Groundwater-Surface Water Interactions in Texas

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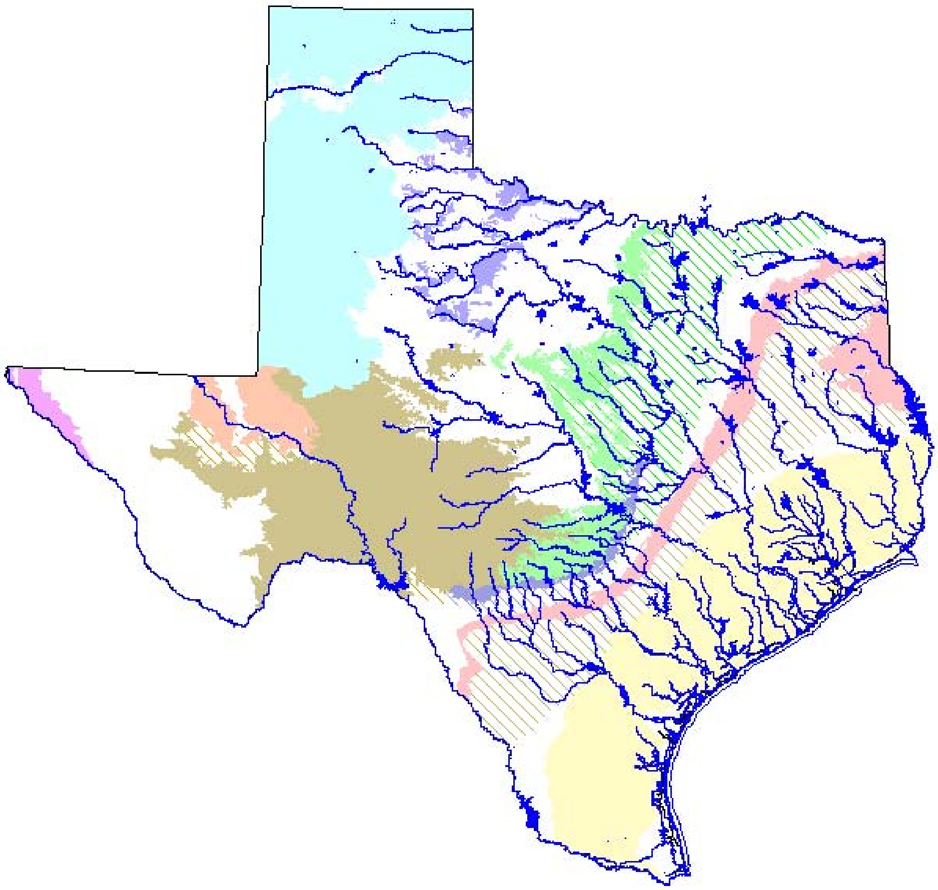

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Executive Summary

Groundwater-surface water interactions need to be evaluated to optimize water management in Texas. This study provides an overview of the impacts of groundwater-surface water (gw-sw) interactions on water quality and water quantity using available data. A literature review was conducted to assess the status of knowledge of gw-sw interactions. A total of 300 references was compiled. References were subdivided into those related to water quantity issues, water quality including point and nonpoint sources of contamination, and methods such as seepage and temperature approaches and modeling analyses. Additional topics covered by the reference list include impacts of climate variability and land use/land cover changes on gw-sw interactions and ecologic issues. A compilation of data and information sources for assessing gw-sw interactions in Texas is also provided. This section includes web links to online report catalogs and databases and a listing of offline reports and catalogs provided by state and federal agencies.

Potential impacts of gw-sw interactions on water quality were evaluated. Previous regional studies related to surface water salinity with groundwater sources are reviewed. A GIS reconnaissance study was conducted using stream-gauge data and groundwater data to evaluate interconnections between the two systems. However, this analysis indicates that very few wells are located adjacent to stream gauges resulting in extremely limited information on interactions between the two systems. Trends in surface water quality in 12 USGS stream gauging stations representative of the major stream in the state were examined. Double mass curves were used with daily streamflow data to assess trends. The largest changes in Total Dissolved Solids (TDS) occurred in the Colorado River in 1986-1988 related to overflow of Natural Dam Salt Lake, at the headwaters of Beals Creek on a tributary to the Colorado River. This increase in TDS resulted in 2.5 times higher load inflowing to the Highland Lakes in Austin even though the drainage area for Natural Dam Salt Lake is only 1% of that of Highland Lakes; however, the Natural Dam Salt lake contributed 27% of the load to Highland Lakes. Much smaller increases in TDS were recorded in many other stream gauges. The impact of gw-sw interactions on impaired stream segments, on the Lower Pecos River and the Little Wichita River, which are targets for the Total Maximum Daily Load (TMDL) program. The impairment listed for both is TDS. Results of this analysis indicate that groundwater discharge contributes significant loads to the Lower Pecos River (51-74%) but contributes very little to the Lower Wichita River (0 - 7%). The impact of gw-sw interactions on Superfund sites was examined

using the Alcoa Plant at Point Comfort (TX) and the Longhorn Army Ammunition Plant in Karnack, Texas. Results indicate that groundwater provides a primary pathway for contaminants from the Superfund sites to nearby surface water and site remediation involves treatment of groundwater.

Riparian vegetation can play a critical role in gw-sw interactions by reducing flood flows and mitigating nonpoint source contamination of surface water bodies from groundwater discharge. The geographic distribution of riparian vegetation was evaluated from existing map products. The Vegetation Types of Texas map was developed by the Texas Parks and Wildlife Department in the late 1970s to 1980s. The map titled Ecoregions of Texas also provides information on riparian vegetation. Information on the dominant types of riparian vegetation in Texas was also reviewed and compiled. Lists of representative riparian vegetation are provided in this report. Data sources and methodologies for improved riparian vegetation mapping are discussed including the use of satellite imagery at varying scales from m to km. Proposed methods for mapping riparian vegetation are also described.

The impacts of gw-sw interactions on water quantity were also evaluated. It was found that three automated methods for baseflow estimation (BFI, PART, RDF) produced similar results, and could be manipulated to mimic each other. In general, BFI calculated the lowest estimates. Baseflow estimates over 91 gauges ranged from nearly 0% to over 90 % of streamflow; the average was 34 %. For 80 percent of stations analyzed, return flows were less than 10% of baseflow. For 95% of stations analyzed, public water intakes comprised less than 10% of baseflow. It was found that while baseflow index (BFI, as %), and total annual baseflow (acre-ft/yr) were useful in evaluating a particular stream, total annual baseflow normalized by contributing area of the basin (acre-ft/yr-mi^2) was better for comparing gauges in different basins. When total annual baseflow normalized by contributing area was plotted, gauges located in the Gulf Coast aquifer displayed a trend of high normalized flows to the northeast, decreasing to the southwest.

Analytical approaches are often used to evaluate the impact of groundwater pumpage on surface water flow. Various analytical approaches for quantifying groundwater pumpage impacts on stream flow are described and evaluated.

There is considerable interest in using output from Groundwater Availability Models as input to Water Availability Models which focus on surface water to ensure that surface water calculations are reliable and to develop procedures to simulate impacts of increased groundwater pumpage on surface water. The approaches to simulating gw-sw interactions in GAM and WAM models are reviewed with reference to the central Carrizo Wilcox GAM.

Because GAMs were not originally designed to address gw-sw interactions, there are a number of limitations associated with using these models for this purpose. Various limitations, particularly those related to spatial and temporal scales, are outlined and future studies that would improve simulations of gw-sw interactions are outlined. A GIS tool was also developed for displaying WAM loss factors.

This reconnaissance relied on existing data and helped identify gaps in data that are required to assess gw-sw interactions. Future work should include collocation of groundwater monitoring (both water levels and water quality) and stream gauge stage and quality monitoring. Streamflow gain loss studies should be conducted in selected areas in the state. The location of existing stream gauges should be optimized relative to aquifer outcrop areas to improve our understanding of gw-sw interactions. Stream channel morphologies should be mapped using existing TX Dept. of Transportation borehole data.

CONTENTS

Reconnaissance Study of Groundwater-Surface Water Interactions in Texas

INTRODUCTION

Understanding interactions between groundwater and surface water is essential because linkages and feedbacks between the two systems affect both the quantity and quality of available water to meet human and ecosystem needs. Human needs are increasingly evident as population in Texas is projected to double by 2050 and demand for water continually increases. Ecosystem needs are being recognized as instream flow programs attempt to establish minimum flow requirements to maintain healthy ecosystems. Because groundwater and surface water form a single resource, factors such as development or contamination of groundwater may impact surface water and vice versa. Increased development of groundwater can change streams from gaining to losing status, affecting the quantity of surface water available for water rights and instream flows. Contamination of groundwater can impact nearby surface water bodies where groundwater discharges to surface water. An estimated 75% of hazardous waste sites related to the US national Superfund program are located within 0.5 miles of surface water bodies and 50% of all Superfund sites have impacted surface water (US EPA, 2000). Previous studies show that nutrient contamination (e.g. nitrate, salinity) of groundwater from nonpoint sources has impacted gaining streams (Slade and Buszka, 1994; Paine, 2003). Quantity and quality of surface water has also impacted groundwater in areas where surface water recharges groundwater, such as playas in the Southern High Plains (Scanlon and Goldsmith, 1997; Fryar et al., 2000). Therefore, quantitative assessment of available water of sufficient quality requires an understanding of gw-sw interactions.

The objective of this study was to assess the impacts of groundwater-surface water interactions on the quantity and quality of water in Texas. This was accomplished through a review of existing studies, an evaluation of the potential impact of groundwater-surface water interactions on both water quality and water quantity, and technology transfer of results to interested agency staff.

SCOPE

The Bureau of Economic Geology conducted a number of tasks to accomplish the above objective:

1. Review of studies assessing (groundwater/surface water) gw-sw interactions in the US relative to water quality and water quantity issues.
2. Evaluation of impacts of gw-sw interactions on water quality including a comparison of stream water quality with adjacent groundwater quality to assess connectivity. Potential impacts of groundwater discharge on river segments identified as impaired in the Total Maximum Daily Load program were also examined. The status of knowledge on the distribution of riparian vegetation was also evaluated because riparian vegetation can markedly affect attenuation of contamination of surface water from groundwater discharge (REFS).
3. Assessment of impacts of gw-sw interactions on water quantity including evaluation of different approaches for hydrograph separation to quantify the component of surface water that is groundwater. Previous programs to model water quantity of surface water (Water Availability Models) and groundwater (Groundwater Availability Models) were examined to assess linkages between these models.

Deliverables are described according to the tasks set forth in the contract.

Task 1: Review Studies Related to Groundwater Surface Water Interactions in the US

1. Review of studies on groundwater surface water interactions in US that focus on methods of quantifying interactions, and evaluation of impacts on water resources and contaminant transport issues

A list of about 300 references was compiled of papers related to groundwater-surface water interactions (Appendix 1). The main topics addressed are water quantity and quality issues related to gw-sw interactions and methods for quantifying interactions. Water quality references were further subdivided into those related to nonpoint and point sources of contaminants. Methods were subdivided into those based on seepage measurements, temperature, sampling, and modeling. Additional topics are also addressed such as the impact of climate variability and land use/land cover changes on gw-sw interactions.

Data and information pertinent to groundwater-surface water interactions related to Texas is also provided (Appendix 2). This compilation focuses on readily available online sources of data.

Task 2: Evaluate Potential Impacts of Groundwater Surface Water Interactions on Water Quality

2a. Compile existing data to conduct a study of spatial and temporal variability in stream water quality that may be impacted by groundwater discharges using statewide reconnaissance and subsequently focusing on selected areas as appropriate.

2b. Compare stream water quality with groundwater quality adjacent to the streams to evaluate connectivity and relationships

2c. Evaluate potential impacts of groundwater/surface water interactions on TMDL stream segments selected by agency staff. Examples of types of elements that may be considered include total dissolved solids, salinity, and/or nitrate.

The results of these tasks are described in Appendix 3.

2d. Assess the status of knowledge on the mapped distribution and types of riparian vegetation. The types of vegetation will also be evaluated and its ability to mitigate groundwater contamination of adjacent surface water bodies. Evaluating approaches for improving riparian vegetation mapping that would be beneficial to TCEQ programs.

This work is described in Appendix 4.

Task 3: Examine the Effects of Groundwater Surface Water Interactions on Groundwater Quantity

1. Calculate baseflow recession for selected stream gauges in Texas
2. Compare different approaches for quantifying baseflow discharge using codes such as Base Flow Index, HYSEP, and PART

The results of these two tasks are described in Appendix 5.

3. Evaluate chemical data from groundwater and surface water to assess the potential for using chemical hydrograph separation to estimate groundwater discharge to surface water

Insufficient data were available from online databases to conduct this subtask.

4. Evaluate potential effects of groundwater pumpage adjacent to streams on stream flow using analytical approaches

The results of this subtask are described in Appendix 6.

5. Evaluate feasibility of using GAM output for a selected aquifer as input to the WAM program.

The results of this subtask are described in Appendix 7.

Task 4: Technology Transfer

1. Develop technology transfer materials on groundwater surface water interactions for interested agency staff.

Two short courses will be presented, one focusing on water quantity issues and the other on water quality issues. Outlines for the short courses are included.

Appendix 1

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<u>Section</u>

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Appendix 2

Task 1: Data, Information, and Methods to Document Groundwater- Surface Water Interactions in Texas

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Sections

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2.1 Introduction

Most reports, data, and information presented or referenced in this report are available on the World Wide Web (Internet). Where identified, a hyperlink to the data or digital version of the report or report reference is presented. References are given for reports not available on the Web.

Overview

Traditionally management of water resources has focused on groundwater or surface water as if they were separate entities. As development of land and water resources increases, it is apparent that development of either of these resources affects the quantity and quality of the other. Nearly all surface-water features (streams, lakes, reservoirs, wetlands, and estuaries) interact with groundwater. These interactions take many forms. In many situations, surface-water bodies gain water and solutes from groundwater systems, and in others the surface-water body is a source of groundwater recharge and causes changes in groundwater quality. As a result, withdrawal of water from streams can deplete groundwater, or, conversely, pumpage of groundwater can deplete water in streams, lakes, or wetlands. Pollution of surface water can cause degradation of groundwater quality, and, conversely, pollution of groundwater can degrade surface water. Thus, effective land and water management requires a clear understanding of the linkages between groundwater and surface water as they apply to any given hydrologic setting (from USGS Circular 1139, titled “Ground Water and Surface Water: A Single Resource,” on the Web at http://water.usgs.gov/pubs/circ/circ1139/).

Texas Background

As concluded later in this report, during **low-flow conditions,** most large streams in Texas, except for most stream reaches on the Edwards aquifer, exhibit discharge gains rather than losses. Although some of the discharge gains could represent perched subsurface water, temporary stream bank storage, streambed underflow, or a combination of these factors, most gains are attributed to shallow groundwater discharge. Many, if not most, tributaries to large streams, however, exhibit discharge losses because

1. Topography of shallow water tables is generally flatter than that of overlying land.
2. Streambeds for major streams generally are topographically lower than those for their tributaries.

As a result, major streambeds often intersect the water table, whereas tributary streambeds often overlie the water table.

During **precipitation runoff conditions,** the following is a popular general conceptual model for the relationship between precipitation, runoff, and recharge for most of Texas:

1. Much initial precipitation falling on natural land surfaces is directly absorbed by soil and vegetation.
2. After the ground becomes saturated, additional precipitation becomes overland flow.
3. Overland flow either infiltrates to the subsurface or enters streams.
4. Some streamflow infiltrates the subsurface, while some flows into larger streams, reservoirs, or oceans.

During runoff, the stage in large streams can exceed the elevation of the water table; therefore, storm runoff can recharge aquifers in major streambeds, as well as tributary streambeds.

As a result, groundwater often discharges to large streams during low-flow conditions, whereas streams recharge groundwater during high-flow conditions. Tributaries and areas with overland flow often are dry during low-flow conditions but provide recharge during high-flow conditions.

Although the actual relationship between streams and groundwater for most areas is more complex than explained above, the **interactions between groundwater and surface water vary** from location to location and change temporally within locations.

Interactions between groundwater and surface water are critical for assessing the quantity and quality of water for both sources, but only a few studies in Texas directly document these interactions. The lack of such studies represents one of the most critical deficiencies of water-resource knowledge in the state.

Many thousands of reports presenting data pertinent to groundwater/surface-water relations have been prepared by State and Federal agencies in Texas. Some of the reports represent statewide conditions; however, many characterize regional studies such as river basins or aquifers, whereas most reports present local information. Some reports are available digitally on the Internet; however, most reports, many of which are not readily available, exist only in hard copy.

Also, many State and Federal agencies maintain water-resource databases pertinent to groundwater/surface-water relations. As is the case with reports, many of the data are available online; however, older data are generally contained in reports and field notes that are not on the Internet and not readily available.

Report Objective

The objective of this report is to

- identify and catalog existing reports and data pertinent to groundwater/surface-water interactions in Texas,
- identify and summarize investigations used to assess those interactions, and
- present methods and tools that could be used to document interactions.

2.2 Report Catalogs and Databases for Texas Water Resources

Report Catalogs

Texas Water Development Board

Most groundwater data and groundwater reports in Texas are available from the Texas Water Development Board (TWDB). Their publication homepage is at http://www.twdb.state.tx.us/publications/pub.asp, and a link to their report homepage is http://www.twdb.state.tx.us/publications/reports/Reports.asp.

An Adobe Acrobat file containing a **TWDB Publication Catalog** is at http://www.twdb.state.tx.us/publications/reports/Publications%20Catalog/catalog.pdf. The Adobe search feature can be used to find reports concerning specific hydrologic or water-quality topics or specific locations. Most reports presented in the catalog are available in hard copy only, and many are not readily available.
Locations for **Repository Libraries of TWDB reports** are presented at http://www.twdb.state.tx.us/publications/reports/Publications%20Catalog/Repository%20Libraries.pdf

Some TWDB water-resource publications exist as **digital files** and are available from Web addresses presented below.

Groundwater Bulletins:
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/bulletins/Bulletins.asp.
Groundwater Numbered Reports:
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/GWreports.asp.
Contracted Reports:
http://www.twdb.state.tx.us/RWPG/rpfgm_rpts.asp.
Limited Publications (only a few reports):
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/LimitedPublications/LimitedPublications.asp.

U.S. Geological Survey

Most surface-water data and reports in Texas are available from the U.S. Geological Survey (USGS). An online publication warehouse references USGS reports at http://pubs.er.usgs.gov/pubs/index.jsp?view=adv. Report searches from the warehouse include options for online reports and can include report subjects, report dates, author names, and report series. As of August 2005, the catalog presents 1,441 Texas reports, 716 of which are available as digital files on the Internet.

USGS also has an online library containing 325,000 records at http://igsrglib03.er.usgs.gov:8080/ipac20/ipac.jsp?session=1K2S31272A567.77016&profile=r&menu=home&ts=1122313076473#focus. The search engine for reports in the library includes keywords for title, subject, and author.

Bureau of Economic Geology (The University of Texas at Austin)

Publications of the Bureau of Economic Geology (BEG) are listed at http://www.beg.utexas.edu/mainweb/pubs01.htm.
A subject catalog for BEG reports is at http://www.beg.utexas.edu/mainweb/publications/2002-SubjectIndex.pdf. Many of their groundwater reports are part of their Report of Investigations series at http://www.beg.utexas.edu/mainweb/publications/pubs-BookRptInvest.htm.

Center for Research in Water Resources (The University of Texas at Austin)

Printed publications of the Center for Research in Water Resources (CRWR), which can be searched by author or publication year, are listed at http://www.crwr.utexas.edu/print.shtml. Their online publications can be searched by publication year at http://www.crwr.utexas.edu/online.shtml.

Texas Commission on Environmental Quality

The Texas Commission on Environmental Quality (TCEQ) homepage for water issues is at http://www.tceq.state.tx.us/nav/eq/eq_water.html. Although primarily involved in water-management issues, TCEQ lists many reports related to the quantity and quality of surface water available through links at the above Internet address.

Texas Water Resources Institute (Texas A&M University)

Reports by the Texas Water Resources Institute (TWRI) are listed at http://twri.tamu.edu/reports.php. The search engine for their catalog includes keywords for author, title, and abstract, as well as publication year and report number.

U.S. Environmental Protection Agency

U.S. Environmental Protection Agency (EPA) water-resource publications are listed at http://yosemite.epa.gov/water/owrccatalog.nsf/. The catalog includes searches by title or report keywords.

U.S. Army Corps of Engineers

Publications of the U.S. Army Corps of Engineers (COE) are listed at http://www.hec.usace.army.mil/publications/pub_catalog.html. Most of their reports represent manuals and procedures for surface-water hydrology or hydraulics and are aggregated by subject index.

Texas River Agencies

Agency name and link to catalog of reports:

Brazos River Authority: http://www.brazos.org/WQ/Report/4_SpecialStudies.pdf
Houston-Galveston Area Council: http://www.h-gac.com/HGAC/Home/Publications.htm
Lower Colorado River Authority: http://www.lcra.org/water/index.html
Nueces River Authority: http://www.nueces-ra.org/
Red River Authority: http://www.rra.dst.tx.us/
Sabine River Authority: http://www.sra.dst.tx.us/
San Antonio River Authority: http://www.sara-tx.org/site/water_quality/water_qual_mon/Projects_and_Studies.html
Sulphur River Basin Authority: http://www.sulphurr.org/reports/reports.html

Texas Parks and Wildlife Department

The Texas Parks and Wildlife Department (TPWD) presents links to reports and information about water resources at http://www.tpwd.state.tx.us/texaswater/sb1/.
Most reports involve water-resource overviews and threats to wildlife.

Federal Government

Most Federal agency technical publications are available from the National Technical Information Service at http://www.ntis.gov/products/types/publications.asp?loc=4-4-4.

Professional Associations

Many Texas water-resource reports, articles, and abstracts are reported in journals and publications other than those of governmental agencies. The following organizations are identified as providing a substantial number of reports related to Texas water resources.

American Institute of Hydrology: http://www.aihydro.org/publications.htm
American Water Resources Association: http://www.awra.org/publicationindex.html
Center for Watershed Protection: http://www.cwp.org/pubs_download.htm
Environmental & Water Resources Institute of American Society of Engineers: http://www.ewrinstitute.org/publications/
Geological Society of America: http://www.geosociety.org/pubs/
Hydrology Web: http://hydrologyweb.pnl.gov/links.asp?id=Publications
National Ground Water Association: http://www.ngwa.org/publication/publications.cfm
National Ground Water Association Online Information: http://www.ngwa.org/gwonline/index.cfm
Universities Council on Water Resources Abstracts: http://www.uwin.siu.edu/dir_database/wrsic/wrsic.htm

Databases

Texas Water Development Board

TWDB databases are accessible at: http://www.twdb.state.tx.us/data/data.asp.

Groundwater data reports for counties, aquifers, or other geographic areas, are at http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWDatabaseReports/GWdatabaserpt.htm.

A **map-based database** for groundwater data and submitted driller's reports is at http://wiid.twdb.state.tx.us/.

The TWDB homepage for **surface-water data** is at http://www.twdb.state.tx.us/data/surfacewater/surfacewater_toc.asp**.**

An interactive Web page presenting information for all **major Texas reservoirs** is online at http://wiid.twdb.state.tx.us/ims/resinfo/viewer.htm**.** By clicking on the link "all reservoirs" near the bottom of the page, you will open a file presenting a Texas Reservoir Information Sheet. That file can be stored by saving as a Web Archive or Web page.

U.S. Geological Survey

All USGS water data for Texas are available at http://waterdata.usgs.gov/tx/nwis/nwis, with the exception of historical daily stream-water-quality data, historical daily suspended-sediment data, and historical daily reservoir water level and storage content data. The availability for these data is discussed below.

General Data Links

USGS surface-water data are online at http://waterdata.usgs.gov/tx/nwis/sw.
Presented are

- real-time and recent data for reservoir water levels and streamflow discharges and water levels;
- historical data for daily, monthly, and annual streamflow-discharge and annual-peak discharge; and
- streamflow measurements of instantaneous discharge.

USGS groundwater data are online at http://waterdata.usgs.gov/tx/nwis/gw.
Presented are well-site descriptions, and real-time and historical water levels.

USGS water-quality data are online at http://waterdata.usgs.gov/tx/nwis/qw.
Presented are real-time and recent data for stream water quality, and historical data for stream and groundwater quality.

Specific Data Links

Real-time Data

Real-time incremental stream-water-level and discharge data for the present and past 31 days are available for about 429 stream sites at http://waterdata.usgs.gov/tx/nwis/current/?type=flow.

Real-time incremental reservoir-water-level data for the present and past 31 days are available for about 121 reservoirs at http://waterdata.usgs.gov/tx/nwis/current/?type=lake&group_key=NONE.

Real-time incremental groundwater-level data for the present and past 31 days are available for about 47 wells at http://waterdata.usgs.gov/tx/nwis/current/?type=gw

Real-time incremental stream-water-quality data for the present and past 31 days are available for about 46 stream sites at http://waterdata.usgs.gov/tx/nwis/current/?type=quality.

Historical Data

Historical daily streamflow data
The primary Web page for these data is http://waterdata.usgs.gov/tx/nwis/sw.
Click on the "streamflow" link to obtain daily values or on the "monthly" or "annual" links to obtain these data. A link to historical daily streamflow data for all sites in Texas is presented in Appendix 1.

Historical annual streamflow peak data
The Web page for these data is http://nwis.waterdata.usgs.gov/tx/nwis/peak.

Historical daily reservoir water level and storage content data
By the end of 2005 the USGS is scheduled to present online values for daily water levels and daily storage contents for about 150 major Texas reservoirs. Many of the data represent daily mean values, but some will be once-daily values for data collected at specific times each day.

Historical periodic groundwater-level data
The primary Web page for these data is http://waterdata.usgs.gov/tx/nwis/gw.
A link to groundwater level data for all sites in Texas is presented in Appendix 1.

Historical periodic stream-water-quality data
The primary Web page for these data is http://waterdata.usgs.gov/tx/nwis/qw.
Click on the "samples" link, then the box next to the "site type" link, then "submit," then "surface water" to obtain these data. A link to periodic stream-water-quality data for all sites in Texas is presented in Appendix 1.

Historical daily stream-water-quality data
Daily values for water-quality data exist for stations having real-time water-quality data. Daily water-quality data are published but not presented online for the 46 sites having such data, but a list of the sites is presented at http://waterdata.usgs.gov/tx/nwis/current?type=quality&group_key=basin_cd. Historical data for about 150 sites having daily water-quality data are presented in Appendix 1.

Historical periodic groundwater-quality data
The primary Web page for these data is http://waterdata.usgs.gov/tx/nwis/qw.
Click on the "samples" link, then the box next to the "site type" link, then "submit," then "ground water" to obtain these data. A link to groundwater periodic water-quality data for all sites in Texas is presented in Appendix 1.

Historical daily suspended-sediment data for Texas streams are online at http://webserver.cr.usgs.gov/sediment/selState.cfm

Texas Natural Resource Information System

The Texas Natural Resources Information System (TNRIS), a Division of the Texas Water Development Board, is the state's clearinghouse for maps, aerial photos, and digital natural resources data. Its data and information are online at http://www.tnris.state.tx.us/index.htm and its digital data are at http://www.tnris.state.tx.us/DigitalData/data_cat.htm.

Texas Commission on Environmental Quality

Most water data for TCEQ represent surface-water-quality data online at http://www.tceq.state.tx.us/compliance/monitoring/water/quality/data/wqm/swqm_data.html.

Surface-Water-Quality Monitoring data from TCEQ are available at http://www.tnrcc.state.tx.us/water/quality/data/wmt/samplequery.html. An explanation of the database is at http://www.tnrcc.state.tx.us/water/quality/02_twqmar/02_305b/02_program_summary/09-swqmprg.pdf, and a data management reference guide for the database is at http://www.tceq.state.tx.us/compliance/monitoring/water/quality/data/wdma/2004dmrg.html.

Information about the Surface-Water-Quality Monitoring database is presented in Appendix 2 near the end of this report.

The TCEQ statewide summary of sampling results from the Statewide **Clean Rivers Program** involving surface-water-quality inventories of all rivers is presented at http://www.tceq.state.tx.us/compliance/monitoring/water/quality/data/wqm/305_303.html, and the site map for 2004 is online at http://www.tnrcc.state.tx.us/water/quality/04_twqi303d/sitemap.html

Data and information for **water rights permitting** and availability are at http://www.tnrcc.state.tx.us/permitting/waterperm/wrpa/permits.html#pending.

Data and information about **water-quality permits** are at http://www.tceq.state.tx.us/nav/permits/water_qual.html.

The **TCEQ Data Clearinghouse** is at http://www.tceq.state.tx.us/admin/data/data.html.

Texas River Agencies

Web homepages for Texas River Authorities and other river agencies present surface-water-quality data collected through the Clean Rivers Program sponsored by the TCEQ. Some river agencies collect and present additional water-resource data. Links to homepages for all river authorities and other agencies participating in the Clean Rivers Program are at http://www.tnrcc.state.tx.us/water/quality/data/wmt/contract.html. Those agencies with identified water-resource databases are listed below:

Agency name and database link:

Angelina and Nueces River Authority: http://www.anra.org/index_cleanrivers.htm

Brazos River Authority: http://www.brazos.org/CleanRiversProgram/CRP_WaterQualityDB.asp
Guadalupe-Blanco River Authority: http://www.gbra.org/templates/crp_basin_map.asp
Houston-Galveston Area Council: http://www.h-gac.com/HGAC/Programs/Clean+Rivers+Program/default.htm
International Boundary and Water Commission: http://www.ibwc.state.gov/CRP/monstats.htm (water quality)
International Boundary and Water Commission: http://www.ibwc.state.gov/html/rio_grande.html (surface water)
Lavaca Navidad River Authority: http://www.lnra.org/RI/water_quality/default.htm (water quality)
Lavaca Navidad River Authority: http://www.lnra.org/RI/reservoir_data/default.htm (reservoir data)
Lower Colorado River Authority: http://www.lcra.org/water/index.html
Lower Neches Valley Authority: http://www.lnva.dst.tx.us/
Northeast Texas Municipal Water District: http://www.netmwd.com/reports/reports.html
Nueces River Authority: http://www.nueces-ra.org/cgi-bin/SW/access.cgi
Red River Authority: http://www.rra.dst.tx.us/
Sabine River Authority: http://www.sra.dst.tx.us/data/wq/swqm/default.asp (water-quality data)
Sabine River Authority: http://www.sra.dst.tx.us/basin/lake_and_river_conditions.asp (lake and river data)
San Antonio River Authority: http://www.sara-tx.org/site/water_quality/water_qual_mon/stream_monitoring.html
Sulphur River Basin Authority: http://www.sulphurr.org/reports/reports.html
Trinity River Authority: http://www.trinityra.org/Lake%20River%20Data/data_menu.htm (river and lake data)

Texas River Watch Program

Texas State University, in cooperation with other agencies, manages a stream sampling program for limited water-quality constituents. Site information is at http://jones.geo.txstate.edu/index.asp.

Texas General Land Office

The GLO provides Geographic Information Systems data at http://www.glo.state.tx.us/gisdata/gisdata.html. All files are presented in ESRI Arc/Info coverage export file and/or ArcView shape-file formats. Shape files may be viewed using ESRI's free viewing software, ArcExplorer.

Texas Investigations Relevant to Groundwater/Surface-Water Relations

Streamflow Gain-Loss Studies

Streamflow gain-loss studies probably represent the easiest, cheapest, and most direct method to document interactions between groundwater and surface water. Since 1918, USGS has conducted gain-loss studies on streams throughout much of Texas. The objective for most of the studies was to obtain data that could be used to estimate discharge from, or recharge to, shallow aquifers.

According to the studies, with the exception of most stream reaches on the Edwards aquifer, most large streams in Texas gain rather than lose water during low-flow conditions. Therefore, groundwater discharge dominates base flow throughout most of Texas.

The streamflow data, along with flow gain or loss to each subreach, are presented online at http://water.usgs.gov/pubs/of/ofr02-068/. The report presents results of 366 gain-loss studies involving 249 unique reaches of streams throughout Texas and provides channel gains and losses for 2,872 subreaches. A detailed summary of the data and associated analyses is presented in Appendix 3 at the end of this report.

Along with the flow data, water temperature and other limited water-quality data were documented for some of the flow studies. References for all identified reports containing these data are presented in the next section. References for selected gain-loss study reports are presented in Appendix 4.

In 1960, the Texas Water Development Board published a report containing data for all flow studies completed at that time (Bulletin 5807D "Channel Gain and Loss Investigations, Texas Streams, 1918–1958," April 1960). This report presents two sections: (1) low-flow investigations, including tabulation of measurements, text, and substantiating information; and (2) delivery of water investigations (releases from reservoirs), including discussion of purpose and scope, summary of results, and presentation of results in hydrographs and time-of-travel curves for delivered water.

Low-Flow Characteristics

Base-flow discharges for streams typically are void of direct surface runoff and generally represent groundwater discharges to streambeds. Therefore, documentation of the quantity and water quality of low-flow characteristics is an important tool for establishing groundwater/surface-water relations.

A Texas report providing base-flow characteristics as determined from streamflow hydrograph-separation analysis in West-Central Texas is online at http://pubs.er.usgs.gov/pubs/wri/wri884218. Although other similar reports could not be identified for Texas, studies documenting flow and water-quality characteristics during low-flow conditions have been identified for many streams in Texas.

Thirty-one USGS and TWDB reports containing the words "low-flow" or "base flow" in the title were identified and are presented below. The online (digital) reports are available as digital files in the links provided below, and reports not online are identified in the following section. The studies involve relations between flow in channels and aquifers, characteristics for low-flow discharges, and presentation of stream-flow discharge and water-quality data.

These reports provide direct or indirect information about relations between groundwater and streamflow and should be used in the development of any additional studies to document such relations. A USGS report presenting methods to collect and analyze data for low-flow investigations is online at http://water.usgs.gov/pubs/twri/twri4b1/.

2.3 Online Reports

Stream Name and Report Link

Brazos River: http://pubs.er.usgs.gov/pubs/wri/wri974117

Cibolo Creek:
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%20112.htm

Lower Colorado River: http://pubs.er.usgs.gov/pubs/wri/wri964225

Upper Colorado River: http://pubs.er.usgs.gov/pubs/wri/wri944036

Upper Guadalupe River:
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%2029.htm

Pecos River:
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/report%2022.asp

Prairie Dog Town Fork of the Red River:
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%20116.htm

Sabine and Old Rivers:
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%2066.htm

East and West Fork San Jacinto River: http://pubs.er.usgs.gov/pubs/ofr/ofr70124

Southeast Texas: http://pubs.er.usgs.gov/pubs/wri/wri884154

Southeast Texas: http://pubs.er.usgs.gov/pubs/fs/fs12299

West-Central Texas: http://pubs.er.usgs.gov/pubs/wri/wri884218

Wichita River: http://pubs.er.usgs.gov/pubs/wri/wri954288

2.4 Reports Not Online

Stream Name and Report Reference

Barton Creek (Colorado River basin): http://pubs.er.usgs.gov/pubs/ofr/ofr7015
Big Elkhart and Little Elkhart Creek (Trinity River basin): TWDB, Report 026, Quantity and Quality, 1966
Blanco River: http://pubs.er. usgs.gov/pubs/ofr/ofr6426
Cibolo Creek: TWDB, Bulletin 6511, Quantity and Quality, 1965
Guadalupe River: TWDB, Bulletin 6503, Comal County, Quantity, 1965
Leon and Lampasas Rivers: TWDB, Report 097, Quantity and Quality, 1969
Lampasas River: TWDB, Bulletin 6506, Quantity and Quality, 1965
Little Cypress Creek: TWDB, Report 025, Upshur, Gregg, and Harrison Counties, Texas, Quantity and Quality, 1966
Llano River: TWDB, Bulletin 6505, Quantity and Quality, 1965
Neches River: http://pubs.er.usgs.gov/pubs/ofr/ofr536
Northeast Texas: http://pubs.er.usgs.gov/pubs/pp/pp448G
Nueces River: http://pubs.er.usgs.gov/pubs/ofr/ofr65134
Pecos River below Girvin, Texas: TWDB, Report 107, Quantity and Quality, 1970
Pedernales River: http://pubs.er.usgs.gov/pubs/ofr/ofr5656, and TWDB, Bulletin 6407, Quantity and Quality, 1964
San Gabriel River: TWDB, Bulletin 6510, Quantity and Quality, 1965
San Jacinto River: http://pubs.er.usgs.gov/pubs/ofr/ofr70124
San Antonio River: TWDB, Report 142, Reconnaissance of the Oxygen Balance and the Variation of Selected Nutrients in the San Antonio River during Low Flow

Stream Basin Studies

Water-resource characteristics for stream basins dictate quantity and quality of streamflow and recharge to underlying aquifers; therefore, they are important in assessing groundwater/surface-water relations.

Basinwide studies involving various water-resource subjects have been conducted for major river basins in Texas (presented below). Most of the studies involve assessment of surface-water quality, but many involve streamflow discharges or sources of contaminants to streamflow. Eight online reports representing small basins are presented after the section below.

Additionally, from 1964 through 1974, a series of 14 reports presenting a reconnaissance of water quality for each major river basin in Texas was published by TWDB. Those reports are presented in Appendix 5. Most of these reports provide historical background data or information that could be valuable in documenting changes relative to current or more recent groundwater streamflow relations.

Large basins

Basin name	Year	Subject of publication
Brazos River Basin http://pubs.er.usgs.gov/pubs/wri/wri014057	(2001)	sand transport

http://pubs.er.usgs.gov/pubs/wri/wri974117	(1997)	low-flow statistics
http://twri.tamu.edu/reports/1993/tr160.pdf	(1993)	natural salt pollution
http://pubs.er.usgs.gov/pubs/wri/wri884216	(1988)	suspended-sediment loads
http://twri.tamu.edu/reports/1988/tr144.pdf	(1988)	water availability
http://pubs.er.usgs.gov/pubs/wsp/wsp1779K	(1964)	water-quality assessment
http://pubs.er.usgs.gov/pubs/wsp/wsp1669CC	(1964)	natural sources of salinity
http://pubs.er.usgs.gov/pubs/ofr/ofr67184	(1967)	sources of saline water

TWDB Report 168, Woody Phreatophytes along the Brazos River and Selected Tributaries above Possum Kingdom Lake.

Canadian River Basin

http://pubs.er.usgs.gov/pubs/wri/wri964304	(1996)	trends in streamflow

Colorado

http://pubs.er.usgs.gov/pubs/wri/wri944036	(1994)	assessment of Upper Colorado
http://pubs.er.usgs.gov/pubs/wri/wri884154	(1989)	groundwater/surface-water relations
http://pubs.er.usgs.gov/pubs/wri/wri854181	(1986)	statistical summary of water quality
http://pubs.er.usgs.gov/pubs/wsp/wsp2084	(1982)	salinity trends and sources
http://pubs.er.usgs.gov/pubs/ofr/ofr741088	(1974)	water-quality assessment
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%2071.htm	(1968)	water-quality reconnaissance

TWDB Report 182, Woody Phreatophytes along the Colorado River from Southeast Runnels County to the Headwaters in Borden County, Texas, 1974.

Guadalupe River

http://twri.tamu.edu/reports/1992/tr154.pdf	(1992)	sediment transport

Neches

http://pubs.er.usgs.gov/pubs/wsp/wsp1839A	(1967)	water-quality assessment

Nueces

http://pubs.er.usgs.gov/pubs/ofr/ofr65134	(1965)	base-flow study

Pecos

http://pubs.er.usgs.gov/pubs/wsp/wsp596D	(1928)	water-quality assessment

Pedernales

http://www.crwr.utexas.edu/reports/1998/rpt98-6.shtml	(1998)	water-quality assessment

Red River

http://pubs.er.usgs.gov/pubs/fs/fs10603	(2003)	water quality in the lower Red River
http://pubs.er.usgs.gov/pubs/wri/wri034086	(2003)	changes in flow and water quality—North Fork Red

Rio Grande

http://pubs.er.usgs.gov/pubs/cir/cir1162	(1998)	water quality in Rio Grande Valley
http://pubs.er.usgs.gov/pubs/fs/fs09897	(1997)	trace elements and organic compounds

http://pubs.er.usgs.gov/pubs/ofr/ofr97644	(1997)	water-quality assessment—Upper Rio Grande
http://twri.tamu.edu/reports/1995/169/tr169.pdf	(1995)	flow salts and trace elements
http://pubs.er.usgs.gov/pubs/wri/wri944061	(1994)	nutrients suspended sediment and pesticides
http://pubs.er.usgs.gov/pubs/pp/pp1370C	(1989)	high-level radioactive waste
http://pubs.er.usgs.gov/pubs/wsp/wsp839	(1938)	water-quality assessment
Sabine		
http://pubs.er.usgs.gov/pubs/wsp/wsp1809H	(1965)	water-quality assessment
San Antonio		
http://pubs.er.usgs.gov/pubs/wri/wri034030	(2003)	streamflow constituent loads
http://pubs.er.usgs.gov/pubs/ofr/ofr95148	(1995)	biology of Olmos Creek and Upper San Antonio
http://twri.tamu.edu/reports/1992/tr154.pdf	(1992)	sediment transport
San Jacinto		
http://pubs.er.usgs.gov/pubs/fs/fs06302	(2002)	dissolved oxygen and aquatic biota
http://pubs.er.usgs.gov/pubs/ofr/ofr70124	(1970)	quantity and quality of low flow
Trinity River		
http://pubs.er.usgs.gov/pubs/fs/fs12803	(2003)	indicators of hydrologic alteration
http://pubs.er.usgs.gov/pubs/wri/wri014253	(2001)	West Fork Trinity
http://pubs.er.usgs.gov/pubs/cir/cir1171	(1999)	water-quality assessment
http://pubs.er.usgs.gov/pubs/wri/wri974057	(1997)	organochlorine compounds
http://pubs.er.usgs.gov/pubs/ofr/ofr96124	(1996)	pesticides in a coastal prairie agricultural area
http://pubs.er.usgs.gov/pubs/ofr/ofr96558	(1996)	nutrients in two coastal prairie streams
http://pubs.er.usgs.gov/pubs/fs/fs09095	(1995)	water-quality assessment
http://pubs.er.usgs.gov/pubs/fs/fs23195	(1995)	nutrients in streams
http://pubs.er.usgs.gov/pubs/fs/fs16095	(1995)	pesticides in streams
http://pubs.er.usgs.gov/pubs/fs/fs08895	(1995)	pesticides in streams
http://www.twdb.state.tx.us/RWPG/ rpgm_rpts/94483019.pdf	(1995)	Upper Trinity basin
http://pubs.er.usgs.gov/pubs/wri/wri944218	(1994)	pesticides in streams
http://pubs.er.usgs.gov/pubs/wri/wri944086	(1994)	nutrients and suspended sediments
http://pubs.er.usgs.gov/pubs/wri/wri854318	(1985)	Upper Trinity
http://www.twdb.state.tx.us/publications/ reports/GroundWaterReports/GWReports/ Individual%20Report%20htm%20files/ Report%2067.htm	(1967)	water-quality reconnaissance
Wichita		
http://pubs.er.usgs.gov/pubs/fs/fs11000	(2000)	water quality and biological assessment
http://pubs.er.usgs.gov/pubs/wri/wri954288	(1995)	effects of low-flow diversions on salinity
http://pubs.er.usgs.gov/pubs/ofr/ofr6354	(1963)	sources of natural pollution

Additionally, two other reports representing multiple river basins are referenced below:

Bureau of Economic Geology, The University of Texas at Austin, The Guadalupe-Lavaca-San Antonio-Nueces River Basins Regional Study, San Antonio East-Llano East Sheets, T. C. Gustavson and E. G. Wermund, project directors, 5 pls., color, scale 1:250,000, 1985. RB0001.

Bureau of Economic Geology, The University of Texas at Austin, The Guadalupe-Lavaca-San Antonio-Nueces River Basins Regional Study, Seguin West-Austin West Sheets, T. C. Gustavson and E. G. Wermund, project directors, 5 pls., color, scale 1:250,000, 1985. RB0002.

Small basins

Basin name and report link.

Comal River (Guadalupe River Basin)
http://pubs.er.usgs.gov/pubs/fs/fs09997

Cow Bayou (Brazos River Basin)
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%2099.htm

Escondido Creek (San Antonio River Basin)
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%2039.htm

Little Elm Creek (Trinity River Basin)
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%2014.htm

Pin Oak Creek (Trinity River Basin)
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%2054.htm

Richland and Chambers Creek (Trinity River Basin)
http://pubs.er.usgs.gov/pubs/wri/wri974132

San Marcos River (Guadalupe River Basin)
http://pubs.er.usgs.gov/pubs/fs/fs05997

Seco Creek (San Antonio Basin)
http://pubs.er.usgs.gov/pubs/ofr/ofr98627

Regional aquifer studies.

As concluded in the “Streamflow Gain-Loss Studies” section earlier, with the exception of most stream reaches on the Edwards aquifer, most large streams in Texas gain rather than lose water during low-flow conditions. Therefore, the water-resource characteristics for aquifers dictate the quantity and water quality of base flows throughout much of Texas.

Many regional reports have been prepared for Texas aquifers, and many of those are available online (links below). The reports referenced below without links are not available as digital files. Although the reports primarily present data and information concerning groundwater hydrology, hydraulics, and water quality, many also present direct or indirect information about the relationship between groundwater and streamflow. In addition, many TWDB reports present groundwater resources by aquifer, county, or other geographic area; can be identified by word search in the TWDB Publication Catalog file; and can be obtained as hard copies.

TWDB publication catalog:
http://www.twdb.state.tx.us/publications/reports/Publications%20Catalog/catalog.pdf.
Many of the reports in the catalog also are available online as digital files in four separate catalogs identified as

> **TWDB Groundwater Bulletins:**
> http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/bulletins/Bulletins.asp;
> **TWDB Groundwater numbered reports:**
> http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/GWreports.asp; and
> **TWDB contracted reports:**
> http://www.twdb.state.tx.us/RWPG/rpfgm_rpts.asp.
> A few such reports are presented in **TWDB limited publications:**
> http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/LimitedPublications/LimitedPublications.asp

Aquifer and report link or reference:

Carrizo Wilcox aquifer
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%20332.htm

http://www.twdb.state.tx.us/RWPG/rpgm_rpts/IndividualReportPages/99483279.asp

BEG, Report of Investigations No. 269, Hydraulic Properties of the Carrizo-Wilcox Aquifer in Texas: Information for Groundwater Modeling, Planning, and Management**,** by R. E. Mace and R. C. Smyth, 2003.

Carrizo Wilcox and Gulf Coast aquifers
http://pubs.er.usgs.gov/pubs/wri/wri994233

Central High Plains aquifer water quality
http://pubs.er.usgs.gov/pubs/wri/wri024112

Cretaceous aquifers in North-Central Texas
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%20269.htm

Cretaceous aquifers in Texas Panhandle
BEG, Geological Circular 8803, Hydrogeology and Hydrochemistry of Cretaceous Aquifers, Texas Panhandle.

Dockum
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%20359.htm

BEG, Report of Investigations No. 161, Hydrogeochemistry and Water Resources of the Triassic Lower Dockum Group in the Texas Panhandle and Eastern New Mexico, by A. R. Dutton and W. W. Simpkins, 1986.

Edwards aquifer (Barton Springs segment)
http://pubs.er.usgs.gov/pubs/wri/wri864036

Edwards aquifer (northern segment)
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%20358.htm

BEG, Report of Investigations No. 192, Hydrogeology of the Northern Segment of the Edwards Aquifer, Austin Region, by R. K. Senger, E. W. Collins, and C. W. Kreitler, reprinted 1996.

Edwards aquifer (San Antonio area)
http://pubs.er.usgs.gov/pubs/sir/sir20045277

http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%20239.htm

Edwards Plateau
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%20235.htm

http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/R360AEPC/AEPCindex.htm

Edwards-Trinity (Plateau) aquifer
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%20255.htm

Edwards and Trinity aquifers
http://pubs.er.usgs.gov/pubs/sir/sir20045201

Gulf Coast aquifers hydrology
http://pubs.er.usgs.gov/pubs/ofr/ofr9164

High Plains
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%20288.htm

High Plains water quality
http://pubs.er.usgs.gov/pubs/ofr/ofr03345

Lower Rio Grande Valley
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%20316.htm and

http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/bulletins/Bull.htm/B6014.htm

Ogallala aquifer
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%20342.htm

BEG, Report of Investigations No. 177, Hydrogeology and Hydrochemistry of the Ogallala Aquifer, Southern High Plains, Texas Panhandle, 1988.

South Central Texas water quality
http://water.usgs.gov/pubs/circ/circ1212/

Southern High Plains water quality
http://pubs.er.usgs.gov/pubs/ofr/ofr03345

Texas counties bordering the Rio Grande
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/LimitedPublications/LP214/LP-214.pdf

Trinity River Basin aquifers (Trinity, Carrizo-Wilcox, and Gulf Coast aquifers)
http://pubs.er.usgs.gov/pubs/wri/wri994233

West Texas aquifers
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%20356.htm

Groundwater vulnerability.

Investigations of groundwater vulnerability from surface contamination require knowledge of groundwater/surface-water relations and represent a valuable resource for protecting and managing aquifers. Although many groundwater vulnerability reports have been done in other states, only a few such reports have been identified in Texas.

A USGS report presenting procedures for assessing groundwater vulnerability to contamination is presented online at http://water.usgs.gov/pubs/circ/2002/circ1224/. A recent groundwater vulnerability report conducted for the Edwards aquifer in Bexar County is online at http://pubs.er.usgs.gov/pubs/wri/wri034072.

The EPA has a publication presenting methods for assessing aquifer vulnerability to surface contamination at http://www.epa.gov/cgi-bin/claritgw?op-Display&document=clserv:OW:0182;&rank=4&template=epa

Time of travel for contaminants.

Time-of-travel studies involve use of dye to document the time of travel of water or water-borne solutes between two points in a stream or aquifer. By sampling over the time that a dye cloud is detected at a sampling point, time of travel and dispersion characteristics of the stream or aquifer can be documented. Although primarily used to document travel time of solutes in streams, these studies have documented groundwater/surface-water interactions for many areas outside Texas. Although a few time-of-travel studies have been conducted in Texas, most document travel for streams rather than the interaction of streams and groundwater.

A manual presenting methods to conduct these studies is presented at http://water.usgs.gov/pubs/twri/twri3-a9/, and a manual presenting methods to analyze water samples for the tracers is presented at http://water.usgs.gov/pubs/twri/twri3-a12/.

USGS has conducted only eight time-of-travel studies for Texas streams. Report references for the studies are presented below. The first four of these reports and the seventh report below are available as digital files.

Stream name and report link or reference

Buffalo Bayou and tributaries: http://pubs.er.usgs.gov/pubs/wri/wri004236
Sabine River: http://pubs.er.usgs.gov/pubs/wri/wri974065
Trinity River from Dallas to Trinidad: http://pubs.er.usgs.gov/pubs/ofr/ofr89614
Upper Sabine River: http://pubs.er.usgs.gov/pubs/ofr/ofr72257
East Fork Trinity River and Elm Fork Trinity River: http://pubs.er.usgs.gov/pubs/ofr/ofr76683
Trinity River: http://pubs.er.usgs.gov/pubs/ofr/ofr75558

Brazos, Leon, and Little Rivers:
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%20115.htm
The report determines the time required for translatory waves to travel through the reach of the Brazos River from Whitney Reservoir to Richmond, and through the Leon, Little, and Brazos Rivers from Belton Reservoir to Bryan.

Ollman, R.O., 1973, Time of travel of solutes, field observations of water quality, and suspended sediment data for stream reaches in the Trinity River basin, Texas, July 31 to August 14, 1972: U.S. Geological Survey Open-File Report.

A limited number of time-of-travel studies have been conducted on aquifers in Texas—mostly for the Edwards aquifer. A summary of such studies done for the Edwards aquifer associated with Barton Springs is online at
http://www.bseacd.org/graphics/Report_Summary_of_Dye_Trace.pdf.

Springflow.

Springs represent surface discharge of groundwater and dominate the base flow of many Texas streams. Therefore, in many areas flow rate and water quality of stream base flows are dependent upon the groundwater that provides spring flow. Much of the water in these aquifers originates from surface recharge in aquifer outcrop areas; thus, springs truly represent the interaction of groundwater and surface water. The locations, flow rates, and water quality of springs are perhaps the best direct indicators of groundwater/surface-water interactions, and trends in the flow and water quality of springs characterize a direct measure of changes in those interactions.

Groundwater withdrawals and changes in land use, along with inundation by reservoirs, have caused many springs to cease flowing or to have reduced flows. Gunnar Brune (1975, report link below) reported that Texas originally had 281 major and historical springs, 63 of which had failed as of 1975. Therefore, groundwater/surface-water interactions have substantially changed in areas proximate to many Texas springs. Brune (1975) also stated that 139 of these springs are in the Edwards aquifer or Edwards-Trinity (Plateau) aquifer. Thus, at least for those aquifers, springs are an important source of the quantity and quality of stream base flows.

Information about springs in Texas is online in the *Handbook of Texas*: http://www.lib.utexas.edu:8080/tsha/search_hoto.jsp?collections=tsha-handbook&queryParser=Simple&queryText=springs&searchButton=Search

In 1975, TWDB published a report on major springs in Texas—it is online at http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%20189.htm. The report, authored by Gunnar Brune, presents detailed information for each of 281 springs, including location, geologic setting, historical background, and discharge.

Subsequent investigations for springs, including ongoing investigations, are identified in Appendix 6 near the end of this report.

The most recent publication documenting Texas springs is USGS CD-ROM Open-File Report 03-315, "Database of Historically Documented Springs and Springflow Measurements in Texas," by Franklin T. Heitmuller and Brian D. Reece—it is available online at http://pubs.er.usgs.gov/pubs/ofr/ofr03315. Information about this report is in Appendix 6.

Water budgets and atmospheric energy budgets.

Budgets of inflow and outflow of water volumes for aquifers or watersheds generally provide direct information and data that can be used to assess groundwater/surface-water relations. Likewise, atmospheric energy budgets document values for evapotranspiration, which can be used in water budgets to assess inflows and outflows often involving interactions between surface water and groundwater.

The homepage for a USGS research program for **Water, Energy, and Biogeochemical budgets** is http://water.usgs.gov/webb/. The program was initiated in 1991 to document processes controlling water, energy, and biogeochemical fluxes over a range of temporal and spatial scales and to understand the interactions of these processes, including the effect of atmospheric and climatic variables.

A report presenting methods to conduct watershed studies for water, energy, and biogeochemical budgets is presented at http://water.usgs.gov/pubs/fs/fs-165-99/

Even though **water budget studies** are important in documenting groundwater/surface-water relations, few such studies could be identified for Texas. Four such studies are identified below:

A water budget to document evapotranspiration was performed for the Edwards aquifer, referenced at:
Woodruff, C.M., Jr., Water budget analysis for the area contributing recharge to the Edwards aquifer, Barton Springs segment: *in* Woodruff, C.M., Jr., and Slade, R.M., Jr., eds., Hydrogeology of the Edwards aquifer–Barton Springs segment: Austin Geological Society Guidebook no. 6, p. 36–42.

A water budget for **Lake Medina** is included in the online report referenced at http://pubs.er.usgs.gov/pubs/wri/wri004148.

A water budget study for the **Lower El Paso Valley** is online at http://pubs.er.usgs.gov/pubs/ofr/ofr73185

A water budget for **Hubbard Creek Reservoir** is referenced as
TWDB, Report 151, Water Budget and Quality of Water Studies of Hubbard Creek Reservoir, Texas, 1963–67.

Lack of **evapotranspiration data** is probably the main reason that few water budget analyses are done. However, the technology to document evaporation and transpiration has dramatically improved over the last few decades, and the data needed for such documentation is becoming readily available. For example, a regional-scale evapotranspiration of Texas from NOAA satellite was reported at: http://twri.tamu.edu/reports/2002/2002-005/2002-005.pdf.

The "Water Use and Evapotranspiration" heading within the section "Statewide Reports Relevant to Groundwater/Surface-water Relations" below presents many Texas reports and investigations that document data for evaporation and transpiration from crops, rangeland, and brush. Also, research is now being conducted that uses atmospheric energy data to document evapotranspiration values.

Variations and Trends in Hydrologic Conditions.

Because of its location in a semiarid region of the United States, Texas frequently experiences short and long durations of drought conditions for local and regional areas. However, Texas also experiences some of the most substantial flood volumes in the nation. Therefore, Texas experiences substantial variations in water-resource conditions. Information on droughts and floods in Texas is presented at
http://onlinepubs.er.usgs.gov/lizardtech/iserv/browse?cat=WSP&item=%2Fwsp_2375.djvu&page=525&cp=0.5%2C0.5&lev=0&wid=750&hei=600&props=img%28Name%2CDescription%29&style=simple%2Fview-dhtml.xsl&bg=ff%2Cff%2Cff&x=32&y=7.

During low-flow conditions, changes probably occur in interactions between groundwater and surface water. For example, other than most stream reaches on the Edwards aquifer, most streams display gains rather than losses in low-flow discharges. However, this characteristic is likely to change as springs fail and groundwater levels decrease during sustained droughts—increases in groundwater withdrawals could have the same effect. During such conditions, waste and permitted discharges into streams could dominate base flow conditions.

Also, many reports have concluded that El Niño Southern Oscillation (ENSO) causes variations in precipitation and hydrologic conditions. However, other than a preliminary analysis produced as part of the project producing this report, other reports documenting the relation of ENSO to hydrologic conditions in Texas could not be identified.

Studies that document recent and current hydrologic conditions in comparison with past conditions would be important in predicting water availability and groundwater/surface-water interactions. Especially beneficial would be a comprehensive Texas study documenting the relation between ENSO and hydrologic conditions.

A comprehensive database of scientific literature pertaining to climate change and worldwide freshwater resources is online at http://www.pacinst.org/biblio/index.php. The National Weather Service operates a homepage for information about ENSO at http://www.ncdc.noaa.gov/oa/climate/elnino/elnino.html. A USGS report documenting streamflow trends in the United States is online at http://water.usgs.gov/pubs/fs/2005/3017/#pdf. Many of the streamflow-gaging stations used in the report are in Texas.

2.5 Texas Reports Relevant to Groundwater/Surface-Water Relations

Many reports presenting statewide scope contain information pertinent to groundwater/surface-water relations. Most of the reports are available on the Internet. Below are subjects for such reports and Web links or references to the reports:

Groundwater

TWDB, Major and minor aquifers of Texas
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%20345.htm

USGS, Groundwater atlas of Oklahoma and Texas
http://capp.water.usgs.gov/gwa/ch_e/index.html

TWDB, Groundwater availability in Texas
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%20238.htm

TWDB, Groundwater recharge in Texas
http://www.twdb.state.tx.us/RWPG/rpgm_rpts/2000483340.pdf

TWDB, Aquifer storage recovery feasibility
http://www.twdb.state.tx.us/RWPG/rpgm_rpts/IndividualReportPages/91483788.asp

TWDB, Geographic areas in Texas suitable for enhanced recharge
http://www.twdb.state.tx.us/RWPG/rpgm_rpts/IndividualReportPages/2001483388.asp

USGS, Texas groundwater quality
http://pubs.er.usgs.gov/pubs/ofr/ofr87754

TWDB, Report 157 Vol. 1, Survey of the Subsurface Saline Water of Texas, V. 1. A Descriptive Inventory of the Principal Saline Aquifer and Their Characteristics, by Core Lab. Inc., October 1972.

TWDB, Report 345, Aquifers in Texas, by John B. Ashworth and Janie Hopkins, November 1995
Discusses lateral extent, composition, water quality, and water-level changes in the nine designated major aquifers and 20 designated minor aquifers. Includes maps of each aquifer, a short list of selected references for each, and schematic cross sections of the major aquifers.

TWDB, Report 098, Compilation of Results of Aquifer Tests in Texas, by B. N. Myers, July 1969
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%2098.htm
Presents in graph form results of approximately 480 aquifer tests. Also includes a section on methods of analyzing aquifer tests and a table of transmissibilities estimated from one drawdown measurement for wells on the Southern High Plains.

Bureau of Economic Geology, The University of Texas at Austin, Report of Investigations 257, Using Airborne Geophysics to Identify Salinization in West Texas, by J. G. Paine, A. R. Dutton, and M. U. Blüm. 69 p., 59 figs., 2 tables, 3 apps., 1999.

Surface Water

TWDB, Geospatial representation of Texas stream channels
http://www.twdb.state.tx.us/RWPG/rpgm_rpts/2002483439.pdf

TWDB, Drainage areas and river miles for Texas streams have been documented in many TWDB reports. A search within the catalog below using "drainage areas" presents many reports with drainage areas and river miles. It is believed that most if not all river miles are done using 1:24,000 scale.
http://www.twdb.state.tx.us/publications/reports/Publications%20Catalog/catalog.pdf. The reports can be found in TWDB Repositories as documented in the "Databases" section of this report.

USGS, Trends in water-quality data in Texas
http://pubs.er.usgs.gov/pubs/wri/wri894178

USGS, Sources of trends in water quality data for selected streams in Texas, 1975–89
http://pubs.er.usgs.gov/pubs/wri/wri944213

TWDB, Suspended sediment yields for Texas streams
http://www.twdb.state.tx.us/RWPG/rpgm_rpts/96483148.pdf

TWDB, Report 306, Suspended-Sediment Load of Texas Streams: Compilation Report, October 1975–September 1982

TWDB, Limited Publication 098, State of Texas Water Quality Assessment, April 1979
Provides information on segments within 23 river basins including a summary of TDWR surface-water monitoring data for each segment.

TWDB, Report 065, Temperature of Texas Streams, by W. H. Goines, November 1967
Presents in tabular form, stream temperature data collected through September 30, 1966.

Water Use and Evapotranspiration

USGS, Water use in Texas
http://water.usgs.gov/watuse/

TWDB, Surveys of irrigation in Texas
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%20347.htm

TWDB, Consumptive use of water by major crops
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/bulletins/Bull.htm/B6019.htm

TWDB, Crop consumptive use and free water evaporation
http://www.twdb.state.tx.us/RWPG/rpgm_rpts/95483137.pdf

TWDB, Water yield improvement from rangeland
http://www.twdb.state.tx.us/RWPG/rpgm_rpts/8483437.pdf

TWRI, Effects of brush management on water yields for four basins
http://twri.tamu.edu/reports_abstract.php?number=TR-207

TWRI, Effects of brush management on water yields for eight basins
http://twri.tamu.edu/reports_abstract.php?number=TR-182

TWDB, Effects of brush management on water yield from rangelands on the Edwards Plateau
http://www.twdb.state.tx.us/RWPG/rpgm_rpts/95483134.pdf

TWDB, Effects of brush control on water management strategy
http://www.twdb.state.tx.us/RWPG/rpgm_rpts/99483312.pdf

TWDB, Texas brush control plan,
http://www.twdb.state.tx.us/RWPG/rpgm_rpts/90483751.pdf

USDA Soil Conservation Service, 1985, Texas Brush Inventory**:** NRCS State Office, Temple, Texas

TWRI, Determination of regional-scale evapotranspiration of Texas from NOAA satellite
http://twri.tamu.edu/reports/2002/2002-005/2002-005.pdf

TWDB, Report 064, Monthly Reservoir Evaporation Rates for Texas, 1940 through 1965, by J. W. Kane, October 1967

Climatology

USGS, A summary report on floods and droughts in Texas
http://floodsafety.com/texas/USGSdemo/PDFs/flooddrought.pdf

USGS, An atlas of depth-duration frequency for precipitation in Texas
http://water.usgs.gov/pubs/sir/2004/5041/

TWDB, Climatic Atlas of Texas
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/LimitedPublications/LP192.pdf.

TWDB, The Climate and Physiography of Texas
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/report53.asp

Miscellaneous

Bureau of Economic Geology, The University of Texas at Austin, Land Resources of Texas, Other Report 0005, 4 figs., 18 tables, 1 map, 4 sheets, scale 1:500,000, 1977.

TWDB, The State Water Plan for Texas
http://www.twdb.state.tx.us/publications/reports/State_Water_Plan/2002/FinalWaterPlan2002.asp

TWDB, Computer program to create Stiff Diagrams for characterization water quality
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/Open-File/Open-File_01-001.asp

2.6 Methods and Models to Document Groundwater/Surface-water Interactions

Concepts, principles, information, and data about the relations between surface water and groundwater are presented online by the U.S. Geological Survey at http://water.usgs.gov/ogw/gwsw.html. The site presents publications, Web sites, and software pertinent to such interactions. A publication presenting mathematical formulas describing groundwater/surface-water interactions is presented at http://www.usace.army.mil/publications/eng-manuals/em1110-2-1421/c-6.pdf.

The USGS also operates a National Research Program concerning “Hydrologic and Chemical Interactions between Surface Water and Ground Water” at http://water.usgs.gov/nrp/jharvey/site/index.html. The program presents reports (http://water.usgs.gov/nrp/jharvey/site/bibcomplete.html) and methods (http://water.usgs.gov/nrp/proj.bib/jharvey.html) to document groundwater/surface-water relations and is testing new field methods (http://water.usgs.gov/nrp/jharvey/site/tnfmmt.html) and models (http://water.usgs.gov/nrp/models.html) to evaluate such relations.

In January 1999, the EPA conducted a **Workshop on Ground-Water/Surface-Water Interactions.** The proceedings from the workshop are presented at http://clu-in.org/download/techdrct/gwsw/gwsw_part1.pdf.
Poster session abstracts from the workshop are at http://www.clu-in.org/download/techdrct/gwsw/gwsw_part2.pdf.
Appendices from the workshop are presented at http://www.clu-in.org/download/techdrct/gwsw/gwsw_part3.pdf.

Proceedings from a conference sponsored by the American Water Resources Association in 2002 titled Ground water/Surface water Interactions can be purchased as indicated at http://www.awra.org/proceedings/paper.html#groundwater.

The abstracts from a conference in 2004 sponsored by the American Institute of Hydrology titled Integrated Water Resources Management is online at http://www.aihydro.org/2004Prgm2.pdf

Methods

An overview of many methods and tools for understanding and documenting interactions between groundwater and surface water is presented online at http://www.agu.org/revgeophys/winter01/winter01.html.

An overview of such methods is given below:
Analytical methods
http://www.agu.org/revgeophys/winter01/node4.html#SECTION00040000000000000000
Numerical methods
http://www.agu.org/revgeophys/winter01/node5.html#SECTION00050000000000000000
Field methods
http://www.agu.org/revgeophys/winter01/node6.html#SECTION00060000000000000000
Chemical methods
http://www.agu.org/revgeophys/winter01/node7.html#SECTION00070000000000000000
Biological indicators http://www.epa.gov/safewater/swp/bioind.pdf

Books presenting **general methods** to assess interactions include the following:

Packman, A.I., and Bencala, K.E. 2000, Modeling methods in the study of surface-subsurface hydrologic interactions, in Streams and Ground Waters, J.B. Jones and P.J. Mulholland (eds.), Academic Press, 45–80.

Medina, M.A., Doneker, R.L., Grosso, N., Johns, D.M., Lung, W., Mohsen, M.F.N., Packman, A.I., and Roberts, P.J. 2004, Surface water-ground water interactions and modeling applications. In Contaminated Ground Water and Sediment: Modeling for Management and Remediation, C.C. Chien, M.A. Medina, Jr., G.F. Pinder, D.D. Reible, B.E. Sleep; and C. Zheng (eds.), CRC Press, 1–62.

Selected **field methods recommended** for use in documenting interactions are presented below.

A report presenting methods to compute the rate and volume of stream depletion by wells is at http://water.usgs.gov/pubs/twri/twri4d1/**.**

Seepage meters have been used to measure groundwater/surface-water exchange as presented at http://sofia.er.usgs.gov/publications/ofr/2004-1369/.

A simple device for **measuring differences in hydraulic head** between groundwater and surface water is at http://pubs.usgs.gov/fs/fs-0077-00/.

Use of **tracer injection** to document interactions is presented at http://pubs.er.usgs.gov/pubs/wri/wri034172.

Use of **temperature profiles** beneath streams to determine rates of vertical groundwater flow and vertical hydraulic conductivity is presented at http://pubs.er.usgs.gov/pubs/wsp/wsp2337.

Groundwater movements and bank storage due to flood stages in surface streams can be documented by using methods presented at http://pubs.er.usgs.gov/pubs/wsp/wsp1536J.

An indicator of interaction using **microscopic particle analysis** is at http://yosemite.epa.gov/water/owrccatalog.nsf/9da204a4b4406ef885256ae0007a79c7/55e72db4e0b0321c85256b06007232f6?OpenDocument&CartID=948-020750.

Application of **surface geophysics** to groundwater investigations is presented at http://water.usgs.gov/pubs/twri/twri2-d1/.

Many reports throughout the nation have **documented groundwater/surface-water interactions**—a few of them are presented below:

http://sofia.usgs.gov/publications/ofr/00-483/
http://water.usgs.gov/pubs/of/2004/1387/.
http://sofia.usgs.gov/publications/ofr/00-168/
http://pubs.er.usgs.gov/pubs/wri/wri984214

Models

Selected models for documenting groundwater/surface-water interactions are identified below:

A list of popular models used to document interactions is online at http://water.usgs.gov/nrp/models.html.

A coupled surface-water and groundwater flow model (MODBRANCH) for simulation of stream-aquifer interaction is documented at http://pubs.er.usgs.gov/pubs/twri/twri06A6.

Documentation of a computer program (Streamlink) to characterize direct-flow connections in a coupled groundwater and surface-water model is presented at http://pubs.er.usgs.gov/pubs/wri/wri934011.

A finite-element model for simulating hydraulic interchange of surface and groundwater is online at http://pubs.er.usgs.gov/pubs/wri/wri864319.

A modification of the finite-difference model for simulation of two-dimensional groundwater flow to include groundwater/surface-water relationships is presented at http://pubs.er.usgs.gov/pubs/wri/wri834251.

2.7 Supplemental Information

Appendix A—USGS Historical Data

Historical daily streamflow data
The primary Web page for these data is http://waterdata.usgs.gov/tx/nwis/sw.
Below is a link to a list of 782 Texas sites for which daily-mean historical streamflow data are available:
http://nwis.waterdata.usgs.gov/tx/nwis/discharge?search_site_no=0&search_site_no_match_type=exact&format=station_list&sort_key=site_no&group_key=NONE&sitefile_output_format=html_table&column_name=agency_cd&column_name=site_no&column_name=station_nm&column_name=lat_va&column_name=long_va&column_name=state_cd&column_name=county_cd&column_name=alt_va&column_name=huc_cd&list_of_search_criteria=search_site_no
If the link doesn't work directly, copy it via mouse click and paste it into the Internet Explorer browser.

Historical periodic groundwater level data
The primary Web page for these data is http://waterdata.usgs.gov/tx/nwis/gw.
Below is a link to an inventory of more than 5,500 Texas wells with periodic water-level data. The inventory is sorted by well number and by county name.
http://nwis.waterdata.usgs.gov/tx/nwis/gwlevels?gw_type_cd=W&format=station_list&sort_key=site_no&group_key=county_cd&sitefile_output_format=html_table&column_name=agency_cd&column_name=site_no&column_name=station_nm&column_name=lat_va&column_name=long_va&column_name=state_cd&column_name=county_cd&column_name=alt_va&column_name=huc_cd&begin_date=&end_date=&date_format=YYYY-MM-DD&rdb_compression=file&list_of_search_criteria=gw_type_cd
If the link doesn't work directly, copy it via mouse click and paste it into the Internet Explorer browser.

Historical periodic stream water quality data
The primary Web page for these data is http://waterdata.usgs.gov/tx/nwis/gw.
Click on: "samples" link; the box next to "site type" link; "submit"; then "surface water" to obtain these data. Below is a link to a list of 781 Texas streamflow sites for which analyses of periodic water-quality data are available. Several options and methods are available for retrieving data by site, site and water-quality parameter group, site and parameter, parameter groups, dates, or by other options.
http://nwis.waterdata.usgs.gov/tx/nwis/qwdata?station_type_cd=Y______&format=station_list&sort_key=site_no&group_key=NONE&sitefile_output_format=html_table&column_name=agency_cd&column_name=site_no&column_name=station_nm&column_name=lat_va&column_name=long_va&column_name=state_cd&column_name=county_cd&column_name=alt_va&column_name=huc_cd&begin_date=&end_date=&inventory_output=0&rdb_inventory_output=file&date_format=YYYY-MM-DD&rdb_compression=file&qw_sample_wide=0&list_of_search_criteria=station_type_cd
If the link doesn't work directly, copy it via mouse click and paste it into the Internet Explorer browser.

Historical daily stream water quality data
Daily values for water-quality data exist for stations with real-time water-quality data. About 45 such stations exist—their real-time data are presented at http://waterdata.usgs.gov/tx/nwis/current?type=quality&group_key=basin_cd. However,

historical data for daily-water-quality values currently are not presented online. By the end of 2005, the USGS is scheduled to present online values for historical daily water-quality data. These data would include dissolved oxygen, pH, water temperature, and specific conductance for about 200 stream sites. Much of the data represent daily-mean values, but some will represent once-daily values for data collected at specific times each day.

The daily values for specific conductance can be used to estimate daily-mean values and daily loads for dissolved solids and other inorganic-chemical constituents. The calculations are based on statistical relations between values for specific conductance and the other constituents, both of which are available as periodic water-quality data. Values for specific conductance are highly correlated with the values for dissolved solids and inorganic constituents. Therefore, daily specific conductance values can be used, along with the statistical relations between values of specific conductance and those for the other constituents, and also daily streamflow discharge data, to estimate daily-mean concentrations and daily loads for dissolved solids and inorganic chemical constituents. Values for daily streamflow and streamflow periodic water quality can be obtained as explained above.

Additionally, the USGS has developed regression equations relating values for specific conductance to those for dissolved solids and other constituents, and used the approach described above to estimate daily and monthly values for dissolved solids and other constituents—those values have been published in the USGS annual data reports titled "Water Resources Data, Texas, 19XX". These annual data reports are online at http://water.usgs.gov/pubs/wdr/#TX since 1998 but are available in hard copy only prior to 1998.

Historical periodic groundwater quality data
The primary Web page for these data is http://waterdata.usgs.gov/tx/nwis/qw.
Click on: "samples" link; the box next to "site type" link; "submit"; then "ground water" to obtain these data. Below is a link to an inventory of about 2,870 wells with analyses of periodic water-quality data. The inventory is sorted by well number within a sort by county name. Several options and methods are available for retrieving data by site, site and parameter group, site and parameter, parameter groups, dates, or via other options.
http://nwis.waterdata.usgs.gov/tx/nwis/qwdata?station_type_cd=   Y_&format=station_list&sort_key=site_no&group_key=county_cd&sitefile_output_format=html_table&column_name=agency_cd&column_name=site_no&column_name=station_nm&column_name=lat_va&column_name=long_va&column_name=state_cd&column_name=county_cd&column_name=alt_va&column_name=huc_cd&begin_date=&end_date=&inventory_output=0&rdb_inventory_output=file&date_format=YYYY-MM-DD&rdb_compression=file&qw_sample_wide=0&list_of_search_criteria=station_type_cd
If the link doesn't work directly, copy it via mouse click and paste it into the Internet Explorer browser.

Appendix B—TCEQ Surface Water Quality Monitoring Data

Information in the database includes surface water quality monitoring (SWQM) data stored in the TCEQ Regulatory Activities and Compliance System (TRACS) database, finished drinking water quality data in the TCEQ's Water Permits and Resource Management databases, CRP databases, volunteer monitoring programs, and/or other quality-assured data. Data used in the assessment must meet clearly defined acceptance and time-line criteria established by the TCEQ (refer to most recent revision of Methodology for Developing the Texas List of Impaired Water Bodies). In addition to SWQM data collected by the TCEQ, the TRACS database contains quality-assured data from other state and federal agencies, river authorities, cities, and other monitoring groups. State agencies include the Texas Department of Health and the Texas Parks and Wildlife Department. Federal agencies include the USGS and the International Boundary and Water Commission. These data are collected using methods consistent with the Surface Water Quality Monitoring Procedures Manual (TCEQ, 1999a). SWQM data are collected at fixed stations during routine monitoring and from many other sites selected for special studies and intensive surveys.

Appendix C—Data and Findings for Streamflow Gain-Loss Studies in Texas

Introduction

As part of the Ground-Water Availability Modeling (GAM) Program currently (2001) being conducted by the Texas Water Development Board (TWDB), data are needed to quantify the interaction of surface water and groundwater for the nine major aquifers (Ashworth and Hopkins, 1995) and most of the 20 minor aquifers in Texas. Where streams flow across aquifer outcrops, channel gains and losses constitute aquifer discharge and recharge, respectively. To make this aquifer discharge and recharge information available for the GAM Program, the U.S. Geological Survey (USGS), in cooperation with the TWDB, compiled data and computed streamflow gains and losses from all available records of gain-loss studies done by the USGS in Texas.

Since 1918, the USGS has conducted streamflow gain-loss studies on streams throughout much of Texas. The usual objective of the gain-loss studies was to obtain data that could be used to estimate discharge from or recharge to shallow aquifers. Most gain-loss studies were done during low-flow conditions because low flows are more likely to be steady (not changing with time) than other flows (except in reaches downstream from major springs or reaches downstream from reservoirs where sustained releases account for most of the flow).

In 1958, the data for all known streamflow gain-loss studies were compiled and published in a report by the Texas Board of Water Engineers (currently the TWDB) and the USGS (Texas Board of Water Engineers, 1960). The data for most of the studies done since 1958 have been published in annual data reports and other reports by the USGS. This study carries the documentation of gain-loss studies a step further: The gains and losses in stream subreaches (channel segments between flow-measuring sites in a reach) were related to major and minor aquifer outcrops in digital and geographic information system (GIS) databases.

Purpose and Scope

The purpose of this report is to summarize the results of 366 gain-loss studies involving 249 unique reaches of streams throughout Texas since 1918. The locations of subreaches for which gains and losses were computed are indicated by streamflow-measurement sites on maps of major and minor aquifer outcrops. The gain-loss studies are tabulated by sequential number, major river basin, stream name, and reach identification, and the total gain or loss for each reach is given. The gains and losses for each subreach are tabulated by sequential number for the gain-loss study and located by latitude and longitude of the upstream end of the subreach. Where applicable, the major or minor aquifer outcrop traversed by a subreach is identified.

Ancillary Benefits

The compilation of streamflow gain-loss data could be beneficial to the Water Uses and Availability Section of the Water Resources Management Division of the Texas Natural Resource Conservation Commission (TNRCC). That section is responsible for permitting surface-water withdrawals in Texas. Most of the recently issued permits represent contingency permits, which authorize surface-water withdrawals only when the streamflow exceeds a threshold rate. The threshold streamflow rate for each contingency permit generally represents the total discharge needed to sustain permitted withdrawals downstream from the withdrawal point for the contingency permit plus any streamflow required as inflow to receiving bays or estuaries. Contingency permits are used to protect the existing water rights of users downstream from newer users.

The TNRCC and others associated with surface-water usage often use USGS current streamflow data available on the World Wide Web to verify existing streamflow conditions pertinent to contingency permits. However, there are only about 350 existing streamflow-gaging stations, and the location of withdrawal points for contingency permits often are many miles from the nearest streamflow-gaging station. Stream-channel gain and loss data can be used, along with the current streamflow rates for gaging stations, to estimate the current streamflow for sites remote from the gaging stations, including sites that represent surface-water withdrawals for contingency permits.

Reservoir owners also could benefit from the compilation of streamflow gain-loss data. Many reservoir owners are required to release sufficient water to sustain the permitted withdrawal rate for downstream water rights. The permitted users are guaranteed a specific withdrawal rate. The gains and losses of channel flow can be used by reservoir owners to help determine reservoir release rates needed to sustain permitted downstream withdrawal rates.

Method of Gain-Loss Studies

The usual method of gain-loss studies is to identify a stream reach and obtain streamflow measurements along the main channel of the reach. The location of each main-channel measurement site is referenced and documented as a distance on the stream channel, usually upstream from its mouth. The channel gain or channel loss can be computed for the subreach between each main-channel measurement site by equating inflows to outflows plus flow gain or loss in the subreach:

$$\mathbf{Qu + Qt + Qr = Qd + Qw + Qe + Qg,} \quad (1)$$

Where

Qu = streamflow in at upstream end of subreach;

Qt = streamflow from tributaries into subreach;

Qr = return flows to subreach;

Qd = streamflow out at downstream end of subreach;

Qw = withdrawals from subreach;

Qe = evapotranspiration from subreach; and

Qg = gain (positive) or loss (negative) in subreach.

Thus,

$$\mathbf{Qg = Qu + Qt + Qr - Qd - Qw - Qe.} \quad (2)$$

For most streams, underflow (flow parallel to stream through shallow channel-bed deposits) and bank storage are considered negligible or minimal.

Many of the studies were done during winter to minimize evapotranspiration. Also, the short length of most subreaches and minimal width of the streams during low-flow conditions would allow only minimal evapotranspiration losses. Therefore, Qe is assumed to be zero in the computations for this report. In each gain-loss study, attempts were made to identify and measure the discharge for all flowing tributaries, return flows, and withdrawals. If these discharges could not be measured, attempts were made to obtain the discharges from other sources such as the TNRCC. However, the USGS cannot verify that all inflow or outflow sources for the reaches were accounted for.

Results

Studies in All Reaches

Three-hundred sixty-six streamflow gain-loss studies in 249 unique reaches were identified and included in this investigation. More than one study has been done at many of the reaches. The locations of streamflow-measurement sites for the studies are shown on plate 1. The studies included about 4,941 measurements, of which 3,238 were made at sites on the main channels of the study reaches; the remaining measurements were made on tributaries to the main channels or represent withdrawals. A tabular summary of the flow-loss studies (table 1) includes for each study the major river basin, stream name, study reach identification, date of study, reach length (in river miles), total number of measurement sites, number of sites on the main channel, major aquifer outcrop(s) intersected by the reach, total streamflow gain or loss in the reach, streamflow gain or loss per mile of reach length, and reference for the data. The reaches for many studies are identified in table 1 by eight-digit numbers for streamflow-gaging stations. Station numbers and associated station names for Texas streamflow-gaging stations with daily streamflow data are listed in table 2.

Table 3 presents selected streamflow characteristics for all streamflow-gaging stations with computer-stored discharge measurements and daily mean streamflows in Texas (346 sites). These data include the station number and name, latitude and longitude, contributing drainage area, and the following data pertinent to median flow conditions: the streamflow, gage height, stream width, stream cross-sectional area, mean velocity, and mean stream depth. Also presented is the elevation of the datum of the gage, which can be added to the gage height to obtain the water-surface elevation above sea level for the median streamflow. The streamflow at the gaging station during a gain-loss study can be compared with the median streamflow to assess the flow conditions during the study.

Equation 2 was used to compute the streamflow gain or loss for each subreach. The data and information for the gains or losses in each of 2,872 subreaches (table 4) include the latitude and longitude at the upstream end of the subreach, the underlying major or minor aquifer outcrop, the streamflow gain or loss, the stream subreach length, the location (river mile) of the upstream end of the subreach, and a descriptive location for selected upstream ends.

Appendix D—Selected References for Streamflow Gain-Loss Studies in Texas

Ashworth, J.B., and Hopkins, Janie, 1995, Major and minor aquifers of Texas: Texas Water Development Board Report 345, 69 p.

Baker, E.T., Jr., Slade, R.M., Jr., Dorsey, M.E., and Ruiz, L.M., 1986, Geohydrology of the Edwards aquifer in the Austin area, Texas: Texas Water Development Board Report 293, 216 p.

Land, L.F., Boning, C.W., Harmsen, Lynn, and Reeves, R.D., 1983, Streamflow losses along the Balcones fault zone, Nueces River Basin, Texas: U.S. Geological Survey Water-Resources Investigations Report 83–4168, 72 p.

Slade, R.M., Jr., Gaylord, J.L., Dorsey, M.E., Mitchell, R.N., and Gordon, J.D., 1982, Hydrologic data for urban studies in the Austin, Texas, metropolitan area, 1980: U.S. Geological Survey Open-File Report 82–506, 264 p.

Texas Board of Water Engineers, 1960, Channel gain and loss investigations, Texas streams, 1918–1958: Texas Board of Water Engineers Bulletin 5807–D, 270 p.

U.S. Geological Survey, 1963–65, Surface water records of Texas 1962–64: U.S. Geological Survey [variously paginated].

______1966–70, 1972, 1975, Water resources data for Texas, water years 1965–69, 1971, 1974—Part 1. Surface water records: U.S. Geological Survey [variously paginated].

______1976–77, 1981–82a, 1986, Water resources data for Texas, water years 1975–76, 1980–81, 1985—Volume 3. Colorado River Basin, Lavaca River Basin, Guadalupe River Basin, Nueces River Basin, Rio Grande Basin, and intervening coastal basins: U.S. Geological Survey Water-Data Reports TX–75–3, 510 p.; TX–76–3, 557 p.; TX–80–3, 583 p.; TX–81–3, 599 p.; TX–85–3, 447 p.

______1980, Water resources data for Texas, water year 1979—Volume 2. San Jacinto River Basin, Brazos River Basin, San Bernard River Basin, and intervening coastal basins: U.S. Geological Survey Water-Data Report TX–79–2, 511 p.

______1982b, Water resources data for Texas, water year 1981—Volume 1. Arkansas River Basin, Red River Basin, Sabine River Basin, Neches River Basin, Trinity River Basin, and intervening coastal basins: U.S. Geological Survey Water-Data Report TX–81–1, 597 p.

Appendix E—Reports Presenting the Reconnaissance of the Chemical Quality of River Basins
(basins in alphabetical order)

TWDB, Report 086, Reconnaissance of the Chemical Quality of Surface Waters of the Canadian River Basin, Texas, by H. L. Kunze, J. N. Lee, December 1968.

TWDB, Report 130, Reconnaissance of the Chemical Quality of the Coastal Basins of Texas by J. F. Blakey, H. L. Kunze, June 1971.

TWDB, Report 071, Reconnaissance of the Chemical Quality of the Colorado River Basin, Texas, by D. K. Leifeste, M. W. Lansford, March 1968.
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%2071.htm

TWDB, Report 088, Reconnaissance of the Chemical Quality of Surface Waters of the Guadalupe River Basin, Texas, by Jack Rawson, December 1968.

TWDB, Report 092, Reconnaissance of the Chemical Quality of Surface Waters of the Lavaca River Basin, Texas, by H. L. Kunze, 1969.

TWDB, Report 005, Reconnaissance of the Chemical Quality of Surface Waters of the Neches River Basin, Texas, by L. S. Hughes, D. K. Leifeste, November 1965.

TWDB, Report 134, Reconnaissance of the Chemical Quality of Surface Waters of the Nueces River Basin, Texas, by H. L. Kunze, September 1971.

TWDB, Report 129, Reconnaissance of the Chemical Quality of Surface Waters of the Red River Basin, Texas, by D. K. Leifeste, J. F. Blakey, L. S. Hughes, May 1971.

TWDB, Report 180, Reconnaissance of the Chemical Quality of Surface Waters of the Rio Grande Basin, Texas, by H. B. Mendieta, March 1974.

TWDB, Bulletin 6405, Reconnaissance of the Chemical Quality of Surface Waters of the Sabine River Basin, Texas and Louisiana, by L. S. Hughes, D. K. Leifeste, May 1964.

TWDB, Report 093, Reconnaissance of the Chemical Quality of Surface Waters of the San Antonio River Basin, Texas, by Jack Rawson, April 1969.

TWDB, Report 013, Reconnaissance of the Chemical Quality of Surface Waters of the San Jacinto River Basin, Texas, by L.S. Hughes, J. Rawson, January 1966.

TWDB Report 087, Reconnaissance of the Chemical Quality of Surface Waters of the Sulphur River and Cypress Creek Basins, Texas, by D. K. Leifeste, December 1968.

TWDB Report 067, Reconnaissance of the Chemical Quality of Surface Waters of the Trinity River Basin, Texas by D. K. Leifeste, L. S. Hughes, December 1967.
http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWReports/Individual%20Report%20htm%20files/Report%2067.htm

Appendix F—Investigations of Springflow Resources in Texas

In 1981, Mr. Brune also published a **book titled "Springs of Texas,** Volume I" (Brune, Gunnar. 1981. Springs of Texas, Volume I. Branch-Smith, Inc., Fort Worth, Texas). This unique book not only describes springs' geology and hydrology in 183 of Texas' 254 counties, it also describes the flora and fauna found around the springs. Where possible, Mr. Brune included historical water-flow and water-quality measurements. Mr. Brune's interest in history and archaeology are represented in this document as well. He describes the use of individual springs in reference to their role in Texas' prehistorical (pre-European) and historical settlement.

Unfortunately, Mr. Brune's self-published book languished after his death in 1995. Texas A&M Press, along with editor Helen Besse (Ecological Recovery Foundation) reprinted this Texana classic in 2002. For that publication, Ms. Besse provided a new introduction that updates the introductory sections of the older printing. The quality of spring waters, the prehistorical setting of springs, and the decline of springs, are examples of new material in the updated version. Particular attention was paid to Texas water law and the vanishing species that inhabit spring waters, as these areas have changed considerably since Mr. Brune originally compiled his book in the 1970s. The new edition of "Springs of Texas, Volume I" is available from Texas A&M Press (www.tamu.edu/press) or from Ecological Recovery Foundation.

Because 71 counties are lacking in the original "Springs of Texas, Volume I" book, TAMU Press has asked Helen Besse (along with Ecological Recovery Foundation) to complete this important research. They will publish "Gunnar Brune's Springs of Texas, Volume II" when the research can be completed and compiled. At this writing, Ms. Besse has found more than 1,500 springs in the 71-county area (mostly within the central portions of the state). She has completed field studies in several western counties. Because of the role of springs in keeping Texas' rivers flowing and the importance of springs (and their ensuing creeks) in maintaining quality habitat for wildlife and plant species, several state agencies are now committed to springs research. The Texas Water Development Board (through funding from the U.S. Corps of Engineers) has allocated funding for springs research. The Texas Parks and Wildlife Department is currently studying springs in some portions of the Texas Hill Country, and Regional Water Planning Groups must identify significant springs within their planning regions, as required by the state.

Independent from Ms Besse's work, an **ongoing USGS project** began several years ago with funded support from the TWDB, has identified springs throughout Texas. Upcoming work identified with the project include aggregating existing springflow measurements and water-quality data for all known springs, documenting major springs in Texas, and collecting springflow and water-quality data for major springs. In the current phase of this project, the USGS is seeking information from agencies, groups, and individuals about springs in their geographic locales. In their goal of identifying several hundred "significant" springs for future monitoring, the USGS is looking at various parameters to determine a significant spring: importance as habitat, cultural or historical significance, aquifer source, and geographic location, among others.

An initial phase of the USGS work published detailed information about Texas Springs in USGS CD-ROM Open File Report 03-315, “Database of Historically Documented Springs and Springflow Measurements in Texas,” by Franklin T. Heitmuller and Brian D. Reece—it is available online at http://pubs.er.usgs.gov/pubs/ofr/ofr03315

Definitions for codes in the "Texas Springs" HTML file can be found in the Appendix of the file "TWDB Groundwater Data Dictionary" online at
http://www.twdb.state.tx.us/publications/manuals/UM50%20Data%20Dictionary/um50.pdf
The code definitions are presented in the Appendices of the dictionary as follows:

Code in "Texas Springs" file	Appendix name in "TWDB Ground-Water Data Dictionary"
county_cd	B
FIPS_cd	B
aquifer_cd	D
basin_cd	E

Appendix G—TxDOT Driller's Logs at Bridges and Culverts over Water

Driller's logs exist for almost all federal and state system bridges in Texas. The logs generally present lithologic descriptions of streambed material. Some logs of older bridges may be incomplete. Very little data may exist for bridges owned by cities and counties. Throughout most of the state, the logs extend to bedrock—in parts of East Texas the logs may extend down to a material suitable to support the bridge, but even in these cases the logs are deep.

Driller's logs at bridges and culverts can be requested from the appropriate TxDOT District Office. A map of TxDOT districts is available at http://www.dot.state.tx.us/localinfo/localinfo.htm. The counties in each district are identified. The site will also allow a district associated with a county of interest to be identified.

Clicking on a district depicted on the map also will provide contact information for that district. Each district generally has its own operating procedures. However, the likely person to contact would be the District Bridge Engineer—there is no public listing for this position; thus, each engineer would have to be identified on a district-by-district basis.

Appendix 3

Task 2: Evaluate Potential Impacts of Groundwater-Surface Water Interactions on Water Quality

Sections

3.1 Previous Regional Studies

Bridget Scanlon (Bureau of Economic Geology, Univ. of Texas at Austin)

Regional studies have previously been conducted comparing groundwater and surface water quality (Paine et al., 1994; Slade and Buszka, 1994; Paine et al., 1999; Paine, 2003). Detailed ground-based electromagnetic surveys along the Canadian River documented groundwater discharge of high salinity water in certain reaches. Conductivity values up to 300 mS/m were measured along certain sections of the river. The high salinity sections were attributed to groundwater dissolution of halite from Permian San Andres Formation and Artesia Group through open bedrock joints either directly beneath the Canadian River or indirectly beneath tributary valleys and subsequently flowing into the river (Paine et al., 1994). Slade and Buszka (1994) conducted regional studies of groundwater and streams to assess sources of salinity in the Upper Colorado River. The Colorado River is gaining in this region, i.e. groundwater discharges to surface water in this region. Large increases in salinity along the Colorado River were related to tributary inflow from Beals Creek and also from Natural Dam Slat Lake. Sources of salinity include:

1. Dissolution of sulfur bearing minerals (gypsum and pyrite) in shallow aquifers
2. Mixing with brine associated with oil and gas production (upward brine movement along abandoned oil and gas boreholes, leakage from brine pits, disposal wells, and secondary recovery wells)

Salinity studies in the drainage basin of the Red River identified oil field activity as the cause of the high salinity plume (Paine, 2003). Airborne and ground-based EM surveys were conducted to delineate the plume and to determine the mass of chloride within the saline water plume.

The above studies focused on salinity contamination of surface water. Studies of arsenic in the Gulf Coast indicated that high arsenic concentrations in the stream and in Lake Corpus Christi could be attributed to high arsenic concentrations in groundwater, rather than from surface uranium pits (Brandenberger et al., 2004).

3.2 Reconnaissance Analysis of the Impact of Groundwater-Surface Water Interactions on Water Quality

Venkatesh Merwade (Center for Research in Water Resources, Univ. of Texas at Austin)
Robert Reedy (Bureau of Economic Geology, Univ. of Texas at Austin)

Introduction

The objective of this study is to assess the relationship between groundwater and surface-water quality by establishing spatial connectivity between USGS gauging stations and Texas Water Development Board's (TWDB) wells. The surface-water-quality data are available from the USGS NWIS Website (http://waterdata.usgs.gov/tx/nwis/qw) for 781 stations in Texas. The time period represented by the data varies from 1901 to 2004. Most stations, however, have data only after 1960. The surface-water-quality data are available for both high and low flows, with data collection frequency varying from station to station. The number of samples collected at these stations ranges from 1 to 1,610 samples for the entire period of record. Parameters monitored at these stations include biological, nutrients, organics, inorganics, physical properties, radiochemical, sediment, flow, and stage.

Data on groundwater quality are available from the TWDB Website (http://www.twdb.state.tx.us/DATA/waterwell/well_info.asp). The TWDB groundwater database contains information on well location (latitude and longitude), land-surface elevation, well depth, water level, and water-quality constituents (major and minor ions). There are about 129,817 wells in the TWDB database and 104,231 water-quality records. Although the number of wells is much higher than the number of stream gauges, the data on groundwater quality are relatively sparse compared with stream-water quality. To establish connectivity and compare water quality between groundwater and surface water, it is necessary to reduce the number of wells and stream gauges to some reasonable number (< 1,000 wells and associated gauging stations). To accomplish this objective:

1. Only wells adjacent to streams are assumed to be hydraulically connected to stream gauges for comparing water quality. All wells that lie within a buffer of 1 km adjacent to all major, perennial streams and water bodies were evaluated and others discarded, thus reducing the number of wells from 129,817 to 42,026.
2. Hydraulic gradient (difference in water surface levels divided by the distance) was calculated between wells and streams. All wells without water levels were discarded. Water levels in

streams were assumed to be equal to land-surface elevation (extracted from DEM). Hydraulic gradient from wells to streams was also calculated. A positive hydraulic gradient indicates water flowing from a well to a stream and vice versa. It is assumed that all wells having a hydraulic gradient of >5 percent are more likely to be hydraulically connected. Therefore, all wells with a hydraulic gradient >5 percent were discarded, thus reducing the number of wells to 4,400.

3. Water quality in shallow groundwater wells (well depth <30 m) was assumed to be more closely related to water quality in adjacent streams than that of deeper wells. All wells deeper than 30 m were discarded, thus reducing the number of wells to 2500.
4. Finally, wells that lie within an alluvial aquifer and alluvium are more likely to have interaction with the adjacent streams than wells in confined aquifers. Therefore, wells that lie within an alluvial aquifer and alluvium were selected and others discarded, thus reducing the number of wells to 315.

After the number of groundwater wells was reduced to a manageable number, the next step was to establish spatial connectivity of these wells with corresponding USGS stream gauges. The spatial connectivity was established in GIS by using the streams, USGS gauging stations, and TWDB wells. Figure 1 shows a map of selected wells, major perennial streams, and all USGS gauging stations in Texas. The streams were extracted from 1:100000 National Hydrography Dataset (NHDFlowline).

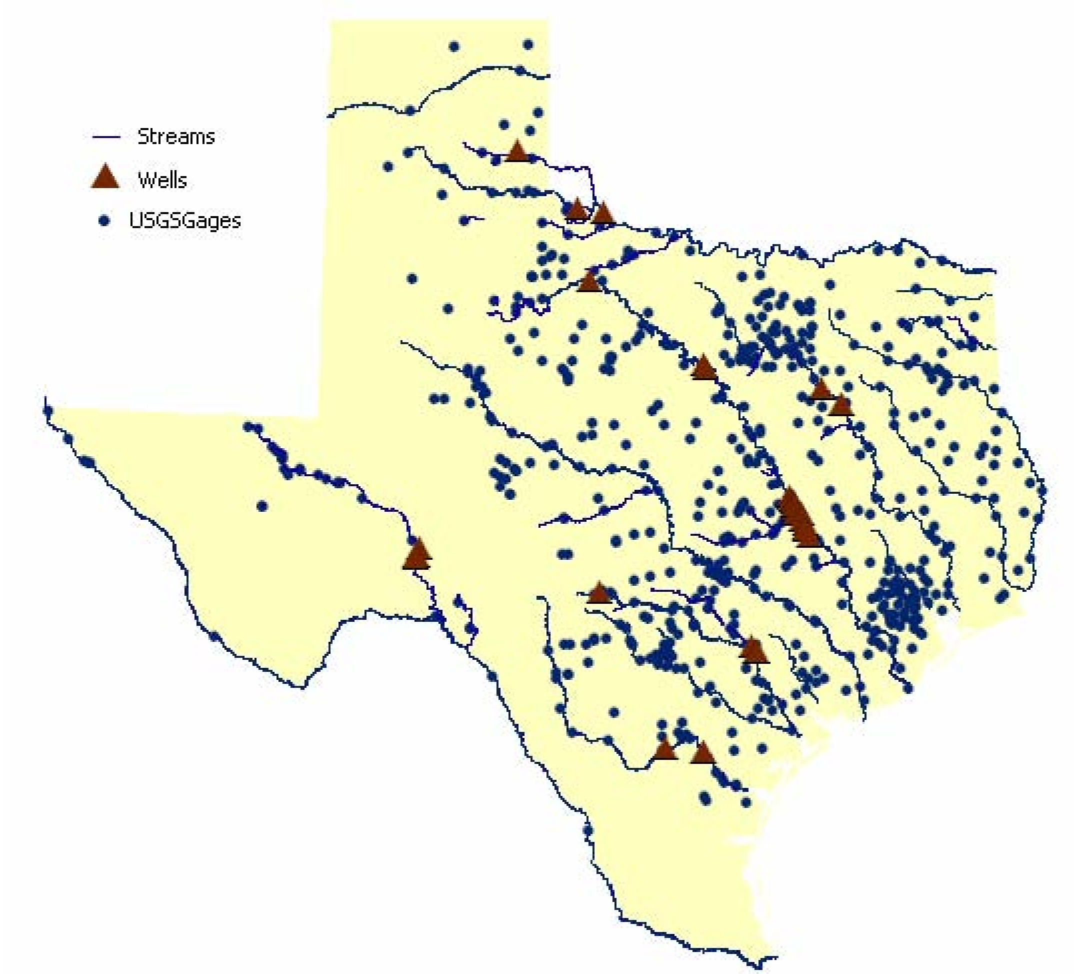


Figure 1. Map of USGS gauges and TWDB wells (after pre-processing) in Texas

Establishing Spatial Connectivity between Wells and USGS Gauges

To establish spatial connectivity, the first step was to remove unwanted USGS gauging stations. All stations not on (or within 1 km from) major streams were removed. Spatial connectivity was established by finding upstream and downstream USGS gauges for all wells. The procedure is described in the following steps:

1. Identify all features by selecting an appropriate attribute. All NHD reaches were identified by river name, USGS gauges were identified by station number, and wells were identified by well identifier.
2. Merge all NHD reaches representing a particular river to form a single polyline.
3. Snap all wells and USGS gauges to the closest stream segments in order to relate all wells and USGS gauges to corresponding river segments by using river names.

4. Assign measures, distance along the river, starting from the upstream end to all river segments. Thus, the most upstream point on a river has a measure of zero, and the most downstream point has a measure equal to the length of the river.
5. Assign measures to all points (USGS gauges and TWDB wells) by using measures assigned to rivers. After this step, each point is associated with the nearest river segment, and the distance from the upstream end is also known.
6. Evaluate each well, and using the name of the river and the measure, find the upstream and downstream USGS gauging station corresponding to each well. Each well has an UpStation and DownStation attribute to store station numbers of upstream and downstream stations, respectively. Remove all wells that do not have USGS gauges associated with them. Similarly remove all USGS gauges that are not associated with any wells.

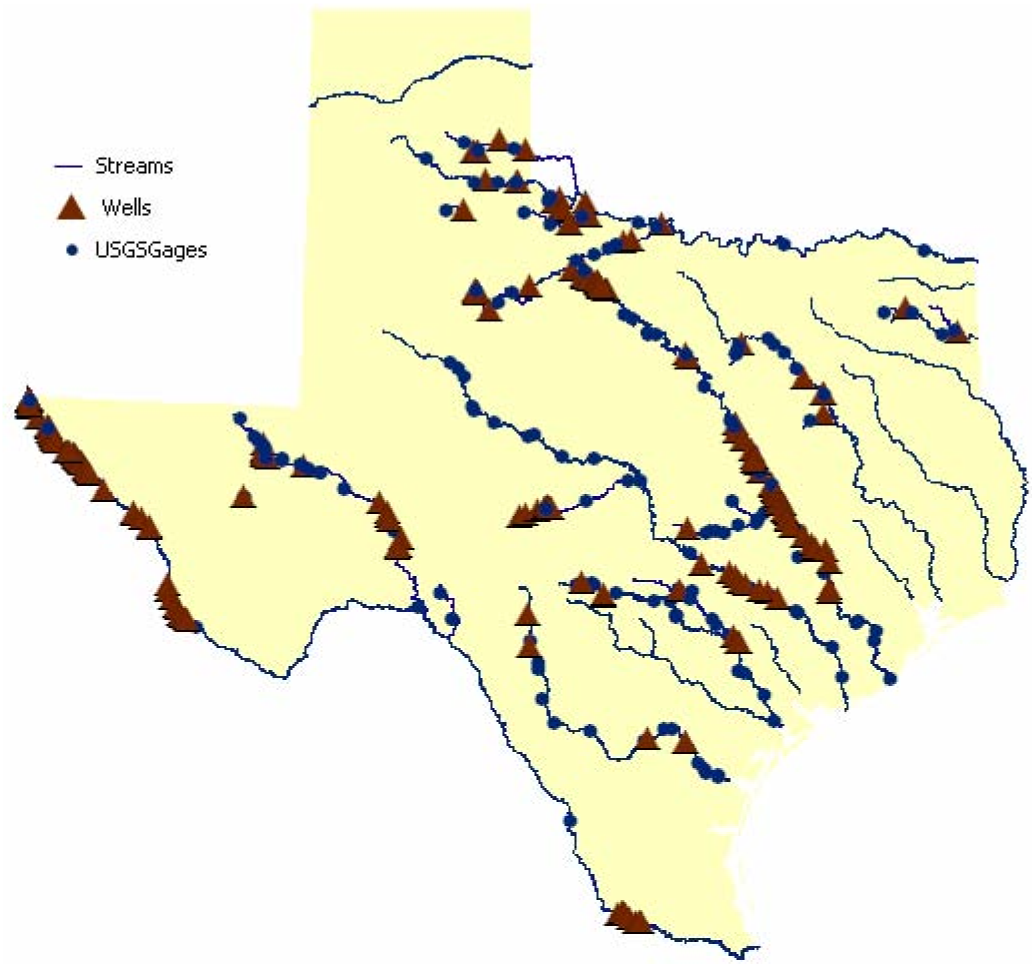
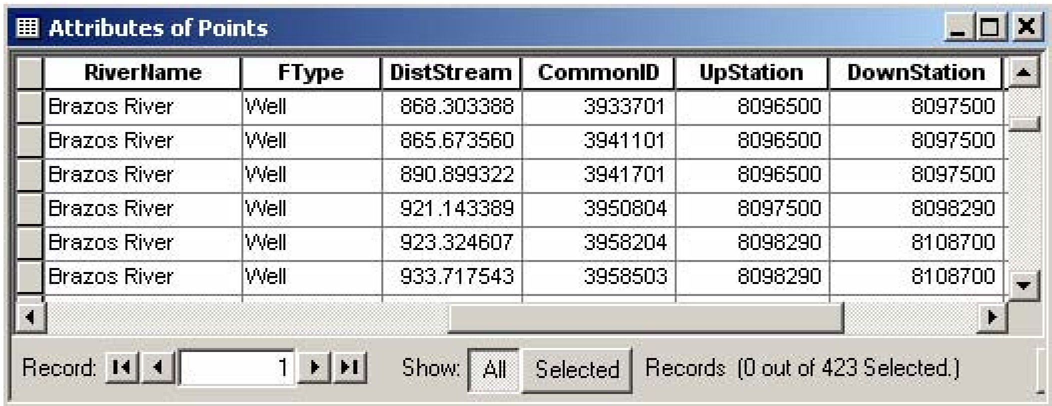


Figure 2. Map of USGS gauges and TWDB wells after snapped to major perennial streams in Texas.



Attributes of Points

RiverName	FType	DistStream	CommonID	UpStation	DownStation
Brazos River	Well	868.303388	3933701	8096500	8097500
Brazos River	Well	865.673560	3941101	8096500	8097500
Brazos River	Well	890.899322	3941701	8096500	8097500
Brazos River	Well	921.143389	3950804	8097500	8098290
Brazos River	Well	923.324607	3958204	8098290	8108700
Brazos River	Well	933.717543	3958503	8098290	8108700

Record: 1 Show: All Selected Records (0 out of 423 Selected.)

Figure 3. Attribute table for wells and stream gauges in Texas.

After spatial connectivity was established, the next step was to use time series of water-quality constituents for both wells and USGS gauges for comparison. The time series data for wells and gauges were extracted from the TWDB database and NWIS Website, respectively. TDS was used as a representative constituent for water quality. The time series data were organized in a table with each record having an identifier (StationID), which is the station number for gauges and the well identifier for wells. StationID in the time series table was used to relate time series records to corresponding points (wells/gauges) in GIS. For 227 wells there are only 411 groundwater quality records. With regard to surface-water quality, only 25 gauges associated with wells have water-quality records. The period of records at all wells is different from the period of records at the associated gauges. Therefore, at all wells the mean TDS was compared with the mean TDS at the associated USGS gage. Figure 4 shows locations of wells where water-quality data for both groundwater and surface water are available, and the results are shown in Table 1.

Figure 5 shows the small number of wells and gauges that meet the criteria for this analysis. The correlation between the total dissolved solids in nearby wells is very low. Because of the sparcity of wells located adjacent to surface water gauges and the minimal amount of water chemistry data available for wells, wells should be installed specifically adjacent to stream gauges to assess interconnectivity between the two systems.

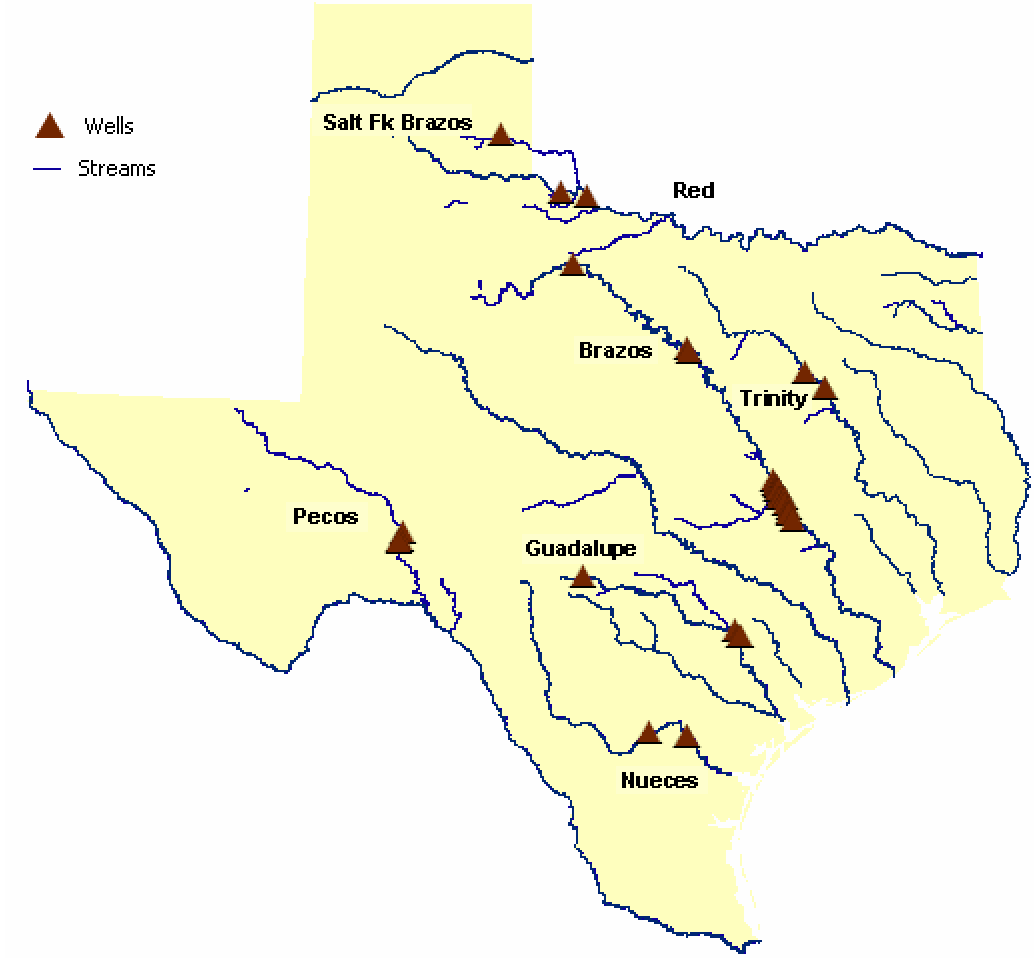


Figure 4. Well locations where water-quality data for groundwater and surface water are available.

Table 1. Summary of reconnaissance on groundwater/surface water quality comparison

Well ID	USGS StationID	Groundwater		Surface water		Number of Samples		Mean TDS	
		From	To	From	To	GW	SW	GW	SW
561908	07300000	10/26/1938	10/26/1938	10/25/1974	12/8/1977	2	36	5143	2608
1336802	07308500	4/9/1941	6/29/1947	10/15/1974	8/26/1994	4	153	501	4668
1347105	07308500	11/6/1970	8/3/1982	10/15/1974	8/26/1994	8	153	4155	4668
2129501	08082500	9/16/1969	9/16/1969	10/26/1974	8/4/1977	1	31	1324	9766
3225301	08091000	2/23/1950	2/23/1950	2/17/1999	8/3/2004	2	21	351	1316
3225603	08091000	6/25/1987	6/25/1987	2/17/1999	8/3/2004	2	21	1079	1316
3346402	08062700	4/30/1968	7/5/1976	5/5/1966	6/28/1994	4	122	368	345
3356703	08062700	9/2/1970	9/2/1970	5/5/1966	6/28/1994	2	122	427	345
3356704	08062700	3/10/1936	3/10/1936	5/5/1966	6/28/1994	2	122	609	345
3958204	08108700	6/21/1963	7/20/1964	9/11/1961	9/30/1965	4	99	1495	534
3958603	08108700	7/17/1963	8/14/1972	9/11/1961	9/30/1965	4	99	1622	534
3958607	08108700	7/17/1963	7/17/1963	9/11/1961	9/30/1965	2	99	1139	534
3958902	08108700	7/25/1963	7/25/1963	9/11/1961	9/30/1965	2	99	1591	534
3958909	08108700	7/12/1963	7/12/1963	9/11/1961	9/30/1965	2	99	1220	534
3958910	08108700	7/12/1963	6/9/1971	9/11/1961	9/30/1965	4	99	1333	534
3959704	08108700	6/7/1972	6/7/1972	9/11/1961	9/30/1965	2	99	550	534
5427602	08447410	3/1/1963	3/1/1963	10/30/1974	8/30/2004	2	231	554	2093
5435101	08447410	3/6/1963	3/6/1963	10/30/1974	8/30/2004	2	231	3295	2093
5435202	08447410	9/14/1960	3/6/1963	10/30/1974	8/30/2004	4	231	461	2093
5662502	08165500	3/6/1963	5/5/1966	7/19/1965	6/4/1997	4	5	548	222
5902601	08108700	7/12/1963	7/12/1963	9/11/1961	9/30/1965	2	99	1362	534
5903110	08108700	8/4/1964	6/7/1972	9/11/1961	9/30/1965	4	99	595	534
5903409	08108700	7/18/1963	7/18/1963	9/11/1961	9/30/1965	2	99	806	534
5903703	08108700	4/26/1961	4/26/1961	9/11/1961	9/30/1965	2	99	834	534
5903801	08108700	5/26/1961	7/22/1980	9/11/1961	9/30/1965	6	99	690	534
5903804	08108700	8/4/1964	8/4/1964	9/11/1961	9/30/1965	2	99	1811	534
5911203	08108700	7/26/1963	7/26/1963	9/11/1961	9/30/1965	2	99	979	534
5911605	08108700	6/19/1963	6/19/1963	9/11/1961	9/30/1965	2	99	680	534
5912721	08108700	7/3/1963	7/3/1963	9/11/1961	9/30/1965	2	99	907	534
5920101	08108700	7/27/1964	4/19/1972	9/11/1961	9/30/1965	4	99	689	534
5920522	08108700	7/17/1963	7/17/1963	9/11/1961	9/30/1965	2	99	704	534
6738403	08175800	12/18/1962	12/18/1962	12/6/1966	12/6/1966	2	1	510	331
6738802	08175800	12/18/1962	12/18/1962	12/6/1966	12/6/1966	2	1	423	331
6738803	08175800	12/18/1962	12/18/1962	12/6/1966	12/6/1966	2	1	428	331
7844602	08194600	5/21/1963	5/21/1963	5/21/1965	9/11/1967	2	12	512	236
7848901	08211000	3/16/1992	3/16/1992	10/1/1959	7/1/1965	2	53	906	313
7848902	08211000	7/16/1997	7/16/1997	10/1/1959	7/1/1965	2	53	864	313

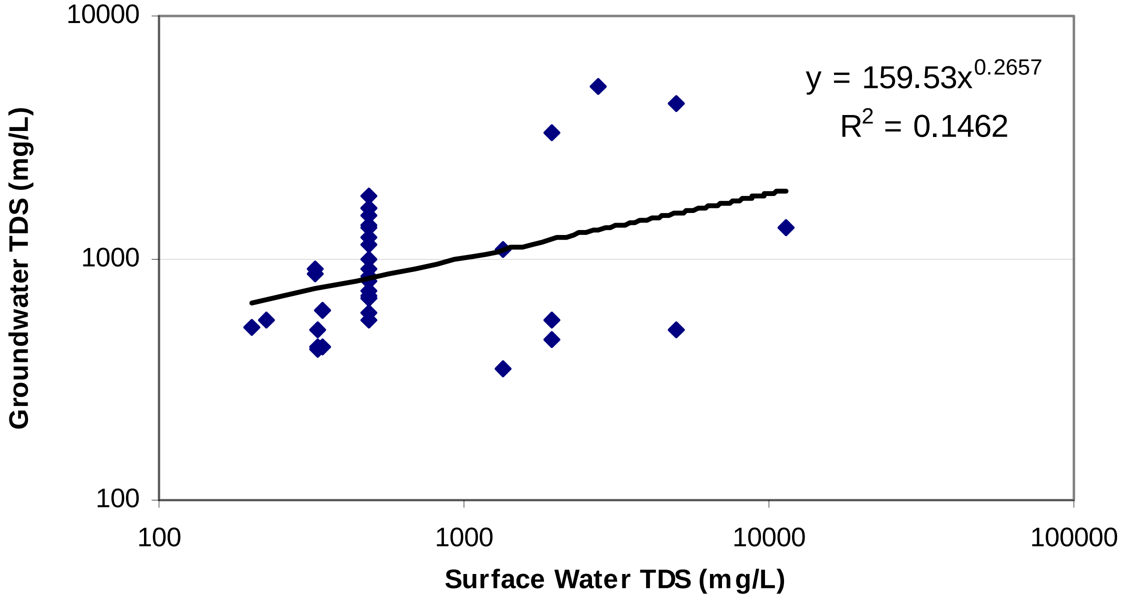


Figure 5. Relationship between log median TDS in wells with log median TDS in surface water.

3.2 Trend Analysis for Selected USGS Gauging Stations in Texas

Venkatesh Merwade (Center for Research in Water Resources, Univ. of Texas at Austin)

Introduction

Continuous (daily) water quality data from the USGS were used to perform water-quality trend analysis at a few selected streamflow-gaging stations in Texas by using double mass-curve analysis (Searcy and Hardison, 1960). In this analysis, a cumulative plot of annual load from a water quality constituent is plotted against the cumulative annual mean flow over a period of time. If the plot (double mass curve) is a straight line with a single slope, there is no change in the water quality over time. A double mass curve plot with bend/bends separating regions with different slops indicates that there are changes in water quality.

The parameter used for studying trends is Total Dissolved Solids (TDS; USGS parameter code = 70300). The daily water quality data measured by the USGS includes streamflow discharge, dissolved oxygen, temperature, pH, and specific conductance. Besides daily values, USGS also has a collection of discrete samples for many water quality constituents including TDS and specific conductance. Since specific conductance is highly correlated with TDS, the discrete samples were used to derive a relationship between specific conductance and TDS. This relationship was then used to estimate daily TDS values.

Selection of Stations for trend analysis

Twelve USGS gaging stations were selected to analyze the trend in water quality at these stations. The stations were selected based on their location and data availability. The selected stations were located on major Texas Rivers (Fig. 1) with at least 20 years of discrete water quality data and at least 200 samples. The list of stations and the inventory (period and number of samples) of available data are presented in Table 1.

Figure 1. Selected stations for studying water quality trends in Texas

The period and number of samples (count) presented in Table 1 represent information for all parameters collectively at a particular station. For example, Count = 1259 at station number 07227500 does not mean that each parameter at this stations has 1259 records starting from 1938 to 2004. It means there are 1259 samples in total for all parameters with measurements recorded from 1938 to 2004.

Table 1: Summary of discrete water quality data for selected stations in Texas

Site Number	Site Name	From	To	Count
07308500	Red River nr Burkburnett, TX	1901	9/7/2004	564
07342500	S Sulphur River nr Cooper, TX	10/1/1959	8/7/2001	702
08030500	Sabine River near Ruliff, TX	10/1/1967	10/11/2000	655
08041000	Neches River at Evadale, TX	10/1/1959	6/10/2004	642
08066500	Trinity River at Romayor, TX	10/1/1959	9/7/2000	804
08082000	Salt Fk Brazos River near Aspermont, TX	10/1/1959	8/15/2001	854
08098290	Brazos River near Highbank, TX	11/8/1967	6/22/2001	450
08123850	Colorado River above Silver, TX	8/30/1967	9/2/2003	471
08162000	Colorado River at Wharton, TX	1/22/1965	4/4/2001	455
08176500	Guadalupe River at Victoria, TX	10/1/1959	7/21/2000	642
08188500	San Antonio River at Goliad, TX	10/1/1959	9/13/1996	874
08475000	Rio Grande near Brownsville, TX	2/15/1966	9/8/2004	344

Data Retrieval and Pre-processing

The discrete water quality data for trend analysis were downloaded from USGS NWIS website (http://waterdata.usgs.gov/nwis/qw) for stations presented in Table 1. The pre-processing of discrete data involved the following two steps:

- Filtering the data for TDS and specific conductance (parameter code = 90095) and discharge (parameter code = 60 or 61).
- Deriving relationships between TDS and specific conductance, and using these relationships to estimate TDS from specific conductance.

The daily specific conductance and discharge values for stations presented in Table 1 were obtained from Hydrodata West 2 region CD (version 3.1) from Hydrosphere Inc. (http://www.hydrosphere.com/HDP/index.htm). The data available on the Hydrodata CD were extracted from the USGS WATSTORE database. The daily data from WATSTORE include daily values for streamflow discharge, dissolved oxygen, temperature, pH, and specific conductance. The pre-processing of data involved filtering out specific conductance and discharge, using the specific conductance versus TDS relationship to get TDS values, and organizing the data in a tabular form with Date, TDS and discharge values.

Specific conductance is highly correlated with TDS and was used to estimate TDS at all stations for the daily dataset. For example, the discrete dataset at Colorado River above Silver (# 08123850) has TDS records from 1974 to 1994, and specific conductance records from 1980 to 2003. The specific conductance and TDS measurements from 1980 to 1994 were used to derive a relationship between the two variables as shown in Figure 2. This relationship was then used to estimate daily values of TDS from 1968 to 1996.

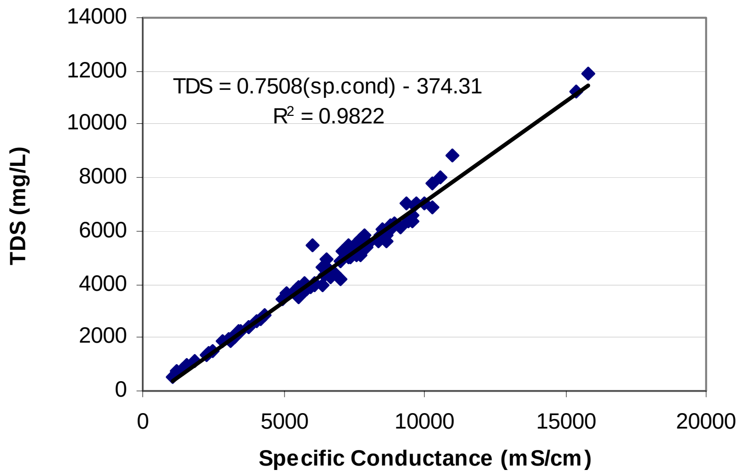


Figure 2. Specific conductance versus TDS for Colorado River above Silver

Double Mass Curve Analysis Using Daily Data

Table 2 gives a summary of data used for daily analysis. The daily data were used to perform double mass curve analysis. A double mass curve is a plot of accumulated values of two time series. In this study the accumulated values of yearly loads from TDS were plotted against the accumulated annual mean flows. Such a plot shows the change in TDS load corresponding to the change in flow. If a double mass plot for the period of analysis is a straight line (or linear), it means the change in water quality is consistent with the change in flow, and the overall water quality is unchanged. However, if the double mass plot is non-linear or show bends, the water quality in the stream has changed with respect to the flow. Double mass curves for all stations presented in Table 2 were constructed, and shown in Figures 3 -14.

Table 2: Summary of daily specific conductance data for selected stations in Texas

Site Number	Site Name	From	To	Mean (S/cm)
07308500	Red River near Burkburnett, TX	1968	1990	3051
07342500	S Sulphur River near Cooper, TX	1959	1989	419
08030500	Sabine River near Ruliff, TX	1946	1995	173
08041000	Neches River at Evadale, TX	1948	1995	174
08066500	Trinity River at Romayor, TX	1941	1994	488
08082000	Salt Fk Brazos River near Aspermont, TX	1957	1982	48332
08098290	Brazos River near Highbank, TX	1980	1995	1278
08123850	Colorado River above Silver, TX	1968	1996	6262
08162000	Colorado River at Wharton, TX	1945	1992	520
08176500	Guadalupe River at Victoria, TX	1946	1981	601
08188500	San Antonio River at Goliad, TX	1960	1994	955
08475000	Rio Grande near Brownsville, TX	1967	1983	1336

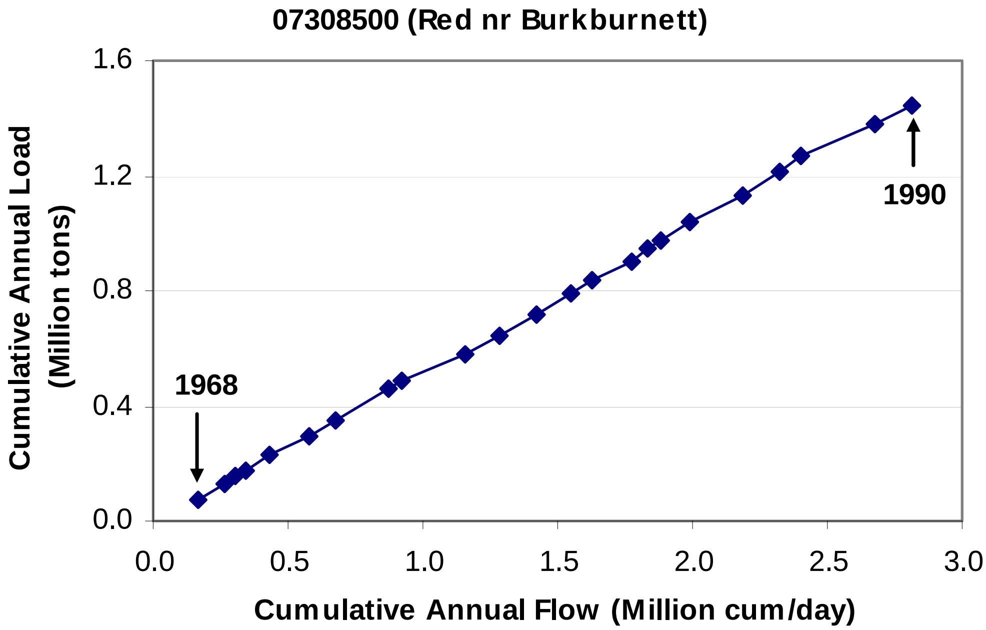


Figure 3. Double mass curve for station 0708500 (Red river near Burnburnett).

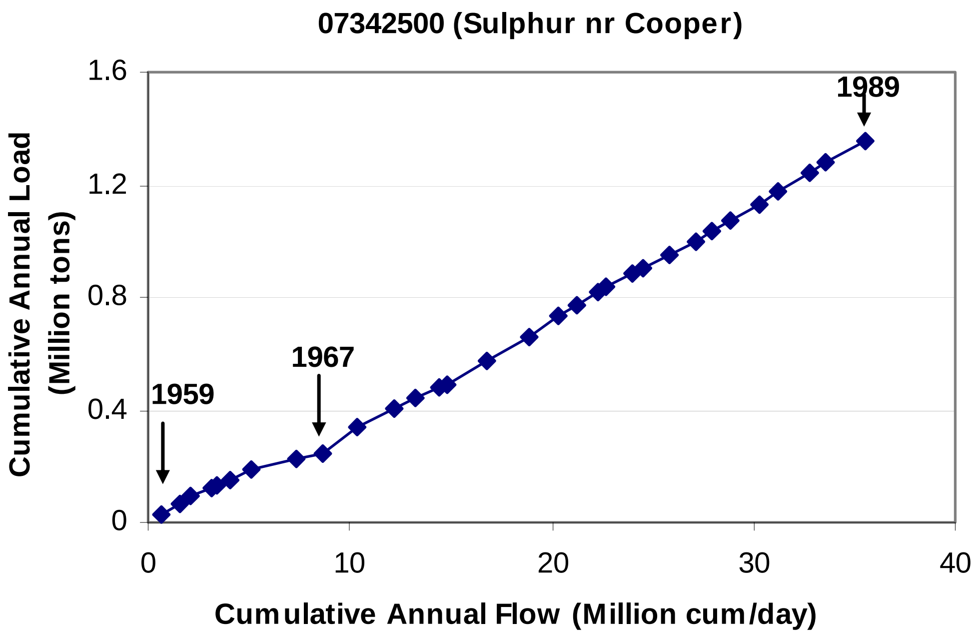


Figure 4. Double mass curve for station 07342500 (Sulphur River near Cooper).

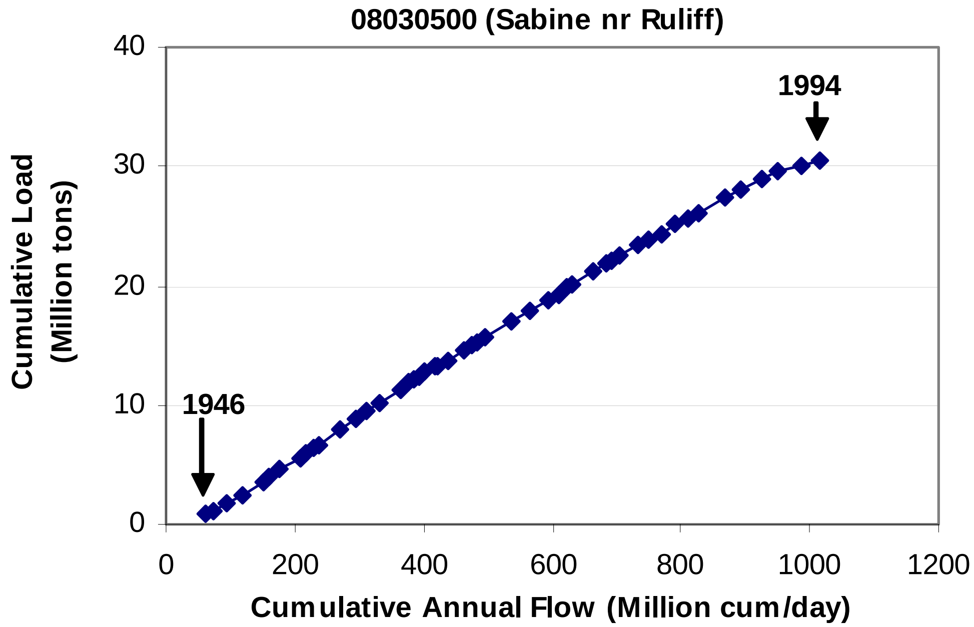


Figure 5. Double mass curve for station 08030500 (Sabine River near Ruliff).

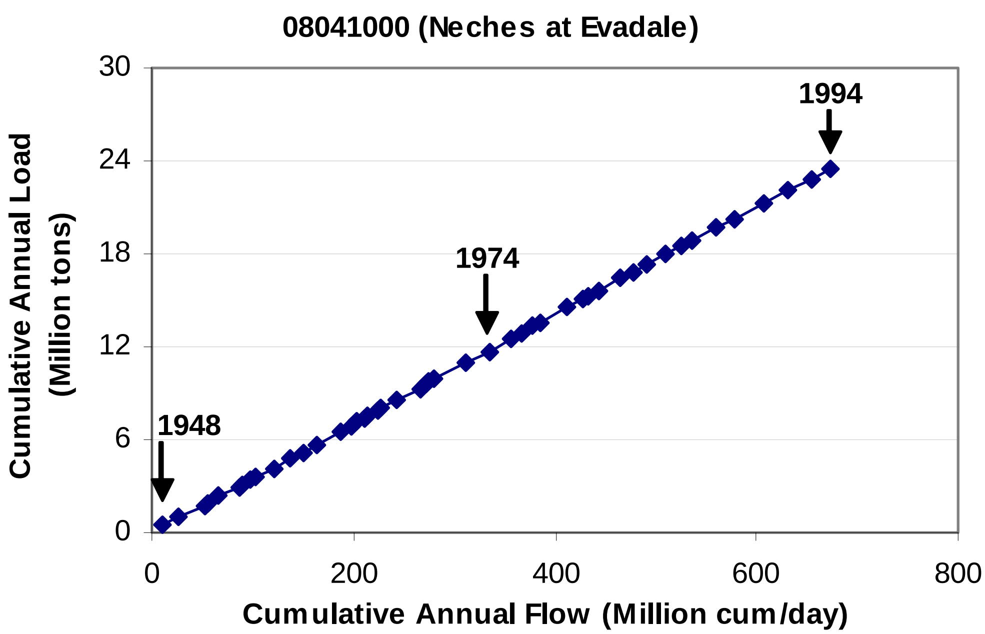


Figure 6. Double mass curve for station 08041000 (Neches River near Evadale).

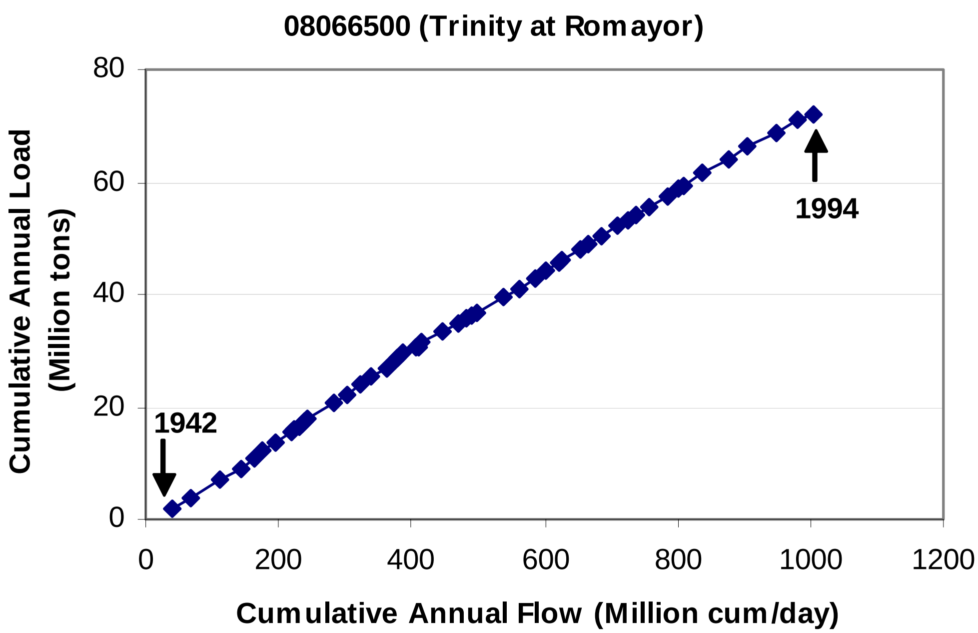


Figure 7. Double mass curve for station 08066500 (Trinity River at Romayor).

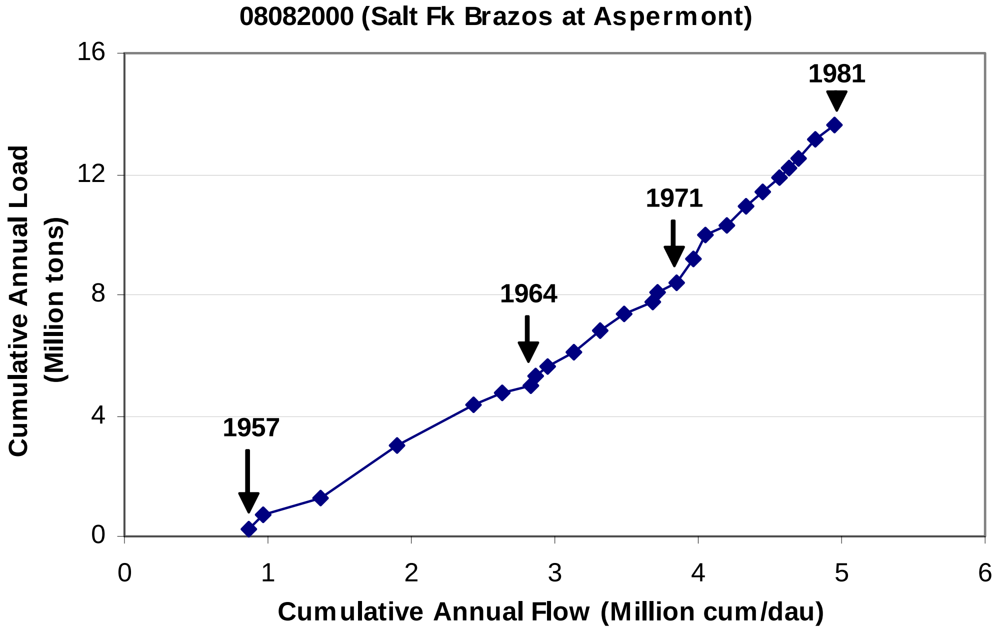


Figure 8. Double mass curve for station 08082000 (Salt Fork Brazos River at Aspermont).

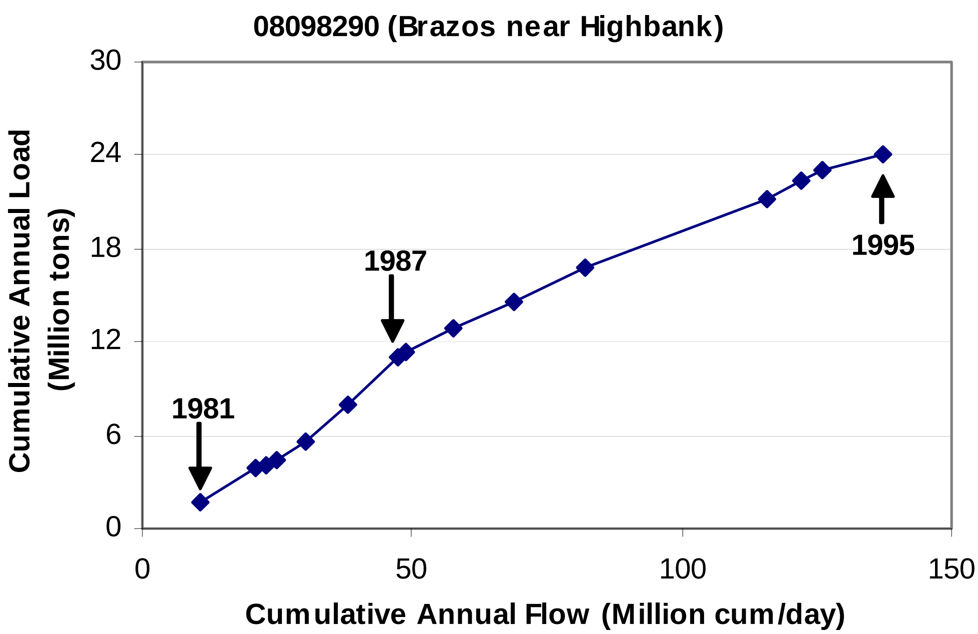


Figure 9. Double mass curve for station 08098290 (Brazos River near Highbank).

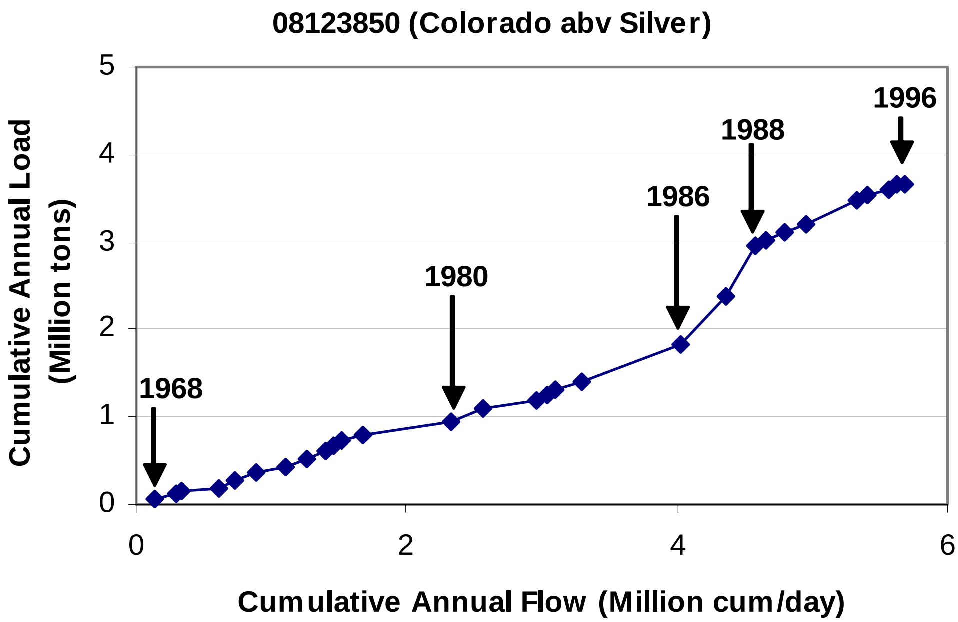


Figure 10. Double mass curve for station 08123850 (Colorado River above Silver).

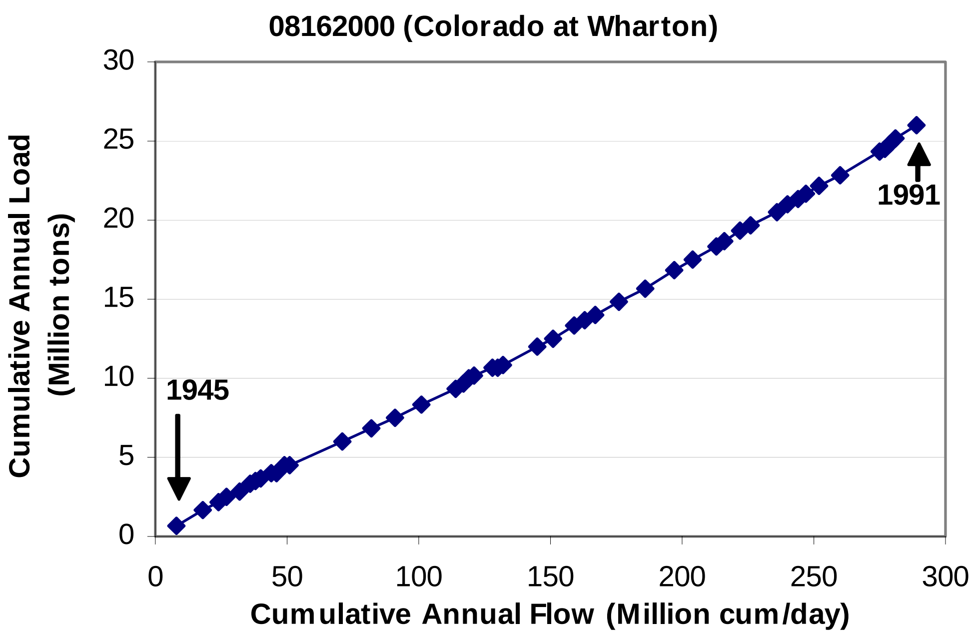


Figure 11. Double mass curve for station 08162000 (Colorado River at Wharton).

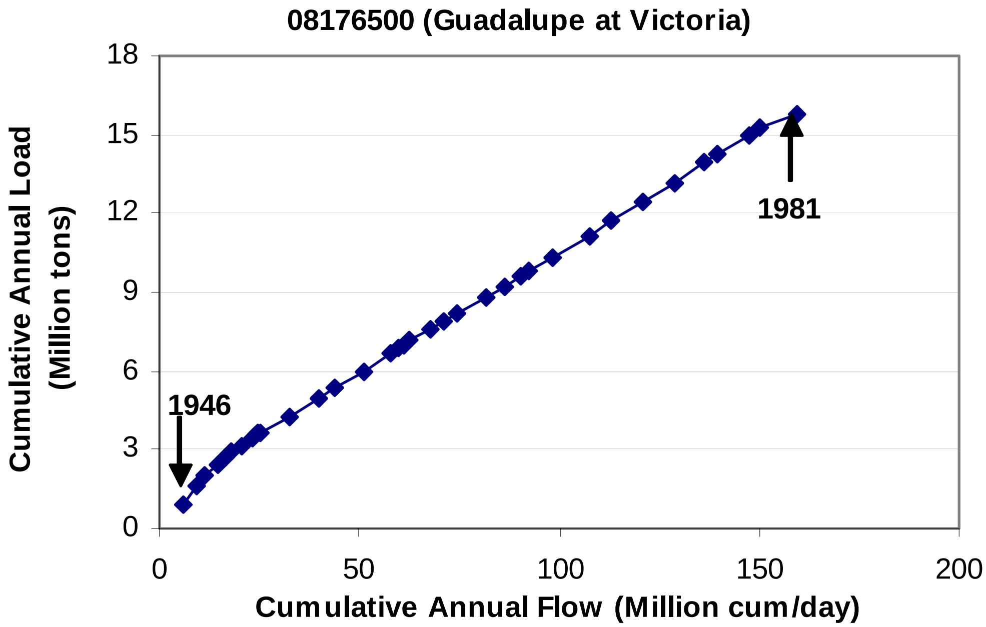


Figure 12. Double mass curve for station 08176500 (Guadalupe River at Victoria).

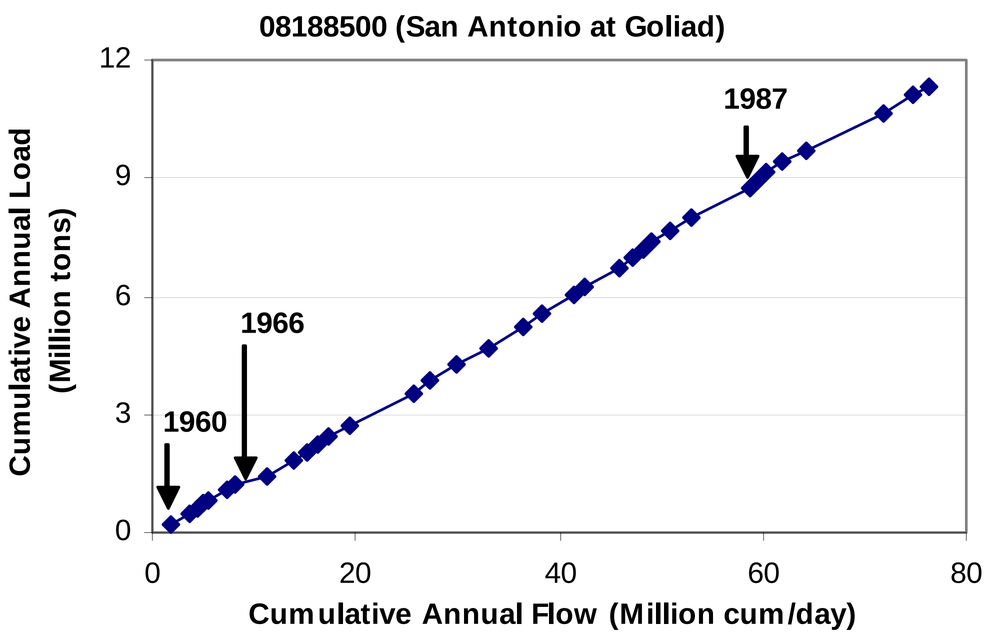


Figure 13. Double mass curve for station 08188500 (San Antonio at Goliad).

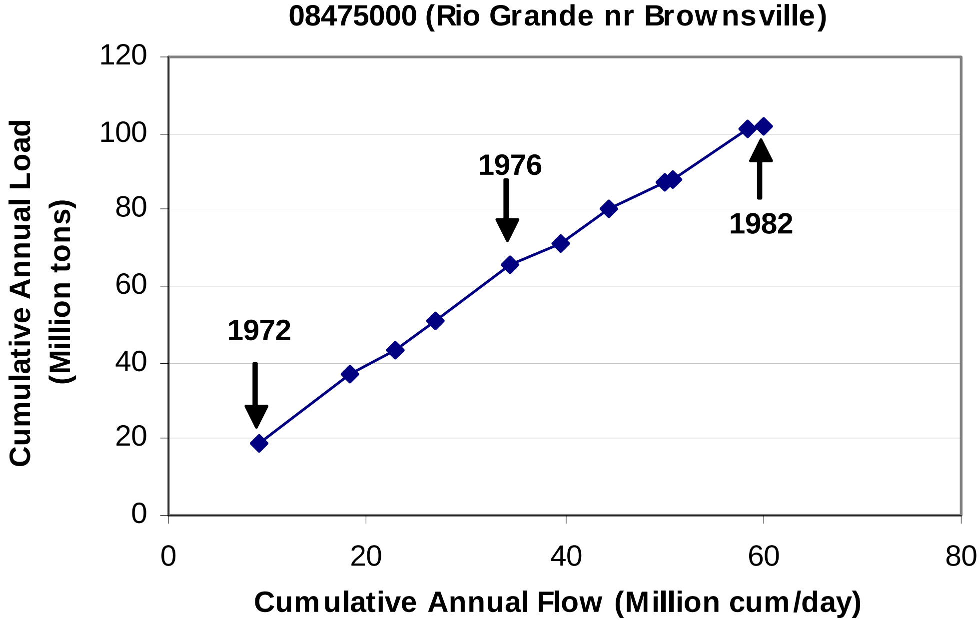


Figure 14. Double mass curve for station 08475000 (Rio Grande River near Brownsville).

The following stations show change in water quality (Figures 3-14):

1. 07342500 – Increase in TDS load from 1967 (A steeper slope indicates an increase in the change in annual TDS load per unit change in flow).
2. 08082000 – Increase in TDS load from 1964.
3. 08098290 – Decrease in TDS load from 1987.
4. 08123850 – Increase in TDS load from 1986-1988. This conclusion is consistent with findings of Slade and Buszka (1994) in the Colorado basin.
5. 08475000 – Slight decrease in load from 1976.

References

Searcy, J. K., and Hardison, C. H., 1960. Double-mass curves, U.S. Geological Survey Water Supply Paper, 1541-B, 27-66.

Slade, R. M., Jr and Buszka, P. M., 1994. Characteristics of streams and aquifers and processes affecting the salinity of water in the upper Colorado River basin, Texas, U.S. Geological Survey Water Resources Investigation Report, 94-4036.

3.3 Impact of Groundwater Discharge on Total Maximum Daily Load (TMDL) Stream Segments: Preliminary Results from Independent TMDL Studies Recently Conducted by the Bureau of Economic Geology

Jeff Paine and Seay Nance (Bureau of Economic Geology, Univ. of Texas at Austin)

Independent field studies were conducted to assess sources of salinity in the Colorado River between Lake Thomas and Ivie Reservoir (Segment 1426) and in Petronila Creek between U.S. 77 and Baffin Bay estuarine complex (segment 2204) (Paine et al., 2005a, b). Contaminants of concern include total dissolved solids (TDS), chloride, and sulfate in both systems. Similar approaches were used to assess salinity sources: airborne electromagnetic (EM) surveys along the stream, supporting ground based EM surveys, and limited surface water chemical sampling and analyses. The following results are excerpted from their reports (Paine et al., 2005a, b).

Results from the Colorado River indicate that the dominant source of salinity is regional, predominantly natural groundwater discharge from saline aquifers, locally modified by near surface salinity sources such as produced water from different oil fields. All segments receive significant natural salinity contributions from local and regional dissolution of Permian sulfate-bearing minerals. Impacts from oil fields range from local, near surface salinisation along the river near tributaries that drain parts of the oil fields to deeper infiltration from past surface discharge or leaking wells and possible lateral migration and discharge at riverbank seeps or into adjacent alluvial sediments.

Results from Petronila Creek indicate that the dominant source of salinity is related to oil fields in the region. Salinity in the creek increased from ~500 mg/L in the upstream area to ~ 9,000 – 14,000 mg/L in the contaminated region. High conductivity zones were related to drainage ditches that carried highly saline water produced from the Driscoll Oil Field before surface discharge was ended in 1987. Near surface salinisation is dominantly caused by past discharge of produced brine into ditches and pits, infiltration into sandy permeability horizons and lateral migration in the shallow subsurface toward the creek. TDS load increased about 20,000 kg/d in the vicinity of the Driscoll segment and ~ 60,000 kg/d in a downstream segment (Concordia). The furthest downstream segment (Luby) represents mixing of a local source from the Luby Oil Field and mixing with estuarine water. Therefore, the dominant salinity source is brine produced by local oil fields (Clara Driscoll, North Clara Driscoll, and Luby) that were discharged into ditches before the Railroad Commission of Texas (RRC) ended that practice in 1987 or into pits before the RRC's no-pit order was implemented in 1969.

3.4 Evaluation of Groundwater-Surface Water Interactions on Selected Total Maximum Daily Load Stream Segments

Andrew Tachovsky (Bureau of Economic Geology, Univ. of Texas at Austin)

Summary

Two impaired river segments were investigated for evidence of impact from groundwater discharge: the Lower Pecos River and the Little Wichita River. This analysis indicates that a significant portion of the long-term flow in the Lower Pecos River is a result of base flow originating over the segment of the Pecos River from Girvin to Langtry (50-70%). Base flow estimates in the Little Wichita River were difficult because of backwater effects at the gage used for the estimates. However, an analysis on the East Fork of the adjacent Little Wichita indicated that base flow was probably not a significant factor for long term flow in the basin (>10%), but may be significant for short term flow events.

Introduction

The objective of this section is to examine two impaired river segments identified by the TCEQ as targets of the Total Maximum Daily Load (TMDL) program for further investigation. The first section is the Lower Pecos River in west Texas, which is impaired with total dissolved solids (TDS), and the second section is the Little Wichita River in north central Texas which is impaired with TDS and low dissolved oxygen (DO). Stream flow, surface water quality, and groundwater quality data were evaluated for each segment to determine the contribution of groundwater to surface water, and how groundwater may affect surface water quality.

Lower Pecos River

The Pecos River originates in New Mexico, and runs to the Rio Grande on the Texas-Mexico border. As one of the goals of this study was to examine quantity of groundwater discharge to the Pecos River, hydrograph separation was conducted using USGS gauges located on the Lower Pecos River (Table 1; Figure 1).

Table 1: USGS Gauges on the Lower Pecos River, TX

Site Number	Site Name	Period of Record	
		From	To
8446500	Pecos River near Girvin	9/1/1939	9/30/2004
8447000	Pecos River near Sheffield	10/1/1921	9/30/1949
8447020	Independence Ck near Sheffield	1/17/1974	9/30/2004
8447410	Pecos River near Langtry	10/1/1975	9/30/1985

This study focused on the Lower Pecos River from the gage near Girvin to the gage near Langtry. In addition, the presence of a gage on Independence Creek near Sheffield provided data to subtract contributions of this tributary, resulting only in base flow in the Pecos River. Examination of the flow records indicates a continuous period of record for all three gauges for the years 1976, 1977, 1981, 1982, 1983, and 1984; a total of 6 years.

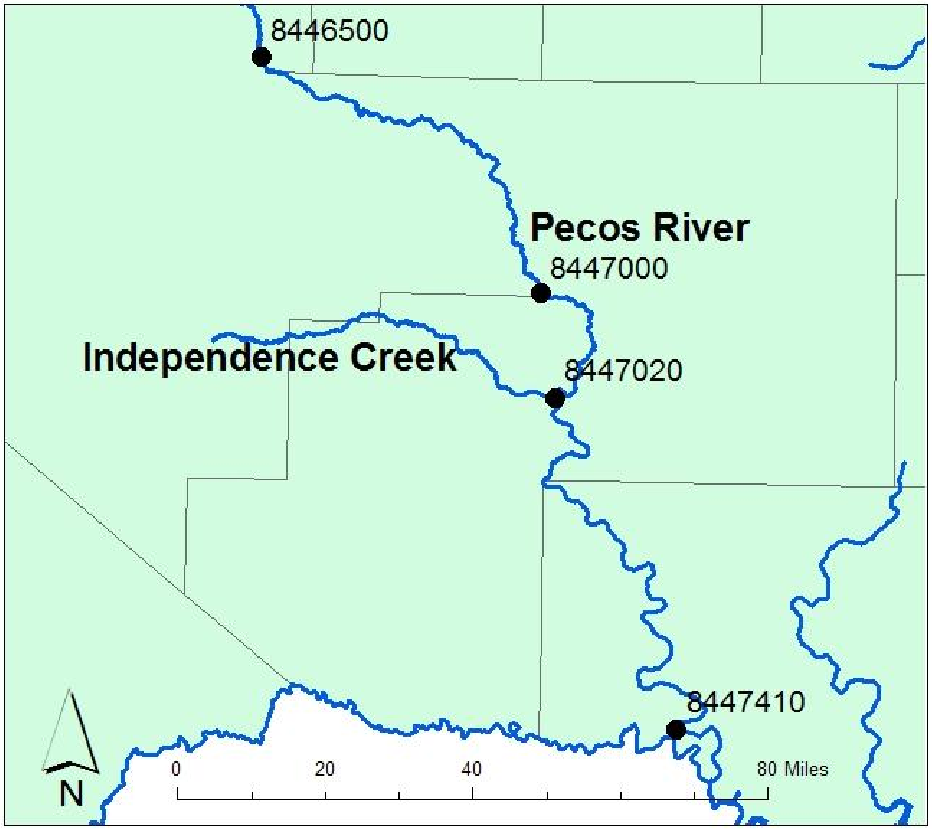


Figure 1: Location of USGS gauges near the Pecos River

The precipitation record was examined for the years of this study. The Lower Pecos River is the dividing line between two climatic divisions: the Edwards Plateau (Region 6) and the Trans Pecos (Region 5) divisions. The total precipitation record extends from 1895 to 2003, and was obtained from NOAA (http://www.cdc.noaa.gov/index.html). Basic data on the years of this study are provided in Table 2 below. From these data it is clear that the two climatic regions are different in terms of quantity, but similar in terms of trend. The years of the study are spread from the 13th to the 91st percentile for region 5, and from the 14th to the 80th percentile for region 6; with each year of the study in the same relative rank. The years of the study cover a wide range of precipitation conditions across the Lower Pecos River.

Table 2: Precipitation data for climate regions 5 and 6

Parameter	Climate Region 5		Climate Region 6	
average precip (in)	12.4		25.4	
median precip (in)	11.7		24.6	
std dev (in)	3.7		6.5	
Study Year	Precip (in)	Percentile	Precip (in)	Percentile
1982	18.0	91.9	30.7	80.2
1976	13.8	68.5	29.8	76.6
1981	13.7	66.7	24.1	47.7
1983	11.2	39.6	20.3	26.1
1984	10.3	27.9	20.2	23.4
1977	9.0	13.5	18.8	14.4

Base flow was estimated using an automated procedure developed by Wahl and Wahl (1995), called Base Flow Index (BFI). BFI is a FORTRAN program that estimates base flow from stream flow records, and calculates the base flow index as the base flow divided by the stream flow, or percent of stream flow that is base flow. Base flow across the stream segment was determined by subtracting estimates at the Girvin and Independence Creek gauges from the Langtry gage for each day of each study year. Quantities of base flow across the segment and stream flow at the Langtry gage were totaled for each study year, and annual BFI was calculated. BFI should be interpreted as quantity of stream flow at the most downstream gage that is base flow from across the segment. Annual BFI is tallied for each study year below in Table 3.

Table 3: Baseflow estimates for Pecos River

Year	Base Flow (acre-ft/yr)	Stream Flow (acre-ft/yr)	**BFI**
1976	1.80E+05	2.82E+05	**0.64**
1977	1.31E+05	1.77E+05	**0.74**
1981	1.72E+05	3.35E+05	**0.51**
1982	1.10E+05	1.51E+05	**0.73**
1983	7.80E+04	1.23E+05	**0.63**
1984	6.58E+04	1.01E+05	**0.65**

Because BFI does not account for return flows such as public water discharges and intakes such as public drinking water intakes, these inputs and outputs must be accounted for when interpreting base flows and BFI. A GIS dataset for return flows was obtained from the TMDL team at TCEQ, and a dataset for public drinking water intakes was obtained from the Drinking Water Protection Program of the TCEQ. There were no surface water intakes located within this segment of the Pecos River, and a total of 13 return flows. Of the thirteen return flows, only two contained significant quantity to trigger reporting. These two flows totaled 1157 acre-ft/yr, approximately 2.4% of base flow in 1984 (lowest base flow year) and approximately 0.8 % of base flow in 1976, (highest base flow year). In addition, these quantified return flows are permitted maximum flows, generally specified with margins of operating safety. Accordingly, actual daily flow is usually well below these permitted maximum flows.

This analysis indicates that a significant portion of the flow in the Pecos River at the Langtry, TX gage is a result of base flow originating over the segment of the Pecos River from Girvin to Langtry. For the study years examined in this investigation, the base flow index is never below 50 percent, and is as high as 74 percent. This represents a major component of total flow in the Pecos River.

Water quality data were also evaluated to assess if the water chemistry in the Pecos River is affected by the water chemistry in groundwater. To conduct this investigation, surface water quality data were obtained from the Texas Clean Rivers Program and the International Boundary and Water Commission, and groundwater quality data were obtained from the Texas Water Development Board Groundwater Database (GWDB). Surface water quality sampling and testing took place at three locations within the study area (Figure 2, large black dots numbered using their Clean Rivers ID). These locations contain surface water quality sampling from 1995 to 2004. The GWDB was plotted and all groundwater wells with water quality data within a 2 km buffer of the Pecos River were extracted. These wells are also depicted in Figure 2 as bright pink dots. Some of these wells were sampled several times at different dates, and the period of record for well sampling events extend to 1939. No quality assurance metrics are provided for the groundwater data. Data from these groundwater and surface water investigations are provided in Table 4. For the groundwater data presented in this table, adjacent rows of identical color (shading) are samples from the same well taken at different times. A change in color in an adjacent row indicates a different well.

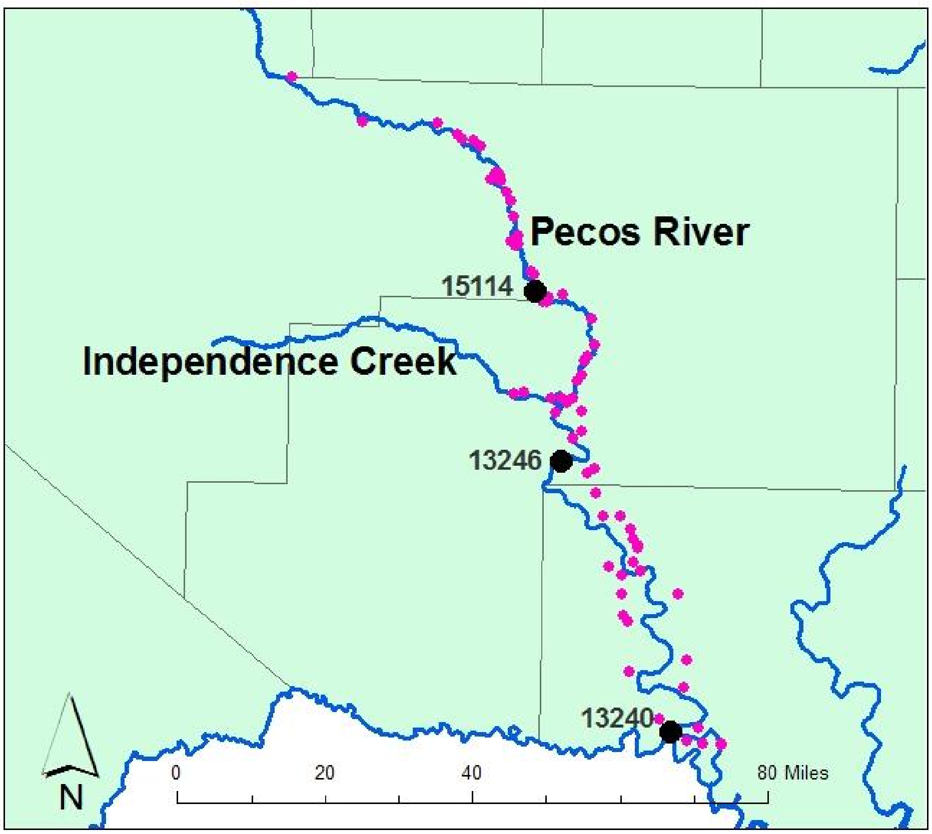


Figure 2: Water quality sampling locations

The water quality data are difficult to interpret. First, the period of record for groundwater samples is earlier than surface water samples, sometimes by decades. Samples taken from the same well at different times are highly variable. While surface water data collected under the Clean Rivers Program generally have been processed under a quality assurance (QA) plan, there are no QA data provided for any of the samples in the GWDB. Even with all of these difficulties, some general trends can be noted. First, the surface water samples generally have higher specific conductance, total dissolved solids, chloride, and sulfate than the groundwater. However, if some of the higher numbers noted in groundwater were coupled with the base flow estimates presented earlier in this discussion, groundwater could be a significant source of salinity to surface water.

Table 4: Comparison of surface water and groundwater quality data

13246: Surface Water: 64 Samples, from Feb. 1995 to Sept. 2002				
Parameter	Specific Conductance (S/cm)	Chloride (mg/L)	Sulfate (mg/L)	Total Dissolved Solids (mg/L)
Average	3201	728	428	2016
Std Dev	967	264	161	818
13240: Groundwater: 3 wells within 1 mile				
Date Collected	Spec. Cond. (S/cm)	Chloride (mg/L)	Sulfate (mg/L)	Dissolved Solids (mg/L)
1/22/1970	557	29	24	
7/21/1939		605	660	2112
5/3/1967	1820	251	226	1106
5/5/1939		45	44	340
13240: Surface Water: 40 Samples, from Feb. 1995 to August 2004				
Parameter	Spec. Cond. (S/cm)	Chloride (mg/L)	Sulfate (mg/L)	Dissolved Solids (mg/L)
Average	5157	1201	724	3266
Std Dev	1494	359	210	1119
13240: Groundwater: 3 wells within 1 mile				
Date	Spec. Cond.	Chloride	Sulfate	Dissolved Solids

Collected	(S/cm)	(mg/L)	(mg/L)	(mg/L)
09/15/60	919	125	50	518
3/7/1963	3696	680	364	1797
3/11/1963	780	77	49	404
3/11/1963	672	39	72	341
15114: Surface Water: 34 Samples, from Aug. 1996 to August 2004				
Parameter	Spec. Cond. (S/cm)	Chloride (mg/L)	Sulfate (mg/L)	Dissolved Solids (mg/L)
Average	12400	3453	1932	8426
Std Dev	3897	1103	652	2548
15114: Groundwater: 4 wells within1 mile				
Date Collected	Spec. Cond. (S/cm)	Chloride (mg/L)	Sulfate (mg/L)	Dissolved Solids (mg/L)
12/10/62	4914	1288	89	2431
01/26/54	5880	1350	914	3666
05/02/85	640	33	41	343
05/15/73	4371	920	363	2149
05/19/93	660	63	44	390
11/16/83	775	47	61	389

If parallels between water quality in surface and groundwater are to be fully investigated, groundwater near the Pecos River should be sampled during time periods when the Clean Rivers Program is sampling surface water; generally every quarter. Data collected during the same time period and as nearby as possible could be used along with short term estimates of base flow from the USGS gage data to estimate flux from groundwater to surface water.

Little Wichita River

The Little Wichita River is located in north central Texas. The river begins in Archer County and flows generally northeast to the Red River. Several dams are located on the Little Wichita, one of which forms Lake Kickapoo 26 miles southwest of Wichita Falls, and one forms Lake Arrowhead 13 miles southeast of Wichita Falls. The Little Wichita runs through the north end of the town of Henrietta approximately 14 miles from the confluence with the Red River. The portion of the Little Wichita between Lake Arrowhead and the Red River is impaired with TDS and low Dissolved Oxygen (DO). The USGS stream gauges located on the impaired section of the Little Wichita were identified along with their period of record (Figure 3, Table 5).

Table 5: USGS Gauges on the Little Wichita River, TX

Site Number	**Site Name**	**Period of Record**	
		From	**To**
7315400	Little Wichita River near Ringgold, TX	3/1/1959	9/30/1965
7314900	Little Wichita River above Henrietta, TX	10/1/1952	9/30/2004
7315200	E Fk Little Wichita River near Henrietta, TX	12/1/1963	9/30/2004

From the data in Table 5, the initial study river reach was designated the Little Wichita between the Ringgold and Henrietta gauges, using data from the East Fork to subtract out effects of this tributary. The initial study period of record was necessarily from 1963, when collection of data began at the East Fork gage to 1965 when data collection at the Ringgold gage stopped. This is a relatively short period of record.

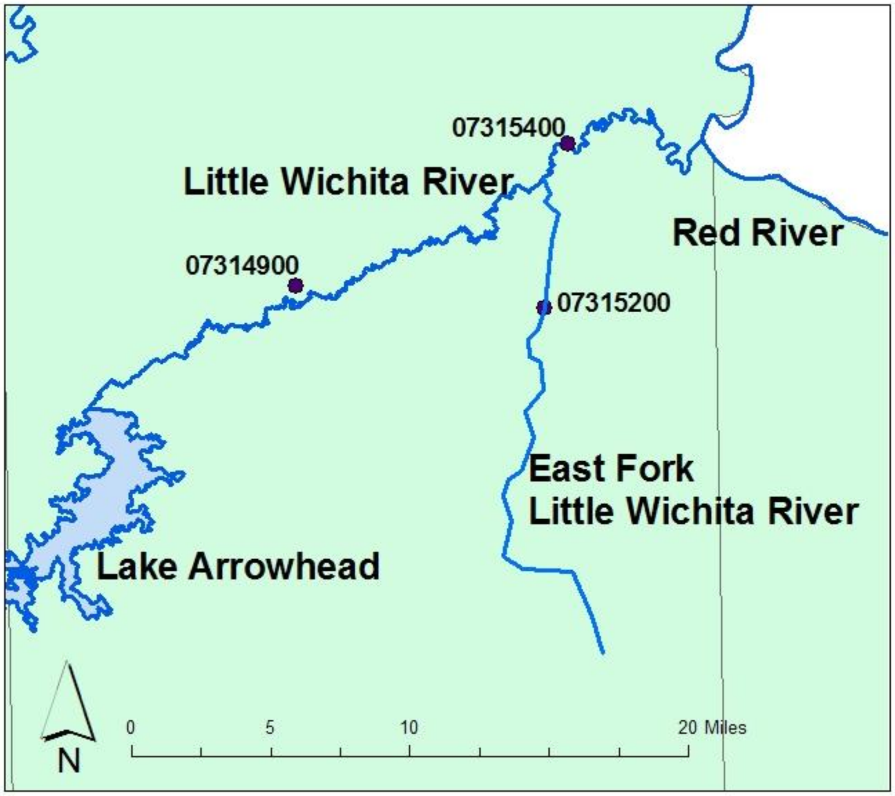


Figure 3: Location of USGS Gauges near the Little Wichita River

The USGS in Wichita Falls was contacted and interviewed about these gauges to determine if there were additional gage data available on this reach of river, and to find out about quality of data from the gauges. Through these communications, it was discovered that there was an additional dam on the river that was not noted in any of the data collected at that time. The City of Henrietta operates a dam on the Little Wichita River approximately ½ mile upstream from Henrietta. The City obtains municipal water from the base of this dam. According to the USGS, the presence of this dam creates great difficulty in collecting quality data at their gage in Henrietta. USGS considers the accuracy of data gathered at the Henrietta gage poor; less than 10%. It became increasingly clear that the Little Wichita would be a very difficult reach of river on which to assess base flow conditions. After discussing the gage on the East Fork, it was discovered that the data collected at this gage was of good quality. Accordingly, it was decided to assess base flow conditions using gage data from the East Fork, assuming base flow estimates on the East Fork were an adequate surrogate for the Little Wichita. The study period of record for the East Fork was from 1965 to 2004, a total of 40 years.

Precipitation data were gathered from NOAA for Climate Division 3, North Central Texas (Fig. 4). It is clear from Figure 4 that the study period of record represents years in the precipitation record across the entire spectrum. Base flow estimates were generated for the study period of record using BFI. Because there are no upstream gauges on the East Fork, there were no subtractions to be conducted. BFI therefore represents total flow at the East Fork gage that is base flow generated over the East Fork watershed upstream from the gage. Base flow calculations are summarized in Figures 5, 6 and 7 below.

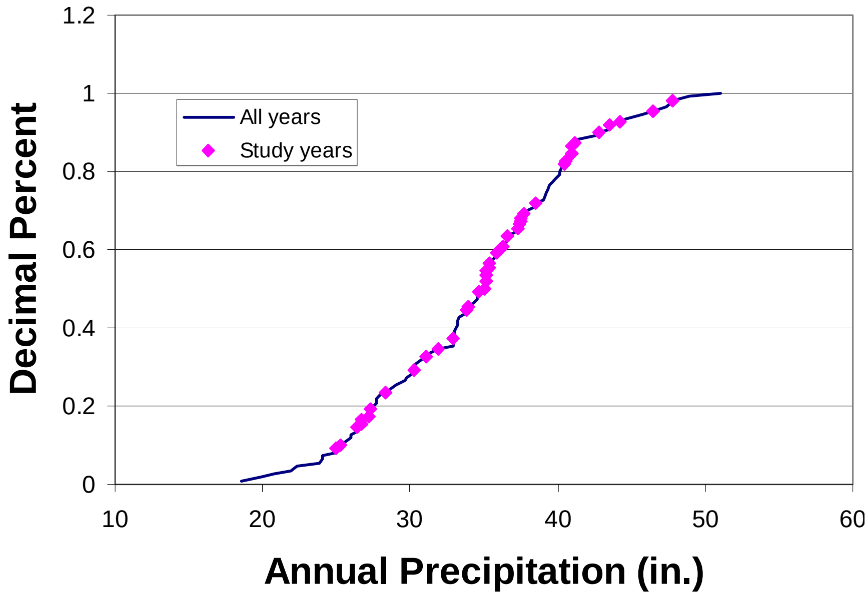


Figure 4: Cumulative Distribution of Precipitation Data for Climate Region 3

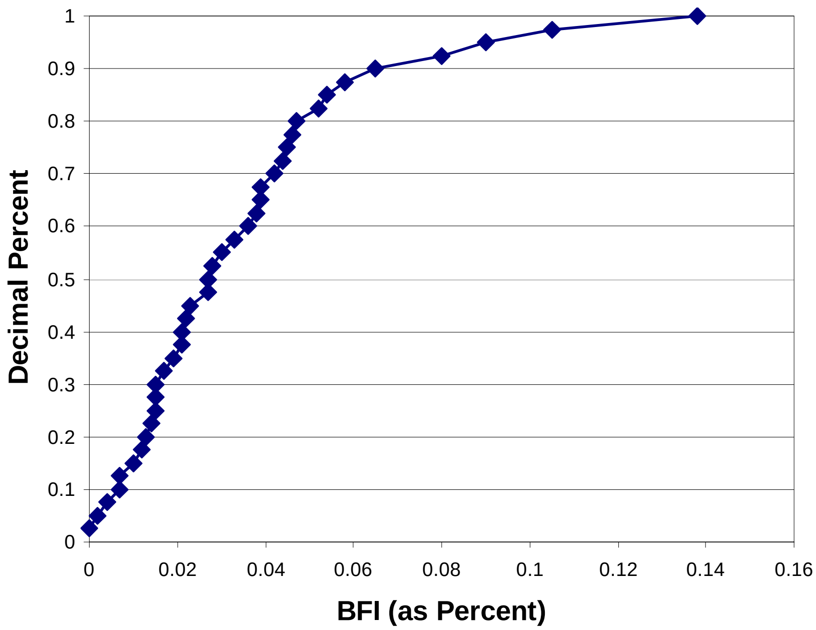


Figure 5: Cumulative Distribution of BFI for East Fork of Little Wichita

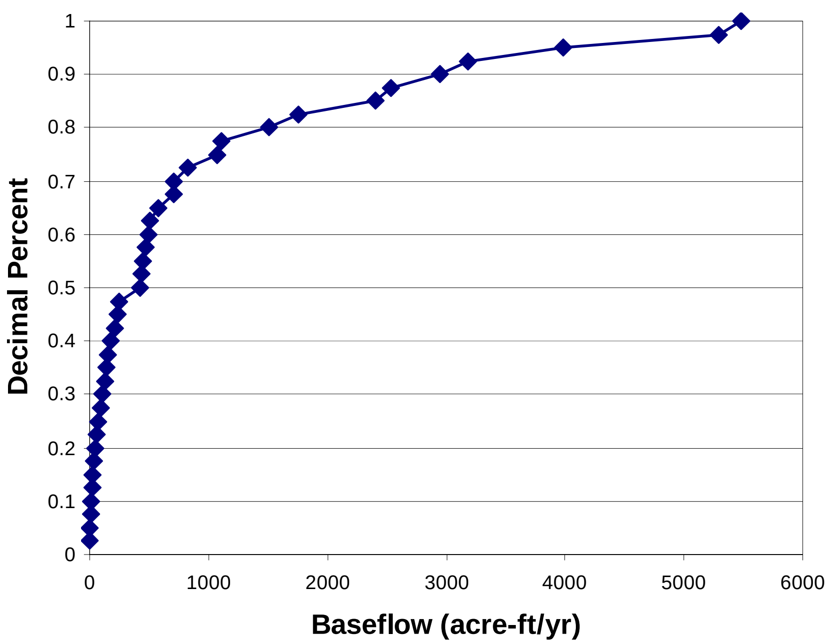


Figure 6: Cumulative Distribution of baseflow for the East Fork of the Little Wichita

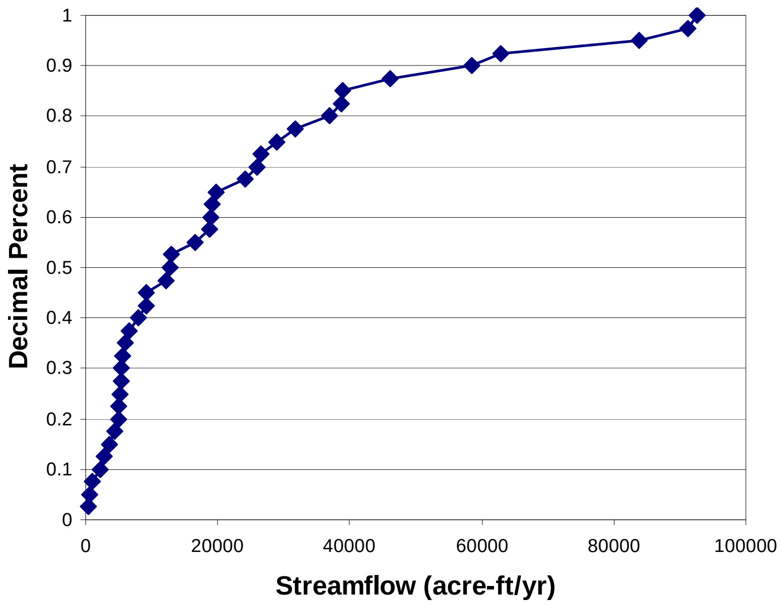


Figure 7: Cumulative Distribution of streamflow for the East Fork of the Little Wichita

From Figure 5, it is clear that base flow on the East Fork of the Little Wichita is very small. At the 50th percentile, there is approximately 2.7% of annual stream flow that is base flow. At the 90th percentile, there is approximately 6.5% of annual stream flow that is base flow. There are no public water intakes on the East Fork of the Little Wichita, and no return flows. These numbers are consistent with anecdotal information provided by the USGS office in Wichita Falls, the National Resource Conservation Service office in Henrietta, and the Clay County Agricultural Extension agent in Henrietta; that the East Fork of the Little Wichita runs dry fairly often, and that there is generally water in the East Fork during relatively wet periods. By contrast, the Little Wichita River is generally flowing, because it is so heavily regulated by Lake Kickapoo, Lake Arrowhead, and the dam near the Henrietta public water intake. Accordingly, the East Fork is best interpreted as a surrogate for the Little Wichita before regulation.

Water quality data were also gathered to examine if the water chemistry in the Little Wichita and the East Fork of the Little Wichita is affected by the groundwater chemistry. To conduct this investigation, surface water quality data were obtained from the TCEQ Surface Water Quality Monitoring (SWQM) Team, and groundwater quality data were obtained from the GWDB, as before. Surface water quality sampling and testing took place at three locations on the Little Wichita and one location on the East Fork of the Little Wichita. These locations are depicted below in Figure 8 as large black dots. Two of the locations are labeled using their numeric TCEQ ID, and two were labeled using the name of the nearest tributary according to SWQM records. These locations contain surface water quality sampling of different periods of record spanning 1980 through 2003.

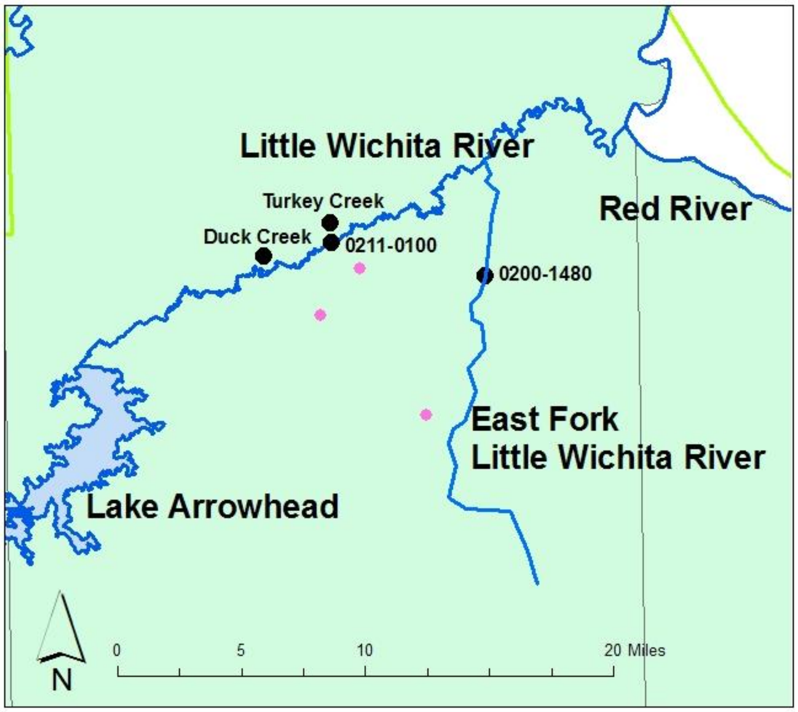


Figure 8: Water quality sampling locations

The GWDB data were plotted and all groundwater wells with water quality data within a 5 km buffer of the Little Wichita and the East Fork were extracted. A larger buffer was used because of the scarcity of groundwater wells in this area. Even with this increased buffer, there were 2 wells in the area of the Little Wichita and 1 well within the area of the East Fork. These wells are also depicted in Figure 8 as bright pink dots. Some of these wells were sampled at several times at different dates, and the period of record for well sampling events extended to 1978. No QA metrics are provided for the groundwater data. Data from these groundwater and surface water investigations are provided in Table 6. For the groundwater data presented in this table, adjacent rows of identical color are samples from the same well taken at different times. A change in color in an adjacent row indicates a different well.

Table 6: Comparison of Surface Water and Groundwater Quality Data

0211-0100: Surface Water: 57 Samples, from Apr. 1980 to Jun. 1999			
Parameter	Specific Conductance (S/cm)	Chloride (mg/L)	Sulfate (mg/L)
Average	475	70	15
Std Dev	226	48	21
Duck Creek: Surface Water: 36 Samples, from Oct. 1981 to Jan. 2005			
Parameter	Specific Conductance (S/cm)	Chloride (mg/L)	Sulfate (mg/L)
Average	290	64	10
Std Dev	152	51	5
Turkey Creek: Surface Water: 7 Samples, from Sept. 2001 to Nov. 2004			
Parameter	Specific Conductance (S/cm)	Chloride (mg/L)	Sulfate (mg/L)
Average	441	51	12
Std Dev	253	53	7
Groundwater: 2 wells within 5km			
Date Collected	Specific Conductance (S/cm)	Chloride (mg/L)	Sulfate (mg/L)
8/18/1978	1377	104	53
8/6/1982	1640	160	78
4/19/1991	1135	102	83
7/19/1978	1557	89	65
0200-1480: Surface Water: 27 Samples, from Oct. 1981 to June 1986			
Parameter	Specific Conductance	Chloride	Sulfate

	(S/cm)	(mg/L)	(mg/L)
Average	1253	256	45
Std Dev	841	218	24
Groundwater: 1 well within 5 km			
Date Collected	Specific Conductance (S/cm)	Chloride (mg/L)	Sulfate (mg/L)
08/18/78	5004	976	200
8/6/1982	5220	1019	205

One of the strengths of this dataset is that it shares water quality data from coincident periods of record. A weakness is the scarcity of groundwater wells that contain water quality data. However, a few general trends may be pointed out. Groundwater measurements are generally higher in chloride, sulfate, and conductivity than surface water measurements. This indicates that under base flow conditions, groundwater could certainly be a source of salinity to surface water. If the base flow estimates for the East Fork of the Little Wichita are accurate, base flow is never above 15% on an annual basis. However, examination of daily values of stream flow and BFI reveals a different picture. The East Fork has measurable flow 70% of the period of record. If a cumulative distribution function of BFI is prepared using daily values of BFI during periods when the East Fork is flowing (Figure 9), one might reasonably conclude that when the East Fork is flowing, that base flow could be as much as 50 percent of the total flow in the East Fork

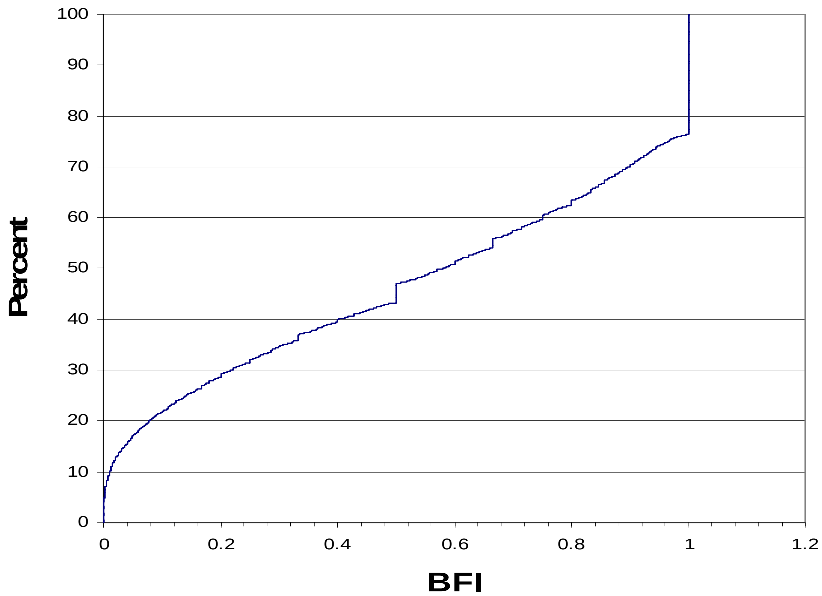


Figure 9: Daily BFI for Flowing Periods in the East fork of the Little Wichita

If parallels between water quality in surface and groundwater are to be fully investigated, groundwater near the Little Wichita and the East Fork should be sampled in more places, and much closer to the surface water sampling points. With the data that has been summarized in this report, the main problem in analyzing the Little Wichita and the East Fork is the scarcity of nearby groundwater samples. Data collected during wet and dry periods and as nearby as possible could be used along with short term estimates of base flow from the USGS gage data to estimate flux from groundwater to surface water of TDS. Using the techniques, this would be a simple and straightforward set of calculations.

References

Wahl, Kenneth L., and Tony L. Wahl, 1995, "Determining the Flow of Comal Springs at New Braunfels, Texas," *Texas Water '95*, American Society of Civil Engineers Symposium, San Antonio, Texas, August 16-17, 1995.

3.5 Impact of Groundwater-Surface Water Interactions on Selected Superfund Sites

Andrew Tachovsky (Bureau of Economic Geology, Univ. Texas at Austin)

Summary

Data from two Superfund sites was reviewed to evaluate evidence of groundwater influence on surface water quality. In each case, concentrations of anthropogenic chemicals in surface water can be linked to groundwater for contaminants found in soil at each superfund site. At each site, a solution involving manipulation of groundwater flow through pumping was selected to alleviate a surface water contamination problem.

Introduction

In this section, we consider the interaction of groundwater and surface water at sites where contamination of soil by industrial activity has lead to contamination of surface waters by leaching and subsequent transport through groundwater. In particular, we will examine physical and chemical data collected in support of clean up activities at two sites: 1) Alcoa at Point Comfort, TX, and 2) the Longhorn Army Ammunition Plant in Karnack, Texas. In each case, we will observe the interaction of groundwater and surface water using the data collected during extensive site characterization activities, and subsequent planning for remedial activities.

Longhorn Army Ammunition Plant (LHAAP), Karnack, Texas

The Longhorn Army Ammunition Plant is located central east Texas in the northeast corner of Harrison County, approximately 14 miles northeast of Marshall Texas. LHAAP occupies approximately 8,500 acres between State Highway 43 and the western shore of Caddo Lake. All surface water from LHAAP drains into Caddo Lake through four drainage systems that run across portions of the plant: Saunders Branch, Harrison Bayou, Central Creek, and Goose Prairie Bayou. LHAAP is located on an outcrop of the Wilcox Group which yields small (less than 50 gpm) to moderate (50-500 gpm) quantities of fresh water to wells throughout the county. LHAAP is a government owned, contractor-operated industrial facility established in 1942 with the primary mission of producing trinitrotoluene (TNT) flake. LHAAP was added to the National Priorities List (NPL) in August of 1990.

LHAAP consists of three Operable Units (OU), each with multiple sites including burning grounds, land fills, test areas, burial sites, open areas, buildings and parking lots. While each site has its own contamination history, this discussion will focus on the LHAAP Site 16 Landfill (Site 16), located in OU2. Site 16 encompasses approximately 20 acres, and is a sloped, open area of grass bounded on the west and north by a gravel road and on the east and south edges by heavy timber. The southeastern edge is in the 100-year flood plain of Harrison Bayou. Site 16 was originally used for the disposal of TNT red water ash generated from the TNT Waste Disposal Plant (from 1940 to 1942), and continued to be used for disposal of a variety of wastes until disposal activities ceased in the early 1980s. The disposal portion of the site is now capped and vegetated.

Harrison Bayou runs along the northeastern edge of Site 16. Surface drainage from Site 16 flows mostly through small gullies and ditches to Harrison Bayou. Harrison Bayou flows into Caddo Lake, to the northeast of the site. Harrison Bayou periodically has no flow with pools of standing water during times of low rainfall. During high rainfall events, Harrison Bayou may flood into the flat areas of Site 16, but not to the capped area. Harrison Bayou captures approximately 30 percent of the surface drainage of the LHAAP.

The subsurface geology at Site 16 consists primarily of a thin veneer of Quaternary alluvium mantling Tertiary age formations of the Wilcox and Midway Groups. Underlying these are the Navarro and Taylor Groups that are Cretaceous in age. The Wilcox group, which constitutes a majority of the unconsolidated sediments underlying Site 16, consists of interbedded sands, silts and clays. Based on nearly 100 borings, monitoring wells, and geoprobes, the subsurface hydrogeology at Site 16 can be characterized as consisting of three water bearing sandy zones that are separated by semi-confining clay layers. There is considerable heterogeneity across the site as the sand layers vary in depth. Based on rising head slug tests and water level measurements, the mean hydraulic conductivity value varies from 1.5E-3 cm/s in the shallow zone to 4.2E-4 in the deep zone. The average hydraulic gradient varies from 1.04E-2 ft/ft in the northeasterly direction (toward Harrison Bayou) in the shallow zone and 2.7E-3 foot/foot in the easterly direction in the deep zone. The groundwater velocity was estimated to vary from 36.7 ft/yr in the shallow and intermediate zones to 0.31 ft/yr in the deep zone. The groundwater in the shallow and intermediate zones eventually enters Harrison Bayou, and it is unlikely that it is migrating past the Bayou and flowing into other watersheds. The deep geologic formation (Midway) is a clayey formation that likely acts as a barrier for groundwater movement.

Investigation activities at Site 16 began in 1980 and continue to the present. Different media have been sampled to determine the nature and extent of contamination including: soil and soil gas in the source area, soil outside the landfill, ditch sediment and surface water, and groundwater. Of all media sampled, groundwater is the medium most impacted by contamination from the Site 16 landfill. Groundwater characterization of volatile organic chemicals (VOCs), metals, and perchlorate demonstrates a plume extending to the northeast, toward Harrison Bayou. Harrison Bayou, in turn, has been sampled three to four times a year since 1995 for VOCs and more recently for perchlorate. There is a seep near Harrison Bayou discharging directly to surface water.

As a result of site characterization at Site 16, two primary remedial actions have taken place. First, a groundwater extraction system was installed in 1996 and 1997. The groundwater extracted from eight wells is piped to a groundwater treatment plant. Because of the slow moving nature of the groundwater (35 ft/y) and the distance to Harrison Bayou (300 ft), the impact of the extraction wells may not be noticed for 5-10 years. The second primary action was the installation of a multilayer cap over the landfill in 1998. The disposal portion of the site is now capped and vegetated.

Two shallow wells in the vicinity of the seep monitor groundwater conditions contributing to the seep. These wells were sampled before implementation of any controls at Site 16. The VOCs detected in both wells were trichloroethene, 1,1-dichloroethene, cis1,2 –dichloroethene, vinyl chloride, 1,2-dichloroethane, and benzene. Trichloroethene was detected at the greatest concentrations (2,700 and 7,500 µg/L). Except for the presence of acetone in the two shallow wells, which has not been routinely detected in the groundwater at Site 16, the seep contaminants have the same signature as the groundwater from Site 16 moving toward the creek. Therefore, there is an established migration pathway from the landfill to the groundwater to the surface water.

A sample collected at the seep before any controls were put into place at the site contained trichloroethene at concentrations of 1,020 µg/L, cis-1,2-dichloroethene concentrations of 609 µg/L, and vinyl chloride concentrations of 65 µg/L. Results indicate that VOCs continue to discharge into Harrison Bayou, but at concentrations below the Texas Water Quality Standards (TWQS). Downstream surface water sampling locations do not show levels of trichloroethene, 1,2-dichloroethene, or vinyl chloride above drinking water levels. These contaminants are easily volatilized or degraded in a surface water environment and pose no threat to Caddo Lake.

The highest concentrations of trichloroethene in the plume are just outside the landfill area (25,000 µg/L in 1997). In a worst-case scenario, assuming no contaminant retardation, the most contaminated portion of the plume may reach the surface water in 15 to 20 years, assuming no engineering control. If this scenario is carried to Harrison Bayou, concentrations could exceed the TWQS. However, because of dilution in Harrison Bayou with upstream water as well as volatilization that would occur in surface water, Caddo Lake is not jeopardized. In support of this argument, downstream surface water monitors consistently show no detection of trichloroethene, even when upstream concentrations near the seep are above 200 µg/L.

The perchlorate distribution pattern in 200 and 2001 is very similar to the trichloroethene distribution in 1997 and 1998. Perchlorate concentrations in the wells closest to the seep are 280 and 507 µg/L. The highest perchlorate concentration is 900 µg/L at a location very close to the northeast corner of the landfill. While it is possible that perchlorate concentrations in groundwater could also affect surface water in Harrison Bayou, recent perchlorate concentrations have been non-detect. Accordingly, it is difficult to determine what extent perchlorate in groundwater at Site 16 is affecting surface water in Harrison Bayou.

Alcoa Point Comfort, TX Operations

The Aluminum Company of America (ALCOA) Point Comfort Operations plant is located in southeast Texas in Calhoun County near the city of Point Comfort. Alcoa Point Comfort is bordered by Lavaca Bay on the east, State highway 35 on the northwest and industrial and agricultural areas on the north and northeast. The site consists of the Alcoa Plant, an associated dredge spoil island, and portions of Lavaca Bay, Cox Bay, Cox Creek, Cox Cove, Cox Lake, and western Matagorda Bay. The plant covers approximately 3,500 acres, and the dredge spoil island is approximately 420 acres.

The Point Comfort Operations plant began operation as an aluminum smelter in 1948 and ran until 1980. The plant is currently an alumina refining operation that utilizes bauxite ore to produce alumina. From 1966 to the 1970s, Alcoa operated a chlor-alkali plant which produced chlorine gas and sodium hydroxide. Part of the process involved the use of mercury cathodes. Waste water containing mercury was discharged into Lavaca Bay through outfalls located on an off-shore gypsum lagoon on Dredge Island. Bay sediments are now contaminated with waste mercury. The oil and gas refining and power generation at the Neumin Gas Plant was operated by Alcoa from 1958 to 1988. Alcoa sold the gas plant and associated land to Formosa Plastics. Whitco Chemical Corporation operated from 1964 to 1985 on approximately 7 acres located within the boundaries of the Alcoa plant. Whitco Chemical processed coal tar for the manufacture of the electrode binder pitch. A metal plating operation was also operated but is now inactive. The site was placed on the National Priorities List on March 25, 1994. The listing was primarily based on levels of mercury found in several species of finfish and crabs in Lavaca Bay.

The Beaumont formation underlies the site and generally consists of a sequence of silty clays, sandy clayey silts, clays and silty sands. Three primary saturated sand and silt zones, with intervening clay units have been identified in the upper 100 feet beneath the site. The water table is generally 14 to 20 ft below the surface. Several transmissive zones occur at relatively consistent depths across the site and have been named Zones A, B, and C (from shallowest to deepest. Zone A occurs at an elevation of approximately 5 to 0 ft msl, and is overlain and underlain by the Beaumont Clay. Zone A consists of interbedded sand, silt, and clay sediments characteristic of overbank flood basin depositional environments. Zone A has some hydraulic interconnection with recharge processes at the surface, although groundwater occurs under confined conditions. Zone B typically occurs at elevations of -20 to -30 ft msl. Zone B includes strata consisting of fining-upward or massive sequences of silty sand to well-graded sand as well as some finer grained sediments. Zone C is the deepest transmissive zone defined at the plant, and consists of fining-upward or massive sequences of silty sand to well graded sand and gravel.

On the mainland, groundwater discharges to Lavaca Bay and the upper reach of Cox Lake under natural conditions. Zone A discharges to the bay system along the sourthern and western site perimeter, where Zone A crops out at the shoreline of Lavaca Bay. Groundwater in Zone B also discharges into the bay system in the Alcoa ship/barge channel and turning basin, where direct discharge occurs where the deep channel cut intercepts Zone B. Potentiometric data also indicate Zone B water discharge offshore upward into shallower strata, and thus to the bay system. Groundwater from Zone C does not discharge through an outcrop, but rather upward through strata offshore; similar to water in Zone B. On Dredge Island, the groundwater pathway was found to be incomplete because no contaminants were present.

Initial results quickly focused the remedial investigation on an area of the plant referred to as the Chlor-Alkali Plant Area (CAPA). The CAPA is located on the western border of the plant adjacent to Lavaca Bay, and includes the cell building (R-300), several other small buildings, a brine handling area, a tank area, a caustic dock, and other open areas. Total unfiltered mercury concentrations in groundwater from Zone A ranged from below the detection limit to 1700 µg/L across 7 wells. The highest concentration was located near building R-300. Total unfiltered mercury concentrations in groundwater from Zone B ranged from below the detection limit to 6580 µg/L. Total mercury concentrations greater than 1000 µg/L were generally associated with the area directly west of Building R-300. All of the mercury concentrations in Zone C groundwater samples were less than the detection limits.

Elemental mercury DNAPL was observed in soil samples collected at the base of Zone B and in sand filled fissures in the clay just below the base of Zone B during the drilling and installation of two monitoring wells (CA045B and CA047B). In one of the wells (CA045B), elemental mercury droplets were observed during development of the well in the sediment/water mixture produced during bailing. An in-well thickness of approximately 1.6 feet of elemental mercury was measured in this well during the groundwater treatability study. Elemental mercury was not directly observed in the other well (CA047B), although soundings indicated that 0.12 feet of material had accumulated at the base of the well.

Potential mercury transport via groundwater flux was conservatively estimated using several methods for all groundwater sources at the plant. For zone B at the CAPA, the methods produced an estimated range of flux values of 10 to 50 lb/yr. For comparison, the mercury loading by groundwater discharge to the bay system by all segments excluding Zone B at the CAPA (and Witco, which was still being investigated at the time of the report) is approximately 0.003 lb/yr. A weight –of-evidence evaluation and a comparison to risk-based screening criteria indicated that significant sources of mercury to the bay system are limited to discharge of groundwater from Zone B at the CAPA.

Treatability testing activities were performed to develop alternatives that address the potential migration of mercury in Zone B groundwater from the area west of Building R-300 to the bay system. A treatability test of hydraulic containment was performed in 1998 and the system is currently in operation. Based on both surface water chemistry data collected offshore of the CAPA and water level measurements from wells at the CAPA the system appears to be effectively intercepting mercury contaminated groundwater flow to the bay system in Zone B groundwater west of Building R-300.

Appendix 4

Task 2D: Assess the Status of Knowledge of the Mapped Distribution and Types of Riparian Vegetation

M. Teresa Howard, Gordon L. Wells, Gayla J. Mullins, and Dawn M. Ortiz (Center for Space Research, Univ. Texas at Austin)

Sections

4.1 Sources of Existing Map Products showing the geographic distribution of riparian vegetation in the State of Texas

A review of existing map products showing global, national and statewide vegetation distribution indicates the lack of a map that focuses exclusively on the geographic distribution of riparian vegetation within the State of Texas. General land cover and vegetation maps do exist. These vary in currency, level of detail, and appropriateness of mapped categories for the purpose of inferring the location and composition of riparian corridors.

One widely cited map is The Vegetation Types of Texas (McMahan *et al.*, 1984), shown in Figure 1. The map was compiled at the Texas Parks and Wildlife Department (TPWD) in the late 1970s to early 1980s. McMahan and colleagues used Landsat Multi-Spectral Scanner satellite imagery acquired between 1972 and 1976 to classify vegetation associations in the eastern two-thirds of the state. Ground survey data collected by the Bureau of Economic Geology and additional Landsat data dating from 1979 and 1980 were used to map the remainder of the State. Remarks on the general distribution of each vegetation type and commonly associated plants were published in a companion report. TPWD later created a digital version of the map shown in Figure 1. The attributed region polygons are also available in a format suitable for use in a Geographic Information System (GIS). The Vegetation Types of Texas was compiled at a map scale of 1:250,000. As a consequence, riparian vegetation is mapped separately where resolution constraints permit. In many cases, riparian corridors were too narrow to include in the final product. The map authors note that vegetation distribution has been greatly influenced by human activity, becoming more heterogeneous and less characteristic of natural conditions.

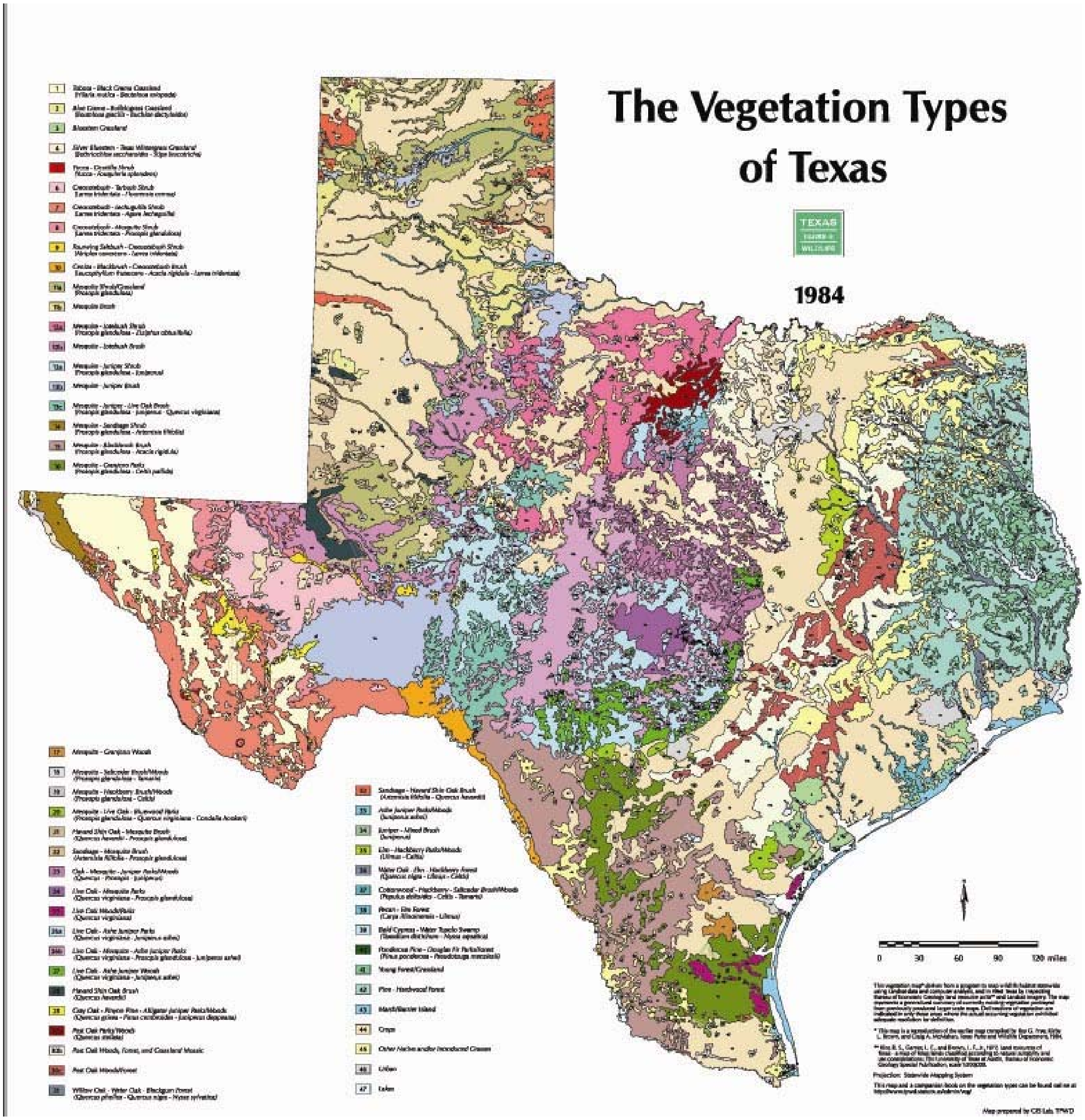


Figure 1. The Vegetation Types of Texas, after McMahan *et al.*, 1984. Map produced by TPWD.

No other statewide vegetation mapping has been attempted in the years since the publication of The Vegetation Types of Texas. However, members of the Texas Geographic Information Council collaborated to provide guidance for any future mapping efforts. The Texas Land Classification System (TGIC, 1999) provides a detailed description of general vegetation classes recommended for use in any future statewide mapping effort. The classification scheme includes a riparian forest class in a nested hierarchy under the categories of vegetated wetland, woody wetland, and forested wetland. Riparian forest is further subdivided into seasonally and temporarily flooded categories. Some organizations have adopted the classification system for small projects. The Texas Parks and Wildlife Department has funded detailed vegetation mapping for limited areas within the State, prior to and following the publication of the Texas Land Classification System. Published mapped areas include the proposed Cibolo and Goliad reservoir sites (Cypher and Frye, 1993), the Cypress Creek watershed (Liu *et al*., 1996b), the potential future Waters Bluff Reservoir site (Liu *et al*., 1996a), and three proposed reservoir sites in Northeast Texas (Liu *et al*., 1997). Unpublished work has been conducted at Lost River, Cow Bayou, and the Middle Neches River in East Texas. All sites include riparian vegetation.

A recent publication resulting from the collaboration of several offices of the Environmental Protection Agency (EPA), the Texas Commission of Environmental Quality, and the US Department of Agriculture-Natural Resources Conservation Service (NRCS) contains information pertinent for riparian vegetation mapping in the State. Ecoregions of Texas (Griffith *et al.*, 2004) is a large format color poster of a map compiled at the scale of 1:2,500,000. The poster includes descriptive text and photographs. A page size version of the map, adapted from materials published on the EPA website, is shown in Figure 2. The map delineates twelve Level III and 56 Level IV EPA ecoregions in Texas, shown in Table 1. Table 2 lists riparian vegetation community composition as indicated for Level IV ecoregions. Not all ecoregion descriptions include explicit references to riparian vegetation. Consequently, it cannot be assumed that all or even most riparian species are mentioned. The species mentioned are predominately trees. Associated shrubs, grasses and forbs are not identified. It is also important to note that the primary goal of the ecoregion map is to describe natural areas based on geology, physiography, soils, vegetation, climate and other discriminating factors. Although mention is made of the human footprint on the landscape, the conversion of the natural landscape for agriculture and human settlement is not emphasized. The vegetation in many riparian areas of present-day Texas may no longer correspond to the riparian vegetation types listed in Table 2.

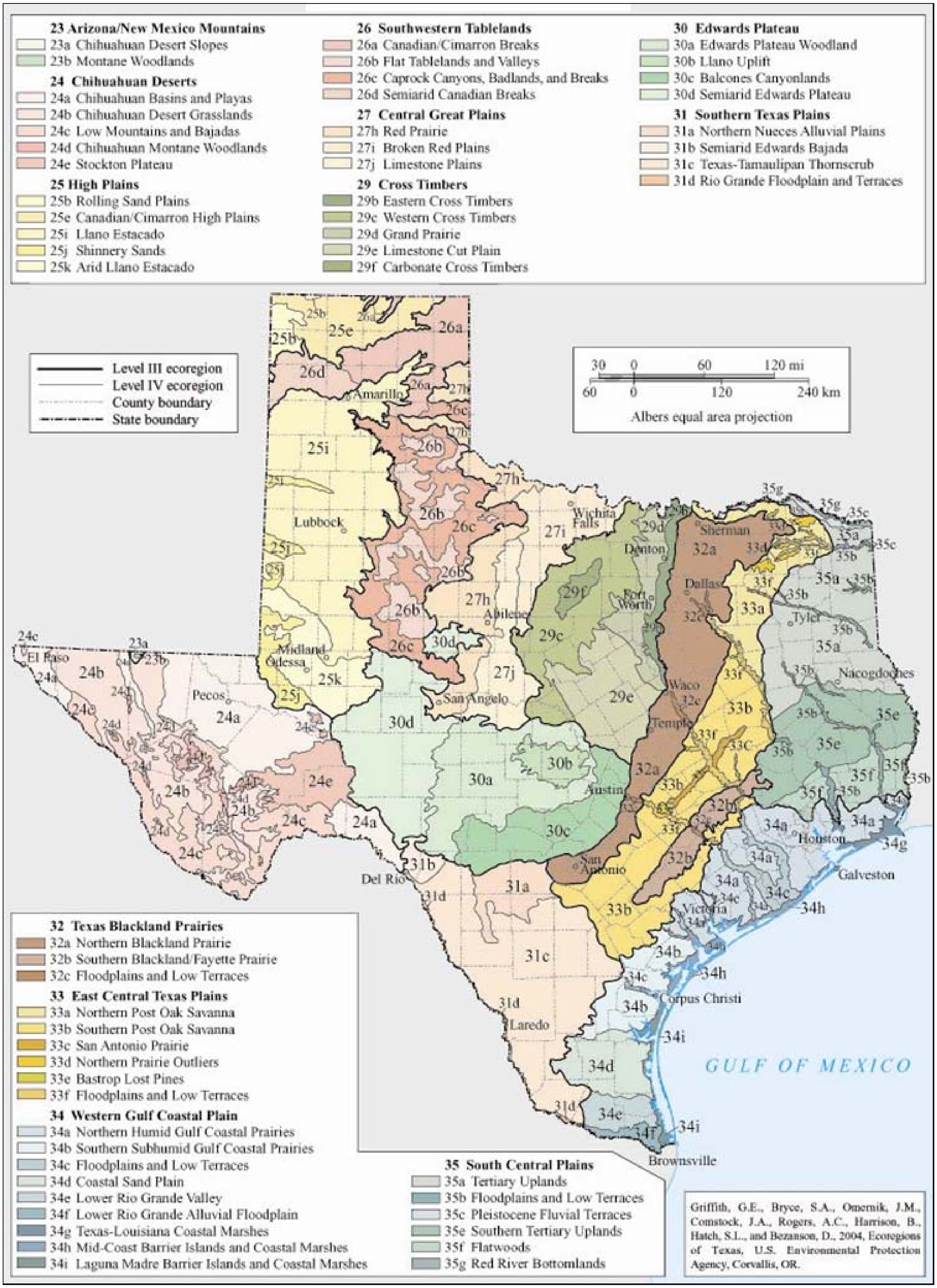


Figure 2. Level III and Level IV EPA Ecoregions of Texas (Griffith *et al.*, 2004)

Table 1. Level III (in bold) and Level IV EPA ecoregions found in Texas (Griffith *et al.*, 2004). Level IV ecoregions that include explicit descriptions of riparian vegetation communities are italicized. Note that gaps in the numbering system exist; the ecoregions are part of a national taxonomy. Many nationally identified ecoregions are not found in Texas.

23. Arizona/New Mexico Mountains
- 23a Chihuahuan Desert Slopes
- 23b *Montane Woodlands*

24. Chihuahuan Deserts
- 24a *Chihuahuan Basins and Playas*
- 24b Chihuahuan Desert Grasslands
- 24c *Low Mountains and Bajadas*
- 24d Chihuahuan Montane Woodlands
- 24e Stockton Plateau

25. High Plains
- 25b Rolling Sand Plains
- 25e Canadian/Cimarron High Plains
- 25i Llano Estacado
- 25j Shinnery Sands
- 25k Arid Llano Estacado

26. Southwestern Tablelands
- 26a Canadian/Cimarron Breaks
- 26b *Flat Tablelands and Valleys*
- 26c *Caprock Canyons, Badlands, and Breaks*
- 26d *Semiarid Canadian Breaks*

27. Central Great Plains
- 27h Red Prairie
- 27i *Broken Red Plains*
- 27j *Limestone Plains*

29. Cross Timbers
- 29b Eastern Cross Timbers
- 29c Western Cross Timbers
- 29d *Grand Prairie*
- 29e Limestone Cut Plain
- 29f Carbonate Cross Timbers

30. Edwards Plateau
- 30a Edwards Plateau Woodland
- 30b Llano Uplift
- 30c *Balcones Canyonlands*
- 30d *Semiarid Edwards Plateau*

31. Southern Texas Plains
- 31a *Northern Nueces Alluvial Plains*
- 31b Semiarid Edwards Bajada
- 31c Texas-Tamaulipan Thornscrub
- 31d *Rio Grande Floodplain and Terraces*

32. Texas Blackland Prairies
- 32a *Northern Blackland Prairie*
- 32b Southern Blackland/Fayette Prairie
- 32c *Floodplains and Low Terraces*

33. East Central Texas Plains (Post Oak Savanna)
- 33a Northern Post Oak Savanna
- 33b Southern Post Oak Savanna
- 33c San Antonio Prairie
- 33d Northern Prairie Outliers
- 33e Bastrop Lost Pines
- 33f *Floodplains and Low Terraces*

34. Western Gulf Coastal Plain
- 34a Northern Humid Gulf Coastal Prairies
- 34b Southern Subhumid Gulf Coastal Prairies
- 34c *Floodplains and Low Terraces*
- 34d Coastal Sand Plain
- 34e Lower Rio Grande Valley
- 34f *Lower Rio Grande Alluvial Floodplain*
- 34g Texas-Louisiana Coastal Marshes
- 34h Mid-Coast Barrier Islands and Coastal Marshes
- 34i Laguna Madre Barrier Islands and Coastal Marshes

35. South Central Plains (Pineywoods)
- 35a Tertiary Uplands
- 35b *Floodplains and Low Terraces*
- 35c Pleistocene Fluvial Terraces
- 35e Southern Tertiary Uplands
- 35f Flatwoods
- 35g *Red River Bottomland*

Table 2. Riparian Vegetation Types of Texas as listed by Level IV EPA Region from Griffith *et al.*, 2004.

Level III Ecoregion	**Level IV Ecoregion**	**Riparian Vegetation Types**
Arizona/New Mexico Mountains	Montane Woodlands (Guadalupe Mountains)	velvet ash, chinkapin oak, Texas madrone, bigtooth maple, maidenhair fern, and sawgrass
Chihuahuan Deserts	Chihuahuan Basins and Playas	saltcedar, common reed (non-native)
Chihuahuan Deserts	Low Mountains and Bajadas	gray oak, velvet ash, little walnut
Southwestern Tablelands	Flat Tablelands and Valleys	saltcedar (non-native)
Southwestern Tablelands	Caprock Canyons, Badlands, and Breaks	cottonwood, willow, hackberry, big bluestem grasses (native), elm, saltcedar (non-native)
Southwestern Tablelands	Semiarid Canadian Breaks	cottonwood, willow, hackberry (native), saltcedar (non-native)
Central Great Plains	Broken Red Plains	cottonwood, hackberry, cedar elm, pecan, little walnut
Central Great Plains	Limestone Plains	hackberry, cottonwood, elms, willows
Cross Timbers	Grand Prairie	elm, pecan, hackberry
Edwards Plateau	Balcones Canyonlands	bald cypress, American sycamore, black willow
Edwards Plateau	Semiarid Edwards Plateau	live oak in floodplains only
Southern Texas Plains	Northern Nueces Alluvial Plains	hackberry, plateau live oak, pecan, cedar elm (floodplain), black willow, eastern cottonwood (river banks)
Southern Texas Plains	Rio Grande Floodplain and Terraces	sugar hackberry, cedar elm, Mexican ash, black willow, black mimosa, common and giant reed, cattails, bulrushes, sedges, cotton, grain sorghum, cool-season vegetables
Texas Blackland Prairies	Northern Blackland Prairie	bur oak, Shumard oak, sugar hackberry, elm, ash, eastern cottonwood, pecan (historically), now widely converted to cropland, pasture, non native vegetation, urban sprawl
Texas Blackland Prairies	Floodplains and Low Terraces	bur oak, Shumard oak, sugar hackberry, elm, ash, eastern cottonwood, pecan (historically), now widely converted to cropland/pasture
East Central Texas Plains	Floodplains and Low Terraces	hackberry, eastern cottonwood (west); water oak, post oak, elms, green ash, pecan, willow oak (east); more forest in north, more cropland/pasture in south
Western Gulf Coastal Plain	Floodplains and Low Terraces	pecan, water oak, southern live oak, elm, bald cypress, widespread conversion to cropland/pasture
Western Gulf Coastal Plain	Lower Rio Grande Alluvial Floodplain	Texas ebony, Texas palmetto, sugar hackberry-cedar elm (small parcels)
South Central Plains	Floodplains and Low Terraces	water oak, willow oak, sweetgum, blackgum, elm, red maple, southern red oak, swamp chestnut oak, loblolly pine, baldcypress, water tupelo
South Central Plains	Red River Bottomlands	water oak, sweetgum, willow oak, southern red oak, eastern redcedar, blackgum, blackjack oak, overcup

		oak, river birch, red maple, green ash, American elm (historically), now widely converted to cropland/pasture

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Other maps investigated during the review process were compiled to show the distribution of land cover and land use. The mapped categories include broad vegetation classes but do not focus on riparian vegation. The most recent available products are the 1992 National Land Cover Dataset (NLCD) and the MODerate-resolution Imaging Spectroradiometer (MODIS) Land Cover Classification. A new National Land Cover Dataset representing conditions in 2001 is in production at the USGS. Three of the five map regions encompassing Texas are slated for release in late 2005; the other regions are not yet in production and may be delayed for more than a year. The MODIS Land Cover product is available for 2001 and 2002. It is not known when additional updates will be published.

The 1992 NLCD, derived from imagery collected with the Landsat 5 Thematic Mapper instrument, characterizes 21 land cover classes, including three forested upland classes, one shrubland class, one herbaceous upland class, five planted or cultivated classes, and two wetlands classes. The wetlands classes, based on definitions adopted by the National Wetlands Inventory (NWI) consist of woody wetlands, periodically saturated areas with 25 to 100 percent forest or shrubland canopy cover, and emergent herbaceous wetlands, periodically saturated areas with 75 to 100 percent perennial herbaceous vegetation (Cowardin *et al.* 1979). The 2001 NLCD classification is similar, with the same general definitions for upland forest, shrubland, and herbaceous classes. The cultivated classes are reduced to two. Each wetlands class has been subdivided into four additional classes for all coastal mapping regions. The additional eight class subdivisions are also based on the NWI classification system. Two Texas mapping regions will include the additional classes. Source data for the 2001 NLCD consist of triplicate dates of Landsat 7 Enhanced Thematic Mapper-Plus data ranging in dates from 1999 to 2002, supplemented with Thematic Mapper data as needed. Both datasets use a 30 meter ground cell mapping resolution. The NLCD products, used in conjunction with other GIS data layers such as the National Hydrography Dataset, may serve as useful starting points for future Texas-based riparian vegetation mapping projects. However, the land cover classes are too generalized and the products themselves too dated for immediate assessment of current riparian conditions. More information about both NLCD programs is available at http://www.mrlc.gov .

The MODIS Land Cover Classification uses the International Geosphere-Biosphere Programme (IGBP) global vegetation classification scheme mapped to a one-kilometer ground cell resolution (Friedl *et al*., 2002). The scheme includes eleven natural vegetation cover types –

five forest classes, two shrubland classes, two savanna classes, one grasslands class, and one permanent wetlands class. In addition, one class is designated as a mosaic of cropland and natural vegetation. Three to four other related classification schemes are included in the product. The MODIS Land Cover Classification shows promise, in part because of its use of seasonal time series data and supervised decision trees for class definition. With daily data collections, the product can be refined and regenerated more frequently and rapidly than the NLCD. However, the product has serious limitations for the assessment of riparian vegetation in Texas. The scope of the product is to map global vegetation trends; therefore, the dataset's suitability for smaller regional applications is questionable. The classification schema does not explicitly represent the riparian environment and the product has not been validated for use in Texas. Most importantly, the one kilometer mapping unit cannot capture the variation within the narrow riparian corridors of West and Central Texas. More information about the MODIS Land Cover Classification products is available at http://modis-land.gsfc.nasa.gov/landcover.htm and http://geography.bu.edu/landcover .

Two national biological programs that hold great promise for vegetation mapping have yet to yield results for Texas. Both programs are sponsored by the US Geological Survey (USGS). The Gap Analysis Program is concerned with the inventory of native species and natural land areas within the United States and the preservation of biodiversity (USGS, 2005a). One of the program's five primary objectives was to map the nation's land cover. The status of the Texas Gap Analysis program is difficult to determine at present. The land cover map has not been published to date. Although other states have successfully completed the program, Texas may never fully realize its intended benefits. The National Biological Information Infrastructure (NBII) is a related program (USGS, 2005c). The intent of the NBII is to serve as an information clearinghouse rather than to guide a national project. The program highlights biodiversity and invasive species as current biological issues. Vegetation mapping is critical to the understanding of both topics. Riparian vegetation would be an essential component of any mapping effort, but few products are available at present.

In recent years, more mapping resources have been focused on the issue of invasive species. Some generalized maps of species distributions are available. An example is the US distribution of the Giant and Common Salvinia, aquatic invasive species (USGS, 2005b). Attempts have been made to map occurrences of saltcedar in the US Southwest. However, detailed mapping is limited, mapping methods are inconsistent, temporal content may vary, and few species are represented. An attempt to incorporate single species map products into a comprehensive statewide map seems inadvisable at present.

4.2 Information about Types of Riparian Vegetation in the State of Texas and their Geographic Distribution.

The Texas Parks and Wildlife Department has conducted many vegetation assessments within Texas with a focus on the condition of riparian vegetation and other wetlands. The companion report to the map of the Vegetation Types of Texas includes brief descriptions of species associated with the vegetation communities whose geographic distribution is presented in the map. The map and report are frequently cited in TPWD publications. In subsequent work based on the Vegetation Types of Texas, Frye (1987) quantified the geographic distribution of bottomland hardwoods in Texas at 5,973,000 acres, excluding 95,000 acres of swampland. An estimated 1,169,000 acres of forested wetlands were located along the Trinity, Neches, Sabine, Sulphur, and Angelina rivers and the Cypress Bayou. Another 3,062,000 acres lined river tributaries and riparian drainages east of the Navasota River. The remaining 1,742,000 acres of riparian forest was found in other Texas rivers, creeks, and riparian drainages. Subsequent studies conducted at TPWD, Texas A&M University, and the US Forest Service have measured changes in the bottomland hardwood population. In 1990, TPWD and the US Fish and Wildlife Department published an assessment of the impacts of new reservoir construction on wildlife habitat, also based on earlier vegetation mapping projects. In an undated Texas Parks and Wildlife Department publication, Wagner reviews riparian habitats of Texas with brief characterizations of vegetation and general indications of the quantity of riparian vegetation. The habitats are organised by natural areas (Gould *et al*., 1960). Table 3 summarizes Wagner's

Table 3: Vegetation of riparian habitat by natural area from Wagner (Undated TPWD Report).

Natural Area	**Representative Riparian Species**	**Other comments**
Rolling Plains	cottonwood, willow, hackberry, soapberry or locust, associated with persimmon, bumelia, and mesquite	Riparian habitat accounts for 2-5% of wildlife habitat in the High Plains and Rolling Plains
High Plains	unwooded, entrenched draws, frequently dominated by invasive salt cedar	See above
Central Texas/Edwards Plateau	bald cypress and sycamore; pecan and hackberry; hackberry and elm	netleaf hackberry/little walnut; plateau live oak/netleaf hackberry; and sycamore/willow communities predominate in smaller creeks of western Plateau
Trans-Pecos	deciduous riparian woodlands contain ash, cottonwood, willow, walnut, and hackberry communities; shrub or	Riparian habitat in Rio Grande and Pecos River drainages accounts for

	scrubland has understory of mesquite/acaci, and sumac, and overstory of cottonwoods, willows or ash	<5% of wildlife habitat; great vegetation diversity
South Texas	mesquite, retama, granjeno, anacua (Rio Grande), live oak, cedar elm, hackberry, and whitebrush	Riparian habitat found along Nueces River and Rio Grande and associate tributaries
Pineywoods and Post Oak Savanna	Lower floodplains: willow oak, green ash and overcup oak; upper flood plains: water oak, cherrybark oak and sweetgum; swamps: bald cypress and water tupelo	No additional comments

report findings. Land use activities that impact the quality of riparian wildlife habitat include grazing, farming and timber production. Signs of negative impacts include bank destabilization, erosion, topsoil loss caused by removal of perennial native vegetation, and tree harvesting along drainage banks. Recommended mitigation practices are improved grazing strategies, the establishment of wide riparian zones in areas of cultivation, and the implementation of sound streamside management in silvaculture zones. Any future inventory of riparian vegetation conditions should assess both negative and positive impacts. The Texas Wetlands Conservation Plan (TPWD, 1997) and the recently published Land and Water Resources Conservation and Recreation Plan (TPWD, 2005) are also based on vegetation assessments conducted at the agency.

Griffith *et al.* (2004) provide a rich bibliography of sources related to the distribution of natural vegetation in Texas, as does Bezanson (2000). It may be possible to tease out information related to riparian vegetation with a thorough review of cited references. Bezanson (2000) identified 120 natural vegetation communities in Texas. Figure 3 shows Bezanson's compilation of the natural areas of Texas as delineated by Gould *et al*. (1960) with revisions based on other sources. Vegetation communities are organized by natural areas. Of the 120 vegetation communities, at least 37 contain riparian elements (Table 4), not including other wetland environments, such as playas, bogs, coastal marshes. Bezanson presents an exhaustive list of woody and herbaceous species associated with the named plant communities. Table 5 is a compilation of his findings for each identified community, with geographical notes where available. For each natural area of Texas, Bezanson presents lists of protected areas and the percent of each vegetation community represented in each area. Although no maps of the vegetation communities are included, it would be possible to infer the distribution of riparian species within the protected areas. The publication includes an extensive bibliography of regional and local surveys, reports and research. Although Bezanson's work represents an excellent reference about the distribution of riparian species in Texas, his focus is on conservation areas and native species and does not constitute a quantitative assessment of conditions in disturbed areas.

In the arid west, some invasive riparian vegetation is subject to removal. Phreatophytes such as saltcedar are considered to be pest species that transform native habitat, establish monocultures, increase stream salinity, and reduce water flows (TAES, 2003). Saltcedar has been removed along the Pecos River in West Texas, and studies of the effects of the vegetation removal are ongoing (Clayton *et al.,* 2000; Hart *et al.*, 2005). Other brush control projects in Texas focus on upland vegetation, primarily Ashe juniper and mesquite, and do not directly

Table 4: Riparian vegetation communities by region as described in Bezanson (2000).

Natural Area of Texas	Vegetation Type #	General Description
East Texas Pineywoods	9	Forested acid seeps/wet creeksides
	10b	American beech mesic slope forests
	12	Forested depressional wetlands (baygalls)
	14	Swamp chestnut oak-oak floodplain forests
	15a	Floodplain hardwood forests
	15b	Frequently inundated floodplain forests
	16	Sloughs/seasonally flooded floodplain forests
	17	Bald cypress-tupelo inundated forests
	18	Freshwater shrub swamps
	19	River banks
Post Oak Savannas	25	Water oak floodplain forests
	26	Sugarberry-elm floodplain forests
Blackland Prairies	32	Bur oak-Shumard oak mesic (or floodplain) forests
Gulf Coast Prairies and Marshes	37	Live oak-water oak floodplain forests
South Texas Plains	61a	Wetland brush
	63a	Texas ebony floodplain forests
	63b	Texas palmetto floodplain forest
	64	Sugarberry-elm floodplain forests (South Texas Plains)
	65	Sugarberry-elm floodplain forests (Lower Rio Grande Valley)
Edwards Plateau	72	Deciduous mesic canyon forests
	73	Limestone bluffs and seeps
	75	Spring-fed streams (Edwards Plateau)
	76a	Pecan-elm floodplain woodlands (Edwards Plateau)
	77	Streambeds
	78	Bald cypress riparian woodlands
	79	Netleaf hackberry-plateau live oak floodplain woodlands
Prairies and Cross Timbers	76b	Pecan-elm floodplain woodlands (Cross Timbers)
Rolling Plains	87	Mesquite floodplain brush
	88	Cottonwood-willow riparian woodlands
West Texas	95	Saline or alkaline wetlands
	101	Mesquite thickets
	102	Cottonwood-willow riparian woodlands
	103	Arroyo scrub
	108	Riparian shrublands
	110	Spring-fed streams/cienegas
	114	Canyon riparian woodlands
	117	Deciduous canyon forest

Table 5: Examples of riparian plant communities in Texas as compiled by Bezanson (2000).

East Texas Pineywoods

9. Forested acid seeps/wet creeksides
Woody species: *blackgum, sweetbay, titi,red maple, red bay, hollies, evergreen bayberry, Elliott's blueberry, sweetgum, azaleas, poison sumac, other evergreen shrubs; occasional pines and southern magnolia; possomhaw viburnum, smooth alder, Elliott's blueberry, southern wax-myrtle to north and west*
Other species: *ferns, beaksedges, sphagnum, club mosses*

10b. American beech mesic slope forests
Dominant species: *American beech*
Associated species: *white oak, maple, other hardwoods*
Geographical note: *limited distribution; found in sandy, calcareous slopes, ravines, and creeksides from Sabine County to Jasper, Newton, and Tyler counties; western extent of some southeastern forbs (not described)*

12. Forested depressional wetlands (baygalls)
Dominant overstory species: *swamp gum, laurel oak*
Common associated species: *red maple, sweetbay, gallberry holly, Carolina ash, titi, mayhaw, bald cypress, Virginia sweetspire, southern wax myrtle, greenbriar, sedges, cinnamon fern, sphagnum, rare orchids, saprophytic forbs*
Aquatic species: *Carolina water hyssop, waterlily*
Geographical note: *floodplain margins of Jasper, Hardin, Newton, and Tyler counties*

14. Swamp chestnut oak-oak floodplain forests
Woody and other species: *Loblolly pine, swamp chestnut oak, cherrybark oak, sweetgum, blackgum, willow oak, southern red oak, green ash, laurel oak, red maple, American elm, deciduous holly, hornbeams, Sebastion bush, partridgeberry*

15a. Floodplain hardwood forests
Common dominant species: *water oak, sweetgum, willow oak, American hornbeam, elm, hophornbeam, blackgum, southern red oak, loblolly pine, river birch, deciduous holly, poison ivy, muscadine grape, Virginia creeper, rattan vine, crossvine, greenbriar, violet, St. John's wort, Sebastian bush, longleaf spikegrass, ferns, mosses; occasional giant cane stands*
Co-dominant species in Southern East Texas: *laurel oak, swamp chestnut oak, southern magnolia*

15b. Frequently inundated hardwood forests
Overstory species: *Willow oak, overcup oak, bottomland post oak, elms, green ash, sweetgum*
Understory species: *Dwarf palmetto*

16. Sloughs/seasonally flooded floodplain forests
Common dominant species: *water hickory, planer tree, overcup oak, sweetgum, swamp privet, green ash, Carolina ash, red maple, mayhaw, buttonbush, lizard's tail, sedges, cutgrass, water willow, smartweed*

17. Bald cypress-tupelo inundated forests
Dominant species: *bald cypress, water tupelo*

Common associated species: *red maple, Carolina ash, buttonbush, water hickory, planer tree, sweetgum, swamp privet, common persimmon*
Other species: *Spanish moss, water millefoil, water pennyworts, water willows, false nettle, cypress swamp sedge, lizard's tail, water primroses, other floating leaf aquatic plants*

18. Freshwater shrub swamps
Dominant species: *buttonbush*
Common associated species: *green ash, smartweeds, water willows, sedges, water primroses, grasses, lizard's tail, black willow, smooth alder, river birch*

19. River banks
Common species: *Black willow, sycamore, eastern cottonwood, green ash*
Non-native species: *giant reed, planted grasses*

Post Oak Savannas

25. Water oak floodplain forests
Dominant species: *water oak*
Associated overstory species: *American elm, green ash, sugarberry and other woody floodplain species*
Understory species: *grapevine, poison ivy, rattan vine, switchcane, sedges, Virginia wildrye, other grasses*

26. Sugarberry-elm floodplain forests
Overstory species: *cedar elm, sugarberry, green ash, American elm, box elder, pecan, western soapberry, eastern cottonwood, sycamore, occasional bald cypress*
Understory species: *Virginia creeper, rattan vine, poison ivy, peppervine; in undisturbed areas, longleaf spikegrass, sedges, switchgrass, Virginia wildrye, coralberry, white avens, ruellia, Turks cap; in disturbed areas, giant ragweed and other weedy forbs*
Geographical note: *also common in Blackland Prairies, Cross Timbers, Coastal Prairies, northern South Texas, eastern Edwards Plateau, and Rolling Plains*

Blackland Prairies

32. Bur oak-Shumard oak mesic (or floodplain) forests
Dominant species: *bur oak, shumard oak, elm, pecan, green ash, sugarberry, eastern cottonwood*
Associated species: *yaupon, roughleaf dogwood, elderberry, bois d'arc, Virginia wildrye, sedges, rattan vine, Virginia creeper, peppervine, autumn bluegrass, low ruellia, frostweed, and other floodplain forbs*

Gulf Coast Prairies and Marshes

37. Live oak-water oak floodplain forests
Dominant species: *live oak, in swamps, green ash, black willow, swamp privet, sedges, smartweed*
Co-dominant species: *pecan, water oak, bald cypress on larger streams*
Associated species: *sugarberry, elm, dwarf palmetto, gum bumelia, bois d'arc, holly, grapevine, rattan vine, Virgina creeper, poison ivy, basketgrass, longleaf spikegrass, Cherokee sedge*

South Texas Plains

61a. Wetland brush
Dominant species: *huisache, mesquite, retama*

Associated species: *seep-willow, baccharis, rattlebush, bermudagrass, Guineagrass, silver bluestem, knotroot bristlegrass, buffalograss, Texas virgin's bower, western ragweed, spiny aster, blueweed sunflower, flatsedges, dwarf spikesedge, cattail, bulrush; black mimosa, amantillo, black willow, hairy panicum, common reed, giant reed in the Lower Rio Grande Valley*
Note: *found in disturbed wet areas such as depressions, streamcourses, resaca banks*

63a. Texas ebony floodplain forests
Overstory species: *Texas ebony, anacua, tepeguaje, coma, tenaza, mesquite, sugarberry*
Mid- and understory species: *snake-eyes, lotebush, brasil, granjeno, colima, Barbados cherry, chapotillo, crucillo, tropical heartseed, snailseed, pigeonberry, serjania vine, sparse ground cover*
Geographical note: *found in alluvial bottomland of Lower Rio Grande Valley in Hidalgo and Cameron counties on natural levees adjoining resacas and river channels; rarely found due to human intervention*

63b. Texas palmetto floodplain forest
Dominant species: *Texas palmetto and sometimes tepeguaje*
Associated species: *sugarberry, tepeguaje, Texas ebony, anacua, tenaza, colima, snake-eyes, lotebush, mesquite, granjeno*
Geographical note: *found in lower delta of the Rio Grande on floodplain ridges; exceedingly rare because of widespread clearing in early twentieth century*

64. Sugarberry-elm floodplain forests (South Texas Plains)
Dominant species: *hackberries, live oak, cedar elm, huisache, pecan, Mexican ash, boxelder, mesquite, western soapberry, granjeno, black willow, eastern cottonwood*
Understory species: *peppervine, grapevine, creek oats, Virginia wildrye, Texas wintergrass, bristlegrass, pigeonberry*
Geographical note: *found along Frio and Nueces rivers*

65. Sugarberry-elm floodplain forests (Lower Rio Grande Valley)
Dominant species: *sugarberry, cedar elm, Mexican ash*
Understory species: *tepeguaje, anacua, Barbados cherry, granjeno, brasil, Texas persimmon, coma, snailseed, serjania vine, pigeonberry, Texas virgin's bower, violet ruellia*
Geographical note: *found along lower Rio Grande; possibly in decline due to flood control and diversion*

Edwards Plateau

72. Deciduous mesic canyon forests
Overstory species: *slippery elm, chinquapin oak, other hardwoods in sheltered stream canyons in southern plateau; bigtooth maple, chinquapin and other oak species in riparian stringers in Bandera and neighboring counties and Bell County*
Note: *limited distribution*

73. Limestone bluffs and seeps
Woody species: *Texas persimmon, Mexican buckeye*
Other species: *wand butterfly bush, cedar sage, shrubby boneset, sunflower goldeneye, Lindheimer rock daisy, lip fern, cliffbrake fern, mock orange and other endemic species, southern maidenhair, southern shield fern*
Note: *occurrences in exposed limestone streambeds and canyon bluffs*

75. Spring-fed streams (Edwards Plateau)
Herbaceous species: *sedges, switchgrass, big muhly, bushy bluestem, other graminoids on stream banks*

76a. Pecan-elm floodplain woodlands (Edwards Plateau)
Dominant species: *pecan, American elm, sugarberry, plateau live oak in floodplain; eastern cottonwood, sycamore, black willow along river banks*
Groundcover species: *Virginia wildrye and other grasses, caric sedges, Turk's cap, frostweed*
Geographical note: *examples occur along Guadalupe, Colorado, and South Llano rivers and other sites*

77. Streambeds
Dominant species: *sycamore, ash, willow, walnut, Roosevelt weed, buttonbush, switchgrass, busy bluestem, spike sedge, rushes*
Geographical note: *also found in frequently flooded or scoured limestone streambeds, washes and stream terraces in the Cross Timbers, adjacent areas of the Blackland Prairie and South Texas; species occurrence also along semi-perennial streams in the Rolling Plains and South Texas*

78. Bald cypress riparian woodlands
Dominant species: *bald cypress along frequently flooded perennial streams*
Associated species: *deciduous floodplain forests, oak-juniper woodlands on adjacent terraces*
Geographical note: *widespread on Guadalupe, Frio, Medina, Blanco, and Colorado rivers*

79. Netleaf hackberry-plateau live oak floodplain woodlands
Dominant overstory species: *netleaf hackberry, plateau live oak, pecan, little walnut, ash*
Understory species: *Texas persimmon, Texas mountain laurel, Mexican buckeye*
Associated species: *juniper and oak, mesquite, acacias in adjacent woodlands*
Geographical note: *found in western Edwards Plateau and South Texas west to Pecos River*

Prairies and Cross Timbers

76b. Pecan-elm floodplain woodlands (Cross Timbers)
Dominant species: *bur oak, elm, pecan, hackberry, western soapberry in floodplain in Cross Timbers; mesquite, little walnut, netleaf hackberry, brush species in Rolling Plains along Colorado River; eastern cottonwood, sycamore, black willow along river banks*
Groundcover species: *switchgrass, Torrey rush, western ragweed, smartweed species, warty spurge, plains coreopsis*

Rolling Plains

87. Mesquite floodplain brush
Woody species: *mesquite, western soapberry, netleaf hackberry*
Understory species: *skunkbush, littleleaf sumac, tasajillo, lotebush, saltbush species*
Geographical note: *found in small bottomlands and drainages in southern Rolling Plains; widespread saltcedar encroachment with resulting dominance*

88. Cottonwood-willow riparian woodlands
Woody species: *plains cottonwood, black willow, hackberry, sandbar willow, seep willow, western soapberry along streams and springs*
Groundcover species: *switchgrass, Indian grass, grama species, bluestem species, dropseed species, barnyardgrass, western wheatgrass, vine mesquite, non-native grasses in bottomlands*
Geographical note: *widespread saltcedar encroachment with resulting dominance; similar cottonwood and willow woodlands found along creeks, seeps and wet playas found in High Plains*

West Texas

95. Saline or alkaline wetlands

Associated species: *salt grass, sacaton, seepweed, prairie cordgrass in moist saline soils along stream drainages; Olney bulrush, sedge species, bordered sea lavender, puzzle sunflower(rare), clasping flaveria (rare) along perennial desert springs and creeks*

Geographical note: *limited occurrences in Panhandle and Trans-Pecos*

101. Mesquite thickets

Dominant species: *mesquite, acacia species, fourwing saltbush; saltcedar gaining dominance*

Associated species: *lotebush, creosotebush, knifeleaf condalia, weedy grasses and forbs; alkali sacaton in more saline conditions*

Geographical note: *found in low saline soils near streams, arroyos, and basins in floodplains of the Rio Grande and the Pecos River*

102. Cottonwood-willow riparian woodlands

Dominant species: *Arizona cottonwood, Rio Grande cottonwood, Gooding willow, willow species*

Associated species: *ash, mesquite, acacia, seep willow, desert willow, arrowweed, spiny aster, little walnut, Mexican buckeye, whitebrush*

Geographical note: *limited distribution in Trans-Pecos; non-native bermudagrass, giant reed, tree tobacco and other species encroaching along Rio Grande*

103. Arroyo scrub

Associated species: *desert willow, Apache plume, seep willow, Roosevelt weed, splitleaf brickellia, acacia, mesquite, althorn, catclaw mimosa, dalea, granjeno, burrobush, mariola, little walnut, stool, guayacan, spiny greasebush, netleaf hackberry in Trans-Pecos; whitebrush, desert willow, splitleaf brickellia in southwest Edwards Plateau drainages*

Geographical note: *found in and along arroyos, washes, sheet drainages*

108. Riparian shrublands

Woody species: *little walnut, desert willow, netleaf hackberry in intermittent streams; apache plume, splitleaf brickelia, seep willow, willow species, granjeno, acacia species, mesquite, ash species, whitebrush, agarito, scrub oak, Mexican buckeye, Texas persimmon, lotebush in dryer conditions*

Geographical note: *widespread in drainages of Trans-Pecos and western Edwards Plateau*

110. Spring-fed streams/cienegas

Associated species: *spikesedge, sawgrass, caric sedge, Torrey rush, western umbrella sedge, brookweed, water bentgrass in cienegas; prairie wedgegrass and other grasses on stream banks*

Note: *increasingly rare*

114. Canyon riparian woodlands

Associated species: *velvet ash, netleaf hackberry, oak species, little walnut, Mexican buckeye, granjeno, agarito, sumac, acacia, esperanza, scarlet bouvardia in canyon bottoms; occasional bigtooth maple; Apache plume, splitleaf brickelia, seep willow in streambeds*

Geographical note: *local occurrences in Big Bend National park and Big Bend Ranch State Park*

117. Deciduous canyon forest

Associated species: *gray oak, Gambel oak, Emory oak, alligator juniper, evergreen sumac, Texas madrone, beargrass, Arizona grape, other grass, sedge and forb species; occasional occurrence of bigtooth maple, chinquapin oak, western hophornbeam in Trans-Pecos*

Geographical note: *limited distribution in Davis, Chisos, Glass, Vieja, and Diable mountains*

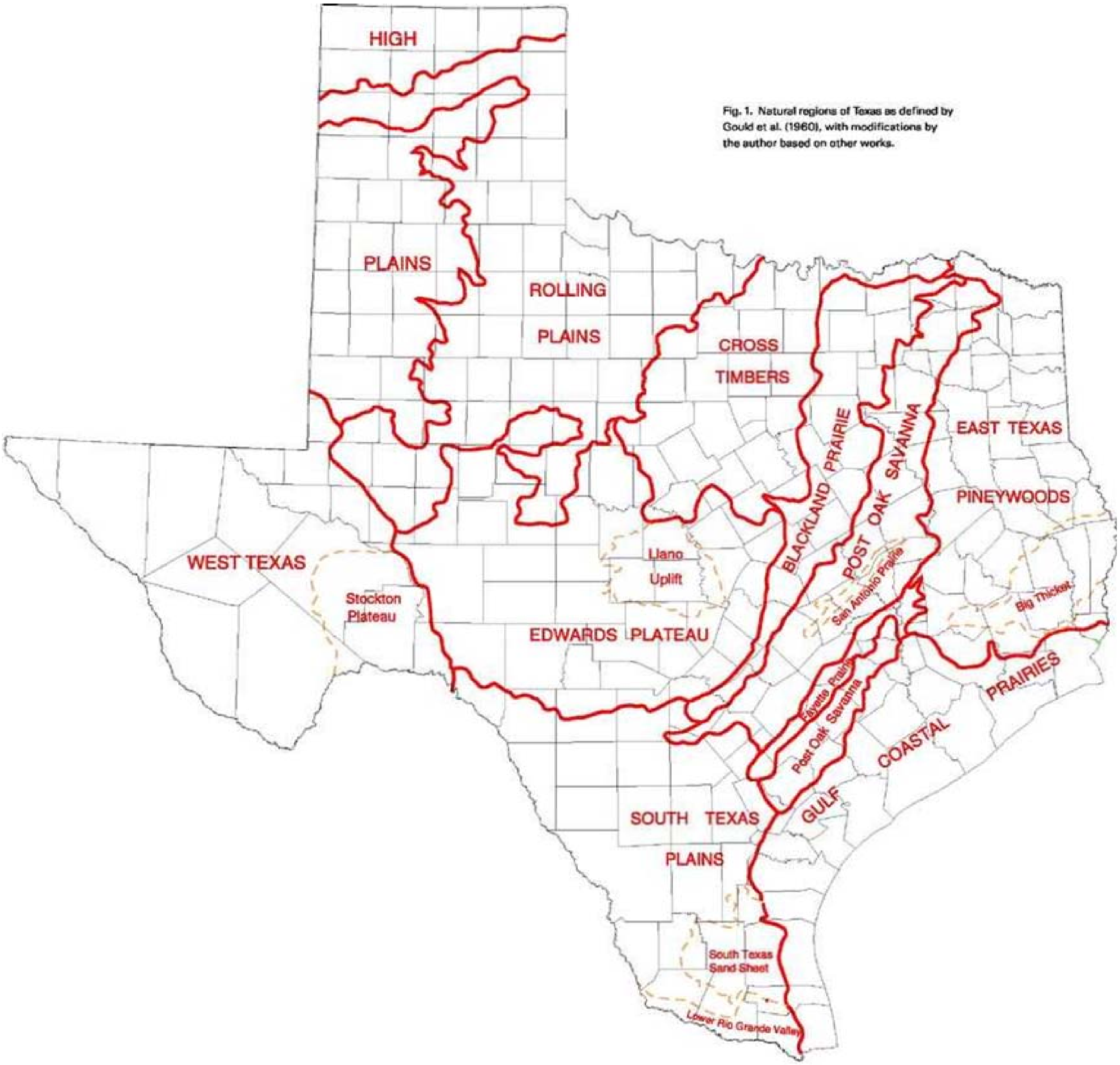

Figure 3. Natural Areas of Texas (Gould *et al.*, 1960) with modifications by Bezanson from Bezanson (2000).

impact vegetation in the riparian zone although the scope of such projects is to increase water flows.

It is beyond the scope of the report to conduct a thorough review of all published studies and resources relating to riparian vegetation in Texas, but a brief mention of some regionalized studies may offer a glimpse of the effort required to compile a comprehensive overview. Watts (1998) mentions the paucity of studies and surveys of riparian vegetation or habitat along the Rio Grande from Elephant Butte to Fort Quitman, although extensive work has been done downstream in Big Bend National Park. Lonard *et al.* (2000) report on riparian zone vegetation in two small sites along the Rio Grande in Starr and Cameron counties, and also lament the lack of previous research. Perhaps more representative of the research that may need to be investigated are the publication by Negrete *et al.* (2002) reporting on vascular species of the Texas Gulf Coast, county reports of flora conducted by governmental agencies and universities (Neill, 2000; Singhurst *et al.*, 2003), and botanical compendiums (Hatch *et al.*, 1990). The level of information about riparian vegetation will vary significantly from source to source. Online resources about the vegetation species of Texas may be a helpful resource. Texas A&M University and the US Department of Agriculture host plant databases. Some sites include maps of geographic distribution by region or county. Others may have more limited geographical information. Such guides are generally organized by botanical taxonomy and do not group species by community or landscape feature, although the USDA Plants Database features a search by state and wetlands indicator status.

4.3 Data Sources Appropriate for Improved Mapping of Riparian Vegetation in the State of Texas.

A number of new satellite and aerial sensors suitable for vegetation mapping have become available since the last state-wide mapping effort undertaken by TPWD in the late 1970s. In addition, the federal and state government have invested in the development of the National Spatial Data Infrastructure. Some of the resulting GIS data layers would significantly enhance riparian vegetation mapping. A list of available resources follows. A brief discussion of the data type, spatial and temporal resolution, availability and appropriate use is included.

Multispectral Remote Sensing Resources:

Multispectral sensors measure reflected light in the visible and shortwave portions of the electromagnetic spectrum. Satellite sensors image the earth from orbit. Most collect data from a pre-ordained path, but others are pointable and may be programmed to image a location from an off-nadir angle. Operational sensors collect data at predetermined times and places and usually guarantee repeat coverage of any given target area. Mission-specific and experimental sensors generally operate less frequently and may not provide complete coverage of a region. Generally, US government programs provide public domain data and data products at reasonable costs. Other government programs, notably the European, French, Indian and Canadian programs, view products as a commodity and may also restrict data use through licensing. Commercial for-profit operations generally collect data as specified by paying customers, and may not provide complete coverage of a region of interest, although most provide archive data at reduced costs.

Moderate-Resolution Imaging Spectroradiometer (MODIS)

Two MODIS sensors are in operation at present on board NASA’s Terra and Aqua satellites. MODIS images the earth in wide swaths; two daytime passes over mid-latitude locations are common, one in mid-morning and another in the early afternoon. Good nadir acquisitions occur less frequently. MODIS collects data in the visible red and the near infrared channels, frequencies used to construct vegetation indices, at the approximate ground cell size of 250 meters. Another five multispectral channels, ranging from the visible blue to the shortwave infrared, are collected at the ground cell size of 500 meters. An additional 29 channels collect data designed for oceanographic and atmospheric applications at a resolution of 1000 meters. MODIS data reside in the public domain and are distributed electronically by NASA and USGS at no cost. The University of Texas Center for Space Research (CSR) acquires the MODIS direct broadcast in near real time, and maintains a large archive for Texas, dating from the summer of 2000. MODIS data are too coarse spatially to effectively map riparian corridors in great detail. However, they provide a low-cost means to map environmental changes over time, and may prove useful for regional ecological mapping. It would be beneficial to attempt a Texas-centric land cover classification with MODIS time series data in conjunction with other geospatial data resources for comparison with the maps of Texas vegetation and ecoregions. More information about the MODIS sensor can be obtained from the NASA MODIS site at http://modis.gsfc.nasa.gov.

The Landsat Program

The Landsat Project, sponsored by the US government program and currently managed by the USGS, launched the first Landsat satellite in 1972. At present, two Landsat satellite sensors are in orbit and imaging the earth on an operational basis. Data collected by the Landsat instruments are a primary resource for regional vegetation mapping.

Landsat Thematic Mapper (TM)

Since July 1982, the Landsat 5 TM sensor has collected data along a 183 kilometer (115 mile) swath on a 16-day repeat cycle. The TM data sensor images the earth in seven multispectral bands. Six multispectral bands (1-5 and 7) are collected at 30 meter resolution, and one thermal infrared band (6) is collected at 120 meter resolution. CSR maintains a fairly extensive archive of Texas TM data. More information about Landsat 5 is available at: http://edc.usgs.gov/guides/landsat_tm.html.

Landsat Enhanced Thematic Mapper-Plus (ETM+)

The Landsat 7 ETM+ satellite was launched in April 1999 and collects data on a 16-day repeat cycle. The 183 kilometer (115 mile) swath width data are collected in eight bands. Six multispectral bands (1-5 and 7) are acquired at 30 meter resolution, one panchromatic band (8) at 10 meter resolution, and one thermal infrared band (6 and 9, the band is split based on gain differences) at 60 meter resolution. On May 31, 2003, Landsat 7 experienced a failure of the Scan Line Corrector (SLC), a device that accounts for the forward motion of the satellite.

Although the satellite remains operational, the mechanical failure has restricted the acquisition of high quality data to an approximately 22 kilometer wide strip in the middle of the swath. CSR maintains a multi-date SLC-on archive of ETM+ data for all of Texas. Although a replacement for the ailing Landsat 7 has yet to be determined and Landsat 5 is not guaranteed to continue long-term data collection, it may be feasible to conduct a regional assessment of riparian vegetation in Texas using data from the CSR archive. The spatial resolution of the data will impede reliable identification of vegetation types in some parts of Texas, as is noted in the results of previous studies in the methodology section. For more information about SLC-off Landsat 7 data, including a sample image, see http://landsat.usgs.gov/slc_enhancements/slc_off_background.php. General information about Landsat 7 is available at: http://landsat.usgs.gov/.

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)

ASTER is an experimental sensor developed in Japan. It resides on the same NASA Terra satellite as MODIS. ASTER data are publicly available. The sensor collects 14 bands of data with a swath width of 60 kilometers (37 miles). The visible and near infrared bands (1-3) are collected at 15 meter resolution, the shortwave infrared bands (4-9) are collected at 30 meter resolution, and the thermal infrared bands (10-14) are collected at 90 meter resolution. A visible blue band is not collected. Because this sensor is experimental, data are not acquired on a regular repeat cycle. Much of Texas has been imaged, but no attempt has been made to collect cloud-free imagery for the entire State. CSR maintains an archive of ASTER data collected over Texas. The 15-meter ASTER data are of high quality, and should be exploited for mapping vegetation. However, it would be difficult to conduct more than a limited project because of the lack of seasonal repeat coverage. For more information about ASTER data, visit: http://asterweb.jpl.nasa.gov.

Satellite Pour l'Observation de la Terre (SPOT) 5

The French satellite SPOT 5 became operational in 2002 and follows in the same orbit as its predecessors: SPOT 1, SPOT 2, and SPOT 4. SPOT 5 is a mission-specific pointable satellite sensor with a swath width of 60 kilometers (37 miles). SPOT 5 passes over the same area every 26 days but does not collect data on a continual basis. One panchromatic band is collected at 2.5 meter resolution, two visible bands (red and green) and one infrared band are collected at 10 meter resolution, and one shortwave infrared band is collected at 20 meter resolution. SPOT 5 data are distributed through the commercial vendor SpotImage. SPOT 5 data may be cost prohibitive for a statewide mapping project. Licensing restrictions impede data sharing. However, the pushbroom technology developed for the SPOT program yields data of a very high quality. Currently, the Texas Forest Service is working with SPOT 5 data to characterize fuel loads in East Texas. More SPOT 5 information is available at http://spot5.cnes.fr/gb/index2.htm.

SPOT Vegetation

The French SPOT VEGETATION instrument was first launched onboard the SPOT 4 satellite in 1998. At present, SPOT 5 carries an advanced version of the sensor called VEGETATION 2 that acquires data with a 2250 kilometer wide swath. This sensor collects three spectral bands, two visible and one shortwave infrared, all at 1 kilometer resolution. These bands can be used for constructing vegetation indices. Additionally, VEGETATION 2 collects another band at 1 kilometer resolution in the visible range to correct atmospheric effects in the other three bands. Some SPOT VEGETATION products are freely available, although most require registration with the commercial vendor, SpotImage. SPOT Vegetation products, like those of MODIS, are likely too coarse for delineation of riparian features. However, they may be useful resources for vegetation mapping planning. More information about SPOT VEGETATION can be found at http://spot-vegetation.com/.

Indian Remote Sensing Satellite IRS-P6 (RESOURCESAT-1)

For the past two decades, the Indian national space agency has sponsored research into Landsat-style multispectral remote sensing satellites. Launched in 2003, the IRS-P6 RESOURCESAT-1 carries an Advanced Wide Field Sensor (AWiFS) that collects imagery in four spectral bands with a ground resolution of 56 meters along a 740 kilometer swath. Three bands are collected in the visible and near infrared, while a fourth band records shortwave infrared radiation. The imagery from RESOURCESAT-1 may be particularly well-suited for studies of riparian vegetation because the wide image swath ensures a frequent repeat cycle of coverage, with the same surface location imaged every 4-5 days. The increased frequency of observations raises the chances that important phenological changes can be traced under relatively cloud-free conditions. RESOURCESAT-1 products are available through Antrix Corporation Ltd., the commercial distribution arm for IRS, which releases imagery of North

America through their channel partner, Space Imaging (http://www.spaceimaging.com). For more information on RESOURCESAT-1 see: http://www.isro.org/pslve5/index.html.

Indian Remote Sensing Satellite IRS-P5 (CARTOSAT-1)

The IRS-P5 CARTOSAT-1, launched in the spring of 2005, is the first Indian Remote Sensing Satellite to collect high-resolution imagery comparable to that acquired by commercial high resolution satellites. Two panchromatic cameras collect imagery with a 2.5 meter ground resolution along a 30-kilometer swath. The dual panchromatic imaging system permits collection of stereographic imagery that can be used to extract surface elevation data from image pairs. CARTOSAT-1 may prove to be a source of economical, high-quality digital surface models for riparian environments. For more information on CARTOSAT-1 see: http://www.isro.org/Cartosat/Page3.htm.

High Resolution Satellite Sensors

Several high resolution satellite sensors collect multispectral data. Increased competition has lowered pricing, although not significantly. Licensing restrictions for governmental agencies have loosened in recent years to allow for mandated data sharing among cooperating organizations. Although current available sensors collect data in a limited number of multispectral channels, the increased bit depth afforded by the technology prevents data loss in areas of very high or low reflectance. It may be many years before it is feasible to conduct a statewide mapping project using high resolution satellite data as the sole image resource.

IKONOS

IKONOS is a high resolution commercial satellite put into orbit by Space Imaging in September 1999. This sensor acquires one band of panchromatic data at 1 meter resolution and four bands of spectral data at 4 meter resolution. The revisit time is every three days within a fairly wide collection angle window. Nadir repeat collections are infrequent. A typical IKONOS product covers a twelve by twelve kilometer extent. The data are costly and protected by copyright. Archival data can be obtained at a slightly reduced price but complete regional coverage most likely does not exist. IKONOS is a programmable, pointable sensor; consequently many images are collected at relatively high angles from nadir. A variety of

IKONOS data products are available for purchase through Space Imaging and approved resellers. More information is available at: http://www.spaceimaging.com/products/ikonos/.

QuickBird

QuickBird is a high resolution pointable commercial satellite operated by DigitalGlobe. One panchromatic band is available at a resolution range of 61-72 centimeters (2-2.4 feet) and four spectral bands are available at a resolution range of 2.44-2.88 meters (8-9.4 feet). An image footprint covers a square bounded by 16.5 kilometers (10.3 miles) on all sides. The repeat cycle of QuickBird is approximately seven days for imagery 0-15 degrees off-nadir and four days for imagery 0-25 degrees off-nadir. Data can be ordered from archive or a collection can be specified. Imagery are available for purchase through DigitalGlobe. For more information on QuickBird products, go to http://www.digitalglobe.com/product/product_docs.shtml and view the QuickBird Imagery Products FAQ.

Leica Geosystems ADS40 Aerial Sensor System

A byproduct of research by the German space agency, Deutschen Zentrum für Luft- und Raumfahrt, the advanced ADS40 sensor produced by Leica Geosystems is the first digital aerial camera system capable of acquiring high-resolution (1-meter) imagery for large-scale projects, such as the 2004 statewide data collected for Texas by the National Aerial Agriculture Program. The ADS40 is comprised of a series of visible and near infrared line scanners that collect visible color imagery with one set of three detectors, false color infrared imagery with a second set and panchromatic imagery with two other detectors. For 1-meter image collection, the ADS40 is flown in pressurized aircraft at 27,000 feet to collect image data line-by-line across a 10.2-kilometer swath. The digital data products generated by the ADS40 are captured in much greater radiometric depth than analog film photographs, allowing features to be discerned within shadows that would otherwise be opaque. Digital data collection with high radiometric fidelity permits the ADS40 data to be used with image classification techniques that were formerly restricted to applications with more costly satellite imagery. Future aerial sensors in the ADS40 category will be five-band common aperture systems in which three visible bands, plus a near infrared band and a shortwave infrared band, will be collected simultaneously. With the ADS40, multispectral, high-resolution imagery can be economically collected for the entire state of Texas, allowing much more frequent production of map-corrected orthoimagery of the state for use in change detection studies. Rapidly changing riparian environments could be documented in greater detail and accuracy than ever before. The ADS40 instrument was used in 2004 to image Texas with one-meter color infrared data for the USDA Farm Service Agency's (FSA) National Agricultural Imagery Program (NAIP).

Other Remote Sensing Resources:

Aerial LiDAR **Systems**

Aerial LiDAR detection of vegetation canopy height can be accomplished by calculating the elevation difference between the first- and last-return records of a laser pulse in which the first laser return indicates the top of the canopy and the last return represents the closest measurement to the ground surface. Different kinds of riparian vegetation, particularly gallery forests, exhibit a distinctive height profile across a floodplain that can be distinguished by LiDAR elevation data. Recent advances in LiDAR collection technology can capture many discrete reflections from each incident laser pulse in a process known as waveform digitization. The waveform data may be used to infer structural characteristics between different canopy types, such as needle-leafed versus broad-leafed trees. The return beam intensity recorded by some LiDAR instruments can also be used to discriminate different tree crown types and densities. The Bureau of Economic Geology and CSR co-own a LiDAR sensor that has been recently equipped with a wave form digitizer.

Aerial Interferometric Synthetic Aperture Radar (IFSAR) Systems

The latest generation of aerial radar terrain mapping systems incorporate P-Band radar frequencies that are capable of penetrating vegetation canopy and X-Band frequencies that are strongly reflected by the top of the canopy. As with aerial LiDAR data, the elevation differences between the P-Band and X-Band data can be used to profile changes in canopy height within riparian environments. Some systems, such as EarthData's GeoSAR sensor, also collect data from a profiling laser altimeter to provide more accurate calibration of the IFSAR data.

Hyperspectral Resources

Hyperspectral instruments are passive optical sensors that collect data in the visible and infrared electromagnetic spectrum. The most significant distinction between multispectral and hyperspectral imaging sensors is that the latter divide the electromagnetic spectrum, typically within the range from 400 to 2500 nm, into very thin slices, usually no wider than 10 nm, resulting in more than 200 channels of data. The basic premise is that the increased spectral resolution will mimic spectral signatures generated by scientific spectrometers, enabling better differentiation among the features imaged. Most hyperspectral instruments are flown on airplanes. The ground cell resolution varies from 2 to 20 meters. Some of the more commonly used sensors for scientific research are the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), the Compact Airborne Spectrographic Imager (CASI), the Hyperspectral Mapper (HyMap), and the Hyperspectral Digital Imagery Collection Experiment (HYDICE). NASA launched an experimental mission named EO-1 in 2000 that included a satellite hyperspectral sensor named Hyperion. Hyperion collects data along a very narrow track (7.5 meters wide) in 220 10 nm channels. The ground cell resolution is 30 meters. Once hyperspectral technology matures, it may become one of the best resources for operational vegetation mapping. At present, however, acquisition costs are high, band-to-band registration is challenging, and data arrays are overwhelming for current computer algorithms and processors.

Airborne Videography

Airborne videography systems have been touted as a rapid, low-cost means of data collection, particularly for linear mapping projects. Industry has adopted the technology for pipeline, road, and power line monitoring. In the past, the utility of videography was limited by the challenges of image rectification. At present, GPS technology can be incorporated into the data acquisition process to facilitate registration (Everitt. *et al.,* 2004). James H. Everitt, a range scientist at the USDA Kika De La Garza Agricultural Research Center in Weslaco, Texas, has conducted extensive work on the use of airborne videography for natural resources management. Airborne videography may be a useful resource for riparian corridor mapping, although its use for a statewide assessment project has not been attempted to date.

Other Geospatial Data Resources

Shuttle Radar Topography Mission (SRTM) and National Elevation Dataset (NED) Elevation Difference Data

The NASA SRTM collected elevation data for most of the global land surface during an 11-day mission in February 2002. The C-Band frequency used by the synthetic aperture radar of the SRTM cannot penetrate vegetation. Thus, the elevations derived from SRTM data produce a digital surface model that includes features of the ground surface, manmade structures, and the top of the vegetation canopy. The National Elevation Dataset is a seamless digital elevation model constructed from the information represented in the form of elevation contours and surveyed spot elevations on 1:24,000 scale U.S. Geological Survey topographic maps. The NED reflects the ground surface without structures and vegetation at the time of field surveying and aerial photography used to compile the topographic map. Subtracting the NED ground surface from the SRTM surface yields an elevation difference dataset that contains information about the relative heights of vegetation canopy across a landscape. Although uncertainties in the SRTM data limit the absolute measurement of tree crown heights within forest stands, different height classes of vegetation can be differentiated. For instance, within riparian environments, areas of dense, mature deciduous woodland can be separated from stands of younger trees and other vegetation.

National Elevation Dataset (NED)

The NED described in the previous paragraph profiles elevation at 30 meter intervals. The NED product has been completed for the entire continental US. A higher resolution dataset is in production at the USGS. A ten-meter product will be generated as funding and partnership opportunities allow. A significant portion of Texas has been completed to date. A status map sponsored by the NRCS is available at http://data4.ftw.nrcs.usda.gov/website. There may be a lag between NED 10-meter production and status map update. The higher resolution NED can be used to better model the riparian environment as the 30-meter product may omit critical information about floodplain structure. It can be used to enhance multispectral image classifications. All NED datasets reside in the public domain and are available through the USGS and other governmental agencies. Information about the NED is available from http://ned.usgs.gov.

National Hydrography Dataset (NHD)

The NHD is an important tool for modeling surface water features at relatively high spatial resolutions. The product is an enhanced version of the standard USGS Digital Line Graph hydrography data set. The NHD combines point, line, and polygon geographic features representing rivers, streams, lakes, wells and other standard hydrography classes with network information and the EPA Reach File Version 3 dataset. For Texas, the NHD is available at the 1:100,000 and 1:24:000 mapping resolutions. The larger scale data set was corrected to match the mid-1990s Digital Orthophoto Quarter Quadrangle framework dataset. Although there may be discrepancies between the NHD and actual riparian conditions, the dataset would be an asset for any local, regional or statewide riparian vegetation mapping effort. Additional information about the NHD is available from http://nhd.usgs.gov.

National Wetland Inventory (NWI) Digital Data and Hard Copy Maps

The NWI, a three-decade US Fish and Wildlife Service (USFWS) program, was undertaken to provide information about the status of wetland, riparian, deepwater and other aquatic habitat resources within the United States. A standard hierarchical classification system that subdivides wetland features into marine, estuarine, riverine, lacustrine, and palustrine systems is used for all products (Cowardin *et al.*, 1979). NWI maps are compiled from high altitude color infrared photography collected through several national programs. The compilation methodology relies primarily on photo-interpretation techniques, not ground surveys. Compilation usually occurs once, as the program is funded piecemeal through partnerships and other similar mechanisms. Wetlands are one of the most rapidly transformed features on the landscape. Consequently, NWI map currency is problematic. Also, not all wetland features are mapped. Wetlands in agricultural production are omitted, as well as some prominent riparian features. A separate USFWS program is responsible for the mapping of riparian areas, but has not been implemented in Texas (USFWS, 1998). A recent NWI status map for Region 2 indicates that all of Texas has been mapped. Most of the state is available in 1:24,000 scale hard copy maps. The extent of NWI digital data for the State is limited to the Gulf Coast. From the 104^{th} to 106^{th} meridians and in some South Texas locations adjacent to the Gulf Coast, only small scale maps are available. Digital data photography for the NWI in Texas dates primarily from the 1990s, with limited areas dating from the 1980s. The currency of NWI hard copy maps for Texas is not indicated. The NWI is not a reliable source for the comprehensive identification of riparian features in the State, but it could provide a useful starting point, in conjunction with other data resources. One serious limitation is the dearth of digital data for Texas. Additional information about the NWI is available from http://wetlands.fws.gov.

4.4 Methodologies Appropriate for Improved Mapping of Riparian Vegetation in the State of Texas.

Numerous publications describe vegetation mapping that rely on remote sensing resources, however, fewer are concerned with the identification of specific species or vegetation alliances. The sources cited herein primarily differentiate among a single riparian class and other general vegetation cover types.

Sohn and Qi (2005) mapped biotic communities in southeastern Arizona using a single Landsat ETM+ scene acquired in 2000. Their classification schema included a riparian gallery, a vegetation community of willows and cottonwoods found in narrow perennial and intermittent stream channels. However, the riparian class demonstrated a very low producer's accuracy in relation to other desert biotic communities. The authors attributed the poor classification performance to the narrowness of the riparian corridor, typically only one or two trees deep along either side of the channel. Dowling and Accad (2003) estimated vegetation height classes within the riparian zone of an Australian river using LiDAR data and an automated classification regime but report that manual interpretation was necessary in order to calculate canopy cover and to determine species composition. Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data have been investigated as a resource for improved riparian and wetlands vegetation mapping. Neuenschwander *et al.* (1998) report on the successful discrimination of spectrally similar wetlands species in Florida. Almeida and de Souza Filho (2004) mapped riparian forests, grasslands and crops in Brazil. Neither AVIRIS study focused exclusively on distinguishing among different riparian vegetation communities. Everitt *et al.* (2004) identified giant reed along the Rio Grande in three Texas locations. The project methodology included videography capture, color infrared photographs and spectra measurements of giant reed, common reed, honey mesquite, sunflower, bermudagrass and other herbaceous species. Aerial videography integrated with GPS was deemed to be a cost–effective way to image a long riparian corridor. Scanned color infrared photography, ground reflectance measurements and an unsupervised classification process were used for a riparian study in South Texas (Everitt *et al.*, 2002). Soil, water and several dominant vegetation types were identified. Another South Texas study identified dominant overstory, understory, and ground cover species in the riparian zone of the Rio Grande using ground transects and large scale color infrared photography (Lonard *et al*., 2000).

Congalton *et al.* (2002) also investigated the use of color infrared photography for riparian vegetation mapping in a project that compared classification results generated from Landsat TM data with those based on higher spatial resolution photography. The study found large discrepancies between the classification results, with class agreement ranging from 25 to 36 percent. The methodology for the classification of the color infrared photography featured a combination of photointerpretation and GIS analysis. A vector representation of hydrography was co-registered with scanned color infrared photography, and a buffer was generated around the stream centerline. A dynamic segmentation technique utilized more commonly in transportation applications was used to quickly divide features in the buffer area into several pre-determined vegetation types. An unspecified unsupervised-supervised hybrid classification was applied to the TM data. Seven general riparian vegetation types were identified in both classifications. The authors suggest that high resolution satellite imagery may be useful for riparian mapping, and that coarser spatial resolution TM and ETM+ data are not suitable for mapping the inherently linear features of the riparian environment or for defining structural components. In an earlier publication, Muller (1997) comes to a similar conclusion. He submits that a ground cell spatial resolution of no greater than 10 meters is required for riparian vegetation applications.

Muller also emphasizes the need to select a suitable classification scheme that can be implemented using available geospatial resources and algorithms. The riparian environment is inherently a dynamic one, particular in Texas where land use conversion and frequent flash flooding contribute to rapid changes to floodplain vegetation. Such conditions lead to heterogenous vegetation distributions that may not conform to desired ecological associations, as noted by the map authors of the Vegetation Types of Texas. A workshop designed by the US Army Corps of Engineers (1994) includes a discussion of possible classification schemes for riparian areas, distinct from other accepted schemes for wetlands and other hydrographical features. Proposed national and regional schemes, several of which have been adapted for use in the arid Southwest, should be reviewed prior to the commencement of a major mapping project. USFWS (1998) has developed a system based on photointerpretation techniques for the western United States, including most of Texas, that complements the existing NWI system. The classification scheme divides riparian systems into lotic and lentic subsystems that are further subdivided into forested or scrub-schrub deciduous, evergreen, or mixed subclasses or an emergent class. Dominant species are indicated. Many are found in Texas, although some species associations may be more appropriate for the State than others.

Based on the findings of the map product and literature review conducted for the current project, and ongoing research at CSR, a general approach to mapping riparian vegetation in Texas is proposed. The primary constituents of the program would be data resources that are currently available:

- ADS40 color infrared imagery collected under the auspices of the NAIP program, augmented where available with concurrent visible color imagery acquired from the vendor for other governmental programs,
- SRTM-NED difference data,
- digital NHD, NED and NWI data, at appropriate mapping resolutions, and
- additional geospatial resources, such as the Level IV Ecoregions of Texas, supplemented by field data where available.

The NAIP imagery would provide the necessary framework for class identification. The elevation difference data would be used to enhance classification and interpretation procedures. NHD data, supplemented by 10-meter NED and available NWI digital data, could be used to reduce the number of image tiles required for the project, by identifying the quarter quads that potentially contain riparian features. Buffers of appropriate extent would be generated from the NHD data, further reducing the area requiring review.

Figures 4 and 5 demonstrate how the interpretation of high resolution NAIP imagery can be enhanced with information derived from SRTM-NED difference data. Figure 4 shows the Nueces River as it traverses San Patricio and Nueces counties. Figure 5 covers the same map extent at a coarser resolution but provides information about canopy structure that is not immediately evident in the NAIP product.

A successful program would also require extensive field verification data and a practical classification scheme. Ideally, more than one complete NAIP acquisition for Texas would be used, and climatic conditions prior to acquisition would be recorded. Since the NAIP will be collected at frequent intervals, annually if current FSA plans are maintained, such a goal may be attainable. One of the shortcomings of the NWI mapping program was the reliance on single date aerial imagery and photointerpretation by people who were not familiar with conditions in the field. Although the computer automation of the classification process is desirable, a semi-automated methodology that incorporates image processing and GIS techniques may yield more accurate results.

Figure 4. Example of one-meter color infrared ADS40 imagery collected in 2004 for the USDA National Agricultural Imagery Program. Note the contrast in vegetation appearance near the banks of the Nueces River with areas in the surrounding agricultural fields and scrubland. The imagery is not shown at full resolution.

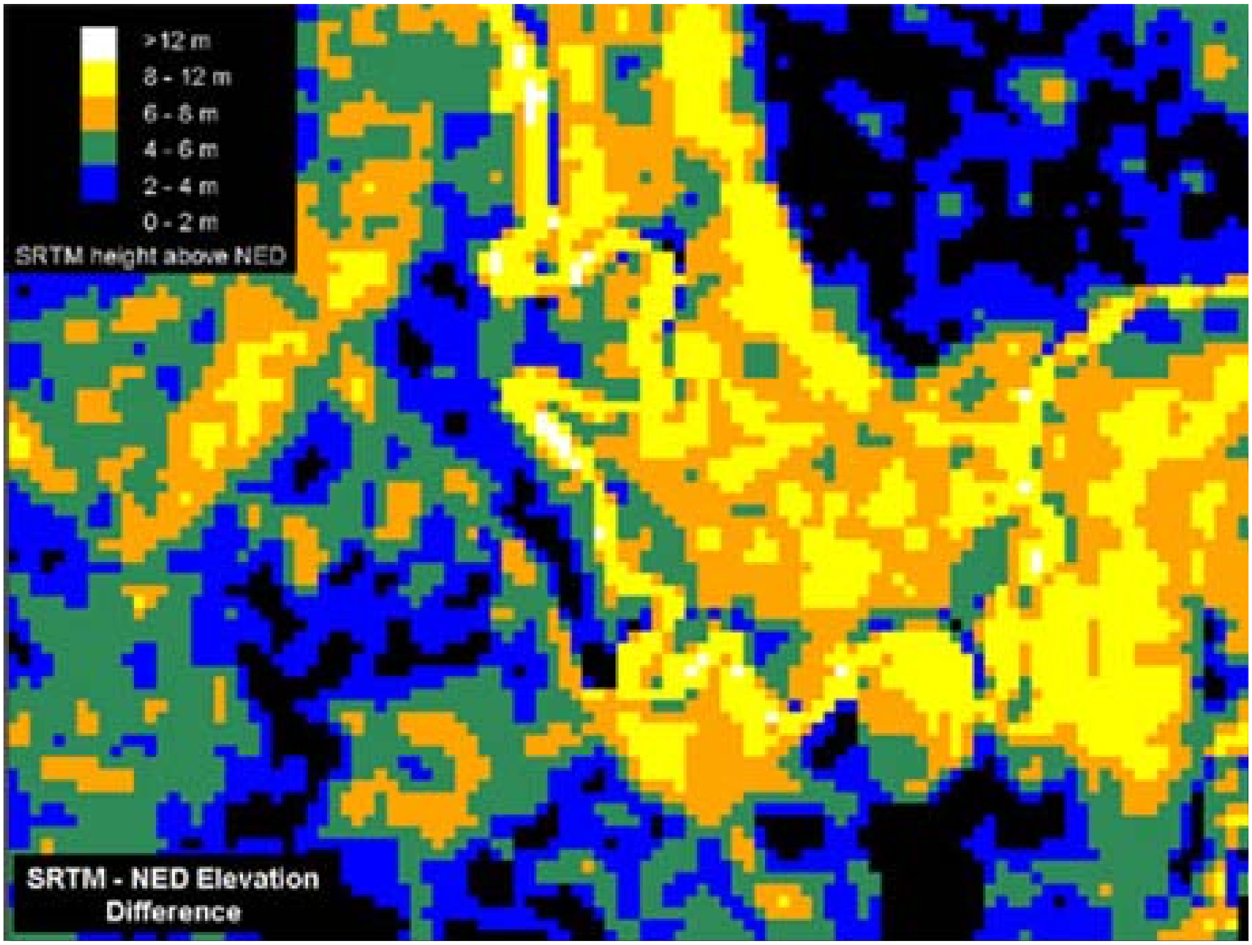

Figure 5. An illustration of relative canopy heights as calculated from the difference between Shuttle Radar Topography Mission elevation data and National Elevation Dataset bare earth elevation data for the same extent depicted in Figure 4. Heights model conditions present in early 2000.

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Online Resources

A Checklist of the Vascular Plants of Texas, Texas A&M University
http://www.csdl.tamu.edu/FLORA/taes/tracy/regecoNF.html

Biology of the Rio Grande Border Region: A Bibliography
http://www.cerc.cr.usgs.gov/pubs/riogrande/woody.HTM

Texas Endemics: Distribution of all endemics, Texas A&M University
http://www.csdl.tamu.edu/FLORA/cgi/endemics_map_page2?all=yes
(Note: click on link to All Endemics to get to a list of plants, which in turn leads to maps of species distribution)

Texas Native Trees, Texas A&M University
http://aggie-horticulture.tamu.edu/ornamentals/natives/tamuhort.html

USDA Plants Database, Natural Resources Conservation Service
http://plants.usda.gov/index.html

Appendix 5

Task 3: Examine the Effects of Groundwater Surface Water Interactions on Groundwater Quantity

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Bureau of Economic Geology

Section

Summary

There were two objectives associated with this project: 1) to compare different automated approaches for quantifying baseflow discharge (task 3b), and 2) to calculate baseflow recession for selected stream gauges in Texas (task 3a). Task 3b, in which different baseflow estimation techniques are evaluated, is discussed first followed by task 3a in which one of the codes is used to evaluate selected gauges.

It was found that the three automated methods for baseflow estimation (BFI, PART, RDF) produced similar results, and could be manipulated to mimic each other. Since none of these automated codes includes return flows or bank storage, the method that produced the lowest baseflow estimates (BFI) was chosen to analyze gauges. Using this code, over 90 stream segments were evaluated for baseflow. Baseflow estimates ranged from nearly 0% to over 90 % of streamflow; the average was 34 %. Return flows and public water intakes were located on each segment, and the percent of return flow or in flow was calculated to investigate the significance of these factors. For 80 percent of stations analyzed, return flow was less than 10% of baseflow. For 95% of stations analyzed, public water intakes comprised less than 10% of baseflow. It was found that baseflow index (BFI, as %), and total annual baseflow (acre-ft/yr) were useful in evaluating a particular stream. However, total annual baseflow normalized by contributing area of the basin (acre-ft/yr-mi^2) was more meaningful when comparing gauges in different basins. When total annual baseflow normalized by contributing area was plotted, gauges located in the Gulf Coast aquifer displayed a trend of high normalized flows to the northeast, decreasing to the southwest.

5.1 Compare Different Approaches for Quantifying Baseflow Discharge

A literature and internet search was conducted to assess available automated techniques. Four techniques were evaluated: 1) a USGS produced hydrograph separation model called HYSEP, 2) a USGS produced model used to estimate baseflow index by hydrograph separation called BFI, 3) a USGS produced model that performs streamflow partitioning to estimate baseflow called PART, and 4) a baseflow filter program designed by Texas A&M University as part of the SWAT (Soil and Water Assessment Tool) program. Each program is briefly discussed below.

HYSEP was produced and documented by Sloto and Crouse (1996) as a tool to separate a streamflow hydrograph into baseflow and surface runoff components. HYSEP is a FORTRAN program compiled with an older DOS compiler that does not run on Windows 98/2000, unless security patch KB835732 is uninstalled. It does not run on newer versions of Windows at all, unless it is recompiled and graphics issues are resolved. USGS stated that there were no plans to update HYSEP, and recommended that another of their programs (such as PART or BFI) be used. Accordingly, HYSEP was not used in this study. Because of the mention of HYSEP in the literature, a brief discussion regarding techniques used by HYSEP is provided below.

HYSEP uses three techniques to separate baseflow and surface runoff discussed in Pettyjohn and Henning (1979): 1) fixed-interval, 2) sliding interval, and local-minimum methods. All methods make use of the following calculation for duration of surface runoff (N):

$$N = A^{0.2} \qquad (1)$$

where A = drainage area (mi^2)

Further, the term 2N* is defined as the odd integer between 3 and 11 nearest to 2N. In HYSEP, hydrograph separation begins one interval 2N* days prior to the start of the date selected for the start of the separation, and ends 2N* days after the end of the selected date. In the fixed interval method, the lowest discharge in each interval (2N*) is deemed “baseflow” for all days in that interval. The sliding interval method finds the lowest discharge in one half the interval minus 1 day [0.5(2N*-1)] before and after the day being considered and deems the lowest discharge to be “baseflow” for that day. The local minimum method checks each day to determine if it is the lowest discharge in one half the interval minus 1 day [0.5(2N*-1)] before and after the day being considered. If it is, then it is a local minimum and is connected by a straight line to adjacent local minimums. The “baseflow” a particular day is calculated by linear interpolation between local minimums.

PART was developed and documented by Rutledge (1998) at USGS as component within a a suite of tools designed to describe recession of groundwater discharge and estimate mean groundwater recharge and discharge from streamflow records. The PART algorithm is similar in concept to the local minimum method discussed above in that it locates low points on the streamflow record and interpolates daily values between these low points. The PART algorithm also makes use of N, calculated above in equation (1). PART operates on the value K, which is equal to the largest integer less than the value of N.

PART checks each day in the streamflow record to see if it is the smallest value of streamflow within the preceding K day interval. Each day that is the smallest within its interval is said to meet the criterion of antecedent recession, referred to as an AR day. Each AR day is then checked to see if it is followed by a daily decline of the log of streamflow exceeding 0.1.

Points not meeting this criterion are deemed "baseflow" and are used to interpolate (linear) values for all other points. Baseflow values are checked against streamflow values for each day. Baseflow is then checked to make sure that it does not exceed streamflow on any day. This procedure is executed three times: for K as mentioned above, for K+1, and for K+2. A curvilinear interpolation is done to determine the value of baseflow for the value of N (which should be between K and K+1). All four results are then reported: K, K+1, K+2, and N. PART was downloaded from http://water.usgs.gov/ogw/part/

BFI was developed and documented by Wahl and Wahl (1995) at USGS to determine baseflow index. Baseflow index, or BFI, is the ratio of baseflow to streamflow. Values of BFI range between 0 (for no baseflow contribution to streamflow) to 1 (for 100% streamflow as baseflow). This program has two options, the first is the Institute of Hydrology method (1990), and the other is referred to as the Modified method. These methods are similar in concept to the local minimum method described above in that they locate low points on the streamflow record (referred to as turning points) and interpolate daily values between these low points. Instead of using the N described above in equation (1), BFI uses a user defined period, which is referred to as L.

The year is separated into L day periods, and each point within a period is checked to determine if it is a turning point. For three points, A, B, and C, the following rationale is used to determine turning points

$$\text{If } A*F \leq B \text{ and } A*F \leq C, \text{ then A is a turning point} \qquad (2)$$

F is a user defined turning point test factor that is greater than zero and less than one. To use this method, F and L should be tuned to the watershed. Wahl and Wahl (1995) comment that the L factor usually has the most dramatic influence on results obtained using BFI. To determine what L should be used, several L values should be run, and the BFI results plotted against L. The L value corresponding to a large change in slope should be used. An example is provided below in Figure 1 for Aquilla Creek near Aquilla, TX (USGS Gauge number 08093500).

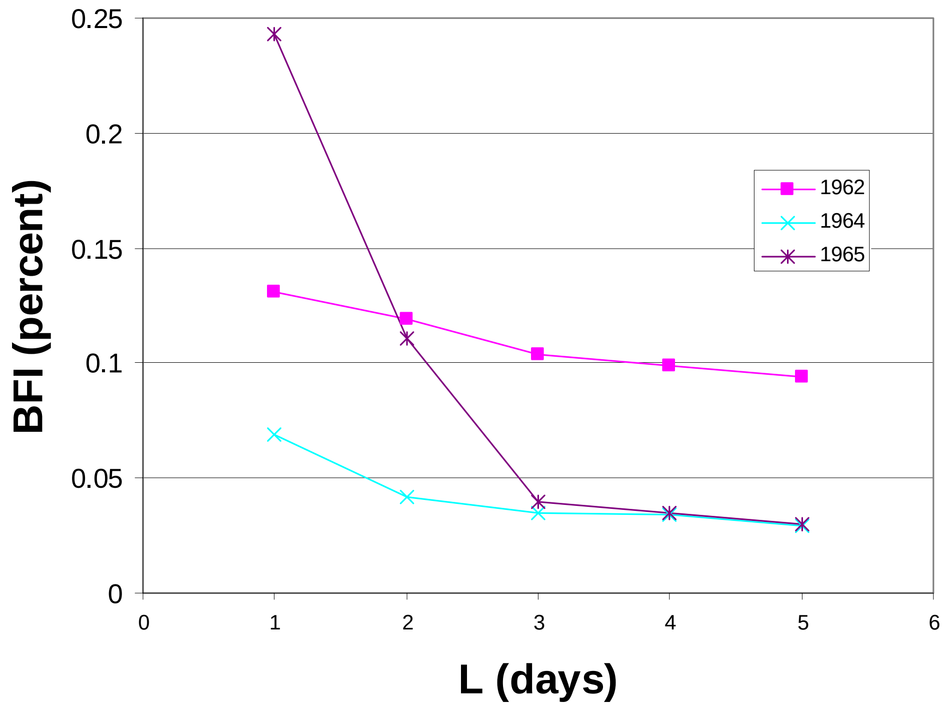

Figure 1: Aquilla Creek near Aquilla, TX (08093500), BFI vs. L

As indicated in Figure 1, the L value can change the number of years of data used for BFI analysis, even for a single gauge. In Figure 1 1965 clearly demonstrates L equal to 3, while an L value of 2 is probably more appropriate for 1964. Over 20 gauge locations were plotted, most with over 10 years each. Generally speaking, the L values were between 2 and 4, with most L equal to 3. Accordingly, the L value was set to three for all runs in this study. The F tuning point test parameter is less definite. Wahl and Wahl (1995) state that a value of 0.9 seems appropriate in most applications for which the Institute of Hydrology method is suitable, and that the method is generally not highly sensitive to variations in F. For this reason, the BFI default value of 0.9 was used for all gauges in this study. BFI was downloaded from http://www.usbr.gov/pmts/hydraulics_lab/twahl/bfi/bfidownload.html

The fourth and final technique addressed in this study is called a Recursive Digital Filter (RDF) and is documented in Nathan and McMahon (1990), Arnold and Allen (1999) and Arnold, Allen, Muttiah, Bernhardt (1995). The filter operates on streamflow gauge data, and attempts to separate out high frequency signals (streamflow) from low frequency signals (baseflow). The filter is commonly used in signal analysis, and takes the form indicated below in equation 3.

$$f_k = \alpha * f_{k-1} + (1 + \alpha) / 2 * (y_k - y_{k-1}) \qquad (3)$$

where

α	=	filter parameter
f_k	=	filtered quick response (streamflow) at the kth sampling instant
y_k	=	original streamflow

Using this approach, baseflow would be calculated as the difference between f_k and y_k. As stated in Nathan and McMahon (1990), “The justification for the use of this technique rests merely on the fact that filtering out high-frequency signals is intuitively analogous to the separation of low-frequency signals baseflow from the higher frequencies of quickflow, the technique is in fact just as arbitrary and physically unrealistic as, say, the separation of baseflow based on a series of straight lines.” In practice, the filter parameter that yielded the most acceptable baseflow separation was in the range of 0.9 to 0.95. For the purposes of this investigation, a filter parameter of 0.925 was used. The filter parameter affects the degree or attenuation, and the number of passes determines the amount of smoothing. The filter can be passed over the data as many times as the user chooses; typically alternating forward and backward passes. In Nathan and McMahon (1990), the filter was passes 3 times. The RDF approach was automated by the SWAT (Soul Water Assessment Tool) team at Texas A&M University. The program was downloaded from http://www.brc.tamus.edu/swat/soft_baseflow.html.

Ultimately, each of these methods is meant to automate a subjective manual process. The purpose of automation is to provide consistency in baseflow determinations from reach to reach, so that they may be compared on a common basis. In this section, baseflows are determined using BFI, PART and RDF, and compared.

While over ten reaches were compared using these techniques, the results were very similar for each reach. Using PART, the differences in period K, K+1, and K+2 (as discussed above) are apparent in the graph below in Figure 2 (for Big Creek near Freestone, TX, USGS Gauge 08110430). In this figure, annual BFI is plotted for a twenty four year period from 1978 to 2002. BFI is defined as the volume of baseflow divided by the volume of streamflow; a lower BFI indicating a smaller quantity of baseflow in the streamflow record. As the number of days over which local minima are determined is increased from K to K+2, the BFI decreases.

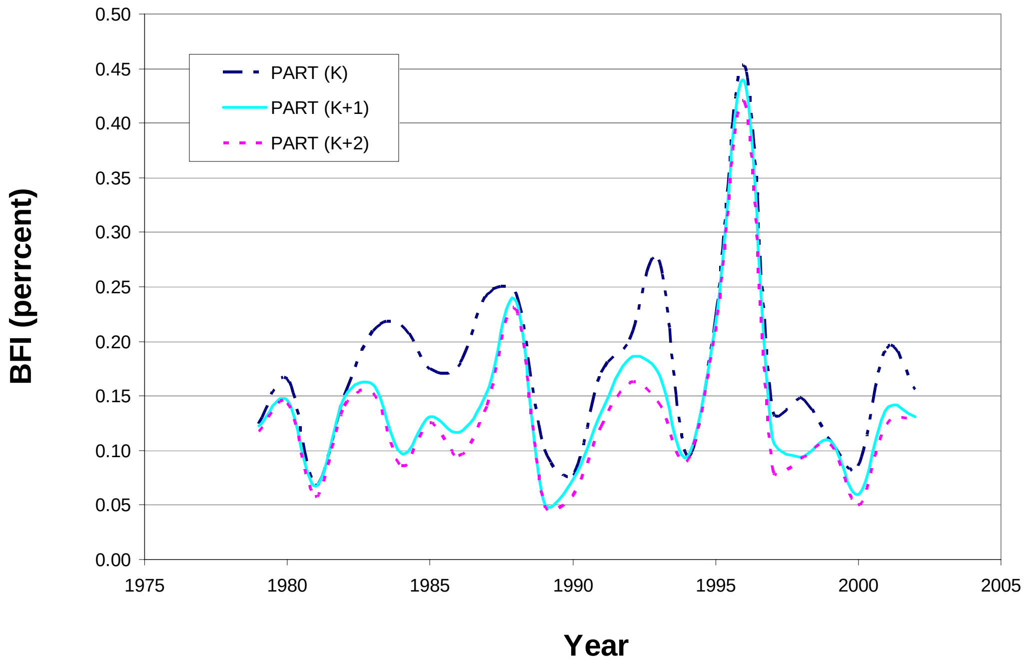

Figure 2: Methods of baseflow analysis: PART Big Creek near Freestone, TX (08110430)

Baseflow determination using RDF demonstrates a similar trend with number of passes of the filter over the streamflow data. As the number of passes is increased, the BFI tends to decrease. This trend is demonstrated below in Figure 3.

All methods are demonstrated together in Figure 4. In this figure, the lowest baseflow estimates are obtained using BFI, with the exception of higher baseflows (BFI > 0.30, in 1996) in which the RDF (3rd pass) provides a slightly lower baseflow estimate (0.35 vs. 0.38). It should be noted that none of these programs includes in-stream detention and subsequent discharge of surface water, alluvial aquifer recharge such as bank storage/release following flood events, perched groundwater zones, or fractured zone recharge/discharge in the near subsurface. Because of these unaccounted sources of baseflow, it is believed that these programs will tend to overestimate total baseflow. For this reason, a baseflow algorithm that estimates a lower baseflow for the majority of cases is probably preferable, since it would produce more conservative results for BFI in the presence of unaccounted streamflow contributions.

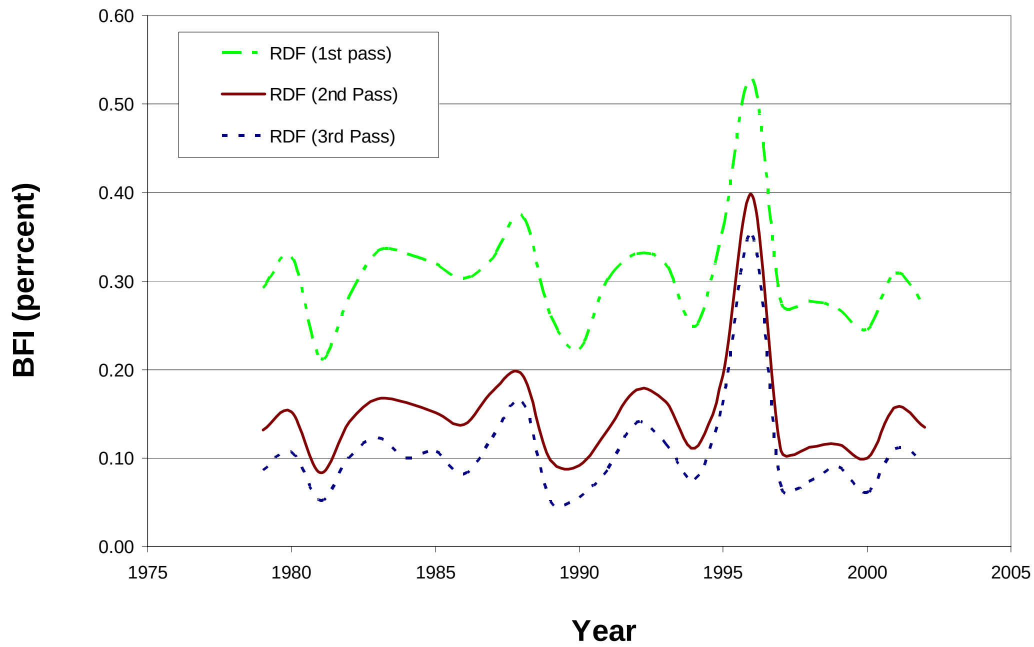

Figure 3: Methods of baseflow analysis: RDF Big Creek near Freestone, TX (08110430)

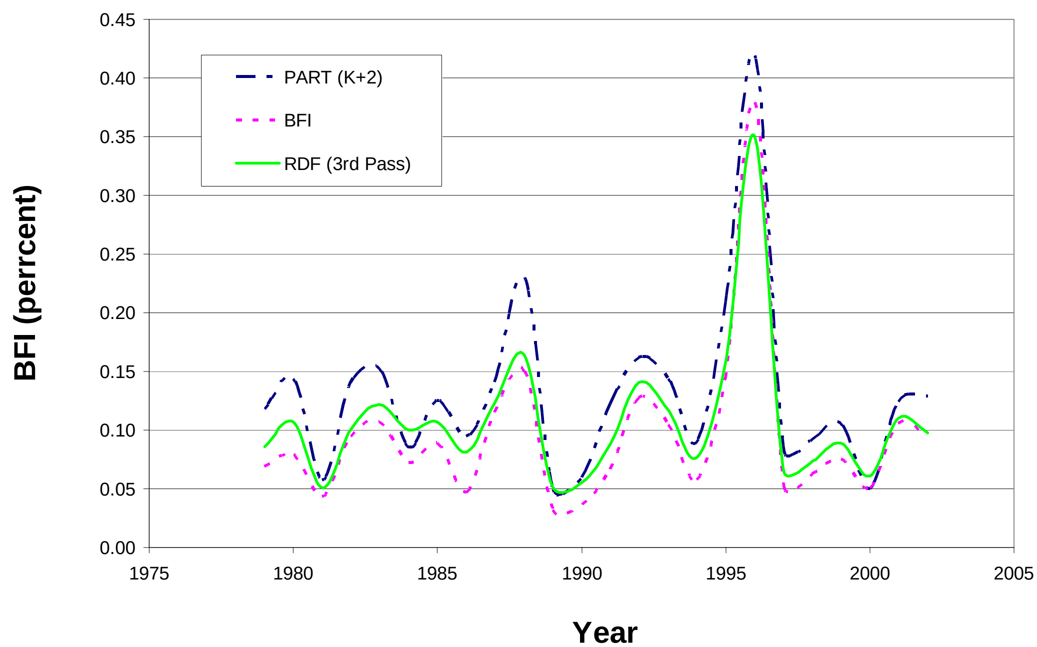

Figure 4: Methods of baseflow analysis: PART, BFI, RDF Big Creek near Freestone, TX (08110430)

In addition, in the absence of reach specific measurements of baseflow make it difficult to decide which period (K, K+1, K+2) to use for PART output, or which pass to use for RDF output. This makes BFI a compelling choice for estimating baseflow.

5.2 Evaluation of Selected Gauges in Texas

GIS shapefiles of the aquifers to locate stream gauges upstream and downstream of aquifer outcrop areas. GIS shapefiles were also obtained for reservoirs, and USGS gauges in Texas. These data were obtained from the sources indicated in Table 1:

Table 1: GIS Information sources

Data	**Agency**	**Website**
Major Aquifers	TWDB	http://www.twdb.state.tx.us/mapping/gisdata.asp
Minor Aquifers	TWDB	http://www.twdb.state.tx.us/mapping/gisdata.asp
Major Rivers	TWDB	http://www.twdb.state.tx.us/mapping/gisdata.asp
Existing Reservoirs	TWDB	http://www.twdb.state.tx.us/mapping/gisdata.asp
Detailed Hydrography	TxGLO	http://www.glo.state.tx.us/gisdata/gisdata.html
USGS Gauge Location	USGS	http://waterdata.usgs.gov/tx/nwis/sw

These data were plotted in ArcGIS 9.0, and the USGS gauges associated with the outcrop area of the Carrizo-Wilcox aquifer, the Queen City aquifer, the Gulf Coast aquifer, the Trinity aquifer, the Cenozoic-Pecos aquifer, and the Edwards-Trinity Plateau aquifer were identified.

Each of these gauges was then inspected to decide whether it is a candidate for baseflow analysis. Ultimately, analysis of a gauge is reflective of baseflow coming from the outcrop area under the reach of the river (and associated tributaries) upstream from the gauge. Generally, a gauge (and its associated upstream reach) was considered a good candidate for analysis if all or most of the upstream reach of the river was located within the outcrop area of the aquifer. This situation is depicted below in Figure 5.

If a river or stream is large enough to have several gauges on it, then the drainage area between each pair of gauges was considered as a candidate for analysis. In this case, baseflow from the upstream gauge was subtracted from baseflow estimated at the downstream gauge to find the contribution from only the reach in question. Sometimes one or two upstream gauges were subtracted from the downstream gauge, depending on the number of tributaries, and how they were situated. This situation is depicted below in Figure 6 (2 upstream gauges). This operation was only successful if the gauges contained coincident period of record. This practice was also used to subtract out the effect of reservoir storage in the event that there were two gauges, one near the outfall of a reservoir, and one downstream. In this case, the reach downstream could be analyzed. Otherwise, streams with significant reservoir storage were avoided.

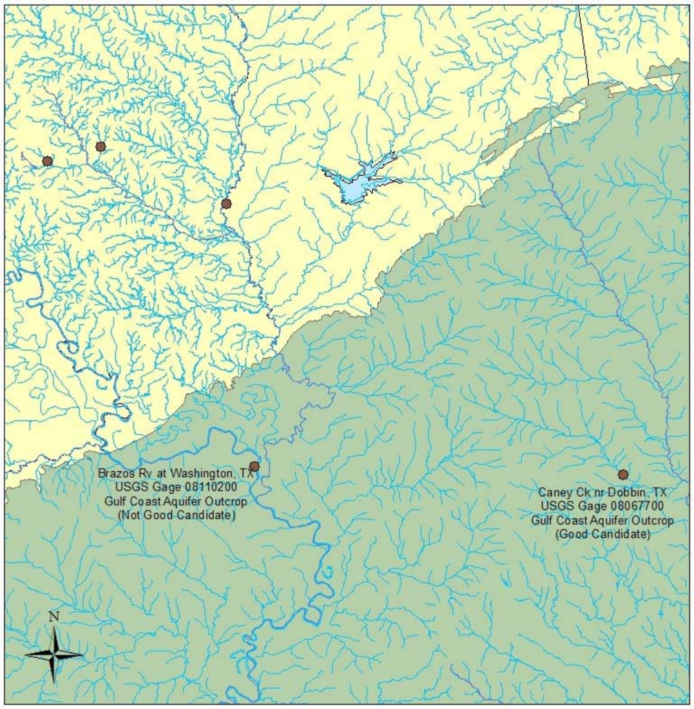

Figure 5: Gauge evaluation and analysis

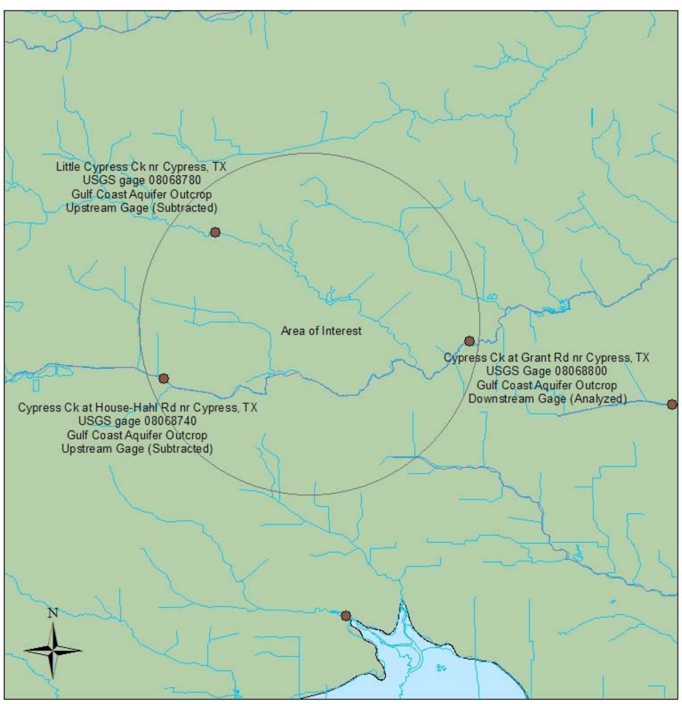

Figure 6: Gauge evaluation and analysis

Each gauge located in any of the outcrop areas mentioned above was evaluated, and baseflow estimates were generated for each stream reach using BFI along with the assumptions mentioned above (N = 3, turning point test factor F = 0.9). Annual numbers for baseflow [acre-ft/yr], baseflow index [%], and baseflow per unit outcrop drainage area (acre-ft/year-mi^2) and BFI were calculated and compiled. In instances where one or more upstream gauges and a downstream gauge were analyzed, daily baseflow numbers were compiled for each date, and the appropriate subtraction performed to find the specific study reach baseflow. In instances where a negative number was obtained, it was set to zero (as negative baseflow is not meaningful in this investigation). Then, total annual study reach baseflow and streamflow were calculated, and a BFI determined.

Permitted return flows and public water intakes were located to establish whether water was added or removed (respectively) across the reach, and whether these additions or subtractions may have affected baseflow calculations. Return flows were obtained from the TCEQ Total maximum Daily Load (TMDL) team, and public water intakes were obtained from the TCEQ Drinking Water Protection Program. Data for return flows and public water intakes were not temporal in nature, and generally included permitted maximum values. Also, it was questionable whether the return flow and intake data was significant for the period of record. Therefore, it was not meaningful to subtract (in the case of return flows) or add (in the case of public water intakes) to baseflow estimates that were made using daily streamflow data. Instead, the data were evaluated qualitatively; if the quantity of addition or subtraction was under 10% of the baseflow estimate, the effect of addition or subtraction was said to be minor.

Another factor that was thought to have a major impact on baseflow estimates was reservoir storage. As mentioned above, streams with TCEQ permitted reservoirs were generally avoided, unless there was an upstream and downstream gauge after the reservoir to omit the reservoir's effects on baseflow estimates. In Texas, there are far more small unpermitted reservoirs than there are larger permitted reservoirs. In most cases, these small reservoirs could not be avoided. When a reservoir was noticed in the GIS, it was noted. Data for each of the gauges is presented below in Table 2, grouped by river basin, 91 gauges total.

Table 2: Cypress

Parameter	Big Cypress Ck nr Winnsboro, TX	Brushy Ck at Scroggins, TX	Boggy Ck nr Daingerfield, TX	Black Cypress Bayou at Jefferson	Little Cypress Ck nr C City, TX	Frazier Ck nr Linden, TX
USGS Gauge Number	7344482	7344486	7345000	7346045	7346050	7346140
Period of Record (from)	3/15/1974	12/21/1997	4/1/1943	10/1/1968	1/1/1963	12/1/1964
Period of Record (to)	9/30/1991	9/30/2004	10/5/1977	9/30/2004	3/17/2001	9/30/1991
Baseflow Index (%)						
average	0.19	0.35	0.27	0.53	0.40	0.40
median	0.17	0.33	0.29	0.53	0.41	0.39
stdev	0.09	0.10	0.09	0.09	0.08	0.08
max	0.47	0.62	0.44	0.78	0.56	0.57
min	0.07	0.24	0.08	0.35	0.23	0.16
Baseflow (acre-ft/yr)						
average	2736	4653	13891	136948	80931	12662
median	2507	4169	10586	133023	71870	12437
stdev	1294	1764	9047	64208	46731	6589
max	5873	9408	38266	282123	190575	27862
min	1177	2330	2078	31346	11145	3095
Baseflow (acre-tt/yr-sq mi)						
drainage area (sq mi)	27	23	20	365	383	48
average	0.140	0.279	0.958	0.518	0.292	0.364
median	0.128	0.250	0.730	0.503	0.259	0.358
Characteristics						
Upstream Regulation	y	n	N	y	y	n
Number of Return Flows	6	2	0	5	17	1
Qty return flows	0	0	0	841	591	0
return flow/ baseflow ave	0.00	0.00	0.00	0.01	0.01	0.00
Number of Water Intakes	0	0	0	0	0	0
Qty. Water Intakes	0	0	0	0	0	0
Intake / baseflow ave	0	0.00	0.00	0.00	0.00	0.00

Table 2: Sabine

Parameter	Big Cow Ck Newton, TX	Big Sandy Ck Sandy, TX	Prairie Ck nr Gladewater, TX	Sabine Rv n Emory, TX	Burke Ck nr Yantis, TX	Mill Ck nr Henderson,	Mill Ck nr Longview, TX	Socagee Ck n Carthage, TX	Tenaha Ck nr Shel TX
USGS Gauge Number	8029500	8019500	8020200	8017500	8018730	8020960	8020980	8022400	8023200
Period of Record (from)	5/1/1952	3/1/1939	1/20/1968	8/1/1952	9/6/1978	10/1/1978	10/1/1978	3/1/1962	3/1/1952
Period of Record (to)	9/30/2004	9/30/2004	1/31/1977	9/30/1973	9/30/1989	10/7/1981	10/8/1981	9/30/1973	9/15/1981
Baseflow Index (%)									
average	0.50	0.50	0.48	0.16	0.18	0.36	0.50	0.13	0.21
median	0.48	0.49	0.49	0.16	0.20	0.40	0.48	0.13	0.22
stdev	0.09	0.10	0.09	0.17	0.09	0.07	0.04	0.06	0.07
max	0.71	0.75	0.61	0.28	0.32	0.41	0.54	0.24	0.35
min	0.33	0.32	0.33	0.04	0.06	0.28	0.47	0.01	0.07
Baseflow (acre-ft/yr)									
average	44646	64696	11662	17868	2880	3679	11964	3729	12214
median	43987	59546	11589	17868	2815	3676	14275	1837	9816
stdev	15902	26955	4733	388	1611	1289	4413	3300	8924
max	85818	140462	17700	18142	5554	4970	14741	9914	31044
min	19900	20180	4476	17594	723	2392	6875	63	1070
Baseflow (acre-tt/yr-sq mi)									
drainage area (sq mi)	128	231	49	27	33	20	48	83	98
average	0.481	0.386	0.328	0.913	0.120	0.254	0.344	0.062	0.172
median	0.474	0.356	0.326	0.913	0.118	0.254	0.410	0.031	0.138
Characteristics									
Upstream Regulation	n	y	y	y	n	y	y	n	y
Number of Return Flows	0	10	0	0	3	12	16	1	9
Qty return flows	0	689	0	0	0	420	420	0	4589
return flow/ baseflow ave	0.00	0.01	0.00	0.00	0.00	0.11	0.04	0.00	0.38
Number of Water Intakes	0	0	0	1	0	0	0	0	1
Qty. Water Intakes	0	0	0	372	0	0	0	0	805
Intake / baseflow ave	0	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.07

Table 2: Neches River Basin

Parameter	Village Ck nr Kountze, TX	Pine Island Bayou nr Sour Lake, TX	Kickapoo Ck nr Brownsboro, T	Striker Ck nr Summerfield, TX	E Fk Angelina nr Cushing, TX	Arenoso Ck nr San Augustine, TX
USGS Gauge Number	8041500	8041700	8031200	8033700	8033900	8037500
Period of Record (from)	6/1/1924	10/1/1967	5/1/1962	10/1/1940	1/1/1964	6/1/1938
Period of Record (to)	9/30/2004	9/30/2004	9/30/1989	9/30/1949	9/30/1989	9/30/1940
Baseflow Index (%)						
average	0.46	0.20	0.32	0.39	0.43	0.48
median	0.47	0.20	0.31	0.35	0.43	0.48
stdev	0.10	0.09	0.10	0.12	0.08	0.05
max	0.72	0.38	0.56	0.54	0.61	0.51
min	0.22	0.04	0.08	0.25	0.32	0.45
Baseflow (acre-ft/yr)						
average	278651	67702	30550	50238	33564	23004
median	279421	58390	22549	51309	36744	23004
stdev	141724	45028	18687	14501	14489	2050
max	665777	198591	68360	74383	56981	24453
min	76759	5582	5719	26004	9421	21554
Baseflow (acre-tt/yr-sq mi)						
drainage area (sq mi)	860	336	85	146	158	75
average	0.447	0.278	0.496	0.475	0.293	0.423
median	0.448	0.240	0.366	0.485	0.321	0.423
Characteristics						
Upstream Regulation	y	n	y	Y	n	n
Number of Return Flows	14	8	9	11	2	0
Qty return flows	1521	1242	90	132	158	0
return flow/ baseflow ave	0.005	0.018	0.003	0.003	0.005	0.000
Number of Water Intakes	0	0	0	0	0	0
Qty. Water Intakes	0	0	0	0	0	0
Intake / baseflow ave	0	0.00	0.00	0.00	0.00	0.00

Table 2: Nueces

Parameter	Nueces Rv at Laguna, TX	Frio Rv at Concan, TX	Dry Frio Rv nr Reagan Wells, TX	Sabinal Rv nr Sabinal, TX	Hondo Ck nr Tarpley, TX	Seco Ck at Miller Ranch Utopia, TX	Seco Ck nr Utopia, TX	Ramirena Ck George West,
USGS Gauge Number	8190000	8195000	8196000	8198000	8200000	8201500	8202000	8210300
Period of Record (from)	10/1/1923	11/1/1923	9/1/1952	10/1/1942	9/1/1952	5/1/1961	8/1/1952	3/1/1968
Period of Record (to)	9/30/2004	9/30/2004	9/30/2004	9/30/2004	9/30/2004	9/30/2004	9/30/1961	3/31/1972
Baseflow Index (%)								
average	0.69	0.75	0.59	0.63	0.55	0.59	0.29	0.01
median	0.72	0.79	0.60	0.69	0.61	0.62	0.11	0.00
stdev	0.21	0.17	0.20	0.23	0.22	0.17	0.31	0.01
max	0.98	0.97	0.91	0.94	0.90	0.82	0.77	0.02
min	0.11	0.26	0.11	0.00	0.01	0.15	0.00	0.00
Baseflow (acre-ft/yr)								
average	71374	61591	14273	30628	16245	7843	4939	3
median	58103	54854	10817	22284	12039	5593	1093	2
stdev	44028	40713	10551	30296	15558	7992	5885	4
max	245768	236405	45524	146967	66750	36321	13522	8
min	11543	5917	1669	0	1	476	0	0
Baseflow (acre-tt/yr-sq mi)								
drainage area (sq mi)	737	389	126	206	96	45	53	84
average	0.134	0.218	0.156	0.205	0.234	0.241	0.129	0.000
median	0.109	0.195	0.118	0.149	0.173	0.172	0.028	0.000
Characteristics								
Upstream Regulation	y	y	y	Y	y	n	n	n
Number of Return Flows	1	2	0	2	0	0	0	0
Qty return flows	0	0	0	0	0	0	0	0
return flow/ baseflow ave	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Number of Water Intakes	1	0	0	0	0	0	0	0
Qty. Water Intakes	929	0	0	0	0	0	0	0
Intake / baseflow ave	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 2: San Antonio | San Antonio-Nueces

Parameter	Medina Rv at Bandera, TX	Medina Rv nr Pipe Ck, TX	Red Bluff Ck nr Pipe Ck, TX	Cibolo Ck at IH 10 Boerne, TX	Cibolo Ck nr Boerne TX	Cibolo Ck Bulverde, TX	Copano Ck nr Refugio, TX	Medio Ck Beeville, TX	Aransas Rv nr Skidmore TX	Chiltipin Ck at Sinton, TX
USGS Gauge Number	8178880	8179000	8179100	8183850	8183900	8184000	8189200	8189300	8189700	8189800
Period of Record (from)	10/1/1982	12/1/1922	4/1/1956	5/23/1996	3/1/1962	5/1/1946	6/17/1970	3/1/1962	4/1/1964	7/23/1970
Period of Record (to)	9/30/2004	10/19/1982	11/27/1981	9/30/2004	12/17/1997	11/30/1965	9/30/2004	9/30/2004	9/30/2004	9/30/1991
Baseflow Index (%)										
average	0.70	0.59	0.21	0.45	0.52	0.01	0.08	0.06	0.21	0.05
median	0.72	0.61	0.19	0.51	0.53	0.00	0.06	0.03	0.17	0.03
stdev	0.17	0.20	0.19	0.20	0.15	0.03	0.09	0.08	0.17	0.07
max	0.91	0.90	0.63	0.72	0.78	0.09	0.38	0.29	0.79	0.33
min	0.18	0.17	0.00	0.17	0.11	0.00	0.00	0.00	0.00	0.00
Baseflow (acre-ft/yr)										
average	69764	64214	2656	5241	10462	240	3112	429	2886	678
median	44339	50790	2365	5128	9219	0	812	161	2772	448
stdev	64184	52083	2708	2985	9419	680	4066	637	1637	750
max	258521	173334	9825	9854	34597	2903	12892	2291	6675	2977
min	12798	1895	0	183	419	0	1	1	309	38
Baseflow (acre-tt/yr-sq mi)										
drainage area (sq mi)	328	474	56	29	68	198	88	204	247	128
average	0.294	0.187	0.065	0.249	0.212	0.002	0.049	0.003	0.016	0.007
median	0.187	0.148	0.058	0.244	0.187	0.000	0.013	0.001	0.015	0.005
Characteristics										
Upstream Regulation	y	y	n	y	y	Y	y	y	y	y
Number of Return Flows	1	3	0	0	2	4	0	2	2	4
Qty return flows	0	310	0	0	0	0	0	118	2229	66
return flow/ baseflow ave	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.77	0.10
Number of Water Intakes	0	0	0	1	2	3	0	0	0	0
Qty. Water Intakes	0	0	0	867	867	867	0	0	0	0
Intake / baseflow ave	0	0.00	0.00	0.17	0.08	3.61	0	0.00	0.00	0.00

Table 2: Guadalupe

Parameter	Fifteenmile Ck r Weser, TX	Plum Ck nr Luling, TX	San Marcos Rv at Ottine,	N Fk Guadalupe Hunt, TX	Guadalupe Rv r Spring Branch,	Rebecca Ck n Spring Branch	Blanco Rv at Wimberley, TX
USGS Gauge Number	8176550	8173000	8173500	8165300	8167500	8167600	8171000
Period of Record (from)	10/1/1984	4/1/1930	7/1/1915	8/1/1967	7/1/1922	2/1/1960	9/1/1924
Period of Record (to)	9/30/1989	9/30/2004	1/31/1943	9/30/2004	9/30/2004	2/26/1979	9/30/2004
Baseflow Index (%)							
average	0.52	0.16	0.06	0.72	0.23	0.57	0.66
median	0.57	0.13	0.06	0.76	0.23	0.53	0.69
stdev	0.23	0.10	0.04	0.21	0.09	0.15	0.17
max	0.74	0.51	0.10	0.97	0.40	0.85	0.97
min	0.20	0.05	0.02	0.30	0.06	0.38	0.12
Baseflow (acre-ft/yr)							
average	4273	10814	17107	19367	70699	1968	61007
median	3634	9187	9633	17844	62528	2103	51715
stdev	2728	8841	16039	6854	64161	1187	45869
max	8452	33017	35519	38280	290800	3548	224248
min	1150	1962	6168	9395	775	380	3500
Baseflow (acre-tt/yr-sq mi)							
drainage area (sq mi)	167	200	102	169	476	10.9	355
average	0.035	0.075	0.231	0.158	0.205	0.249	0.237
median	0.030	0.063	0.130	0.146	0.181	0.266	0.201
Characteristics							
Upstream Regulation	y	y	y	n	y	y	y
Number of Return Flows	1	16	42	2	12	0	10
Qty return flows	291	1753	4497	0	2556	0	308
return flow/ baseflow ave	0.07	0.16	0.26	0.00	0.04	0.00	0.01
Number of Water Intakes	0	0	3	0	2	0	1
Qty. Water Intakes	0	0	2881	0	3183	0	651
Intake / baseflow ave	0	0.00	0.17	0.00	0.05	0.00	0.01

Table 2: Colorado

Parameter	Big Sandy Ck nr McDade, TX	Big Sandy Ck nr Elgin, TX	S Concho Rv at Christoval, TX	San Saba Rv at Menard, TX	Brady Ck nr Eden, TX	Pedernales Rv at Stonewall, TX
USGS Gauge Number	8159165	8159170	8128000	8144500	8144800	8153000
Period of Record (from)	7/13/1979	7/12/1979	3/1/1930	10/1/1915	5/1/1962	8/1/1924
Period of Record (to)	9/30/1985	9/30/1985	9/30/2004	9/30/2004	10/9/1985	9/30/1934
Baseflow Index (%)						
average	0.17	0.11	0.71	0.53	0.39	0.26
median	0.08	0.07	0.81	0.56	0.43	0.25
stdev	0.25	0.12	0.26	0.26	0.27	0.15
max	0.68	0.34	0.98	0.94	0.76	0.60
min	0.02	0.02	0.07	0.04	0.00	0.06
Baseflow (acre-ft/yr)						
average	394	443	12590	16372	252	10172
median	396	396	10937	13546	171	8691
stdev	208	283	9946	10785	306	6555
max	685	791	57629	54412	1155	20982
min	152	96	1440	701	0	3596
Baseflow (acre-tt/yr-sq mi)						
drainage area (sq mi)	37.8	63.8	354	1128	101	647
average	0.014	0.010	0.049	0.020	0.003	0.022
median	0.014	0.009	0.043	0.017	0.002	0.019
Characteristics						
Upstream Regulation	y	y	y	y	y	y
Number of Return Flows	6	8	2	1	0	3
Qty return flows	0	5	0	0	0	1074
return flow/ baseflow ave	0.00	0.01	0.00	0.00	0.00	0.11
Number of Water Intakes	0	0	0	0	0	0
Qty. Water Intakes	0	0	0	0	0	0
Intake / baseflow ave	0	0.00	0.00	0.00	0.00	0.00

Table 2: Colorado (cont)

Parameter	Bull Ck at Loop 360 nr Austin, TX	Barton Ck at SH 71 nr Oak Hill, TX	Onion Ck nr Driftwood, TX	Slaughter Ck at FM 1826 nr Austin, TX	Williamson Ck at Oak Hill, TX
USGS Gauge Number	8154700	8155200	8158700	8158840	8158920
Period of Record (from)	7/18/1978	2/7/1978	7/1/1979	1/16/1978	1/10/1978
Period of Record (to)	9/30/2004	9/30/2004	9/30/2004	9/30/2004	9/30/2004
Baseflow Index (%)					
average	0.41	0.50	0.57	0.35	0.19
median	0.37	0.50	0.59	0.31	0.18
stdev	0.11	0.17	0.16	0.21	0.10
max	0.72	0.78	0.83	0.92	0.37
min	0.25	0.20	0.23	0.00	0.06
Baseflow (acre-ft/yr)					
average	4192	17091	21754	1332	705
median	4344	17469	22533	1261	692
stdev	2780	15817	18971	1060	559
max	11963	66146	72953	3322	1727
min	492	74	189	0	24
Baseflow (acre-tt/yr-sq mi)					
drainage area (sq mi)	22.3	90	124	8	6
average	0.259	0.262	0.242	0.230	0.162
median	0.269	0.268	0.251	0.218	0.159
Characteristics					
Upstream Regulation	y	y	n	n	n
Number of Return Flows	4	5	8	1	0
Qty return flows	0	0	0	0	0
return flow/ baseflow ave	0.00	0.00	0.00	0.00	0.00
Number of Water Intakes	0	0	1	0	0
Qty. Water Intakes	0	0	0	0	0
Intake / baseflow ave	0.00	0.00	0.00	0.00	0.00

Table 2: Brazos

Parameter	Mill Ck nr Bellville, TX	E Yegua Ck nr Dime Box, TX	Paluxy Rv at Glen Rose, TX	N Bosque Rv at Stephenville, TX	N Bosque Rv at Hico, TX	Cowhouse Ck at Pidcoke, TX	Cowhouse Ck nr Killeen, TX	Lampasas Rv nr Kempner, TX	S Fk Rocky Ck Briggs, TX	Big Ck nr Freestone, TX
USGS Gauge Number	8111700	8109800	8091500	8093700	8094800	8101000	8101500	8103800	8103900	8110430
Period of Record (from)	8/1/1963	8/1/1962	1/1/1924	3/1/1958	1/1/1962	10/1/1950	10/1/1924	10/1/1962	5/1/1963	7/1/1978
Period of Record (to)	9/30/2004	9/30/2004	9/30/2004	9/30/1979	9/30/1999	9/30/2004	7/31/1942	9/30/2004	9/30/2004	9/30/2004
Baseflow Index (%)										
average	0.20	0.29	0.34	0.04	0.23	0.24	0.29	0.49	0.39	0.10
median	0.19	0.17	0.33	0.03	0.19	0.25	0.29	0.48	0.44	0.08
stdev	0.09	0.22	0.16	0.03	0.12	0.16	0.28	0.16	0.21	0.09
max	0.51	0.83	0.74	0.15	0.47	0.70	0.49	0.83	0.82	0.46
min	0.04	0.07	0.05	0.00	0.04	0.00	0.09	0.21	0.00	0.03
Baseflow (acre-ft/yr)										
average	28380	10184	18029	472	13089	18726	88346	50076	3556	2810
median	24869	7262	13191	336	6338	7327	88346	23691	2758	2776
stdev	17244	7987	16582	503	18797	25808	118265	56113	3545	1946
max	68891	28297	83021	1618	101331	130303	171972	266060	16095	9341
min	3478	1042	2060	2	460	48	4720	6423	0	368
Baseflow (acre-tt/yr-sq mi)										
drainage area (sq mi)	376	120	410	95.9	359	455	667	818	33	97.2
average	0.104	0.117	0.061	0.007	0.050	0.057	0.183	0.084	0.149	0.040
median	0.091	0.084	0.044	0.005	0.024	0.022	0.183	0.040	0.115	0.039
Characteristics										
Upstream Regulation	y	y	y	y	y	y	y	y	y	y
Number of Return Flows	9	15	11	44	89	9	15	2	0	3
Qty return flows	1179	875	0	1882	3764	0	4062	541	0	319
return flow/ baseflow ave	0.04	0.09	0.00	3.99	0.29	0.00	0.05	0.01	0.00	0.11
Number of Water Intakes	0	0	0	0	0	0	0	0	0	0
Qty. Water Intakes	0	0	0	0	0	0	0	0	0	0
Intake / baseflow ave	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 2: Trinity

Parameter	S Twin Ck nr Eustace, TX	Tehuacana Ck nr Streetman, TX	Big Sandy Ck nr Chico, TX	Big Sandy Ck nr Bridgeport, TX	Garrett Ck nr Paradise, TX	Salt Ck nr Paradise, TX	Walnut Ck at Reno, TX
USGS Gauge Number	8063003	8064700	8043950	8044000	8044135	8044140	8044800
Period of Record (from)	10/1/1982	4/1/1968	10/1/1936	10/1/1936	10/1/1993	12/14/1992	10/1/1995
Period of Record (to)	2/29/1984	9/30/2004	8/31/2004	2/5/1998	9/30/1994	9/30/1995	9/30/2004
Baseflow Index (%)							
average	0.14	0.04	0.17	0.16	0.93	0.98	0.24
median	0.14	0.03	0.14	0.14	0.93	0.98	0.22
stdev	N/A	0.03	0.11	0.11	N/A	0.01	0.10
max	0.14	0.12	0.45	0.45	0.93	0.99	0.37
min	0.14	0.01	0.00	0.00	0.93	0.98	0.06
Baseflow (acre-ft/yr)							
average	1389	2528	9055	9259	103430	179209	2865
median	1389	1863	5510	5568	103430	179209	1365
stdev	N/A	2718	11761	11984	N/A	124525	3826
max	1389	15448	58902	58902	103430	267261	11938
min	1389	96	1	1	103430	91156	262
Baseflow (acre-tt/yr-sq mi)							
drainage area (sq mi)	27	10	312	333	53	53	76
average	0.071	0.349	0.040	0.038	2.693	4.666	0.052
median	0.071	0.257	0.024	0.023	2.693	4.666	0.025
Characteristics							
Upstream Regulation	y	y	y	y	n	n	y
Number of Return Flows	2	4	4	4	1	0	2
Qty return flows	25	219	659	659	9	0	538
return flow/ baseflow ave	0.02	0.09	0.07	0.07	0.00	0.00	0.19
Number of Water Intakes	0	2	0	0	0	0	0
Qty. Water Intakes	0	719	0	0	0	0	0
Intake / baseflow ave	0	0.28	0.00	0.00	0.00	0.00	0.00

Table 2: Rio Grande

Parameter	Pecos Rv nr Girvin, TX	Madera Canyon nr Toyahvale, TX	Limpia Ck nr Ft Davis, TX	Barrilla Draw nr Saragosa, TX	Pecos Rv nr Sheffield, TX	Pecos Rv nr Langtry, TX	Devils Rv nr Juno, TX	Devils Rv at Pafford Crsg nr Comstock, TX
USGS Gauge Number	8446500	8424500	8432000	8433000	8447000	8447410	8449000	8449400
Period of Record (from)	9/1/1939	8/1/1932	3/1/1925	12/1/1924	10/1/1921	10/1/1975	6/1/1925	2/1/1978
Period of Record (to)	9/30/2004	9/30/1949	7/31/1932	9/30/2004	9/30/1949	9/30/1985	9/30/1973	10/8/1985
Baseflow Index (%)								
average	0.28	0.14	0.25	0.04	0.20	0.65	0.67	0.85
median	0.29	0.12	0.24	0.00	0.18	0.65	0.79	0.89
stdev	0.09	0.09	0.19	0.07	0.08	0.08	0.31	0.12
max	0.39	0.32	0.54	0.19	0.38	0.74	0.99	0.98
min	0.02	0.00	0.02	0.00	0.12	0.51	0.09	0.66
Baseflow (acre-ft/yr)								
average	15657	392	481	48	220673	195296	60083	187254
median	10752	256	258	0	75931	164583	62803	179071
stdev	15921	402	473	89	349815	93380	22679	59620
max	70464	1241	1099	268	1109692	335777	125392	280501
min	4499	0	20	0	44945	100890	17122	117323
Baseflow (acre-tt/yr-sq mi)								
drainage area (sq mi)	1740	54	303	612	2040	4856	2730	3960
average	0.012	0.010	0.002	0.000	0.149	0.056	0.030	0.065
median	0.009	0.007	0.001	0.000	0.051	0.047	0.032	0.062
Characteristics								
Upstream Regulation	n	n	n	n	n	n	n	n
Number of Return Flows	28	0	3	0	8	0	6	6
Qty return flows	154	0	154	0	2905	0	1542	1542
return flow/ baseflow ave	0.01	0.00	0.32	0.00	0.01	0.00	0.03	0.01
Number of Water Intakes	1	0	0	0	0	0	0	0
Qty. Water Intakes	108	0	0	0	0	0	0	0
Intake / baseflow ave	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 2:	Colorado-Lavaca	Lavaca	Lavaca-Gradalupe	San Ja Brazos	Brazos-Colorado	Trinity-Sa Jacinto	Nueces-Rio Grande	
Parameter	Tres Palacios Rv nr Midfield, TX	Sandy Ck nr Ganado, TX	Garcitas Ck nr Inez, TX	Clear Ck nr Pearland TX	San Bernard Rv nr Boling, TX	Cypress Ck nr Hockley, TX	San Diego Ck at Alice, TX	Los Olmos Ck nr Falfurrias, TX
USGS Gauge Number	8162600	8164450	8164600	8077000	8117500	8068720	8211800	8212400
Period of Record (from)	6/17/1970	10/1/1977	6/15/1970	8/1/1944	5/1/1954	6/1/1975	10/1/1963	1/1/1967
Period of Record (to)	9/30/2004	9/30/2004	9/30/2004	9/4/1994	9/30/2004	9/30/2004	9/30/1989	9/30/2004
Baseflow Index (%)								
average	0.15	0.09	0.08	0.15	0.23	0.09	0.06	0.09
median	0.14	0.09	0.07	0.13	0.23	0.08	0.02	0.01
stdev	0.07	0.03	0.05	0.08	0.08	0.05	0.09	0.22
max	0.33	0.15	0.26	0.39	0.39	0.22	0.39	0.77
min	0.06	0.04	0.04	0.06	0.10	0.02	0.00	0.00
Baseflow (acre-ft/yr)								
average	15168	14750	3030	3630	86490	4342	304	105
median	13350	12703	2580	3179	64511	2584	35	13
stdev	6507	9500	2136	2604	57576	4543	1016	160
max	31658	38165	9570	14379	333296	19400	5178	564
min	3546	2140	228	551	7578	89	0	0
Baseflow (acre-tt/yr-sq mi)								
drainage area (sq mi)	145	289	92	39	727	110	319	476
Average	0.144	0.070	0.045	0.128	0.164	0.054	0.001	0.000
Median	0.127	0.061	0.039	0.112	0.122	0.032	0.000	0.000
Characteristics								
Upstream Regulation	y	y	y	y	y	y	y	y
Number of Return Flows	4	2	2	16	16	3	1	3
Qty return flows	34	0	22	1379	1895	567	841	0
return flow/ baseflow ave	0.002	0.00	0.01	0.38	0.02	0.13	2.77	0.00
Number of Water Intakes	0	0	0	0	0	0	0	0
Qty. Water Intakes	0	0	0	0	0	0	0	0
Intake / baseflow ave	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00

Average baseflow indices range from 0.985 to 0.006, a very wide range. Bringing context to this number is important to understanding the significance to baseflow index. First, baseflow index is the flow rate of baseflow divided by streamflow. Accordingly, for a constant baseflow contribution, a small stream with relatively small storm flow contribution may have a very large baseflow index while a large stream with significant flow may have a small baseflow index. Baseflow index, therefore, is a good stream specific estimate of the significance of baseflow to total flow for the reach of the river and the portion of the basin that is represented. However, it is difficult to compare BFI from stream to stream and basin to basin. One could also look at annual volume of baseflow, which ranges from over 27,000 acre-ft/yr to 3 acre-ft/year (using average estimates). Baseflow volume estimated from gauge data very near to the origin of a stream may indicate a small volume of baseflow, while a downstream gauge on the same stream crossing the same aquifer outcrop may indicate much higher volume of baseflow; simply because the downstream gauge is estimating baseflow over a larger portion of aquifer outcrop. Volume of baseflow is a useful stream and basin specific number that describes the total annual volume of water that is baseflow. A third way to view baseflow is to view the baseflow volumes normalized by drainage area that is aquifer outcrop (acre-ft/yr-mi^2). Normalized baseflow averages range from 4.66 to 0.000. This metric is analogous to yield. With this metric, one gets a sense of the capacity of the aquifer outcrop to contribute to baseflow. Normalized baseflow volumes can be compared regardless of which aquifer outcrop they are crossing, or how big is the drainage basin they represent.

Automated baseflow estimates are commonly regarded with skepticism because they fail to include the effects of reservoir storage, return flows, and surface water intakes. This investigation attempted to develop some evidence to indicate the importance of each of these factors. While the significance of TCEQ permitted reservoir storage was minimized by avoiding steam reaches with TCEQ permitted reservoirs and by using gauge pairs to subtract out the effects of these reservoirs, many reaches had smaller reservoirs on them. Of the 91 gauges used to estimate baseflow, at least 63 had small reservoirs present on them, while on 28 small reservoirs could not be found. The range of average BFI estimates from the 28 gauges without noticeable reservoir storage was identical to the range of average BFI estimates from the gauges with small reservoir storage. In addition, gauges in close geographic proximity were generally very close in both BFI, baseflow volume, and normalized baseflow. However, in the TMDL segment analysis section of this report, it was found that a small reservoir located on the Little Wichita River operated by the City of Henrietta for the purpose of drinking water intake caused such uncertainty in the nearby USGS gauge that the regional USGS office regarded the numbers obtained at that gauge as very low quality. Accordingly, small reservoir storage does not appear to be a major factor in baseflow estimation unless the presence of a small reservoir causes uncertainty in the stream gauge data on which the baseflow estimate is based.

Return flows were identified by the TCEQ TMDL team in a GIS geodatabase, with quantitative information on flow rate. Failure to account for return flow in baseflow estimates would lead to over estimation of baseflow. Out of 91 gauges analyzed, 21 gauges did not have return flows. Of the remaining 71 gauges, 23 did not have a reportable quantity of return flow. That is a total of 44 of 91 gauges that did not have a significant quantity of return flow in the baseflow analysis. For the remaining 47 gauges, 30 gauges had return flow that was less than 10 percent of baseflow, and 17 had return flow that was between 10 and 25 percent of baseflow; 6 that had return flow that was between 25 and 50 percent, and 3 that were above 50 percent. The results of this investigation suggest that return flow can have a significant impact on automated baseflow estimation, and accordingly, a baseflow analysis should include enumeration of return flow. However, over 80 percent of reaches analyzed either had no measurable return flow or return flows that were less than 10 percent of baseflow estimates.

Public water system intakes were provided by the TCEQ Drinking Water Protection Program. Failure to account for drinking water intakes in baseflow estimates would lead to under estimation of baseflow. Of the 91 reaches analyzed, 78 did not contain public water intakes. Of the remaining 11 reaches, 7 had public water intakes with flow less than 10 percent of baseflow; 2 had intake flow between 10 and 25 percent, 1 had intake flow between 25 and 50 percent, and 1 had intake flow over 50 percent. While it is important to check for public water intakes when conducting baseflow analysis, for the majority of reaches analyzed, public water intakes were not a factor.

It is important to keep in mind that the return flow data and the public water system intake data were not time series data. Accordingly, streamflow records could not be adjusted for the relevant period of record. The above analysis regarding the significance of return flows and intakes is therefore strictly qualitative in nature. Since the intake and return flow data is the most current data available (2004), one might suggest that return flows and intakes are at a historical maximum because of the increasing population of Texas. This argument is plausible for public water systems, but does not account for the incorporation, disassociation, and movement of business entities that may contribute return flows, or withdrawal surface water. A study could be conducted to investigate the significance of return flow or public water intake with time series data for return flow coincident with period of record at a stream gauge.

5.3 Flow Duration Curves

A duration curve was prepared for many of the gauges analyzed in this study. This was done by obtaining all of the streamflow data for a gauge, sorting it from high to low, eliminating all zero values. The sorted nonzero values were then ranked from 1 to n. As MS Excel can not prepare probability plots, the ranks were recalculated using the NORMSINV function, which calculates the inverse of the standard normal cumulative distribution. Equation (4) was used to calculate new ranks for the sorted nonzero streamflow values.

$$rank_{new,i} = NORMSINV((rank_{old,i} - 0.5)/ rank_{max}) \qquad (4)$$

The new rank values were plotted (x) against the sorted non-zero streamflow values (y). Two such duration curves are depicted below in Figures 7 and 8.

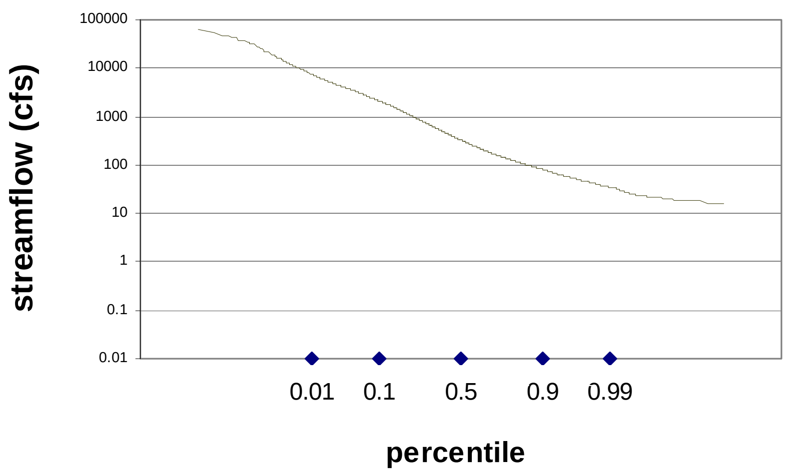

Figure 7: Duration curve for Village Creek near Kountze, TX (08041500)

The duration curve depicted in Figure 7 (Village Ck nr Kountze, TX) was typical for streams with significant baseflow contributions from the outcrop. This reach had an average BFI of 47%, average annual volume of baseflow of 278,651 acre-ft/yr, and a baseflow contribution from the Gulf Coast aquifer outcrop of 0.447 acre-ft/yr-mi^2 over a 67 year period of record. There were 14 return flows contributing less than 1 percent of baseflow, and no public water intakes.

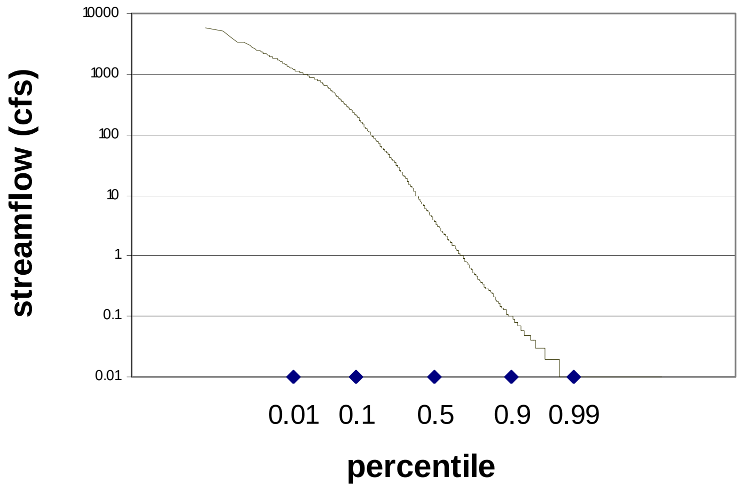

Figure 8: Duration curve for Copano Creek near Refugio (08189200)

The duration curve depicted in Figure 8 (Copano Ck nr Refugio) was typical for streams with low baseflow contributions from the outcrop. This reach had an average BFI of 8%, average annual volume of baseflow of 3,112 acre-ft/yr, and a baseflow contribution from the Gulf Coast aquifer outcrop of 0.049 acre-ft/yr-mi^2 over a 33 year period of record. There were no return flows and no public water intakes.

5.4. Geographic Trends in Baseflow

After estimating baseflows for the reaches crossing aquifer outcrops, these data were plotted in GIS to examine spatial trends associated with baseflow in Figure 9 (BFI, as percent) and Figure 10 (normalized baseflow, acre-ft/yr/mi^2). In this plot, all gauges analyzed are displayed together, regardless of how many years comprise the period of record, or when the period of record begins and ends.

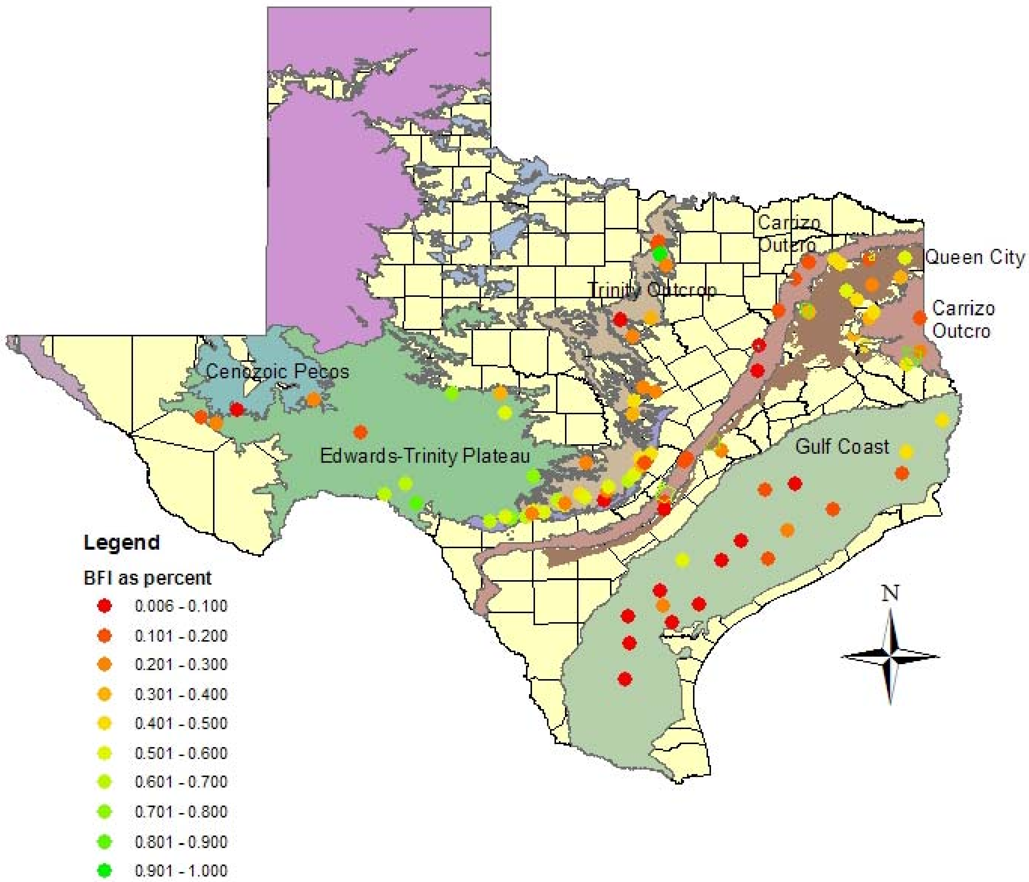

Figure 9: Spatial distribution of BFI (as percent)

From Figure 10 a few basic trends can be noted. For the Gulf Coast aquifer outcrop, there is a general trend of decreasing baseflow from northeast to southwest. This trend is also apparent in the Queen City and Carrizo outcrop areas. Gauges analyzed in the Trinity outcrop do not appear to demonstrate any clear spatial pattern at this point. In the Edwards-Trinity Plateau aquifer, there is a trend of decreasing baseflow from south to northeast and northwest. However, this trend must be treated with caution, as there are approximately 15 gauges analyzed over a very large area. In the Cenozoic-Pecos alluvium, there are too few gauges to note any particular trends other than small contribution of baseflow to streamflow everywhere.

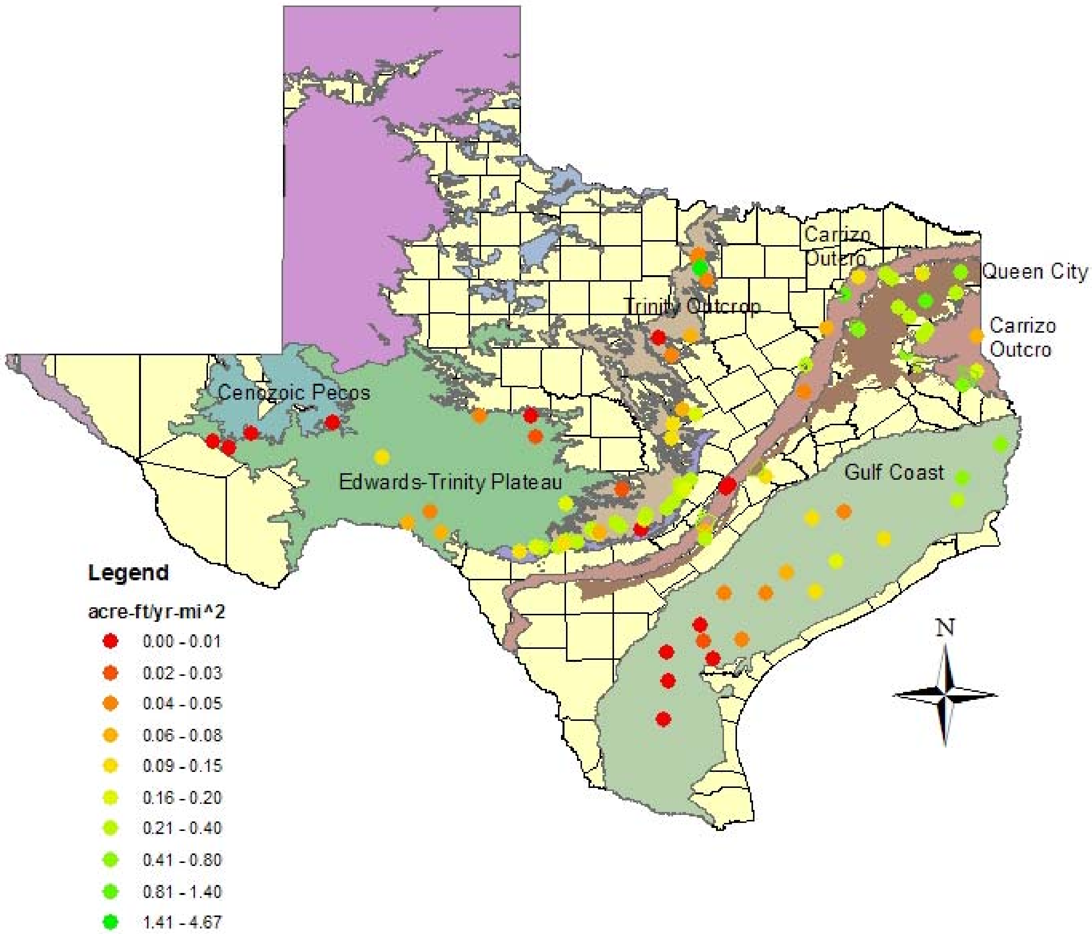

Figure 10: Spatial distribution of normalized baseflow (acre-ft/yr-mi^2)

5.5 References

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Appendix 6

Task 3.4: Evaluate Potential Effects of Groundwater Pumpage Adjacent to Streams on Streamflow Using Analytical Approaches

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Sections

6.1 Introduction

The effect of pumping from a well near a stream has long been of interest to water managers. Pumping can lower groundwater levels and potentially reduce water flow within a stream. Analytical solutions for estimating stream depletion from groundwater pumping are used as a management tool for water rights administration. Currently, these analytical solutions are screening tools that may be used when resources are not available to construct a numerical model, or to justify the use of numerical modeling when analytical solutions are unable to accurately predict complex interactions between groundwater and surface water. An understanding of what analytical models are available, and their assumptions and limitations is important in choosing the appropriate analytical model for a set of physical constraints.

6.2 Discussion

The first unsteady solution to this problem was provided by Theis (1941). This solution depicted the river as a long straight line, completely penetrating a homogeneous aquifer, with zero drawdown. Groundwater was assumed to move horizontally, and vertical movement of groundwater was not included. Theis (1941) derived the solution in the form of an integral, which he evaluated using an infinite series. Theis' integral was later evaluated by Glover and Balmer (1954) using the complimentary error function (erfc). This solution is provided below in equation 1.

$$\frac{\Delta Q}{Q_w} = erfc\left(\sqrt{\frac{S * l^2}{4 * T * t}}\right) \qquad (1)$$

where ΔQ [L^3/T] is stream depletion flow rate, Q_w [L^3/T] is pumping flow rate, t is time [T], T is aquifer transmissivity [L^2/T], S is aquifer storage coefficient [L^{-1}], and l [L] is perpendicular distance from the well to the stream edge.

Jenkins (1970) applied equation 1 to specific problems, and developed a set of graphical tools that could be used by practitioners to analyze water rights problems without the use of complex mathematical functions. Jenkins also applied the principles of superposition and time translation to equation 1 to solve intermittent pumping schedules. Example calculations demonstrating how the graphical tools are applied in different situations are also described in Jenkins (1970). Jenkins (1970) makes the following assumptions: 1) transmissivity does not change with time (drawdown is negligible compared to saturated thickness), 2) temperature of groundwater and stream water are equal and constant, 3) the aquifer is isotropic, homogeneous, and semi-infinite in areal extent, 4) the stream is straight and fully penetrates the aquifer, 5) water is released instantaneously from storage, 6) the well is open to the full saturated thickness of the aquifer, and 7) pumping rate is steady during pumping.

Sophocleous et al. (1995) tested the solution originally proposed by Theis (and updated by Balmer and Glover (1954), Jenkins (1970)) by comparing results from the analytical solution to results generated using numerical simulations with MODFLOW. Assumptions regarding local aquifer homogeneity were problematic and stream bed clogging was a major factor in leakage calculations (Sophocleous et al., 1995). The assumption of full penetration of a stream into an aquifer was also a major factor, and the degree of partial penetration of the stream into the aquifer could dramatically change leakage estimates. Large scale aquifer heterogeneity was significant, and the analytical solution was found to be risky for layered systems. By contrast, estimates of aquifer properties such as storativity and hydraulic conductivity, and assumptions regarding partial or full penetration of the well were less sensitive to stream leakage calculations.

Hantush (1965) provided an analytical solution for a fully penetrating stream and identical set of conditions considered by Theis (1941) and Glover and Balmer (1954) with the addition of a vertical layer of semi-pervious material lining the stream bed. This solution is provided below in equation 2.

$$\frac{\Delta Q}{Q_w} = erfc\left(\sqrt{\frac{S*l^2}{4*T*t}}\right) - \exp\left(\frac{T*t}{S*L^2} + \frac{l}{L}\right) * erfc\left(\sqrt{\frac{T*t}{S*L^2}} + \sqrt{\frac{S*l^2}{4*T*t}}\right) \qquad (2)$$

where L [L] is stream leakance defined as the permeability of the aquifer, K [L^2], multiplied by the thickness of the semi-pervious layer, b′ [L], divided by the permeability of the semi-pervious layer, K′ [L^2] . Hunt (1999) proposed a similar solution, additionally including the assumption that streambed penetration of the aquifer and dimensions of the streambed cross section are relatively small. The solution is general enough to include earlier solutions provided by Theis, Glover and Balmer, and Hantush. The solution is provided below in equation 3.

$$\frac{\Delta Q}{Q_w} = erfc\left(\sqrt{\frac{S*l^2}{4*T*t}}\right) - \exp\left(\frac{\lambda^2*t}{4*S*T} + \frac{\lambda*l}{2*T}\right) * erfc\left(\sqrt{\frac{\lambda^2*t}{4*S*T}} + \sqrt{\frac{S*l^2}{4*T*t}}\right) \qquad (3)$$

Where λ (L/T) is a constant of proportionality between the seepage flow rate per unit distance (along the stream) through the stream bed and the difference between river and groundwater levels at the stream center.

Hunt et al. (2001) carried out a field experiment to test the formulation in equation 2. A pump test was conducted using a well located 55 m from the nearest edge of a long, straight portion of Doyleston Drain, New Zealand. The drain is 2.5 m wide with a silt and gravel lined stream bed approximately 1 m below the ground surface. The aquifer, composed of unconsolidated sand and gravel, is about 20 m thick and is capped on top with 2.8 m of less permeable material. Water was abstracted from the well at a constant rate of 0.0175 m^3/s for a period of 10 hours. During this time, water levels were measured in nearby observation wells, while flow measurements were taken in the drain with the use of installed weirs. Values for T and S were estimated from observation well drawdowns at early times, and λ was estimated using measured stream depletion flows at later times. Reasonable agreement was obtained for values of these parameters from data measured in four observation wells. The authors point out that these methods for determining parameters are dependent upon accurate measurements of flow in the river. While this criterion is well suited to small channels, it would be difficult to apply these methods at larger streams.

An analytical solution was proposed by Zlotnik et al. (1999) which incorporates shallow stream penetration and a low permeability stream bed (as did Hunt), but added the effects of finite stream width. The solution was apparently originally obtained by Grigoryev (1957). As presented by Zlotnik et al. (1999) the solution is displayed in equation 4. In this derivation, the domain is divided up into three zones: Zone I represents land directly under the stream bed, Zone II represents land on the side of the stream bed with the well, and Zone III represents land on the side of the stream bed without the well. Variables are subscripted I, II, and III to indicate which zone they represent. Variables pertaining to the stream bed are superscripted with a strike (′).

$$\frac{q}{Q} = erfc\left(\frac{l}{2*\sqrt{\alpha * t}}\right) - \exp\left(b_1^2 * t + \frac{b_1 * l}{\sqrt{a}}\right) * erfc\left(\frac{l}{2*\sqrt{\alpha * t}} + b_1 * \sqrt{t}\right) \qquad (4)$$

where:

$$\alpha = k * m / S_y$$
$$a = k' * m' / k$$
$$b_1 = \mu * \sqrt{\alpha} * [1 - 1/\cosh(2 * w * v)]$$
$$v^2 = k' / (m' * k * m_1)$$
$$\mu = \beta * v * \coth(2 * w * v)$$
$$\beta = T_I / T_{II} \approx m_1 / m$$

In these equations, m represents vertical thickness, k [L/T] represents hydraulic conductivity, w [L] is the half-width of the stream, T [L^2/T] is transmissivity, S_y [unitless] is specific yield, l [L] is distance from the well to the stream bank, Q [L^3/T] is pumping rate, q [L^3/T] is stream depletion, and t [T] is time.

For pumping wells relatively close to the stream, equation 4 is the preferred approach because stream width cannot be considered negligible relative to the distance from the pumping well to the stream. For pumping wells at larger normalized distances from the stream, equations 3 and 4 produce similar results. This model makes several key assumptions including: 1) vertical flow is negligible, 2) the aquifer is isotropic, 3) aquifer heads remain above the stream bottom, 4) the stream level is unaffected by pumping, and 5) the pumping well is fully screened across the aquifer.

Four primary methods for relating pumping effect on groundwater have been presented: the solution of Theis (as proposed by Glover and Balmer, and Jenkins), the solution of Hantush (which adds stream bed clogging), the solution of Hunt (which adds stream bed clogging, and partial stream penetration), and the solution of Zlotnik (which adds stream bed clogging, partial stream penetration, and finite stream width). Each of these solutions incorporates different assumptions, and is appropriate for different circumstances. One does not necessarily need to use the complex model of Zlotnik for circumstances in which the simpler solution proposed by Theis is sufficient for the site specific physical characteristics and geographic layout. Hunt demonstrated the difficulty in gathering field data for benchmarking of these analytical approaches. However, his approach was reasonable for small streams. A set of field conditions must be constructed carefully to gather the data that are required to estimate field parameters and construct a model that depicts groundwater and surface water interaction under the influence of pumping.

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Appendix 7

Feasibility of Using GAM Output for a Selected Aquifer as Input to the WAM Program

Section

7.1 Feasibility of Using GAM Output for a Selected Aquifer as Input to the WAM Program

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Introduction

This report describes the feasibility of using output from Groundwater Availability Models (GAMs), developed for the Texas Water Development Board (TWDB), as input to Water Availability Models (WAMs), developed for the Texas Commission on Environmental Quality (TCEQ). The approach is tested for a selected aquifer, the Carrizo Wilcox aquifer. General information about GAMs and WAMs is currently posted on the TWDB GAM (http://www.twdb.state.tx.us/gam/index.htm) and TCEQ WAM (http://www.tnrcc.state.tx.us/permitting/waterperm/wrpa/wam.html) web sites, respectively.

The first sections of this document describe how gw-sw interactions are incorporated in GAMs and WAMs. The feasibility of using GAM output in WAMs is then evaluated with respect to the Carrizo Wilcox aquifer.

7.1.1 GW-SW Interactions in GAMs

The purpose of GAM models is to provide information on groundwater availability for major and minor aquifers in Texas. Therefore, the original purpose was not to provide information on gw-sw interactions; therefore, there are limitations to the information that can be obtained from GAMs on gw-sw interactions. GAMs can simulate groundwater discharge to surface water (e.g. baseflow to streams) and surface water recharge to groundwater. GAMs also simulate groundwater discharge through evapotranspiration (ET). Baseflow data for comparison with model simulations is limited. Slade et al. (2002) compiled all gain/loss studies in the state that previously were not published. However, most of these studies are for time periods prior to the 1950s. Hydrograph separation can also be used to estimate baseflow using existing gauge data. Independent estimates of ET are not available for any of the GAM sites to constrain model estimates of ET. Therefore, the lack of independent field measurements of these parameters makes it difficult to assess the reliability of model estimates based on the GAMs.

All GAMs use the USGS modular numerical model MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996a; Harbaugh and McDonald, 1996b). MODFLOW is used to simulate the dynamic water mass balance of an aquifer or a series of aquifers by solving the groundwater equation. A user typically first defines the geometry of the modeled aquifer system and its hydraulic properties. The second step consists in applying stresses to the system. Important stresses include recharge, evapotranspiration (ET), and pumping. The aquifer system may be studied under a steady-state assumption where stresses are invariant through time and all fluxes to and from the aquifer are balanced. It can also be approached in a transient mode when the user is interested in describing flux changes relative to variations in stress. In this case, the total mass of water contained in the aquifer system changes through time. Understanding the evolution of an aquifer mass balance (or budget) consists mainly in looking at fluxes. Recharge and ET represent unidirectional fluxes. Other fluxes include cross-formational flow, lateral flow from the model boundaries and losing and gaining streams. The relative order of magnitude of these fluxes depends on the model. As an example, the Central Carrizo-Wilcox model water budget for the transient phase is shown on **Error! Reference source not found.**. It includes only the major components of the budget.

MODFLOW modules are used to simulate these processes. MODFLOW modules are called packages. Commonly used packages are the recharge, ET, well, general-head boundary, reservoir, river, and streamflow routing (SFR) packages. GAMs incorporate gw-sw interactions directly using either one or some of the following packages: streamflow routing (SFR), river, general-head boundary (GHB), or drain. More creative approaches have also been used. A quick review of the previously completed GAMs shows several ways to incorporate gw-sw interactions. Findings are summarized in Table 1. Most major aquifer GAMs, especially in the eastern part of the state, use the SFR or river package with or without the drain package. Some GAMs do not simulate streams explicitly because of local conditions. This is the case of the Northern Gulf Coast GAM where a general-head boundary (GHB) is used in the outcrop areas under the assumption that the GHB captures the dynamics of the system sufficiently within the range of uncertainties (Kasmarek and Robinson, 2004, p.45) and that few calibration points are available from the stream gain/loss study conducted by Slade et al. (2002). Some GAMs use only the drain package recognizing that most streams are predominantly gaining (e.g., Northern Edwards GAM). The GAM for the Barton Springs segment of the Edwards Aquifer uses recharge to model gw-sw interactions because most recharge occurs through losing streams and all streams are losing. The compilation of gain/loss studies by Slade et al. (2002) has been used extensively in many of the GAMs; approximately half of the GAMs use these data. An example of coverage is given in Figure 2**Error! Reference source not found.**.

All gw-sw features are implemented as head-dependent (third order) boundary conditions that offer a first approximation to gw-sw interactions. All fluxes are expressed relative to the aquifer (>0 = gain to the aquifer, losing surface water body; <0 = loss from the aquifer, gaining surface water body). Built-in assumptions include instantaneous exchanges and independence of gw-sw fluxes and stages (in other words, exchange fluxes are assumed small).

Table 1

GAM	Contractor		Target Development	Stream Mo[d] Approach
	Primary	Stream Flow		
Gulf Coast North	USGS	N/A	No streams in model	No-flow bound. (Sabine and Lavaca rivers); GHB for other streams
Gulf Coast Central	TWDB & Waterstone	TWDB	Gain/Loss studies from Slade et al. (2002)	SFR package
Gulf Coast South	TWDB	TWDB	2 major streams with only Rio Grande with Gain/Loss studies from 1964; many lakes and smaller water bodies	River package
CZWX North	Intera	Intera	Gain/Loss studies from Slade et al. (2002)	SFR package
CZWX Central	BEG	HDR	Gain/Loss studies from Slade et al. (2002) Base flow separation	SFR package
CZWX South	Intera	Intera	Gain/Loss studies from Slade et al. (2002)	SFR package
Trinity	R.W. Harden & Assoc.	HDR	Gain/Loss studies from Slade et al. (2002) Base flow separation	SFR package
Trinity Hill Country	TWDB	TWDB	Calibration targets only on springs and on a few streams Gain/Loss studies of 1975	Drain package
Edwards North	TWDB	TWDB	Gain/Loss studies from Slade et al. (2002)	Drain package
Edwards Barton Spri[ngs]	BEG	BEG	Diverse Gain./Loss studies; recharge through losing streams	Recharge package
Edwards San Antonio	*USGS – Work in progress*			
Seymour	Intera	Intera	Gain/Loss studies from Slade et al. (2002), few targets	SFR package
Ogallala North	BEG	BEG	Recharge through playas; historical discharge to rivers and springs; baseflow studies of some streams provide targets	Recharge package River and drain packages
Ogallala South	D.B. Stephens & Assoc.	D.B. Stephens & Assoc.	Spring flow rates	Drain package
Edwards Trinity/	TWDB	TWDB	Gauge measurements	SFR and drain packages

Pecos				
Huelco Bolson	USGS	USGS	Diverse Gain/Loss studies	SFR package
Mesilla Bolson	CH2MHill	CH2MHill	Diverse Gain/Loss studies	SFR package
QCSP (Minor Aquifer)	Intera	R.J. Brandes Company	Naturalized data from WAMs Low flow studies for Colorado and Rio Grande	SFR and drain packages

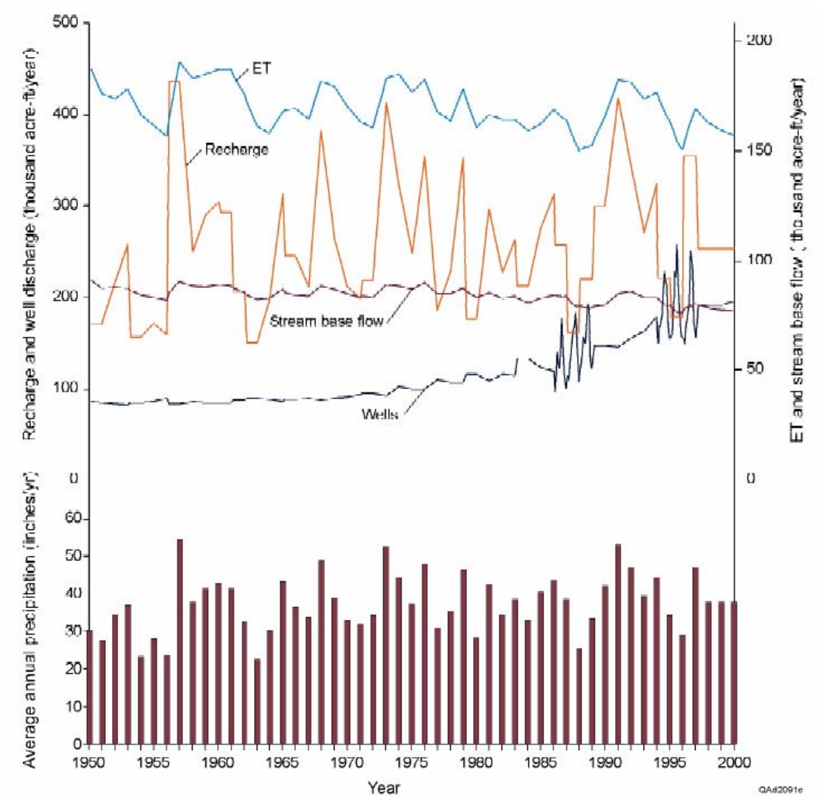


Figure 98. Changes in simulated ET and base-flow discharge to stream with variation in recharge and pumping rates.

Figure 1. Main components of the water budget. Central Carrizo-Wilcox GAM (from Dutton et al., 2003)

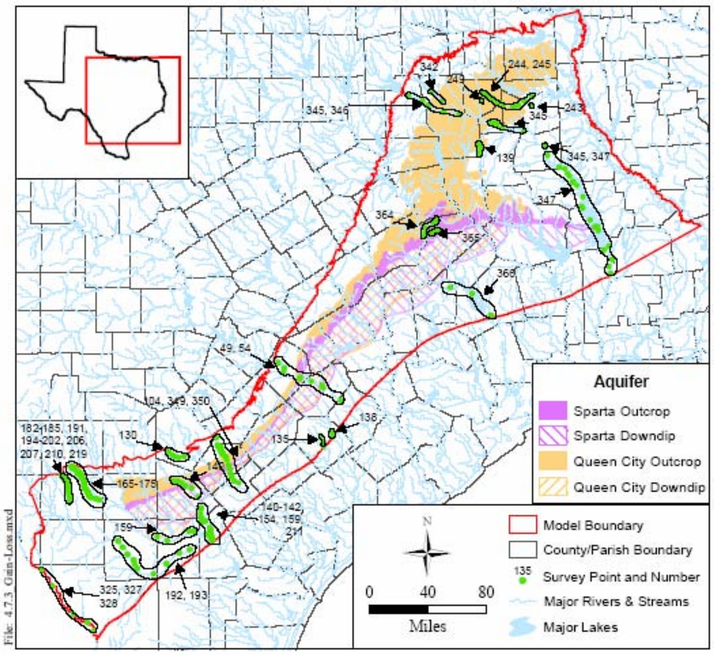


Figure 4.7.3 Stream gain/loss studies in the study area (after Slade et al., 2002).

Figure 2. Example of spatial distribution of Slade et al. (2002) gain/loss studies. Queen City Sparta GAM (from Kelley et al., 2004)

Streamflow Routing Package

MODFLOW-96 (Harbaugh and McDonald, 1996a), currently used in all GAMs, includes a stream-flow routing (SFR) package (Prudic, 1989) and an older river (RIV) package (McDonald and Harbaugh, 1988, chapter 6). The SFR package tracks surface water flow and can also include tributaries and diversions whereas the RIV package does not track flow. Therefore, if the stream is losing, the RIV package may overestimate recharge from surface water bodies because it provides an infinite supply of water. The SFR package also computes the stream stage by providing total stream flow at the beginning of a stream segment (first reach) and stream characteristics (dimensions, slope of stream channel, and Manning's roughness coefficients). Slope and Manning's coefficients are made available by the coverage provided by the EPA river reach dataset. Stream flow may be zero if headwaters are included in the outcrop area of a model. In that case, successive stream reaches may remain dry or become dry depending on the gain/loss status of the reach and the exchange volume. In the RIV package, the stream stage is provided by the user for each stress period (it can be the same for all stress periods). A new stream-routing package (Prudic et al., 2004) is now available in an updated version of MODFLOW, MODFLOW2000 (Harbaugh et al., 2000). However, this newer version is not implemented in GAMs yet.

MODFLOW uses the term reach to describe individual stream segments or that portion of a segment within a finite-difference cell. Leakage to or from a stream reach is computed by applying a variation of Darcy's law:

$$Q = C_S \left(H_{str} - H_{aq} \right) \quad (1)$$

where C_S is streambed conductance and H_{str} and H_{aq} are head in the stream (equivalent to stage) and head in the aquifer cell that contains the reach, respectively. In simple cases, the conductance C_S is given by:

$$C_S = \frac{KWL}{M} \quad (2)$$

where K is hydraulic conductivity of the streambed, W is stream width, L is reach length and M is streambed thickness (**Error! Reference source not found.**Figures 2 and 4). The seepage Q is then incorporated and solved in the groundwater flow equation. The conductance C_S is typically unknown and is calculated empirically during the model calibration phase.

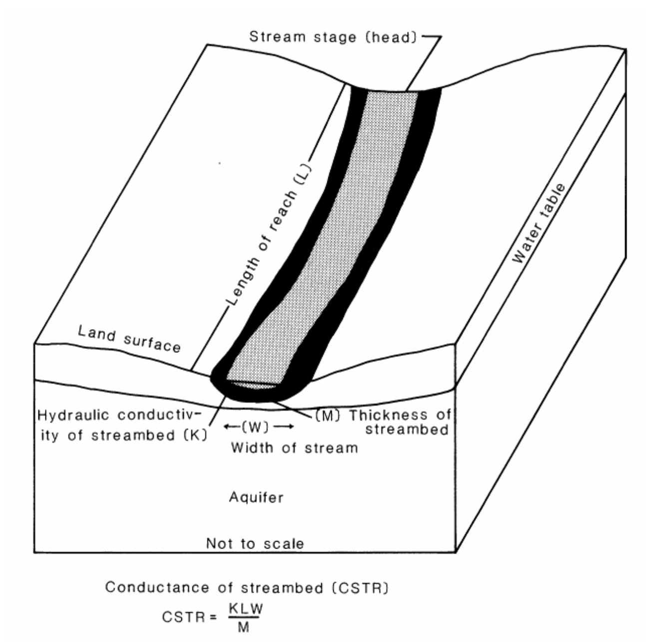


Figure 3. Conceptual model of GW/SW interactions in MODFLOW (from Prudic, 1989)

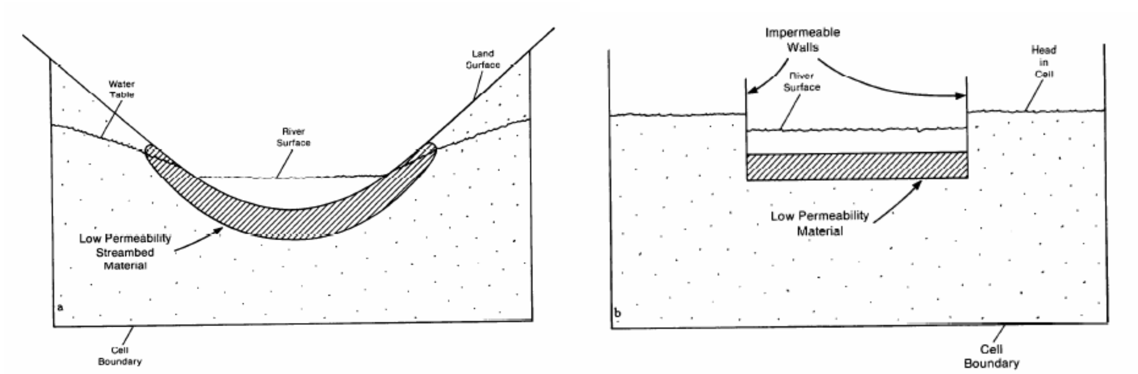


Figure 4. Conceptual representation of a simulated stream-aquifer interconnection (from McDonald and Harbaugh, 1988); case of a gaining stream.

If the aquifer is physically disconnected from the stream as described in **Error! Reference source not found.**. (special case of a perched loosing stream where there is an unsaturated section between the stream and the aquifer), the seepage is not a function of the difference in head anymore but is constant. The seepage Q is then written as:

$$Q = C_S\left(H_{str} - R_{bot}\right) \text{ if } H_{aq} \leq R_{bot} \qquad (3)$$

where R_{bot} represents elevation (relative to the same base level as the aquifer head and river stage) of the bottom of the streambed.

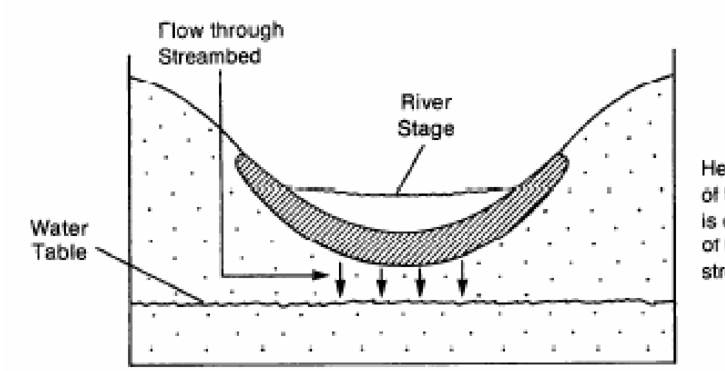


Figure 5. Conceptual representation of a simulated stream-aquifer interconnection (from McDonald and Harbaugh, 1988); case of a perched losing stream.

In a typical 1-square-mile MODFLOW cell (typical cell size of GAMs) stream physical parameters, including stage and river bottom, vary. Yet, MODFLOW cannot take more than one value per cell for all these parameters. A representative value is then required. There are few studies on stream bed conductivity "*K*" and some modelers assume a low permeability stream bed. However, a study by Hibbs and Sharp (1991) determined that the connection between the Colorado River and the alluvium/Carrizo Wilcox aquifer near Bastrop, TX was very good.

Drains

The drain package is typically used to model springs but can also model consistently gaining rivers.

Drain cells work in a way similar to the SFR and river package with the limitations that it can only loose water when the aquifer head is above the drain elevation. If the aquifer head is below the drain elevation, the drain is inactive. The drain leakage Q is represented by:

$$Q = C_d \left(D_{el} - H_{aq} \right) \text{ if } D_{el} < H_{aq}\text{; } Q\text{=0 otherwise} \qquad (4)$$

where C_d is drain conductance and D_{el} and H_{aq} are drain elevation and head in the aquifer cell that contains the drain, respectively. The drain conductance is a calibration parameter and includes effects of the drain size (L) and its hydraulic conductivity (K): $C_d = KL$.

Reservoir Package

The reservoir package is designed for use only when a water body is larger than a single model cell (e.g. lakes and reservoirs) (Fenske et al., 1996). Similarly to the river, stream and drain case, the leakage rate to or from the reservoir is driven by the head difference and proportional to a conductance term:

$$Q = C_R \left(R_{el} - H_{aq} \right) \text{ if } R_{bot} < H_{aq} \qquad (5)$$

$$Q = C_R \left(R_{bot} - H_{aq} \right) \text{ if } R_{bot} > H_{aq} \qquad (6)$$

where C_R is reservoir conductance and R_{el} and H_{aq} are reservoir stage and head in the same aquifer cell, respectively. R_{bot} is the elevation of the base of the reservoir-bed sediments. This formulation is identical to the river package with the additional capability of modeling time-varying reservoir stages. The conductance C_R is also defined similarly:

$$C_R = \frac{K \Delta_x \Delta_y}{M} \qquad (7)$$

where K is bed conductivity of the reservoir sediments, Δ_x and Y_y are the cell dimensions and M is the sediment thickness.

7.1.2 GW-SW Interactions in WAMs

The primary objective of the WAM system is to allocate surface water resources given known water rights. WAM consists of several databases, a code (WRAP; Water Rights Analysis Package) and input files, and pre and post processors (Wurbs, 2001). WRAP is composed of the core program, WRAP-SIM, that simulates allocations, and pre- and post-processors. Naturalized flows are flows that would exist in a stream without man's intervention. A WAM run starts with computation of naturalized flows across the modeled area, using WRAP-HYD, followed by the application of water rights. Computation of naturalized flows represents a large fraction of the total effort required for a WAM study (Wurbs, 2001, p.98). WRAP-HYD is also able to compute net evaporation-precipitation rates but this aspect is more applicable to lakes and reservoirs than to streams. The following discussion presents how naturalized flows are calculated and is a summary of Chapters 4 and 6 of Wurbs (2001) where a much more detailed discussion is available.

Stream flow can be increased by groundwater flow, run-off from precipitation events, return flow (from irrigation, further upstream diversion, and/or groundwater abstraction), and dam release. It can also be decreased by diversions, dams, and evaporation. Land use changes (forest clearing, urbanization) can also have a large impact on stream flow. Wurbs (2001, p.97) states that "WRAP is a river/reservoir system model with little capacity for simulating groundwater or surface/subsurface water interactions". Nevertheless some modeling of gw-sw interactions can be approached through the channel loss coefficients. WRAP does not differentiate baseflow and total flow. A losing stream might be characterized within the lumping "channel loss" coefficient but a gaining stream is not recognized as such.

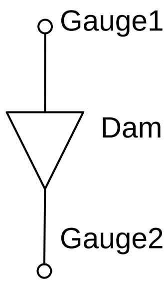
The following tasks are involved in developing naturalized flows (Wurbs, 2001, p.98):

- developing sequences of naturalized flow at gaging stations
- reconstituting flows for gaps of missing data and extending record lengths
- Distributing naturalized flows from gauged to ungauged locations.

The second task has to be performed outside of WRAP because it is not implemented within the program.

Gauged Stream Locations

Historical unadjusted streamflows are available at gauge stations. Adjustments include historical water supply diversions, return flows, reservoir storage changes, and evaporation/precipitation. The focus on historical data allows extrapolation of gauged flows to ungauged streams. The following algebraic equation summarizes the process. The parameter ΔS is change in storage in the reservoir, EP_{dam} is net evaporation/precipitation changes due to the dam, *Div* and *RF* are diversions and return flows. Other terms can be added as well.



$$\text{Gage2}_{\text{Nat}} = \text{Gage2}_{\text{Obs}} + \Delta S + EP_{dam} + Div + RF + \text{Other Terms}$$

In a more complex model, channel losses can be included too. Channel losses *L* represent the portion of the streamflow between 2 control points that is lost through infiltration, ET, and diversions not reflected in the water rights (Wurbs, 2001, p.105). They are represented as a linear function of the flow at the upstream control point: $L=C_L Q_{up}$ where the channel loss coefficient C_L ranges from 0 to 1.

Ungauged Streams

Wurbs (2001, p.109) and Wurbs and Sisson (1999) described three methods to develop data from gauged to ungauged control points. The level of sophistication of the effort can be determined by the user as the weight of a particular control point on the final results increases. The first method, “incremental watersheds” method, applies mainly to ungauged control points located in watersheds where gauges are present. It consists in scaling flow to that part of the drainage area directly related to the ungauged control point. The simplest method of the second group of methods, “flow distribution” methods, implies linearly relating flow (*Q)* and drainage area (*DA)* of gauged and ungauged control points: $Q_u/Q_g=DA_u/DA_g$. A more accurate representation would include geological and land use information through the introduction of curve numbers and possibly other parameters such as precipitation. A third black-box type of approach can also be used by directly relating gauged and ungauged stream flow through a regression analysis: $Q_u = aQ_g^b + c$ where the coefficients *a*, *b*, and *c* are empirically determined. The coefficient *a* can also be an explicit function of, for example, ratios of drainage area and of curve number. Those coefficients can be developed based on watersheds with multiple gauges.

7.1.3 GW-SW Interaction Results

The Carrizo-Wilcox (CW) model and its Queen City Sparta (QS) addition are well suited for evaluating gw-sw interactions because major rivers cross the formation outcrops (Figure 6). The Queen City GAM also includes the Carrizo and Wilcox formations. These models are actually divided into 3 models with largely overlapping domains. The central model of both the Carrizo Wilcox (Dutton et al., 2003) and Queen City Sparta aqufiers (Kelley, 2004) GAMs will be used. Streams of interest are, from South to North, the Guadalupe, Colorado, Brazos, and Trinity rivers.

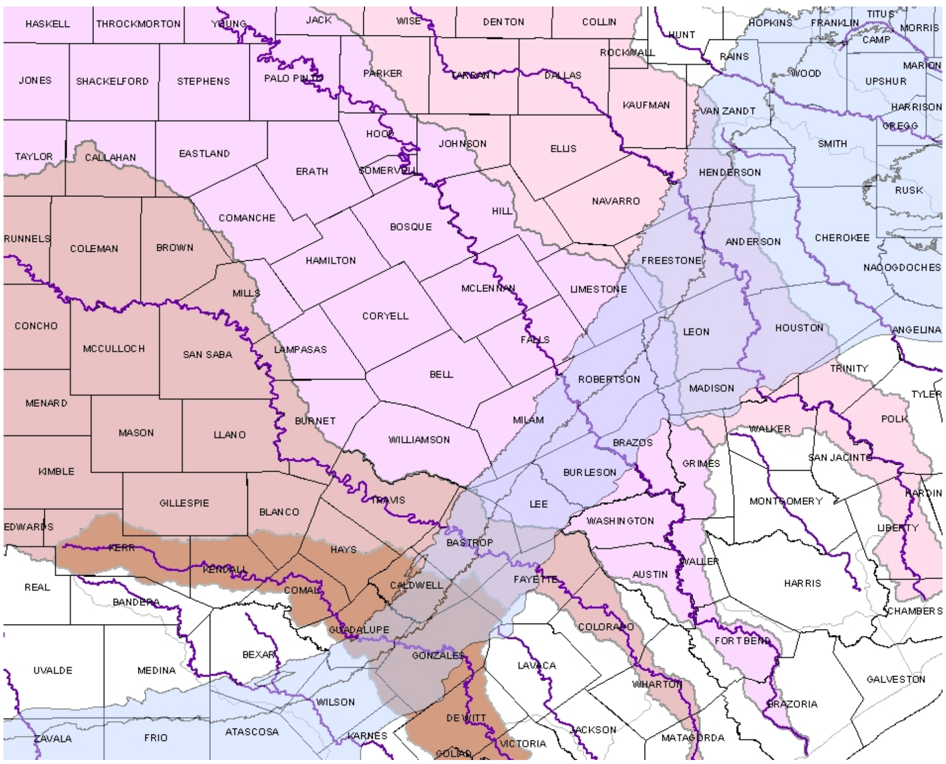


Figure 6. Conceptual representation of a simulated stream-aquifer interconnection (from McDonald and Harbaugh, 1988); case of a perched losing stream.

Carrizo-Wilcox Central Model

The central Carrizo Wilcox GAM report (Dutton et al., 2003) includes a section on gw-sw interactions (O'Rourke and Choffel, 2003). Estimates of baseflow for comparison with simulations were obtained from low-flow studies and base flow separation using the Base Flow Index (BFI) program (Wahl and Wahl, 2001) on daily flow. The following steps were followed:

- (gauged segments) Gather data from low-flow studies conducted in the outcrop area of the aquifers of the Carrizo and Wilcox formations. As an example, the 1918 low flow study on the Colorado river (Slade et al., 2002) showed that the Carrizo and Wilcox formations gained 36 cfs across the outcrop (the low flow characteristics are checked by comparing the “low-flow” to the flow duration curve). This value was obtained by plotting flow from all gauges in the vicinity or on the outcrop and by interpolating on the outcrop area.
- (gauged segments) Apply base flow separation on daily flow on gauges bracketing the outcrop of the formation of interest. Difference in baseflow between the 2 gauges was used as an estimate of the amount of groundwater discharge from the aquifer to the stream in the reach between the gauges. Complications can arise depending on the location of the gauges and number of tributaries. To avoid complications related to dams and naturalized flow, the base flow analysis focused on smaller streams.
- (ungauged segments) Make the assumption that base flow is a function of the watershed area and of the geology of the watershed and extrapolate to ungauged streams similar in size and location (e.g., Guadalupe and Brazos rivers are modeled from Colorado River data). This approach is conceptually similar to that of the flow distribution method from gauged to ungauged watersheds presented in Wurbs (2001, p.111).
- (final target development) Determine what the total base flow is at the most downstream cell of a stream system and calibrate the model relative to these numbers. This translated into 14 values for steady state and theoretically 14 values for each stress period in the transient stage (practically, steady-state values were used too during the calibration process)

Simulated baseflow generally underestimates calculated baseflow from gain/loss studies and BFI calculations (Figure 7). The comparison with calculated baseflows was restricted to the predevelopment period. Simulated baseflows were not compared with calculated values for the transient simulations. There are a number of possible explanations for the discrepancies between simulated and calculated baseflows that will be discussed under a general discussion of MODFLOW simulations of gw-sw interactions. The original model of the Central Carrizo Wilcox aquifer indicated that under projected future pumping scenarios, the Colorado could change from a gaining to a losing stream (Dutton, 1999).

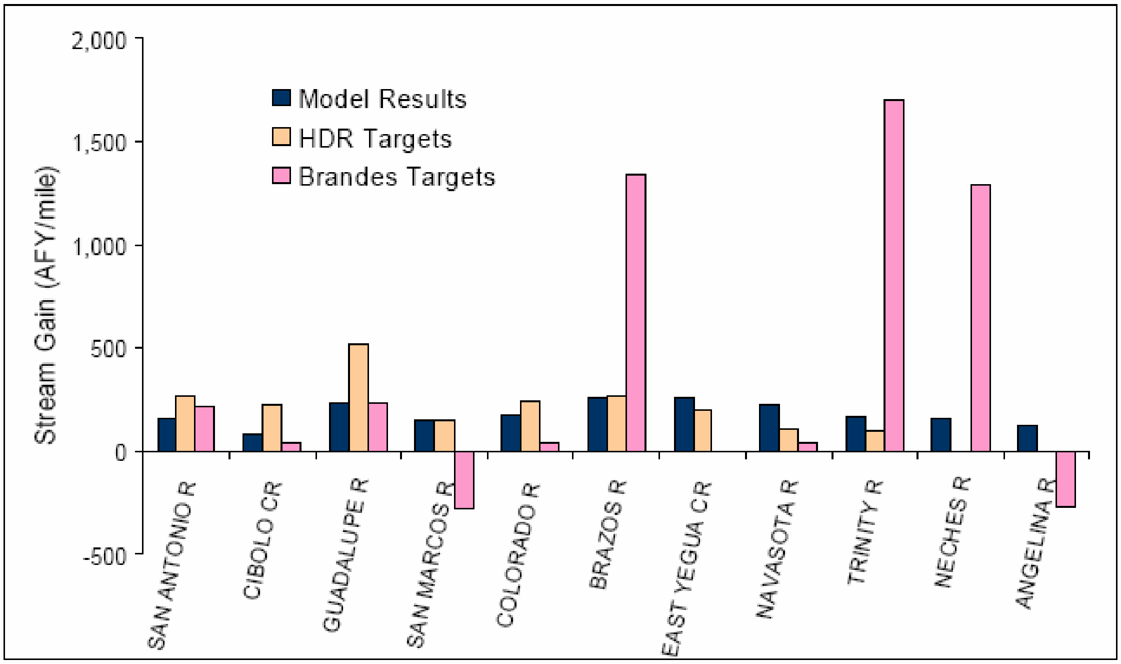


Figure 7. Comparison to measurements of steady-state model gain/loss for the central model of the Queen City GAM (from Figure 8.2.8 of Kelley et al., 2004)

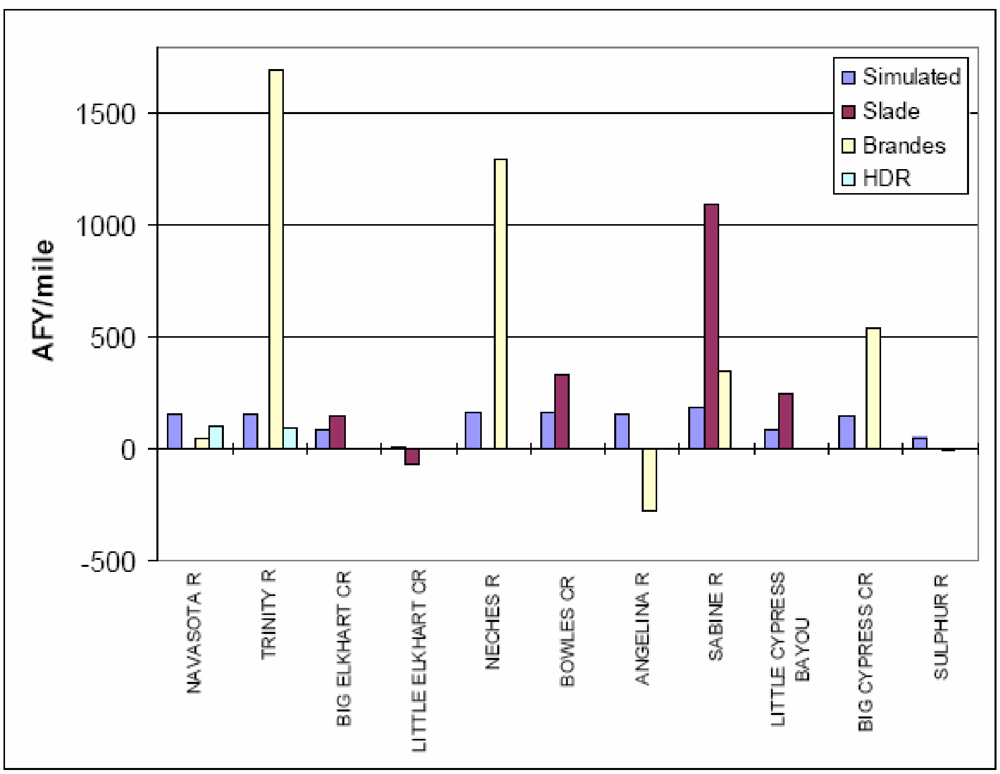


Figure 8. Comparison to measurements of steady-state model gain/loss for the northern model of the Queen City GAM (from Figure 8.3.10 of Kelley et al., 2004)

Carrizo-Wilcox North and South Models

The north (Fryar et al., 2003) and south (Deeds et al., 2003) Carrizo Wilcox GAMs use a slightly different approach. Those models rely mainly on the gain/loss studies during low flow conditions compiled by Slade et al. (2002). The north model had 9 relevant gain/loss studies while the south model had 33 studies; however, some of the studies were on the same reach in the south model. The model was calibrated to the gain/loss values of all the reaches in all studies (~70, south model; ~ 100, north model). Flow rates for ungauged stream segments were constructed from the EPA RF1 dataset by assuming that nearby streams behave similarly, that the monthly stream flow is lognormal and that standard deviations are identical. Again, the models have a tendency to underestimate baseflow.

Queen City Sparta North, Central, and South Models

The Queen City GAM models (Kelley et al., 2004) represent both a model of the Queen City and Sparta formations and include an update to the Carrizo Wilcox models (Deeds et al., 2003; Dutton et al, 2003; Fryar et al., 2003). The Queen City GAM model footprint is identical to that of the Carrizo Wilcox GAM models. Three models (north, central, and south) were also used although their construction and calibration was much more integrated than in the earlier Carrizo Wilcox models. Groundwater-surface water interactions were approached similarly to the work done for the Carrizo Wilcox GAM models and built on the experience acquired in developing the Carrizo Wilcox GAMs since the same team was involved. Slade et al. (2002) documented 41 gain/loss studies intersecting the Queen City and Sparta outcrop. In addition to the same dataset, WAM results were tentatively used to help calibrate the models (RJB, 2004).

RJ Brandes (2004) used monthly naturalized flows to calculate gain/loss between two WAM control points located as close as possible to the outcrop of the formations of interest. For each monthly flow, it involved computing the incremental flow (*IF*) between the upstream and downstream naturalized flows and applying a correction to take into account runoff from *n* tributaries:

$$Gain / Loss = IF - \frac{\sum_{j=1}^{n} NF_J}{\sum_{j=1}^{n} DA_j} IDA \qquad (8)$$

where NF_j and DA_j represent naturalized flow and drainage area of tributary *j*. *IDA* is drainage area contributing to the incremental flow. Outliers were eliminated from the collection of at least 20 years of monthly gain/loss and the median was chosen as representative value for this segment (expressed in flow for a unit stream length). This approach can be applied regardless of the month or alternatively for each month of the year. The method is probably not as accurate as conventional low flow studies because it entails taking the difference, however small, of two large uncertain numbers. To increase stream flow to match calculated baseflows, drain cells were also implemented in all valley bottoms (except in the far south Texas) to implicitly simulate small streams and springs.

Simulated baseflow generally underestimated calculated baseflows, particularly for some streams (Figure 8). Comparison with calculated baseflows was restricted to predevelopment conditions and no attempt was made to compare simulated baseflows with calculated values during transient simulations.

7.1.4 Uncertainties in GAM Simulations of Groundwater-Surface Water Interactions

There are many potential sources of uncertainty related to GAM simulations of gw-sw interactions. Uncertainties may be categorized according to those related to scaling issues, timescale issues, and lack of field based measurements for comparison with model simulations.

The one square mile grid cell used in all GAMs imposes severe limitations on the resolution of simulated gw-sw interactions. The streams cannot be represented accurately with this grid resolution. Simulated fluxes depend on differences in head between stream stage and groundwater; however, it is difficult to determine what representative stream stage should be in such a large grid cell; similarly for groundwater heads. Each cell may represent a large range of elevations, particularly in incised valleys. Averaging decreases the elevation contrast and consequently driving force for a gaining stream. Variations in thickness, width, and hydraulic properties of the alluvial deposits are also lost in the averaging process. Previous studies have documented difficulties with simulating gw-sw interactions using large grid cells (Jorgensen et al., 1989). Representing the actual elevation of the stream with a representative value for a one square mile grid is also extremely difficult. Many of these parameters are estimated during calibration; however it is difficult to determine if the calibrated parameters will work well for simulating future scenarios. The number of stream cells can have a large impact on simulated baseflow because small numbers of stream cells would result in many small streams not being represented that could contribute to baseflow (RW Harden, 2004, p.8-9).

Timescales are also important for simulating gw-sw interactions. The timescale that a regional aquifer reacts to stresses is generally on the order of months to years whereas streams are generally much more dynamic and respond within days to months to external stresses. Accordingly, stress periods for GAMs were initially set at monthly (e.g., Carrizo Wilcox GAM). However, in the most recent GAMs (Queen City and NT), the stress period was changed from monthly to yearly. The reaction time of the aquifer system justified such a change. It has the additional advantage of minimizing data manipulation. In contrast, time steps for WAMs is generally monthly. Some mechanism needs to be implemented to address the different response times of the surface water and groundwater systems.

The lack of field based measurements of baseflow and evapotranspiration is a severe limitation to simulating gw-sw interactions because there is no clear target for these fluxes. Also most GAMs have focused on baseflow simulations for the predevelopment period but many ignore transient simulations of baseflow. More reliable field based estimates of baseflow and ET are required to constrain simulated fluxes. In addition, process information could provide valuable insights into accurate representation of these fluxes in models.

7.1.5 Proposed Future Studies to Improve Simulations of Groundwater-Surface Water Interactions

1. GAMs may be useful in assessing impacts of future increased pumpage on gw-sw interactions. Studies should be conducted to test the validity of simulated baseflow response to increased pumpage using more detailed site specific simulations and field-based measurements.
2. Because several GAMs cross single surface water basins, simulation of gw-sw interactions in various GAMs should be standardized to be able to provide consistent input to WAMs.
3. The resolution of stream networks represented by GAMs should be standardized because simulated baseflow generally increases with the number of stream cells. For example, the Carrizo Wilcox GAM used 452 stream cells to cover the Reklaw, Carrizo and Wilcox formation outcrop but 963 cells were used to cover the exact same area in the Queen City GAM.

4. Field-based studies should be conducted to provide reliable estimates of baseflow and ET for comparison with model estimates. Stream gauges should be optimally located relative to aquifer outcrops. Ideally stream gauges should be located upstream and downstream of the aquifer outcrop. Currently, many gauges are not appropriately positioned.
5. Current WAMs provide total stream flow and do not distinguish between baseflow (groundwater discharge) and runoff. Future modifications of WAMs should consider gw-sw interactions.

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7.2 A Technique for Displaying WAM Loss Factors in GIS

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A prototype tool was developed using ArcObjects and Visual Basic for Applications (VBA) for displaying WAM (Water Availability Modeling) loss factors in ArcGIS. The tool interacts with the WAM input files to read the channel loss factors at control points, and then assigns these factors to WAM reaches for display in GIS. The goal of this exercise is not to make assessments about channel loss factors, but to demonstrate the technique, which can be applied in a similar fashion to other WAM models. The display of WAM loss factors is useful to visualize and compare the corresponding recharge and drain cells from GAM (Groundwater Availability Modeling) output in GIS.

7.2.1 Study Area and Data

The study area chosen for developing the prototype tool is the part of Guadalupe-San Antonio WAM model that overlaps with the southern part of Carrizo Wilcox GAM (Figure 1). For demonstration purposes, only the intersection of Guadalupe Basin with the Carrizo Wilcox aquifer is considered.

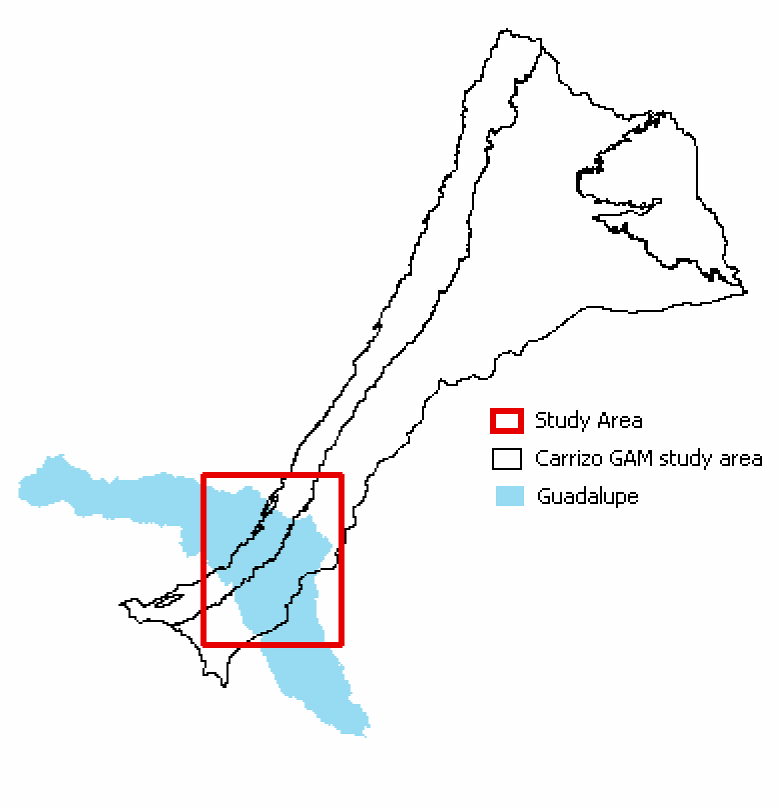


Figure 1. Study area for displaying WAM loss factors in GIS.

The data used for the study mainly include the input data file (*.dat) for the Guadalupe-San Antonio WAM and associated GIS WAM reaches and control points. The input data file gsa_run8.dat was obtained from the TCEQ website (http://www.tnrcc.state.tx.us/permitting/waterperm/wrpa/wam.html#G) by selecting the "Input data for current conditions" link. The GIS files were obtained by making a written request to the WAM project coordinator at TCEQ.

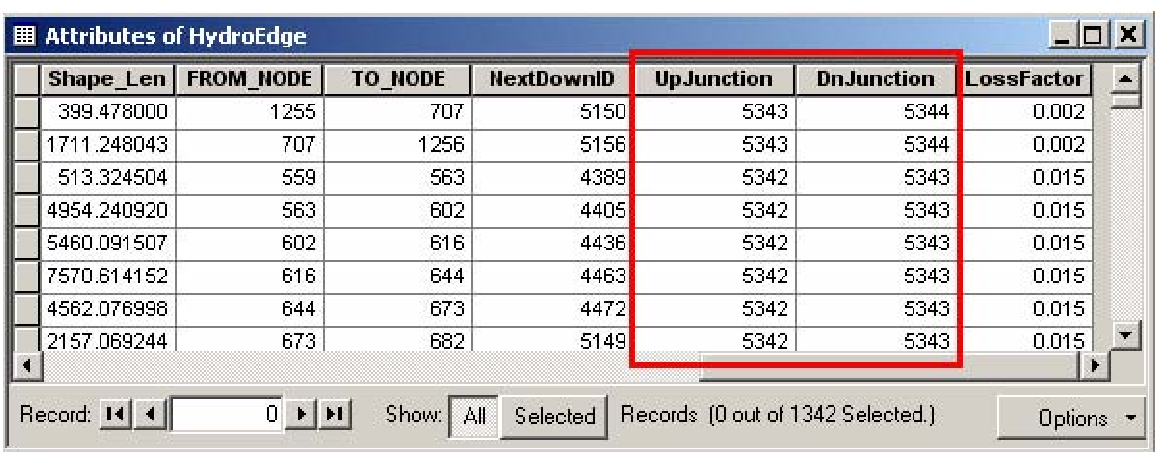
7.2.2 Methodology

The following steps were followed for displaying the WAM loss factors in GIS:

1) Build an Arc Hydro network (Maidment, 2002) in ArcGIS using WAM reaches and control points. An Arc Hydro network (generic ArcGIS geometric network) enables tracing of paths

between two adjacent control points, which is useful for assigning loss factors recorded at control points to reaches associated with them.

2) Read loss factors associated with control points from the WRAP (Water Rights and Analysis Package) input file and store these as attributes of WAM control points. The WAM control points in GIS have WAM or TCEQ ID, which do not match with the water right number in the WRAP input files. A decoder file was obtained from TCEQ to link the water right numbers with WAM IDs in GIS files. This task of linking IDs and storing loss rates as attributes on WAM control points is accomplished by writing a VBA macro in ArcGIS.
3) Assign HydroID, a unique number within a geodatabase for identifying features in Arc Hydro, to each control point. Instead of HydroID, WAM ID or WRAP ID can also be used for identifying control points.
4) After assigning HydroID to control points, a VBA macro is developed for tracing paths between adjacent control points, and indicating the upstream and downstream control points for all WAM reaches. Each WAM reach has UpJunction and DnJunction attributes to store the HydroID of upstream and downstream control points, respectively. Figure 2 shows the attribute table for WAM reaches with UpJunction and DnJunction attributes.
5) A VBA macro was developed to assign the channel loss factor from each control point to downstream reaches. The UpJunction attribute of each reach is used to identify the upstream control point, read the associated channel loss factor, and store the loss factor as an attribute.
6) The loss rate attribute is used to symbolize the reaches, and display in GIS.



Shape_Len	FROM_NODE	TO_NODE	NextDownID	UpJunction	DnJunction	LossFactor
399.478000	1255	707	5150	5343	5344	0.002
1711.248043	707	1256	5156	5343	5344	0.002
513.324504	559	563	4389	5342	5343	0.015
4954.240920	563	602	4405	5342	5343	0.015
5460.091507	602	616	4436	5342	5343	0.015
7570.614152	616	644	4463	5342	5343	0.015
4562.076998	644	673	4472	5342	5343	0.015
2157.069244	673	682	5149	5342	5343	0.015

Figure 2. Attribute table for WAM reaches (called HydroEdge in Arc Hydro) with UpJunction and DnJunction attributes for identifying upstream and downstream control points.

7.2.3 Results

Figure 3 shows the results with WAM reaches in the Guadalupe Basin that overlap with the Carrizo Wilcox GAM model, and Figure 4 shows a close-up of the San Marcos River.

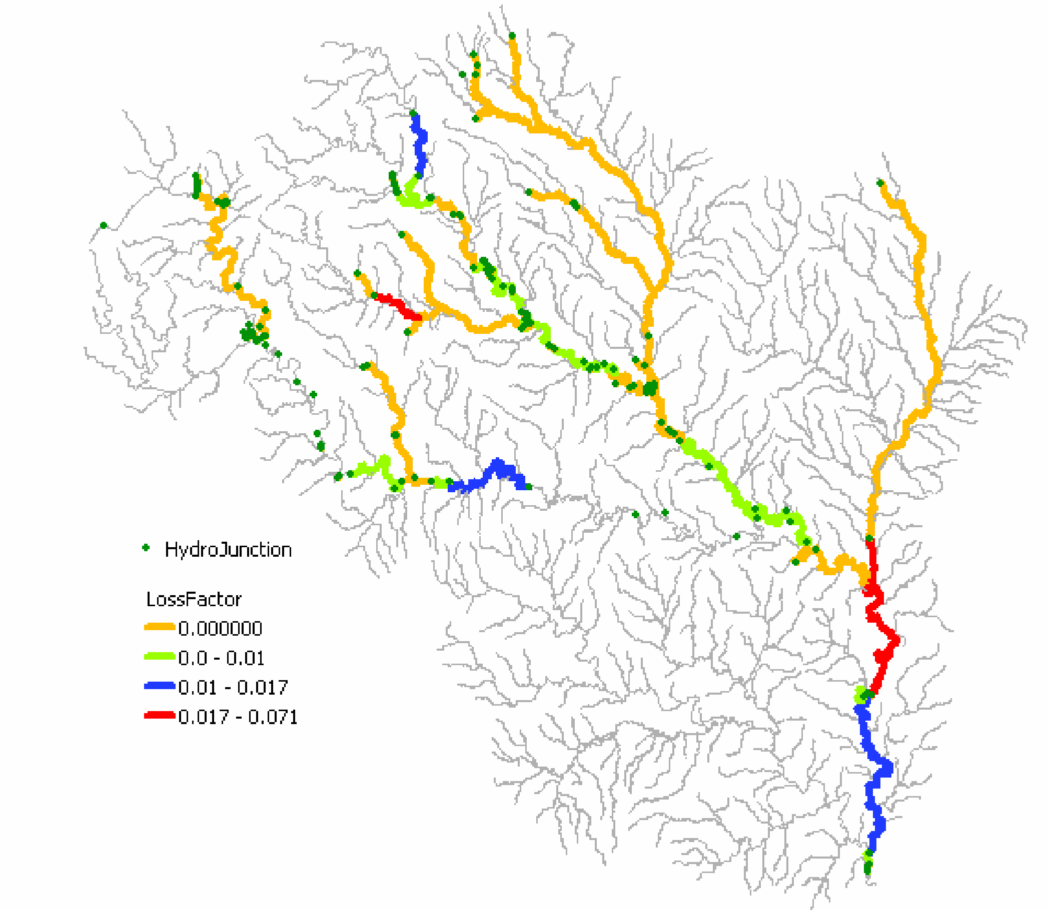


Figure 3. Display of WAM reaches with associated loss factors.

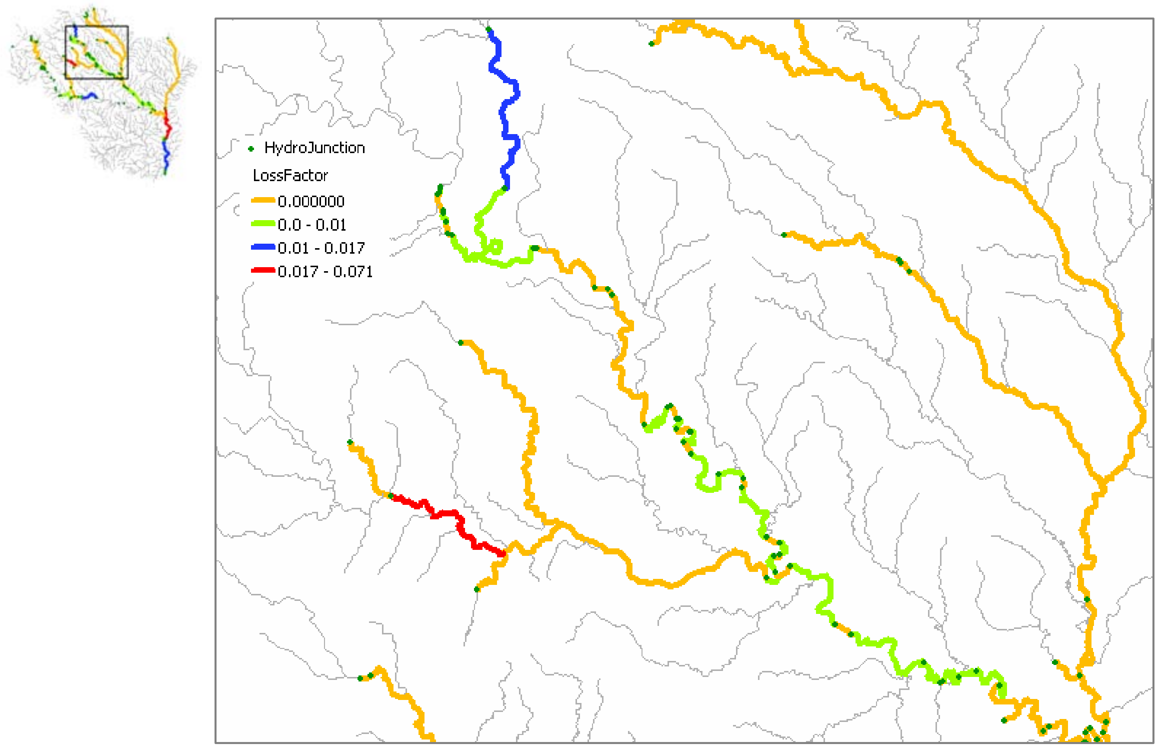


Figure 4. Loss Factors associated with San Marcos River in the Guadalupe Basin.

Displaying WAM reaches and GAM cells in GIS

The GAM data were extracted from the Carrizo Aquifer GAM model obtained from the Texas Water Development Board. The steady state model was used for this analysis, which is actually a transient model with one long stress period (36525 days, about 100 years). Budgets for cells of the San Marcos River (segment 4 in the MODFLOW stream package) were calculated using the water budget functions of PMWIN. The budgets were calculated for the last time step (200) in the stress period. Stream leakage values for each cell of the stream segment were linked back to the model and were overlaid with the WAM reaches in the GIS environment. This process allows comparison of gaining and loosing stream reaches between the WAM and GAM models. Figure 5 shows the result. For demonstration purposes and simplicity, both WAM reaches and GAM cells in Figure 5 were categorized as losing and gaining streams instead of displaying numbers. A blue cell/reach means the stream is gaining and a red cell/reach means the stream is losing. Also, the data used for preparing Figure 5 are for different time periods. The main goal of Figure 5 was to demonstrate the use of displaying WAM and GAM in GIS, and not to make any assessment on groundwater/surface water interaction. However, if the data used for same time period under similar conditions, the GIS tools can be a very useful product for comparing WAM and GAM input/output.

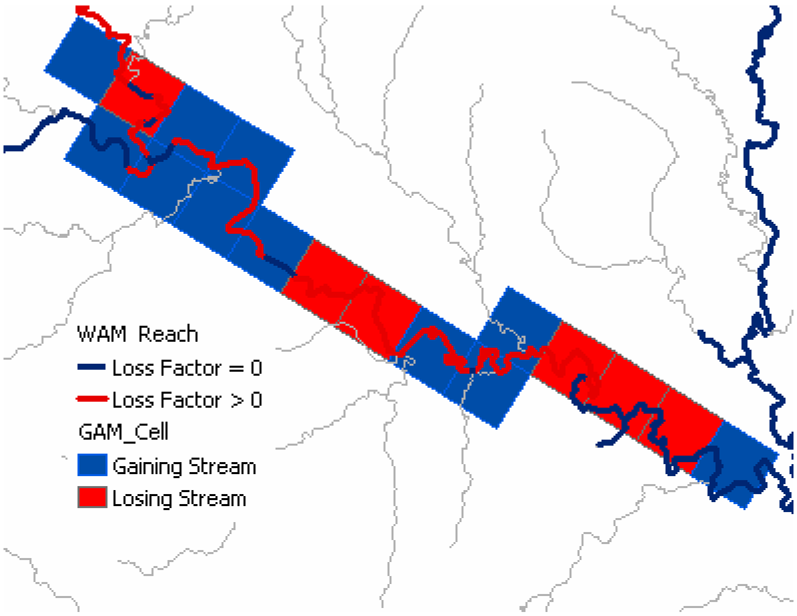


Figure 5. Display of GAM cells and WAM reaches in GIS.

Appendix 8

Proposed Future Studies Related to Groundwater-Surface Water Interactions

8.1 Proposed Future Studies Related to Groundwater-Surface Water Interactions

The reconnaissance study funded by TCEQ helped identify a number of gaps in our understanding of gw-sw interactions. A variety of studies may be conducted to address the gaps in our knowledge of gw-sw interactions and to provide baseline data to better assess the degree of connectivity between groundwater and surface water.

Collocated Monitoring of Groundwater and Surface Water: The most direct approach to assessing groundwater-surface water interactions is through collocated monitoring of groundwater and surface water. Groundwater wells should be installed adjacent to stream gauge recorders that are currently monitored by the USGS. These wells should be installed at varying distances from the stream gauges and at varying depths. Monitoring of the stream stage and groundwater levels will quantify the direction of water movement and how water movement varies with stream stage. In addition to monitoring stage and water levels, other physical and chemical parameters such as temperature, dissolved oxygen, specific conductance should be monitored. Monitoring these additional parameters may provide insights into water quality variations. Continuous monitoring (e.g. hourly or less)of all parameters is extremely important to record impacts of high intensity, short duration surface water flows on groundwater and stream bank storage.

Streamflow Gain-loss Studies: Where not already done or not pertinent to present conditions, streamflow gain-loss studies are required to document streamflow gains and losses to shallow aquifers. These studies generally should be conducted during winter conditions in order to minimize evapotranspiration losses. Studies need to be conducted during low-flow and high-flow conditions to document variations in streamflow gains and losses to channels. Monitoring stream water quality at each streamflow site would allow the water-quality of streamflow gains (groundwater discharge) to be calculated by a budget analysis of water-quality loads.

Location of Stream Gauges: Substantial amounts of data exist for surface water in Texas; however, location of stream gauges is not optimal for assessing gw-sw interactions. Stream gauges should be located directly upstream and downstream of the outcrop areas of aquifers such as the Carrizo Wilcox aquifer, Queen City Sparta aquifer and others parallel to the Gulf Coast and at right angles to streams. Information on these gauges would be invaluable for assessing the net impact of groundwater on surface water from an entire outcrop area and would also be very important for evaluating the output from groundwater availability models (GAMs).

Stream Channel Morphology: Cross-sections along streambeds presenting the thickness and description of sediments and geology would provide information about the potential and magnitude of underflow parallel to streams and about water exchange between streams and shallow aquifers. The best data source for such sections are available from driller's logs collected by the Texas Department of Transportation (TxDOT) during construction of about 40,000 bridges and culverts over water. Information about obtaining copies of the logs from TxDOT district offices is presented in appendix 7 at the end of this report.

Aquifer Tests for Sites Adjacent to Streams: Aquifer pumping tests conducted adjacent to streams can provide the depletion rate of streams caused by pumping from a well. The volume and rate of stream depletion can be calculated during any time period, during pumping and non-pumping periods, by using dimensionless curves and tables presented in the report at http://water.usgs.gov/pubs/twri/twri4d1/.

Time of Travel Studies: The time for water to travel between streams and wells can be documented by use of dyes or other tracers. Only a few travel time studies in Texas for streams or groundwater, and no such study could be identified documenting travel time between streams and aquifers. These studies should be done during base flow and storm runoff conditions, so that travel time differences can be determined for various flow conditions.