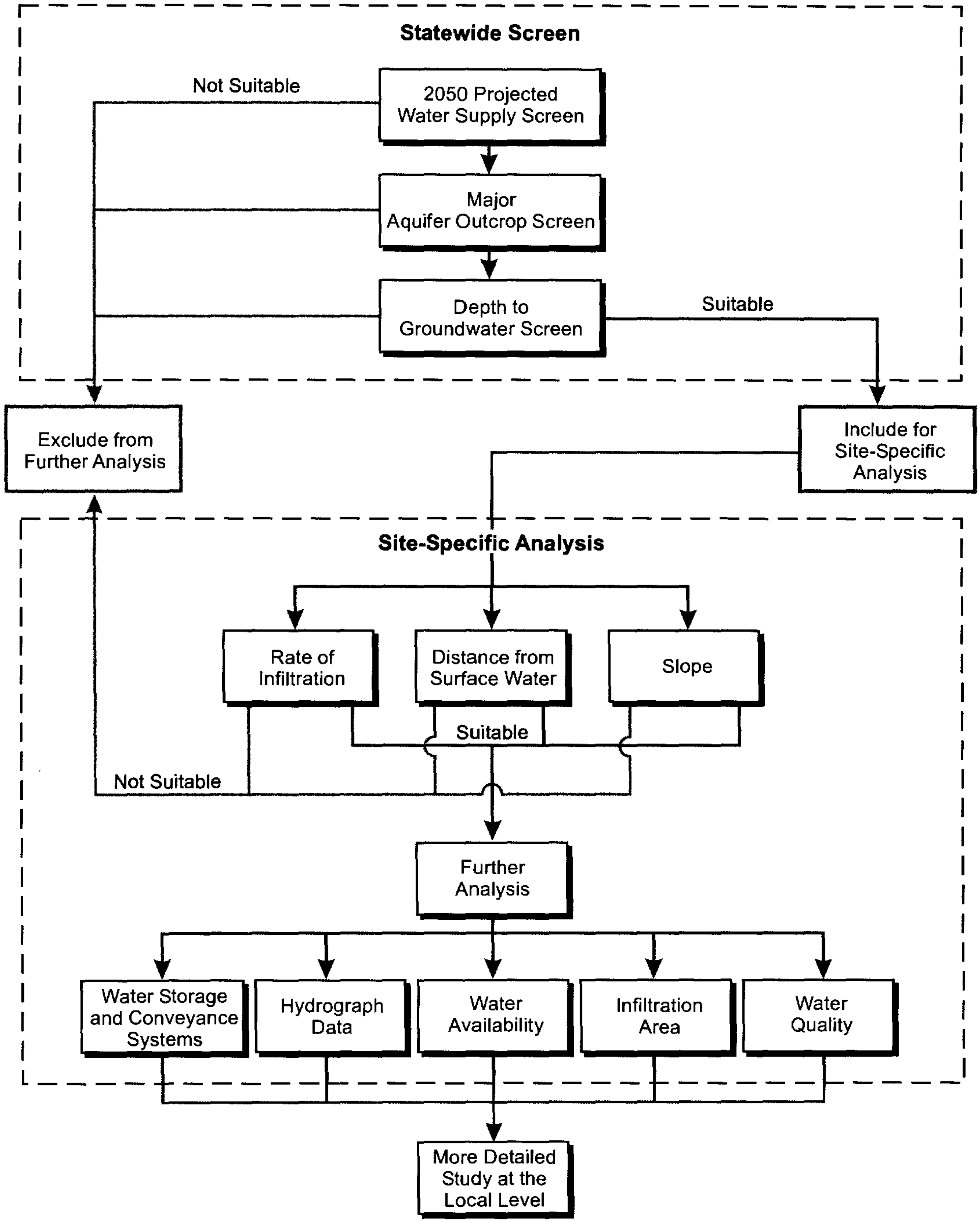
Pflugerville. Region N has also planned an ASR system to artificially recharge the Gulf Coast Aquifer.

1.3 Project Objectives and Scope of Work

The purpose of this study is to identify geographic areas suitable for artificial recharge of surface water using spreading basins. Because this study was limited to the evaluation of locations for spreading basins and did not consider areas suitable for vadose zone wells or ASR systems, only those geographic areas that overlie unconfined aquifers were considered.

As defined in the project scope of work (included in Appendix A to this report), the study was divided into two analysis tasks: Task 1, a statewide screening analysis, and Task 2, a site-specific analysis. Figure 1 is a project flow chart that shows the various steps involved in the two analysis tasks. Section 2 of this report describes the methods we used to identify promising regions for artificial recharge through statewide screening (Task 1). Section 3 presents an overview of our site-specific analysis approach applied to regions identified for further analysis as part of Task 1, with the ultimate goal of providing a method for identifying promising locations for future study. Sections 3 through 9 present the results of Task 2, including discussions of six regions that appear promising for artificial recharge based on the screening criteria used at the state and regional level (Sections 4 through 9). Conclusions and recommendations are provided in Section 10.

Appendices B and C provide supporting information related to the geographic information system (GIS) data and ArcView GIS Screening Analysis Tool. Development of the GIS tool was a significant component of this work, and as explained in Section 2.2, users can conduct their own analyses using this tool.



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Project Flow Chart

Daniel B. Stephens & Associates, Inc.

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Figure 1

2. Statewide Screening Analysis

Task 1 of this study was a screening analysis, performed at a statewide level. The overall purpose of this task was to show how a GIS can be used to identify broad regions that may be suitable for artificial recharge through the use of spreading basins. Once these regions were identified, we performed further analysis at a more site-specific level (Task 2), as described in Sections 3 through 9.

The Task 1 screening analysis was conducted using the methods and criteria described in Sections 2.2 and 2.3, following a brief introduction to GIS in Section 2.1. The screening criteria used for this Task 1 analysis, although reasonable, may or may not be appropriate for use by the TWDB or other interested users for a given situation. However, the methodology is flexible enough to accommodate different selection criteria, as users can run custom data screens using the GIS tool provided as part of this study.

2.1 Geographic Information Systems

The primary focus of any GIS is to associate information in the form of a database with geographic locations such as points, lines, or areas on a map. A GIS may include, for example, monitor well data associated with the well location, soils data for a large region, or data associated with rivers and streams. Regardless of the specific nature of the data, a GIS integrates it into a coherent package and allows cost-effective and efficient querying, analysis, and presentation.

GIS is a powerful tool for assembling large amounts of data and analyzing 'what if' scenarios. Data sets evaluated for this study included digital elevation models (DEMs); data on soils, geology, hydrology, and wetlands; census data and county population projections; RWPG water use surveys and projections; water well data; and environmental hazards. The data used for this study were obtained from various sources, including:

- Regional water plans
- Texas Natural Resources Information System (TNRIS) Texas streams GIS coverage

- Texas counties GIS shapefile
- EPA National Drinking Water Standards
- TWDB groundwater database
- U.S. Department of Agriculture (USDA) Soil Survey Geographic (SSURGO) database
- USDA State Soil Geographic (STATSGO) database
- U.S. Geological Survey (USGS) DEM data
- USGS stream gauging station and water quality database
- Water Availability Model (WAM) data, sponsored by the Texas Commission on Environmental Quality (TCEQ, formerly known as the Texas Natural Resources Conservation Commission [TNRCC])

Appendix B provides a detailed explanation of the data used for the statewide GIS analysis.

2.2 Screening Methods

The initial step in screening potential sites for spreading basins used the GIS to integrate and analyze thematic data layers that affect the potential suitability of a site for artificial recharge. Criteria were developed and applied to each thematic layer to rate the suitability of each site for artificial recharge. For example, groundwater well information in the TWDB database was integrated into the GIS, and the locations of these wells were associated with tabular groundwater quality data in a file that can be displayed on a map. Review of this information in a spatial presentation helps determine if groundwater quality should be a consideration in screening potential artificial recharge sites.

The second step in the process used Boolean (true-false) logic, which enables the organization of data into sets by examining relationships such as those implied by the logical operators "and," "or," and "not." This step (1) sieved overlying data layers within the GIS to identify best potential recharge sites and (2) evaluated the limitations of the available data and tools for identifying these areas consistently and accurately. The GIS data have been assembled in a way that will allow users to sieve the data according to their particular needs. Depending on how they intend to use the data, users can rank the importance of particular screens or screening criteria differently, perhaps even changing or eliminating a factor that we used in our analysis.

Appendix C provides an overview of the ArcView GIS Screening Analysis Tool and how it can be used to modify screening criteria for particular thematic data layers.

To allow this type of flexible use, all geographic data layers are in a consistent geo-referenced coordinate system (Appendix B). A GIS user can analyze the overlaying layers in relationship to one another and make quantitative decisions based on the results. One user may decide to include only those counties that anticipate a water deficit in 2050 and that have regions overlying unconfined areas of a major aquifer, as defined by the aquifer's outcrop area. Another user may decide to include counties directly adjacent to those with projected deficits with the idea that water transfers might be appropriate. The GIS allows these flexible applications of data and associated analyses to help answer specific questions that may arise throughout the decision-making process.

Data quality issues, particularly the scale at which data can accurately or confidently be used, are an important factor in deciding which sets of data should be used in the statewide or site-specific analyses. For example, a Boolean query on averaged low-resolution data is likely to miss promising recharge sites that the same query would find on a high-resolution data set. Some limitations of a low-resolution data survey, such as the use of low-resolution soils and DEM data, can be overcome by using high-resolution data for site-specific analysis where they are available.

2.3 Statewide Screening Criteria

This section discusses the various screening criteria used for the Task 1 statewide analysis. We felt that some of the screening criteria presented below, although originally anticipated be used for statewide screening in the scope of work, could not be reasonably applied at the statewide level. For example, data sets that were too sparse, as was the case with surface water quality data, or too restrictive, as with the 1:250,000 DEM data used to determine topographic suitability, were not used in the statewide screening, but were instead applied at the site-specific level (Sections 3 through 9). Also, the high resolution of stream coverage data used for the distance-from-surface-water screening seemed better suited to a site-specific than to statewide analysis. Depending on the circumstances, however, other users may decide to apply one or more of these data sets at the statewide screening level rather than the site-specific screening level. Consequently, we have included brief discussions for these data sets in the statewide screening criteria and noted why we did not use the criteria for our statewide analysis.

The factors originally considered in the statewide screening process to identify promising regions for spreading basins are shown below; some of these factors were later dropped from the statewide screening and used for site-specific analyses, as indicated:

- Water quality (surface and groundwater) Site-specific
- Regional water demand Statewide
- Characteristics of underlying aquifer Statewide
- Distance from surface water Site-specific
- Topography Site-specific

Explanations for each the screening criteria are provided in Sections 2.3.1 through 2.3.8. These sections address the data used and an associated statewide map that provides a visual example of the GIS data for each set of screening criteria.

2.3.1 Surface Water Quality

Both the quantity and quality of surface water are important considerations when developing an artificial recharge project. Such projects are often located where runoff of excess surface water following storm events can be captured for infiltration into the groundwater system. Consequently, it is important to know whether the quality of the surface runoff is suitable for mixing with the local groundwater. For a given watershed, the concentrations of many dissolved and/or suspended constituent chemical species can change dramatically as flow conditions change. The combined use of stream gauges, which can determine the volumetric flow rate at a particular location along a river channel, and periodic water quality sampling and analysis provides the data needed to determine water quality under specific flow conditions.

Surface water quality was initially evaluated at a statewide scale; however, although there are more than 555,000 individual surface water quality records in the database, they are geographically isolated in many instances. For example, several sample locations in west Texas are more than 100 miles from any other sample location. Because of the sparse nature of available data, we opted to apply surface water quality screening criteria at the site-specific level, as described below.

Available water quality records were analyzed in conjunction with surface water flow data. The database was examined for concentrations of both primary and secondary non-organic constituents listed in the EPA National Drinking Water Standards (Appendix B, Table B-1). Listed concentrations for primary constituents are legally enforceable standards that apply to public water systems and are intended to protect public health by limiting the levels of these contaminants in drinking water. Listed concentrations for secondary constituents are non-enforceable guidelines for contaminants that may cause cosmetic or aesthetic effects in drinking water.

Over 555,000 individual analyses, covering most of the EPA primary and secondary concentration standards, were analyzed for this report. Individual GIS database files were generated for each of the constituents. The attributes, descriptions, and units of measurement used in the water quality analyses files are provided in Appendix B. Each water quality record in the source database that was associated with a flow record was analyzed. Constituent concentrations were converted to log base 10 values, and the average concentration was calculated for all samples from a given location that were collected under similar flow conditions (within the same 20th percentile increment). All average concentration values are reported in mg/L.

This generalized approach to water quality analysis has several limitations. First, the source of the streamflow analysis data should be considered. If the streamflow and quality sampling data for a particular location are based on a limited or discontinuous record, flow and/or quality conditions at that location may not be adequately characterized. Additionally, this analysis provides only average concentration values. It does not provide information about the quantity or variability of the data within a given flow percentile interval, nor does it provide information concerning temporal trends in water quality at a given location. The highest flow rate (i.e., the 100th percentile) at a given location is frequently much larger than the flow rate for the 95th percentile, often by a factor of 10 or greater. Although these higher flows are the most likely to be diverted to an infiltration structure, they also occur infrequently and may not have been sampled adequately for water quality.

Finally, the detection limit of the method used to analyze a water sample for a given constituent may be higher than the EPA standard. This is especially likely for older samples collected prior to the development of improved analytical techniques. The source database records contain an attribute field that indicates whether the reported concentration value is a maximum value, in which case the reported value is the detection limit. If a maximum value was lower than the EPA standard value, the data were retained for this analysis. However, in cases where the detection limits were equal to or greater than the EPA standard for a given constituent, the data were not used for this analysis. Also withheld from this analysis were values reported as "not detected" because there was no indication of the actual detection limit.

Because surface water criteria were applied at the site-specific level during this analysis, no statewide map was prepared. Detailed surface water quality data are provided in Appendix B. Sections 3 through 9 provide additional discussions of how surface water quality data were applied to site-specific analyses.

2.3.2 Groundwater Quality

Groundwater quality data, which were derived from the TWDB groundwater database, can be displayed easily on a base map. This allows users to view a particular chemical constituent of concern in relation to potential recharge sites to determine if groundwater quality is an issue of concern. However, care must be taken when analyzing historical groundwater quality data. Regional data should be reviewed and any regional trends in groundwater quality should be noted.

Figure 2 shows an example statewide groundwater quality map for one constituent (sulfate) that exceeds the EPA secondary standard for drinking water. For detailed groundwater quality data information, see Appendix B.

2.3.3 High Demand Regions

This study focused on regions that anticipate a water supply deficit by the year 2050. Regions with high demand for water were determined using regional water plans, and a table was created that incorporated the various water supply and demand projections for each county in the state (Appendix B, Table B-8). Any county with a projected total demand that exceeded the projected available supply as of 2050 was considered a high-demand region. All other counties were eliminated from the analysis.

The decision to use only counties with a projected deficit is somewhat subjective. An alternative approach, for example, would be to also include counties that border high-demand counties, as these may be close enough to be potential supply areas.

Figure 3 shows Texas counties that project a water deficit in 2050. For detailed supply and demand data, see Table B-8 in Appendix B.

2.3.4 Aquifer Characteristics

As discussed in Section 1, artificial recharge using spreading basins is appropriate only in locations where an aquifer is unconfined. In addition, the aquifer underlying a spreading basin should have sufficient storage capacity to accommodate infiltrating water. During the statewide screening, we considered only those areas that (1) overlie unconfined sections of major aquifers and (2) have moderately deep water tables.

We chose to screen out areas that did not overlie the outcrop area of a major aquifer because their storage capacities and/or residence times are more likely to be small. Also, major aquifers generally serve larger populations and a greater amount of information is available for these aquifers. Only unconfined sections of aquifers were considered; any confining layers would prohibit recharge. The TWDB GIS layer of major aquifers distinguishes between confined and unconfined portions of the major aquifers in the state of Texas based on outcrop areas of the aquifers. This GIS layer was used to identify outcrop areas and eliminate areas that do not overlie the outcrop area of a major aquifer. Additional analysis could be performed using outcrop areas of minor aquifers, if desired. Figure 4 indicates regions suitable for artificial recharge based on their association with unconfined sections of major aquifers.

Regions underlain by aquifers with low available storage capacity, as indicated by shallow depths to groundwater, were also excluded from further analysis through a statewide screen. Depth to the water table is an important variable when considering the location of a spreading basin. In areas where the water table is shallow, there may be insufficient available storage capacity to accept infiltrated water. Conversely, in areas where the water table is quite deep, a significant portion of the infiltrated water may be required to satisfy the storage deficit in the unsaturated zone, and recovery pumping costs may be prohibitive. Accordingly, depth-to-water maps were created for the outcrop areas of all the major aquifers in Texas to identify areas with a minimum depth to groundwater of 40 feet (to ensure ample potential storage capacity) and a maximum depth to groundwater of 500 feet (to keep costs for pumping stored groundwater reasonable). As with any of the screens presented in this analysis, these numbers can be altered according to the specific needs of local sites. Figure 5 shows the depth-to-groundwater screen used for the analysis. For detailed depth to groundwater data, see Appendix B.

2.3.5 Distance from Surface Water

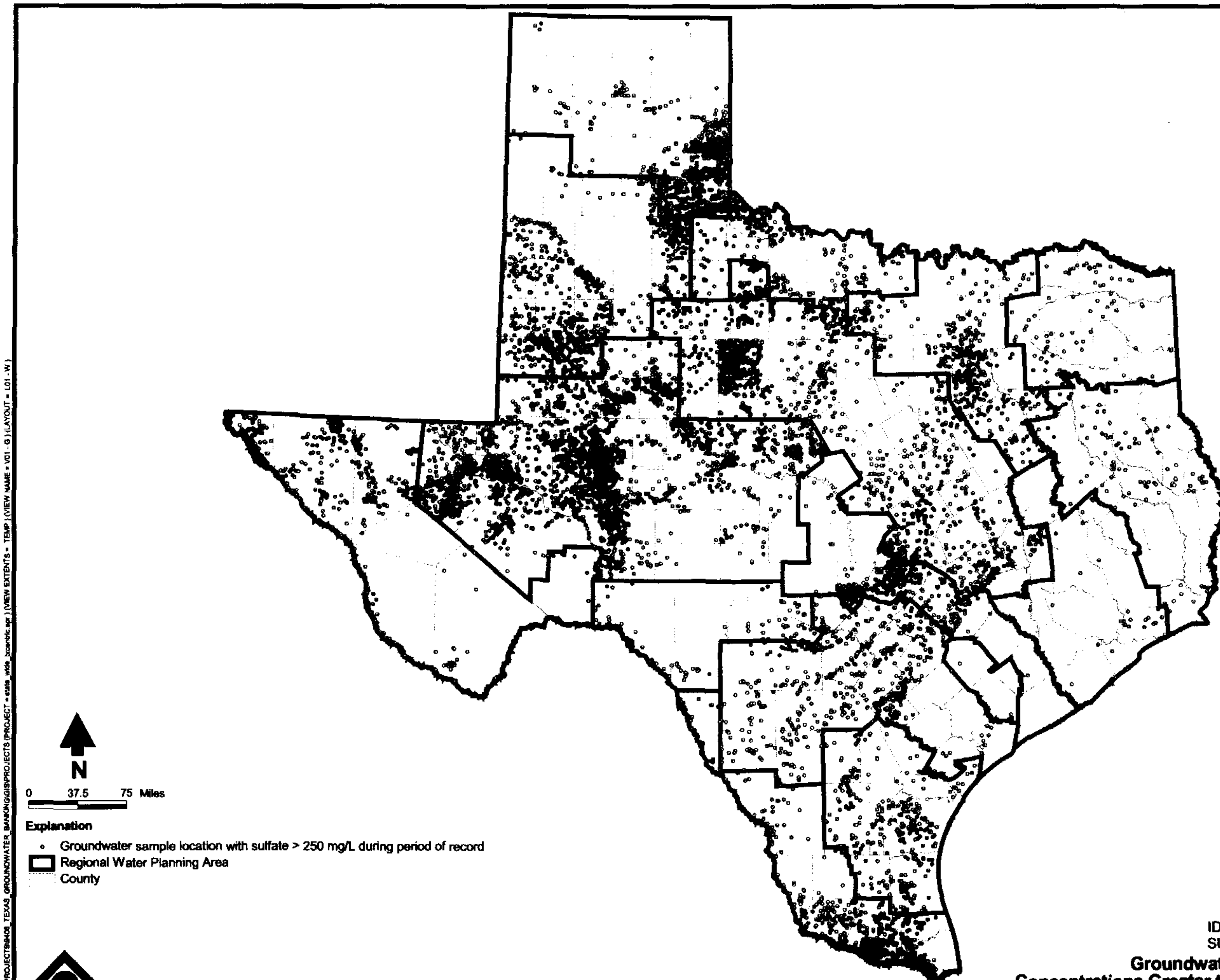
A recharge site's suitability is based, in part, on whether or not the location is practical in terms of its proximity to source water for recharge. The cost associated with moving water long distances may prohibit the use of recharge basins that are too far away from the surface water source.

Like the surface water quality screen, this screen was initially considered a statewide screening criterion. After consideration, however, we felt this type of high-resolution detailed screening is better suited for the site specific analysis, and therefore, the distance to surface water evaluation was used only as part of the site-specific analysis portion of this study (Section 3).

However, because we had already done an initial screening using a distance of 3 miles from any stream class (1 through 4) as our criteria, we have included the results of this statewide screen in Figure 6 for illustrative purposes.

2.3.6 Topography (Slope of Area)

In general, recharge basins are located on relatively flat sites to eliminate the need for major excavation. For the statewide analysis, we developed slope coverage for the entire state from 1:250,000 USGS DEM data, with the intention of excluding areas with a topographic slope greater than 5 degrees. Data from the STATSGO database, published by the USDA, also have a slope designation, but the spatial resolution for the STATSGO data is not as detailed as that of the 1:250,000 USGS DEM data. However, the 1:250,000 USGS data consist of 100-meter data cells, so when this screen was applied at a statewide scale, many acceptable basin areas were excluded. As a result, we decided to apply the slope data at the local, site-specific level and not at the statewide screening level. Figure 7 shows the results of applying the initial statewide slope screening criteria, but is included for illustrative purposes only.



IDENTIFICATION OF GEOGRAPHIC AREAS
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Groundwater Sample Locations with Sulfate Concentrations Greater than the EPA Secondary Standard

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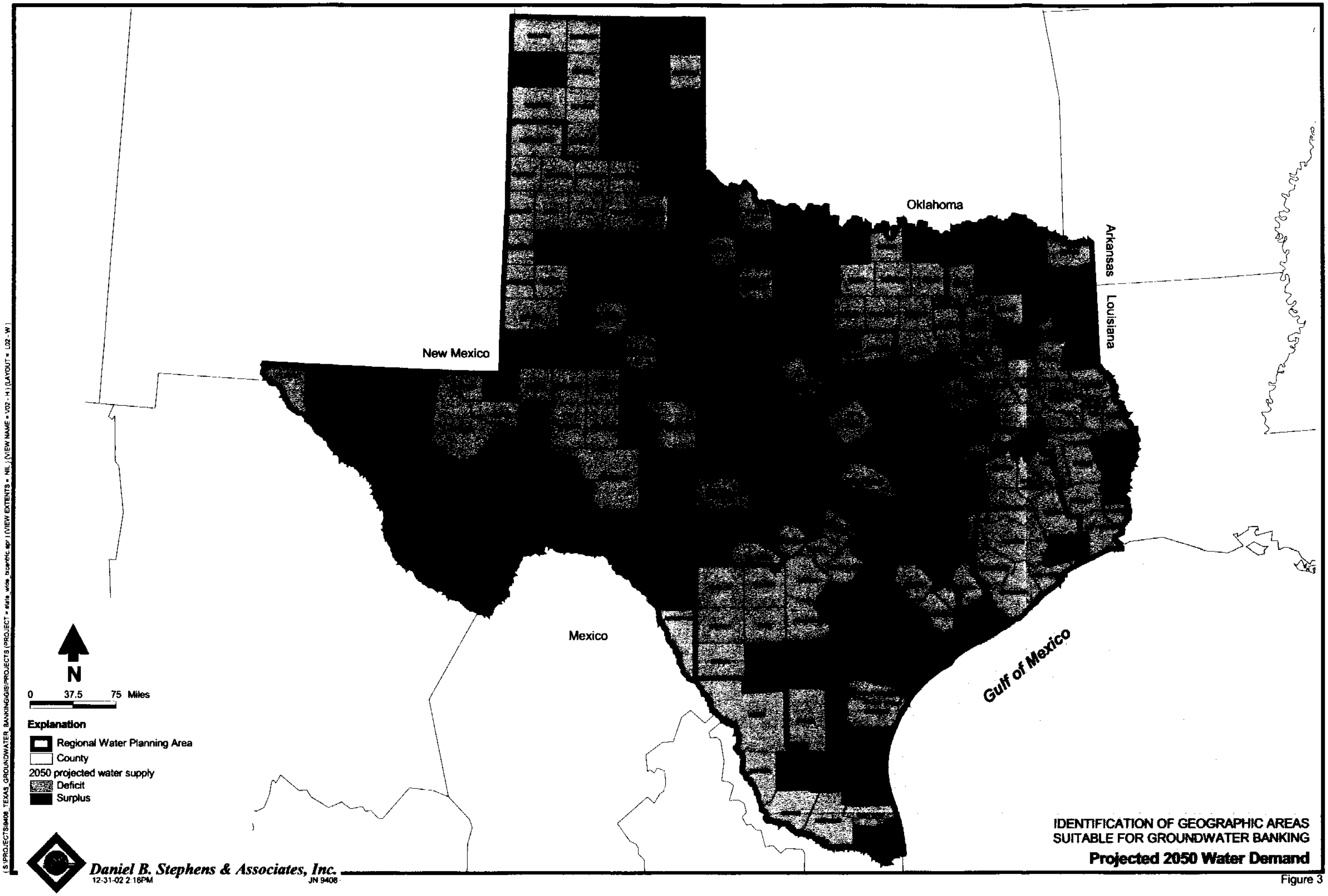
Figure 2


Oklahoma
Arkansas
Louisiana
New Mexico
Mexico
Gulf of Mexico
N
0 37.5 75 Miles
Explanation
Regional Water Planning Area
County
2050 projected water supply
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Projected 2050 Water Demand
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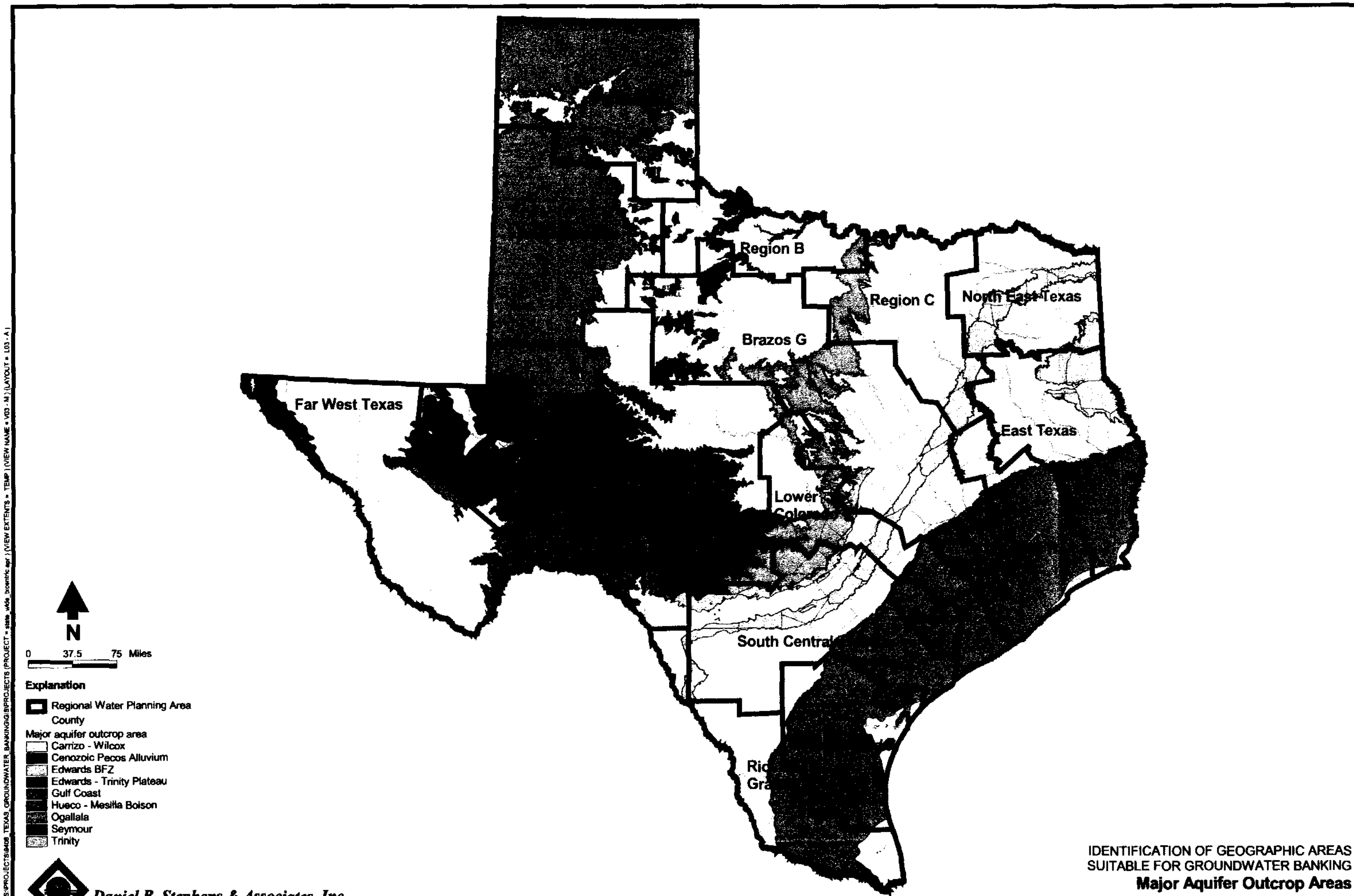
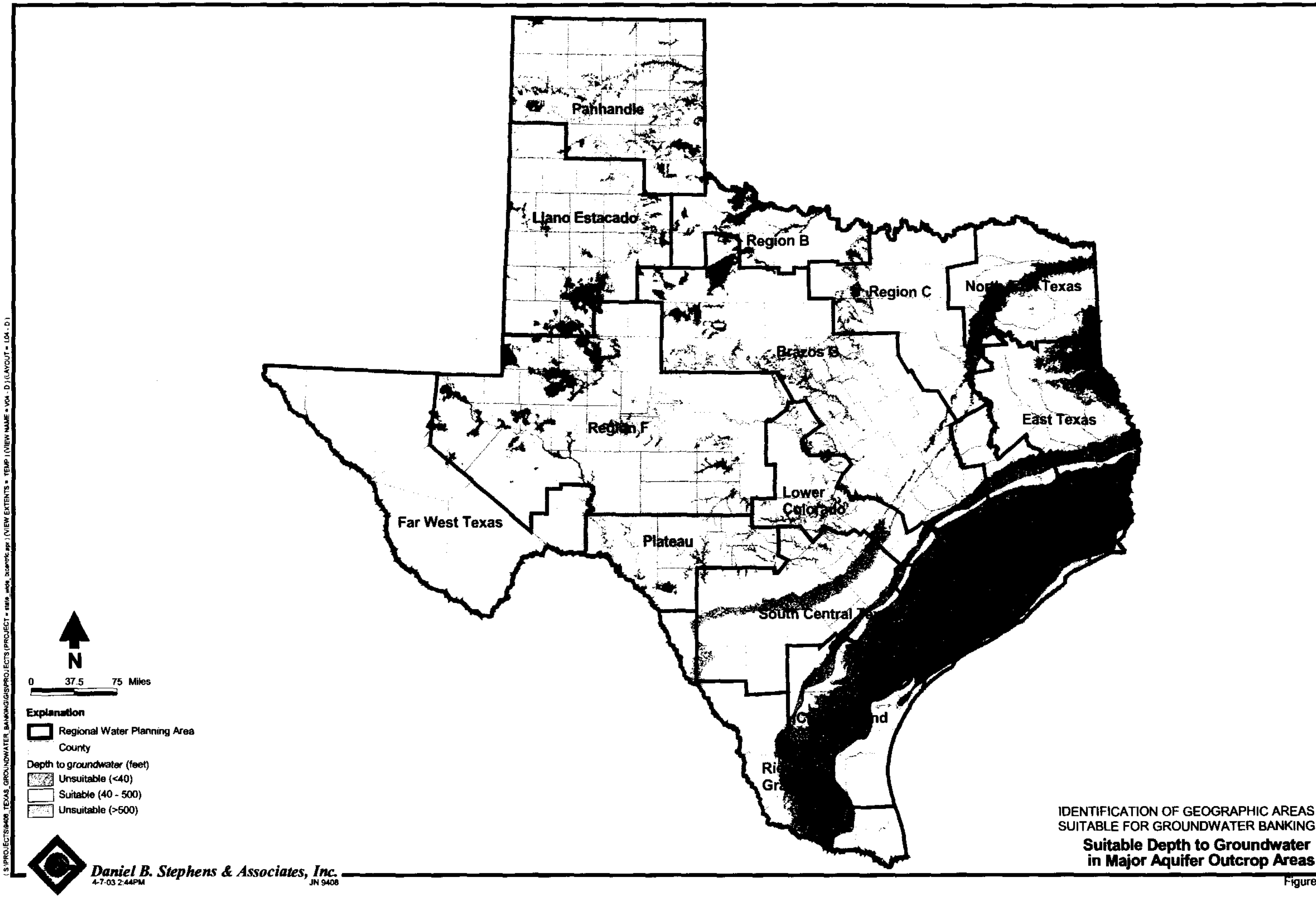
Figure 3



IDENTIFICATION OF GEOGRAPHIC AREAS
SUITABLE FOR GROUNDWATER BANKING
Major Aquifer Outcrop Areas

Figure 4



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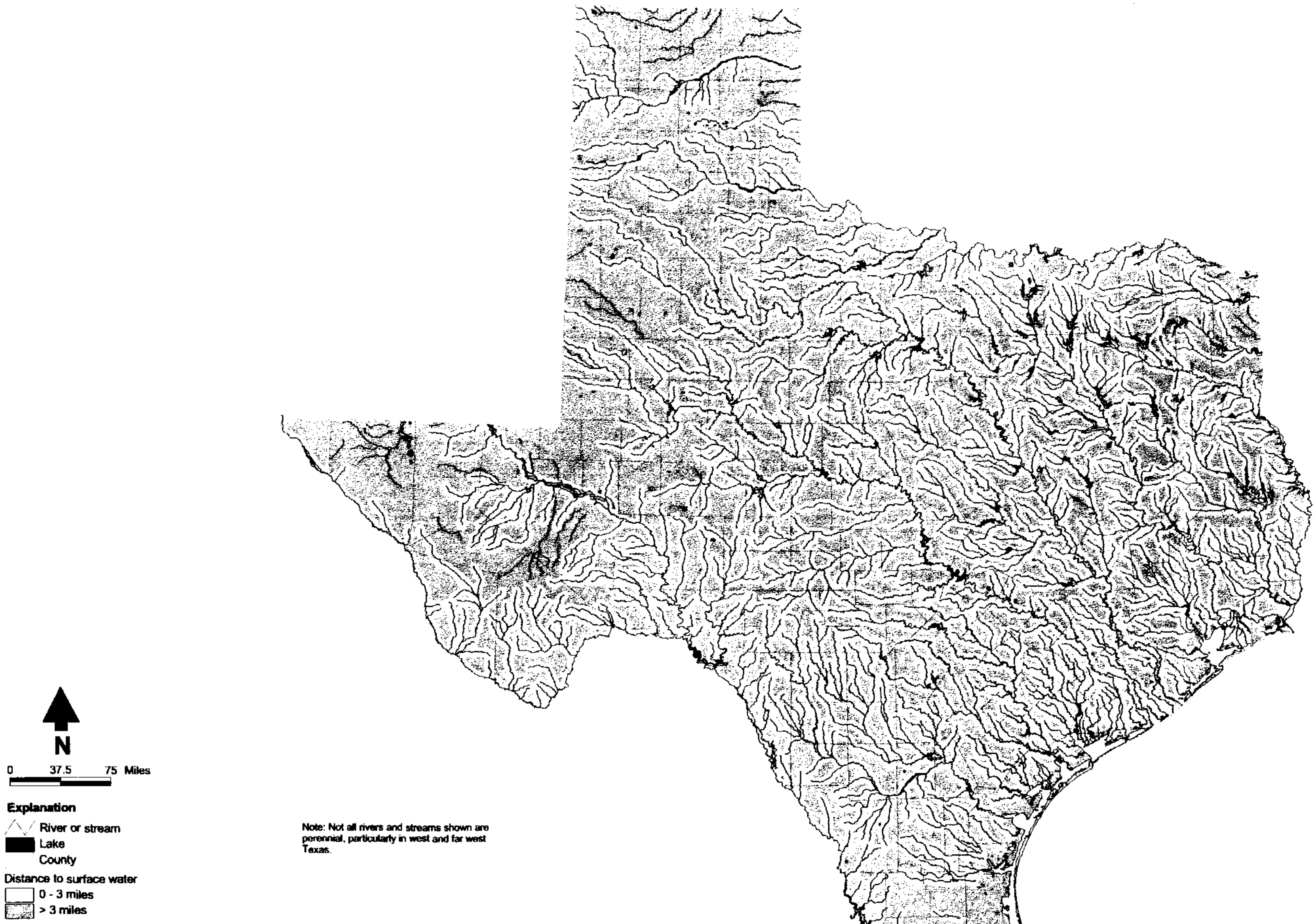
Suitable Depth to Groundwater in Major Aquifer Outcrop Areas

Figure 5



IDENTIFICATION OF GEOGRAPHIC AREAS
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Distance to Surface Water Screen

Figure 6

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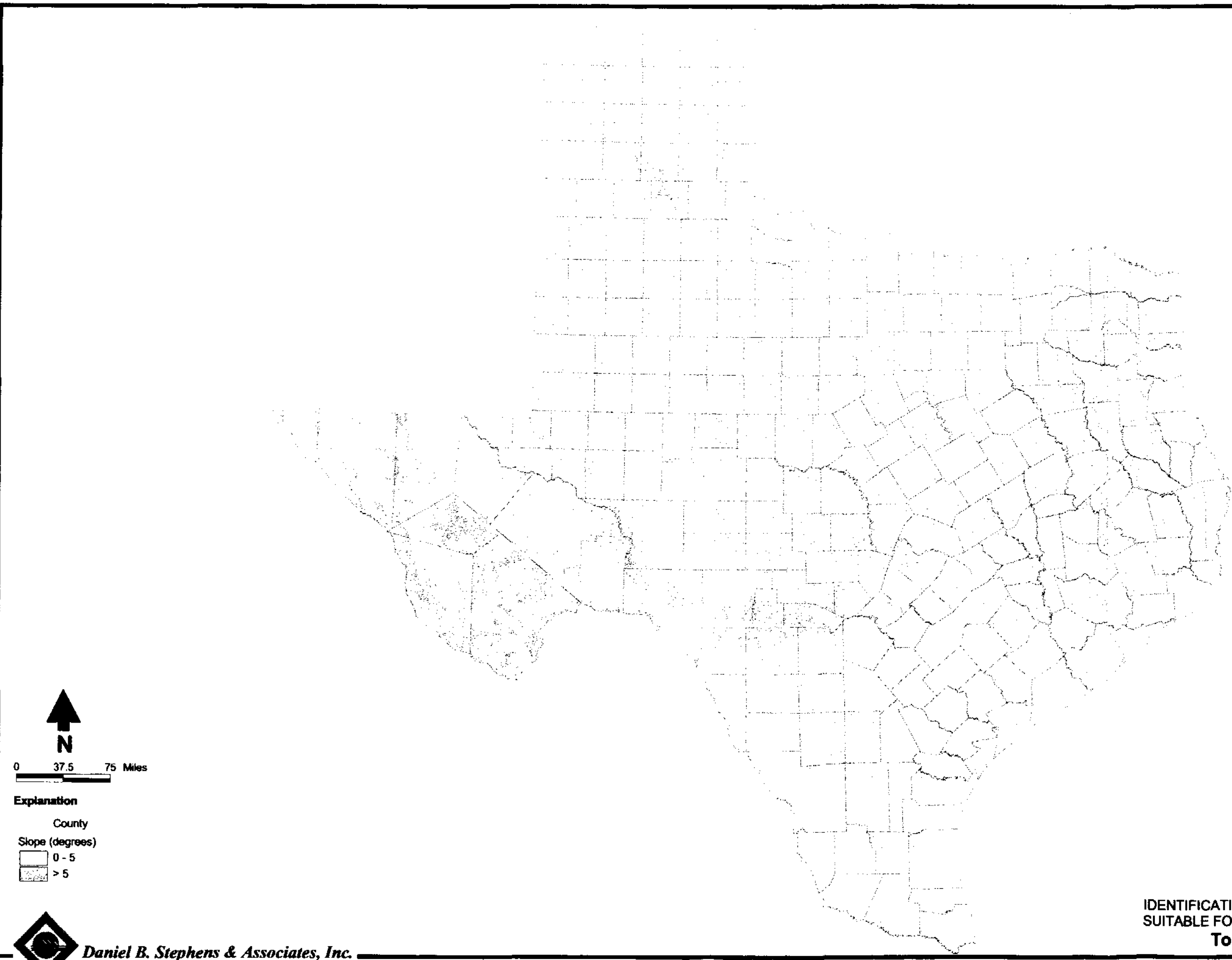

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IDENTIFICATION OF GEOGRAPHIC AREAS
SUITABLE FOR GROUNDWATER BANKING
Topographic Slope Screen

Figure 7

3. Site-Specific Analysis

Based on the statewide screening analysis described in Section 2, we concluded that 48 counties fit the criteria for preliminary site-specific evaluation of recharge basin suitability (Figure 8). Because some of our statewide screening analysis was conducted at the county level, there are likely many additional potentially suitable sites in other counties that were excluded from further analysis. Database users wishing to identify other sites can conduct an analysis similar to that described in Section 2 (statewide screening) using customized selection criteria. The ArcView GIS 3.2 Screening Analysis Tool described in Appendix C was developed to assist other users in developing their own screening criteria and subsequent analysis for site selection. The remainder of this section presents our grouping of the 48 selected counties into regions, our methodology for selection of one example county from each region for which site-specific computations were performed, and our site-specific analysis methodology.

3.1 Regional Grouping of Counties

As shown in Table 1, selected counties were grouped into six regions based primarily on their Regional Water Planning Area (RWPA), but also using factors such as associated aquifers and general proximity to other selected counties. For example, selected counties from the Panhandle and Llano Estacado RWPAs were combined into a single region designated as the Ogallala, because these counties overlie a single major aquifer (the Ogallala).

The six selected regions were evaluated for suitability for groundwater banking using recharge or spreading basins. For each of the regions shown in Table 1, an analysis was performed that included:

- Overview of water resources
- Identification of water storage and conveyance systems
- Discussion of infiltration rate, area, and time period for infiltration
- Surface water quality

The methods and criteria used for these analyses are presented in this section; results of the analyses for each region are presented in Sections 4 through 9.

Table 1. Counties Selected for Site-Specific Analysis Grouped by Region

Site-Specific Region	Counties	
South Central	Atascosa Bandera Bexar Comal Dimmit Guadalupe	Hays Kendall Maverick Medina Uvalde Zavala
Brazos G	Comanche Coryell	Williamson
Region C	Parker	Wise
Region F	Crockett Ector Glasscock Kimble Loving Midland	Reagan Reeves Tom Green Upton Ward
Ogallala	Bailey Briscoe Castro Cochran Dallam Deaf Smith Floyd Gaines Hale Lamb	Moore Oldham Parmer Potter Randall Sherman Swisher Terry Yoakum
West Texas	El Paso	

Sections 4 through 9 include detailed site-specific screening results for an example county from each region. The example counties were chosen on the basis of data availability. The USDA STATSGO database has a much coarser spatial resolution than does the SSURGO database (Section 3.2.1). Consequently, we used only those counties with SSURGO data available as example counties (Figure 9). Also, surface water flow data are extremely sparse and many counties have no USGS gauging stations. Therefore, in addition to selecting counties that had the higher-resolution SSURGO soil data, we attempted to select counties that had at least one surface water gauging station reasonably near potential recharge sites so that example infiltration calculations could be made.

Each regional discussion is accompanied by a table that shows the availability of SSURGO soil data for each county, projected water deficits (supply minus demand) by county for 2000 through 2050, and the total number of acres identified as suitable for recharge within each county. Where applicable, a second table provides information about major reservoirs in the region. In addition, figures are provided that show, at the regional level:

- Potential recharge sites based on soil permeability, topographic slope, and distance from streams
- Surface water quality data
- Reservoirs and conveyance infrastructure
- Surface water availability as determined from TCEQ Surface Water Availability Models, which are based on precipitation and streamflow patterns

A county map showing potential recharge sites for the example county is also provided. This map has the same information about potential recharge as the regional map, but includes stream gauge locations and has a higher resolution. Finally, the results of sample infiltration calculations for a hypothetical basin are provided using one or more example hydrographs from within the example county.

3.2 Site-Specific Analysis Methodology

The economic feasibility of recharge basins improves with surface water availability, with basin recharge rates, and with proximity to the point of use of the banked water. Accordingly, each of the 48 selected counties was screened for:

- Areas with surficial soil permeability greater than or equal to 2 inches per hour

- Topographic slopes of less than 5 degrees
- Areas within 3 miles of a stream

Table 2 summarizes water deficits and potential high-permeability soils close to various-order streams within each of the six example counties. The acreage of good soils close to various stream-order water sources varies dramatically both within and among counties. County-specific observations are discussed in Sections 4 through 9.

Table 2. Water Deficit and Potential High-Permeability Soils

County	2050 Water Deficit Projection (ac-ft/yr)	High-Permeability Soils (acres)		
		Stream Order 1	Stream Order 2	Stream Order 3
Uvalde	32,332	16,525	38,792	46,269
Randall	72,661	1,198	1,312	3,024
El Paso	412,237	17,580	27,078	0
Reeves	35,134	0	7,560	0
Coryell	7,732	0	0	80
Parker	33,874	5,244	5,932	2,763

ac-ft/yr = Acre-feet per year

Individual county maps show the results of the site-specific screens for six example counties (one in each region). While ideal locations would have slopes less than 5 degrees and be less than 3 miles from the surface water source, the county figures from this screen will likely provide the information needed for subsequent field reconnaissance and testing. Sections 3.2.1 through 3.2.5 summarize the factors used to determine the suitability of site-specific areas for banking. Section 3.3 provides sample infiltration calculations to illustrate our technical approach and provides an overview of the TCEQ WAMs. The results of each site-specific analysis are discussed in Sections 4 through 9.

3.2.1 Rate of Infiltration

The volume of water that can be recharged through a spreading basin is equal to the rate of infiltration times the area of the basin times the period of time over which infiltration occurs. Each of these factors can be locally limiting.

The rate of infiltration is controlled primarily by the hydraulic conductivity (permeability) of surface and near-surface materials. For this study, soil maps were used to identify the possible presence of near-surface soil layers that might impede infiltration beneath an impoundment structure. Soil permeability data were derived from two on-line databases published by the USDA. The SSURGO database provides the most detailed level of information and was designed for county-scale natural resource and management planning. The STATSGO database was designed primarily for use at the regional (multi-county to state) scale and generally does not provide enough detail for application at smaller scales. SSURGO data are currently available for 152 of the 254 Texas counties, while STATSGO data are available for the entire state.

The primary difference between the SSURGO and STATSGO databases is in the number of soil components represented by a single map unit. The STATSGO soil maps are compiled by generalizing more detailed soil survey maps into map unit components; their percentage composition represents the estimated areal proportion of each component within a STATSGO map unit (White, 1999). The SSURGO data for 26 counties were analyzed for this study. Approximately 79 percent of the SSURGO map units contain only 1 component and none contain more than 3 components. In contrast, for the entire state of Texas, the STATSGO map units contain as many as 21 components, with the middle 50 percent containing from 6 to 12 components. Thus, with regard to analysis at the county scale, most of the SSURGO map units provide sufficient detail with regard to individual soil component locations, while most of the STATSGO map units do not.

Because of the differences in resolution between the two data sources, map results based on soil permeability may show apparent boundaries along county lines where the more detailed SSURGO data join with the less detailed STATSGO data. Prior to detailed application of either the SSURGO or STATSGO data, users should be aware of the methods used to compile these data and the inherent limitations of these databases, as described in their respective user manuals.

Where available, SSURGO data were used instead of the STATSGO data. For this particular screen, a soil hydraulic conductivity of 2 inches per hour or greater was determined to be necessary for a suitable recharge site. This value is equivalent to 4 ft/d, which would permit 4 feet of water (a reasonable depth of water to assume for a spreading basin) to infiltrate into the subsurface over the course of one day. This threshold value can, of course, be adjusted for detailed site evaluation as deemed appropriate based on other design criteria, such as water availability.

A very important point to keep in mind regarding basin hydraulic conductivity is that it can (and most likely will) change with time, primarily due to clogging of the soil pore space by finer-grained sediments transported into the basin with the recharge water. For this reason, basins generally need to be maintained to preserve maximum infiltration capacity.

3.2.2 Slope of Area

As discussed in Section 2.3.6, a recharge basin generally needs to be located on a relatively flat area to eliminate the need for major excavation. A slope of 5 degrees or less was determined to be acceptable for this level of analysis. Topographic slopes were derived from the USGS 1:250,000 DEM (Appendix B).

3.2.3 Distance from Surface Water

Another important consideration regarding a site's suitability for basin recharge is distance from the surface water source. Higher costs associated with moving water long distances reduce the economic benefits of recharge basins located far from their source of recharge water. Accordingly, we used a maximum distance of 3 miles from a stream as the cut-off value for selecting suitable sites at the site-specific scale.

The distance that a potential recharge site is from a stream is easily calculated using GIS. As discussed in Section 2.3.7, we used the TNRIS Texas stream GIS coverage to delineate areas within a given distance of a stream (Appendix B). The six example county maps provided in Sections 4 through 9 show all acreages that occur within the 3-mile cut-off distance and meet the other screening criteria. Alternative distance screens can be applied using the GIS tool provided with this report.

3.2.4 Water Quality and Environmental Hazards

Areas where the quality of groundwater and surface water are significantly different may not be suitable for groundwater banking, as either the quality of the aquifer water or the recharge water could be degraded. Evaluation in this regard is also dependent upon the intended use of the banked water; for example, water quality requirements for agricultural use are not as stringent as potable uses. Available information is generally insufficient, however, to make this determination on a site-specific basis. Although measured data for surface water and groundwater quality are included as part of the GIS tool and are discussed in detail in Appendix B, these data were not used to exclude any region from site-specific analysis.

The EPA has identified impaired stream segments that will need to be addressed at the local scale. Sections 4 through 9 present water quality maps that show these impaired stream segments for each of the site-specific regions selected through the statewide screening. The designation that a stream reach is impaired is not sufficient reason in itself to exclude a given region from further consideration as a potential site for groundwater banking. It does, however, indicate that surface water quality should be carefully evaluated as part of any project to bank water.

Other potential environmental hazards were identified from the TNRIS Environmental Hazards GIS layer and could be used for additional screening (Appendix B). These sites include landfills, radioactive dumps, and industrial and chemical disposal facilities. Such facilities could impact groundwater quality, including water that has been recharged from spreading basins.

3.2.5 Water Storage and Conveyance Systems

The existence or lack of water storage and conveyance systems may also be important in evaluating the usefulness of a water banking project. Existing spreading basins in other southwestern states are typically connected to massive regulated water management and distribution systems that include canals, dams, pipelines and other water storage and conveyance structures.

Conveyance structures might be used to deliver water to recharge sites or to deliver recharged water that has been pumped from an aquifer to points of use. Because many of the existing conveyance facilities in Texas are associated with water compacts and are subject to very specific legal limitations, however, the presence or lack of conveyance systems was not specifically included as an evaluation factor in this analysis. Nevertheless, the potential for use of an existing conveyance system to store and/or convey recharge water could play an important role in site-specific analysis within a given region. Several key points to consider include (1) the system capacity for transmitting or storing recharge water, (2) the proximity of the conveyance to potential surface water sources and recharge sites, and (3) the type of water (potable or non-potable) the system conveys.

Water storage systems in Texas generally consist of reservoirs. Additional information concerning conveyance systems and reservoirs is provided at the site-specific analysis level in Sections 4 through 9.

3.3 Water Availability and Infiltration Computations

Water availability at potential banking sites was determined using hydrograph data and TCEQ WAM results. The modeling results provide estimates of average available water (non-appropriated water) at various locations in a given stream system (Section 3.3.2). Because the source of banked water would most likely come from large streamflows of short duration caused by summer rainfall, an estimate of water volume available from large storm flows is more appropriate than average annual estimates of available water. For this reason, water availability was estimated using hydrograph data rather than modeling results for example counties within each region. Our methodology for conducting basin infiltration calculations is provided in Section 3.3.1.

3.3.1 Basin Infiltration Calculations

The recharge basin area required to infiltrate a given volume of water depends on the timing of the source water supply, basin storage capacity, and basin permeability. The availability of surface water for groundwater banking is determined using observed or estimated stream hydrographs. A hydrograph is a plot of stream discharge versus time. Stream hydrographs vary by year, storm event, watershed, stream order (stream size), and location along a stream. In addition, previous allocations and other restrictions will limit the volume of water available for banking.

In many cases, no gauging station is located near potential water banking sites, and therefore no observed surface water flow data are available to estimate the amount of water potentially available for banking. For such situations, climatological data and drainage basin characteristics such as slope, soil and vegetation type, and land use can be used to construct synthetic (estimated) hydrographs for a point of interest. Alternatively, observed hydrographs from other nearby regions with similar climatological and geographic attributes (e.g., drainage basin size, slope, and land use) may be used.

Because site-specific stream hydrograph data are not available for most sites identified as potentially suitable for groundwater banking, water availability was estimated using hydrographs from USGS gauging stations within the general vicinity of potential banking sites that had reasonable periods of record. For each site, one or two hydrograph records were evaluated over a 10-year period, generally the 1990s. For each hydrograph, a flow threshold was selected such that storm flows could be separated from base flows and typical annual flows. Half of the water volume above the selected threshold value for each hydrograph was assumed to be available for banking at a given site. This approach assumes that observed flow at the selected gauge provides a reasonable estimate of available water for the drainage area upstream of the gauge and is sufficient for the example infiltration calculations provided in Sections 4 through 9.

Where available, maps of average annual water availability determined using the TCEQ Surface Water Availability Models are provided for each site-specific region. Although these maps (and the associated GIS coverages provided with the GIS tool) provide a general indication of water availability, they are likely not sufficient for determining volumes available for banking because they do not separate available water into storm flows and base flows.

3.3.1.1 Evaporation Rates in Selected Counties

Evaporation rates vary widely across Texas, with higher rates in the semiarid western portion of the state. Evaporation rates from the 1950s to the present are available from the TWDB website (TWDB, 2002b). However, evaporation rates were not included in the example calculations of available recharge because evaporative losses were considered negligible compared to the infiltration rates. For example, in Randall County, the mean evaporative loss in July is 8.86 inches or 0.28 inch per day, and the maximum amount of infiltration is 8.17 ft/d based on the soils permeability identified in the screening analysis. Therefore, evaporation losses are substantially less than 1 percent of the potential infiltration, and during non-summer months, the evaporation losses would be substantially less. Lake surface evaporation rates corresponding to the example counties for each selected region are provided in Table 3.

Table 3. Lake Surface Evaporation Losses by County

County	Mean Annual Evaporation (inches)	Mean July Evaporation		Maximum Available Recharge in July[a] (in/d)	Evaporative Losses (% of infiltration)
		(inches)	(in/d)		
Randall	64.77	8.86	0.29	98	0.28
Parker	58.33	8.49	0.27	129	0.21
El Paso	71.06	8.97	0.29	96	0.30
Reeves	69.42	8.87	0.29	96	0.30
Coryell	55.76	8.12	0.26	241	0.11
Uvalde	57.85	8.02	0.26	128	0.20

Source: TWDB, 2002b
in/d = Inches per day
[a]Assumes 1 foot per day x 31 days in July.

3.3.1.2 Basin Storage Capacity

Basins can store as well as recharge water. Storage allows more effective capture of peak flows. Optimal basin depth is dependent upon grade, excavation costs, value of water, and the presence or absence of any impeding subsurface layers. For the example scenarios provided in this and other sections, basins were assumed to have the capacity to store 4 feet of water.

The recharge calculations presented in Section 3.3.1.3 illustrate the amount of cumulative infiltration in 10- and 100-acre basins with an assumed maximum ponding depth of 4 feet. During major storm events and subsequently high streamflow, the hypothetical basins will be able to maintain a depth of 4 feet of water, while infiltration occurs at a rate equal to the basin hydraulic conductivity as determined from the SSURGO data. No allowance was made for decreases in basin hydraulic conductivity with time.

3.3.1.3 Example Infiltration Calculations

Example infiltration calculations are presented to illustrate our computational approach and demonstrate some basic hydrologic principles. Data from Uvalde County in the South Central Texas region were selected for the example calculations since this is the only county from our site-specific example counties that had both SSURGO soil data and streamflow data from consistent dates on three different-order streams. We used a set of hydrographs from first, second, and third order streams in Uvalde County from 1960 to generate an example of how varying basin size and streamflows affect infiltration volumes.

The hydrographs from these three locations are superimposed in the top graph of Figure 10. The hydrograph patterns illustrated in Figure 10 are typical in that the magnitude and duration of peak (or storm) flows diminish with increased stream order (higher stream order indicates smaller streams). Stated another way, the volume of water associated with storm events is smaller and the time between storm events is greater for the smaller streams as compared to the larger streams. Therefore, reduced water availability for recharge facilities along higher-order (smaller) streams results in reduced opportunity for groundwater banking.

The threshold flow values for each of the streams are also illustrated in the top graph of Figure 10. The threshold values represent a flow value used to separate storm flows from base flows and typical annual flows. Half of the water volume above the selected threshold value for each hydrograph was assumed to be available for banking, as large flow peaks are difficult to capture and may have an unacceptable sediment load. The available water hydrograph, shown at the bottom of Figure 10, indicates the amount of water available for capture and subsequent recharge based on the above assumptions.

Figure 11 shows the cumulative amount of water recharged for each stream for two infiltration basin sizes: 10 acres (top) and 100 acres (bottom). The volume of recharge was calculated using a basin permeability of 1 foot per day and other assumptions as outlined in this section (i.e., no evaporation and basin storage of 4 feet). For the 10-acre basin, the recharge from the first- and second-order streams is nearly identical, illustrating the fact that the basin is too small to handle the additional volumes of available water from these two streams relative to the third-order stream. For the 100-acre basin, the calculated recharge increases by about 6.5 and 5.3 times for the first- and second-order streams, respectively. For the third-order stream the calculated recharge only increases by a factor of about 2.2 for the 100-acre versus 10-acre basin, illustrating that the recharge is more limited by available water for the smaller stream than basin size. For the first- and second-order streams, however, the 100-acre basin provides enough suitable land to recharge virtually any available water.

3.3.2 TCEQ Surface Water Availability Models

Surface water availability for selected Texas river basins was quantified using data from the WAM project sponsored by the TCEQ (TCEQ, 2002). The WAM models were designed to provide information on surface water availability for evaluating existing and new appropriation permits and for developing or reviewing overall surface water management plans. At present, WAM models have been developed for 22 of the 23 Texas river basins, with the Rio Grande basin to be completed by December 31, 2003. The WAM manual, available through the TCEQ website (http://www.tnrcc.state.tx.us/permitting/waterperm/wrpa/wam.html), provides specific information on modeling requirements and procedures.

Most surface water in Texas has been appropriated, especially in the western portion of the state. Theoretically, this means that no excess flow is available for artificial recharge. However, the results of the WAMs obtained from the TCEQ indicate that simulated streamflow at many locations exceeded appropriated amounts during the historical analysis period. This may be the result of local precipitation and streamflow response patterns that exhibit flashy behavior and result in short-term streamflow that exceeds the diversion system withdrawal capacity or reservoir storage capacity. Also, flashy streamflow may exceed limitations on permitted monthly diversion amounts. In the case of agricultural irrigation, excess water may be available during periods outside the local growing season when no diversions are occurring. These factors may result in enough streamflow for artificial recharge, even though a given basin may be termed fully appropriated.

The WAM models contain several components, including GIS spatial data files and tools, a database of permitted water rights and historical water use, naturalized streamflows, and Water Rights Analysis Package (WRAP) software. The GIS components were provided by the Center for Research in Water Resources at the University of Texas at Austin. The remaining components were provided by the TCEQ Water Rights Permitting and Availability division.

Naturalized streamflows, defined as the flows that would have occurred in the absence of human activity, were generated from historical stream gauge data to remove the effects of reservoir development and water use. Naturalized streamflows were developed for specific locations, termed control points, for each month of the historical period of record, which spanned from 51 to 63 years for the basins included in this report. Control points represent reservoir, diversion, and return flow locations associated with specific water rights and key stream network features, including stream gauge, confluence, and basin outflow locations.

The control points, water rights, and naturalized flows are used as inputs to the WRAP model. The WRAP model, developed at Texas A&M University, uses historical hydrologic river basin characteristics and specific water rights information (based on seniority) to determine water availability at control points. The WRAP model results for each control point are then cross-referenced and linked to a corresponding set of GIS spatial data files for the basin(s) being modeled. At present, comprehensive cross-reference linkages between the WRAP control points and the GIS files have not been completed. The files provided with this report represent the best currently available information as provided by the TCEQ.

Limitations must be considered in applying the WAM modeling results reported in the GIS files. The simulated streamflows presented in this report are annual average values and provide only a general indication of water availability for banking. Streamflows for any particular time interval during an analysis period may be significantly different from the attribute values in the GIS files. In extreme cases, reported streamflows may be dominated by only a few months or years of actual flow averaged with long periods of no flow. The user must examine more detailed model output to evaluate the historical and seasonal streamflow variability at specific locations.

3.4 Calculation of Recovery Efficiency

The recovery efficiency for banked water is a measure of the volume of recharged water recovered for use at a later date. Recovery efficiency can be viewed on a local or regional scale.

At the local scale, one or more pumping wells can be placed in such a way as to recover the banked water using basic hydraulic principles. The general concept is that banked water must be extracted by a well or well field within a given time frame before it flows past the zone of capture for the well or well field. The time period involved varies based on site-specific aquifer conditions; it will often be on the order of one-half to several years, but could be substantially longer if recovery wells are placed some distance downgradient of recharge sites. If the recharge to the aquifer occurs within or upgradient of an existing cone of depression, the recharge water will be recovered by the pumping well or wells that formed the cone of depression, and a new capture system may not be required.

A rough estimate of the rate of groundwater migration away from a recharge site can be made using the following equation:

$$v = \frac{Ki}{n_e}$$

where v = groundwater flow velocity (length/time)

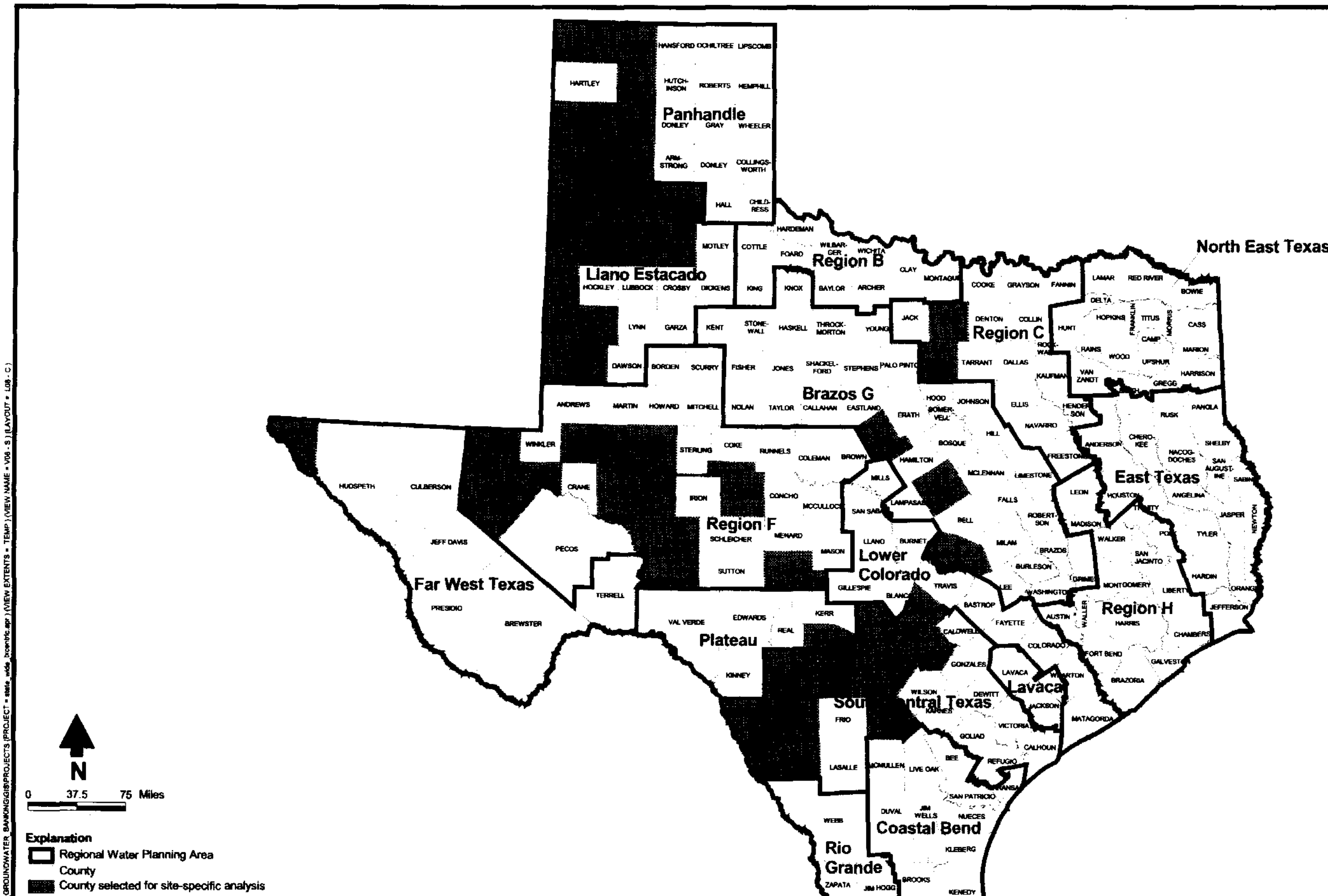
K = average hydraulic conductivity of the aquifer (length/time)

i = average hydraulic gradient in the vicinity of the recharge area (length/length)
n_e = effective porosity (dimensionless)

Although highly variable, typical values for these parameters lead to groundwater flow velocities from less than 1 up to 10 ft/d or more. Accurate, site-specific hydraulic properties and measurements, therefore, are required to design an effective capture system for recharged water.

At the regional scale, groundwater banking could be viewed as increased recharge to the aquifer, potentially available for use by multiple users at multiple points. Under this concept, water would be recharged at one or more sites and would be allowed to flow through the aquifer according to existing and future groundwater flow paths. The banked water could then contribute to a variety of uses, depending upon the location of banking sites relative to points of aquifer water use. This type of approach might be appropriate for regions of irrigated lands that overlie the Ogallala Aquifer, for example, where numerous existing irrigation wells would likely capture any banked water. This concept might also be appropriate for the Edwards Aquifer, which is highly dynamic, making it very difficult or impossible to recover water near its point of recharge after some time has passed, but which would nonetheless benefit from greater recharge.

If local-scale capture and use of the banked water is required, traditional hydrological analyses of efficiency based on aquifer hydraulic conductivity (or transmissivity), storage, ambient hydraulic gradient, and feasible well pumping rates should be a component of a formal feasibility study. Detailed calculations were not made as part of this study because data limitations and the uncertainties associated with identified sites—such as ultimate use of the water, water availability, site location, whether recovery is desired on a local or regional scale, and site-specific aquifer properties–make such calculations of very limited value at this stage of analysis.



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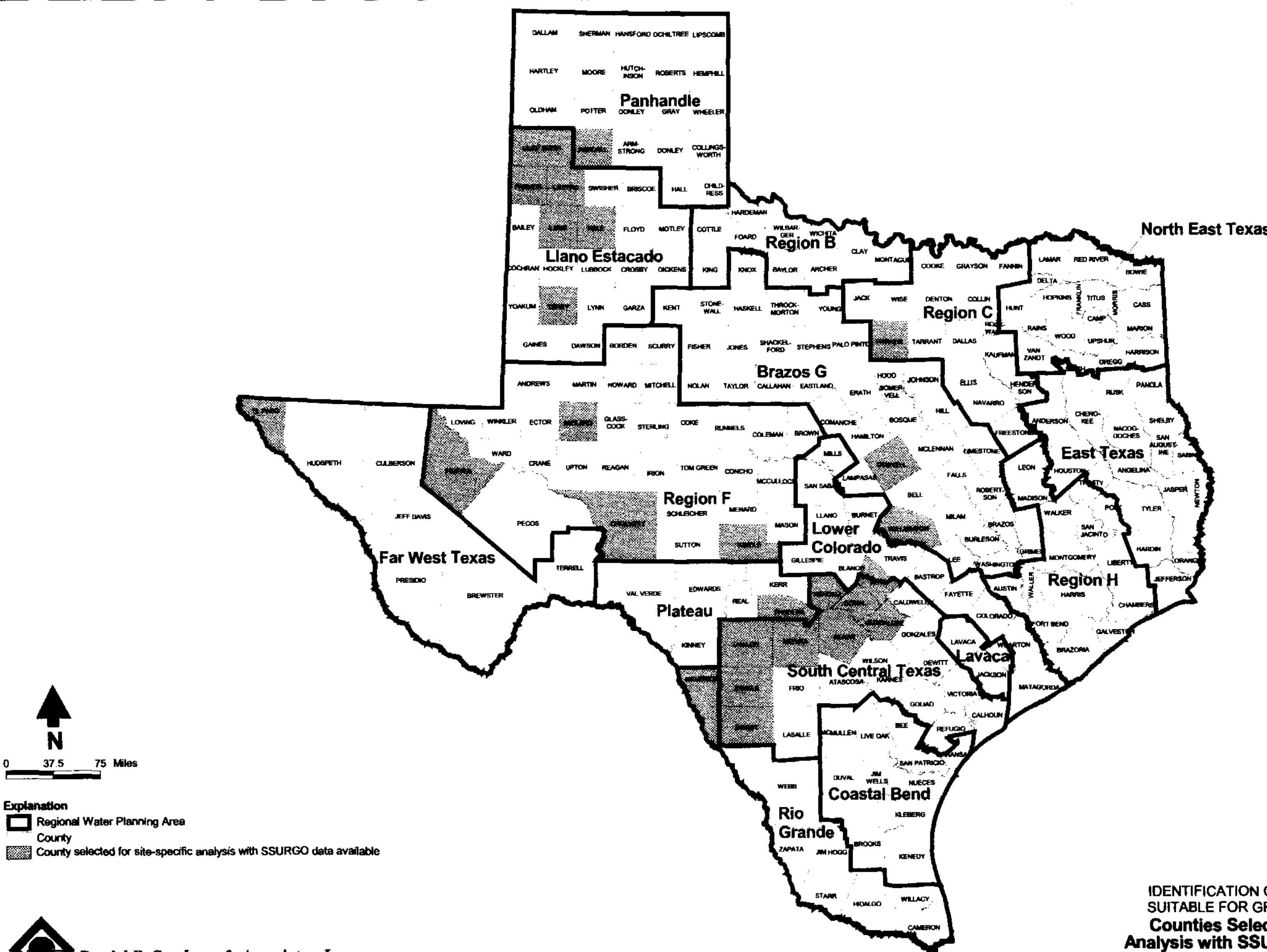
IDENTIFICATION OF GEOGRAPHIC AREAS
SUITABLE FOR GROUNDWATER BANKING

Counties Selected for Site-Specific Analysis

Figure 8



Explanation
- Regional Water Planning Area
- County
- County selected for site-specific analysis with SSURGO data available

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING
Counties Selected for Site-Specific Analysis with SSURGO Data Available

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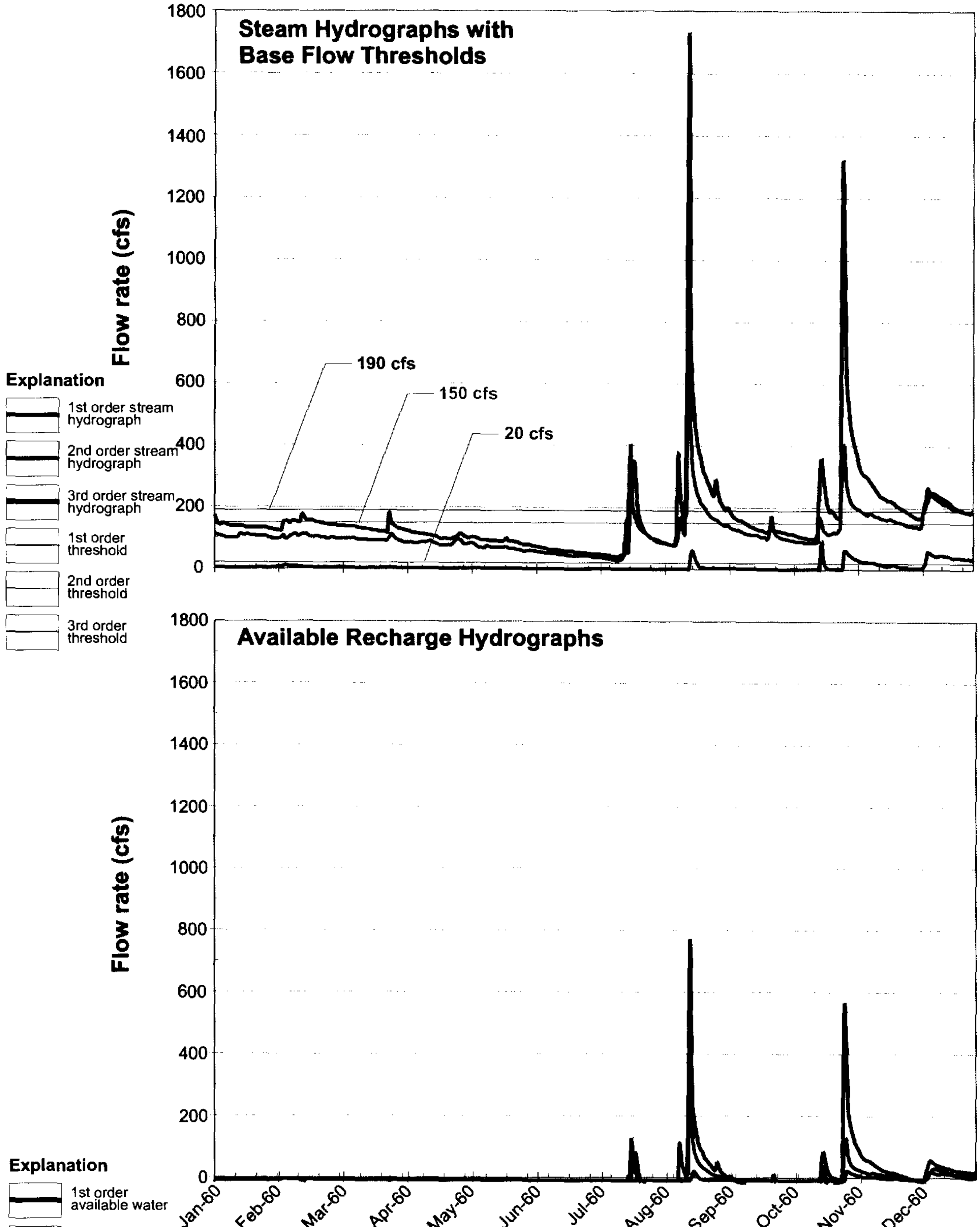
Figure 9



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Stream Hydrographs and Corresponding Available Recharge Hydrographs, Uvalde County

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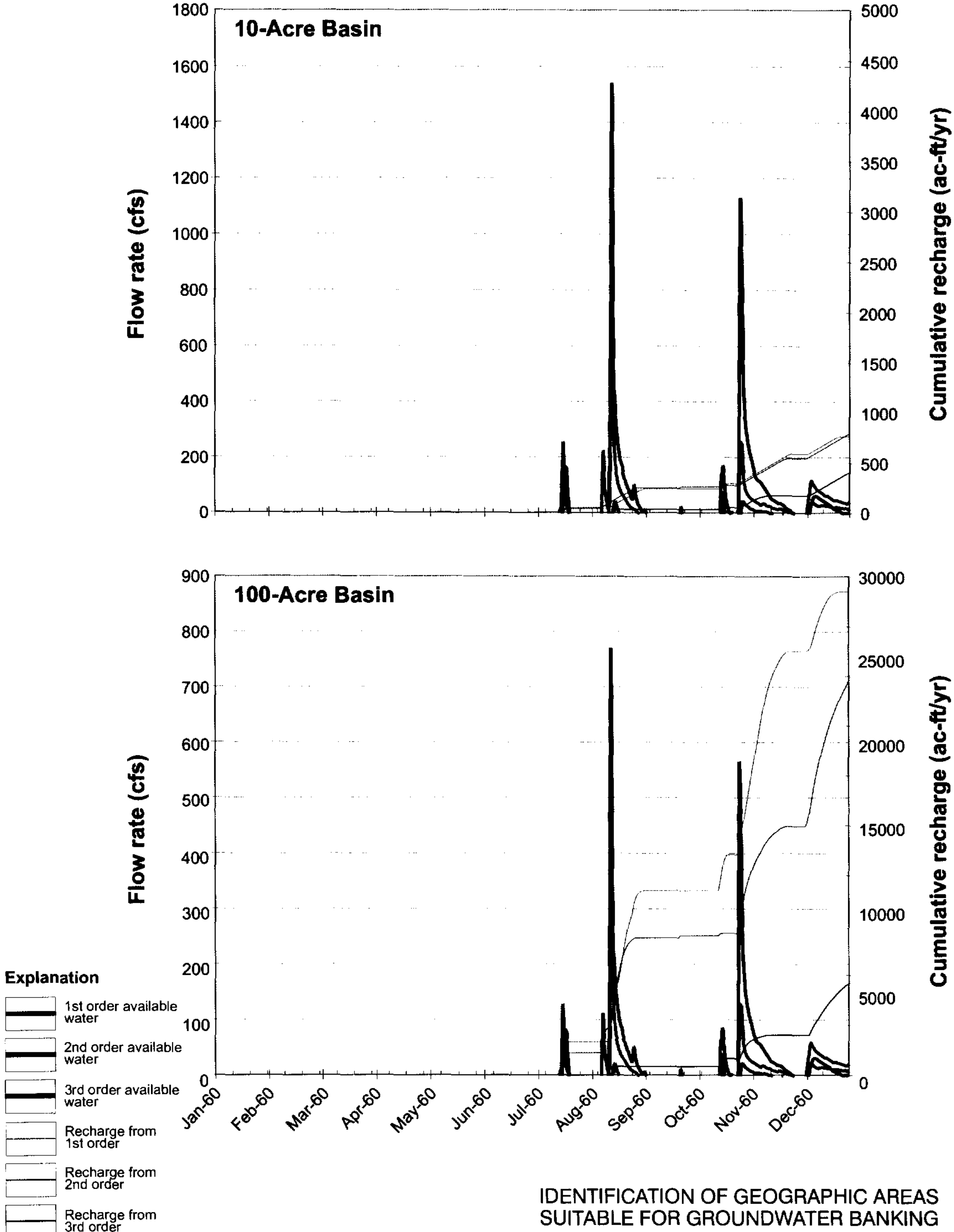
Figure 10



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Available Recharge Hydrographs for 10-Acre and 100-Acre Basin Areas

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Figure 11

4. South Central Texas Region

For the purposes of this study, the South Central Texas Region is defined as including the following counties from the South Central RWPA (Region L): Atascosa, Bexar, Comal, Demit, Hayes, Guadalupe, Kendal, Medina, Uvalde, and Zavala. It also includes Maverick County from Region M (Rio Grande) and Bandera County from Region J (Plateau) (Figure 12).

4.1 Water Resources Overview

The presence of significant quantities of groundwater has meant that development of surface water resources has not been a priority in the South Central Texas Region (SCTRWPG, 2001). Table 4 provides projected water supply for 2000 to 2050 and indicates the approximate acreages suitable for recharge in each county. Figure 12 indicates the areas suitable for recharge, and Figure 13 shows EPA-designated impaired streams and water quality exceedances at available sampling locations.

Table 4. Projections for Selected Counties in the South Central Texas Region

County	SSURGO Soil Data Available	Projected Water Supply[a] (ac-ft/yr)						Acreage Suitable for Recharge[b]
		2000	2010	2020	2030	2040	2050	
South Central								
Atascosa	No	–22,689	–21,569	–20,734	–39,922	–42,501	–48,830	---
Bexar	Yes	–119,398	–151,686	–199,458	–271,882	–332,961	–379,396	16,371
Comal	Yes	–3,506	–14,287	–20,401	–28,685	–33,755	–40,613	2,605
Dimmit	Yes	4,103	3,871	3,555	–3,952	–4,041	–4,187	6
Guadalupe	Yes	6,315	3,704	741	–7,045	–10,860	–15,635	3,169
Hays	Yes	3,364	2,118	1,214	–22	–1,464	–2,553	1,217
Kendall	Yes	166	–1,059	–2,515	–4,586	–6,836	–9,220	11,844
Medina	Yes	–79,157	–73,528	–67,925	–67,128	–62,095	–57,372	5,410
Uvalde	Yes	–50,723	–45,829	–41,096	–39,854	–35,912	–32,332	104,333
Zavala	Yes	–77,016	–72,903	–68,924	–84,700	–81,319	–78,147	689
Plateau								
Bandera	Yes	–2,264	–3,993	–3,880	–4,343	–4,894	–5,508	7,516
Rio Grande								
Maverick	Yes	–42,662	–43,168	–41,632	–41,667	–48,707	–57,582	8,291

[a] Negative values indicate a deficit in supply
[b] Identified through site-specific analysis described in this report.

ac-ft/yr = Acre-feet per year
SSURGO = Soil Survey Geographic database
--- = Not available

As discussed in Section 1.2, artificial recharge in the Edwards Aquifer consists of four concrete in-channel dams in Parkers, Seco, Verdy, and San Geronimo Creeks that have been operational since the 1960s and 1970s (Johnson et al., 2002). The Region L RWPG has planned an ASR system for Bexar County to store water from the Edwards Aquifer in the Carrizo Wilcox Aquifer during periods of excess for use during periods of peak demand.

The existing surface water supplies of the region include storage reservoirs and run-of-river water rights (Table 5 and Figure 14).

Table 5. Major Reservoirs, South Central Texas Region Site-Selected Counties

County	Reservoir	Water Right Owner	Authorized Diversion (ac-ft/yr)
San Antonio Basin			
Bandera and Medina	Medina Lake System	Bexar-Medina-Atascosa Counties (WCID No. 1)	66,750
Bexar	Victor Braunig Lake	City of Public Service Board of San Antonio	12,200[a]
	Calaveras Lake		37,000[b]
Guadalupe Basin			
Comal	Canyon Reservoir	Guadalupe-Blanco River Authority	50,000[c]

Source: SCTRWPG, 2001.

ac-ft/yr = Acre-feet per year
WCID = Water Control and Improvement District

[a] Includes rights to divert up to 12,000 ac-ft/yr from the San Antonio River to Braunig Lake and to consume up to 12,000 ac-ft/yr at Braunig Lake.

[b] Includes rights to divert up to 60,000 ac-ft/yr of reclaimed wastewater from the San Antonio River to Calaveras Lake and to consume up to 37,000 ac-ft/yr.

[c] Guadalupe-Blanco River Authority has applied to TCEQ to increase Canyon Reservoir authorized diversions to approximately 90,000 ac-ft/yr.

Uvalde County was selected as the example location for site-specific discussion of the South Central Texas Region because high-resolution SSURGO soils data from the county are available and it has the largest amount of acreage identified as potentially suitable for groundwater banking. In Uvalde County, the total demand in 2050 is projected to be 123,087 ac-ft/yr. Municipal demand is 9,271 ac-ft/yr and agricultural demand is 110,728 ac-ft/yr (SCTRWPG, 2001).

4.2 Rate, Area and Time Period of Infiltration

Bandera, Medina, and Bexar Counties all have potentially suitable locations along stretches of the Medina and San Antonio Rivers (Figure 12). As indicated from the WAM model run, there is excess water throughout this stretch of river that could potentially be used for groundwater banking (Figure 15). This excess water ranges from as little as 270 ac-ft/yr in Central Bandera County above Medina Lake to more than 27,000 ac-ft/yr in Bexar County below Victor Braunig Lake.

The Medina River, from its confluence with the San Antonio River, and the San Antonio River have been designated as impaired streams (Figure 13). Further research must be completed regarding water quality before any sites in this area can be seriously considered for groundwater banking.

Zavala and Dimmit Counties have several small potential recharge sites along the headwaters of the Nueces River, including El Morro, Comanche, and Capote Creeks (Figure 12). The WAM data show water availability in the range from 22,000 to 44,000 ac-ft/yr along the stretches of these streams shown in Figure 15. A water deficit is projected for both counties by 2050: 78,147 ac-ft/yr for Zavala County and 4,187 ac-ft/yr for Dimmit County (Table 4).

WAM results are not available for Maverick County, as it is part of the Rio Grande Basin WAM, which has not yet been completed. Nevertheless, a number of potential recharge sites exist in Maverick County in the Rio Grande valley. Suitable areas identified through the screening analysis lie along the stretch of the Rio Grande that runs through the county. However, because this section of the Rio Grande has been designated as an impaired stream, further research must be completed regarding water quality before any of these sites can be seriously considered for groundwater banking.

Figure 16 shows that most irrigated land in Uvalde County, the example county for this region, is in the southern half of the county and most of the suitable recharge areas are in the northern half of the county. Municipal demands are greatest in the southeastern part of the county, but only small acreages of potentially good recharge areas near the cities were identified in the initial screen. If field reconnaissance confirms this initial screen, it may be advisable to reserve these small acreages as future recharge sites. Uvalde County appears to have more than 16,000 acres of high-permeability soils (i.e., with an infiltration rate exceeding 2 inches per hour) near first-order streams and more than 38,000 acres near second-order streams (Table 2). This acreage can easily accommodate the available water for banking as determined from available hydrograph information.

Figure 17 illustrates computations of banked water for two hydrographs. The top graph is for Gauge 8192000 on the Nueces River in the southern part of the county, and the bottom graph is for Gauge 8195000 on the Frio River in the northern part of the county. Both gauges are near potentially suitable recharge sites. The Nueces River site overlies the Carrizo-Wilcox Aquifer outcrop area, and the Frio River site overlies the Edwards-Trinity Aquifer. The average permeabilities for the Nueces and Frio River sites were determined to be approximately 11 and 20 ft/d, respectively. Calculated cumulative recharge for the Nueces River site is about 50,000 ac-ft over 10 years, while calculated cumulative recharge for the Frio River site is about 75,000 ac-ft over 10 years.

In addition to the above infiltration calculations, which were made assuming a basin size of 100 acres, the two selected hydrographs were analyzed to determine the area required to infiltrate all available water (assumed to be one-half of the flow above the threshold values indicated on Figure 17) and the average time period for infiltration. The required areas and average time periods for the Nueces and Frio River sites are 464 acres and 4.7 days and 34 acres and 8.3 days, respectively.

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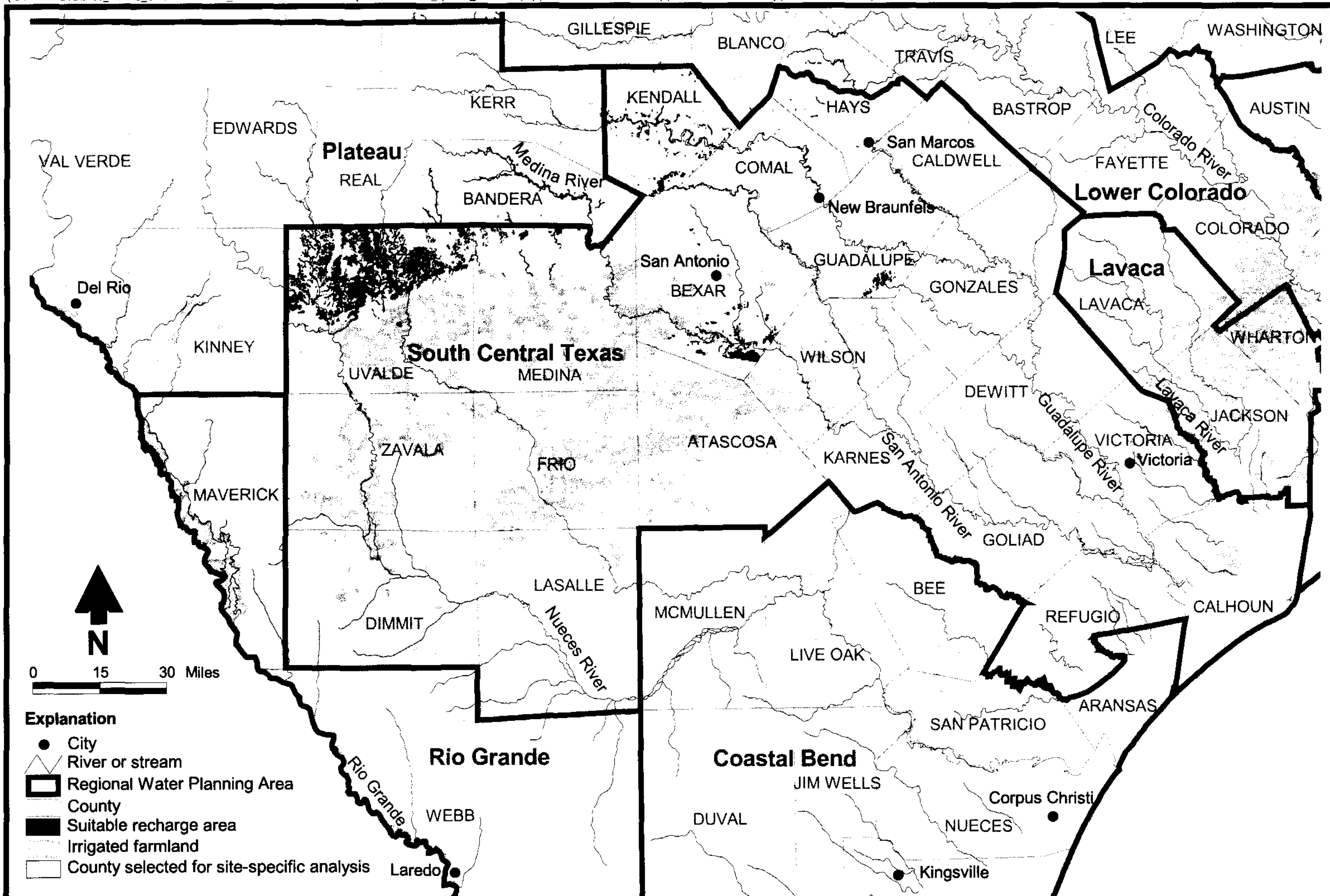

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

South Central Texas Suitable Recharge Areas

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Figure 12

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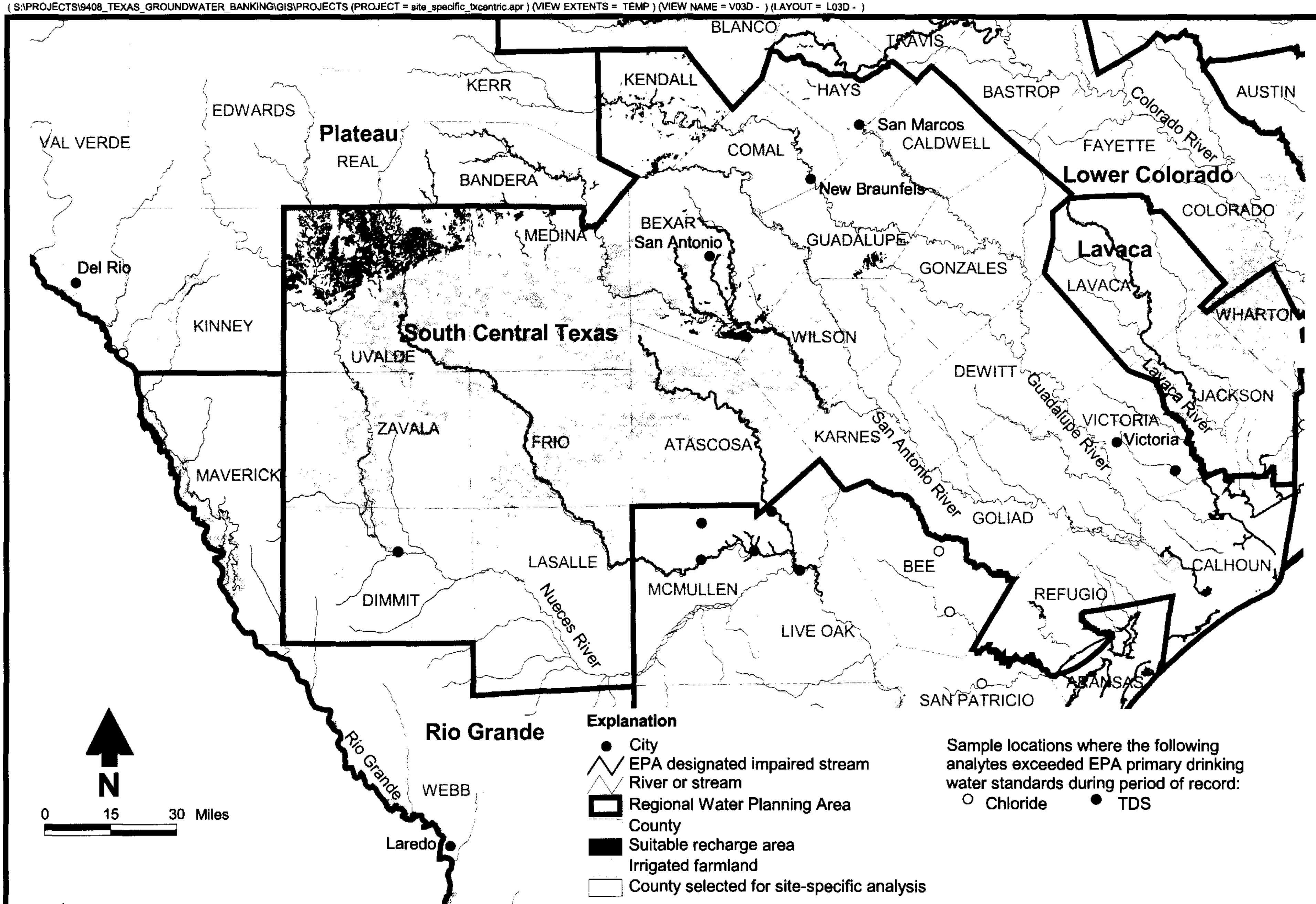

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

South Central Texas Water Quality

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Figure 13

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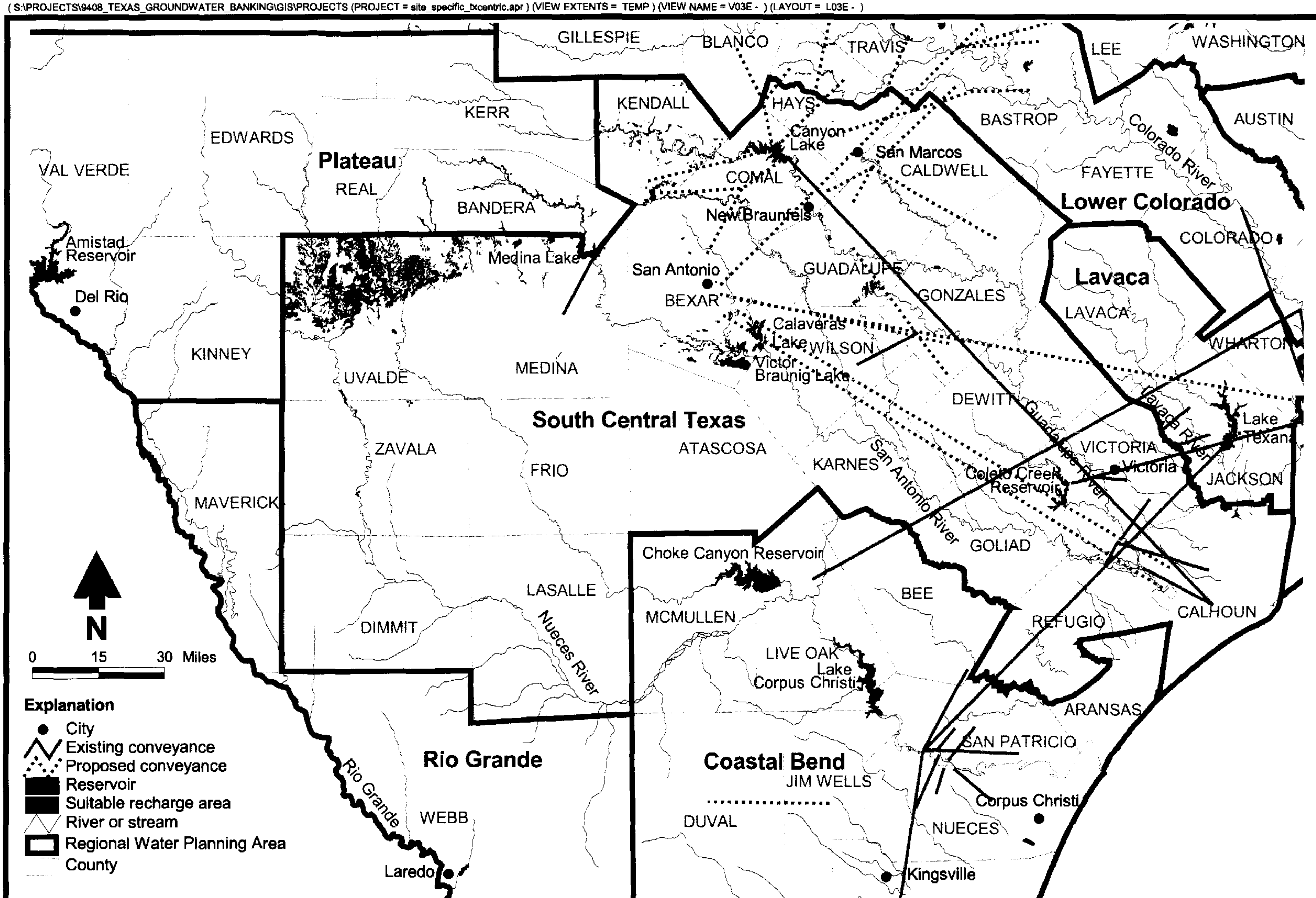

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

South Central Texas Reservoirs and Conveyances

Figure 14

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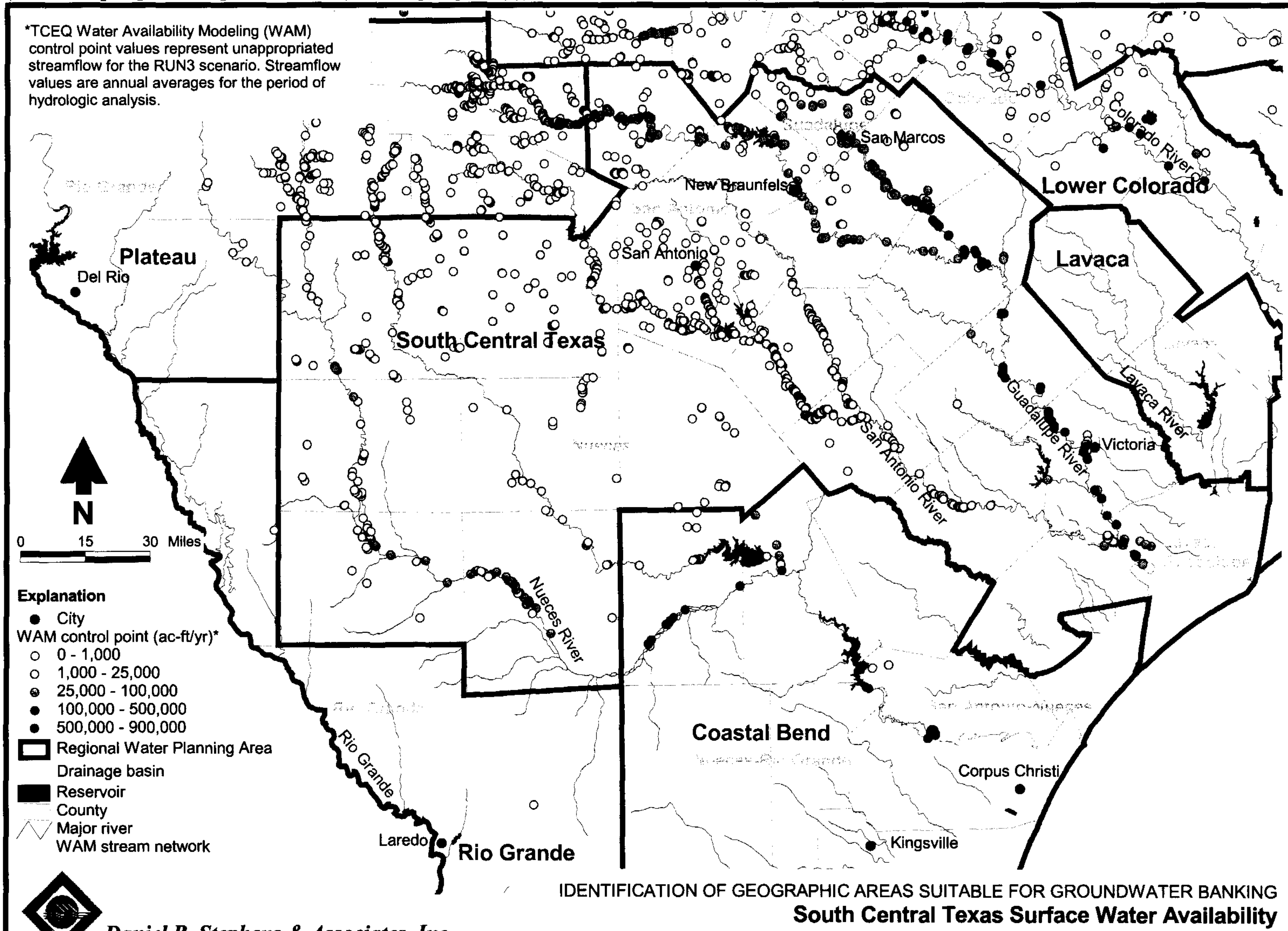

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

South Central Texas Surface Water Availability

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Figure 15

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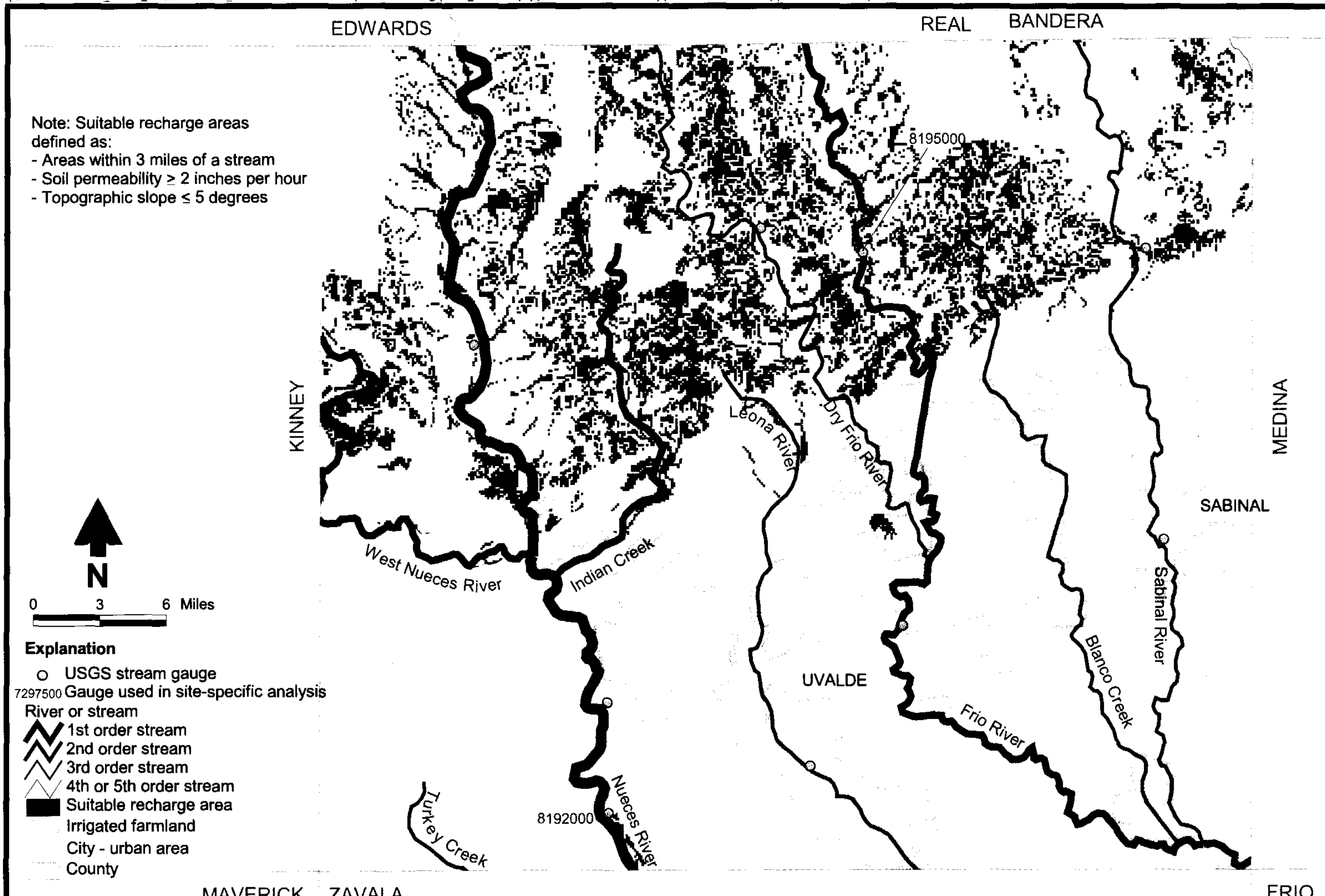

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Uvalde County Suitable Recharge Areas

Figure 16

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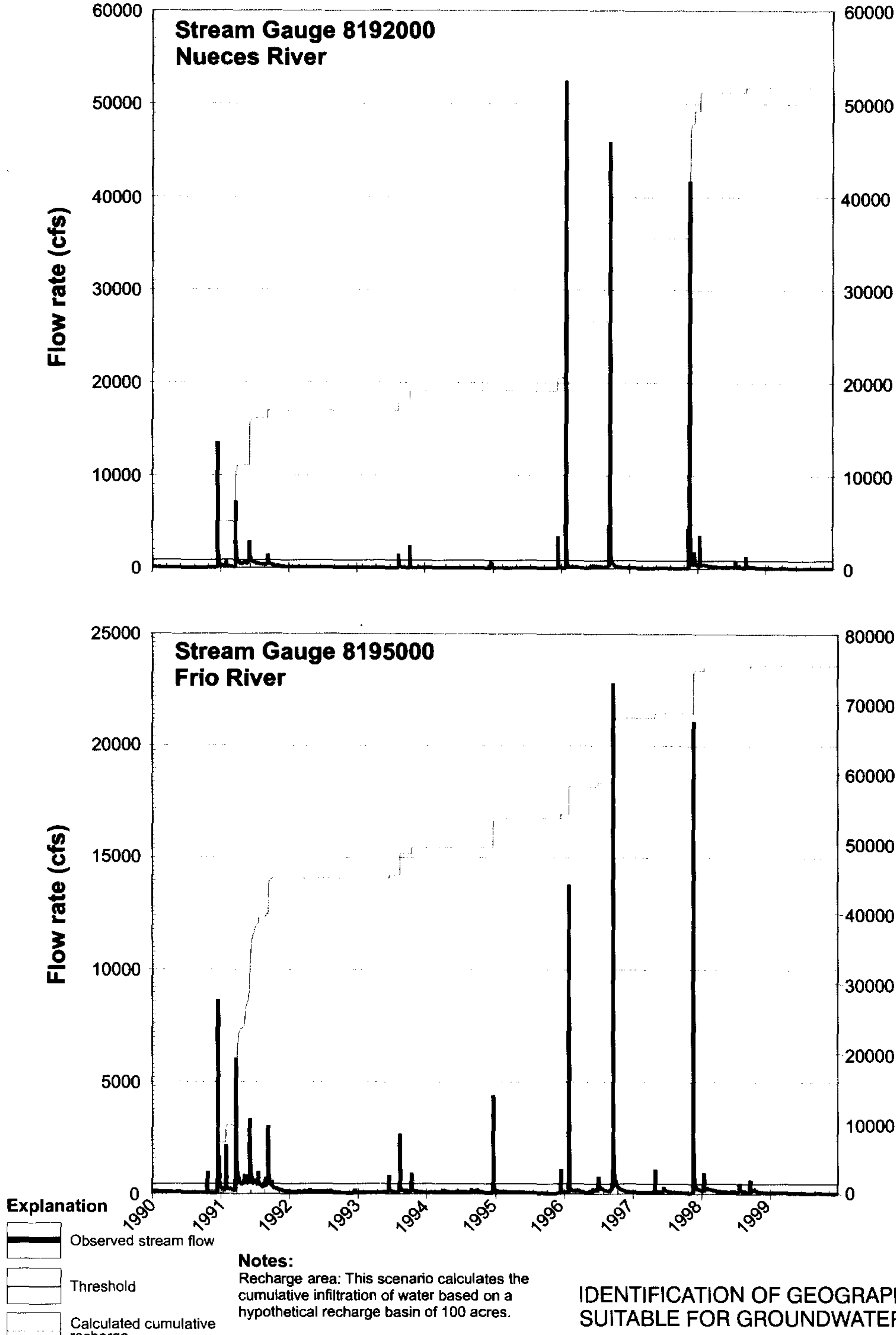

Notes:
Recharge area: This scenario calculates the cumulative infiltration of water based on a hypothetical recharge basin of 100 acres.

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Available Recharge Hydrograph for USGS Stream Gauges, Uvalde County

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Figure 17

5. Brazos Region

The selected counties in the Brazos RWPA (Region G) include Comanche, Coryell, and Williamson Counties. Williamson County is one of the fastest growing counties in the nation.

5.1 Water Resources Overview

The Brazos Region (Figure 18) is a diverse region. Annual rainfall ranges from 24 inches in the western part of the region to 44 inches in the eastern part. The Carrizo-Wilcox Aquifer provides a prolific water supply in the eastern part of the region. The entire region is projected to have a surplus of 500,000 ac-ft in 2050, most of which is projected to come from the Carrizo-Wilcox Aquifer. Water supply projections for the region are shown in Table 6 and selected water quality for the region is shown on Figure 19.

Table 6. Projections for Selected Counties in the Brazos Region

County	SSURGO Soil Data Available	Projected Water Supply [a] (ac-ft/yr)						Acreage Suitable for Recharge [b]
		2000	2010	2020	2030	2040	2050	
Comanche	No	−11,177	−11,640	−11,042	−10,499	−9,960	−9,492	---
Coryell	Yes	3,894	1,834	−597	−3,337	−5,333	−7,732	80
Williamson	Yes	54,537	37,231	21,694	6,685	−5,999	−18,441	---

[a] Negative values indicate a deficit in supply
[b] Identified through site-specific analysis described in this report.

ac-ft/yr = Acre-feet per year
SSURGO = Soil Survey Geographic database
--- = Not available

The four major reservoirs within the selected counties in Region G are Belton, Georgetown, Granger, and Proctor Reservoirs (Figure 20). All of these are controlled by the Brazos River Authority (Table 7).

Coryell County was chosen as the example county for this region because it is the only county with both high-resolution soil (SSURGO) data as well as several USGS stream gauge locations from which surface water flow can be analyzed.

Table 7. List of Major Reservoirs, Brazos Region Site-Selected Counties

County	Reservoir[a]	Water Right Owner	Authorized Diversion (ac-ft/yr)
Bell	Belton	Brazos River Authority	100,257
Williamson	Georgetown		13,610
Williamson	Granger		19,840
Comanche	Proctor		19,658

Source: HDR, 2001.

ac-ft/yr = Acre-feet per year

[a] Major reservoirs are defined as having a capacity greater than 10,000 ac-ft.

5.2 Rate, Area, and Time Period for Infiltration

As shown on Figure 18, few potential areas for recharge exist in the Brazos Region. In fact, based on the criteria used, the only suitable recharge area is in Coryell County. In the Trinity Aquifer outcrop area, two large fingers protrude from the northwest and north-central portions of the county toward the southeast (Figure 4). Using our initial analysis criteria for identifying a potential recharge site, all but 80 acres of the county were eliminated as potential banking sites.

In Coryell County, analysis of projected demand by water use category has not been done. Total projected water deficit in 2050 is approximately 7,700 ac-ft/yr. However, based on the GIS layer, there appear to be only 330 irrigated acres in the county (Figure 19), mostly near streams. The WAM data show more than 160,000 ac-ft/yr available along a stretch of the Leon River (Figure 21).

Coryell County has limited high-permeability soils in suitable recharge locations; most of these appear to be just upstream of Gatesville along the Leon River (Figure 22). Recharge at this particular site is unlikely to supply water to any existing irrigated areas shown on the map, but the site is a candidate for recharge for Gatesville's future water supply. Because of the limited available acreage, a suitable site might be reserved for a future recharge facility. Further site-specific analysis would be needed before a final decision can be made.

Figure 23 illustrates computations of banked water for Gauge 8100500 on the Leon River at Gatesville in the central part of the county, several miles downstream of the potential site identified for recharge. The average permeability for this site was determined to be about 20 ft/d from the SSURGO data. Calculated cumulative recharge for a 50-acre basin is about 34,000 ac-ft over 10 years. Based on the same hydrograph record, the required area to bank all available water as determined using the Leon River gauge is 108 acres, and the average time available for infiltration is 5 days.

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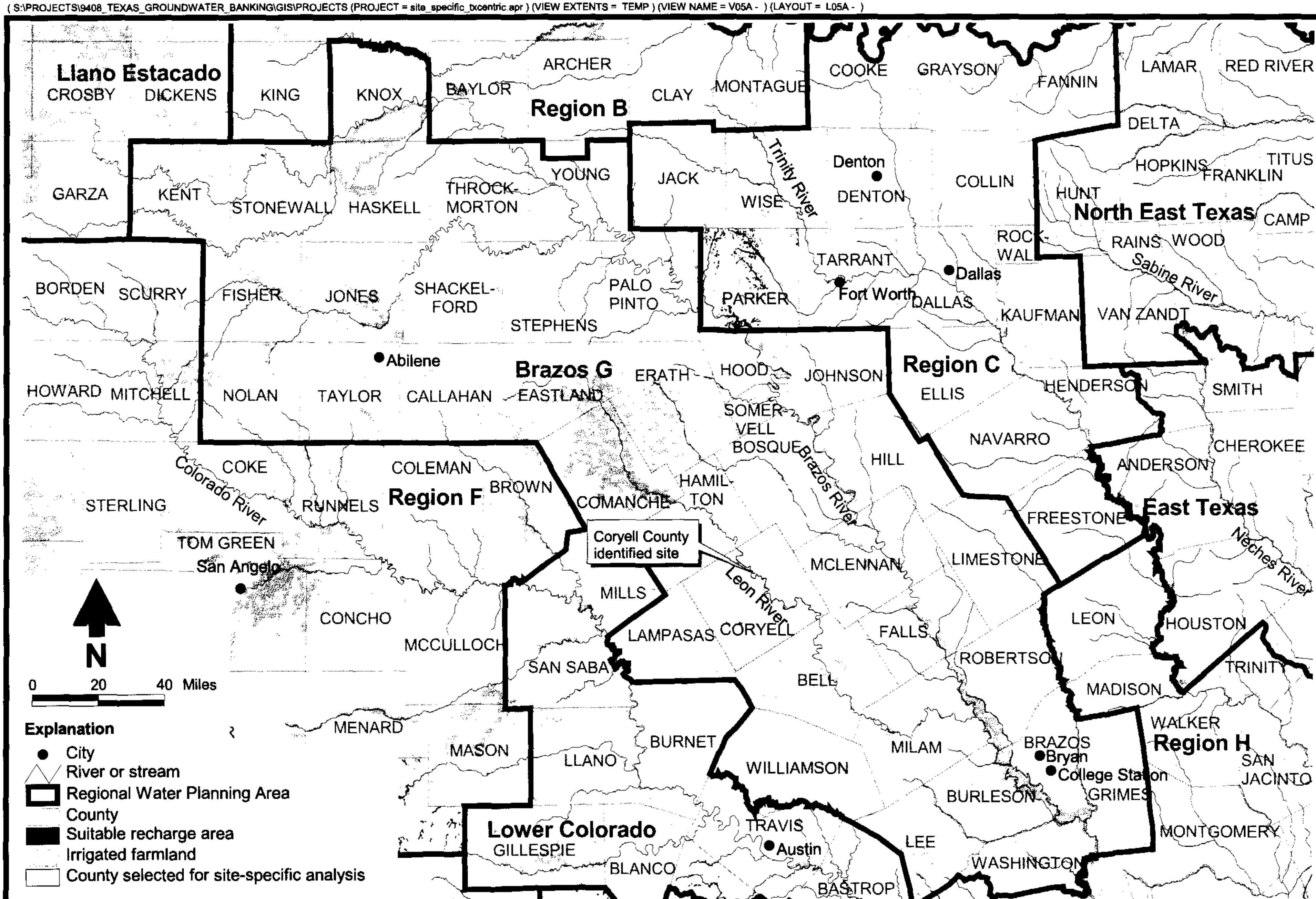

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Brazos G Suitable Recharge Areas

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Figure 18

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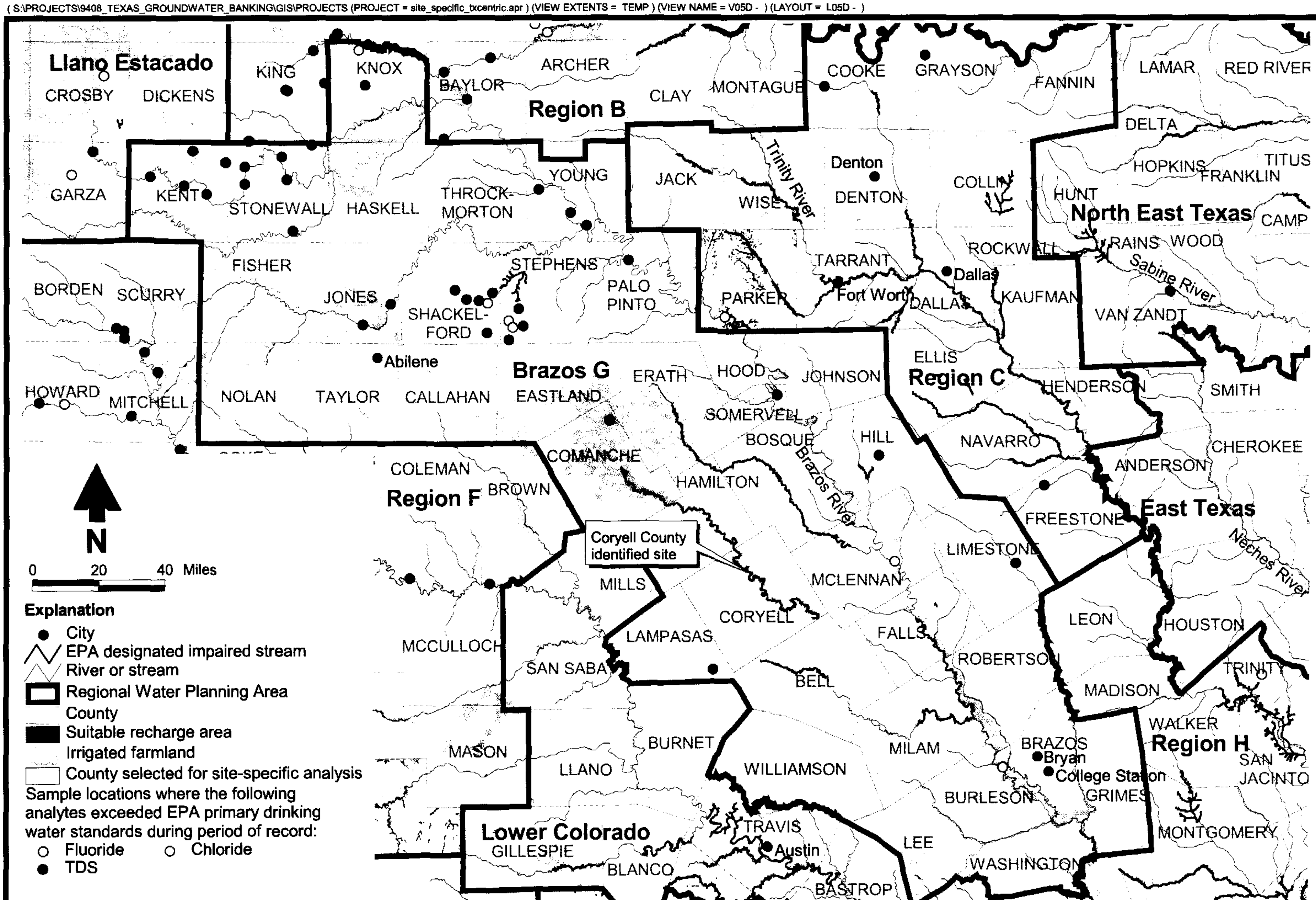

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Brazos G Water Quality

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8-30-02 11:31AM JN 9408

Figure 19

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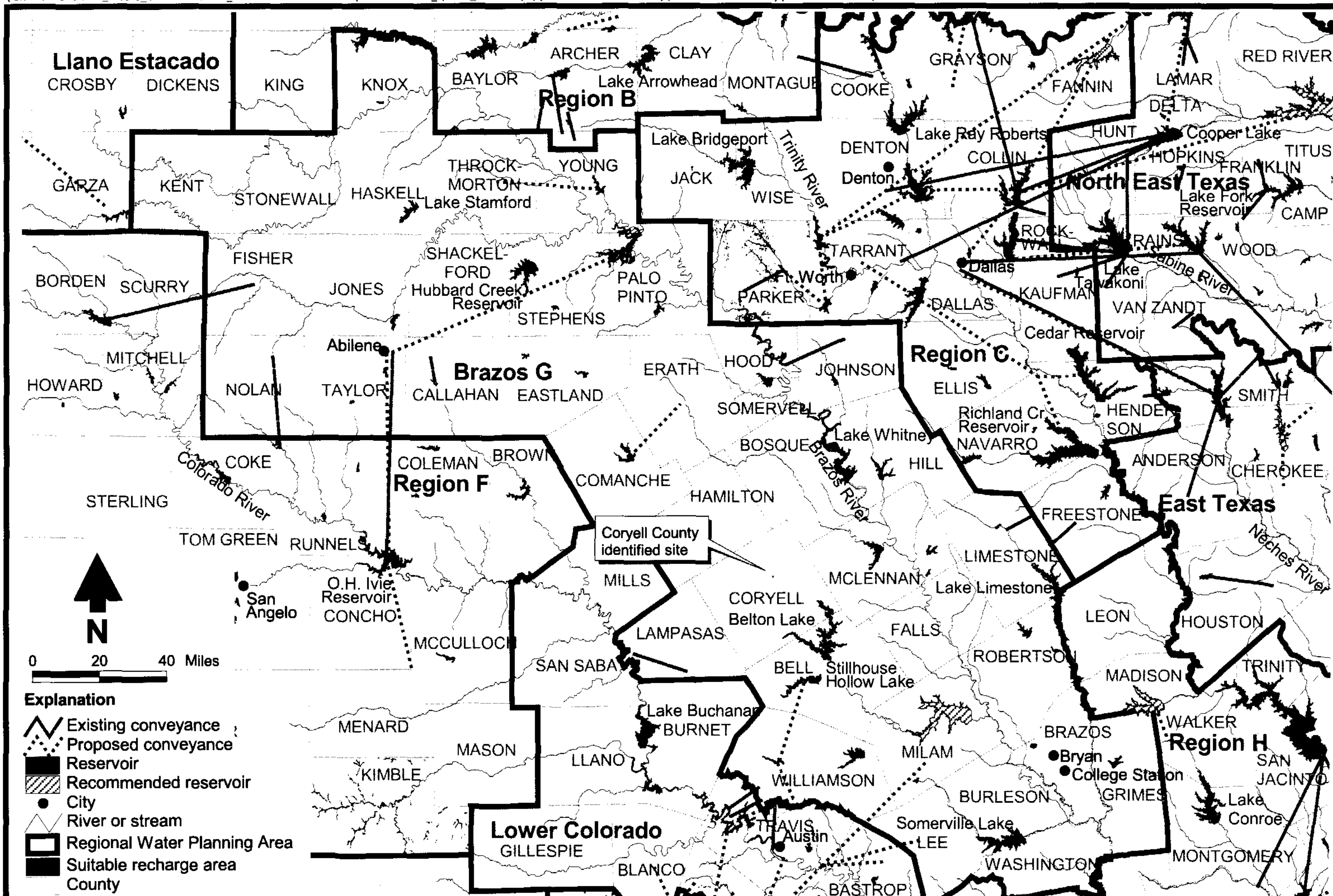

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Brazos G Reservoirs and Conveyances

Figure 20

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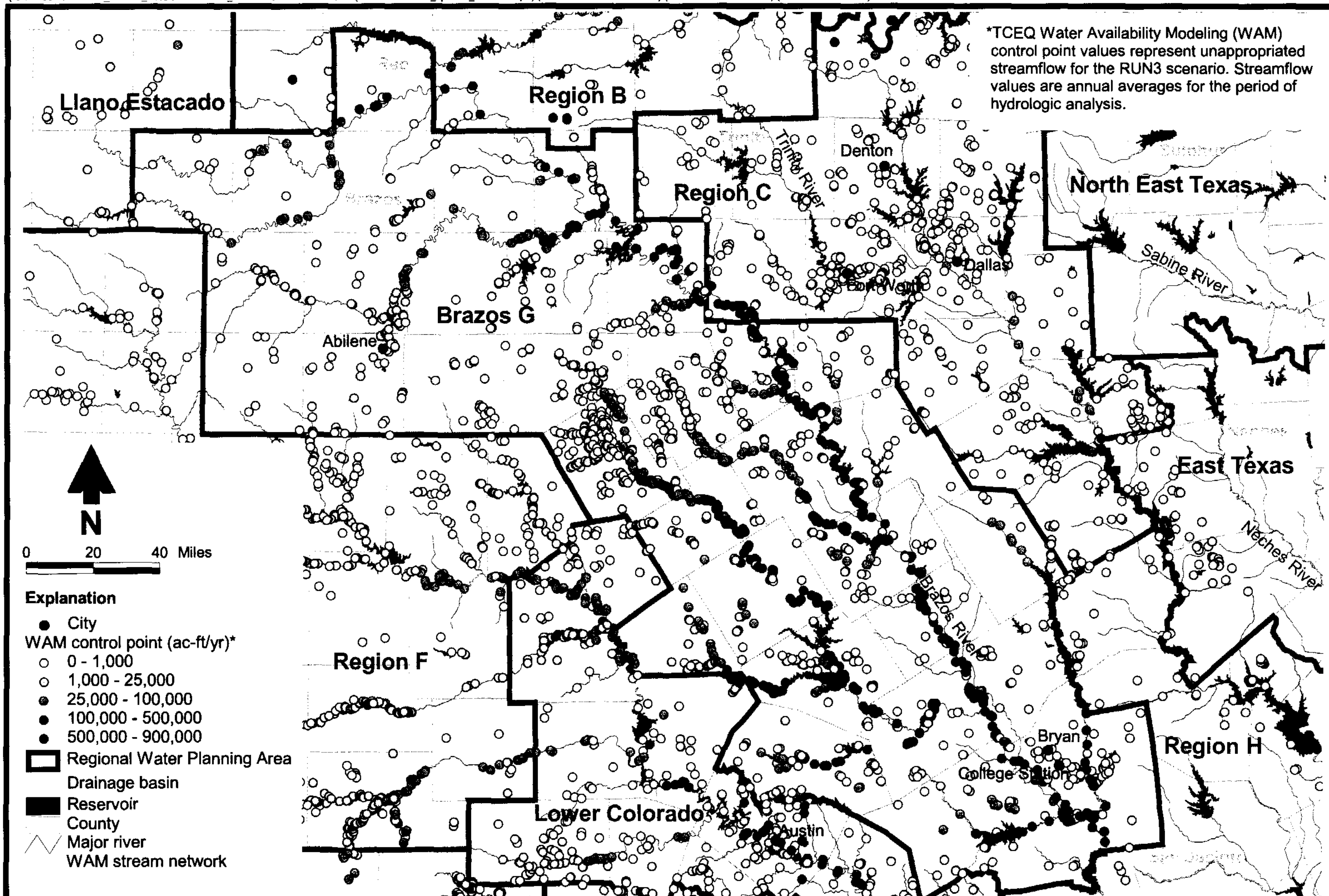

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Brazos G Surface Water Availability

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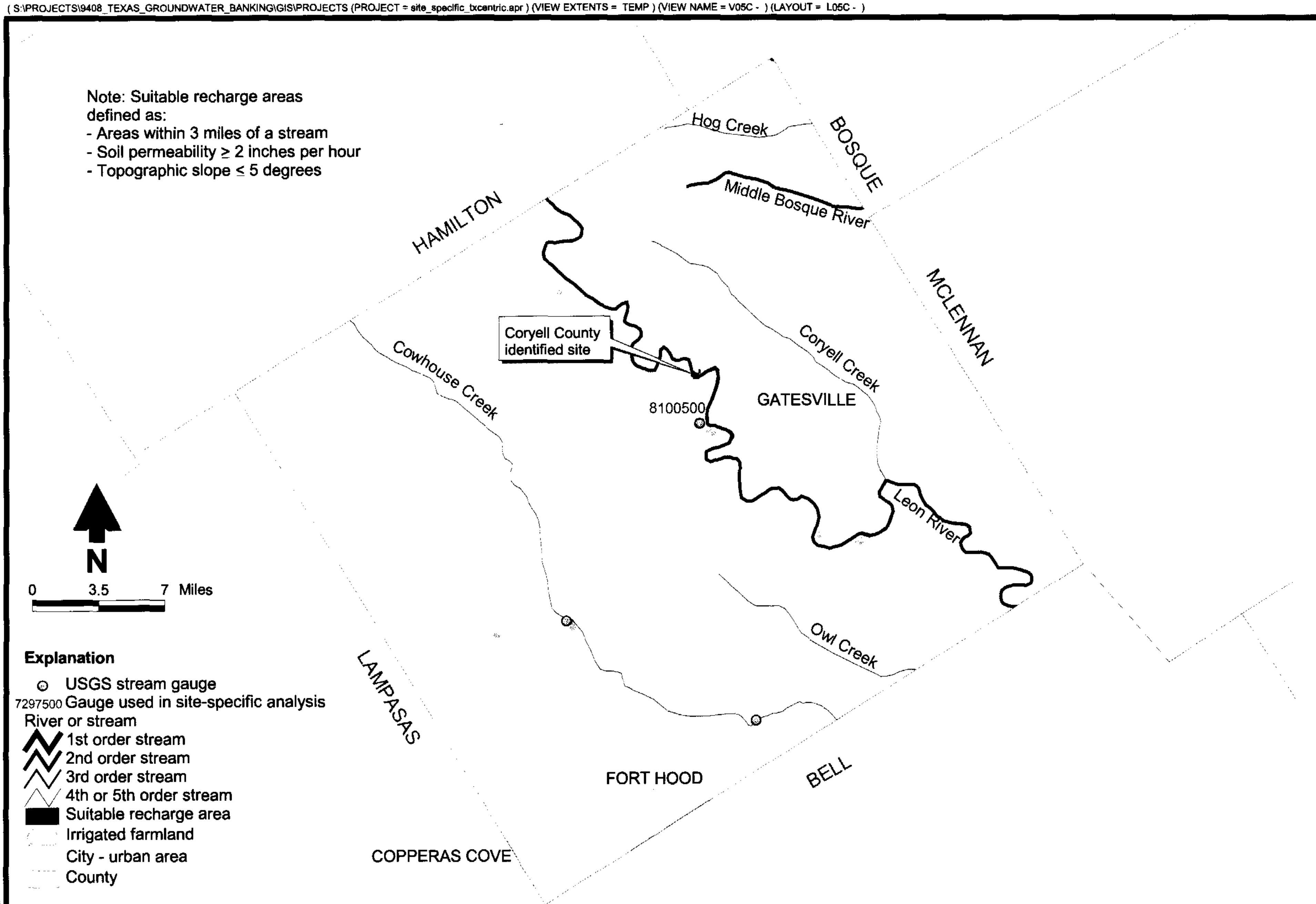
12-30-02 2:14PM JN 9408

Figure 21



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Coryell County Suitable Recharge Areas

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Figure 22

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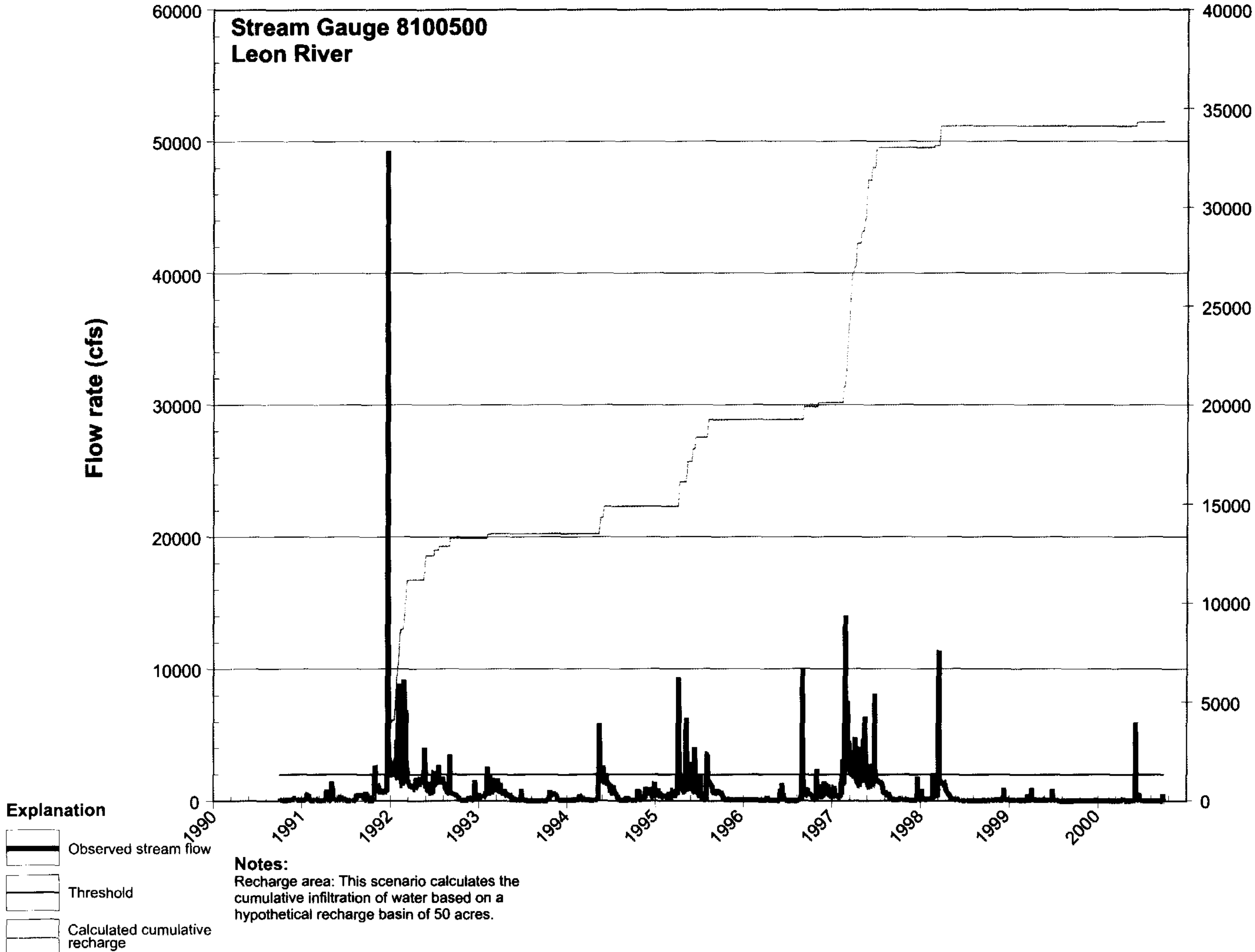

Notes:
Recharge area: This scenario calculates the cumulative infiltration of water based on a hypothetical recharge basin of 50 acres.

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Available Recharge Hydrograph for USGS Stream Gauge, Coryell County

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Figure 23

6. Region C

Parker and Wise Counties are the only counties selected for site-specific analysis from the Region C RWPA (Figure 24).

6.1 Water Resources Overview

Region C currently uses less than half of the total reliable groundwater supply available in the region. In 1996, Parker County was one of nine counties in the RWPA with groundwater use that exceeded TWDB projections of water availability. Table 8 provides water supply projections and Figure 25 shows selected water quality for the region.

Table 8. Projections for Selected Counties in Region C

County	SSURGO Soil Data Available	Projected Water Supply[a] (ac-ft/yr)						Acreage Suitable for Recharge[b]
		2000	2010	2020	2030	2040	2050	
Parker	Yes	–1,613	–11,469	–15,008	–24,715	–30,336	–33,874	13,939
Wise	No	11,531	–1,722	–3,429	–6,126	–7,981	–9,418	---

[a] Negative values indicate a deficit in supply
[b] Identified through site-specific analysis described in this report.
ac-ft/yr = Acre-feet per year
--- = Not available
SSURGO = Soil Survey Geographic database

Of the two counties selected in this region, Parker County is the only one for which high-resolution SSURGO soil data are available. In Parker County, no analysis of demand by type has been completed. However, based on the 1994 irrigated acreage coverage obtained from the TWDB, there appear to be only about 400 irrigated acres in the county.

Approximately 75 percent of the water used in Region C comes from reservoirs, with more than half of the water supply available to Region C coming from in-region reservoirs (Table 9). Figure 26 shows the existing and proposed conveyances within the region, one of which is within Parker County.

Table 9. List of Major Reservoirs, Region C Site-Selected Counties

County	Reservoir	Water Right Number[a]	Authorized Diversion (ac-ft/yr)
Parker	Weatherford	3356	5,220[b]
Tarrant and Wise	Eagle Mountain	3809	159,600[c]
Parker	Mineral Wells	4039	2,520

Source: Freese and Nichols, Inc. et al., 2001a. ac-ft/yr = Acre-feet per year
[a] Water right numbers are Certificate of Adjudication numbers. For permits issued since adjudication, they are the application number.
[b] Diversion does not include 59,400 ac-ft/yr of non-consumptive industrial use.
[c] Permitted diversion includes water released from Lake Bridgeport.

6.2 Rate, Area, and Time Period for Infiltration

Figure 27 shows the Brazos River as a prime potential source of surface recharge water in the southwestern portion of the county. The WAM model data show excess flows of more than 400,000 ac-ft/yr along the Brazos River above Lake Granbury (Figure 27).

Potential recharge sites in Parker County are scattered along the Brazos River in the southwestern portion of the county, along Rock Creek upstream of Mineral Wells, and along Willow Creek and the Clear Fork of the Trinity River upstream from Willow Park (Figure 28). Because of the minimal irrigated acreage in this county, municipal needs are more critical, and these sites are ideal locations because they are upstream from the towns of Mineral Wells, Willow Park, and Weatherford. However, the varying availability of good-quality recharge water affects the usability of the recharge areas for these municipalities:

- Rock Creek WAM data suggest available flows of up to 8,500 ac-ft/yr near Mineral Wells, although the smaller tributaries in this area have available flows less than 100 ac-ft/yr. A number of promising recharge locations exist in this area.

- WAM model data for the Clear Fork of the Trinity River above Lake Weatherford show excess flows of less than 100 ac-ft/yr. In addition, the Clear Fork of the Trinity River has been designated an impaired stream (Figure 25). Because of the small amount of available water and the impaired status of the stream, sites along the Clear Fork of the Trinity River, upstream of Willow Park, are likely unsuitable for banking.

- Willow Creek WAM data suggest excess flows of around 1,800 ac-ft/yr (Figure 27). Sites along Willow Creek could be potentially viable recharge sites for meeting the future needs of Weatherford, Texas.

Figure 29 illustrates computations of banked water for two hydrographs. The top graph is for Gauge 8090800 on the Brazos River in the southwestern portion of the county, and the bottom graph is for Gauge 8045850 on the Clear Fork of the Trinity River at Willow Park. The Brazos gauge is very close to several potential recharge sites, and the Clear Fork of the Trinity gauge is about 7 miles downstream of potential recharge sites (Figure 28). Both sites overlie the Trinity Aquifer outcrop.

The average soil permeability for a 3-mile radius around the Brazos site is about 12 ft/d. The average soil permeability for the soils in the potential recharge areas upstream of the Clear Fork of the Trinity River gauge is about 11 ft/d. Calculated cumulative recharge for the Brazos River site is about 225,000 ac-ft over 10 years, while calculated cumulative recharge for the Clear Fork of the Trinity River site is about 22,500 ac-ft over 10 years. At the Clear Fork of the Trinity River site, more than half of the calculated infiltration volume is supplied by two storm events that occurred in late 1992 (Figure 29). As mentioned above, water quality concerns and limitations on water availability probably limit the utility of the Clear Fork of the Trinity River site. It appears, however, that large quantities of Brazos River water could potentially be banked in Parker County.

In addition to the above infiltration calculations, which were made assuming a basin size of 100 acres, the two selected hydrographs were analyzed to determine the area required to infiltrate all available water (assumed to be one-half of the flow above the threshold values indicated on Figure 29) and the average time period for infiltration. The required areas and average time periods for the Brazos and Clear Fork of the Trinity River sites are 594 acres and 5.6 days and 9 acres and 6 days, respectively.

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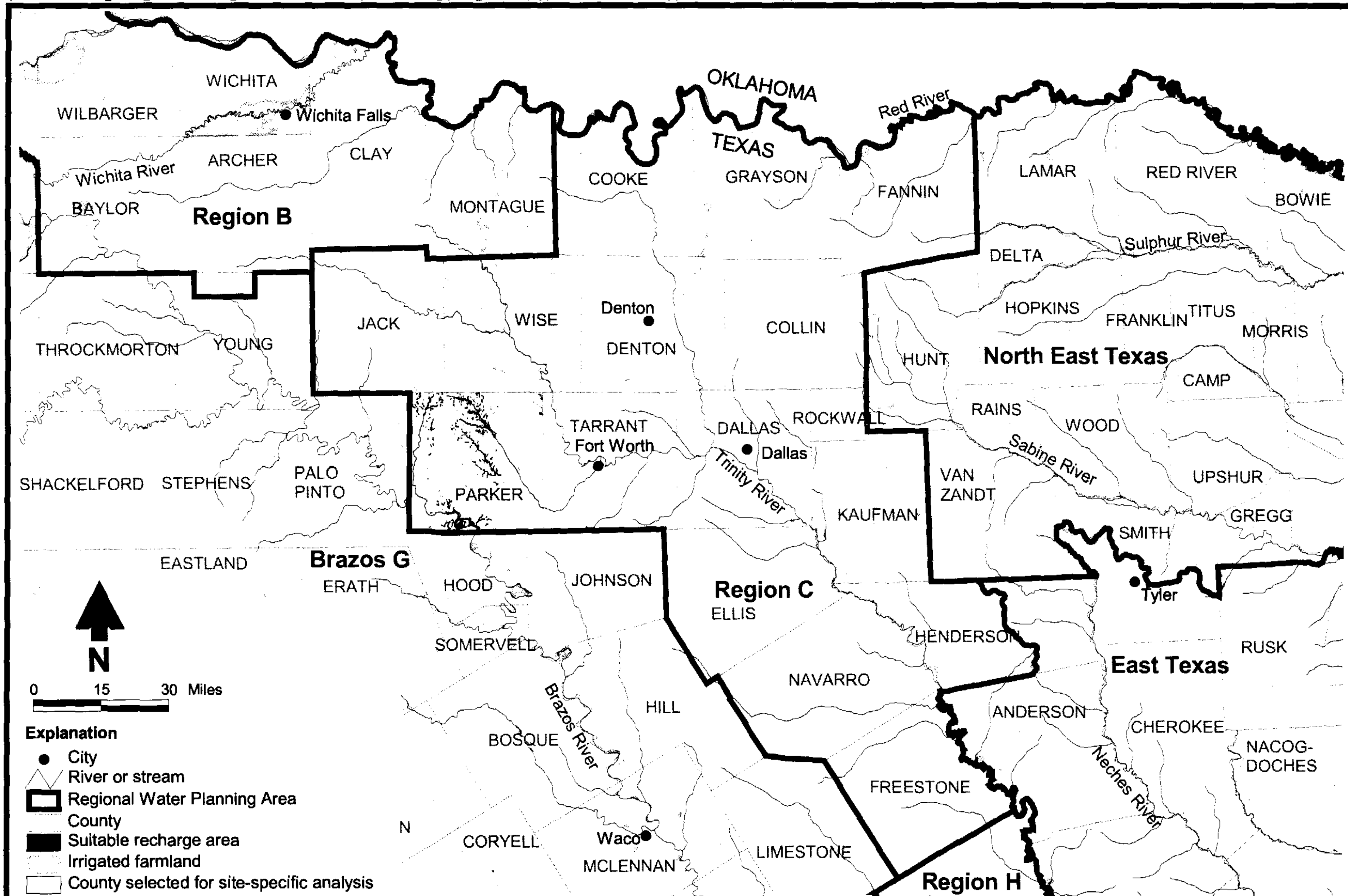

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Region C Suitable Recharge Areas

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Figure 24

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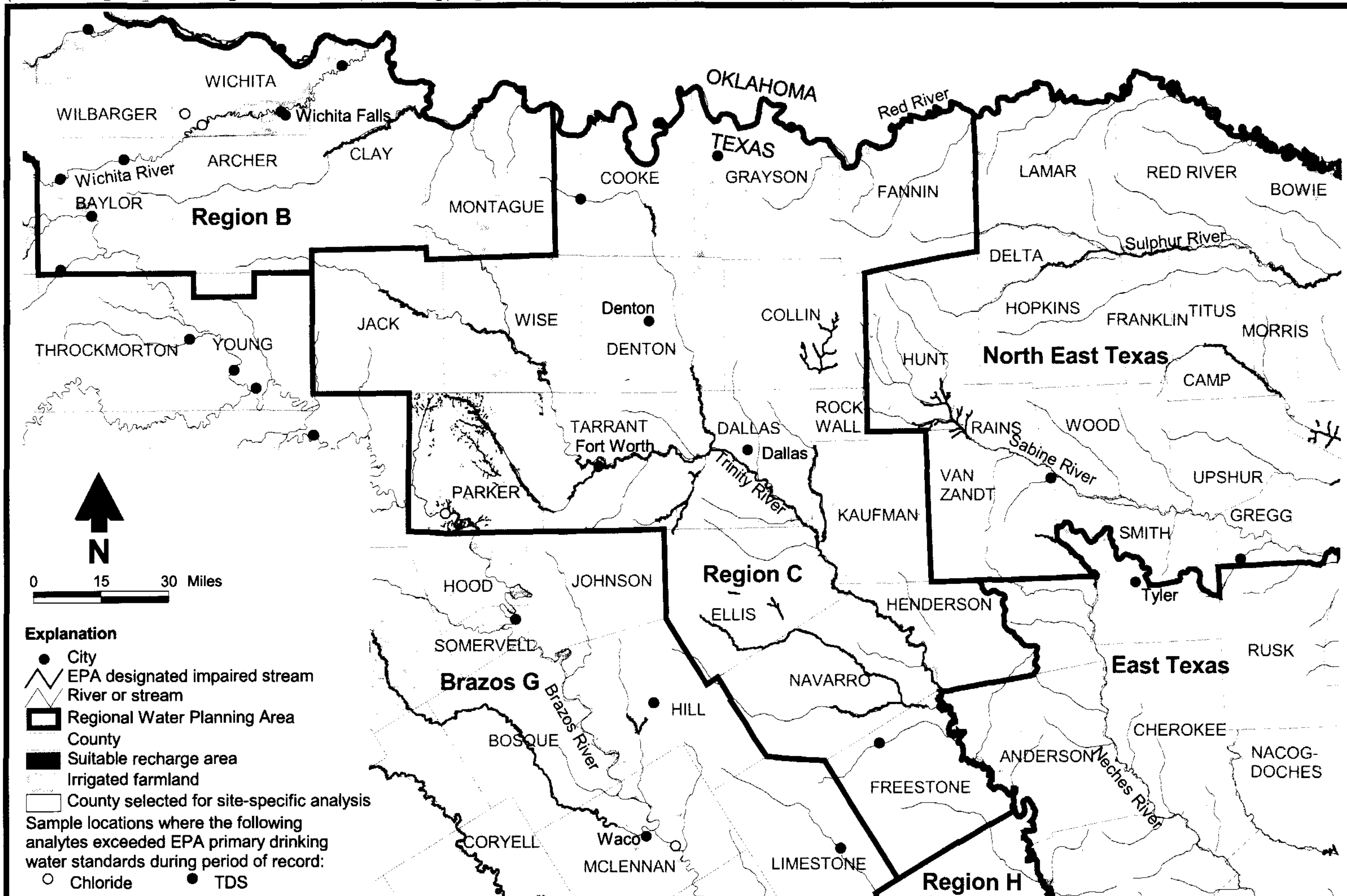

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Region C Water Quality

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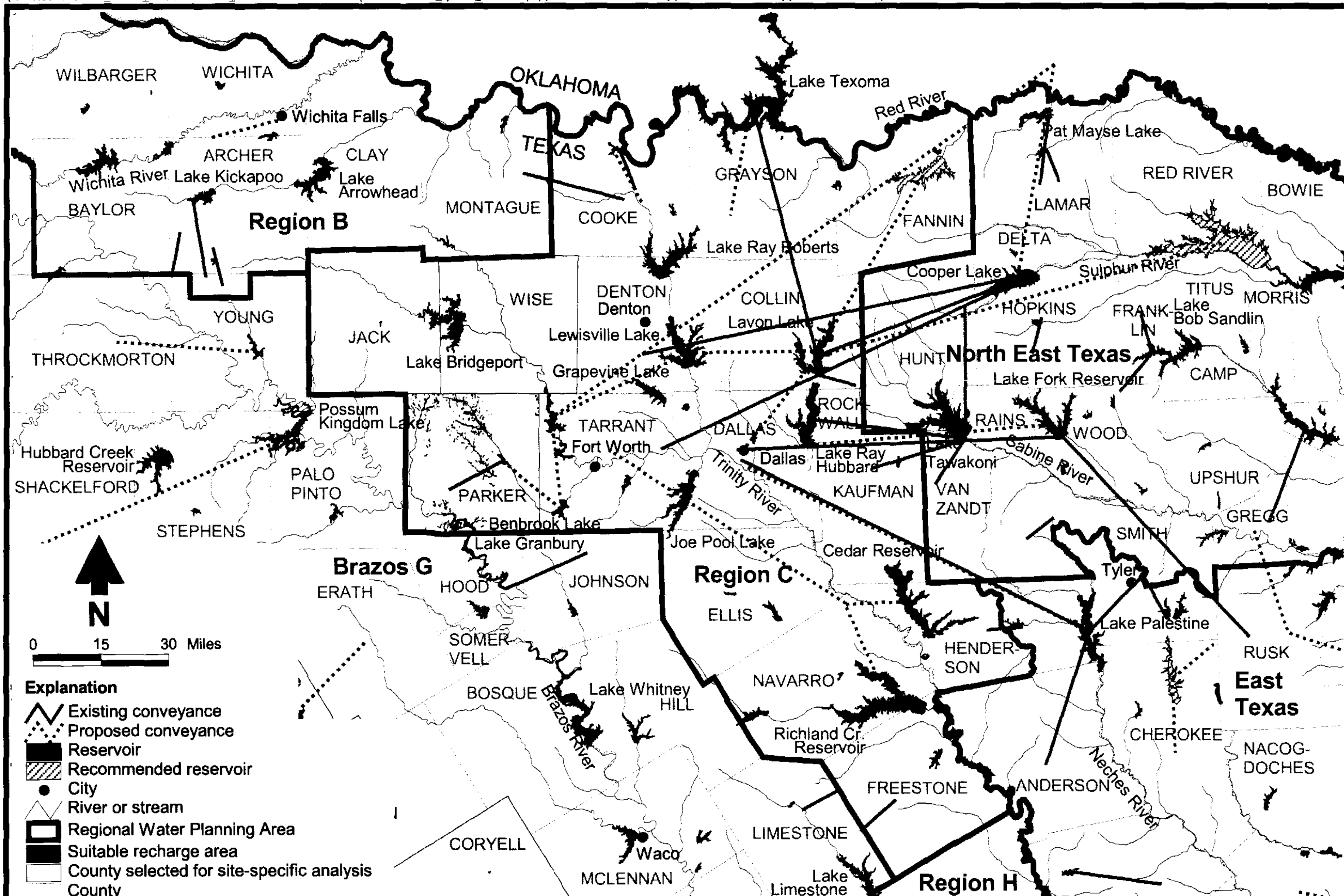
Figure 25



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Region C Reservoirs and Conveyances

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Figure 26

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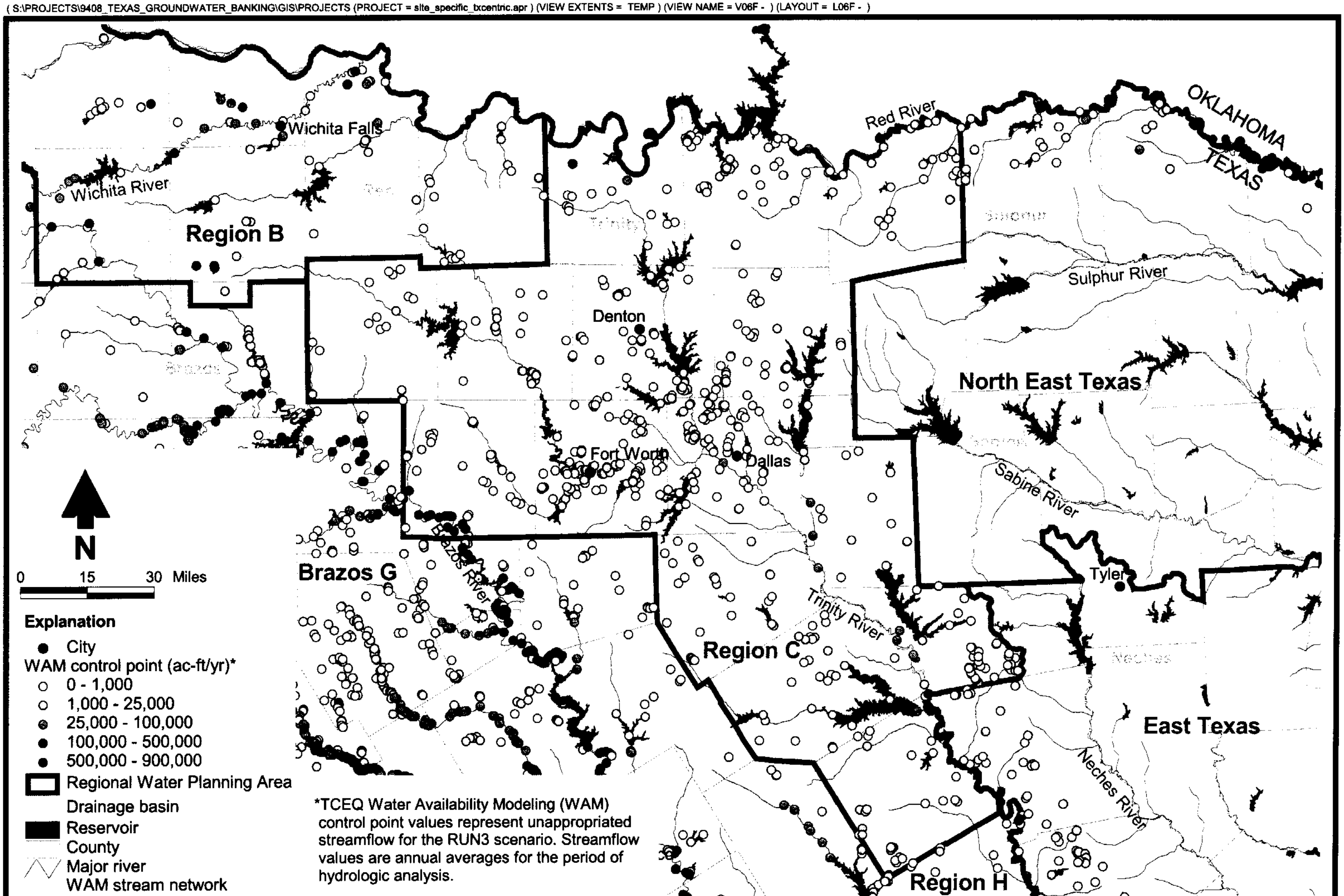

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Region C Surface Water Availability

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Figure 27

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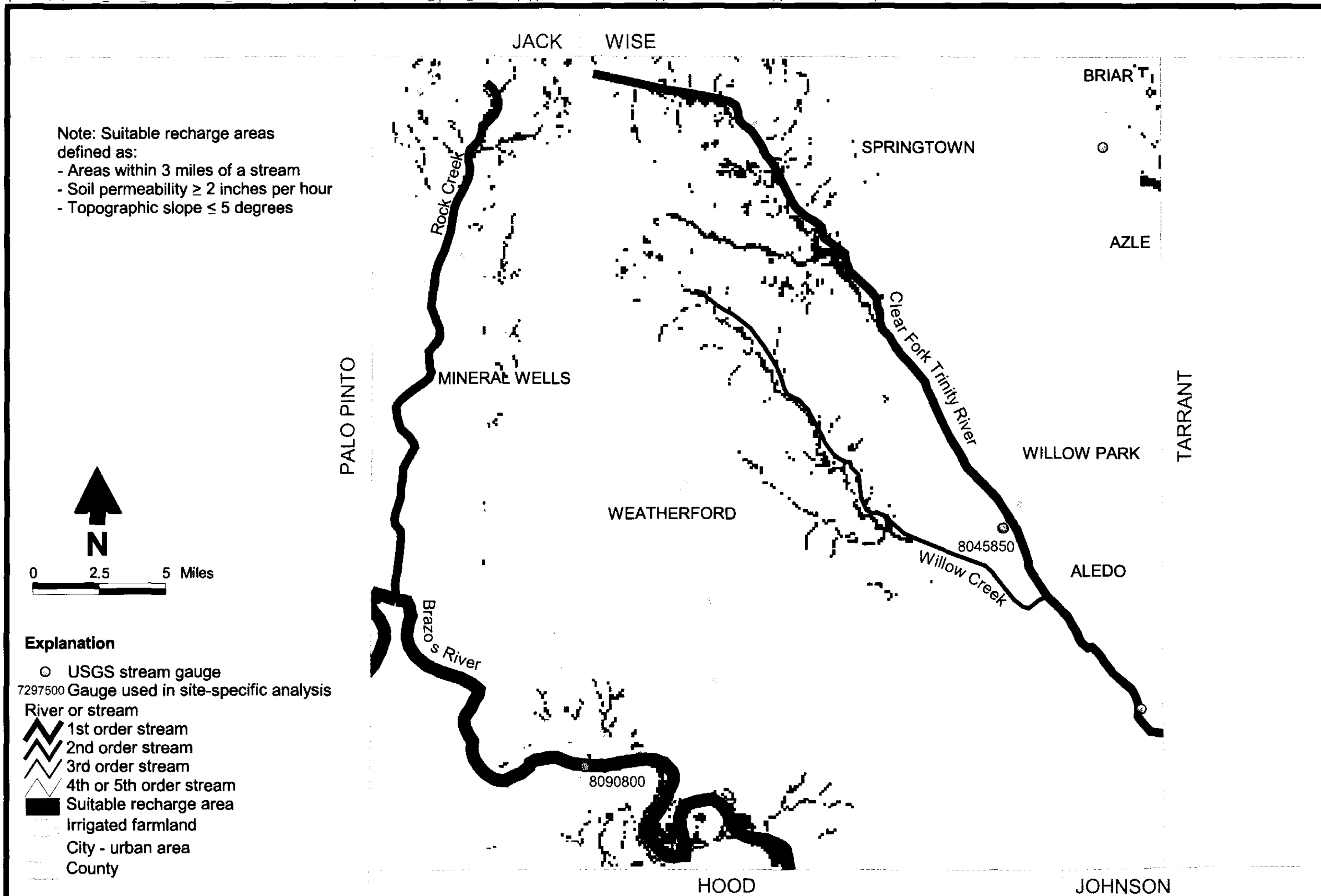

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Parker County Suitable Recharge Areas

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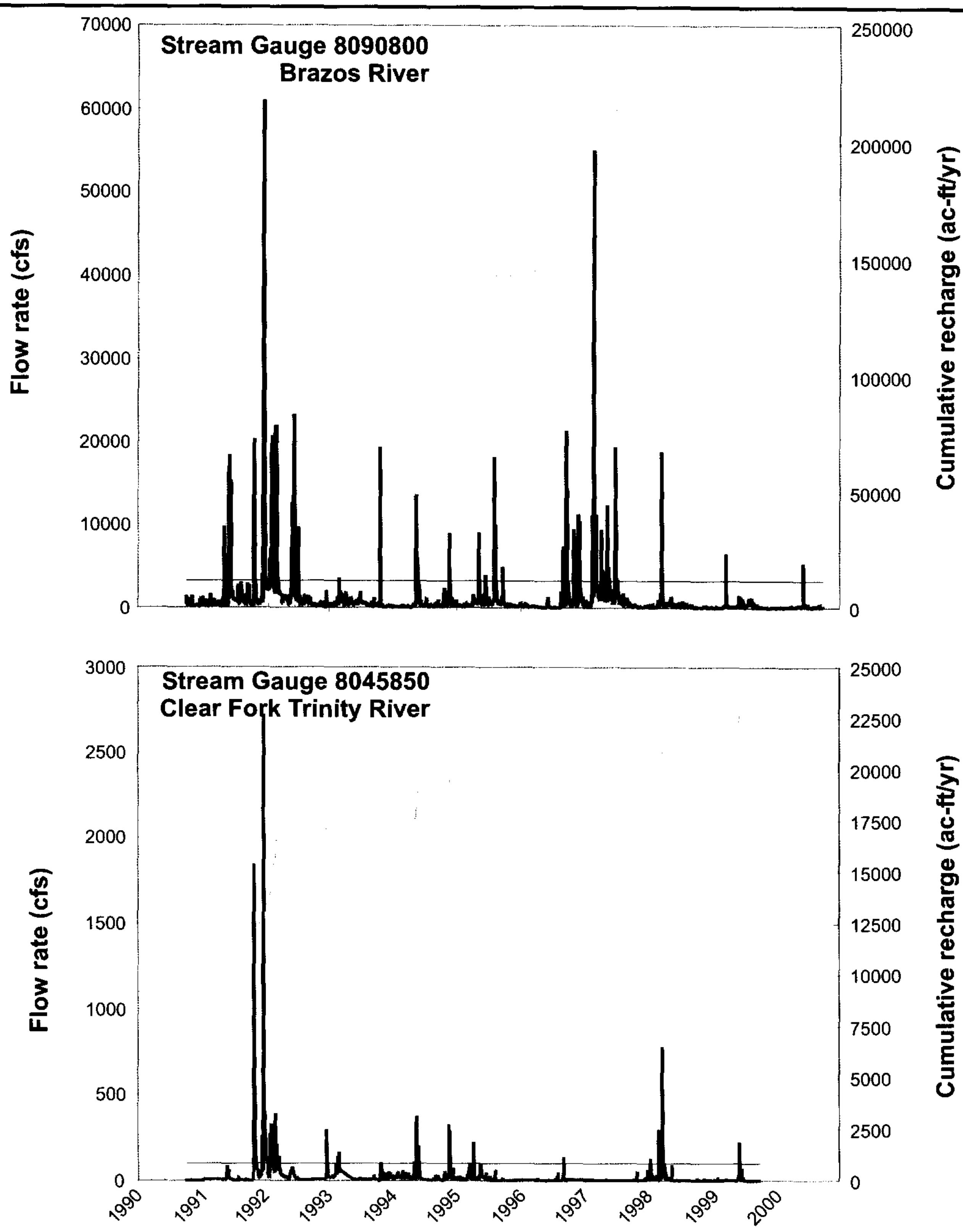
JN 9408

Figure 28



Explanation

Observed stream flow

Threshold

Calculated cumulative recharge

Notes:
Recharge area: This scenario calculates the cumulative infiltration of water based on a hypothetical recharge basin of 100 acres.

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Available Recharge Hydrograph for USGS Stream Gauges, Parker County

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1-08-03 JN 9408

Figure 29

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