Identification of Geographic Areas in Texas Suitable for Groundwater Banking

Prepared for **Texas Water Development Board**
Austin, Texas

Kenneth Calhoun
T. Neil Blandford
Mark D. Ankeny

Bridget R. Scanlon
Robert C. Reedy
Bureau of Economic Geology

December 31, 2002

Daniel B. Stephens & Associates, Inc.
6020 Academy NE, Suite 100 • Albuquerque, New Mexico 87109

Table of Contents

Section **Page**

Executive Summary vii

1. Introduction 1
   1.1 Types of Artificial Recharge Systems 1
      1.1.1 Artificial Recharge at the Ground Surface 2
      1.1.2 Artificial Recharge in the Unsaturated Zone 4
      1.1.3 Artificial Recharge in the Saturated Zone 4
   1.2 Historical Use of Artificial Recharge in Texas 5
      1.2.1 Use of Spreading Basins in Texas 5
      1.2.2 Use of In-Channel Infiltration Techniques in Texas 7
      1.2.3 Use of Aquifer Storage and Recovery in Texas 7
   1.3 Project Objectives and Scope of Work 8

2. Statewide Screening Analysis 11
   2.1 Geographic Information Systems 11
   2.2 Screening Methods 12
   2.3 Statewide Screening Criteria 13
      2.3.1 Surface Water Quality 14
      2.3.2 Groundwater Quality 16
      2.3.3 High Demand Regions 17
      2.3.4 Aquifer Characteristics 17
      2.3.5 Distance from Surface Water 18
      2.3.6 Topography (Slope of Area) 19

3. Site-Specific Analysis 33
   3.1 Regional Grouping of Counties 33
   3.2 Site-Specific Analysis Methodology 35
      3.2.1 Rate of Infiltration 37
      3.2.2 Slope of Area 38
      3.2.3 Distance from Surface Water 38
      3.2.4 Water Quality and Environmental Hazards 39
      3.2.5 Water Storage and Conveyance Systems 40
   3.3 Water Availability and Infiltration Computations 40
      3.3.1 Basin Infiltration Calculations 41
      3.3.2 TCEQ Surface Water Availability Models 44
   3.4 Calculation of Recovery Efficiency 46

4. South Central Texas Region 57
   4.1 Water Resources Overview 57
   4.2 Rate, Area and Time Period of Infiltration 59

5. Brazos Region 73
   5.1 Water Resources Overview 73
   5.2 Rate, Area, and Time Period for Infiltration 74

Table of Contents (Continued)

Section **Page**

6. Region C 89
   6.1 Water Resources Overview 89
   6.2 Rate, Area, and Time Period for Infiltration 90

7. Region F 105
   7.1 Water Resources Overview 105
   7.2 Rate, Area and Time Period for Infiltration 106

8. Ogallala Region 121
   8.1 Water Resources Overview 121
   8.2 Rate, Area, and Time Period for Infiltration 123

9. Far West Texas Region 137
   9.1 Water Resources Overview 137
   9.2 Rate, Area, and Time Period for Infiltration 138

10. Conclusions and Recommendations 151
    10.1 South Central Texas Region 152
    10.2 Brazos Region 154
    10.3 Region C 155
    10.4 Region F 155
    10.5 Ogallala Region 157
    10.6 Far West Texas Region 157
    10.7 Recommendations and Additional Research 158

References 161

List of Figures

Figure **Page**

1 Project Flow Chart 9

2 Groundwater Quality Locations with Sulfate Concentrations Greater than the EPA Secondary Standard 21

3 Projected 2050 Water Demand 23

4 Major Aquifer Outcrop Areas 25

List of Figures (Continued)

Figure **Page**

5 Suitable Depth to Groundwater in Major Aquifer Outcrop Areas 27

6 Distance to Surface Water Screen 29

7 Topographic Slope Screen 31

8 Counties Selected for Site-Specific Analysis 49

9 Counties Selected for Site-Specific Analysis with SSURGO Data Available 51

10 Stream Hydrographs and Corresponding Available Recharge Hydrographs, Uvalde County 53

11 Available Recharge Hydrographs for 10-Acre and 100-Acre Basin Areas 55

12 South Central Texas Suitable Recharge Areas 61

13 South Central Texas Water Quality 63

14 South Central Texas Reservoirs and Conveyances 65

15 South Central Texas Surface Water Availability 67

16 Uvalde County Suitable Recharge Areas 69

17 Available Recharge Hydrograph for USGS Stream Gauges, Uvalde County 71

18 Brazos G Suitable Recharge Areas 77

19 Brazos G Water Quality 79

20 Brazos G Reservoirs and Conveyances 81

21 Brazos G Surface Water Availability 83

22 Coryell County Suitable Recharge Areas 85

23 Available Recharge Hydrograph for USGS Stream Gauge, Coryell County 87

24 Region C Suitable Recharge Areas 93

25 Region C Water Quality 95

26 Region C Reservoirs and Conveyances25 Region C Water Quality 97

27 Region C Surface Water Availability 99

List of Figures (Continued)

Figure **Page**

28 Parker County Suitable Recharge Areas 101
29 Available Recharge Hydrograph for USGS Stream Gauge, Parker County 103
30 Region F Suitable Recharge Areas 109
31 Region F Water Quality 111
32 Region F Reservoirs and Conveyances 113
33 Region F Surface Water Availability 115
34 Reeves County Suitable Recharge Areas 117
35 Available Recharge Hydrograph for USGS Stream Gauges, Reeves County 119
36 Ogallala Suitable Recharge Areas 125
37 Ogallala Water Quality 127
38 Ogallala Reservoirs and Conveyances 129
39 Ogallala Surface Water Availability 131
40 Randall County Suitable Recharge Areas 133
41 Available Recharge Hydrograph for USGS Stream Gauges, Randall County 135
42 Far West Texas Suitable Recharge Areas 141
43 Far West Texas Water Quality 143
44 Far West Texas Reservoirs and Conveyances 145
45 El Paso County Suitable Recharge Areas 147
46 Available Recharge Hydrograph for USGS Stream Gauges, El Paso County 149

List of Tables

Table **Page**

1 Counties Selected for Site-Specific Analysis Grouped by Region 34

2 Water Deficit and Potential High-Permeability Soils 36

3 Lake Surface Evaporation Losses by County 42

4 Projections for Selected Counties in the South Central Texas Region 57

5 Major Reservoirs, South Central Texas Region Site-Selected Counties 58

6 Projections for Selected Counties in the Brazos Region 73

7 List of Major Reservoirs, Brazos Region Site-Selected Counties 74

8 Projections for Selected Counties in Region C 89

9 List of Major Reservoirs, Region C Site-Selected Counties 90

10 Projections for Selected Counties in Region F 105

11 List of Major Reservoirs, Region F Site-Selected Counties 106

12 Projections for Selected Counties in Ogallala Region (Llano Estacado and Panhandle Regional Water Planning Areas) 122

13 Projections for El Paso County in the Far West Texas Region 137

14 Summary of Site-Specific Infiltration Calculations for Selected Counties 153

List of Appendices

Appendix

A Scope of Work and Review Comments on Draft Report

B GIS Data Guide

C ArcView GIS 3.2 Screening Analysis Tool

Page intentionally left blank

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

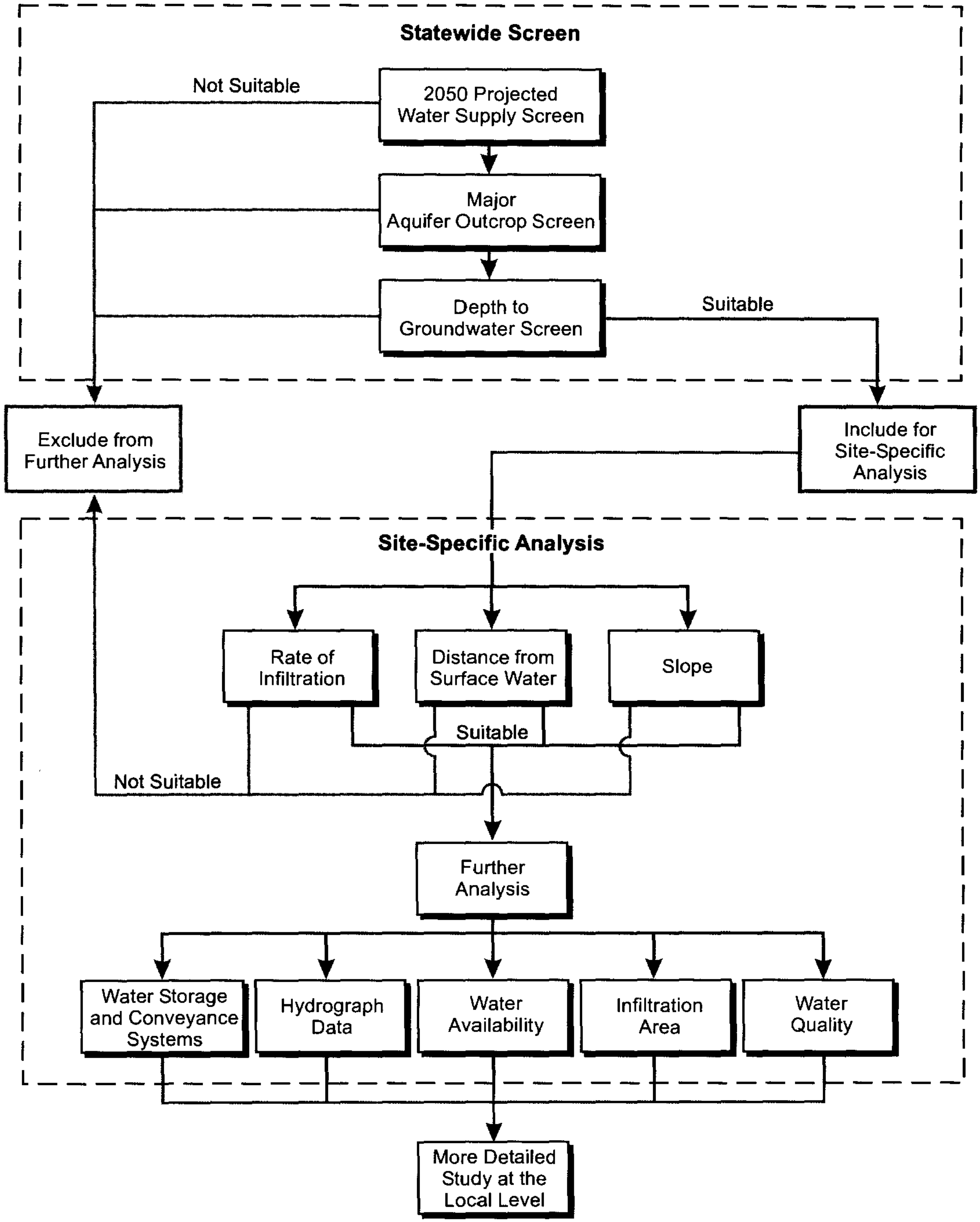
Pflugerville. Region N has also planned an ASR system to artificially recharge the Gulf Coast Aquifer.

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.

1-3-03 JN 9408

Figure 1

T:\DR10-VDR-PROJECTS\9408\940803K.CDR

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

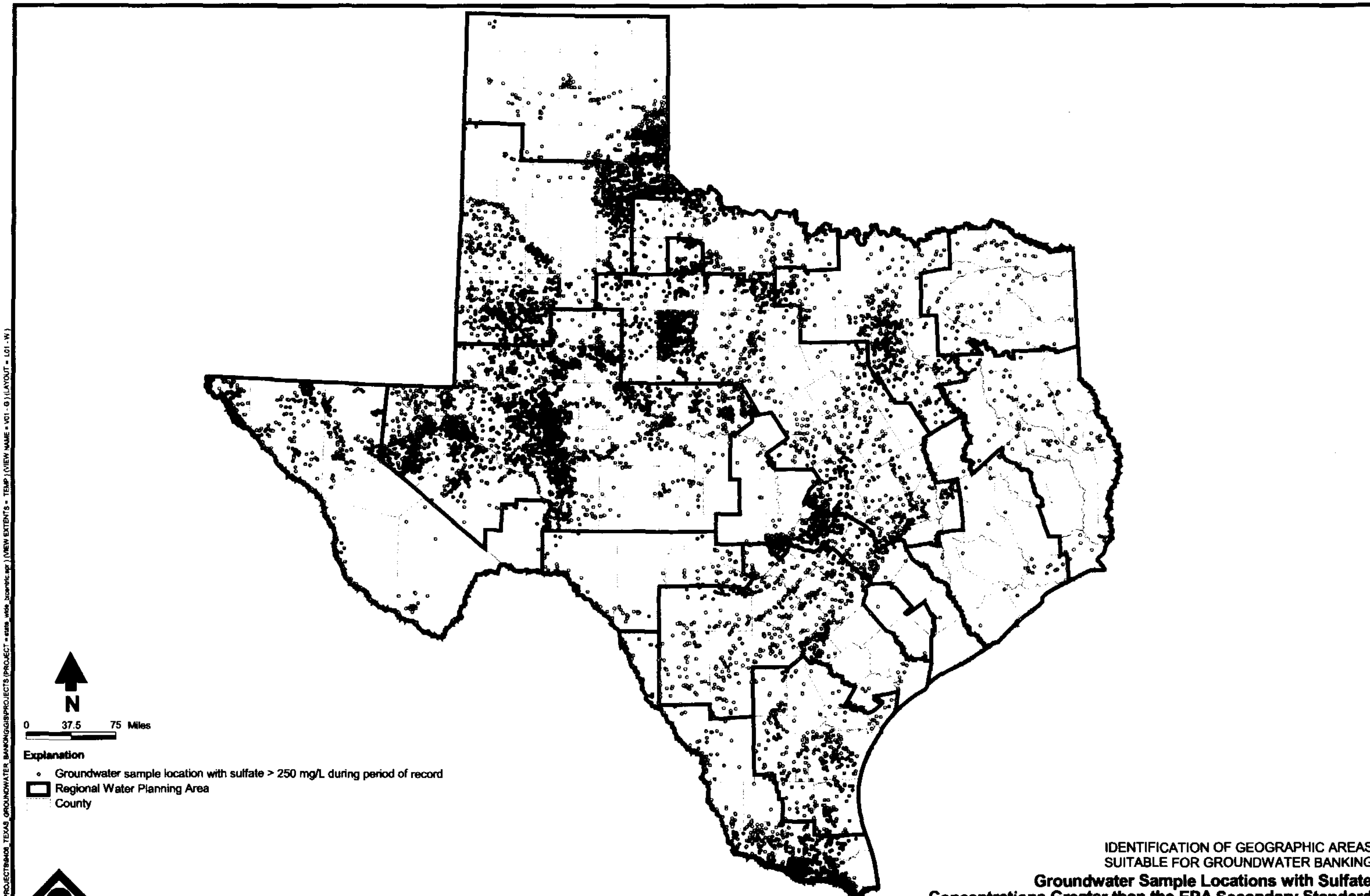
A recharge site's suitability is based, in part, on whether or not the location is practical in terms of its proximity to source water for recharge. The cost associated with moving water long distances may prohibit the use of recharge basins that are too far away from the surface water source.

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
SUITABLE FOR GROUNDWATER BANKING

Groundwater Sample Locations with Sulfate Concentrations Greater than the EPA Secondary Standard

Daniel B. Stephens & Associates, Inc.
12-31-02 2:11PM JN 9408

Figure 2

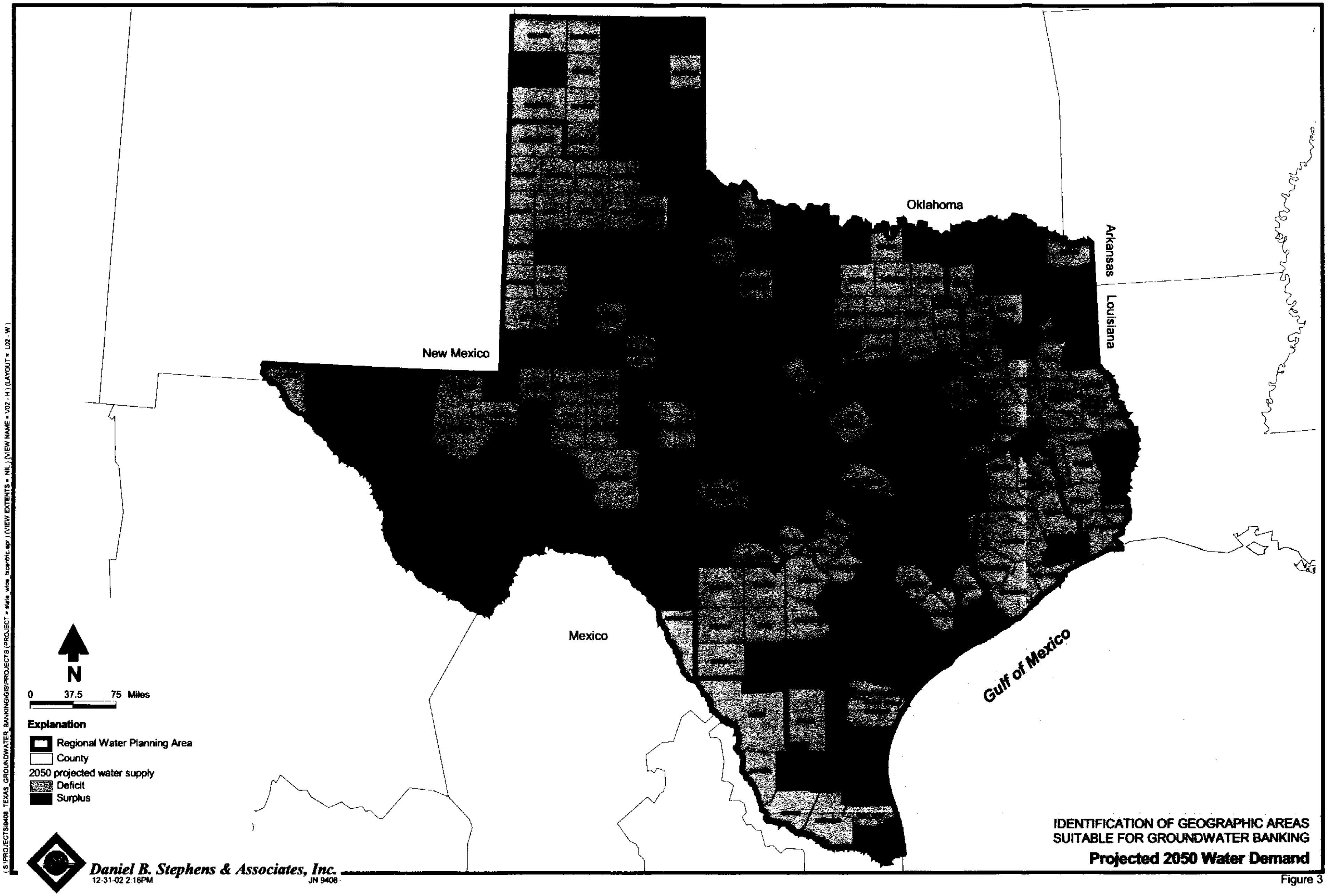
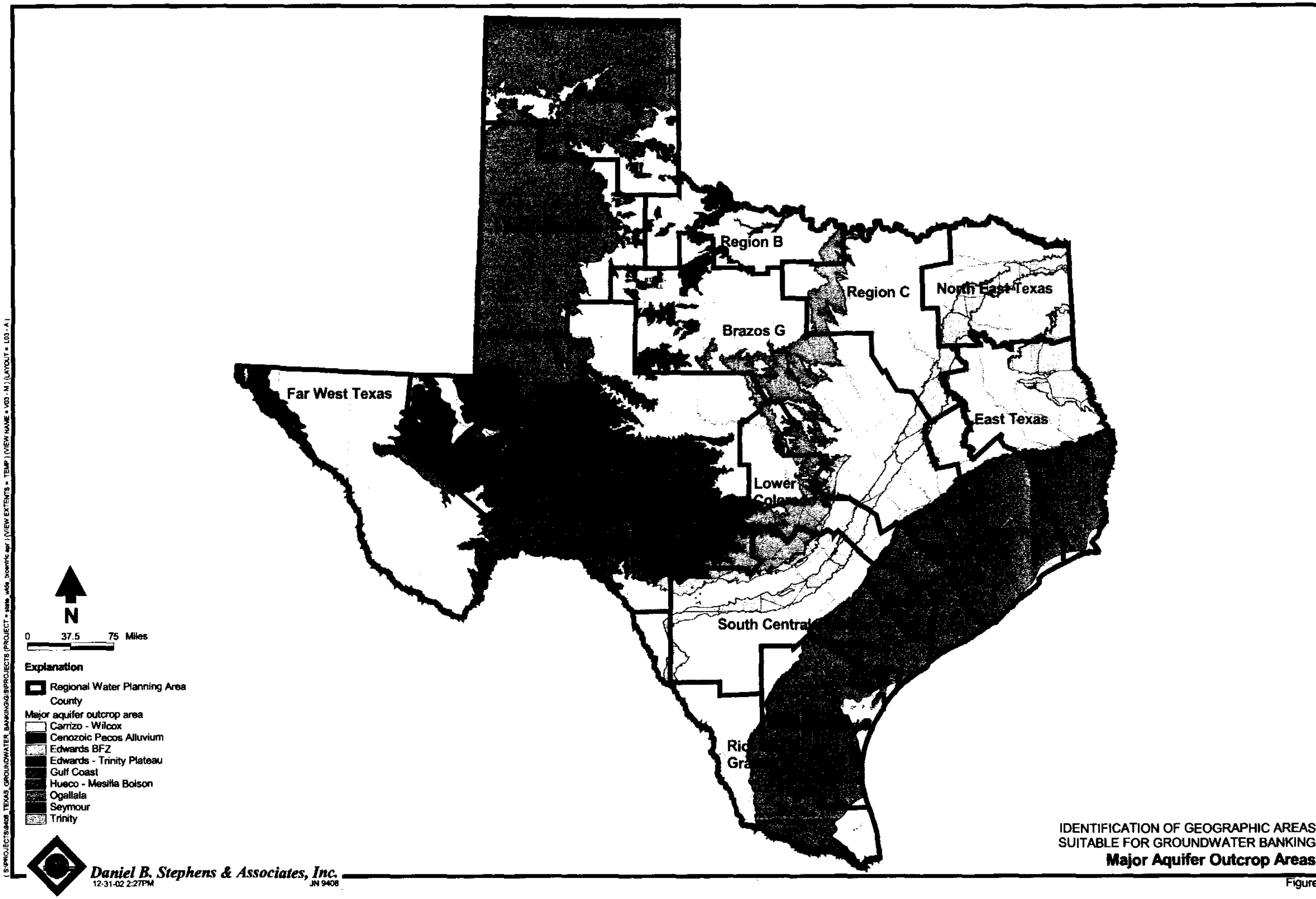
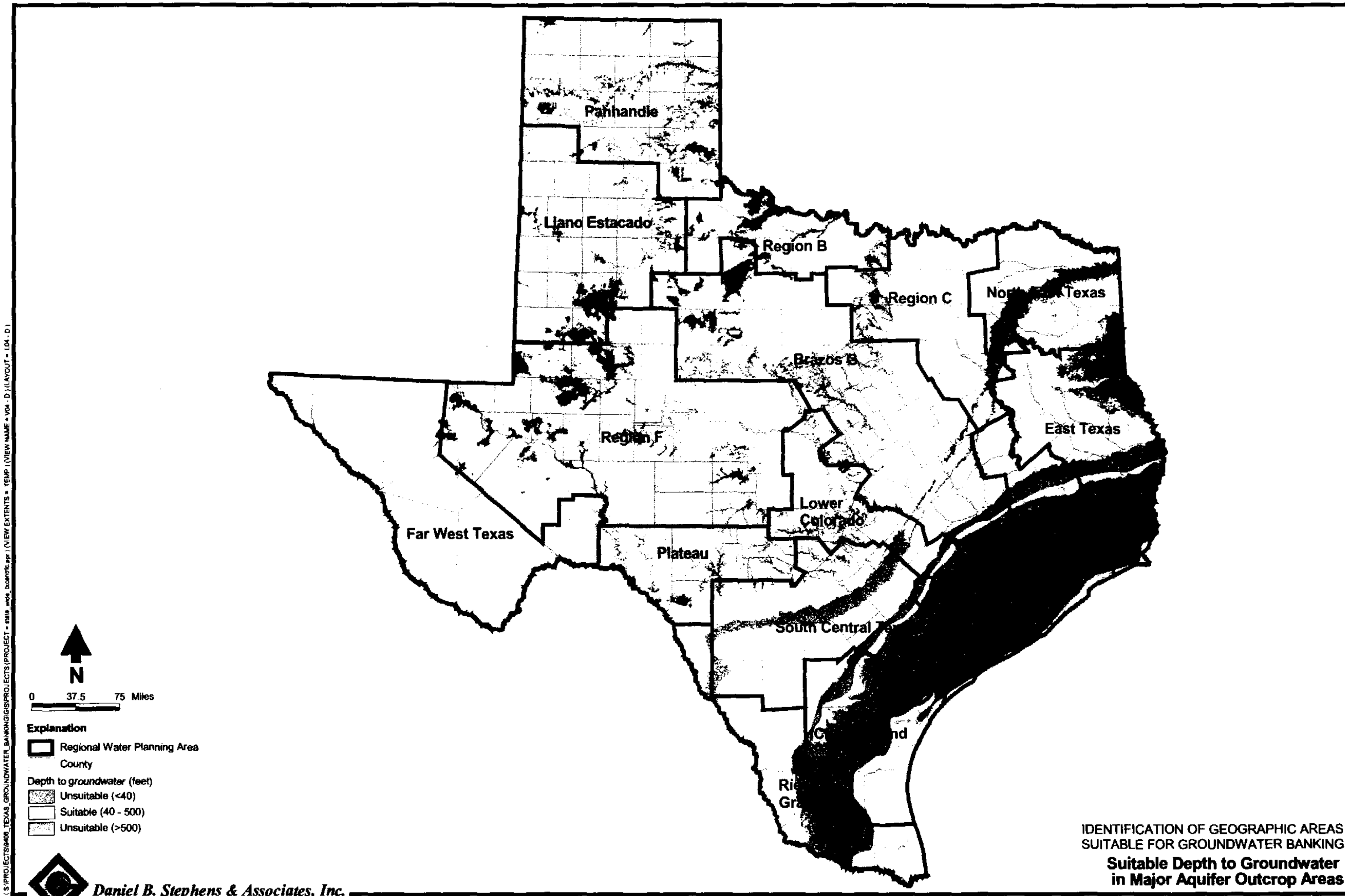

Oklahoma
Arkansas
Louisiana
New Mexico
Mexico
Gulf of Mexico
N
0 37.5 75 Miles
Explanation
Regional Water Planning Area
County
2050 projected water supply
Deficit
Surplus
IDENTIFICATION OF GEOGRAPHIC AREAS
SUITABLE FOR GROUNDWATER BANKING
Projected 2050 Water Demand
Daniel B. Stephens & Associates, Inc.
12-31-02 2:16PM
JN 9408

Figure 3



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

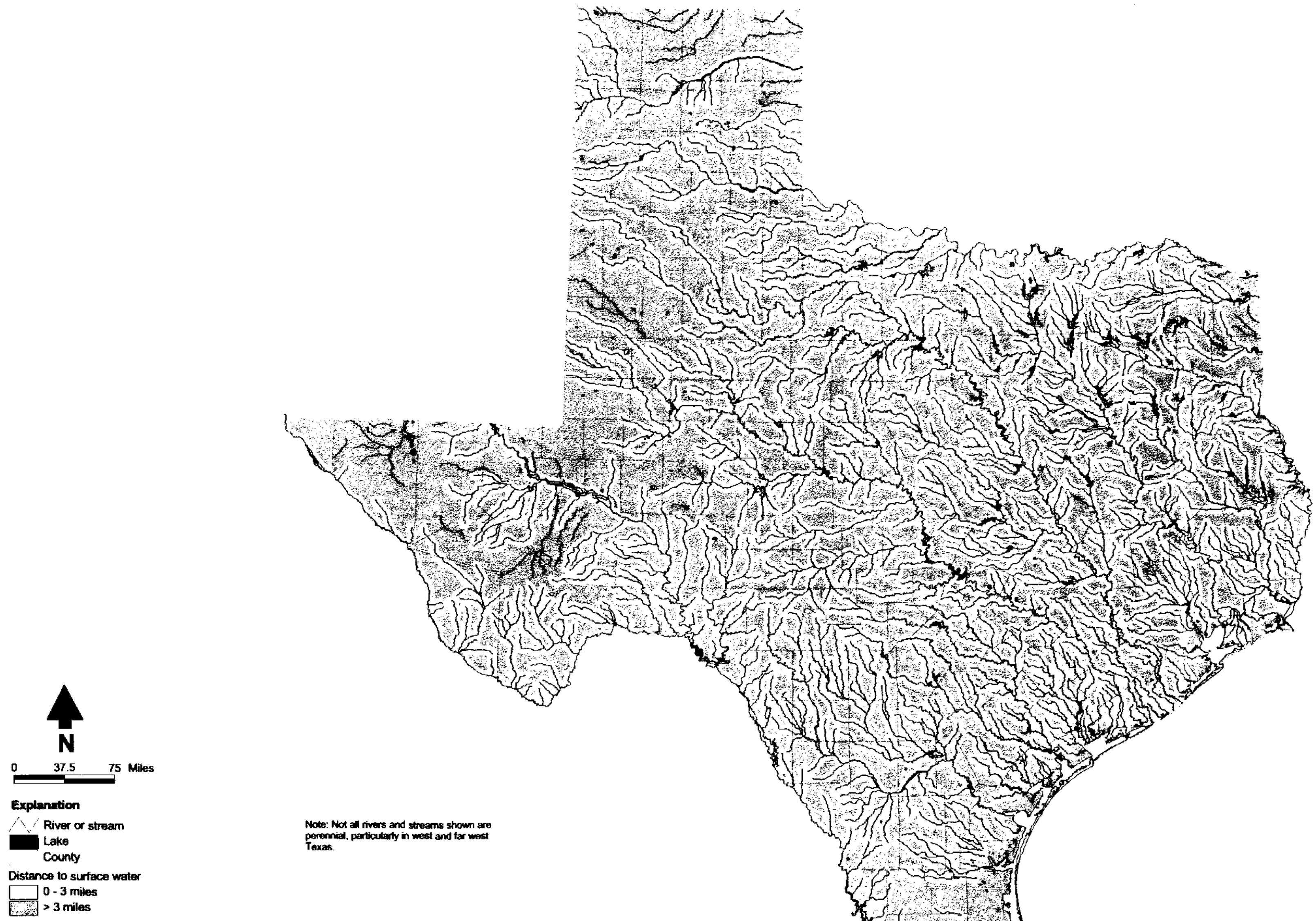
Figure 4



IDENTIFICATION OF GEOGRAPHIC AREAS
SUITABLE FOR GROUNDWATER BANKING

Suitable Depth to Groundwater in Major Aquifer Outcrop Areas

Figure 5



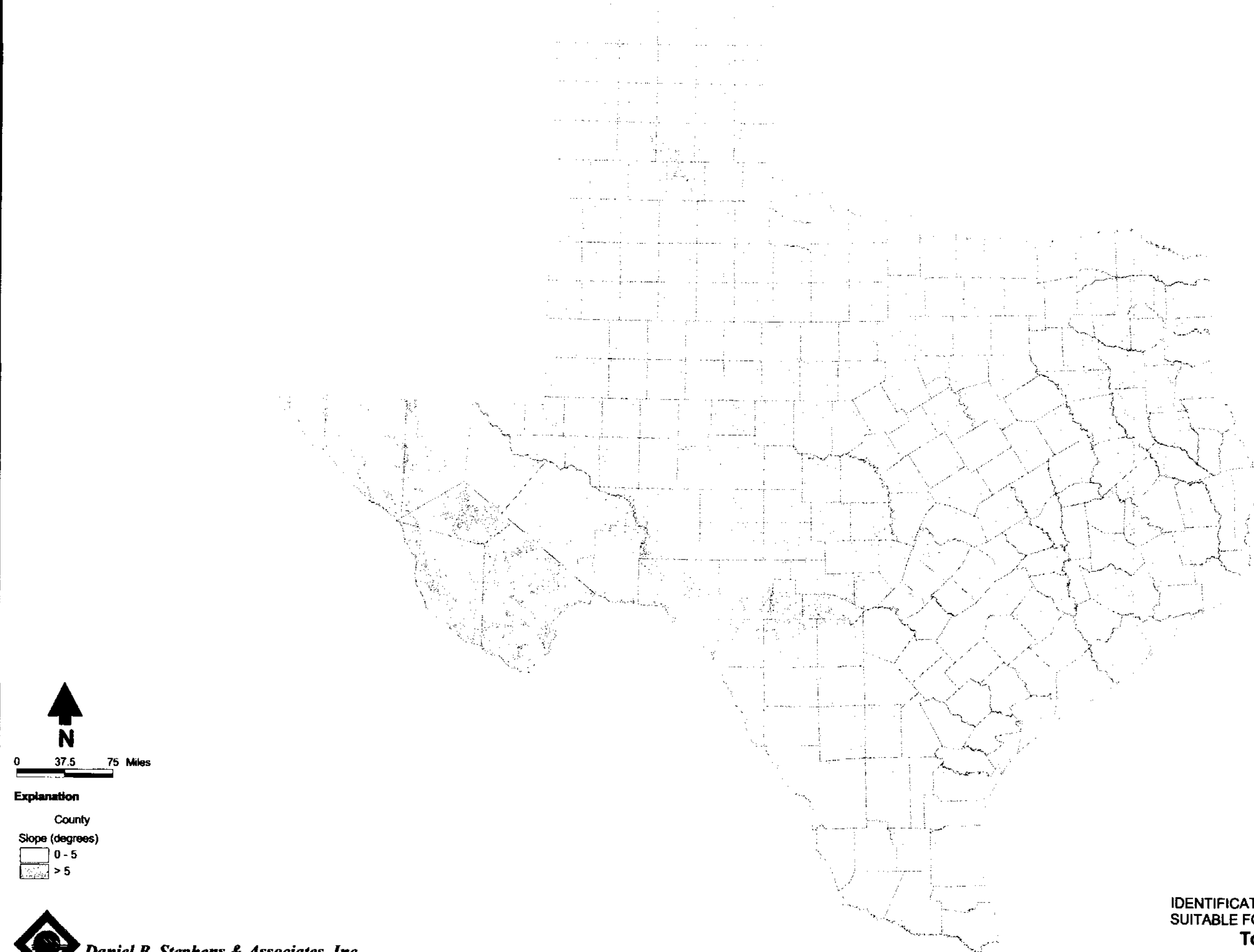
(S:\PROJECTS\9406_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = state_wide_bcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V05 - D) (LAYOUT = L05 - 1)

Daniel B. Stephens & Associates, Inc.
12-31-02 2:33PM
JN 9406

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Distance to Surface Water Screen

Figure 6



(S:\PROJECTS\9406_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = state_wide_bcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V06 - S) (LAYOUT = L06 - S))

Daniel B. Stephens & Associates, Inc.
12-31-02 2:37PM
JN 9406

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)

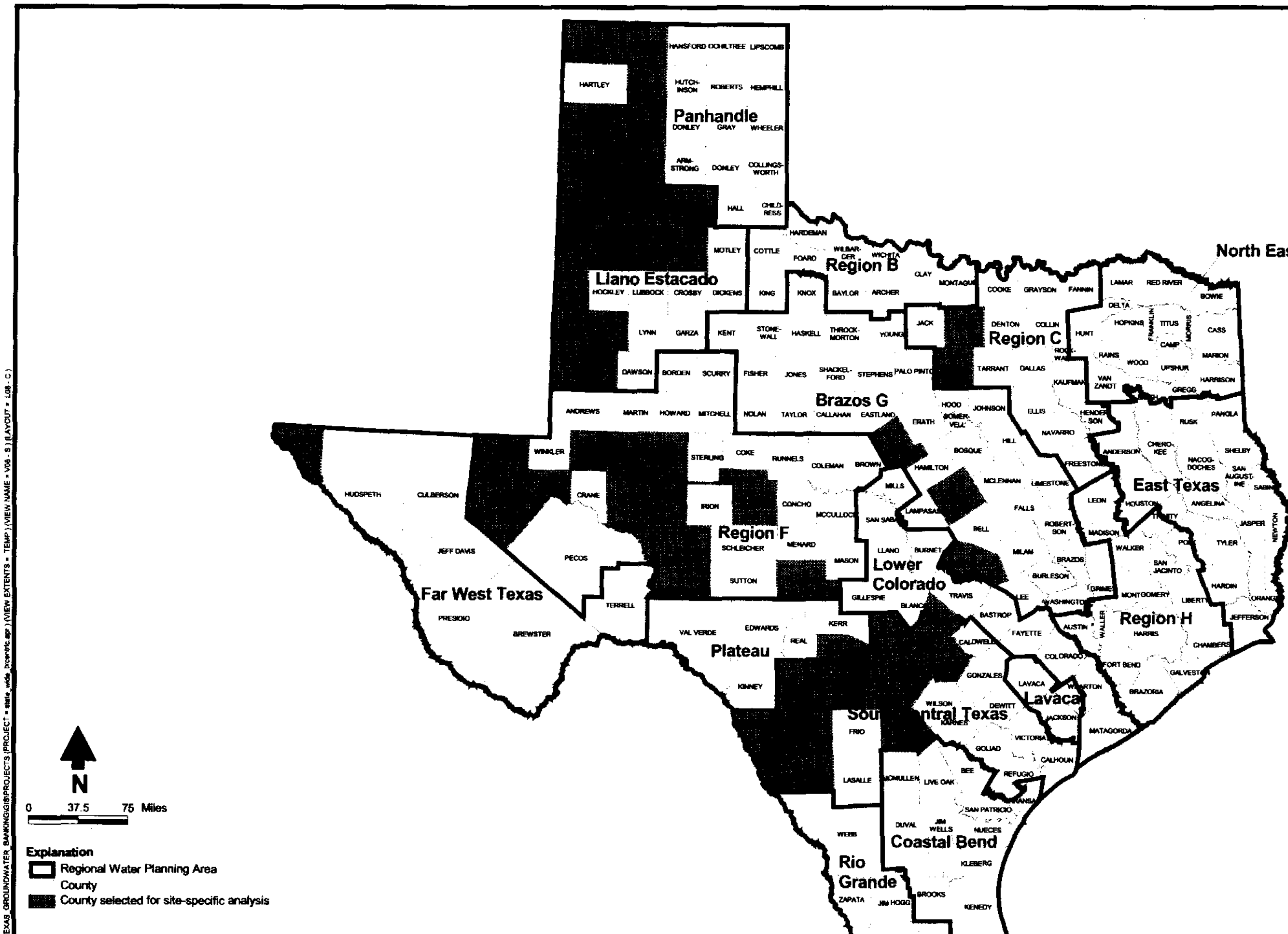
i = average hydraulic gradient in the vicinity of the recharge area (length/length)

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.

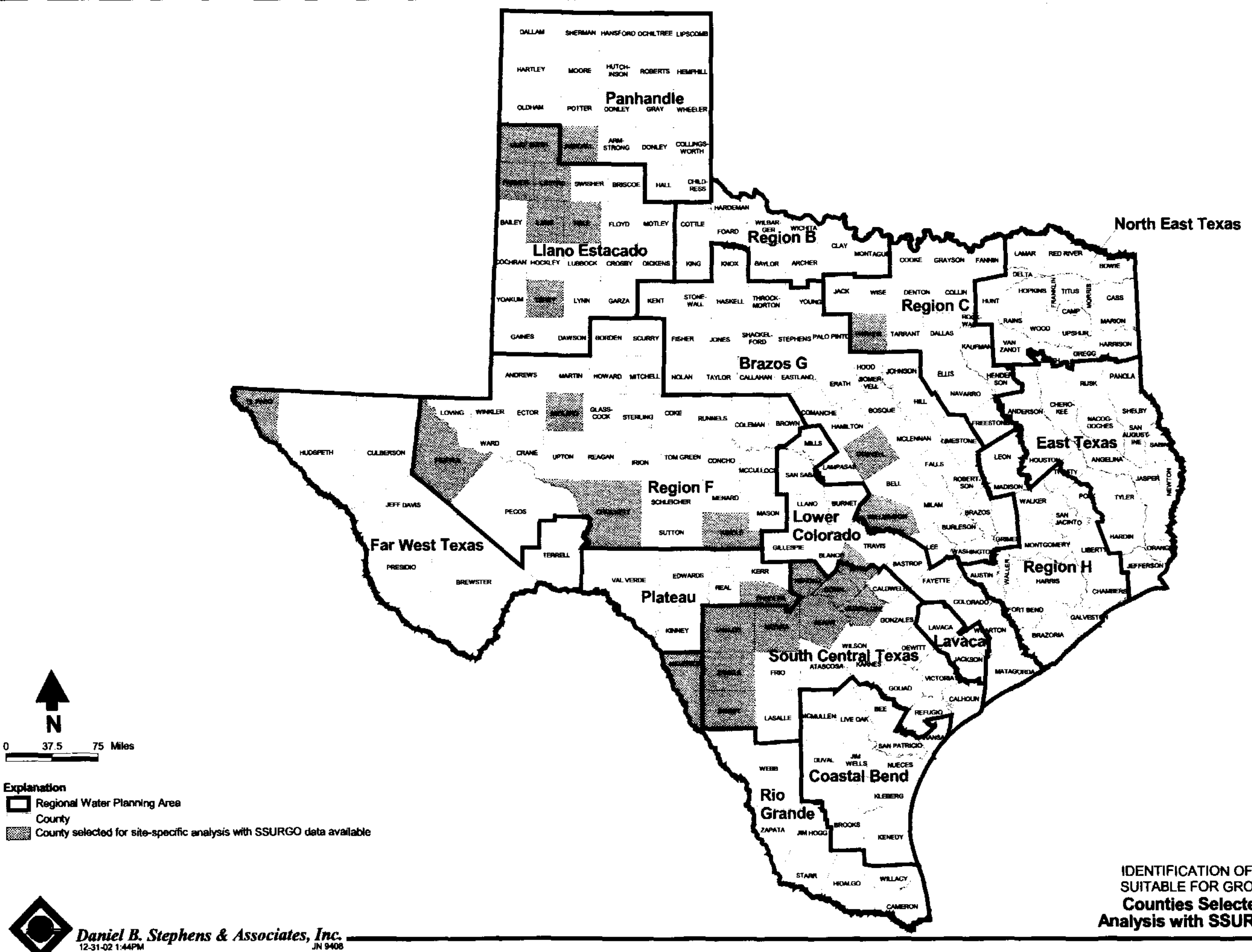
If local-scale capture and use of the banked water is required, traditional hydrological analyses of efficiency based on aquifer hydraulic conductivity (or transmissivity), storage, ambient hydraulic gradient, and feasible well pumping rates should be a component of a formal feasibility study. Detailed 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.



Daniel B. Stephens & Associates, Inc.
12-31-02 2:40PM
JN 9408

IDENTIFICATION OF GEOGRAPHIC AREAS
SUITABLE FOR GROUNDWATER BANKING
Counties Selected for Site-Specific Analysis

Figure 8

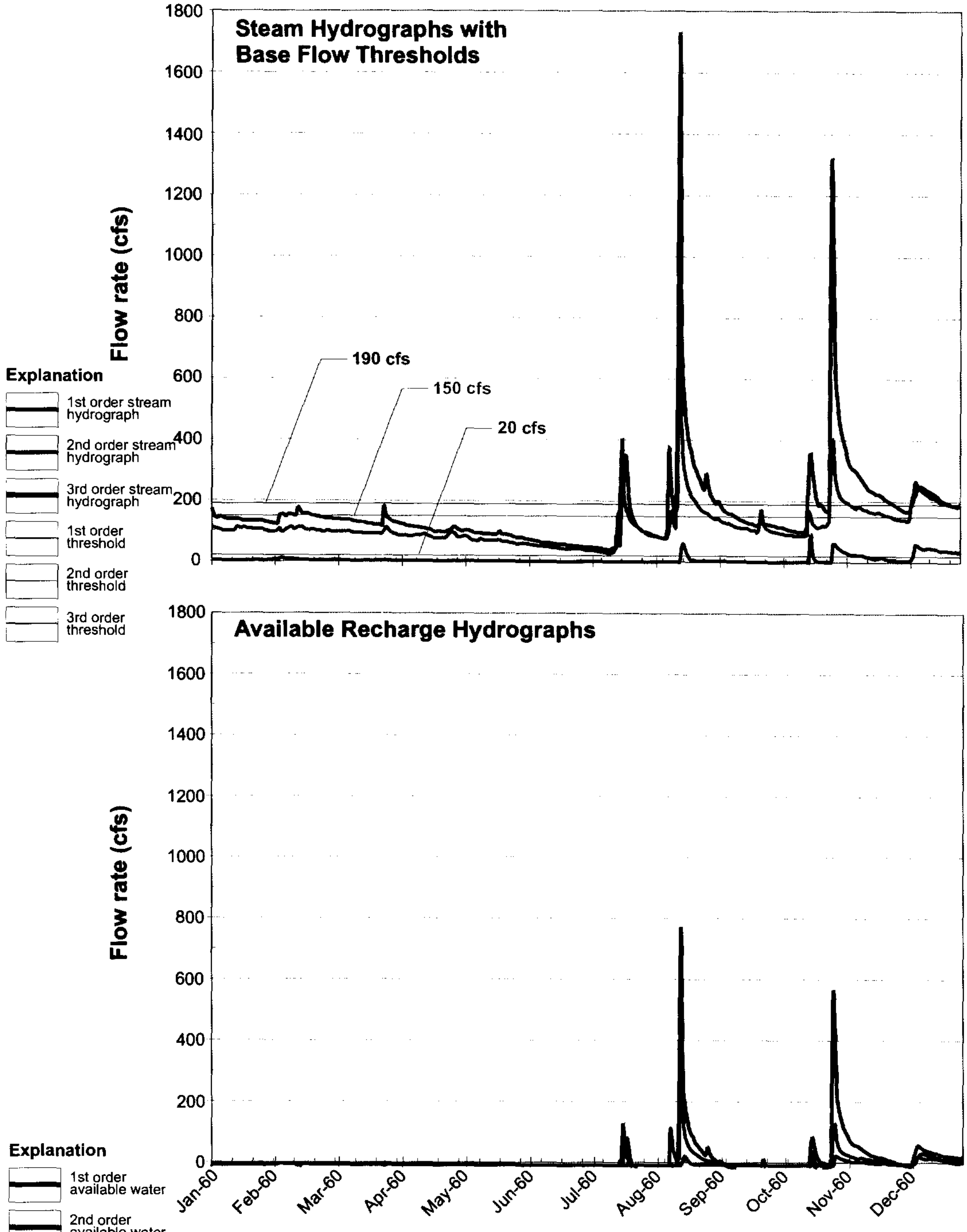


IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Counties Selected for Site-Specific Analysis with SSURGO Data Available

Daniel B. Stephens & Associates, Inc.
12-31-02 1:44PM JN 9408

Figure 9



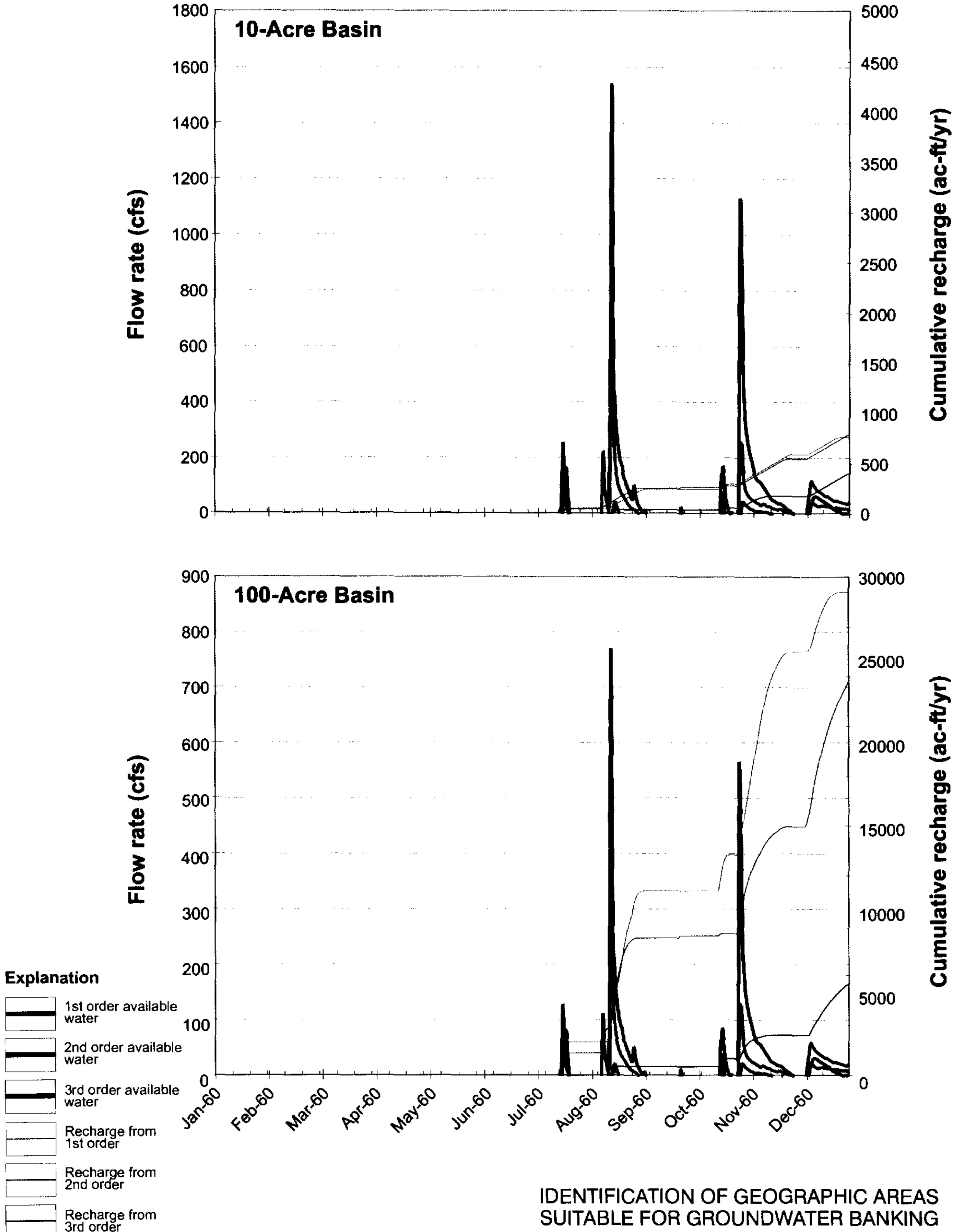
IDENTIFICATION OF GEOGRAPHIC AREAS
SUITABLE FOR GROUNDWATER BANKING

Stream Hydrographs and Corresponding Available Recharge Hydrographs, Uvalde County

T:\VDR\0-VDR-PROJECTS\9408\940809b.CDR

Daniel B. Stephens & Associates, Inc.
1-08-03
JN 9408

Figure 10



TVDR10-VDR-PROJECTS\9408\940811b.CDR

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

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

Daniel B. Stephens & Associates, Inc.

1-08-03 JN 9408

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).

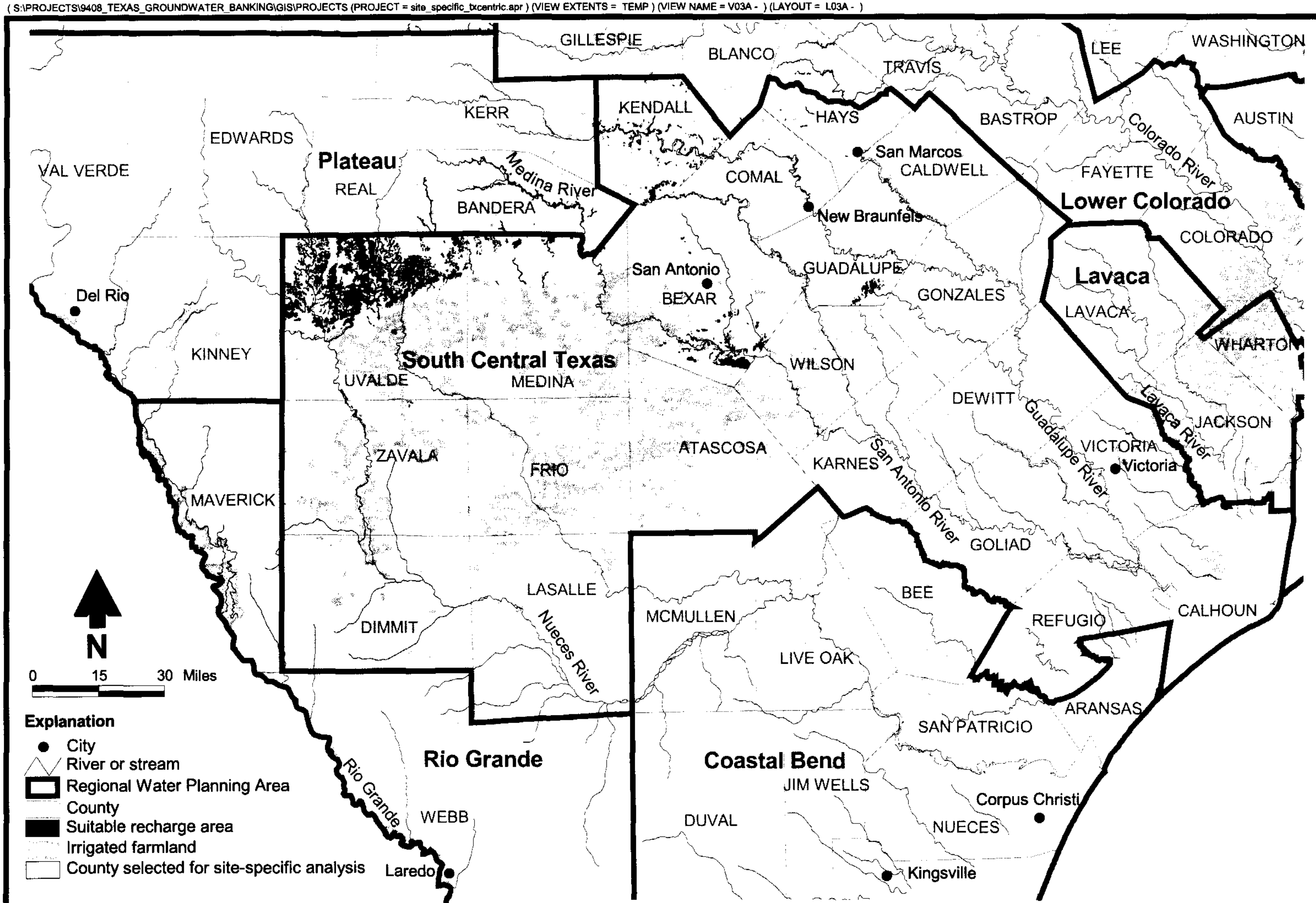
WAM results are not available for Maverick County, as it is part of the Rio Grande Basin WAM, which has not yet been completed. Nevertheless, a number of potential recharge sites exist in Maverick County in the Rio Grande valley. Suitable areas identified through the screening analysis lie along the 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.

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V03A -) (LAYOUT = L03A -)



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

South Central Texas Suitable Recharge Areas

Daniel B. Stephens & Associates, Inc.

4-7-03 2:36PM JN 9408

Figure 12

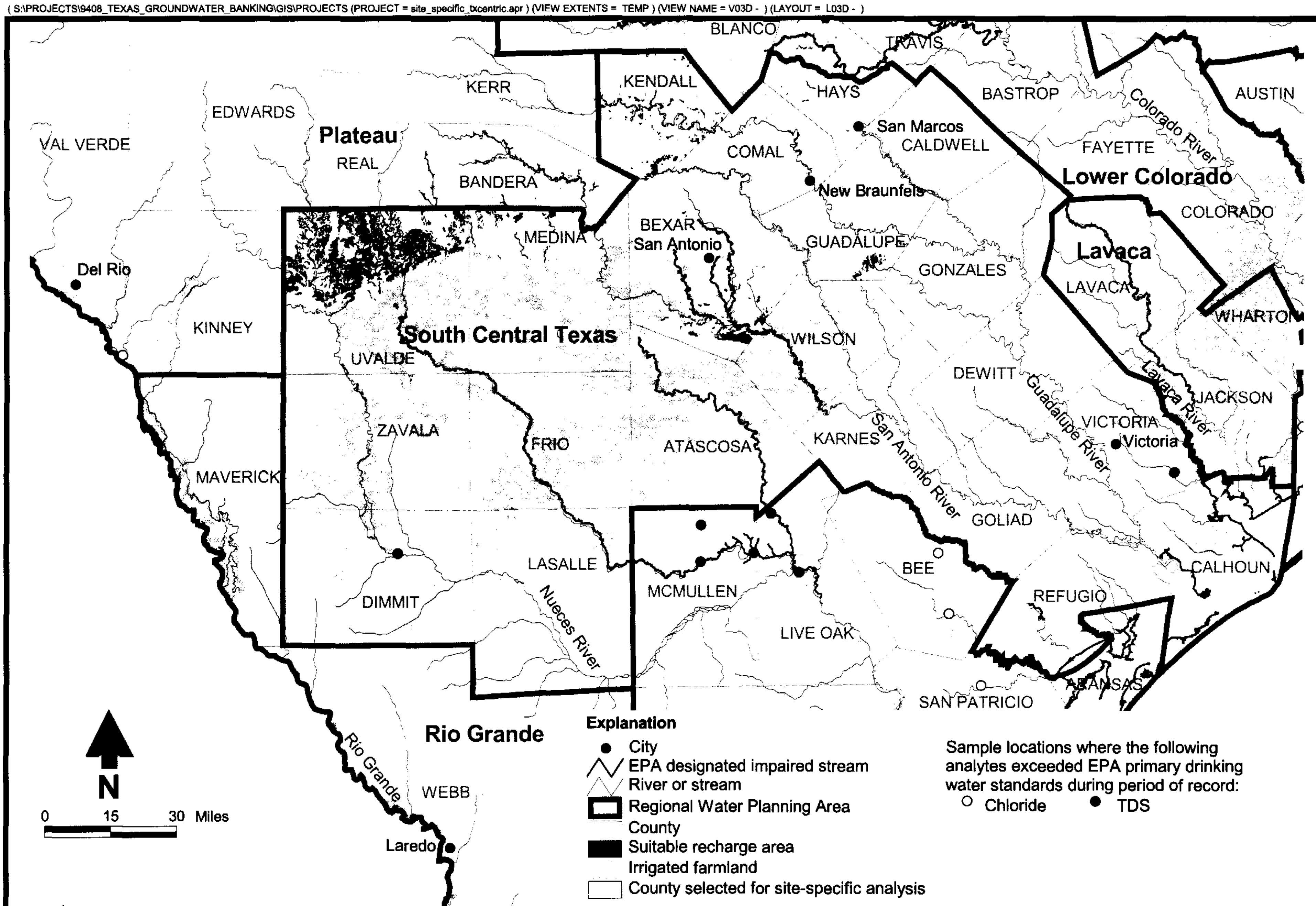


Figure 13

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING
South Central Texas Water Quality

Daniel B. Stephens & Associates, Inc.
4-7-03 2:36PM
JN 9408

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V03E -) (LAYOUT = L03E -)

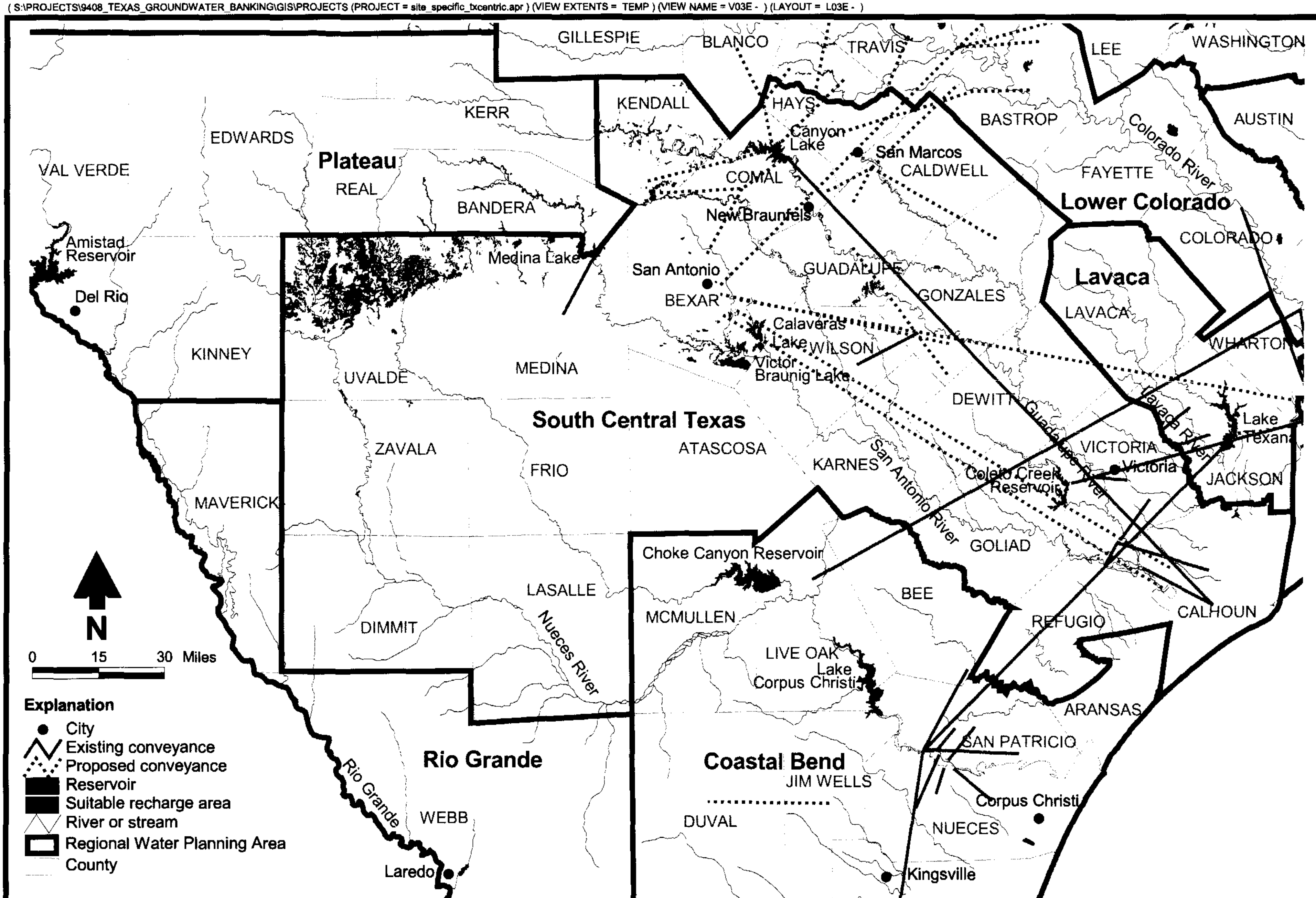


Figure 14

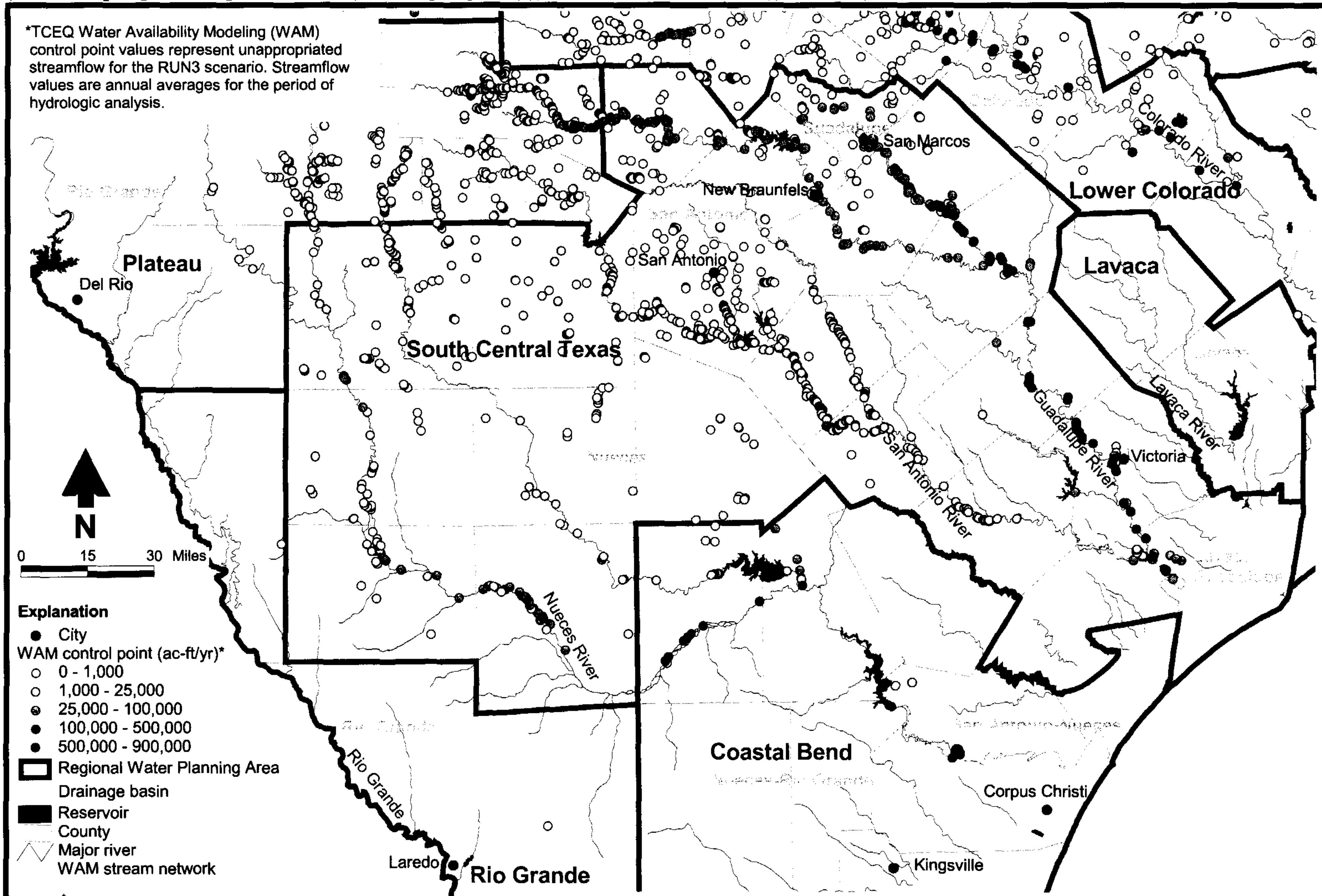
IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

South Central Texas Reservoirs and Conveyances

Daniel B. Stephens & Associates, Inc.

4-7-03 2:36PM JN 9408

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V03F -) (LAYOUT = L03F -)



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

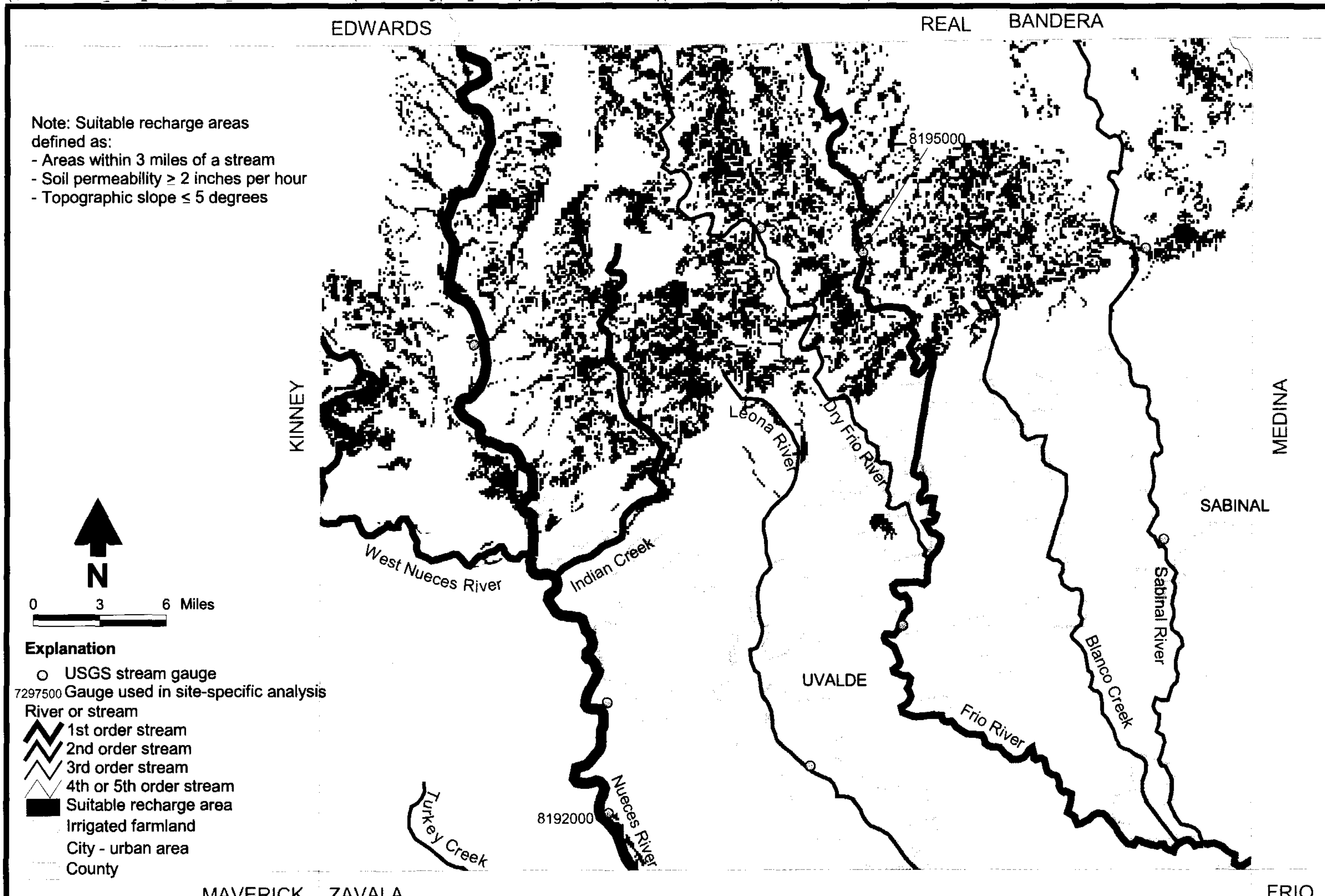
South Central Texas Surface Water Availability

Daniel B. Stephens & Associates, Inc.

12-27-02 8:49AM JN 9408

Figure 15

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V03C-) (LAYOUT = L03C-)



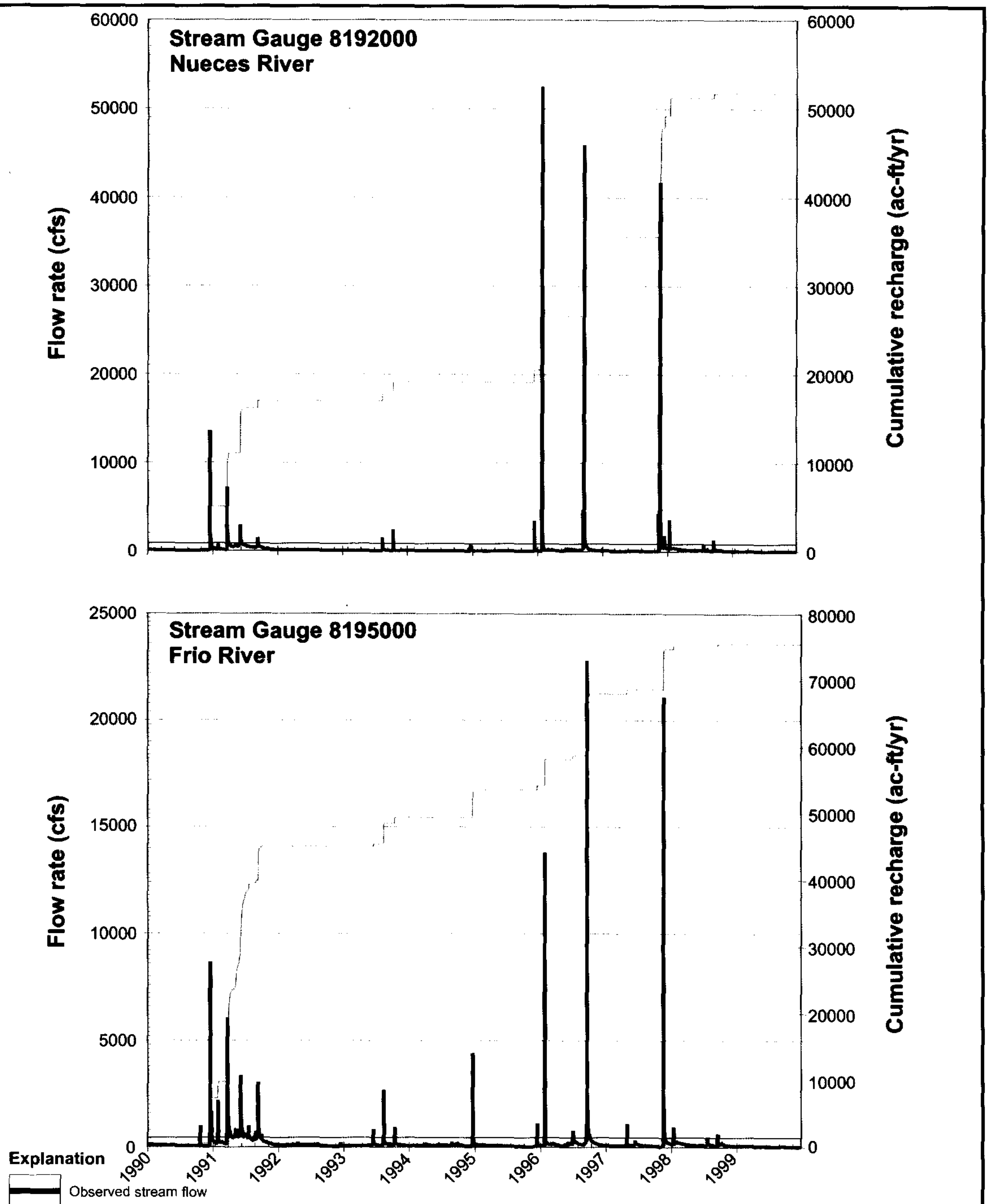
IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Uvalde County Suitable Recharge Areas

Daniel B. Stephens & Associates, Inc.

12-31-02 3:11PM JN 9408

Figure 16



T:\VDR\0-VDR-PROJECTS\9408\940808b.CDR

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

Daniel B. Stephens & Associates, Inc.
1-08-03 JN 9408

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

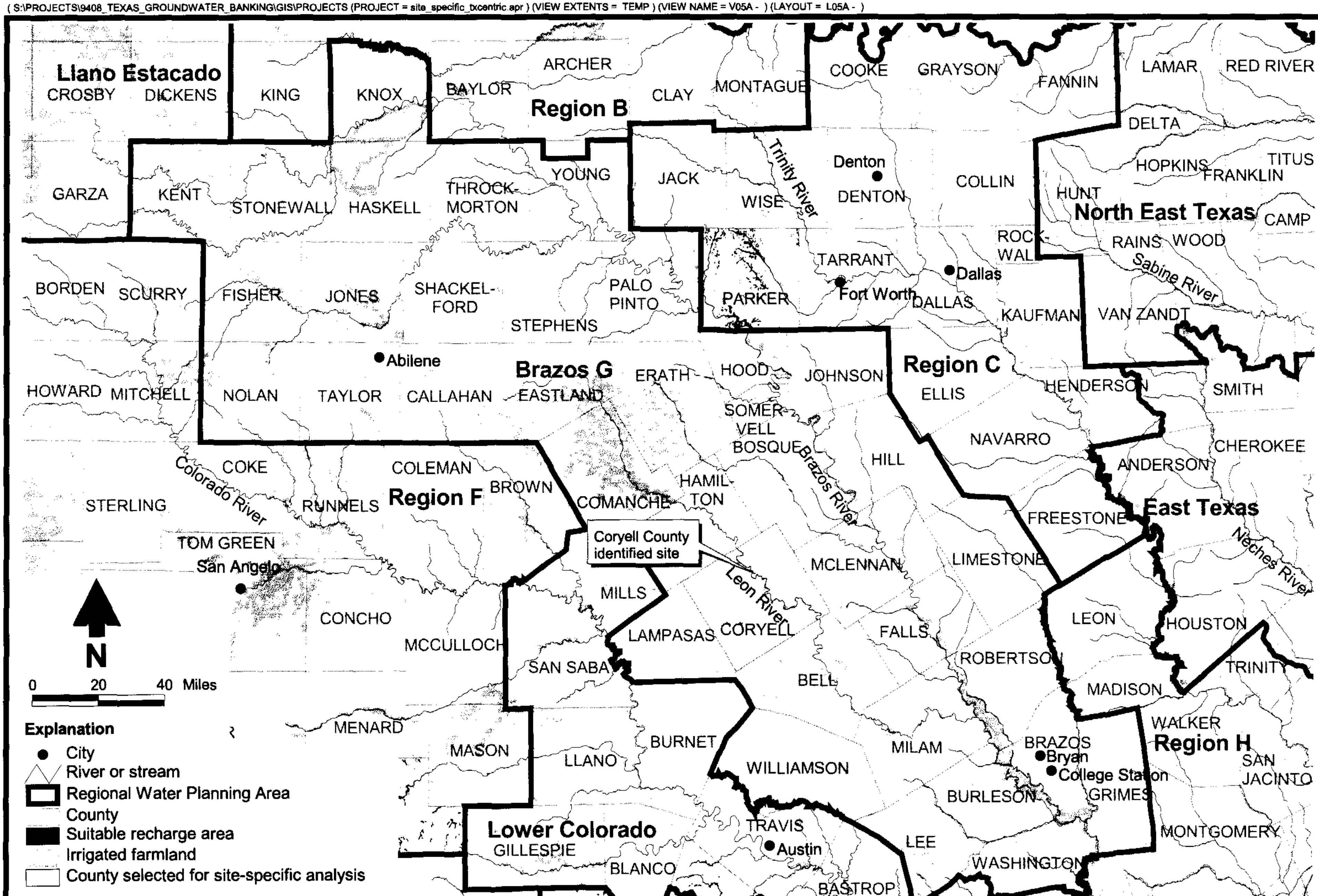
As shown on Figure 18, few potential areas for recharge exist in the Brazos Region. In fact, based on the criteria used, the only suitable recharge area is in Coryell County. In the Trinity Aquifer outcrop area, two large fingers protrude from the northwest and north-central portions of the county toward 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.

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V05A -) (LAYOUT = L05A -)



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

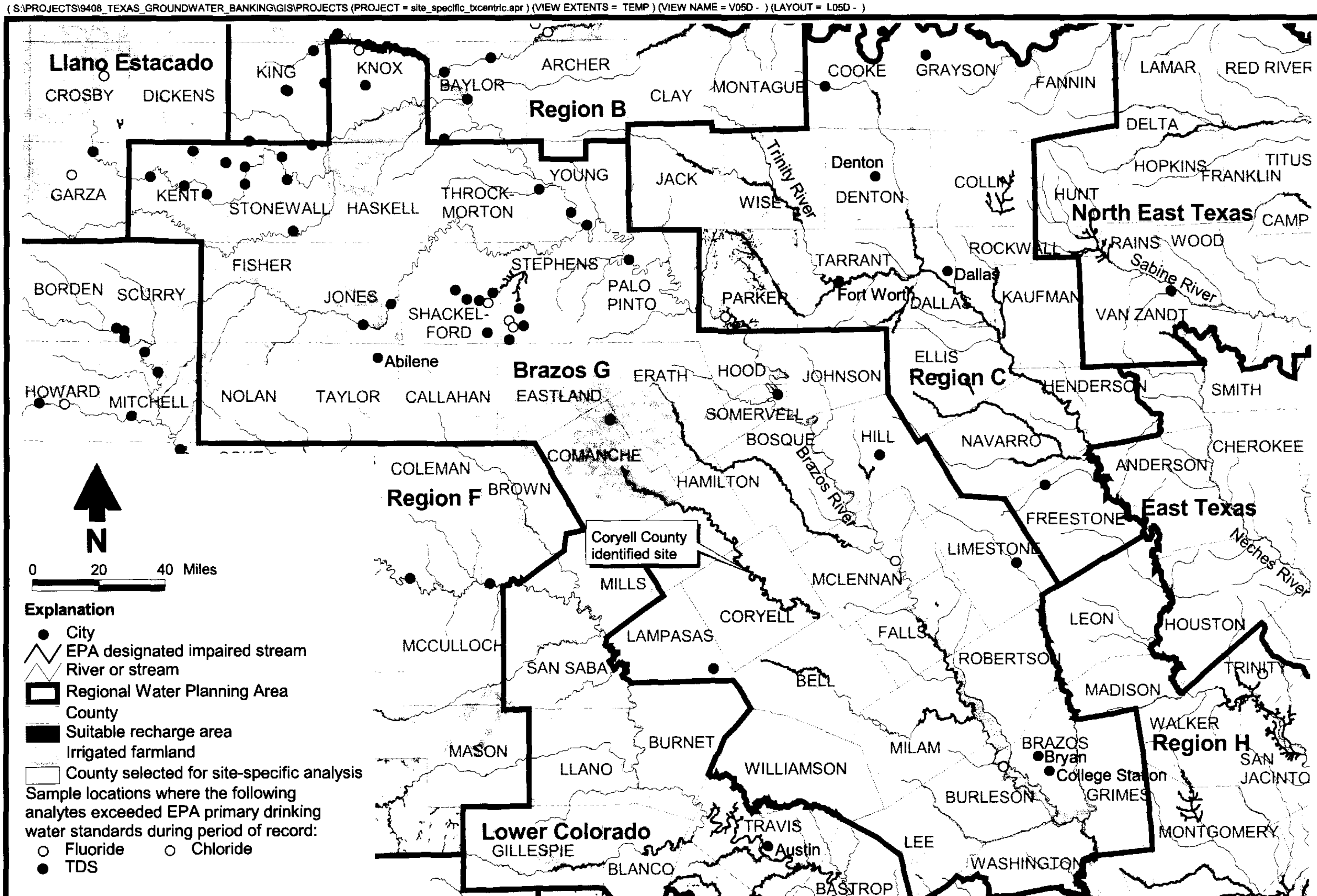
Brazos G Suitable Recharge Areas

Daniel B. Stephens & Associates, Inc.

12-4-02 8:47AM JN 9408

Figure 18

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V05D -) (LAYOUT = L05D -)



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

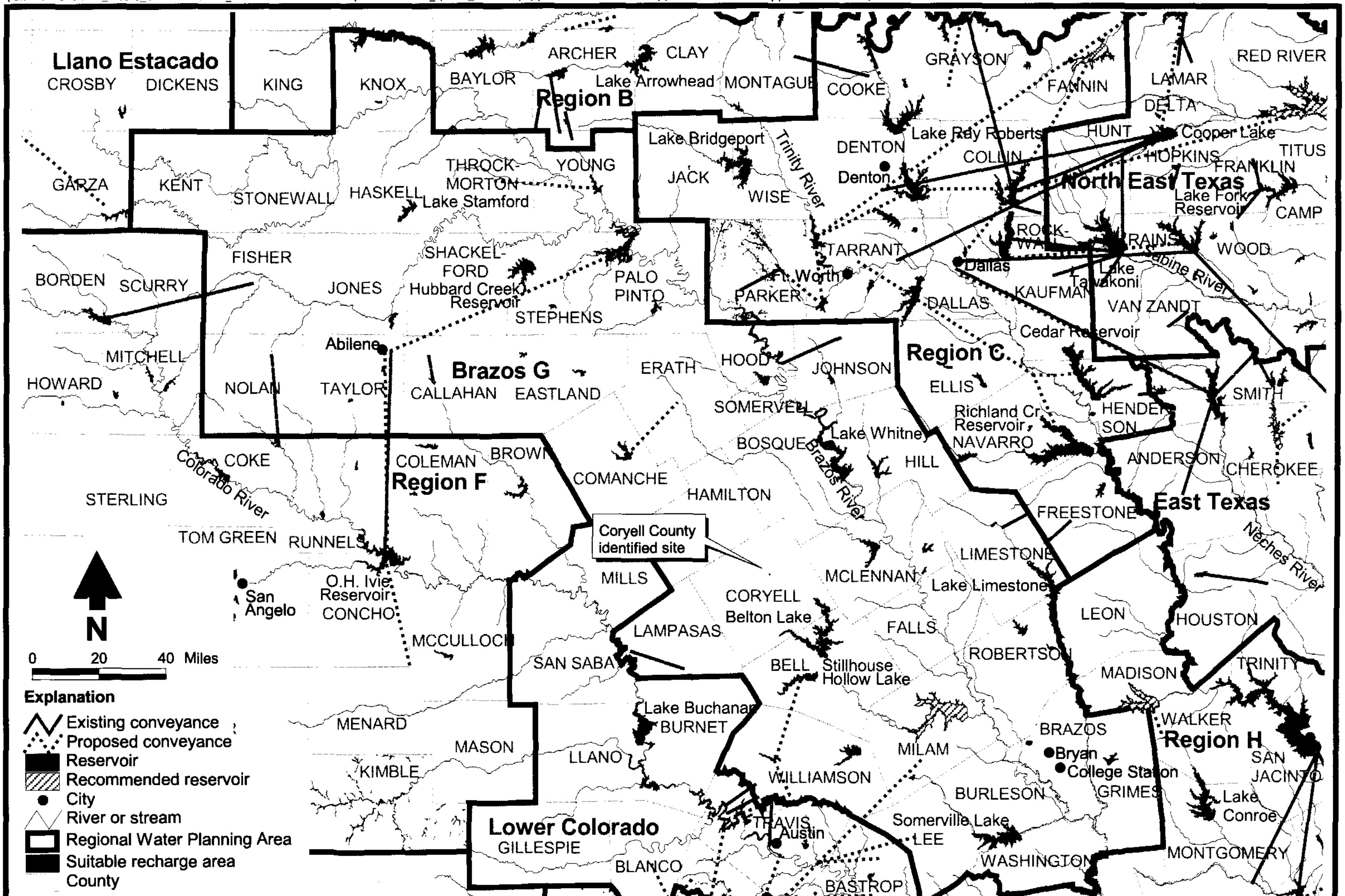
Brazos G Water Quality

Figure 19

Daniel B. Stephens & Associates, Inc.

8-30-02 11:31AM JN 9408

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V05E -) (LAYOUT = L05E -)



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Brazos G Reservoirs and Conveyances

Daniel B. Stephens & Associates, Inc.

12-23-02 3:27PM

JN 9408

Figure 20

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V05F -) (LAYOUT = L05F -)

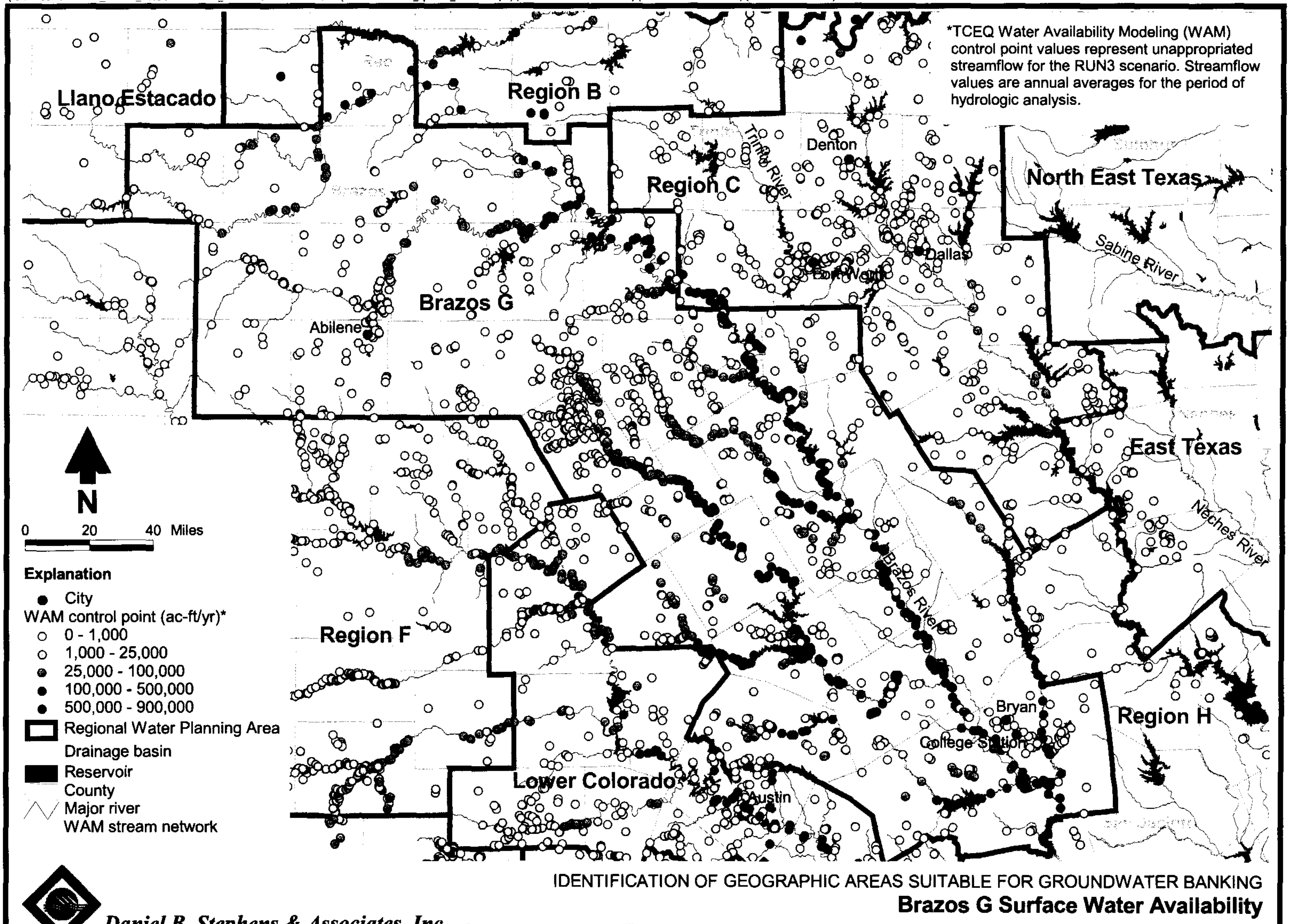
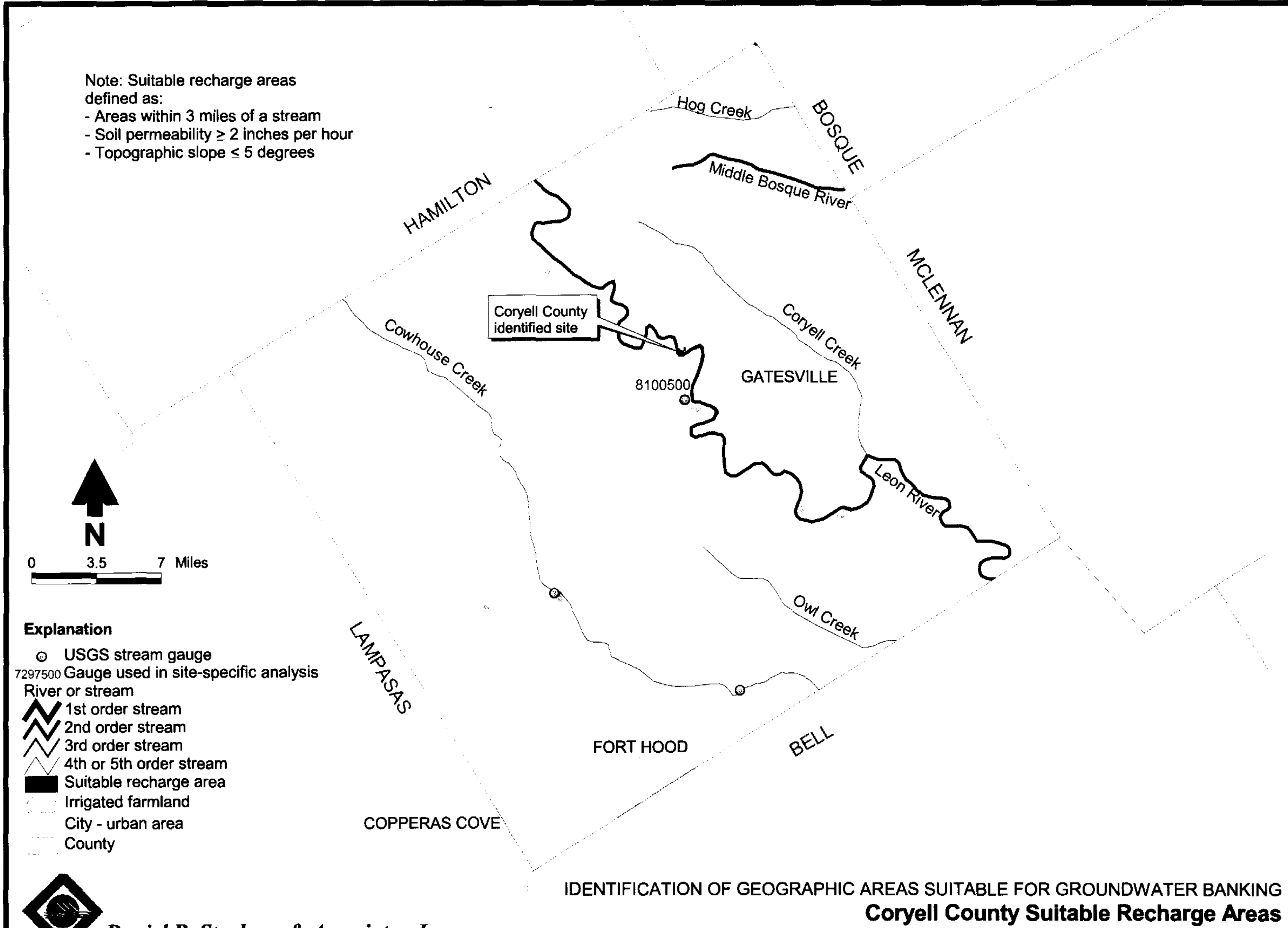


Figure 21

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V05C -) (LAYOUT = L05C -)



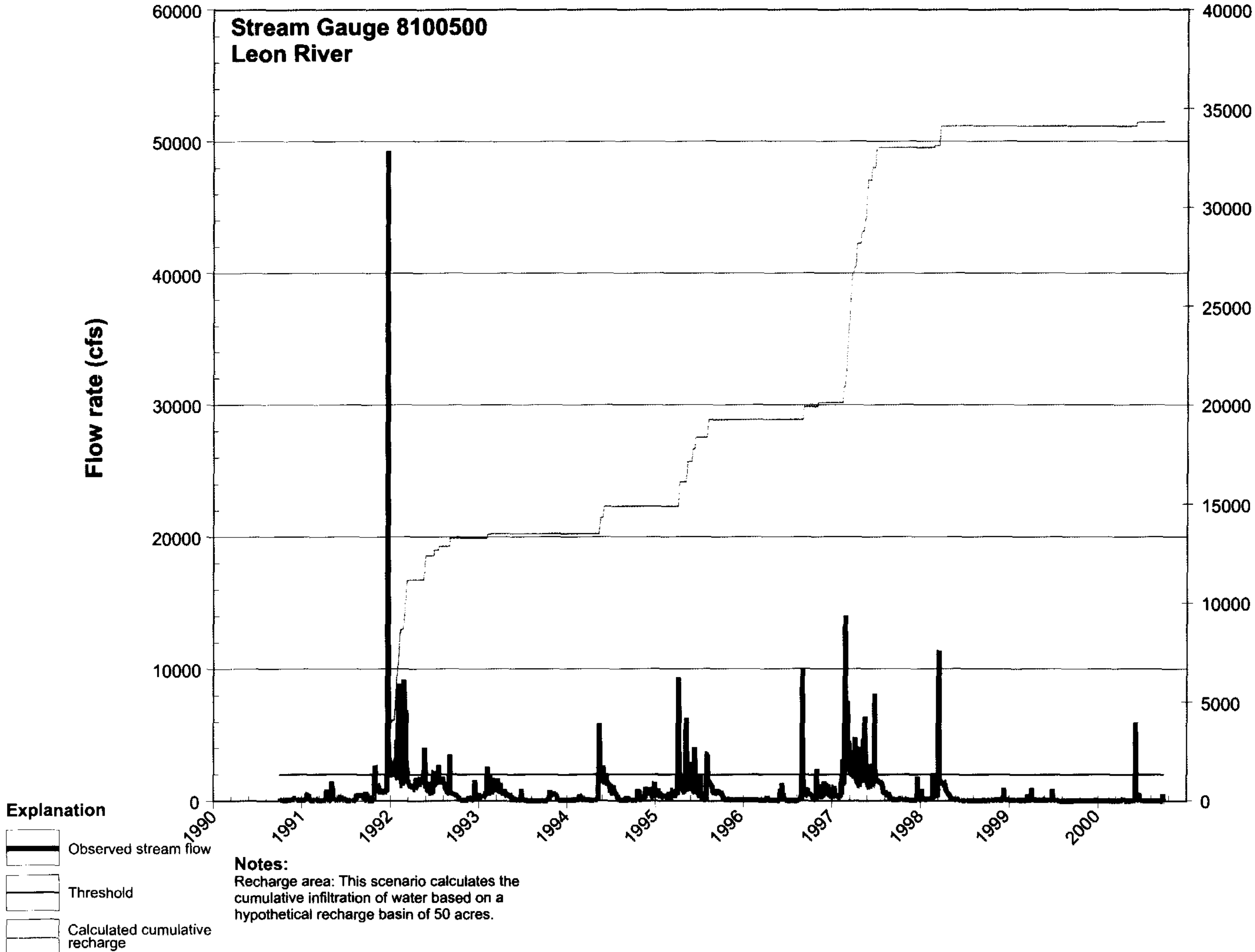
IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Coryell County Suitable Recharge Areas

Figure 22

Daniel B. Stephens & Associates, Inc.
12-31-02 3:28PM JN 9408

T\VDR\0-VDR-PROJECTS\9408\940802b.cdr



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

Daniel B. Stephens & Associates, Inc.
12-31-02 JN 9408

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.

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V06A -) (LAYOUT = L06A -)

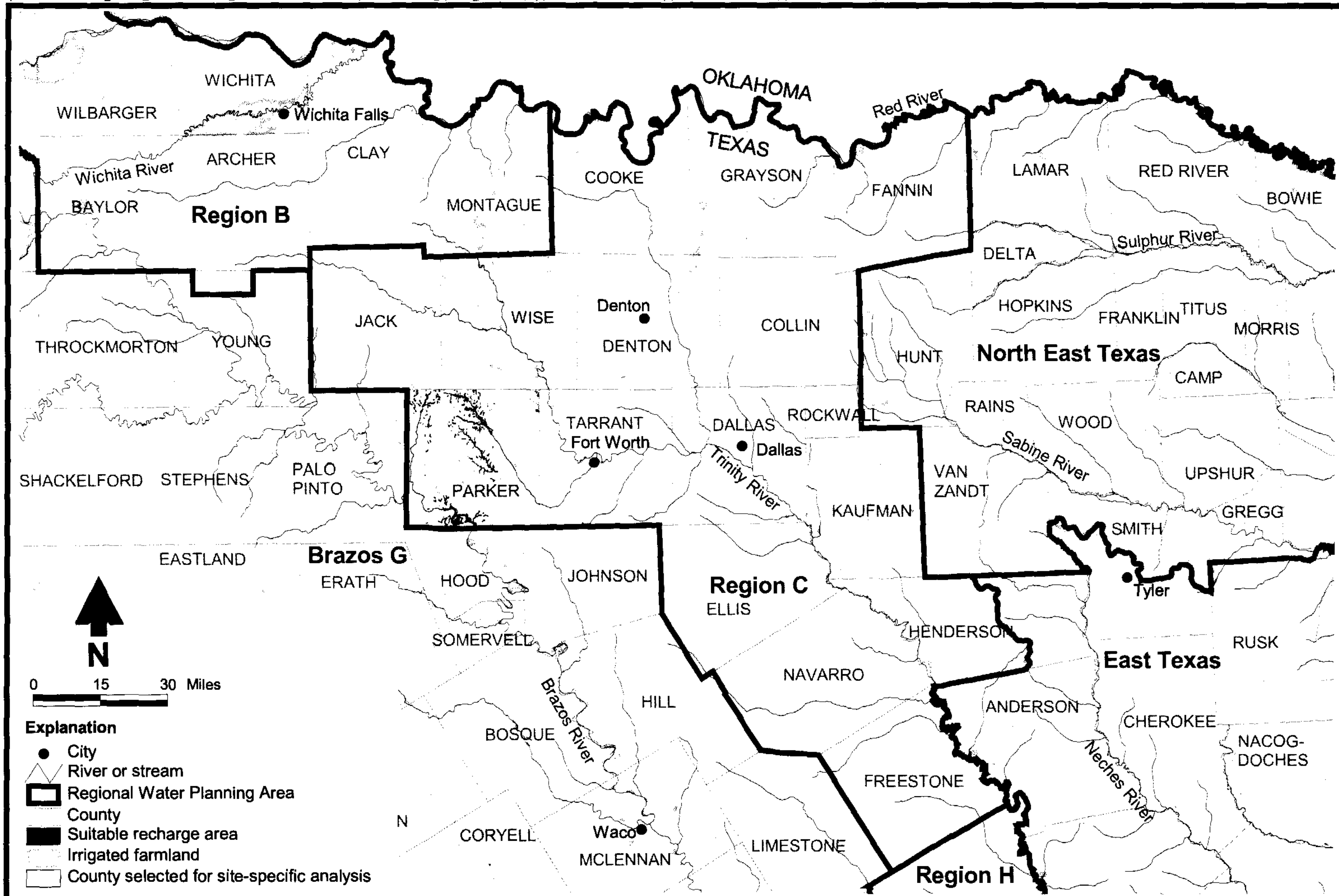


Figure 24

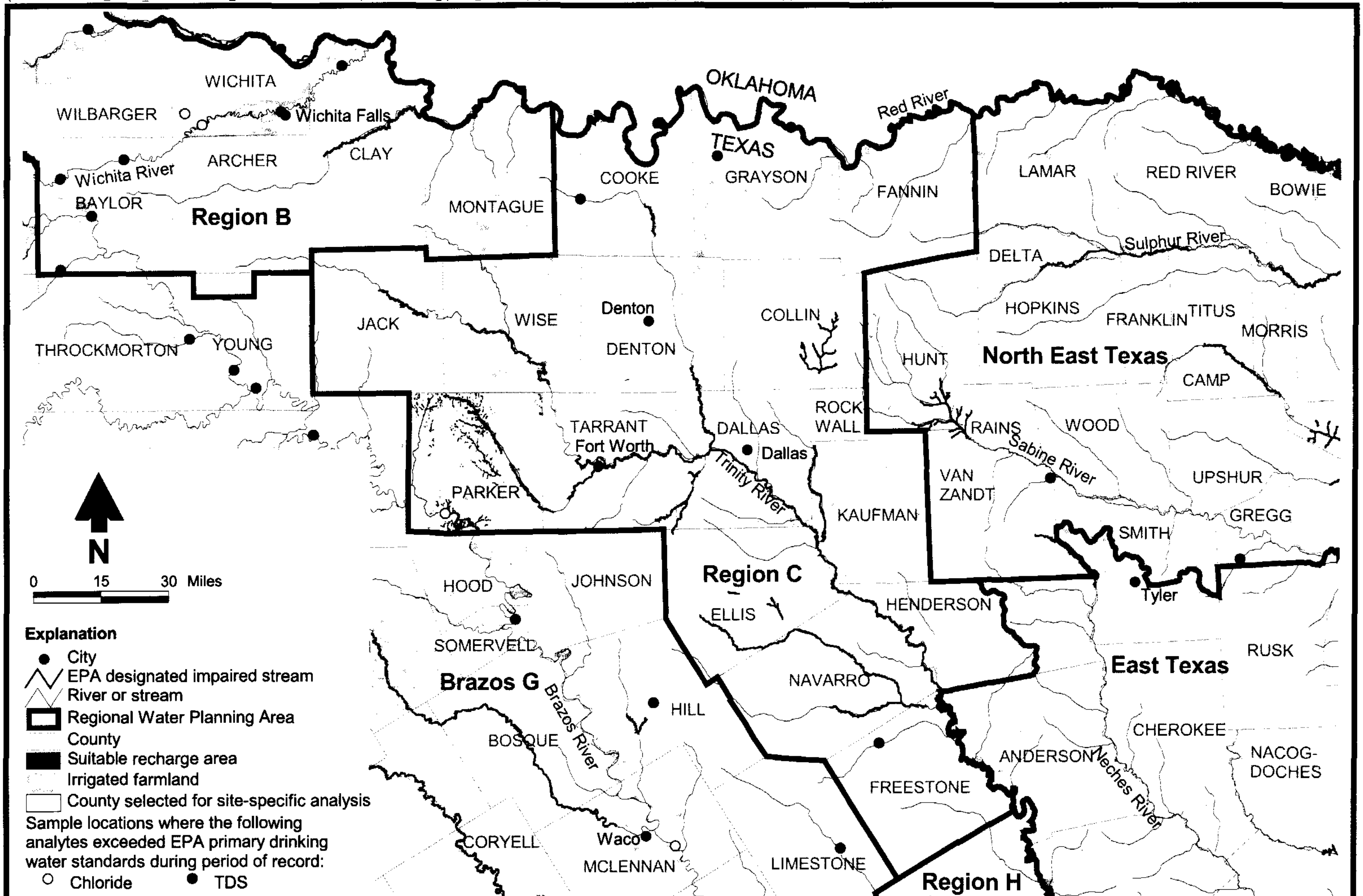
IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Region C Suitable Recharge Areas

Daniel B. Stephens & Associates, Inc.

12-31-02 3:34PM JN 9408

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V06D -) (LAYOUT = L06D -)



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

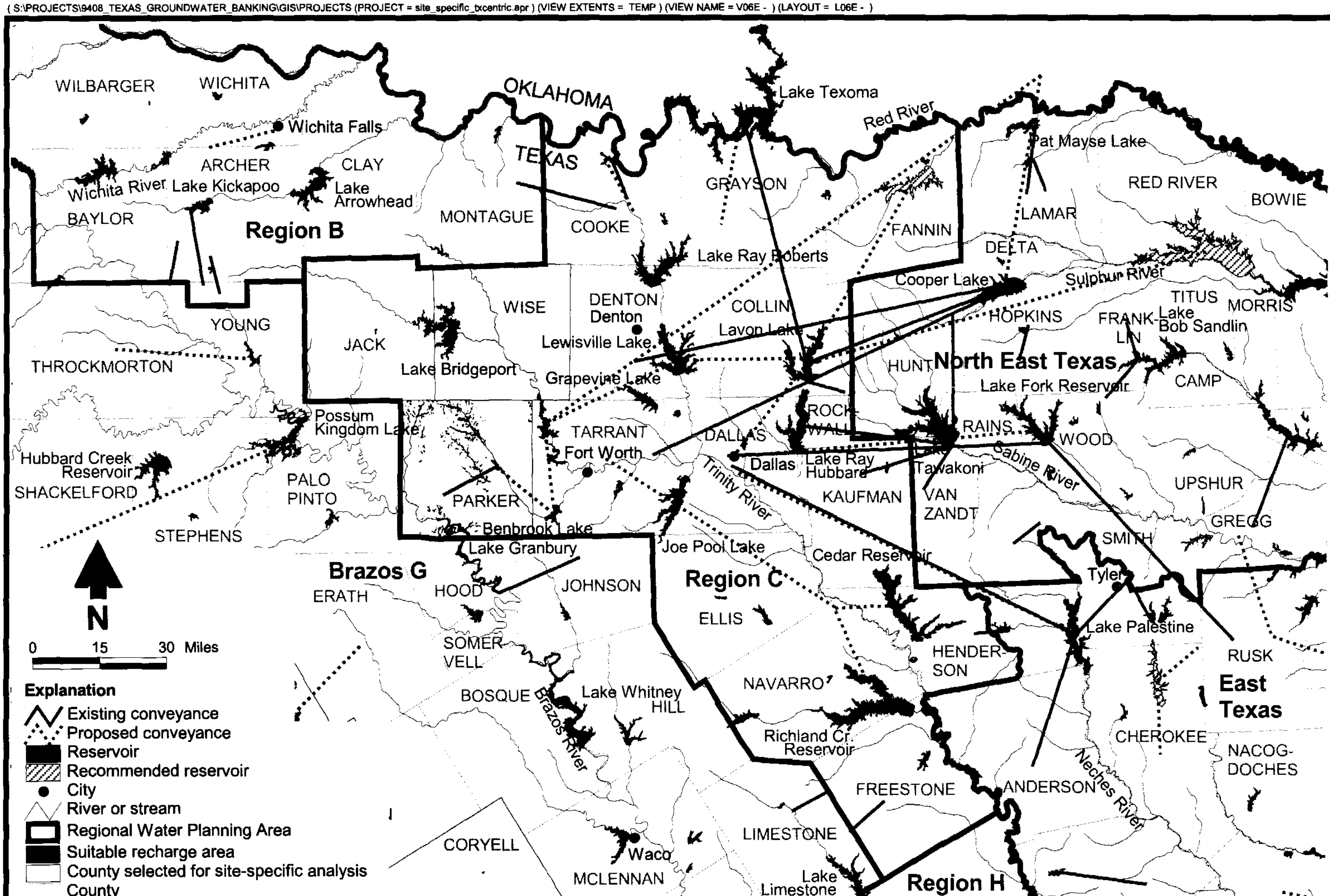
Region C Water Quality

Daniel B. Stephens & Associates, Inc.

12-31-02 3:36PM JN 9408

Figure 25

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V06E -) (LAYOUT = L06E -)



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

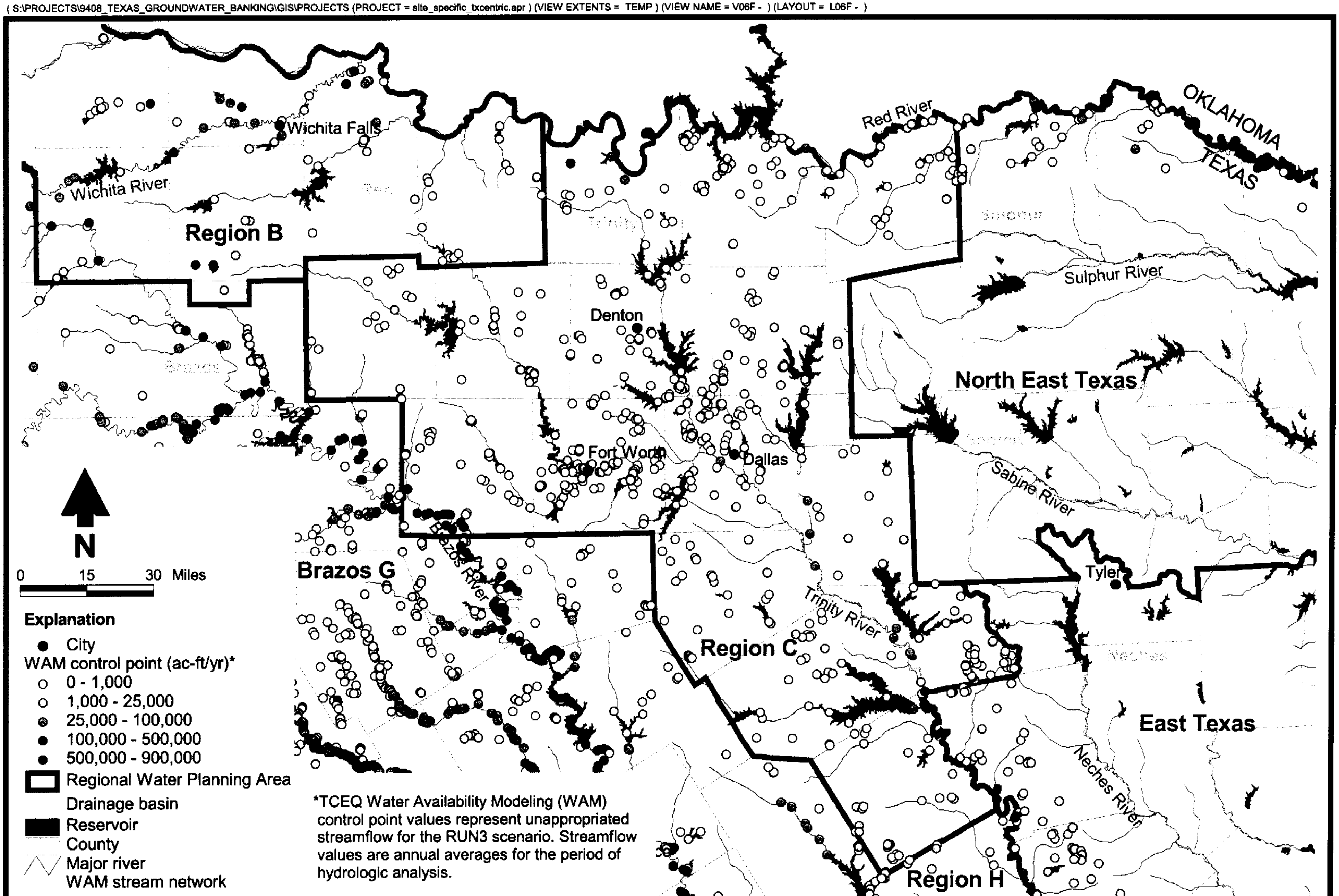
Region C Reservoirs and Conveyances

Daniel B. Stephens & Associates, Inc.

12-30-02 1:34PM JN 9408

Figure 26

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V06F -) (LAYOUT = L06F -)



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

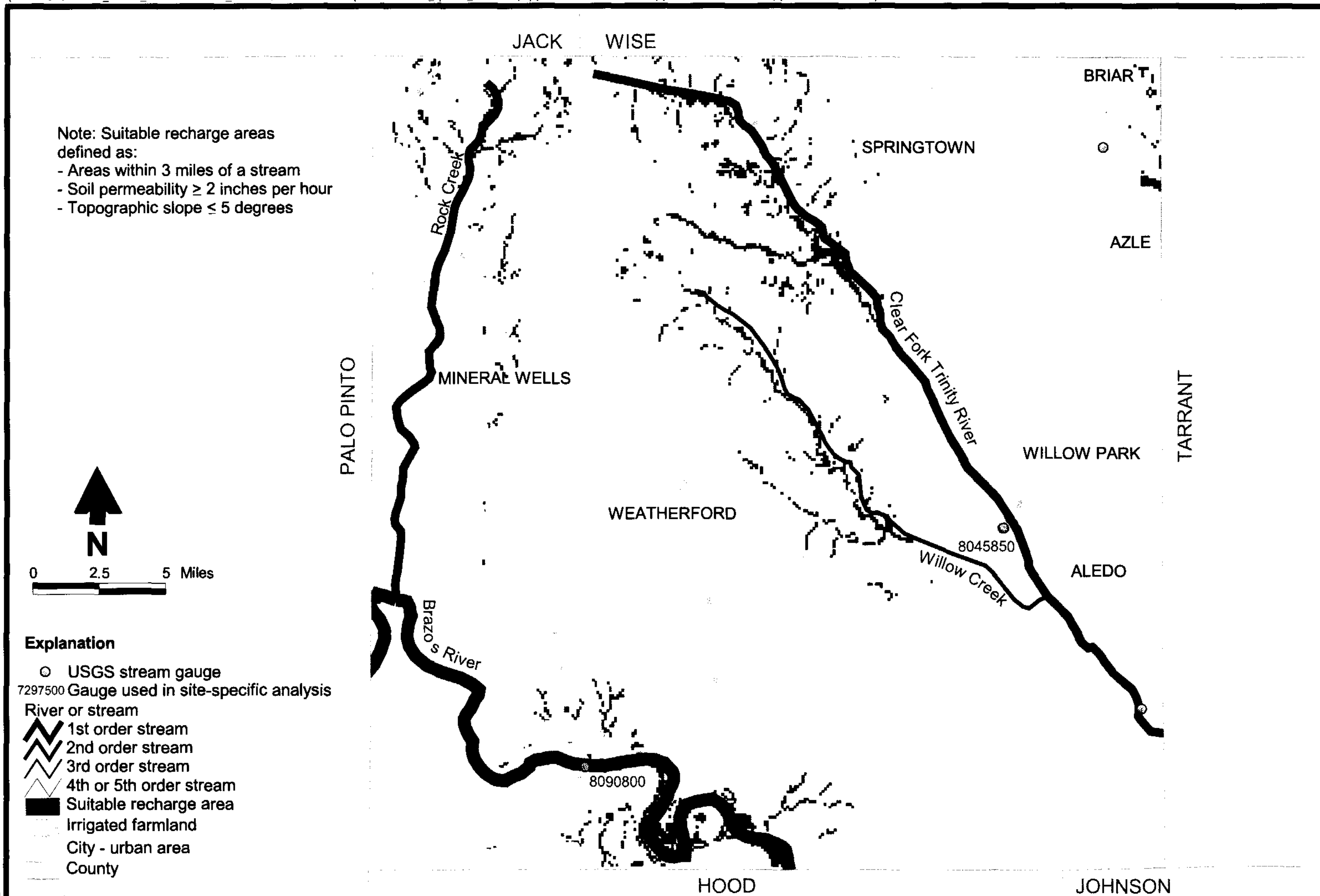
Region C Surface Water Availability

Daniel B. Stephens & Associates, Inc.

12-27-02 8:55AM JN 9408

Figure 27

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V06C- R) (LAYOUT = L06C- R)



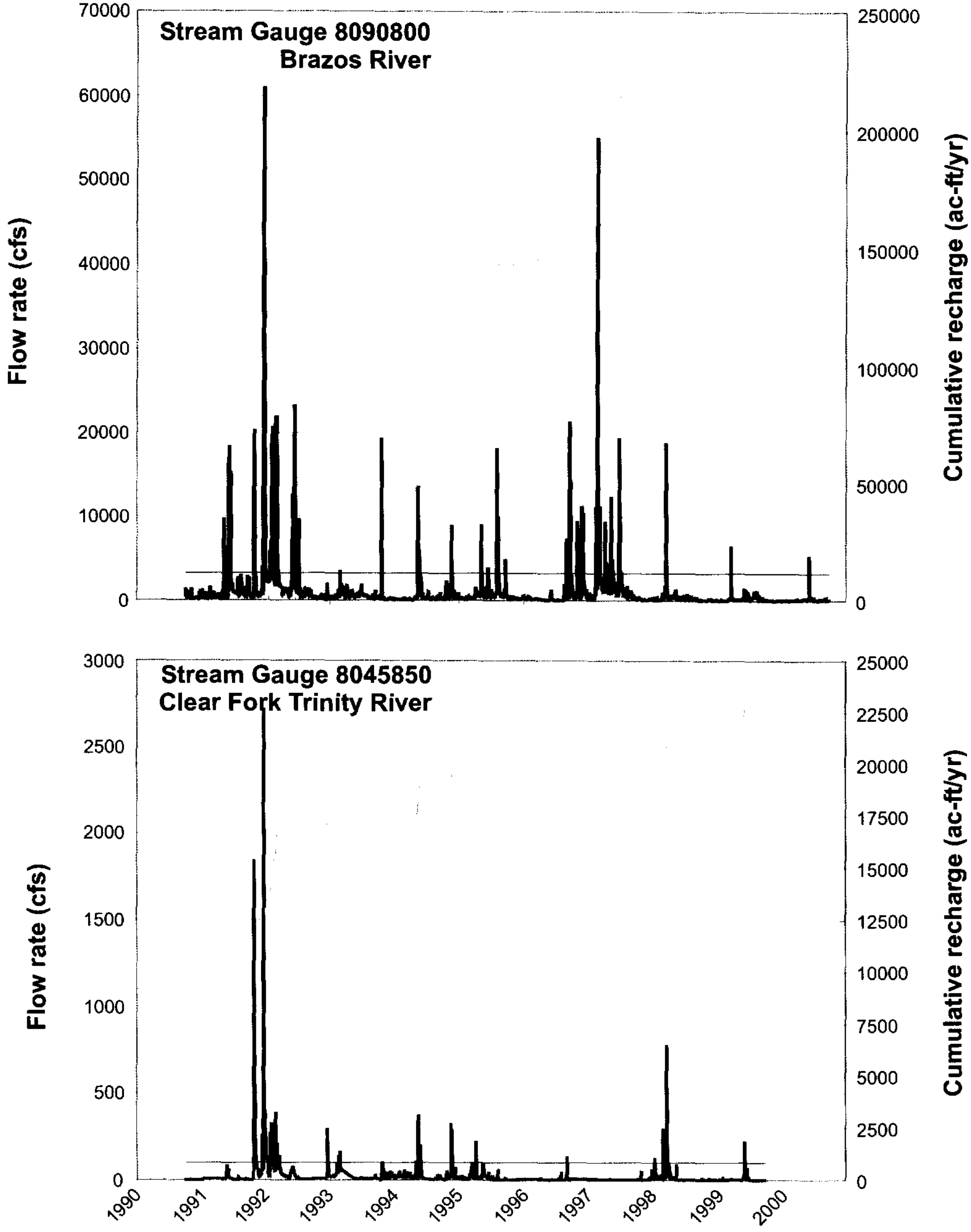
IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Parker County Suitable Recharge Areas

Daniel B. Stephens & Associates, Inc.

12-31-02 3:35PM JN 9408

Figure 28



T:\VDR\0-VDR-PROJECTS\9408\940807b.CDR

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

Daniel B. Stephens & Associates, Inc.
1-08-03 JN 9408

7. Region F

The selected counties in the Region F RWPA include Crockett, Ector, Glasscock, Kimble, Loving, Midland, Reagan, Reeves, Tom Green, Upton, and Ward Counties (Figure 30). The region is predominately rural; ranching, irrigated agriculture, and the oil and gas industry have historically dominated the regional economy and culture. The main cities in the region are Midland, Odessa, and San Angelo (Freese and Nichols, Inc. et al., 2001b).

7.1 Water Resources Overview

The largest water use in the region is irrigated agriculture, which accounts for nearly 75 percent of the total demand. The adopted regional water plan projects a decrease in the demand for irrigation based on the assumed implementation of water-conserving irrigation technologies. Municipal, manufacturing, and steam electric demands are projected to increase in the more populous counties (Freese and Nichols, Inc. et al., 2001b). Water supply projections for Region F are shown in Table 10.

Table 10. Projections for Selected Counties in Region F

County	SSURGO Soil Data Available	Projected Water Supply[a] (ac-ft/yr)						Acreage Suitable for Recharge[b]
		2000	2010	2020	2030	2040	2050	
Crockett	Yes	666	---	–1,533	---	---	–1,530	63,182
Ector	No	–1,688	---	–4,099	---	---	–10,393	10,738
Glasscock	No	–47,853	---	–46,773	---	---	–45,145	522
Kimble	Yes	113	---	22	---	---	–218	13,938
Loving	No	–258	---	–250	---	---	–240	---
Midland	Yes	–29,072	---	–32,826	---	---	–43,490	29,765
Reagan	No	–20,155	---	–18,587	---	---	–16,478	6
Reeves	Yes	–39,210	---	–37,634	---	---	–35,134	7,596
Tom Green	No	–32,219	---	–38,154	---	---	–44,394	---
Upton	No	–6,822	---	–5,708	---	---	–4,871	4,877
Ward	No	–4,643	---	–5,781	---	---	–10,068	10,342

[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

Groundwater accounts for 66 percent of the total currently available supply in the region. Within Region F there are 12 groundwater conservation districts, which manage groundwater supplies, and 3 wholesale water providers.

As shown in Figure 31, six major rivers flow through the region. Some stretches of these rivers are designated as impaired.

Reservoirs account for 21 percent of the supply in Region F and provide most of the municipal supply. The region includes 17 reservoirs, 4 of which fall within the selected counties (Table 11). Figure 32 shows existing and planned conveyances within the region.

Table 11. List of Major Reservoirs, Region F Site-Selected Counties

County	Reservoir	Water Right Owner	Authorized Diversion (ac-ft/yr)
Colorado Basin			
Tom Green	O.C. Fisher Lake	Upper Colorado River Authority (contracted to the City of San Angelo)	---
	Twin Buttes Reservoir	City of San Angelo	---
	Lake Nasworthy		---
Loving and Reeves	Red Bluff Reservoir	Red Bluff Water Power Control District	---

Source: Freese and Nichols, Inc. et al., 2001b.

ac-ft/yr = Acre-feet per year
--- = Not available

7.2 Rate, Area and Time Period for Infiltration

In Region F, the scale difference between the SSURGO soils dataset and the STATSGO dataset are again evident. Because of the differences in resolution between the two data sources, soil permeability maps show artificial differences along the Crockett County line, where the more detailed SSURGO data join with the less detailed STATSGO data of surrounding counties.

The western and southwestern portions of Region F lie within the Rio Grande Basin. Because a WAM model is not yet completed in this area, WAM data are not available for Reeves, Loving, Ward, Crockett, and portions of Upton and Ector Counties (Figure 33).

Midland County has a number of potentially suitable banking locations near the City of Midland (Figure 30). Ector County has a 10,738-acre area within and around the City of Odessa that was identified as a potentially suitable location for groundwater recharge. The WAM model data show that 630 ac-ft/yr of excess surface water might be available for recharge along Monahans Draw. Ward County has a 10,342-acre area on the Pecos River, south of the City of Monahans, that was identified as a potentially suitable location for groundwater recharge. However, there is no WAM data available for Ward County.

Kimble County has several potential recharge locations along the Llano River and its tributaries (Figure 30). The WAM data show excess streamflows ranging from 10,000 ac-ft/yr to 35,000 ac-ft/yr along the main stem of the Llano River and more than 1,000 ac-ft/yr along some of the river's smaller tributaries (Figure 33). These areas tend to be agricultural with few population centers.

Reeves County, the example county for this region, has a total projected 2050 demand of 108,198 ac-ft/yr, of which 34,718 ac-ft/yr is for irrigation. Most of the irrigation demand is south and west of the City of Pecos (Figure 34). Many of the prime recharge areas are located in or near the southern part of this irrigated acreage and might provide local recharge for irrigated agriculture. The City of Pecos shows no prime sites for recharge in the initial analysis.

Soil permeability is low throughout most of Reeves County. Consequently, our site-specific analysis identified only a few small regions of potential recharge areas throughout the central and southeastern portions of the county (Figure 34). However, the existing soil surveys are for near-surface materials that extend no more than 80 inches below ground surface. Potentially, 80 inches is an economically acceptable depth for excavation of a recharge facility. Thus, if in-depth soil analyses of selected locations determines that soil permeability adequate for recharge is available at depths slightly deeper than those included in the SSURGO data, the top layer of these sites could potentially be excavated.

Figure 35 illustrates computations of banked water for two hydrographs. The top graph is for Gauge 8427500 at San Solomon Springs along Toyah Creek, and the bottom graph is for Gauge 8433000 along Barilla Draw. The San Solomon gauge is about 10 miles upstream of a number of potential recharge sites along or in the vicinity of Toyah Creek, and the Barilla Draw gauge is about 15 miles downstream of several potential recharge sites (Figure 34). Both sites overlie Cenozoic Pecos Alluvium Aquifer outcrop. The average soil permeability for potential recharge sites closest to the San Solomon Springs and Barilla Draw gauges was determined to be 8 ft/d for both locations.

Calculated cumulative recharge for the San Solomon Springs site is about 1,150 ac-ft over a 10-year period, while calculated cumulative recharge for the Barilla Draw gauge is about 5,000 ac-ft over about 8 years. As illustrated by the hydrographs in Figure 35, the source of flow at these two gauges is very different. Flow at the San Solomon Springs gauge is fed by flow from San Solomon Spring, which is the largest spring in Reeves County (Brune, 2000). This spring has a constant base flow of about 30 to 35 cubic feet per second (cfs), but spikes that occur in the spring's flow, presumably caused by greater than normal precipitation, could potentially be banked. The Barilla Draw hydrograph is typical for smaller tributaries in semiarid regions. This tributary is ephemeral and only flows after significant precipitation events within its drainage basin. The vast majority of calculated recharge for this gauge comes from two storm events (1979 and 1982) that occurred during the 8-year period of record.

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 35) and the average time period for infiltration. The required area and average time period for infiltration is 0.5 acre and 57 days, respectively, for the San Solomon Springs site, and 22 acres and 2.4 days for the Barilla Draw site. Because the source of flow to the San Solomon Springs gauge is groundwater, the hydrologic record indicates that time periods for infiltration can be substantial following unusually wet periods. Along Barilla Draw and other similar tributaries, however, available time for infiltration, without engineered storage capacity, is very short.

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V04A -) (LAYOUT = L04A -)

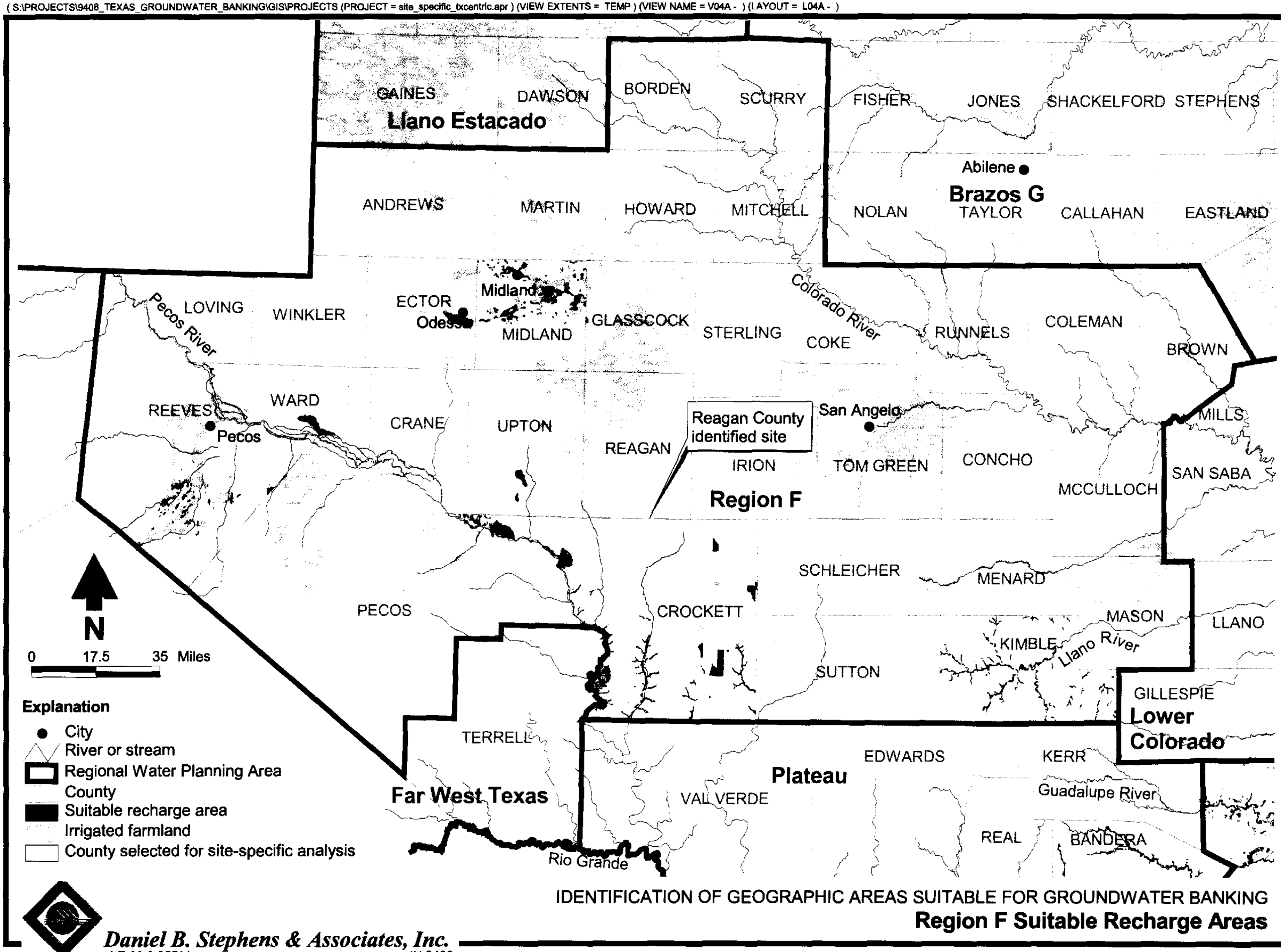
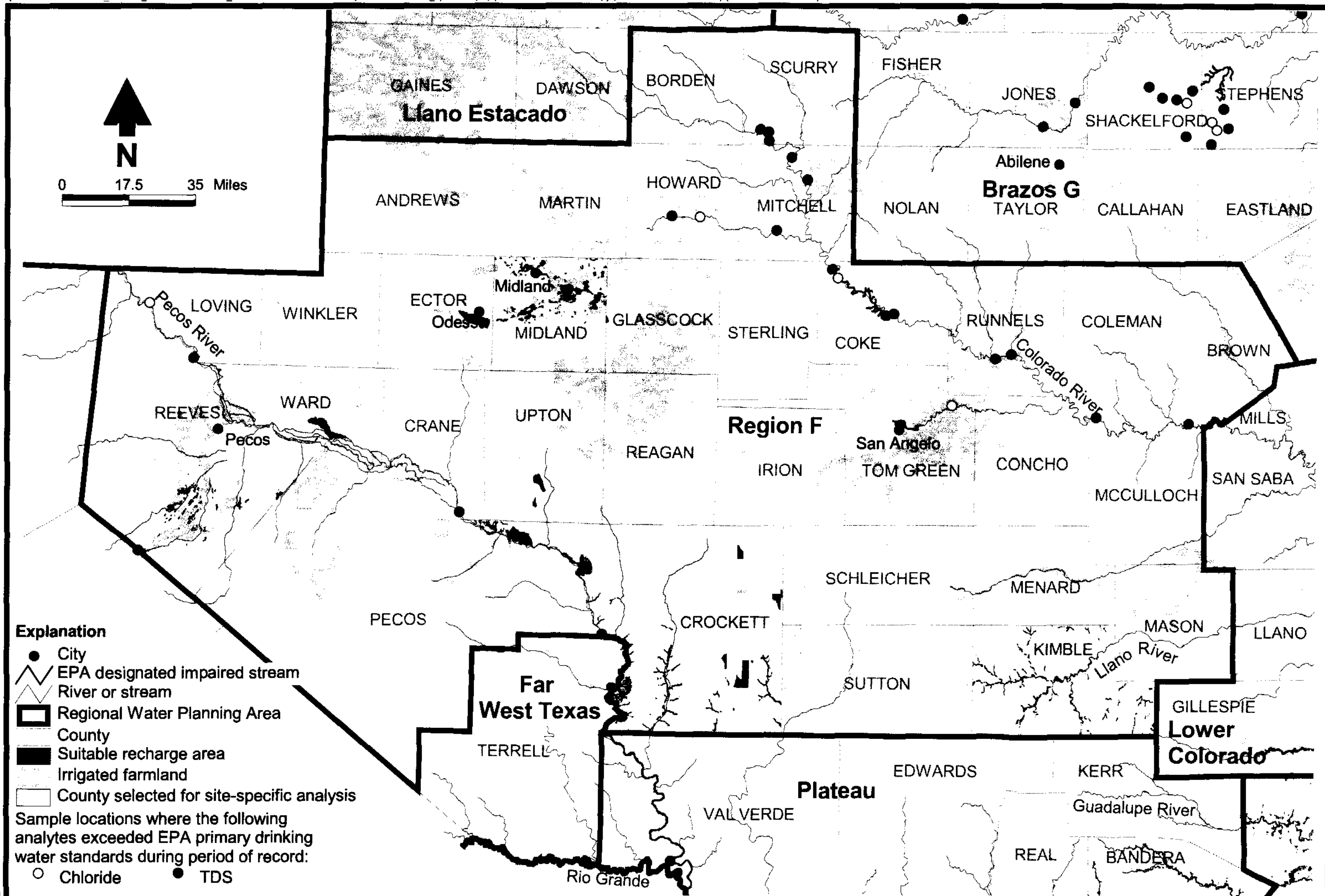


Figure 30

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific.apr) (VIEW EXTENTS = Temp) (VIEW NAME = V04D -) (LAYOUT = L04D -)



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

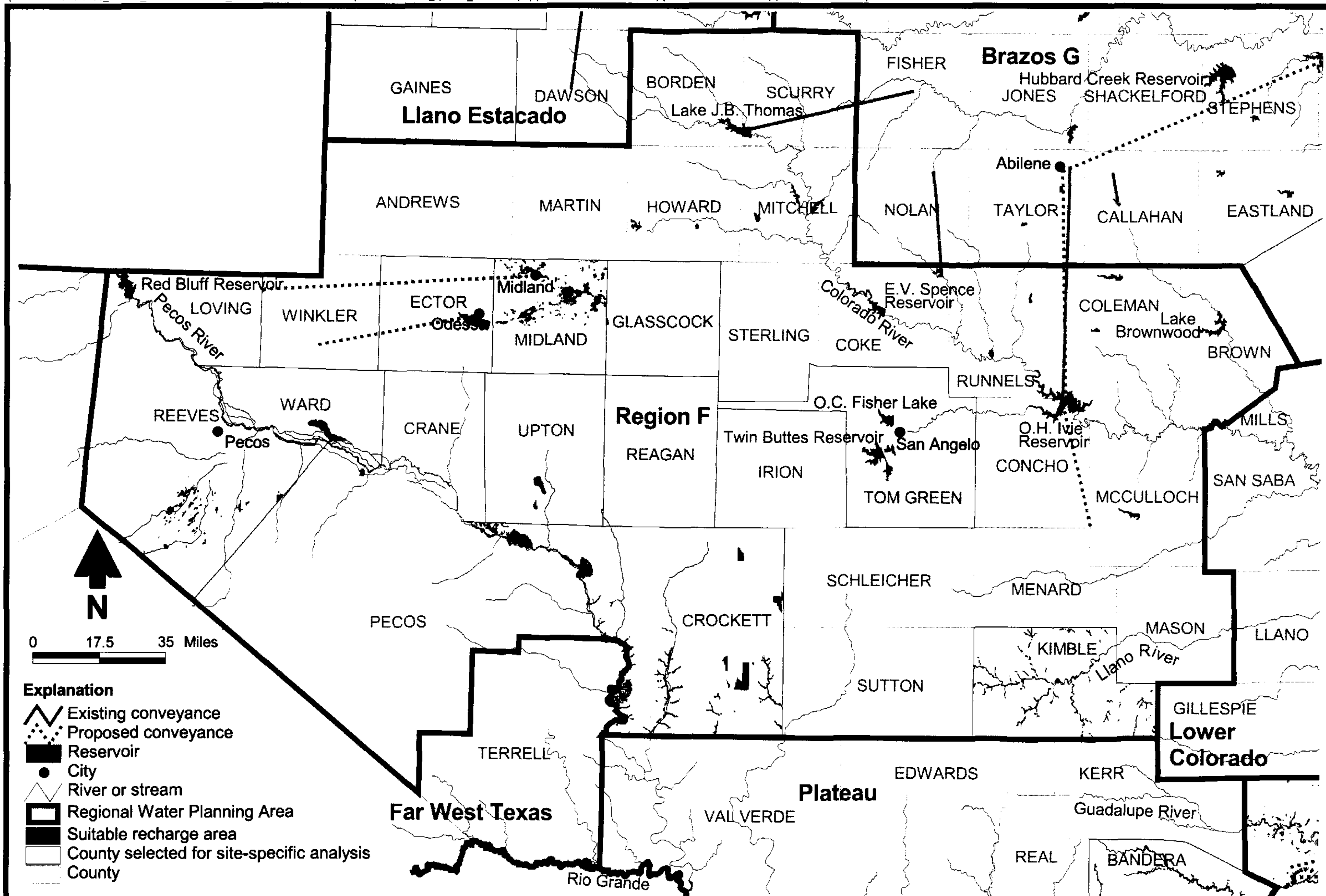
Region F Water Quality

Daniel B. Stephens & Associates, Inc.

4-7-03 2:35PM JN 9408

Figure 31

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V04E -) (LAYOUT = L04E -)



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

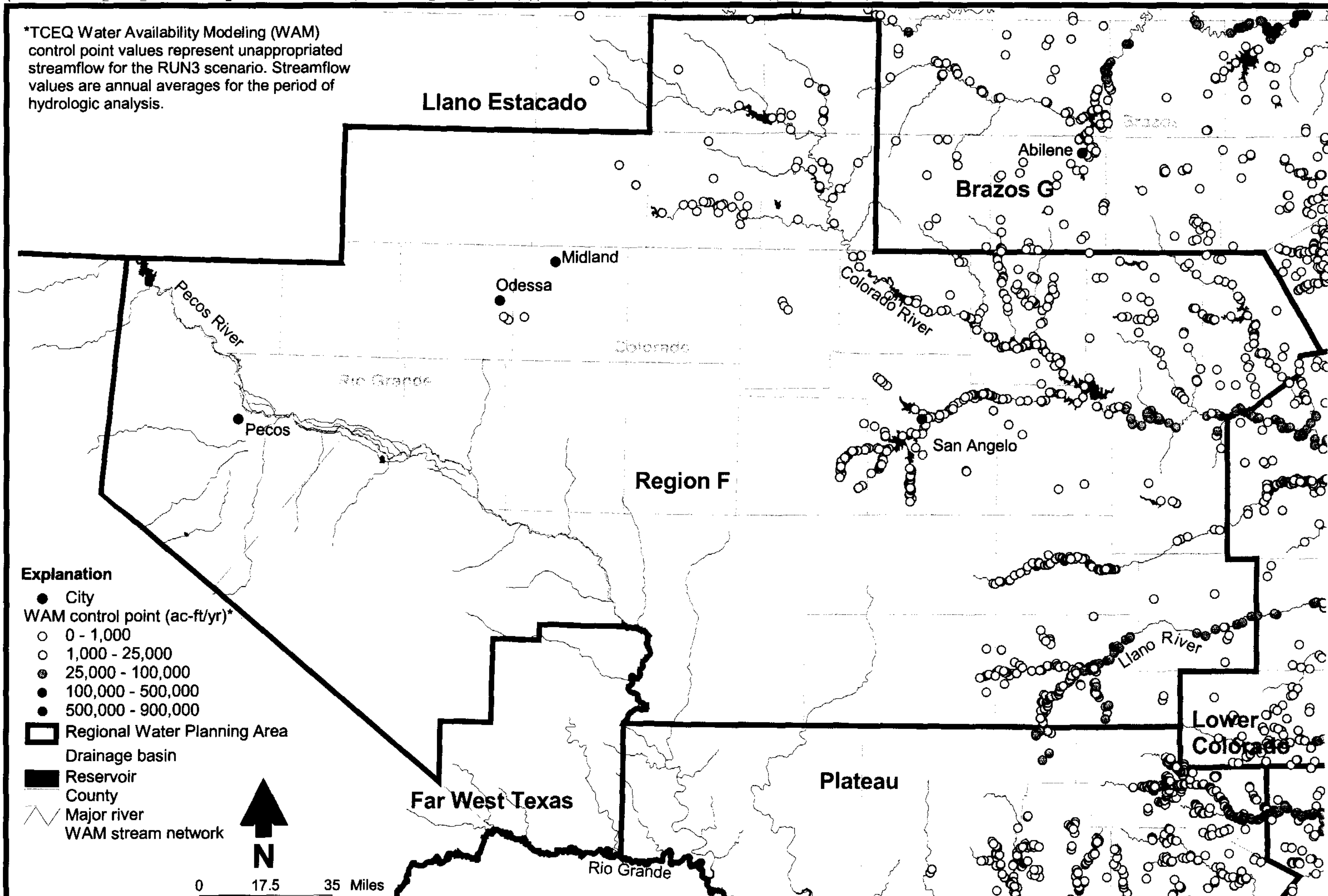
Region F Reservoirs and Conveyances

Daniel B. Stephens & Associates, Inc.

4-7-03 2:35PM JN 9408

Figure 32

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V04F -) (LAYOUT = L04F -)



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Region F Surface Water Availability

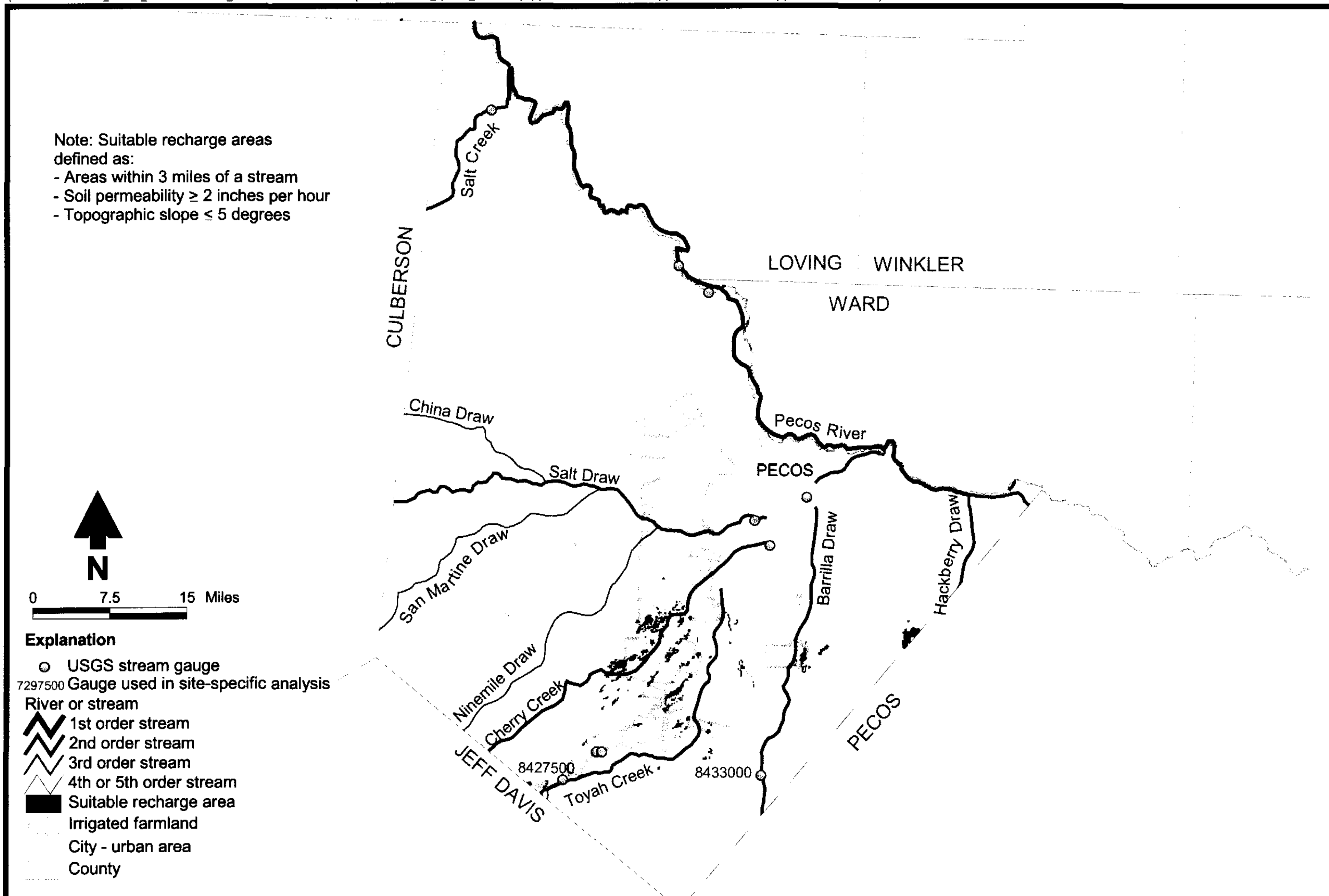
Daniel B. Stephens & Associates, Inc.

12-27-02 8:53AM

JN 9408

Figure 33

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V04C- R) (LAYOUT = L04C- R)



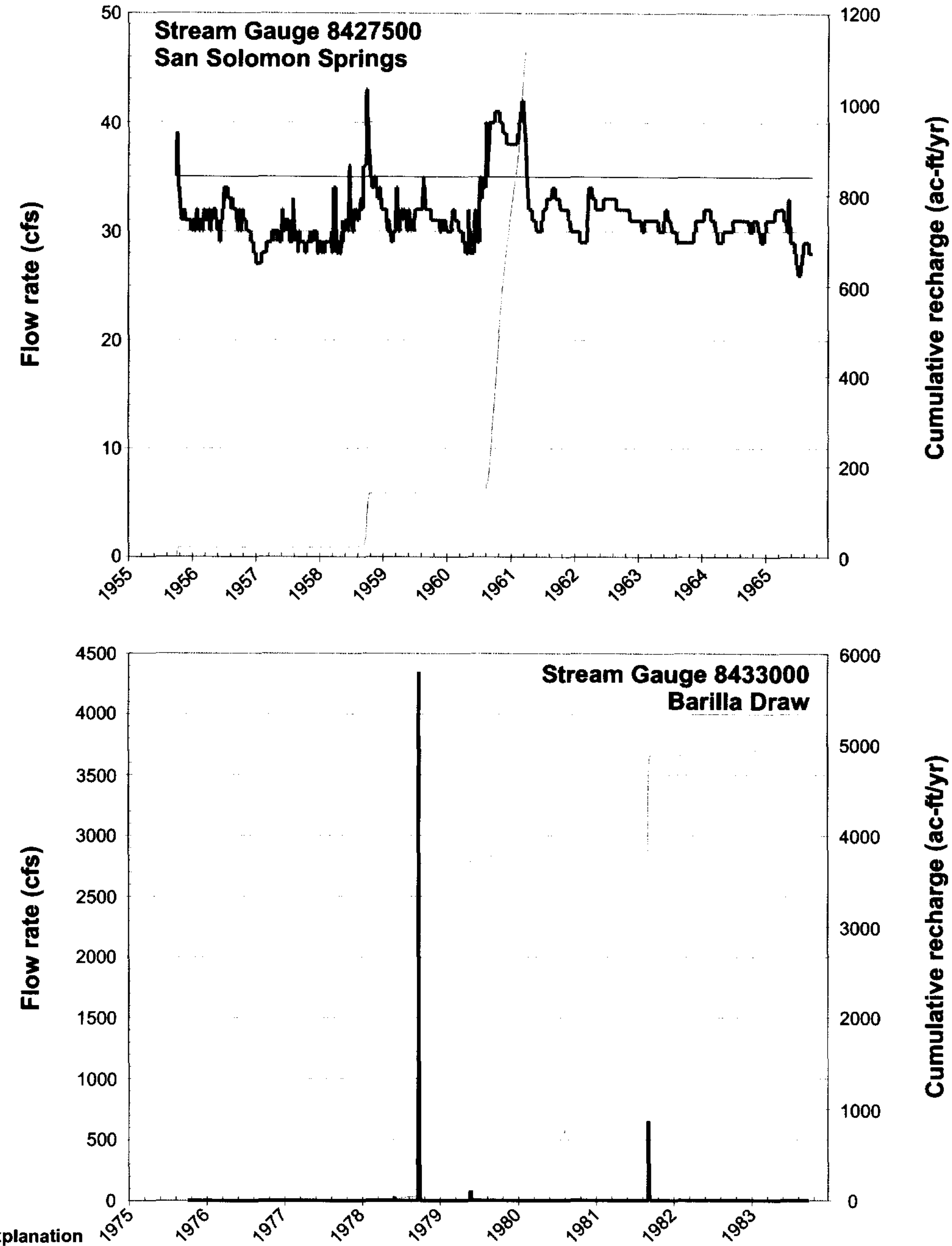
IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Reeves County Suitable Recharge Areas

Figure 34

Daniel B. Stephens & Associates, Inc.

12-31-02 3:20PM JN 9408



Explanation

- Observed stream flow
- Threshold
- Calculated cumulative recharge

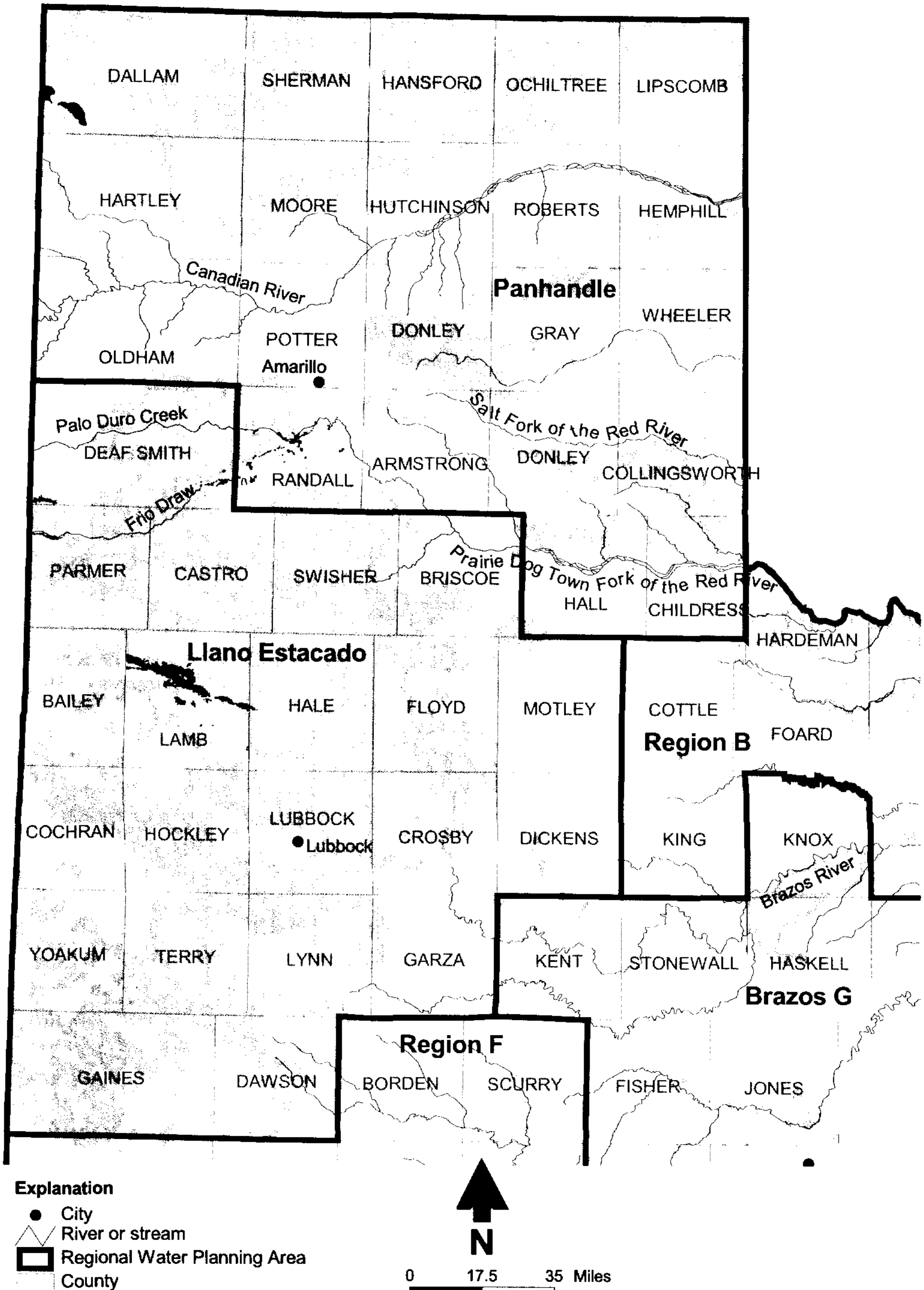
Notes:
Recharge area: This scenario calculates the cumulative infiltration of water based on a hypothetical recharge basin of 100 acres.

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Available Recharge Hydrograph for USGS Stream Gauges, Reeves County

Daniel B. Stephens & Associates, Inc.
1-08-03 JN 9408

T:\VDR\0-VDR-PROJECTS\9408\940806b.CDR



Explanation

- City
- River or stream
- Regional Water Planning Area
- County
- Suitable recharge area
- Irrigated farm land
- County selected for site-specific analysis

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

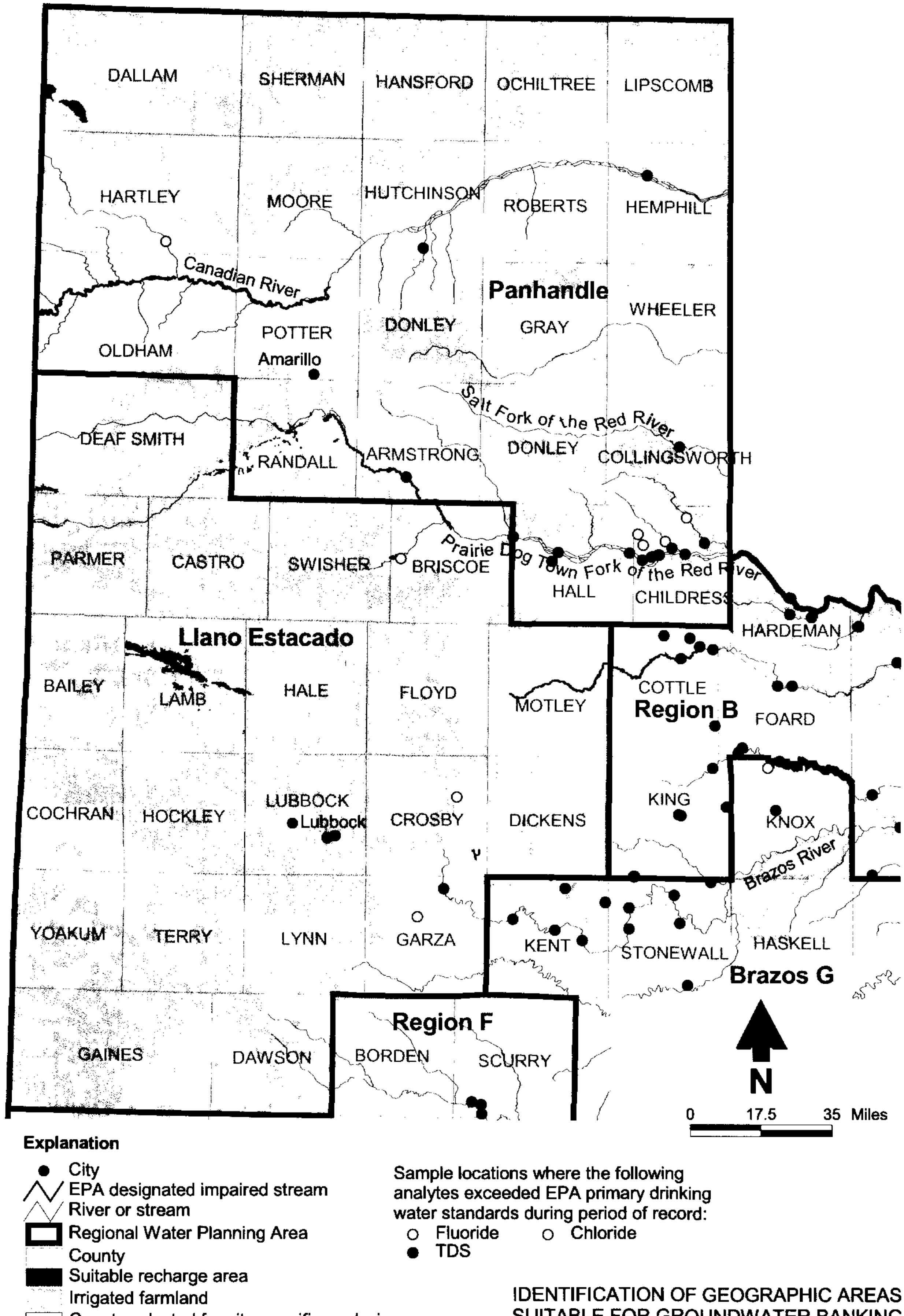
Ogallala Suitable Recharge Areas

Daniel B. Stephens & Associates, Inc.

4-7-03 2:37PM JN 9408

(S:\PROJECTS\9408 TEXAS GROUNDWATER BANKING\GIS\PROJECTS (PROJECT = site specific txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V01A -) (LAYOUT = L01A -)

Figure 36



IDENTIFICATION OF GEOGRAPHIC AREAS
SUITABLE FOR GROUNDWATER BANKING
Ogallala Water Quality

Daniel B. Stephens & Associates, Inc.
4-7-03 2:37PM
JN 9408

S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW NAME = V01D -) (VIEW EXTENTS = TEMP) (LAYOUT = L01D -)

Figure 37

8. Ogallala Region

For the purposes of this analysis, the Ogallala Region includes counties from both the Panhandle (Region A) and Llano Estacado (Region O) RWPAs (Figure 36). These counties were grouped into one region because all of them overlie the Ogallala Aquifer (Figure 5), which is unconfined.

8.1 Water Resources Overview

The primary use of water in regions that overlie the Ogallala Aquifer is for irrigated agriculture. In the Panhandle region of the aquifer, especially north of Amarillo and the Canadian River Valley, approximately 85 percent of the total water use is for irrigated agriculture. In the southern counties of the Ogallala region, approximately 95 percent of the total water use 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. Thus, any large-scale recharge program would need to incorporate some type of playa modification or enhancement. It is probable that the benefits of such a program could be significant, as recent studies have demonstrated that a significant portion of recharge to groundwater on the High Plains occurs through playas. The playas are not addressed specifically in this report due to their unique hydrologic aspects. In addition, playas did not make it through our screening process because they (1) are generally not within 3 miles of a significant watercourse and (2) generally have bottoms that are covered by low-permeability soils. A more detailed overview of enhanced recharge at playas is provided in Section 1.2.1.

Tributaries to the Red, Brazos, and Colorado Rivers cross the southern plains of this region, but these tributaries are ephemeral. When they flow after storm events, most or all of the water typically infiltrates or is lost to evaporation before it flows off the caprock into the central plains. To a certain extent, therefore, these stream courses already act as natural recharge facilities. However, there could be some opportunity for capturing storm flows from these tributaries before they flow off the escarpment.

Table 12 shows the water supply projections and Figure 37 shows selected water quality data for the region.

Table 12. Projections for Selected Counties in Ogallala Region (Llano Estacado and Panhandle Regional Water Planning Areas)

County	SSURGO Soil Data Available	Projected Water Supply[a] (ac-ft/yr)						Acreage Suitable for Recharge[b]
		2000	2010	2020	2030	2040	2050	
Bailey	No	–7,278	–6,463	–5,350	–4,014	–2,431	–925	---
Briscoe	No	---	---	---	---	---	---	---
Castro	Yes	–39,261	–39,143	–38,621	–37,592	–36,449	–35,107	---
Cochran	No	–13,181	–12,046	–10,948	–9,868	–8,836	–7,856	---
Deaf Smith	Yes	---	---	---	–2,516	–2,596	–2,717	3,642
Floyd	No	–23,567	–23,949	–24,088	–23,855	–23,577	–23,199	---
Gaines	No	0	–581	–555	–547	–535	–533	---
Hale	Yes	–2,234	–2,183	–4,180	–7,998	–10,472	–13,442	362
Lamb	Yes	---	---	–918	–1,371	–1,368	–1,381	38,527
Parmer	Yes	–34,176	–42,245	–49,404	–56,597	–62,026	–66,840	1,518
Swisher	No	–45,349	–45,145	–42,545	–44,533	–44,228	–43,921	---
Terry	Yes	–961	–935	–891	–871	–846	–792	---
Yoakum	No	0	0	–457	–1,935	–2,030	–2,158	---
Dallam	No	---	---	–392,701	---	---	–397,991	15,235
Moore	No	851	---	–218,773	---	---	–224,415	---
Oldham	No	456	---	–28,291	---	---	–28,783	---
Potter	No	1,907	---	–35,776	---	---	–45,929	---
Randall	Yes	1	---	–60,150	---	---	–72,661	5,534
Sherman	No	0	---	2,154	---	---	0	---

[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

Of the few counties in the region for which the high-resolution SSURGO soils data were available, Randall County was the only one for which hydrograph data also existed. Therefore, Randall County is the selected example county for the region.

Figure 38 shows the existing and proposed conveyances within the Ogallala region.

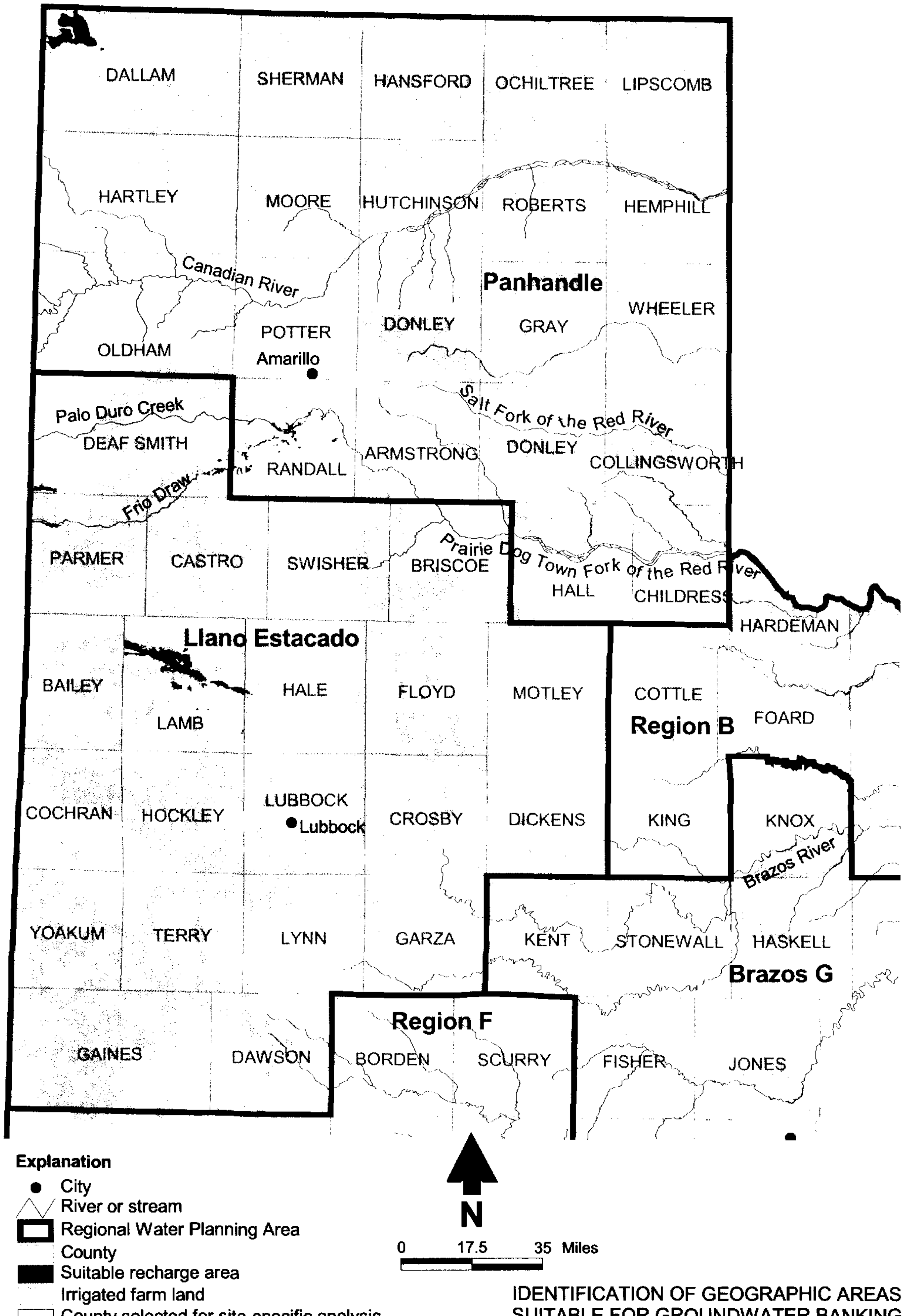
8.2 Rate, Area, and Time Period for Infiltration

The WAM data show excess streamflows ranging from 2,470 ac-ft/yr to more than 32,000 ac-ft/yr along the Prairie Dog Town Fork of the Red River with 579 ac-ft/yr on Frio Draw and 23,422 ac-ft/yr on Palo Duro Creek in Deaf Smith County (Figure 39).

In Randall County, the total demand is 105,116 ac-ft/yr, of which 57,491 ac-ft/yr is for irrigation. Most of the prime acreage for recharge is along the Prairie Dog Town Fork of the Red River and its tributaries, while most of the irrigated agriculture is located well away from the watercourses (Figure 40).

Figure 41 illustrates computations of banked water for Gauge 7297500 on the Prairie Dog Town Fork of the Red River several miles downstream of Canyon. The average permeability for this site was determined to be about 8 ft/d. Calculated cumulative recharge for a 100-acre basin is about 15,800 ac-ft over a 10-year period from the 1940s, when data are available for this gauge. About 80 percent of this calculated recharge is due to two very large precipitation events that occurred during 1942 (Figure 41), which was a record year of precipitation across much of the Southern High Plains. Based on the same hydrograph record, the required area to bank all available water, as determined using the Prairie Dog Town Fork of the Red River gauge, is 75 acres, and the average time available for infiltration is 3.3 days.

The hydrograph record for this site illustrates that the draws that cross the High Plains only flow during storm events. In addition, the volume of water that can be practically captured for banking is small compared to the major demand in the region, which is irrigated agriculture. For example, the site-specific analysis for the Prairie Dog Town Fork of the Red River gauge in Randall County indicated that 15,800 ac-ft of water could have been banked over a 10-year period, yet the estimated 2050 deficit in Randall County is more than 72,661 ac-ft/yr. Therefore, groundwater banking of water from the Prairie Dog Town Fork site, and likely from other stream courses on the High Plains that overlie the Ogallala Aquifer, is probably not an efficient approach to take in general, although some applications for municipal uses (such as Canyon and Amarillo in our example) could be worthwhile. The greatest benefit from artificial recharge on the High Plains would probably be obtained from enhanced recharge at playas in or immediately adjacent to regions of irrigated agriculture.



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

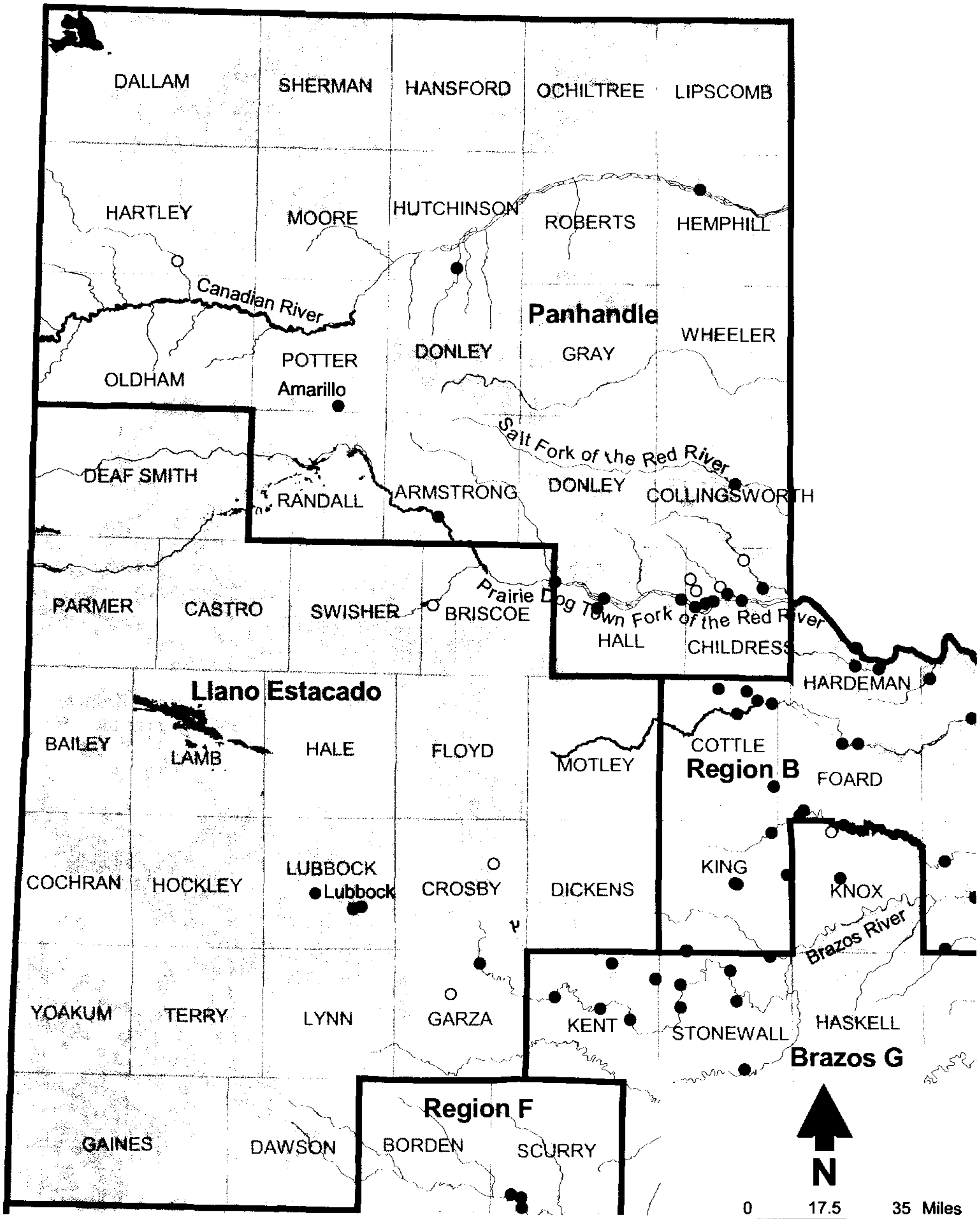
Ogallala Suitable Recharge Areas

Daniel B. Stephens & Associates, Inc.

12-31-02 2:53PM JN 9408

Figure 36

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V01A -) (LAYOUT = L01A -)



Explanation

- City
- EPA designated impaired stream
- River or stream
- Regional Water Planning Area
- County
- Suitable recharge area
- Irrigated farmland
- County selected for site-specific analysis

Sample locations where the following analytes exceeded EPA primary drinking water standards during period of record:

- Fluoride
- Chloride
- TDS

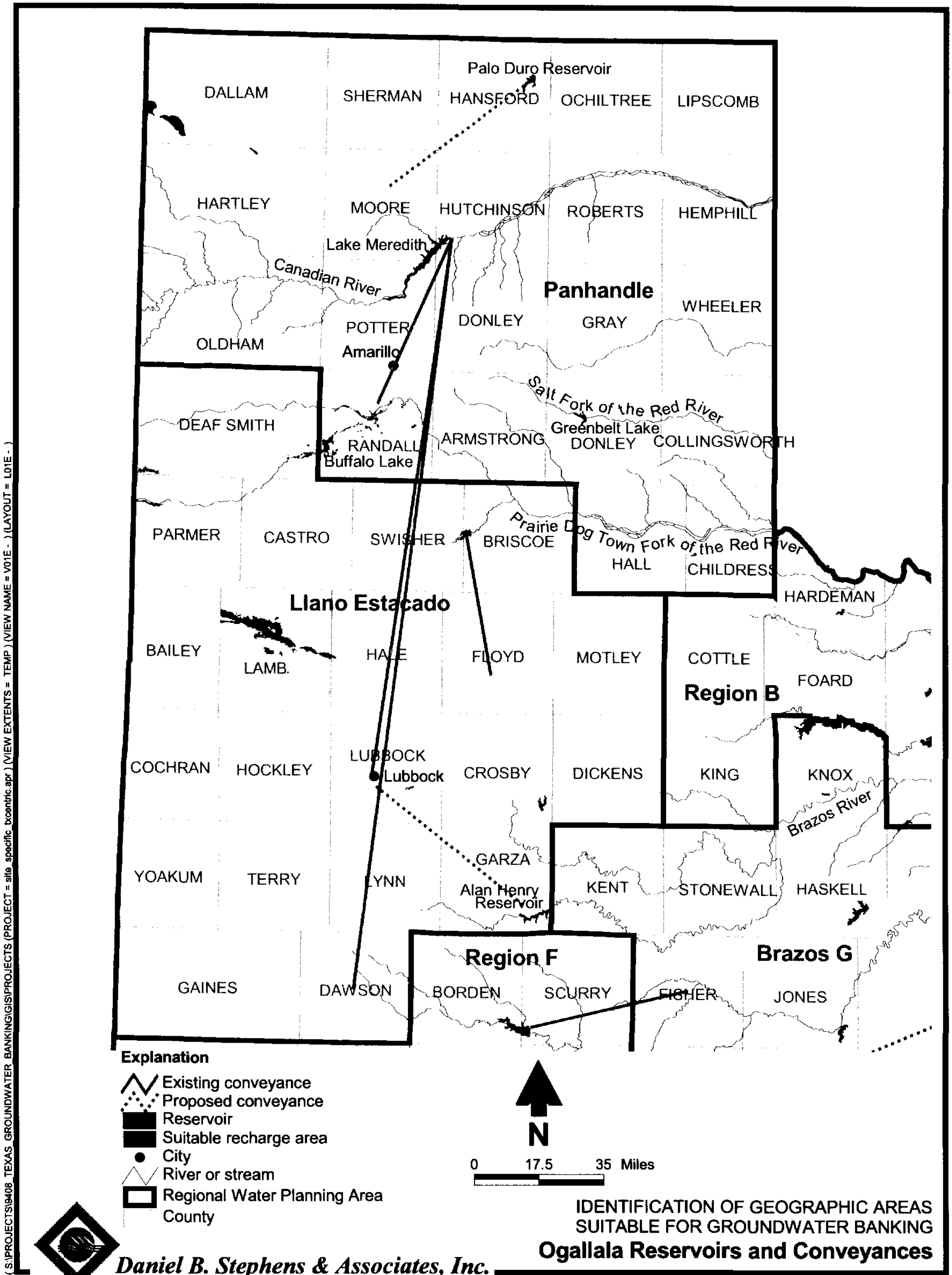
IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Ogallala Water Quality

Daniel B. Stephens & Associates, Inc.
12-31-02 3:01PM JN 9408

Figure 37

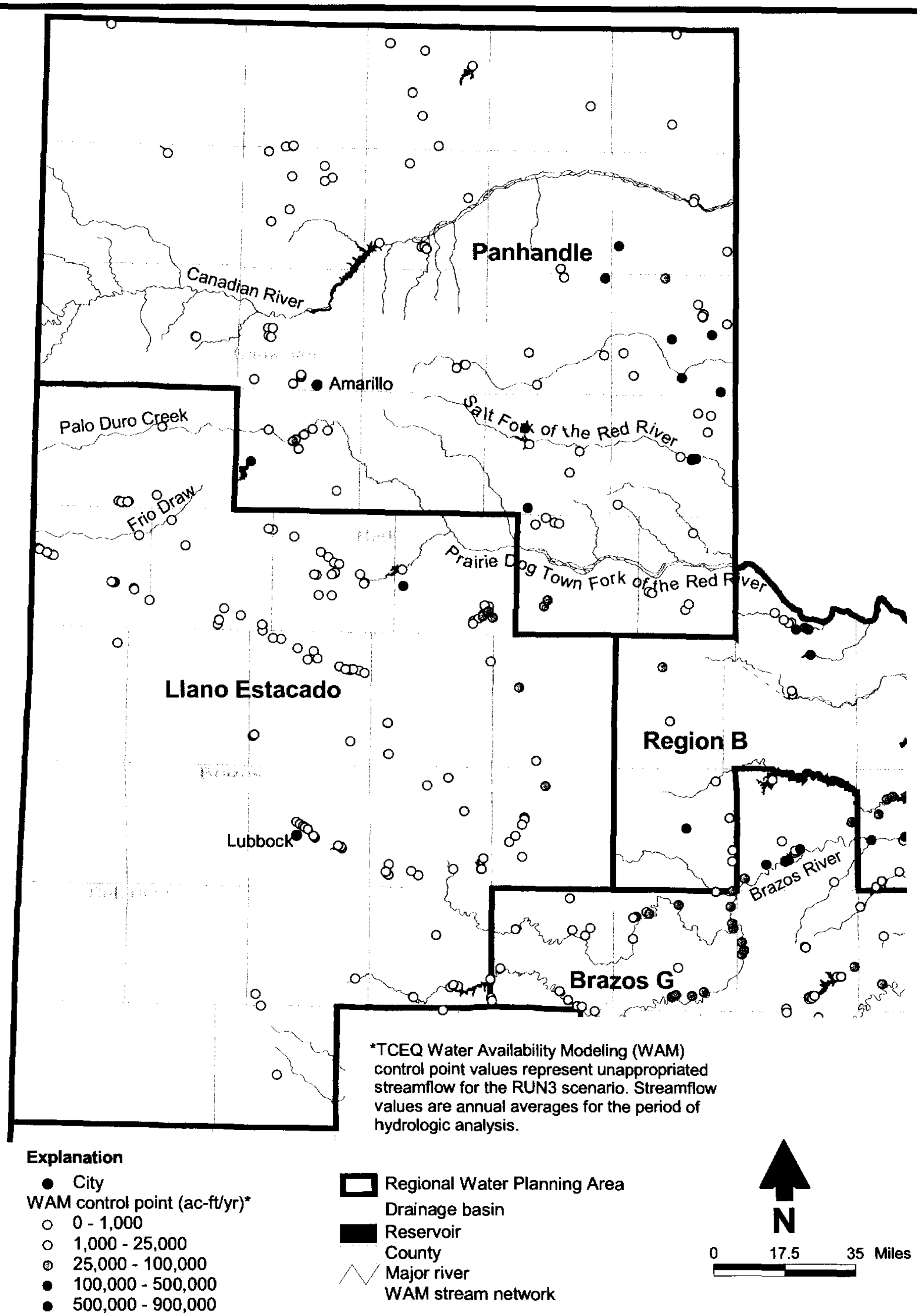
(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V01D -) (LAYOUT = L01D -)



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING
Ogallala Reservoirs and Conveyances

Daniel B. Stephens & Associates, Inc.
4-7-03 2:36PM
JN 9408

Figure 38



IDENTIFICATION OF GEOGRAPHIC AREAS
SUITABLE FOR GROUNDWATER BANKING
Ogallala Surface Water Availability

Daniel B. Stephens & Associates, Inc.
12-27-02 8:47AM
JN 9408

Figure 39

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V01F -) (LAYOUT = L01F -)

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V01C -) (LAYOUT = L01C -)

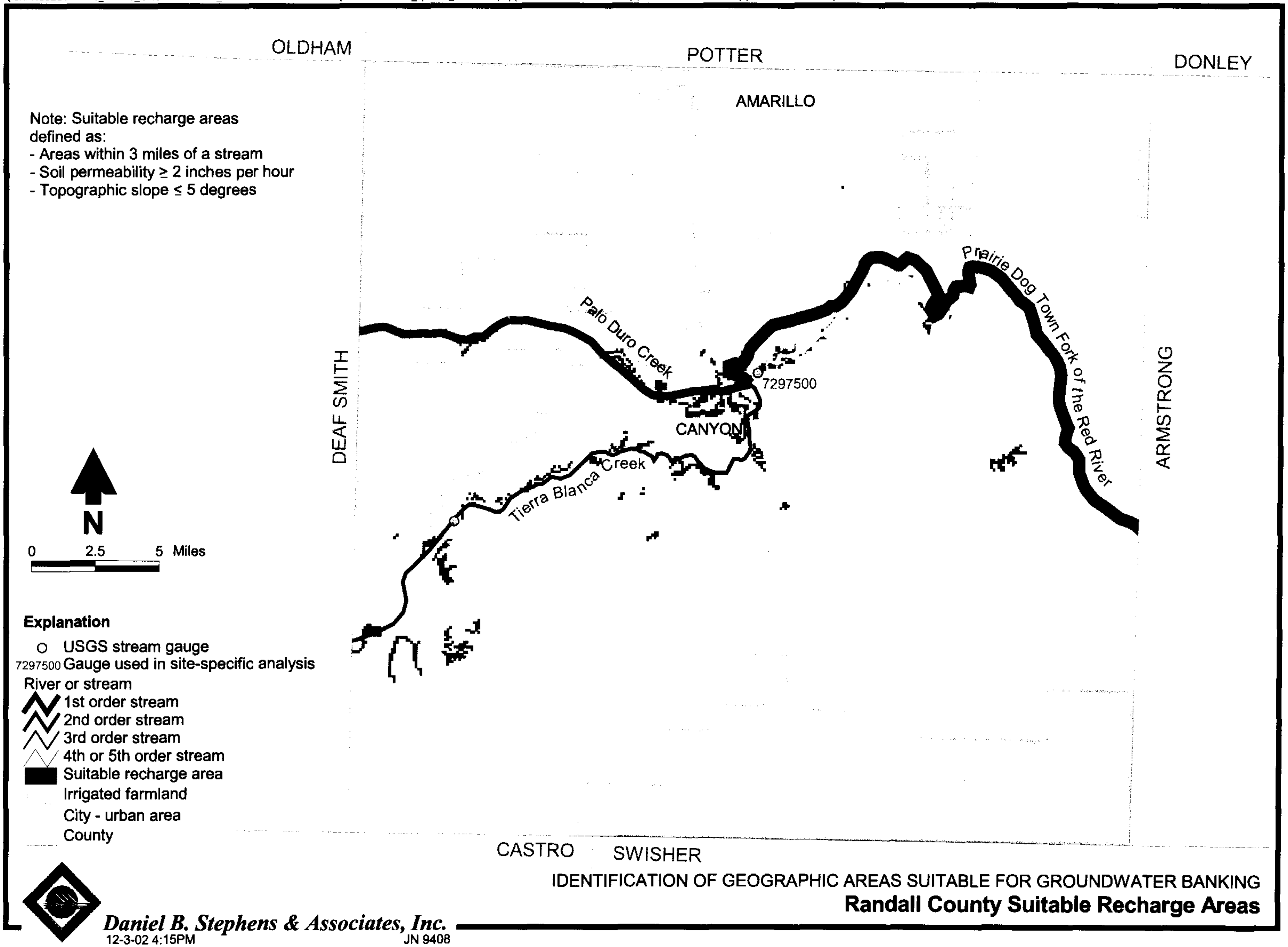
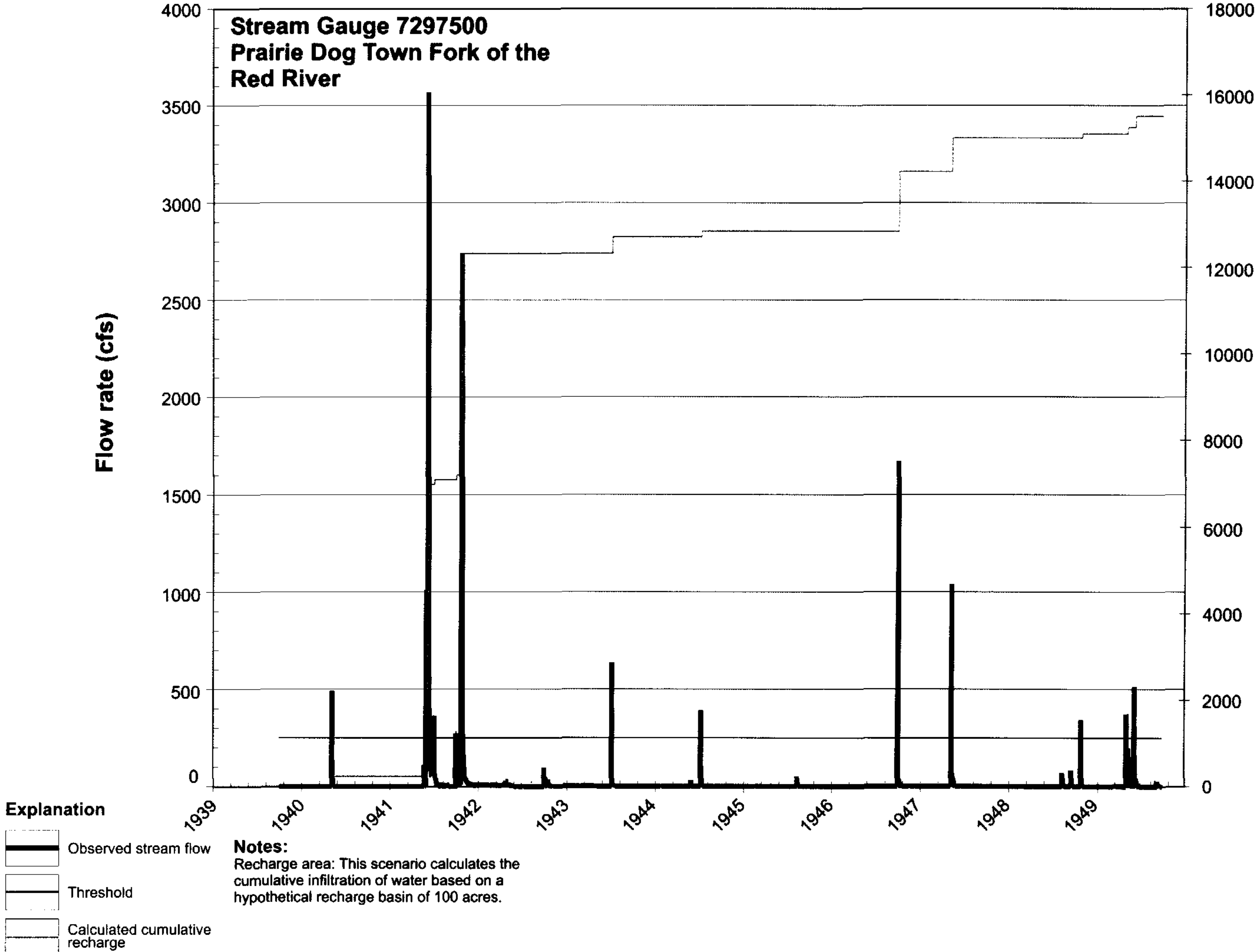


Figure 40

T\VDR\0-VDR-PROJECTS\9408\940805b.cdr



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

Figure 41

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Available Recharge Hydrograph for USGS Stream Gauge, Randall County

Daniel B. Stephens & Associates, Inc.
1-08-03 JN 9408

9. Far West Texas Region

El Paso County was the only selected county from the Far West Texas RWPA (Region E) (Figure 42). Most of the population (96 percent) of the region resides in El Paso County.

9.1 Water Resources Overview

El Paso and Hudspeth Counties account for the majority of irrigation demand (Figure 42) in the Far West Texas Region, although irrigation demand in El Paso County is projected to decrease from 179,842 ac-ft in 2000 to 152,014 ac-ft in 2050. El Paso County is responsible for 66 percent of the current 509,426 ac-ft of water used each year. Municipal water use in El Paso County is expected to nearly double in the next 50 years, from 101,928 ac-ft in 2000 to 199,097 ac-ft in 2050. Water supply projections for the region are shown in Table 13. Surface water quality data are summarized on Figure 43.

Table 13. Projections for El Paso County in the Far West 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	
El Paso	Yes	–118,727	–87,908	–67,526	–376,072	–392,139	–412,237	44,658

[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

The Rio Grande is the major surface water source in the region. Below the El Paso-Hudspeth County line, river flow is primarily irrigation return flow and storm runoff. Groundwater is the major source of water in the region, and the Hueco-Mesilla Bolson is the major aquifer. Large-scale groundwater withdrawals by the cities of El Paso and Juarez have led to severe declines in the aquifer.

Figure 44 shows the existing and proposed conveyances in the region. The Rio Grande Compact provides for the distribution of the waters of the Rio Grande among Colorado, New

Mexico, and Texas above Fort Quitman, Texas. The Compact sets out a schedule of the water-delivery obligation of Colorado at the Colorado-New Mexico state line and requires New Mexico to deliver water to Elephant Butte and Caballo Reservoirs as the deliveries to Texas. Releases from the reservoirs are measured downstream of Caballo Reservoir in south-central New Mexico.

The Rio Grande Project is an irrigation storage and flood control federal reclamation project administered by the U.S. Bureau of Reclamation. The El Paso County Water Improvement District (EPCWID) No. 1 encompasses the project lands in El Paso County, Texas (LBG-Guyton Associates et al., undated). The only viable surface water resource in El Paso County is the Rio Grande. The EPCWID irrigation ditch network is a potential surface water conveyance resource for potential groundwater banking.

9.2 Rate, Area, and Time Period for Infiltration

El Paso County has large areas suitable for recharge (Figure 45), but although the Rio Grande is a first-order stream, very little, if any, water is currently available due to prior appropriations. The TCEQ has not completed the WAM study for the Rio Grande Basin. However, Figure 45 can be used to suggest areas to reserve for recharge of existing well fields should water be made available.

In the El Paso area, there are virtually no opportunities for constructing surface reservoirs; therefore, aquifer storage is the only alternative. Aquifer storage recharge has been considered by the El Paso Water Utility as a method to provide seasonal storage of surplus treated wastewater effluent and to help restore the Hueco Bolson (Basin) in northeast El Paso. The Hueco Basin is the primary source of water for the City of El Paso, Fort Bliss, Biggs Air Force Base, Ciudad Juarez, and private industries in the area. As a result of long-term pumping to supply this water, groundwater levels in the basin have declined as much as 150 feet since 1903 (Ashworth, 1990). Low-cost recharge provides a method of extending the life of existing well fields in El Paso and elsewhere.

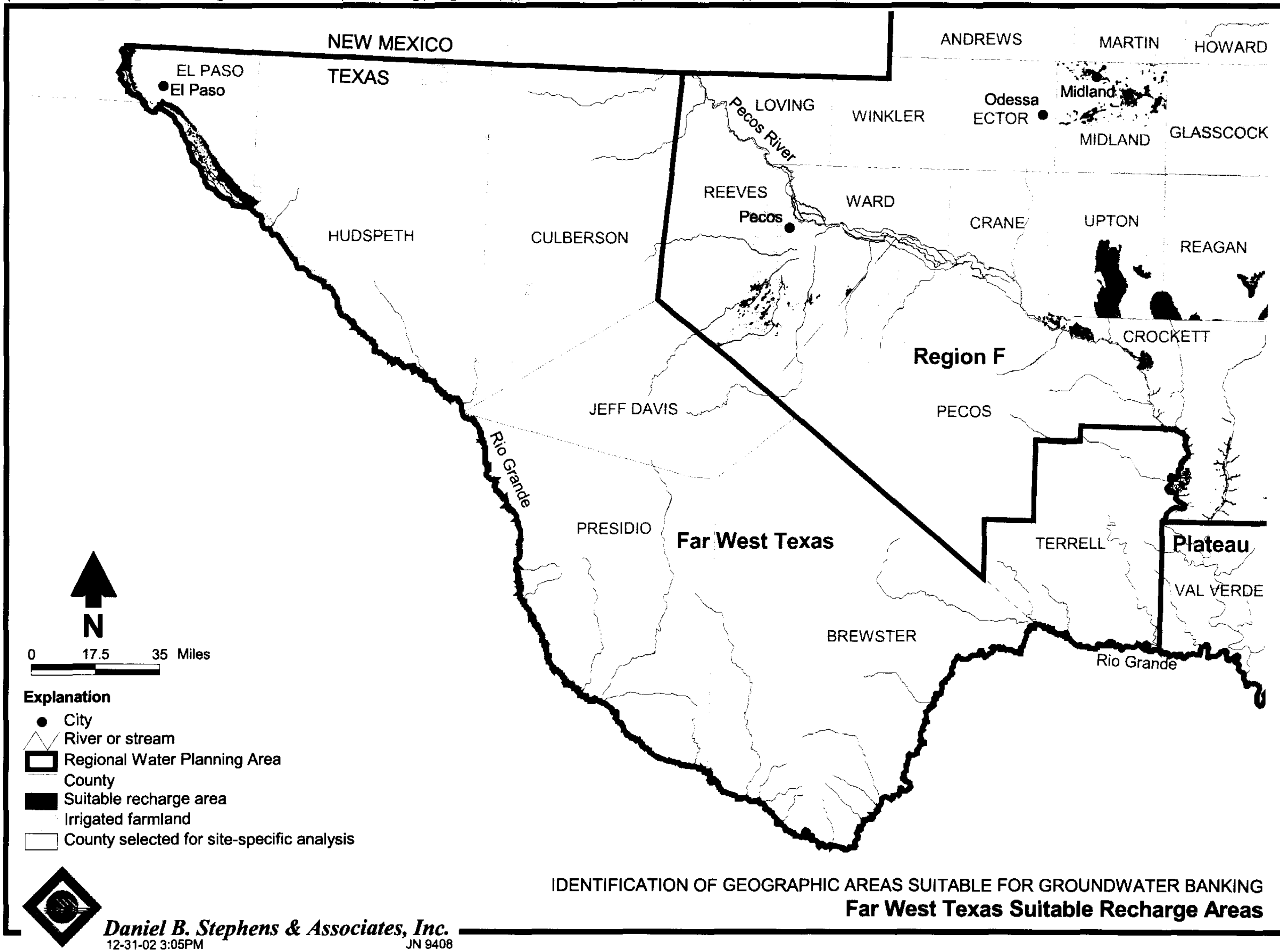
Since the mid-1980s the Hueco Basin has been successfully recharged at modest rates (up to about 10,000 ac-ft/yr) through deep injection wells. The concept of subsurface storage of water as a means of sustaining and/or increasing the water supply available in the area northeast of El Paso was presented in a report prepared by Boyle Engineering Corporation and Parsons Engineering Science, Inc. (1995). This report concluded that the northeast El Paso area appears to have conditions suitable for implementation of large-scale recharge. The area affords ample underground storage space and reasonably high assurances of long-term recovery of stored water. The lowering of water levels in the Hueco Basin has created a substantial depression in the water table into which the recharge water can be placed. The report also concluded that large-scale recharge provides an opportunity to mitigate aquifer overdraft and potentially restore groundwater supplies for continued use (Boyle and Parsons, 1995).

DBS&A and Boyle Engineering have performed a recharge study for the City of El Paso and the American Water Works Association Research Foundation (Hahn et al., 2002) that aims to locate and optimize recharge basin performance for the City of El Paso. The area of investigation, in the northern portion of a cone of depression that has developed around a major pumping center serving the City of El Paso, is well suited for both short-term and long-term groundwater storage. In July 2001, a recharge basin was excavated below a surface caliche layer, and recharge has averaged more than 8 ft/d since construction.

This high-performing site provides an example of how a Boolean query using low-resolution data can miss an excellent recharge location that the same query using high-resolution data would find. The site was missed by our query because it is too far from a natural water source and the slope of the site was identified as too steep. Analysis of high-resolution DEM data at the site would show what field reconnaissance showed, that is, the slope is workable.

Figure 46 illustrates computations of banked water for Gauge 8363840 on the Rio Grande north of Canutillo (Figure 45). The average permeability for this site was determined to be 8 ft/d. Calculated cumulative recharge for a 100-acre basin is about 60,000 ac-ft over a 5-year period, which is appreciable. As indicated on Figure 46, this calculation assumes that one-half of the water greater than the 600-cfs threshold value is available for banking. Flow at this gauge is clearly seasonal, with releases from upstream reservoirs, along with contributions to flow from late summer thunderstorms, accounting for peak flows during the growing season. Based on the hydrograph record, the required area to bank all available water as determined using the Rio Grande gauge is 24 acres, and the average time available for infiltration is 9.2 days.

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V02A -) (LAYOUT = L02A -)

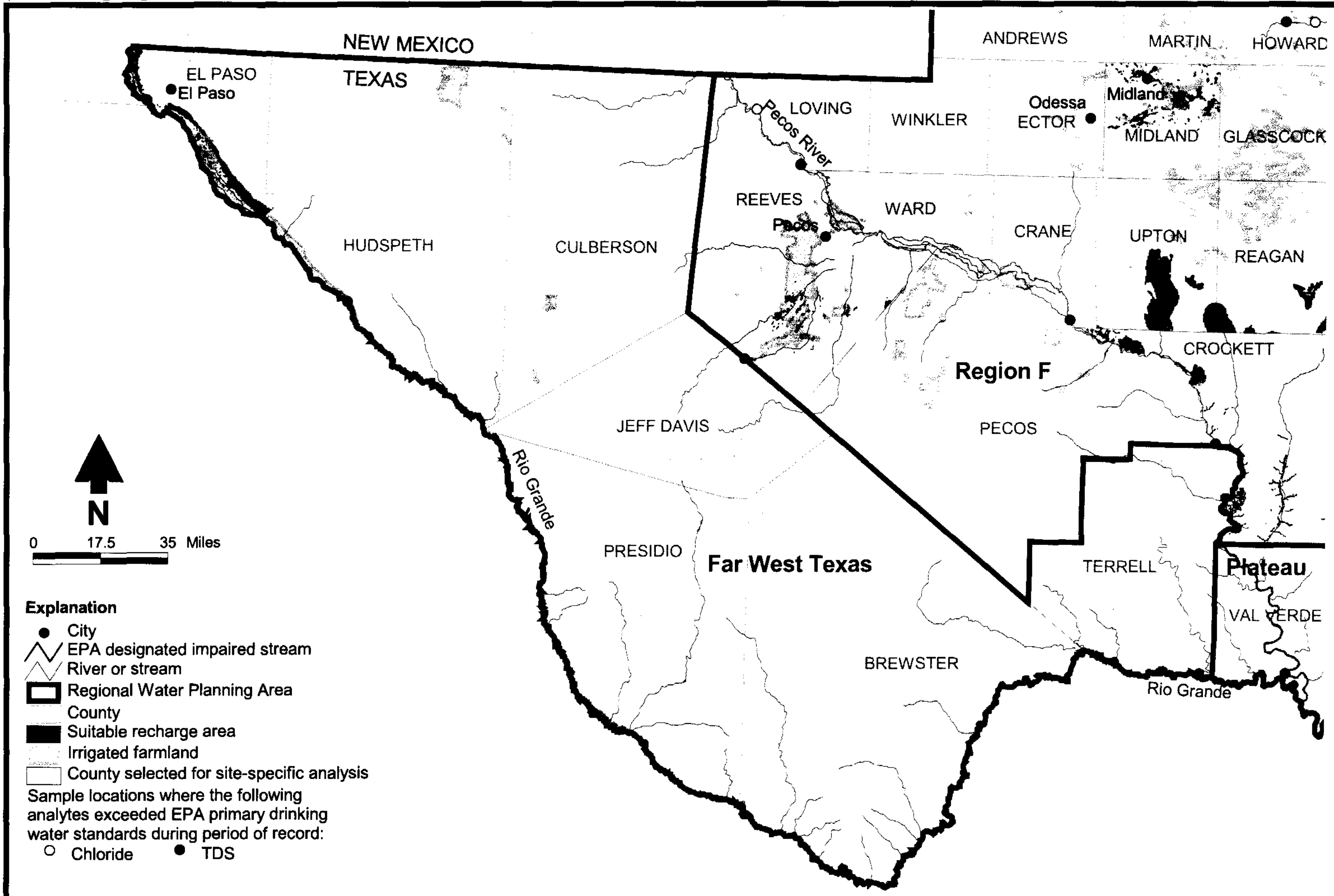


IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Far West Texas Suitable Recharge Areas

Figure 42

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V02D -) (LAYOUT = L02D -)



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Far West Texas Water Quality

Daniel B. Stephens & Associates, Inc.

12-31-02 3:07PM JN 9408

Figure 43

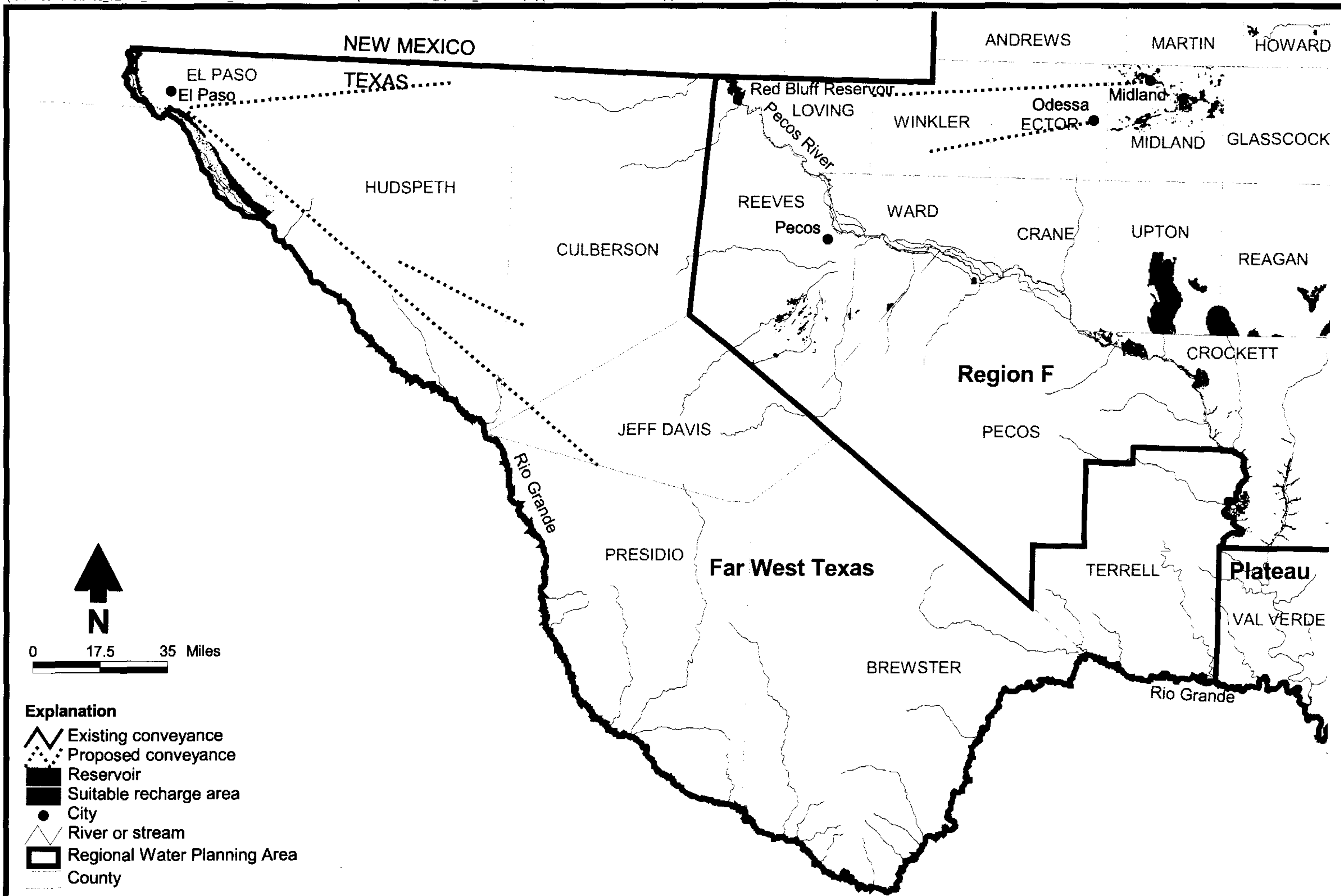


Figure 44

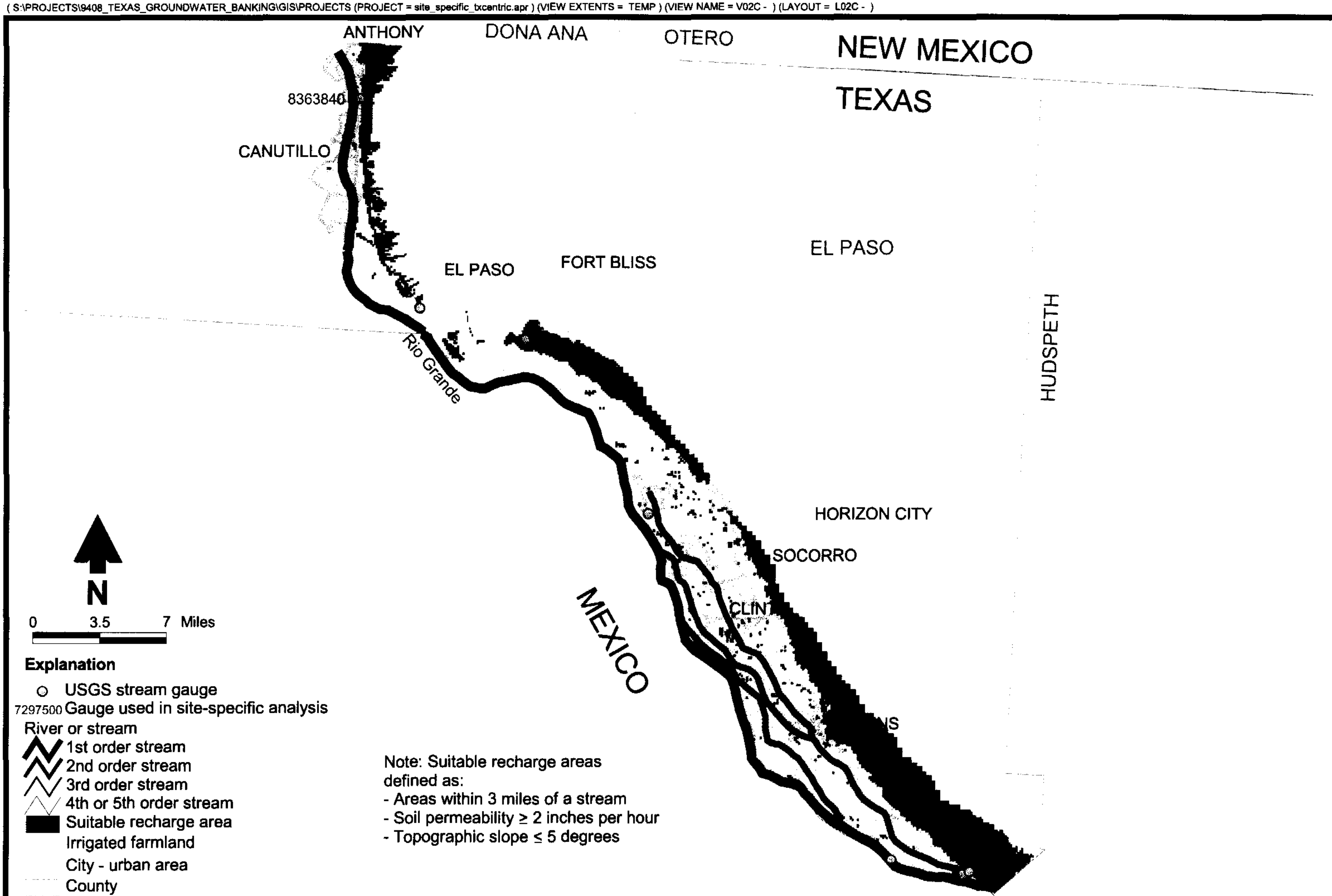
IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Far West Texas Reservoirs and Conveyances

Daniel B. Stephens & Associates, Inc.

12-31-02 3:08PM JN 9408

(S:\PROJECTS\9408_TEXAS_GROUNDWATER_BANKING\GIS\PROJECTS (PROJECT = site_specific_txcentric.apr) (VIEW EXTENTS = TEMP) (VIEW NAME = V02C -) (LAYOUT = L02C -)



IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

El Paso County Suitable Recharge Areas

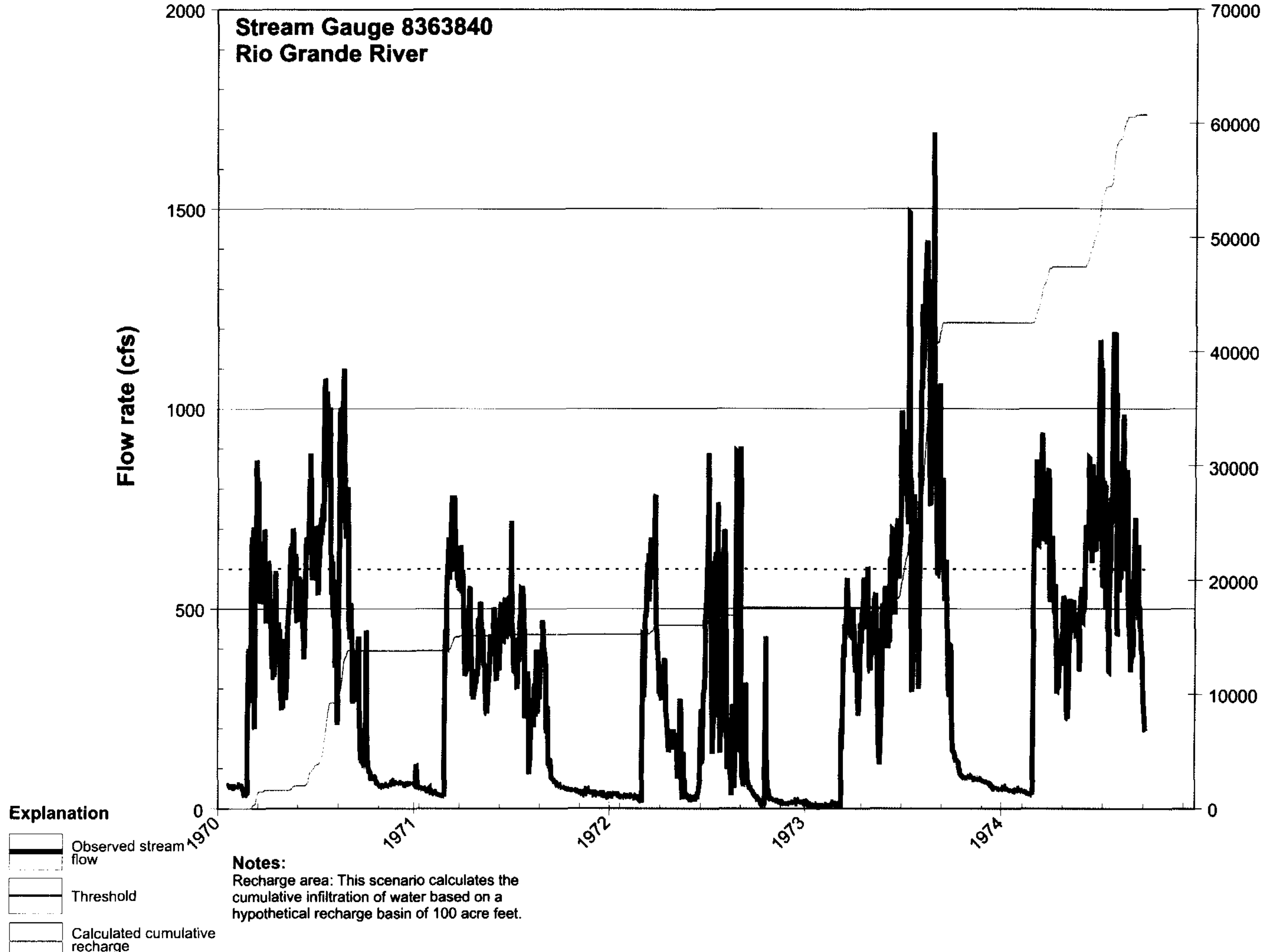
Daniel B. Stephens & Associates, Inc.

12-4-02 10:15AM

JN 9408

Figure 45

T:\VDR\0-VDR-PROJECTS\9408\940804b.cdr



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

IDENTIFICATION OF GEOGRAPHIC AREAS SUITABLE FOR GROUNDWATER BANKING

Available Recharge Hydrograph for USGS Stream Gauge, El Paso County

Daniel B. Stephens & Associates, Inc.
1-08-03 JN 9408

Figure 46

10. Conclusions and Recommendations

The primary goal for this study was to identify areas suitable for groundwater banking (recharge of excess surface water to an aquifer from surface or near-surface infiltration for use at a later date) within the state of Texas. An additional goal was to develop and provide a tool that would allow other users to select potentially suitable sites based on their unique circumstances.

Using a statewide screening analysis, we concluded that 48 counties fit the criteria for preliminary site-specific evaluation of recharge basin suitability (Table 1, Figure 8). The 48 counties were grouped into 6 regions, and 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. Initially, the statewide screen 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 level.

Users can conduct a screening analysis similar to that documented in this report using the ArcView GIS 3.2 Screening Analysis Tool developed as part of this project, described in Appendix C. The GIS tool was developed to assist users with application of custom screening criteria for site selection.

Within each selected region, we used the GIS Screening Analysis Tool to identify areas with soil permeability greater than or equal to 2 inches per hour, slopes of less than 5 degrees, and locations within 3 miles of a designated stream. Other factors, including surface water quality, water availability, 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. Water availability was estimated using TCEQ WAM model results along with one or more hydrographs selected from available stream gauges near potentially suitable sites.

Detailed site-specific screening was conducted for an example county from each region, selected on the basis of data availability including the higher-resolution SSURGO soil data and the presence of at least one surface water gauging station reasonably near potential recharge sites. In addition to the detailed screening, infiltration was calculated for one or two hypothetical basins in each example county; the results of these sample calculations are summarized in Table 14.

Specific findings and conclusions related to each region are provided in Sections 10.1 through 10.6. Additional recommendations and conclusions are provided in Section 10.7.

10.1 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

Table 14. 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

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. The Nueces River site overlies the Carrizo-Wilcox Aquifer outcrop area, and the Frio River overlies the Edwards-Trinity Aquifer. Assuming 100 acres of infiltration basin area at each site, calculated cumulative recharge over 10 years is about 50,000 ac-ft for the Nueces River gauge and about 75,000 ac-ft for the Frio River site. Computed time periods for infiltration are about 5 days for the Nueces gauge and 8 days for the Frio River gauge.

10.2 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 and Belton Lake. Analysis using a hydrograph from the gauge at Gatesville indicated potential infiltration of about 34,000 ac-ft over a 10-year period for a 50-acre basin. The average time period for infiltration at this site was determined to be about 5 days.

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 (HDR Engineering, Inc., 2001). 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.

10.3 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 up to 8,500 ac-ft/yr of available water on Rock Creek near Mineral Wells, although the smaller tributaries in this region have available flows of less than 100 ac-ft/yr. The WAM model data show excess flows of more than 400,000 ac-ft/yr along the Brazos River above Lake Granbury. Site-specific recharge analysis using a Brazos River hydrograph in the southeastern portion of the county, very close to several potential recharge sites, indicated potential infiltration of 225,000 ac-ft over a 10-year period.

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.

10.4 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. Tom Green County failed to meet the final screening criteria of the site-specific analysis; however, no SSURGO data are available for this county, and potential recharge locations might be missed due to lack of data.

Based on our site-specific screening, Midland County has a large area of potentially suitable locations near the City of Midland. Ector County has a fairly large site in the eastern portion of the county, in and around the City of Odessa. However, potentially available surface water for banking in these areas is very small (less than 630 ac-ft/yr on average, according to WAM model data in Midland and Ector Counties). 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 selected for detailed infiltration calculations; only a few small potential recharge areas throughout the central and southeastern portions of the county were identified. As illustrated by the Barilla Draw gauge, water available for banking along most of the area's streams originates in short-duration, infrequent storm events and the capture of this water may be difficult. According to calculations, about 5,000 ac-ft of water might have been banked over an 8-year period at the Barilla Draw gauge. However, the average duration of flow at this gauge is about two days, and most of the 5,000 ac-ft would have come from only two storm events.

Opportunities for efficient banking of water from springs may exist, particularly following wet periods where 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 is likely to be small, as indicated by analysis of the San Solomon Springs gauge data, which indicated that only 1,150 ac-ft of water might be banked over a period of 10 years. Ward County has a large site identified as potentially suitable near the Pecos River, south of the City of Monahans. 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 County.

10.5 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. For example, the site-specific analysis for the Prairie Dog Town Fork of the Red River gauge in Randall County, where the estimated 2050 deficit is more than 72,661 ac-ft/yr, indicated that only about 16,000 ac-ft of water could have been banked over a 10-year period, about 80 percent of which came from two storm events during one year of record precipitation.

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.

10.6 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 calculations for a Rio Grande hydrograph record several miles upstream of El Paso indicated that 60,000 ac-ft of water could be banked using a 100-acre basin over 5 years.

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.

10.7 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.

Evaluation of sites for the alternative recharge techniques discussed in Section 1 (e.g., infiltration through dry wells or aquifer storage and recovery) was beyond the scope of work for this project. However, the GIS tool used for this study is potentially useful in evaluating potential sites where some of these other recharge techniques might be applied.

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 systems)

- 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 (which can dramatically affect the concentrations of many dissolved to suspended constituent chemical species) 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 WAM data are still preliminary and not entirely complete. The Rio Grande Basin WAM will not be completed until sometime in 2003. TCEQ will eventually make much of their final results available as GIS files. Although the WAMs are valuable tools for evaluating water availability, model results should always be cross-checked with observed stream flow data available at or near a potential banking site.

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 (TPWD, 2002).

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.

References

Aronovici, V.S., A.D. Schneider, and O.R Jones. 1972. Basin recharge of the Ogallala aquifer. *J. Irrig. Drain. Div.* ASCE 65-75.

Asano, T. (ed.). 1985. *Artificial recharge of groundwater.* Butterworth Publ., Boston. 767 p.

Ashworth, J.B. 1990. *Evaluation of ground-water resources in El Paso County, Texas.* Texas Water Development Board Report 324.

Boyle Engineering Corporation and Parsons Engineering Science, Inc. 1995. *Study report: Aquifer storage and recovery investigation, final report.* Prepared for New Mexico-Texas Water Commission. September 1995.

Bouwer, H. 2002. Artificial recharge of groundwater: hydrogeology and engineering. *Hydrogeology Journal* 10(1):121-142.

Brune, G. 2002. *Springs of Texas, Volume 1* (2nd ed.). Texas A&M University agriculture series: Texas A&M University Press, College Station, Texas. 590 p.

Dvoracek, M.J., and H.S. Peterson.1971. *Development of systems for ground water recharge into the Ogallala formation.* WRC 71-4, Texas Tech University, Water Resources Center.

Freese and Nichols, Inc., Alan Plummer Associates, Inc., Chiang, Patel and Yerby, Inc., and Cooksey Communications, Inc. 2001a. *Region C Water Plan.* Prepared for Region C Water Planning Group. January 2001. [Available on-line at http://www.twdb.state.tx.us /assistance/rwpg/main-docs/regional-plans-index.htm].

Freese and Nichols, Inc., LBG-Guyton Associates, Inc., S-K Engineering, Inc., Alan Plummer Associates, Inc., Texas Tech University, and Texas Agricultural Experiment Station. 2001b. *Region F Regional Water Plan.* Prepared for Region F Water Planning Group. January

2001. [Available on-line at http://www.twdb.state.tx.us /assistance/rwpg/main-docs/regional-plans-index.htm].

Hahn, W.F., H. Thompson, J. Forbes, and M. Ankeny. 2002. *Comparison of an infiltration basin and vadose zone well for the recharge of a deep aquifer.* Jointly sponsored by AWWA Research Foundation, El Paso Water Utilities, and U.S. Department of the Interior, Bureau of Reclamation. AWWA Research Foundation and American Water Works Association.

HDR Engineering, Inc. 2001. *Brazos G Regional Water Planning Area Regional Water Plan.* Prepared for Brazos G Regional Water Planning Group. January 2001. [Available on-line at http://www.twdb.state.tx.us/assistance/rwpg/main-docs/regional-plans-index.htm].

Johnson, A.I., and R.D.G. Pyne. 1994. Artificial recharge of ground water, II. *In* A.I. Johnson and R.D.G. Pyne (ed.) *Proc. 2nd Int. Symp. on Artificial Recharge of Groundwater,* Florida, July 1994. ASCE, New York.

Johnson, S., R. Esquilin, D. M. Mahula, E. L. Thompson, J. Mireles, R. Gloyd, J. Sterzenback, J. R. Hoyt, and G. Schindel. 2002. *Hydrogeologic data report for 2001.* Edwards Aquifer Authority. 122 p.

LBG-Guyton Associates, Freese and Nichols, Inc., Moreno Cardenas, Inc., M3H Consulting, Inc. Undated. *Far West Texas Regional Water Plan* [Available on-line at http://www.twdb.state.tx.us/assistance/rwpg/main-docs/regional-plans-index.htm].

Meyer, J., A. Richards, and M. Light. 1999. Comparison of operational approaches and hydrologic responses for artificial recharge of Central Arizona Project Water. *In Artificial recharge and integrated water management, Proc. 9th Biennial Symposium on the artificial recharge of groundwater.* Tempe, Arizona, June 1999. p. 25-34.

Peters, J. H. (ed.). *Artificial recharge of groundwater. Proceedings of the Third International Symposium on Artificial Recharge of Groundwater.* TISAR '98, Amsterdam, September 21-25. A.A. Balkema, Rotterdam. 474 p.

Pettyjohn, W.A. 1981. *Introduction to artificial ground-water recharge.* NWWA-EPA Series. 44 p.

Pyne, R.D.G. 1995. *Groundwater recharge and wells: A guide to aquifer storage recovery.* Lewis Publishers, Boca Raton, Florida. 376 p.

Pyne, R.D.G. 2002. *Aquifer storage recovery forum (ASR) water resourcing.* <http://www.asrforum.com> November 12, 2002 (Accessed December 26, 2002)

Schneider, A.D., and O.R. Jones. 1988. Ground water recharge through excavated basins. pp. 292-301 *In Artificial Recharge of Ground Water Symposium.* IR Div. ASCE, Anaheim, California.

Signor, D.C., and V.L. Hauser. 1968. *Artificial ground water recharge through basins in the Texas High Plains.* Texas Agricultural Experiment Station Publication Miscellaneous Publication 895, Texas A&M University, College Station, Texas. 8 p.

South Central Texas Regional Water Planning Group (SCTRWPG). 2001. *South Central Texas Regional Water Planning Area regional water plan, Vol. 1 — Executive summary and regional water plan.* With administration by San Antonio River Authority and technical assistance by HDR Engineering, Inc., Moorhouse Associates, Inc., and Open Forum. January 2001. [Available on-line at http://www.twdb.state.tx.us/assistance/rwpg/main-docs/regional-plans-index.htm].

Texas Commission on Environmental Quality (TCEQ). 2002. *Water Availability Models (WAM).* <http://www.tnrcc.state.tx.us/permitting/waterperm/wrpa/wam.html> (Accessed November 2002).

Texas Parks and Wildlife. 2002. *Biodiversity database survey* <http://fwie.fw.vt.edu/WWW/biodivsur/dbasesurv/tx1.htm>(Accessed December 31, 2002).

Texas Water Development Board (TWDB). 2002a. *Water for Texas.* Vol. 1. 156 p.

Texas Water Development Board (TWDB). 2002b. *Evaporation/precipitation data for Texas* <http://hyper20.twdb.state.tx.us/Evaporation/evap.html> (Accessed December 26, 2002).

White, R.A. 1999. *Description of STATSGO data* <http://dbwww.essc.psu.edu/dbtop/doc/statsgo/statsgo_info.html> August 9, 1999 (Accessed December 31, 2002).

Appendix A

Scope of Work and Review Comments on Draft Report

Appendix A1

Project Scope of Work

Scope of Work for Identification of Geographic Areas Suitable for Groundwater Banking - March 16, 2001

The scope of work for this project is divided into three main tasks. Task 1 involves identification of regions in the state that are clearly not suitable for groundwater banking. These areas will be excluded from further analysis once they are identified. Task 2 involves more detailed analyses for regions not screened out during Task 1 for suitability for groundwater banking. Task 3 involves reporting and submission of deliverables to the Texas Water Development Board (TWDB). Some aspects of the approach outlined below may be modified (with permission of the TWDB project manager) during the study as available data sources are obtained and analyzed. Each of these tasks are presented in detail in the following sections.

Due to the large-scale nature of this research (the entire state of Texas), analyses conducted will depend to a great extent on existing regional or state-wide studies (e.g. the regional water plans and regional U.S. Geological Survey or Bureau of Economic Geology reports) and data available in electronic format from standard sources on the world wide web. Some readily available sources of information on which we will rely heavily include TNRIS, the TWDB well database, and U.S. Geological Survey databases. If sufficient quantitative information is not available for certain regions, we will make a professional judgement as to the suitability of a given region for groundwater banking.

Task 1 - Screening Analysis

The purpose of the screening analysis is to identify regions of the state that are not suitable for water banking so they can be eliminated from further study. The screening analysis will be conducted by looking at the following factors. Additional factors may be determined in conjunction with the TWDB.

- Areas of the state underlain by aquifers that currently reject recharge will not be considered for additional analysis, as their storage capacity and/or residence time is likely to be small.

- Regions underlain by aquifers that have a low available storage capacity as indicated by small depths to groundwater will be excluded from additional analysis.

- Areas where surface water quality is significantly poorer than groundwater quality will not be considered. This is based on the assumption that it is unacceptable to degrade groundwater by infiltrating surface water of significantly lower quality.

- Areas where groundwater quality is significantly poorer than surface water quality will not be considered. This is based on the assumption that it is undesirable to reduce recovery efficiencies by mixing higher quality surface water with more saline groundwater.

- Areas where there is no surplus surface water during non-drought periods will not be considered. These areas will be identified using SB-1 Regional Water Plans, Water Availablity Models where they exist, and by consultation with River Authorities.

- High demand regions will be determined using the SB-1 Regional Water Plans. Any county that has a total demand that exceeds available supply as of 2050 will be considered a high demand region. Regions that are not within reasonable proximity to high demand regions will not be considered. A working definition for reasonable proximity will be developed in conjunction with the TWDB project manager. One approach may be to consider all counties adjacent to high demand counties.

Task 2 – Site-Specific Analysis

Once the screening analysis has been completed, the next step will be to evaluate remaining regions of the state for their suitability for groundwater banking using surface or near-surface infiltration techniques. Suitability for groundwater banking will be assessed by estimating the potential water volume that might be infiltrated for a given region, the estimated recovery of that water, and the availability of existing water storage and conveyance infrastructure. Total volume infiltrated equals the rate of infiltration times infiltration area times the time period during which infiltration occurs. Each of these factors can be locally limiting. Our approach for assessing each of these factors is outlined below.

Rate of Infiltration. The rate of infiltration will be controlled primarily by the hydraulic conductivity of surface and near surface materials. Information on the hydraulic properties of soils in targeted regions will be obtained from the State Soil Geographic Database (STATSGO), which is a 1:250,000 scale generalization of the detailed soil survey. Regional reports will be examined to determine the presence of extensive near-surface impeding layers that might need to be breached for groundwater banking to be effective.

Infiltration Area and Time Period for Infiltration. Because most surplus water in Texas is likely to come from large hydrograph spikes caused by summer rainfall, an impracticably large spreading area might be required to rapidly infiltrate surplus surface water. Therefore, feasibility of groundwater banking may often be more dependent upon the time period a water surplus can be supplied to a basin than on the permeability of surface and near-surface materials. We will compute the total area required to capture identified surplus surface water within each region of evaluation during non-drought periods. These computations will be based on the hydraulic conductivity of surficial materials and available estimates (in terms of both volume and time period available) of surplus water. Comparison of these calculated areas with information about existing land uses in given regions may be a useful tool for planners to consider the feasibility of groundwater banking.

Calculation of Recovery Efficiency. Basic analytical computations of recovery efficiency will be presented for various regions using average aquifer hydraulic parameters available in the literature or collected as part of the Groundwater Availability Modeling studies. If recovery is to be obtained at or near the point of infiltration, recovery efficiencies will primarily be a function of aquifer transmissivity, storage, ambient hydraulic gradient and feasible well pumping rates.

Identification of Water Storage and Conveyance Systems. The existence or non-existence of water storage and conveyance systems is also a useful piece of information for evaluation of the potential for water banking programs in Texas. Existing spreading basins in other southwestern states are typically connected to massive regulated surface storage and conveyance systems (canals, dams, pipelines, etc.). Regions of Texas that have pre-existing water storage and conveyance systems will be identified using the Regional Water Plans.

Task 3 - Reporting

The final report will include the details of the technical approach and methodology used to identify geographic areas suitable for groundwater banking. The report will also include general suggestions for efficient approaches to groundwater banking for various site conditions, and will be suitable for use by water planners as a primer on artificial recharge of surface water.

At the end of the study, DBS&A will provide to TWDB:

1. 10 copies of the final report (more if requested)
2. A digital copy of the final report and all figures
3. An *Adobe Acrobat* PDF file of the final report for posting on the TWDB web site
4. Individual digital copies of each figure from the final report, per format guidelines consistent with the GAM studies
5. All source data and output data in digital format

Electronic files will transmitted to the TWDB in a ready-to-use format. All file formats will be 100 percent PC-compatible and physically reside on either ZIP discs or ISO 9600 compact disks. Two copies of all electronic files and two hard copies of each file list, file description printout, and metadata file will be provided to TWDB.

Electronic deliverables shall be provided to TWDB in the following formats:

Deliverable Type	Format/Software
GIS shapefiles	ArcView 3.2
Database files	MS Access 97

Spreadsheet files	MS Excel 97
Graphs and charts	MS Excel 97
Internet-ready reports	Adobe Acrobat 4.0 PDF

All drawings and graphs will be provided to TWDB in EPS format with a TIFF preview using Pantone Process Colors that can be separated into cyan, yellow, magenta, and black.

Schedule

This schedule for completion of this work will be negotiated with the TWDB. We suggest a time frame of 18 months after contract execution, which corresponds to a completion date around October 2002. This would allow ample time for some existing studies (e.g. the GAM studies) to progress to a stage where useful information should be available for this groundwater banking study.

Appendix A2

Review Comments on *Draft Identification of Geographic Areas Suitable for Groundwater Banking*

Review Comments on Water Research
"Identification of Geographic Areas Suitable for Groundwater Banking"
Contract No. 2001-483-388

Report Comments

- Page 2, second bullet: Infiltration galleries - please provide an explanation of what these are.

- Page 12, 4th paragraph:2.3.8,sentence 3, states"this could be an overlay to add," please provide one.
- Page 13, first sentence - please insert tables immediately after making reference to them in the text or make clearer how to find the table referenced in the text. For example, Table 1 is not near text references made to it and there is no reference to a separate tables appendix.
- Page 24, 1st paragraph, 3rd sentence: there are two commas in a row, perhaps something was left out, please correct to reflect the intended thought.
- Page 28, paragraph 1, 2nd sentence: "beyond the scope of this project" is listed twice in this sentence. Perhaps it only needs to be referred to once.
- Discuss the magnitude and effects of evaporation on water intended to be recharged over large areas.
- Suggest showing maps showing coverages of where certain data is available.

    Volume/Titles
    Executive summary
    Table of contents
    List of figures
    List of tables
    Page numbers-sections/Consecutive page numbering
    Context-Intro-Purpose
    Methodology
    Graph numbers
    Conclusions
    Bibliography
    Appendices/reference
    Scope of work
    Includes input/comment from public scoping/hearings ect

- Regarding the map projection: projecting all GIS data layers into UTN 13 may not be the best choice. Any data outside a certain UTM zone is not appropriate to be included in a different zone because of geometric distortion (there are 3 UTM zones in Texas: 13, 14, and 15). Using a statewide map projection standard like TSMS (Texas State Mapping System) or TCMS (Texas Centric Mapping System) is recommended.
- Information on GIS data sources and quality are not clear. Metadata (data about data) should be provided along with all GIS layers.
- Explanation on methodologies are mostly very subjective lacking appropriate examples/references. Also using equations and/or flow charts would be more helpful for some GIS procedures instead of using descriptive methods.
- This report lacks references that could be used for validation or more information.
- Overall this report gave me an impression of 'briefing" on the topic rather than a technical report.
- Figure 3 - Please revise spelling to provide correct and full names of the aquifers.
- Figure 4 - The color code used for <40 ft. and >500 is the same (reddish brown). Use separate colors for each of the categories (<40) and (>500), and reprint the map.

- Figure 5 - This figure seems misleading because the line thickness of the area around the rivers seems large compared to the actual 3 miles. If this is true, maybe a thinner line would be more realistic.
- Figure 6 - Slope units are not given. If it is a percentage, that should be indicated in the legend.
- Figure 9 - Conveyance structures? What are they? Describe or explain.
- Figure 10 - It appears that the first and second order stream color codes or references are switched.
- Figure 10 - 13 - Why is 40+ year old data used (from 1960)? Replace this data with recent data (late 1990s or preferably 2000 streamflow hydrographs).
- Figures 12 and 13 - Suggest using the same y-scale for both right hand axis to better convey the impact of variations in acreage.
- Figure 12 and 13 - The legend shows some lines with dots, but those cannot be found on the hydrographs. The legend and the lines on the hydrographs should match. Redraw those graphs correctly.
- Figure 17 - No recharge area (dark green) is shown at all in Region G. Is that correct? Some recharge areas may be present in Region G, if so, such areas should be shown in dark green.

- Figure 18 -Flouride should be flouride.
- Figures 18 and 21 - There is no legend reference for why some streams are highlighted in yellow.
- Figure 20 - Same question as above, but for region C. Please explain.
- Figures 23,24,30: The suitable recharge area crossing from Upton and Reagan Counties to Crockett seem to disappear. Perhaps this is an artifact of the screening that could be corrected.
- Figure 26 and 27 -In Figure 27, recharge areas are shown in Lamb, Dallam and other counties but those are not shown as such in figure 26. Please change figure 26 to show the suitable recharge areas (in dark green).
- Table 1 - Comanche is misspelled, please correct.
- Page A-2 - 1st paragraph, 2nd sentence: Hucco-Mesilla is misspelled, please correct.
- Page A-3 - 2nd paragraph, 2nd sentence: "no" should be "not".

Task 2 - Site Specific Analysis

- The site specific analysis in the various regions did not include all of the areas identified in the screening as suitable for groundwater banking.

3.7.1 South Central Region

- The report section focuses on portions of Uvalde County identified in the GIS based screening but ignores the portions of Uvalde, medina, and Bexar Counties where groundwater banking sites are currently operated by the Edwards Aquifer Authority or have been adopted as planned water management strategies by the South Central Texas Regional Water Planning Group.
- The reviewer was unable to locate the discussion of the rate of infiltration of the areas identified in the screening as suitable for groundwater banking as required in SOW Task 2.
- The reviewer was unable to locate the discussion of the time period during which water would be available for infiltration as required in SOW Task 2.
- The reviewer was unable to locate the discussion of the computation of the total area required to capture the identified surplus water during non-drought periods as required in SOW Task 2.
- The reviewer was unable to locate the discussion of the calculation of recovery efficiency as required in SOW Task 2.
- The reviewer was unable to locate the discussion of identified existing water storage and conveyance systems (or lack thereof) as required in SOW Task 2.

3.7.2 Brazos G Region

- The reviewer was unable to locate the discussion of the time period during which water would be available for infiltration as required in SOW Task 2.
- The reviewer was unable to locate the discussion of the computation of the total area required to capture the identified surplus water during non-drought periods as required in SOW Task 2.
- The reviewer was unable to locate the discussion of the calculation of recovery efficiency as required in SOW Task 2.
- The reviewer was unable to locate the discussion of identified existing water storage and conveyance systems (or lack thereof) as required in SOW Task 2.

3.7.3 Region C

- The reviewer was unable to locate the discussion of the rate of infiltration of the areas identified in the screening as suitable for groundwater banking as required in SOW Task 2.
- The reviewer was unable to locate the discussion of the time period during which water would be available for infiltration as required in SOW Task 2.
- The reviewer was unable to locate the discussion of the computation of the total area required to capture the identified surplus water during non-drought periods as required in SOW Task 2.
- The reviewer was unable to locate the discussion of the calculation of recovery efficiency as required in SOW Task 2.
- The reviewer was unable to locate the discussion of identified existing water storage and conveyance systems (or lack thereof) as required in SOW Task 2.

3.7.4 Region F

- The reviewer was unable to locate the discussion of the rate of infiltration of the areas identified in the screening as suitable for groundwater banking as required in SOW Task 2.
- The reviewer was unable to locate the discussion of the time period during which water would be available for infiltration as required in SOW Task 2.
- The reviewer was unable to locate the discussion of the computation of the total area required to capture the identified surplus water during non-drought periods as required in SOW Task 2.
- The reviewer was unable to locate the discussion of the calculation of recovery efficiency as required in SOW Task 2.
- The reviewer was unable to locate the discussion of identified existing water storage and conveyance systems (or lack thereof) as required in SOW Task 2.

3.7.5 Ogallala Region

- The reviewer was unable to locate the discussion of the rate of infiltration of the areas identified in the screening as suitable for groundwater banking as required in SOW Task 2.
- The reviewer was unable to locate the discussion of the time period during which water would be available for infiltration as required in SOW Task 2.
- The reviewer was unable to locate the discussion of the computation of the total area required to capture the identified surplus water during non-drought periods as required in SOW Task 2.
- The reviewer was unable to locate the discussion of the calculation of recovery efficiency as required in SOW Task 2.
- The reviewer was unable to locate the discussion of identified existing water storage and conveyance systems (or lack thereof) as required in SOW Task 2.

3.7.6 West Texas Region

- The reviewer was unable to locate the discussion of the rate of infiltration of the areas identified in the screening as suitable for groundwater banking as required in SOW Task 2.
- The reviewer was unable to locate the discussion of the time period during which water would be available for infiltration as required in SOW Task 2.
- The reviewer was unable to locate the discussion of the computation of the total area required to capture the identified surplus water during non-drought periods as required in SOW Task 2.
- The reviewer was unable to locate the discussion of the calculation of recovery efficiency as required in SOW Task 2.
- The reviewer was unable to locate the discussion of identified existing water storage and conveyance systems (or lack thereof) as required in SOW Task 2.

Task 3 - Reporting

- Conclusions and Recommendations - The conclusions given in this section contain no comments on the suitability of any sites considered for groundwater banking. The report would benefit greatly as an aid to regional water planning groups with the inclusion of comments on the suitability of sites for groundwater banking as a water management strategy.

Comments from Texas Parks and Wildlife Department (TPWD)

- Although the draft report mentions Endangered Species Act requirements as possible limiting factors to groundwater banking projects, there is no discussion of how wildlife habitat value would be included in the analysis. At a minimum, TPWD's Biological Conservation Database (BCD) should be queried on a county by county basis to screen for potential threatened or endangered species habitat. Other, more detailed, habitat analysis should be performed on candidate sites as they are selected.

The "Conclusions and Recommendations" section makes the following statement, "Factors in basin siting beyond the scope of this project include hydrographs, water availability, water rights, and a detailed field evaluation are beyond the scope of this project." I would argue that this analysis should include water availability as a preliminary step. The surface water availability models (WAMs) are now complete (except for the Rio Grande) and should be used to at least screen to exclude fully appropriated sub-basins. The WAMs could also be used to identify underutilized water rights that could be candidates for sources of surface water. Finally, environmental flow needs are not addressed anywhere. Environmental Planning Criteria should be used to estimate how much water should be set aside for instream flows and freshwater inflows to bays and estuaries.

Appendix B

GIS Data Guide

Table of Contents

Section **Page**

Appendix B. GIS Data Guide B-1
B.1 GIS layers B-1
B.1.1 Texas 2050 Water Demand B-1
B.1.2 Depth to Groundwater B-1
B.1.3 Distance to Surface Water B-2
B.1.4 Surface Water Quality B-3
B.1.5 Groundwater Quality B-7
B.1.6 Soil Maps B-7
B.1.7 Slope from Digital Elevation Model Data B-9
B.2 Tabular Data B-13
B.2.1 Surface Water Flow B-13
B.2.2 Surface Water Quality B-15
B.2.3 County Surface Water Supply and Demand and Water Rights B-16
B.2.4 Surface Water Availability B-26
B.2.5 Environmental Hazards B-30

List of Tables

Table

B-1 U.S. EPA Primary and Secondary Drinking Water Standards B-4

B-2 Attributes for GIS Database Files for EPA Drinking Water Standard Data B-5

B-3 Attributes for Soil Survey Geographic (SSURGO) Version 1 Polygon Files B-10

B-4 Attributes for Soil Survey Geographic (SSURGO) Version 2 Polygon Files B-11

B-5 Attributes for State Soil Geographic (STATSGO) GIS Polygon Files B-12

B-6 Attributes for Streamflow Analysis GIS Point Location Files B-14

B-7 Properties and Structure of the Supply Demand and Water Rights Tables B-17

B-8 Projected Water Demands in Acre-Feet B-19

B-9 WRAP Model Statistics for the RUN3 Scenarios for the Seven Analyzed Basins B-28

B-10 Attributes for WAM modeling GIS files B-29

Appendix B. GIS Data Guide

B.1 GIS layers

All GIS data layers are projected in the Texas Water Development Board (TWDB) Groundwater Availability Modeling (GAM) Texas Centric projection. The projection coordinate details are as follows:

Map_Projection:

- Map_Projection_Name: Albers Equal-Area Conic
- Albers_Equal-Area_Conic:
- Standard_Parallel: 27.500000
- Standard_Parallel: 35.000000
- Longitude_of_Central_Meridian: -100.000000
- Latitude_of_Projection_Origin: 31.250000
- False_Easting: 4921250.005939
- False_Northing: 19685000.023755

B.1.1 Texas 2050 Water Demand

Supply and demand values were derived from the various Regional Water Planning Groups (RWPGs). Each group's water plan was downloaded and imported into a Microsoft Access database (see Section B.2.3). Water plan attribute data were joined to the Texas counties GIS shapefile, which could then be displayed graphically on the GIS base map.

The database file containing this information is *counties_site_specific.shp.*

B.1.2 Depth to Groundwater

The depth-to-water map is a GIS grid file with cells matching the digital elevation model (DEM) grid file cells and values representing the depth to groundwater in feet. The maps were created using monitoring well data from the TWDB water level database and the ground surface DEM. The general approach to generating the maps began with the creation of a water table elevation map. Water level data are frequently sparse in many of the aquifer outcrop areas and monitored locations often exhibited irregular or discontinuous records.

To obtain as much information as possible, the latest water level records for all monitored locations within the outcrop areas for the period 1995 to 2001 were used. To supplement the limited point measurements, the water table elevations in the unmonitored areas of the Gulf Coast, Carrizo-Wilcox, Edwards-Trinity Plateau, Cenozoic-Pecos Alluvium, and Ogallala aquifer outcrop areas were generated as subdued reflections of the ground surface topography while honoring the existing measurement locations. The resulting water table elevation maps were then subtracted from the ground surface DEM to generate the depth-to-water maps for these aquifers. For the Trinity aquifer outcrop area, the use of surface elevation data was limited to imposing values at the up-dip outcrop limits and in some stream and river locations. For the Seymour and Hueco-Mesilla Bolson aquifers, monitoring data were particularly sparse and a depth-to-water value was imposed at all locations based upon trends indicated by the available data. There are limitations on the accuracy of the depth to water map. In areas removed from monitored locations, the water table surface is interpolated and may not be accurate.

B.1.3 Distance to Surface Water

The Texas Natural Resources Information System (TNRIS) Texas streams GIS coverage was used as the base file to determine a site's distance from a stream (http://www.tnris.state.tx.us/DigitalData/data_cat.htm). The file has stream order designations that allow one to associate features in the GIS such as streamflow data with stream size. A stream order or class of 1 is a large river or stream, whereas a stream order or class or 4 is a small tributary. A distance buffer was created from this stream file to delineate areas within a certain distance of a stream. This distance buffer is simply a distance value grid file. Each cell contains a value that represents that cell's distance from the nearest stream. One can easily query different distances using this file.

The database file containing this information is *Tx_streams_ z13.shp.*

B.1.4 Surface Water Quality

Water quality records for all of the monitored locations were analyzed in conjunction with the surface water flow data. The database was examined for concentrations of both the primary and secondary non-organic constituents listed in the U.S. Environmental Protection Agency (EPA) National Drinking Water Standards (Table B-1). Primary constituent concentrations are legally enforceable standards that apply to public water systems and are intended to protect public health by limiting the levels of certain contaminants in drinking water. Secondary constituent concentrations are non-enforceable guidelines for contaminants that may cause cosmetic or aesthetic effects in drinking water. State or local regulations may impose concentration limits that are more stringent or comprehensive than the EPA limits.

The EPA primary and secondary drinking water standard maximum contaminant level (MCL) for various contaminants provided in Table B-1 are in shown in milligrams per liter (mg/L). Values for the primary standards for antimony, asbestos, cyanide, and thallium are not listed because the analysis results for these constituents were either limited or not in the database.

Over 450,000 individual analyses for most of the EPA primary and secondary concentration standards were analyzed for this report and individual GIS database files were generated for each of the constituents shown in Table B-1. The attributes, descriptions, and units for the water quality analyses files are given in Table B-2. 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 of all samples for a given location that were collected under the

Table B-1. U.S. EPA Primary and Secondary Drinking Water Standards

Contaminant	Concentration (mg/L) Maximum Contaminant Level	Concentration (mg/L) Recommended Concentration	Number of Locations	Number of Samples
Primary Standard				
Arsenic	0.010	---	277	10,307
Barium	2	---	267	8,837
Beryllium	0.004	---	156	2,429
Cadmium	0.005	---	270	6,859
Chromium	0.1	---	266	7,586
Copper	1.3	---	283	10,533
Fluoride	4.0	---	571	41,714
Lead	0.015	---	273	8,180
Mercury	0.002	---	270	10,000
Nitrate	10	---	502	35,228
Nitrite	1	---	330	23,112
Selenium	0.05	---	266	9,835
Secondary Standard				
Aluminum	---	0.05 to 0.2[a]	169	3,131
Chloride	---	250	595	63,273
Iron	---	0.3	297	10,812
Manganese	---	0.05	292	11,916
pH	---	6.5-8.5	599	60,786
Silver	---	0.10	233	6,525
Sulfate	---	250	585	62,350
Total Dissolved Solids	---	500	552	48,133
Zinc	---	5	282	10,563

[a] A value of 0.2 mg/L was used as the maximum concentration for aluminum.

mg/L = Milligrams per liter
--- = Not applicable

Table B-2. Attributes for GIS Database Files for EPA Drinking Water Standard Data

Attribute Name	Units	Description
site_no	---	USGS Site ID number
num_recs	---	Number of analysis records for this constituent
av_value	mg/L	Average concentration of all analyses for this constituent
av_20	mg/L	0th to 20th percentile flow interval average constituent concentration
av_40	mg/L	20th to 40th percentile flow interval average constituent concentration
av_60	mg/L	40th to 60th percentile flow interval average constituent concentration
av_80	mg/L	60th to 80th percentile flow interval average constituent concentration
av_100	mg/L	80th to 100th percentile flow interval average constituent concentration
cutoff_p	---	Flow percentile above which average concentration is below EPA standard
cutoff_q	cfs	Flow value above which average concentration is below EPA standard

USGS = U.S. Geological Survey
--- = Not applicable
mg/L = Milligrams per liter
EPA = U.S. Environmental Protection Agency
cfs = Cubic feet per second

same 20th percentile-increment flow condition was calculated. All average concentration values are reported in mg/L.

The following files are dBase IV® files of each constituent from the surface water quality analysis. Each of these files can be joined to the *wq_flow.shp* shapefile in order to display the data geographically.

- EPA_dws_Aluminum.dbf
- EPA_dws_Arsenic.dbf
- EPA_dws_Barium.dbf
- EPA_dws_Beryllium.dbf
- EPA_dws_Cadmium.dbf
- EPA_dws_Chloride.dbf
- EPA_dws_Chromium.dbf
- EPA_dws_Copper.dbf
- EPA_dws_Flouride.dbf
- EPA_dws_Iron.dbf
- EPA_dws_Lead.dbf
- EPA_dws_Manganese.dbf
- EPA_dws_Mercury.dbf
- EPA_dws_Nitrate.dbf
- EPA_dws_pH.dbf
- EPA_dws_Selenium.dbf
- EPA_dws_Silver.dbf
- EPA_dws_Sulphate.dbf
- EPA_dws_TDS.dbf
- EPA_dws_Zinc.dbf
- TDS_1000.dbf (uses a total dissolved solids [TDS] concentration of 1,000 instead of 500 mg/L)

B.1.5 Groundwater Quality

Groundwater quality was derived from the TWDB Groundwater database and is available online (http://www.twdb.state.tx.us/data/waterwell/well_info.html). The file contains approximately 99,915 records for approximately 53,436 wells. There are multiple samples for most wells. The 15 constituents in this dataset include:

- Silica
- Calcium
- Magnesium
- Sodium
- Potassium
- Strontium
- Carbonate
- Bicarbonate
- Sulfate
- Chloride
- Fluoride
- Nitrate
- pH
- TDS
- Alkalinity
- Total hardness

The database file containing this information is *AllTxQuality.shp.*

B.1.6 Soil Maps

Both databases provide information on the spatial extent of mapped soil units. Each map unit is defined by a GIS polygon and contains a number of components and, for each component, a number of related attributes such as the component name, percentage, slope, etc. Delineation of the spatial distribution between multiple components within a mapped unit is not possible. Both databases also provide attribute information on the vertical distribution of soil properties. From one to seven layers are identified within a given component. Attributes for each layer such as depth, thickness, texture, permeability, etc, are listed to depths generally varying from 60 to 80 inches. Thus, each map unit polygon contains a number of components, with each component having generally consistent attributes, both spatially and vertically.

The primary difference between the Soil Survey Geographic (SSURGO) and State Soil Geographic (STATSGO) databases is in the number of components represented by a single map unit. 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. However, caution must be exercised in the use of both of these maps. The user should be aware of the methods used to compile and the inherent limitations of these databases and is referred to the respective user manuals.

For this study, the primary component for each map unit, defined as the component occupying the largest spatial percentage, was identified in both the SSURGO and STATSGO databases. The primary components for 26 counties in the SSURGO database resulted in an average of 83 percent coverage for all polygons. For the STATSGO database however, the results were only an average of 40 percent coverage for all polygons. The STATSGO database was additionally analyzed to identify the secondary component (i.e., the second-greatest spatial percentage) that, combined with the primary component, resulted in a total average of 62 percent coverage for all polygons. Finally, for each of the identified components, the deepest layer with the lowest permeability was identified. Note that the process used to identify the lowest permeability layer does not preclude the existence of a shallower layer having a similar permeability value. Also, the shallow depth limitation of the databases is obvious and the presence of deeper impeding layers must be investigated locally.

Each attribute record included in the soil map GIS coverage files generated for this report represents the deepest layer having the lowest permeability within a given component within a given map unit. Attribute names, definitions, and units for each of the files are listed in Tables B-3 through B-5. Some of the attribute values were extracted directly from the respective databases, while other values were calculated.

There are two versions of the SSURGO database. Of the counties analyzed, six were in Version 1 format while the remaining used the Version 2 format. Version 1 is structured similar to the STATSGO database. Version 1 database values for layer properties such as clay content, carbonate content, and permeability are stored internally as high and low values. The values for this report were calculated as the average of the high and low values. The SSURGO Version 2 database stores representative values for the same layer properties in addition to high and low values. When available, these were deemed more appropriate for this report and were extracted directly from the database.

B.1.7 Slope from Digital Elevation Model Data

DEMs were derived from the U.S. Geological Survey (USGS) 1:250,000 DEM data. DEM data were joined into a single file for the purpose of evaluating the slope of potential recharge locations. The file was developed as a mosaic of 91 different DEM files that were pieced into one large file. The slope, which is expressed in degrees, was derived from the 303-foot grid cell size that contains the DEM data. Two files must be imported into ArcView:

- *Slope.flt:*— a binary-raster export file of the state wide slope grid
- *DEM.flt* — a binary-raster export file of the state wide DEM grid

Table B-3. Attributes for Soil Survey Geographic (SSURGO) Version 1 Polygon Files

Attribute Name	Units	Description
muid	---	Map unit key (unique identifier for map unit)
musym	---	Map unit symbol
muname	---	Map unit name
compname	---	Major component name
comp_pct	Percent	Percentage of map unit represented by major component
ave_slope	Percent	Average slope of ground surface where major component is found
layer	---	Soil layer number of lowest permeability layer within major component
ave_depth	Inches	Average depth to top of lowest permeability soil layer
ave_thick	Inches	Average thickness of lowest permeability soil layer
ave_clay	Percent	Average clay content of lowest permeability soil layer
ave_carb	Percent	Average carbonate content of lowest permeability soil layer
ave_perm	Inch/day	Average permeability of lowest permeability soil layer
shrinksw	---	Susceptibility of soil layer to shrink or swell

--- = Not applicable

Inch/day = Inches per day

Table B-4. Attributes for Soil Survey Geographic (SSURGO) Version 2 Polygon Files

Attribute Name	Units	Description
mukey	---	Map unit key (unique identifier for map unit)
compkey	---	Component key (unique identifier for component)
horkey	---	Horizon key (unique identifier for soil horizon)
musym	---	Map unit symbol
muname	---	Map unit name
compname	---	Major component name
comp_pct	Percent	Percentage of map unit represented by major component
rep_slope	Percent	Representative slope of ground surface where major component is found
horizon	---	Layer number of lowest permeability layer
rep_depth	Inches	Representative depth to top of lowest permeability layer
rep_thick	Inches	Representative thickness of lowest permeability layer
rep_clay	Percent	Representative clay content of lowest permeability layer
rep_carb	Percent	Representative carbonate content of lowest permeability layer
rep_perm	Inch/day	Representative permeability of lowest permeability layer

--- = Not applicable

Inch/day = Inches per day

Table B-5. Attributes for State Soil Geographic (STATSGO) GIS Polygon Files

Attribute Name	Units	Description
muid	---	Map unit identifier
muname	---	Map unit name
numseqs	---	Total number of sequences (components) in this map unit
totalpct	Percent	Total area represented by the combined primary and secondary components
seqnum	---	Sequence (component) number
seqname	---	Sequence (component) name
seqpct	Percent	Percentage of map unit represented by major sequence (component)
slope	Percent	Sequence (component) average slope
numlayers	---	Sequence (component) number of soil layers
layer	---	Layer number of lowest permeability layer
depth	Inches	Depth to top of lowest permeability layer
thickness	Inches	Thickness of lowest permeability layer
ave_clay	Percent	Average clay content of lowest permeability layer
ave_carb	Percent	Average carbonate content of lowest permeability layer
ave_perm	Inch/hr	Average permeability of lowest permeability layer
shrinksw	---	Shrink-swell characteristics of lowest permeability layer

--- = Not applicable

Inch/hr = Inches per hour

B.2 Tabular Data

B.2.1 Surface Water Flow

The USGS maintains a network of stream gauging stations and water quality sampling locations throughout the state of Texas and the database is available online (http://waterdata.usgs.gov/nwis/sw). At present, the state has approximately 327 active gauging stations where average daily streamflows are monitored. The database also contains records for an additional 400 historical gauging stations that are no longer actively monitored. Water quality samples were generally obtained periodically from many of these locations and under different flow conditions. Water quality samples were also obtained at an additional 140 locations that did not have continuously monitored gauges, but for which limited flow data are available.

For this report, over 7.65 million individual flow records were analyzed. The daily average flow rates for the period of record for each of the 727 active and historical gauging locations were analyzed. Flow data from the water quality database were used at the 140 water quality locations that were not listed in the flow database and represent a mix of both daily average flow rates and instantaneous flow rates measured at the time of sampling. Flow rate analyses derived from the quality database locations were based on a limited number of flow measurements and may not be representative.

For each location, periods of zero flow were removed from the analysis and non-zero flow rates were converted to log base 10 values for percentile and average flow rate calculations. Percentile and average flow rates are reported in cubic foot per second (cfs). Percentile rankings of flow rates were determined at 5 percent intervals to produce 20 categories for each location. Average flow rates within each 20th percentile interval were calculated to produce 5 average flow rate categories for each station. The attributes, descriptions, and units for the streamflow rate analysis are provided in Table B-6. Each attribute record of the GIS file represents a point location at which the flow measurements were made.

Table B-6. Attributes for Streamflow Analysis GIS Point Location Files

Attribute Name	Units	Description
site_no	---	USGS Site ID number
station_nm	---	Site name
latitude	---	Latitude coordinate
longitude	---	Longitude coordinate
source	---	F for flow, Q for quality database
drainage_area	mi^2	Drainage area
date_from	---	Date of first flow record
date_to	---	Date of last flow record
flow_recs	---	Number of flow records
cmplt	Days/days	Ratio of number of flow records to the total record length
non_zero	Days/days	Ratio of number of non-zero flow records to total number of flow records
av_nzflow	cfs	Average non-zero flow rate
p_5	cfs	5^{th} percentile flow rate
p_10	cfs	10^{th} percentile flow rate
p_100	cfs	100^{th} percentile flow rate
av_20	cfs	Average flow within the 0^{th} to 20^{th} percentile interval
av_40	cfs	Average flow within the 20^{th} to 40^{th} percentile interval
av_100	cfs	Average flow within the 80^{th} to 100^{th} percentile interval

--- = Not applicable
USGS = U.S. Geological Survey
mi^2 = Square miles
cfs = Cubic feet per second

Precautions should be used in applying the streamflow data at a given location. It is generally not valid to employ this data to determine whether a specific reach between measurement points may be gaining or losing. There may be withdrawals of water for municipal or irrigation use as well as inflows from non-gauged tributaries. Additionally there are limitations on the accuracy of the measurements themselves.

The database file containing this information is *wq_flow.shp.*

B.2.2 Surface Water Quality

Over 450,000 individual analyses for most of the EPA primary and secondary concentration standards (Table B-1) were analyzed for this report, and individual GIS database files were generated for each of the constituents. The attributes, descriptions, and units for the water quality analyses files are given in Table B-2. 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 of all samples for a given location that were collected under the same 20th percentile-increment flow condition was calculated. All average concentration values are reported in mg/L. Values for the primary standards for antimony, asbestos, cyanide, and thallium are not listed because the analysis results for these constituents were either limited or nonexistent.

The average concentrations within each percentile increment for a given location were examined in order from high- to low-flow conditions. Concentrations were compared to the EPA concentration standards and appropriate cutoff flow percentile and flow rate values were reported. A reported cutoff value of zero percent indicates that the standard concentration was, on average, not exceeded during any flow condition. A reported cutoff value of 100 percent indicates that the standard concentration was, on average, exceeded during all flow conditions. Intermediate cutoff values of 20 percent to 80 percent indicate the flow percentile that, on average, must be exceeded before the average concentration is below the standard concentration.

Interpretation of the GIS database for pH values is an exception. Most of the pH values not in the range of 6.5 to 8.5 were below 6.5 and generally occurred at higher flow rates. Cutoff values in the pH file represent the percentile and flow values *below* which the pH, on average, is in the acceptable range. Thus, a reported pH cutoff value of zero percent indicates that the pH range was, on average, exceeded during all flow conditions and a reported cutoff value of 100 percent indicates that the pH range was, on average, acceptable during all flow conditions.

B.2.3 County Surface Water Supply and Demand and Water Rights

Data for the Texas Water Supply and Demand database were obtained from the regional water plans. The electronic formatting was performed in two steps. First, it was imported it from its native format into Microsoft Excel® 97. Once in Excel format, custom Microsoft VisualBasic® code was applied to format the data to the projection used in the database. When data were not available electronically, or were available in a format that could not be imported into Excel, they were entered by hand from available records.

The Texas Water Supply and Demand database consists of two related tables. The *Supply Demand* table offers yearly Supply and Demand data (in acre-feet) for each county within each region. County and region are both noted in separate fields and it is possible to sort or query them in any desired combination. For each record, supply and demand are given, as well as the net result (demand – supply). From these figures, maximums, minimums, averages, and other desired mathematical values can be calculated. The second table, *Water Rights*, ties the data provided in the *Supply Demand* table to their respective owners. The *Water Rights* table has information on permit holders, permit numbers, water use and other related information. Water rights were not evaluated for this analysis, however, the data are being made available. Any local site identification work will inevitably have to deal with the issue of water rights.

Table B-7 provides a detailed summary of the structure of database tables for supply and demand and water rights. Table B-8 contains water supply and demand data for Texas counties for the years 2000 through 2050 (in 10-year increments). These data were obtained from the SB-1 Regional Water Plans.

Table B-7. Properties and Structure of the Supply Demand and Water Rights Tables
Page 1 of 2

Table Name: Supply Demand			
Table Properties:			
Date Created	1/8/02 4:58:58 PM		
Description	Supply/demand for each county by region. Surface and groundwater supply/demand split out separately where available.		
Last Updated	8/27/02 12:20:43 PM		
Order By On	True		
Def. Updateable:	True		
Filter:	([Supply Demand].Region="P")		
Order By	[Supply Demand].Supply_Ground		
Record Count	1647		
Table Fields:	Name	Type	Size
	Region	Text	255
	Partial	Yes/No	1
	County	Text	255
	Year	Number (Double)	8
	Demand	Number (Double)	8
	Supply_Ground	Text	255
	Supply_Surface	Text	255
	Supply	Number (Double)	8
	Net	Number (Double)	8
	UpperCounty	Text	50
Table Name: Water Rights			
Table Properties:			
Date Created	1/7/02 5:18:30 PM		
Description	Water rights information -- owners/permit numbers/status for a given water source		
Record Count	21486		
Def. Updateable:	True		
Last Updated	8/27/02 12:23:27 PM		
Table Fields:	Name	Type	Size
	Status	Text	255
	WR Number	Number (Double)	8
	Type	Text	255
	Sequence	Number (Double)	8
	Permit #	Text	255
	WR Issue Date	Date/Time	8
	Amendment	Text	255
	Status_Canc	Text	255
	Owner Name	Text	255
	Owner Type	Text	255
	Amount in Ac-Ft/Yr	Number (Double)	8
	Use	Text	255

Table B-7. Properties and Structure of the Supply Demand and Water Rights Tables

Water Rights Table (continued)			
Table Fields:	Name	Type	Size
	Priority	Number (Double)	8
	Class	Text	255
	Date Can	Text	255
	Expire	Text	255
	Acreage	Number (Double)	8
	Res Name	Text	255
	Res Cap (Ac-Ft)	Text	255
	Site Name	Text	255
	Basin	Number (Double)	8
	River Order	Text	255
	Reg Code	Text	255
	SWRA	Text	255
	Unnamed Trib Of (Y/N)	Text	255
	Stream Name	Text	255
	Other Stream	Text	255
	County	Text	255
	Latitude	Number (Double)	8
	Longitude	Number (Double)	8
	Remarks	Text	255
	Base WR #	Text	255

Table B-8. Projected Water Demands in Acre-Feet
Page 1 of 7

Water supply and demand data were obtained from the SB-1 Regional Water Plans. Positive numbers reflect a projected water surplus and negative numbers represent a projected water deficit.

County	2000	2010	2020	2030	2040	2050
Anderson	12935	1733	1317	816	407	–228
Andrews	–1556	---	1256	---	---	2217
Angelina	16742	13570	9969	5496	507	–5044
Aransas	–46	–12	16	44	59	66
Archer	16355	1608	1491	1341	1193	1219
Armstrong	10833	---	10485	---	---	10333
Atascosa	–22689	–21569	–20734	–39922	–42501	–48830
Austin	1343	1173	954	672	376	1
Bailey	–7278	–6463	–5350	–4014	–2431	–925
Bandera	–2264	–3993	–3880	–4343	–4894	–5508
Bastrop	30436	28918	26523	24802	23824	22590
Baylor	1694	1796	1946	2037	2085	2124
Bee	9762	10118	10464	10715	10923	11072
Bell	57645	33693	20375	12739	8439	6946
Bexar	–119398	–151686	–199458	–271882	–332961	–379396
Blanco	13628	13501	13369	13244	13198	12907
Borden	–8446	---	–8184	---	---	–8115
Bosque	7935	2220	2042	1852	1630	1190
Bowie	–11382	–20730	–21420	–22348	–23051	–23877
Brazoria	52477	–31269	–46047	–84073	–114802	–158698
Brazos	34926	29681	24493	21023	16855	13182
Brewster	4821	4549	4300	4061	3830	3667
Briscoe	0	0	0	0	0	0
Brooks	–657	–364	–231	60	309	555
Brown	3469	---	3390	---	---	3464
Burleson	53495	53708	53915	54096	54272	54389
Burnet	19642	18951	16114	14637	10491	10372
Caldwell	2316	1908	1507	212	253	330
Calhoun	81534	69503	63840	56484	47651	37560
Callahan	2272	2348	2493	2591	2739	2788
Cameron	283404	257501	236391	196364	169119	138814
Camp	15653	13133	13096	13048	12997	12938
Carson	17532	---	17318	---	---	16569
Cass	4805	2384	2303	2199	2107	1990
Castro	–39261	–39143	–38621	–37592	–36449	–35107
Chambers	41879	46819	48061	37967	35383	30904

--- = Not analyzed

Table B-8. Projected Water Demands in Acre-Feet
Page 2 of 7

County	2000	2010	2020	2030	2040	2050
Cherokee	446	–109	–5939	–11875	–12612	–18395
Childress	2095	---	2023	---	---	1926
Clay	3794	3221	3158	3027	2900	2848
Cochran	–13181	–12046	–10948	–9868	–8836	–7856
Coke	1929	---	2075	---	---	2178
Coleman	2039	---	2227	---	---	2339
Collin	23020	–29794	–80743	–124769	–174124	–210431
Collingsworth	8868	---	8745	---	---	8699
Colorado	106178	97717	98635	99683	101047	102637
Comal	–3506	–14287	–20401	–28685	–33755	–40613
Commanche	–11177	–11640	–11042	–10499	–9960	–9492
Concho	627	v	698			766
Cooke	–3008	–3087	–3192	–4034	–4311	–4609
Coryell	3894	1834	–597	–3337	–5333	–7732
Cottle	313	476	642	799	953	1098
Crane	342	---	1022	---	---	919
Crockett	666	---	–1533	---	---	–1530
Crosby	–179	–56	59	174	193	204
Culberson	2740	2925	3067	3195	3331	3450
Dallam	0	---	–392701	---	---	–397991
Dallas	–34250	–168112	–241696	–267472	–350525	–415879
Dawson	195	180	211	243	260	262
Deaf Smith	0	0	0	–2516	–2596	–2717
Delta	9991	10008	9966	9909	9936	9956
Denton	3108	–20744	–92987	–184125	–210954	–234983
Dewitt	2084	2228	2298	2163	2029	1893
Dickens	124	135	148	154	159	162
Dimmit	4103	3871	3555	–3952	–4041	–4187
Donley	1076	---	854	---	---	786
Duval	–6583	–5317	–4750	–4777	–4830	–4957
Eastland	2429	191	–137	40	185	340
Ector	–1688	---	–4099	---	---	–10393
Edwards	626	617	620	617	617	613
El Paso	–118727	–87908	–67526	–376072	–392139	–412237
Ellis	6935	–10542	–13252	–17304	–21678	–23346
Erath	12262	11892	11695	11504	11418	11341
Falls	28766	29018	29212	29323	29418	29465
Fannin	25663	24433	23263	22166	20701	19159
Fayette	57016	56711	56395	55992	55549	54957

--- = Not analyzed

Table B-8. Projected Water Demands in Acre-Feet
Page 3 of 7

County	2000	2010	2020	2030	2040	2050
Fisher	4384	4534	4422	4171	4246	4295
Floyd	–23567	–23949	–24088	–23855	–23577	–23199
Foard	380	534	681	823	960	1098
Fort Bend	60112	31413	–14311	–47200	–163143	–198800
Franklin	10243	9987	9790	6514	2878	2706
Freestone	4057	–6927	–8868	–8903	–13126	–13155
Frio	–67724	–64349	–61123	–73406	–70540	–67774
Gaines	0	–581	–555	–547	–535	–533
Galveston	22943	14770	5803	–3946	–16342	–28214
Garza	–516	–40	79	119	164	189
Gillespie	9805	9496	9268	9080	8487	7987
Glasscock	–47853	---	–46773	---	---	–45145
Goliad	11457	11578	6684	6749	6791	6787
Gonzales	2328	4391	5154	5450	5604	5709
Gray	13696	---	12953	---	---	12307
Grayson	23778	23078	22596	21142	19981	18797
Gregg	28960	13394	11086	7672	–10538	–29613
Grimes	21160	20999	20837	20644	20715	20355
Guadalupe	6315	3704	741	–7045	–10860	–15635
Hale	–2234	–2183	–4180	–7998	–10472	–13442
Hall	3056	---	3048	---	---	3104
Hamilton	2242	2357	2461	2678	2751	2896
Hansford	116677	---	111836	---	---	108133
Hardeman	3074	3179	3265	3355	3438	3515
Hardin	1170	38	52	–193	–549	–1229
Harris	623989	477923	145560	62432	–26272	–119667
Harrison	145113	118937	112706	106390	93288	73356
Hartley	176378	---	174317	---	---	173312
Haskell	3350	2133	2565	2919	3243	3522
Hays	3364	2118	1214	–22	–1464	–2553
Hemphill	1213	---	261	---	---	–65
Henderson	–189	–227	–227	–210	–175	–244
Hidalgo	–300605	–294697	–280995	–272885	–331530	–400425
Hill	7494	7512	6846	5937	5020	4069
Hockley	–3636	401	7	71	191	239
Hood	62147	58481	56687	55766	54999	54242
Hopkins	16289	16123	14623	14107	13061	15575
Houston	898	20	–689	–1497	–2257	–3044
Howard	1871	---	1787	---	---	1504

--- = Not analyzed

Table B-8. Projected Water Demands in Acre-Feet

County	2000	2010	2020	2030	2040	2050
Hudspeth	25226	27801	30333	32815	35249	37627
Hunt	26102	–107	–5748	–11353	–13262	–14475
Hutchinson	2071	---	8100	---	---	2938
Irion	164	---	318	---	---	542
Jack	2102	2357	2372	2355	2331	2238
Jackson	–20689	–21413	–21425	–21688	–21951	–22287
Jasper	9384	11260	11086	12527	10245	7748
Jeff Davis	529	588	653	722	793	857
Jefferson	2757	–440154	–451487	–461617	–481401	–501720
Jim Hogg	9636	9568	9490	9415	9370	9311
Jim Wells	570	714	841	967	1133	1284
Jones	9602	8471	1779	1773	1722	1631
Karnes	359	696	809	815	811	808
Kaufman	2620	–1024	–3566	–7921	–10145	–17119
Kendall	166	–1059	–2515	–4586	–6836	–9220
Kenedy	11924	11926	11931	11940	11946	11951
Kent	3998	4413	4629	4757	4847	4910
Kerr	28730	27758	26852	25695	24553	23176
Kimble	113	---	22	---	---	–218
King	740	742	748	761	773	783
Kinney	2855	3203	3560	3854	4077	4285
Kleberg	2040	1866	1862	2032	2176	2802
Knox	–4345	–3560	–3401	–2677	–1949	–1260
Lamar	26114	24804	24159	22860	21243	19253
Lamb	0	0	–918	–1371	–1368	–1381
Lampasas	10868	10544	10137	9701	9172	8479
Lasalle	387	368	367	337	300	273
Lavaca	–1358	–1358	–1357	–1357	–1358	–1357
Lee	46361	26219	21095	20943	20762	20496
Leon	827	700	574	401	226	18
Liberty	328	95	1	–5160	–7362	–11177
Limestone	35961	33074	32087	31010	29878	28637
Lipscomb	701	---	1376	---	---	148
Live Oak	451	272	4282	3847	3065	3030
Llano	38306	38349	36652	35152	35009	34756
Loving	–258	---	–250	---	---	–240
Lubbock	14919	14178	9430	8256	37458	36288
Lynn	124	115	118	85	119	136
Madison	0	0	0	0	0	0

--- = Not analyzed

Table B-8. Projected Water Demands in Acre-Feet

County	2000	2010	2020	2030	2040	2050
Marion	14885	14844	14807	14768	14527	14685
Martin	–1200	---	–479	---	---	294
Mason	1049	---	1609	---	---	2382
Matagorda	105103	85769	85483	84932	78675	77846
Maverick	–42662	–43168	–41632	–41667	–48707	–57582
Mcculloch	972	---	1086	---	---	1070
Mclennan	72063	67954	64133	59205	54878	51332
Mcmullen	10164	10275	10328	10365	10397	10419
Medina	–79157	–73528	–67925	–67128	–62095	–57372
Menard	–30	---	40	---	---	124
Midland	–29072	---	–32826	---	---	–43490
Milam	19601	29531	19273	19178	19099	13929
Mills	6149	6184	6207	6030	6049	5810
Mitchell	2085	---	1161	---	---	–2358
Montague	2237	2551	2648	2714	2740	2753
Montgomery	904	–8675	–20705	–39317	–58209	–79451
Moore	851	---	–218773	---	---	–224415
Morris	29439	29416	29497	29552	29625	29676
Motley	0	0	0	0	0	0
Nacogdoches	13391	10899	8128	–3249	–7471	–12315
Navarro	13881	13283	12929	12300	11858	11438
Newton	912	734	641	582	522	404
Nolan	1053	1015	1199	1698	2501	2438
Nueces	48832	38359	22299	1530	–14905	–28662
Ochiltree	11303	---	10394	---	---	6979
Oldham	456	---	–28291	---	---	–28783
Orange	38991	28730	20098	11225	–723	–13179
Palo Pinto	100454	95585	90961	85857	75318	64659
Panola	13677	14277	8312	185	–105	117
Parker	–1613	–11469	–15008	–24715	–30336	–33874
Parmer	–34176	–42245	–49404	–56597	–62026	–66840
Pecos	2860	---	5181	---	---	8967
Polk	502	383	240	40	–107	–268
Potter	1907	---	–35776	---	---	–45929
Presidio	9668	9865	10020	10086	10516	10921
Rains	1520	1381	217	–1038	–1191	–1362
Randall	1	---	–60150	---	---	–72661
Reagan	–20155	---	–18587	---	---	–16478
Real	971	1027	1070	1091	1110	1127

--- = Not analyzed

Table B-8. Projected Water Demands in Acre-Feet

County	2000	2010	2020	2030	2040	2050
Red River	12606	9043	6672	3380	3439	3498
Reeves	–39210	---	–37634	---	---	–35134
Refugio	1397	1450	1505	1527	1548	1575
Roberts	6257	---	6385	---	---	6273
Robertson	53718	44030	44143	44564	44954	45286
Rockwall	2941	–6362	–10849	–15603	–21694	–28106
Runnels	2231	---	2280	---	---	2136
Rusk	–2673	–7115	–11746	–16857	–16932	–17098
Sabine	1707	1474	1236	–911	–1198	–1534
San Augustine	–48	–130	–197	–334	–424	–551
San Jacinto	3026	2686	2098	–231	–539	–928
San Patricio	22071	15930	11033	8790	–493	–11789
San Saba	38033	38093	38148	38176	38206	38206
Schleicher	324	---	423	---	---	548
Scurry	2514	---	3135	---	---	3340
Shackelford	660	744	818	905	971	1018
Shelby	4004	2951	1792	337	–1300	–3295
Sherman	0	---	2154	---	---	0
Smith	1241	1073	915	693	456	155
Somervell	211	–21	–243	–509	–824	–1195
Starr	–9137	–12311	–14811	–19271	–24360	–29623
Stephens	22901	19637	18271	17327	16361	15346
Sterling	112	---	328	---	---	443
Stonewall	1053	1125	1160	1234	1302	1335
Sutton	313	---	311	---	---	467
Swisher	–45349	–45145	–42545	–44533	–44228	–43921
Tarrant	30270	–25625	–79466	–109210	–147498	–174233
Taylor	22606	19662	16387	13554	10660	8601
Terrell	784	795	812	830	849	860
Terry	–961	–935	–891	–871	–846	–792
Throckmorton	–189	–168	–144	–122	–105	–98
Titus	67604	64452	64813	51657	50978	50258
Tom Green	–32219	---	–38154	---	---	–44394
Travis	237628	211121	159179	84723	61545	34825
Trinity	1735	1739	1754	1747	1736	1679
Tyler	1815	–3353	–8492	–13668	–18723	–23787
Upshur	11321	5699	5720	5501	5248	5103
Upton	–6822	---	–5708	---	---	–4871
Uvalde	–50723	–45829	–41096	–39854	–35912	–32332

--- = Not analyzed

Table B-8. Projected Water Demands in Acre-Feet

County	2000	2010	2020	2030	2040	2050
Val Verde	8216	7587	7199	6819	5861	4757
Van Zandt	4699	4036	–2276	–3950	–4442	–5092
Victoria	20752	15585	13730	11316	6208	916
Walker	7457	6633	6159	–6101	–6759	–7050
Waller	237	135	–2385	–6499	–8455	–11051
Ward	–4643	---	–5781	---	---	–10068
Washington	14683	14524	14431	14398	14577	14829
Webb	32903	19606	4988	–30591	–35745	–44111
Wharton	–21840	–22341	–22900	–23552	–24292	–25139
Wheeler	1372	---	610	---	---	420
Wichita	23269	–6323	–3064	28	2986	2617
Wilbarger	16728	13370	9894	6352	–13199	–12814
Willacy	–22276	–23094	–23587	–24481	–28051	–32544
Williamson	54537	37231	21694	6685	–5999	–18441
Wilson	8933	7679	7089	5510	3907	2305
Winkler	0	---	309	---	---	528
Wise	11531	–1722	–3429	–6126	–7981	–9418
Wood	6827	6512	6235	5806	869	–7250
Yoakum	0	0	–457	–1935	–2030	–2158
Young	1301	1304	1324	1338	1351	1359
Zapata	800	–133	–1387	–3082	–5655	–9355
Zavala	–77016	–72903	–68924	–84700	–81319	–78147

--- = Not analyzed

B.2.4 Surface Water Availability

Most surface water in Texas has been appropriated, especially in the west where groundwater banking is most needed. However, the results of the Water Availability Modeling (WAM), sponsored by the Texas Commission on Environmental Quality (TCEQ), indicate that streamflow exceeded appropriated amounts at many locations during the historical analysis period. Local precipitation and streamflow response patterns may exhibit flashy behavior and result in short-term streamflow in excess of 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 occur. All of these situations result in streamflow that is possibly available for groundwater banking, even though a given basin may be termed fully appropriated.

Surface water availability for selected Texas river basins was quantified using data from the WAM project. 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. An overview of the WAM modeling and data for some Texas river basins are available at the Texas Natural Resource Conservation Commission (TNRCC) website (http://www.tnrcc.state.tx.us/ permitting/waterperm/wrpa/wam.html). 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 is also available through the TNRCC website, and is a good resource for specific information on modeling requirements and procedures. The following is a brief description of the WAM modeling process.

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 (CRWR) 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 and 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 analyzed for this report. Control points represent reservoir, diversion, and return flow locations associated with specific water rights and additionally 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, utilizes historical hydrologic river basin characteristics and specific water rights information (based on seniority) to determine water availability at specific control points. The WRAP model results for each control point are 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.

The WRAP model provides many statistical analyses at various levels of detail. For this report, unappropriated streamflow associated with specific control points was used. Unappropriated streamflow is defined as the portion of the naturalized streamflow still remaining after all depletions are made and return flows are returned for all the water rights included in the simulation. Streamflow depletions are the amounts appropriated to meet water rights diversions and account for reservoir net evaporation-precipitation, and/or refill reservoir storage. Each depletion value is also associated with a particular water right.

The WRAP model unappropriated streamflows, expressed as the average number of acre-feet per year during the period of analysis, are provided with this report as attribute data in GIS data files. The eight river basins that intersect the counties identified as candidates for groundwater banking are included (Table B-9). WAM model results for two scenarios are included, termed RUN3 and RUN8 by the TCEQ. The RUN3 scenario is used by the TCEQ to review new perpetual water right application requests and requests for amendment of existing perpetual water rights. RUN3 represents the most conservative approach and assumes that all existing water rights are fully exercised and that there is no return flow. The RUN8 scenario is used to review new term permit water right application requests and requests for amendment of existing term permit water rights. RUN8 is based on current conditions and uses the maximum actual diversion amounts for each existing water right over the last 10 year period of the analysis, combined with full estimated return flows and year 2000 reservoir conditions.

Table B-9. WRAP Model Statistics for the RUN3 Scenarios for the Seven Analyzed Basins[a]

River Basin	Analysis Date	Historical Period	Years Spanned	Control Points	Water Rights	Reservoirs
Brazos	11/15/02	1940-97	58	3811	1732	650
Canadian	12/06/01	1948-98	51	85	56	47
Colorado	11/21/02	1940-98	59	2262	1664	504
Guadalupe & San Antonio	09/10/02	1934-89	56	1331	1063	231
Nueces	10/02/02	1934-96	63	544	411	122
Red	12/30/01	1948-98	51	443	558	240
Trinity	11/13/02	1940-96	57	1323	1174	699

[a] RUN8 scenarios were conducted for the same hydrologic periods, though the numbers of control points, water rights, and reservoirs may differ slightly. The Guadalupe and San Antonio basins were modeled together with WRAP but have separate GIS files.

Three GIS files are provided for each river basin listed in Table B-9: *Wam_riv_cp*, *Wam_riv_bas*, and *Wam_riv_str*, where "riv" represents the first three letters of the river basin name. The "cp" files are point coverages representing the control point locations. Not all control points are associated with a water right location; they may represent intermediate points on the stream network required for calculations, such as confluences and streamflow gauges. In some cases, multiple control points may occupy the same location and indicate a single diversion or return flow point associated with multiple water rights. In still other cases, multiple control points may be associated with a single water right. The "bas" files are polygon coverages representing drainage basin areas for specific control points, though generally not all control points have an associated drainage basin polygon. The "str" files are line coverages representing the WAM model stream networks generated from 30m Digital Elevation Model (DEM) grid files of the land surface for each river basin. The "str" files are provided for reference only and some stream network lines in the file may not represent actual flowing stream locations.

Attribute names, descriptions, and units for each of these files are given in Table B-10. Attribute data for each river basin include the average annual unappropriated streamflow results from the RUN3 and RUN8 scenarios and, for reference, the naturalized streamflow. Due to the incomplete state of the currently available cross-reference files,, varying degrees of success were achieved in linking the WRAP model result with the GIS features.

Table B-10. Attributes for WAM modeling GIS files [a]

File	Attribute Name	Description	Units
Control Point (CP) and Basin (BAS)	WAM_ID	Control point identification number	
	Nat	Naturalized streamflow	acre-feet/year
	Una3	Unappropriated streamflow for RUN3 scenario	acre-feet/year
	Una8	Unappropriated streamflow for RUN8 scenario	acre-feet/year
DEM Streams (STR)	Length_ft	Stream segment length	feet
	Name	Stream name	

[a] NAT, UNA3, and UNA8 streamflow values are annual averages for the period of hydrologic analysis (Table B-9). Stream names were not present in all files.

Limitations must be considered in applying the WAM modeling results reported in the GIS files. The streamflow amounts are reported here simply as annual average values and provide only an indication of availability. 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 gain insight into the interannual and seasonal streamflow variability at specific locations.

B.2.5 Environmental Hazards

The Environmental Hazards GIS layer was derived from four GIS layers: Landfills, Permitted Industrial and Hazardous Waste Sites, Superfund Sites, and Radioactive Waste Sites. These GIS layers were downloaded from The Texas Natural Resources Information System (TNRIS) Data Catalog (http://www.tnris.state.tx.us/DigitalData /data_cat.htm). These four files were merged into a single GIS shapefile.

The Landfill layer contains both open and closed municipal solid saste landfill sites in the State of Texas. The Industrial and Hazardous Waste Sites layer contains point locations for operating permitted industrial and hazardous waste locations in Texas. The Superfund layer contains all sites in the State of Texas that have been designated as Superfund cleanup sites; it includes both federal and state sites. The Radioactive Waste Sites layer contains all sites in the State of Texas that have been designated as radioactive waste sites.

The database file containing this information is *environmental_hazards.shp.*

Appendix C

ArcView GIS 3.2
Screening Analysis Tool

Table of Contents

Section **Page**

Appendix C. ArcView GIS 3.2 Screening Analysis Tool C-1
- C.1 Types of Screening Analysis C-1
- C.2 How to Use the Screening Analysis Tool C-2
  - C.2.1 Add the Screening Analysis Extension to ArcView C-2
  - C.2.2 Use the Tool to Screen Locations C-3
  - C.2.3 Reclassify Values Dialog Box Definitions C-6

Appendix C. ArcView GIS 3.2 Screening Analysis Tool

The ArcView Geographic Information System (GIS) 3.2 Screening Analysis Tool was developed to help with the statewide screening of data to identify potential geographic locations for groundwater banking. This tool allows a GIS user to reclassify grid data in a format that allows identification of potential recharge sites based on specific criteria. For example, a water resources manager may decide that potential recharge sites should be (1) within 5 miles of surface water, (2) above an unconfined aquifer that is more than 50 feet below ground surface (ft bgs) but less than 500 ft bgs, and (3) located in an area with little slope. The ArcView GIS 3.2 Screening Analysis Tool can help the GIS user to query the data and find any locations that fit the specified criteria.

C.1 Types of Screening Analysis

The analysis can be performed in one of two ways:

- *A Boolean-type analysis* that determines only whether the defined criteria is met or not For example, if a site is within 5 miles of surface water (entered as 8,046.72 meters using the Screening Analysis Tool interface), the location will be included as a potential site. However, if the site is located more than 5 miles from surface water, this analysis will eliminate it as a potential site.

- *A weighted screen* allows a user to give preference to some criteria over others by assigning weighted values to criteria. For example, locations within 2 miles (entered as 3,218.688 meters using the interface) of surface water may be given a value of 10, while locations that are between 2 miles and 5 miles from surface water may be given a less favorable value of 1. Locations greater than 5 miles from surface water may be eliminated altogether. This type of weighting allows for greater flexibility than a Boolean-type analysis.

C.2 How to Use the Screening Analysis Tool

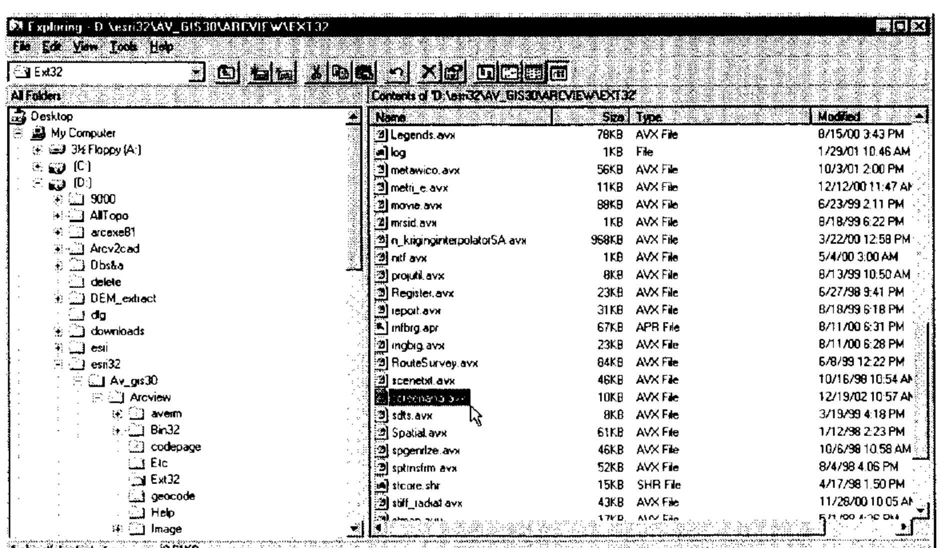
Sections C.2.1 and C.2.2 describe how to use the ArcView GIS 3.2 Screening Analysis Tool; Section C.2.3 provides definitions of the fields on the "Reclassify Values" dialog box. Users should be familiar with the ArcView Spatial Analyst interface before attempting to use the Screening Analysis Tool.

C.2.1 Add the Screening Analysis Extension to ArcView

The interface for the screening tool is an ArcView extension. Before you can successfully use the ArcView database interface the first time, you must make this interface available by adding the extension (*screenana.avx)* to the ArcView extension folder on your hard drive. This folder is typically located on your C or D drive *(e.g., D:\ esri32\Av_gis30\Arcview\Ext32*). The Arcview Spatial Analyst extension is required to run the Screening Analysis Tool. This extension allows you to create, query, map, and analyze cell-based raster data (grids) and to perform integrated vector-raster analysis (ESRI).

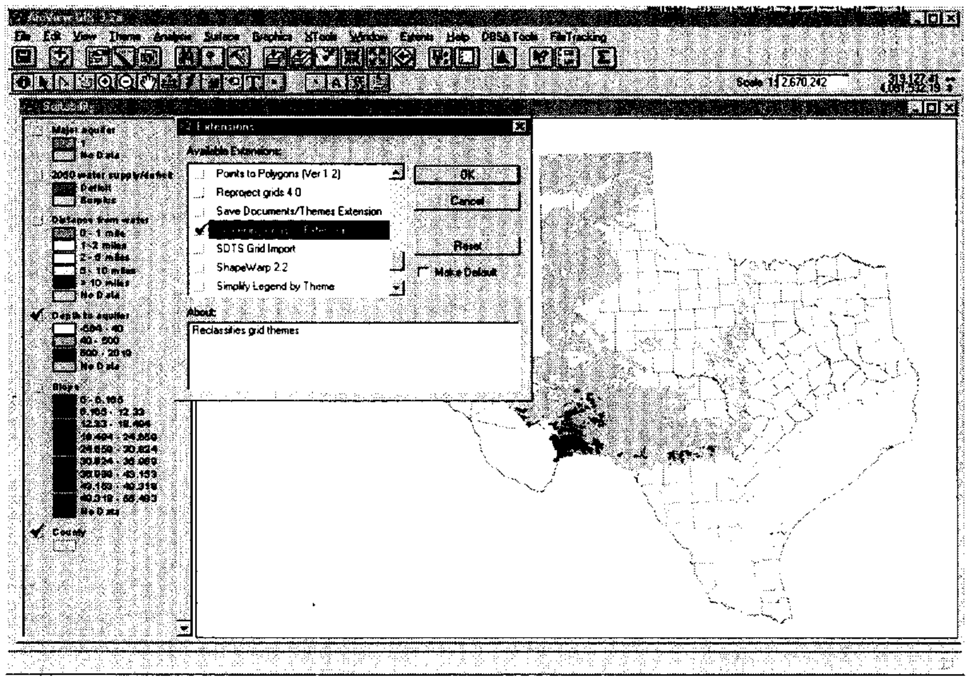
> **Note:** This procedure is only performed once — *before* the first time you use the ArcView Screening Analysis Tool.

Step 1 Copy the database extension (screenana.avx) from the compact disk (CD) to the ArcView extension folder (D:\esri32\Av_gis30\Arcview\Ext32\), as shown below.



Step 2 Open ArcView and select Extensions from the pull-down File menu.

A list of all available ArcView extensions will be displayed in a pop-up window, as shown below.



Step 3 Click on check box next to Screening Analysis Extension and click OK.

A tool button will be added to the ArcView toolbar.

If you place the cursor over this button, you will see the following message:

Weight grid themes for screening analysis

C.2.2 Use the Tool to Screen Locations

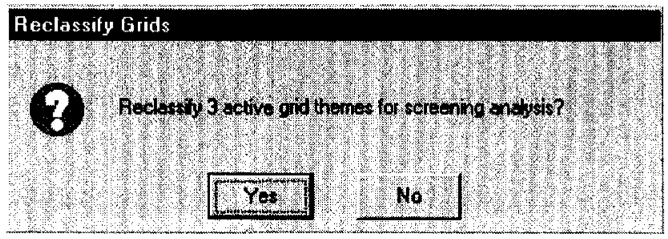
Step 1: From the ArcView view window, activate the grid themes you wish to use as screening criteria.

Note: Make sure there are at least two active grid themes in the view window.

You can apply the weighting utility only to grid themes. There must be at least two grid themes active in the view window for the utility to function.

Step 2: Click on the tool button on the ArcView toolbar.

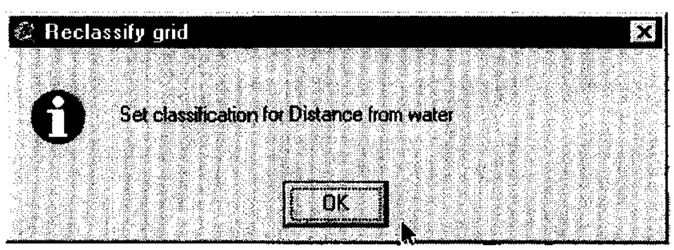
The following message will appear, indicating how many grid themes will be reclassified:



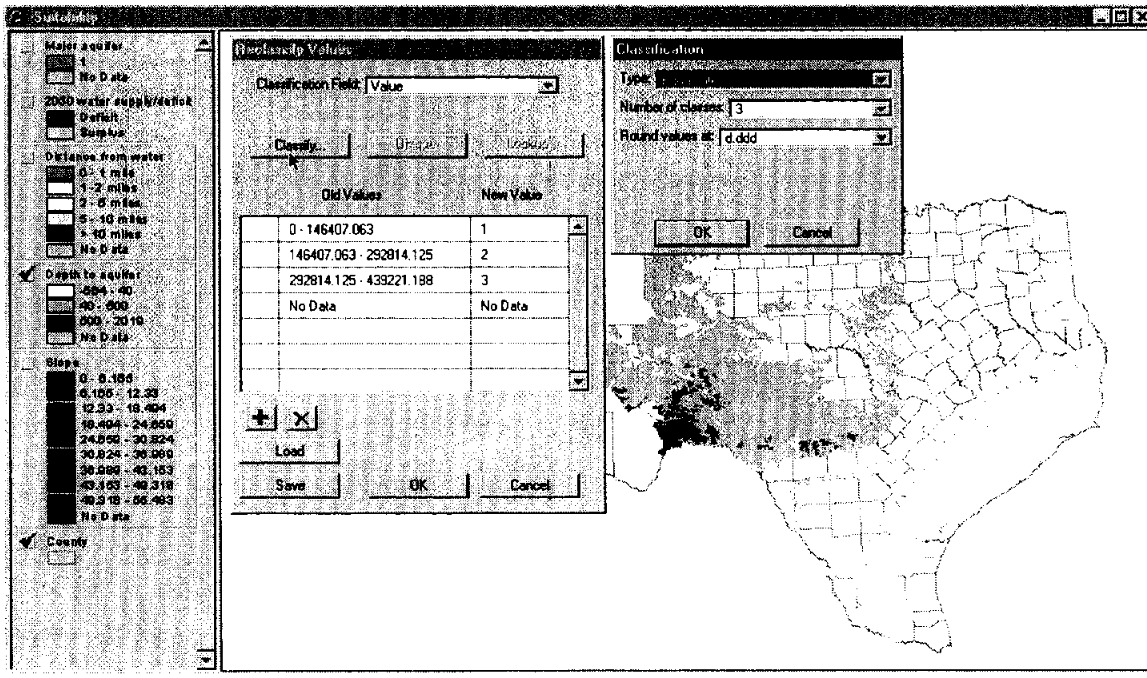
Step 3: Click on Yes if the message shows the correct number of themes to be reclassified. Otherwise, click on No and return to Step 1.

Note: If there are not at least two active grid themes, an error message will appear and the analysis will end. If any other type of theme is active (i.e., a shapefile, image, tin, or ArcInfo coverage), a message will be displayed telling you that these themes will not be included in the process.

Before each grid theme is reclassified, the following message box will appear to let you know which theme is about to be reclassified. Click on OK to continue the reclassification.



For each theme to be reclassified, a "Reclassify Values" dialog box will appear. This window allows you establish the new classification values for the theme. For example, if a distance–to-surface-water grid theme is being reclassified, you will be able to specify the new values for screening.



Step 4: Enter the appropriate screening values in the "Reclassify Values" dialog box.

Refer to the field definitions in Section C.2.3 for additional help.

Note: You must specify "No Data" in the New Value field for any values that should be eliminated from the classification.

The sample screen shots on the following page demonstrate how the same grid theme — in this case, distance from surface water — might be reclassified, based on (1) Boolean logic or (2) weighted values. In the screen on the left, which illustrates Boolean logic, any site located 5 miles or less (i.e., 0-8,046.72 meters) from surface water will be included in the classification (i.e., assigned a value of "1"). However, sites located more than 5 miles (i.e., 8,046.72 – 439,221.188 meters) from surface water will be dropped from the classification (i.e., assigned a value of "No Data"). The screen on the right shows how the same screening criteria might be used to provide a weighted value analysis. In this example, any sites located 2 miles or less (i.e., 0 – 3,218.688 meters) from surface water are assigned a higher weighted value than sites located between 2 and 5 miles (3,218.688 -8,046.72 meters) from surface water. As with the Boolean analysis, sites that are more than 5 miles from surface water will be dropped from the analysis.

Classification Field: The field in the input grid theme's table that will be used to supply the Old Values. If the grid theme does not have a table, like floating point grid themes, the only field shown is Value.

Classify: Opens the Classification dialog for filling out the parameters to classify the Old Values.

Unique: Sets the Old Values to the unique values found in the Classification Field. Only available for integer grid themes.

Lookup: Sets the New Value to a value found in a field in the input grid theme's table. In the Lookup Values dialog, you can pick the field to use as the New Value. Only available for integer grid themes.

Old Values: The range, list, or single value to be changed to the New Value. Any combination of ranges, lists, or single values can be used. Separate ranges with a dash (-) and lists with a comma (,). To edit an entry, click on it and type in the new specification.

New Value: The new value can be either a single value or as "No Data."

Adds a new record to the reclassification, below the selected record. Select a record by clicking on the column to the left of the Old Values column.

Deletes the selected record in the reclassification. Select a record by clicking on the column to the left of the Old Values column.

Load: Enables you to load a previously saved reclassification from a file (.avc). In the Load Classification dialog, you may navigate to the reclassification file you wish to load.

Save: Saves your reclassification to a file (.avc). In the Save Classification dialog, you may navigate to where you would like to save your reclassification file.