Final Report

Agency: Texas State University- San Marcos

Fiscal Year: 2010

Grant Number: CDA #66-202

Descriptive Title: Geography and Water

Project Title: Technical and Educational Assistance to Groundwater Conversation Districts in Texas

PI: Michael Abbott

Background and Purpose

Since the 1950s, Groundwater Conservation Districts (GCDs) have been Texas' only legal method of regulation and management of groundwater resources in the state. Over the years, the Texas Legislature has given GCDs additional legal powers to better regulate groundwater, but seldom has provided the funding necessary to most effectively use these additional powers. Many of the 98 groundwater districts in Texas are small operations with limited funding and few staff members, and rarely do they employ individuals with a background in aquifer science. Consequently, GCDs, which are the key to proper sustainable development and use of groundwater resources, generally lack the training and basic tools to most effectively manage these resources.

The purpose of this project is to provide education and technical assistance to the staff and board members of the GCDs in Texas. In collaboration with the Texas Alliance of Groundwater Districts, the River Systems Institute developed training materials/workshops and provided training to staff and board member of groundwater districts (See Appendix I). The River Systems Institute also provided technical assistance to several groundwater districts, in the conduct of research studies and the development of databases, regarding their groundwater resources.

Objectives

The objectives of the study were to:

1. Identify the training needs and technical assistance needs of the GCDs;
2. Develop training materials to address high-priority needs identified;
3. Conduct workshop on the high-priority needs identified in five regions of the state;
4. Provide training to staff and board members on at least 18 groundwater districts;
5. Make training materials available to groundwater districts;
6. Evaluate workshops and use feedback to improve training efforts.

Methodology

In the summer of 2006, the River Systems Institute (RSI) conducted a survey of general managers and board members of all groundwater districts in Texas to determine areas in which they could use education/training, as well as areas in which they could use technical assistance. The results of the survey are contained in Appendix II.

RSI, in collaboration with the Texas Alliance of Groundwater Districts (TAGD), the Texas Water Development Board (TWDB), the US Geological Survey (USGS), and the Laura Raun Public Relations, agreed to develop training workshops covering the following areas:

1. Basic Hydro Geological Principals
2. Design of Water Level Monitoring Programs
3. Groundwater Modeling and Use of TWDB Groundwater Availability Models
4. Communicating Effectively with the Public

It was determined that the most efficient way to provide training to the GCDs, would be through a series of regional workshops, ideally providing workshops in each of the state's 16 groundwater management areas. It was further determined that the curricula for the four initial training workshops would be pilot-tested at 4-5 workshops. The curricula would be modified based on feedback from attendees at the pilot workshops. Funding would be sought to conduct the modified curricula at all groundwater management areas.

Although the initial focus of this project would be on the development of training materials, RSI agreed to consider providing technical assistance to GCDs on a case by case basis.

Results

Curricula were developed for “Design of Water Level Monitoring Programs”, “Groundwater Modeling and Use of TWBD Groundwater Availability Models”, “Communicating with the Public Effectively”. The curriculum for “Basic Hydro Geological Principals” was not complete when the responsible faculty member left the University. Outlines for the curricula and workshop materials are contained in Appendix III.

A pilot workshop was conducted in Nacogdoches, Texas (Groundwater Management Area II) on November 14, 2007. Curricula modules on “Design of Water Level Monitoring Programs” and “Groundwater Modeling and Use of TWDB Groundwater Availability Models” were presented. Ten participants representing four GCDs attended the workshop; six GCDs were invited to send individuals to this workshop. The feedback from the participants indicated that they were satisfied with the workshop and found the materials presented useful.

A second pilot workshop was conducted in Austin, Texas (Groundwater Management Areas 9 and 10), on November 28th, 2007. Curricula module on “Communicating Effectively with the Public” was presented. Fifteen participants representing eleven GCDs attended the workshop; Eighteen GCDs were invited to send individuals to this workshop. The feedback from participants indicated they were satisfied with the workshop and found the material to be very helpful.

A third pilot workshop was scheduled for GMA 8 and twelve GCDs were invited to send participants. The workshop was cancelled when only one individual registered to attend.

Attempts to schedule pilot workshops in GMA 7 and GMA 13 were not pursued because of lack of interest among GCDs to host the workshop.

Appendix IV contains information on the pilot workshops, attendees, and feedback provided.

Discussions were held with the Executive Director of TAGD, as well as with the TAGD membership at its quarterly meeting regarding the lack of participation in regional workshops. The general feeling of the group was that their small staffs, volunteer board members, and limited budgets inhibited attendance at workshops “away from the office”. It was suggested that other avenues of delivery of training materials, such as DVDs or Internet be explored.

As a result of these discussions a video-disc of presentations made at the July 28th, 2008 TAGD quarterly meeting, including components of the “Communicating Effectively with the Public” workshop and the “Groundwater Availability Models” workshop, was produced and sent to all GCDs in Texas. Moreover, RSI, in partnership with TAGD, developed a training manual, “Legal Primer for Administering a Groundwater Conservation District”, and sent it as a CD to all GCDs in Texas. Informal feedback compiled by the Executive Director of TAGD indicated that very limited use of the DVDs were occurring at the GCDs, but use of the legal manual CD was routinely occurring on an as needed basis. Appendix V contains copies of the DVD presentations and the legal manual CD.

In June 2007, the Hays Trinity Groundwater Conservation District (HTGCD) approached RSI requesting assistance in conducting a hydro geological study of Cypress Creek and Jacob's Well, located in Hays County Texas. Augmented by a grant from a private foundation, RSI provided assistance to HTGCD in defining the hydro geological setting, including recharge, interaction of surface water and groundwater, water quality and local stratigraphy, and to identify a set of metrics to monitor and preserve the flow of Cypress Creek and Jacob's Well. The results of the hydro geological study are contained in Appendix VI. In February 2009, a second study was initiated with HTGCD, building upon the data compiled from the 2007/2008 study, to develop a strategy to preserve the flow of cypress creek and Jacob's Well.

Implications

Groundwater Conservation Districts in Texas are key components to effectively managing and sustaining the groundwater resources of this State. Limited funding, small staffs, and continued reliance on volunteers present significant obstacles in these organizations effectively fulfilling their charge. Although general managers and board members of GCDs indicated that additional training for staff and boards was greatly needed, the reality of fitting such training into the day to day demands of operating a GCD was difficult at best.

Until funding and staffing improve past the point of "significantly suspending operations" while staff are away from the office to attend training workshops, it would appear that the most effective means of providing training to staff and board member would be via some type of self-paced electronic material. While staff who attended our regional workshops found the material very useful, they also suggested that having the means to utilize the material, on-site at their office, in a self-paced mode, would be very beneficial.

Of greater benefit to these small staffs, is the provision of specific technical assistance in compiling basic data about their groundwater resources and establishing databases that provide key information to managers and decision makers about the resources they are managing.

Decision makers, especially layman board members, appear to appreciate the availability of hard data on which to base decisions. It was pointed out that unless a GCD has the funding to support continued outside technical assistance, it would be better, in the long run, to have staff trained in how to compile and maintain such hard data.

List of Appendices

Appendix I	Memorandum of Understanding Between the River Systems Institute and the Texas Alliance of Groundwater Districts
Appendix II	Survey of Groundwater Conservation Districts
Appendix III	Description of Training Workshops
Appendix IV	Pilot Workshop Attendees and Feedback
Appendix V	Training DVD's and CD's
Appendix VI	Hydrogeologic Study for Hays Trinity Groundwater Conservation District

Appendix

I. Memorandum of Understanding

Memoranda of Understanding between the River Systems Institute at Texas State University and The Texas Alliance of Groundwater Districts

This document is a memorandum of understanding between the River Systems Institute at Texas State University and the Texas Alliance of Groundwater Districts that will set forth the program responsibility and procedural mechanisms for Groundwater Conservation District educational and training programs.

(1) Whereas, the River Systems Institute at Texas State University, herein called the Institute, was created to develop and promote programs and techniques for ensuring sustainable water resources for human needs, ecosystem health and economic development; and

(2) Whereas, the Texas Alliance of Groundwater Districts, herein known as the Alliance, was formed to further the purpose of groundwater conservation and protection activities, provide a means of communication and exchange of information between individual districts regarding the day-to-day operation of local groundwater management, and provide member Districts and the public with timely information on activities and issues relevant to groundwater management; and

(3) Whereas, the Alliance and the Institute are both interested in providing quality education and training for Groundwater Conservation Districts across the State; and

(4) Whereas, the Institute obtained grants from the U.S. Environmental Protection Agency and the Meadows Foundation that provide for the education and training to Groundwater Conservation Districts; and

(5) Whereas, the Alliance has the ability to help coordinate education and training conferences for Groundwater Conservation Districts; and

(6) Whereas, the Institute conducted a survey of Groundwater Conservation Districts and determined that the primary education and training needs include groundwater science, public relations and legal issues.

Now, therefore, in consideration of the following promises, covenants, conditions, and the mutual benefits to accrue to the parties of this Agreement, the Parties, desiring to cooperate in function and service agree as follows:

(a) The River Systems Institute at Texas State University agrees to:

(1) Obtain and execute cooperative agreements, grant awards and contracts.

(2) Implement the provisions of each grant or contract in conjunction with the Alliance.

(3) Complete administrative procedures for all projects and programs for which grant funds have been awarded in order to obtain timely payments by the grantee.

(b) The Texas Alliance of Groundwater Districts agrees to:

(1) Serve as a recipient of grants and grant funds to further the purposes of each grant award contract.
(2) Provide the Institute with required reports for all joint projects funded to the Institute. Reports will be submitted in accordance with grant requirements.
(3) Develop and maintain a current electronic database of Texas Groundwater Conservation District contact information and provide a direct conduit to contact those districts.
(4) Provide assistance coordinating and planning educational and training activities for Groundwater Conservation Districts.
(5) Provide any other assistance in obtaining and completing grant contracts that relate to groundwater protection, preservation or regulation.

(c) Both parties agree to:

(1) Coordinate efforts in the development and submission of an annual work program.
(2) Negotiate the percentage of the administrative budget of grant funds that will accrue to each party.
(3) Negotiate the division of labor and work to be performed under each new grant proposal
(4) Communicate and coordinate directly with each other on matters relating to program/project planning and implementation of approved grants.
(6) Provide required reports to the grantors as required by each grant.
(7) Meet as necessary to review and discuss program development, project progress and grant proposals.
(8) Comply with all relevant state and federal statutes and procedures, and grant conditions, including financial audits, data quality assurance and quality control, and progress reports.

(d) General conditions:

(1) Term of Agreement. The term of this MOU shall be from the effective date until termination of this agreement. Future agreements on specific grants must be approved by the TAGD Executive Committee or TAGD membership prior to implementation.
(2) Notice of Termination. Any party may terminate this Agreement upon a 90 day written notice to the other party. Both parties agree to fulfill any grant commitments in place at the time of termination. Only upon written concurrence of the other party can this Agreement be modified.
(3) Cooperation of Parties. It is the intention of the parties that the details of providing the services in support of this Agreement shall be worked out, in good faith, by both parties.
(4) Nondiscrimination. Activities conducted under this Agreement will be in compliance with the nondiscrimination provisions as contained in Titles VI and VII of the Civil Rights Act of 1964, as amended, the Civil Rights Restoration Act of 1987, and other nondiscrimination statutes, namely Section 504 of the

Rehabilitation Act of 1973, Title IX of the Education Amendments of 1972, the Age Discrimination Act of 1975, and the Americans With Disabilities Act of 1992, which provide that no person in the United States shall, on the grounds of race, color, national origin, age, sex, religion, marital status, or handicap be excluded from participation in, be denied the benefits of, or be otherwise subjected to discrimination under any program or activity receiving federal financial assistance.

(5) Notices. Any notices required by this Agreement to be in writing shall be addressed to the respective party as follows: Texas Alliance of Groundwater Districts, Attn: Gregory M. Ellis, 2104 Midway Court, League City, Texas 77573 and to the River Systems Institute at Texas State University, Attn: Andrew Sansom, River Systems Institute, 601 University Drive, San Marcos, Texas 78666-4615.

(6) Effective Date of Agreement. This Agreement is effective upon execution by both parties. By signing this Agreement, the signatories acknowledge that they are acting under proper authority from their governing bodies.

Authorized:

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Gary Westbrook, President
Texas Alliance of Groundwater Districts

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Andrew Sansom, Executive Director
River Systems Institute,
Texas State University-San Marcos

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Billy C. Covington, Associate Vice President for Research
and Director of Federal Relations
Texas State University-San Marcos.

II. Survey of Groundwater Conservation Districts

Texas State University
SAN MARCOS

Groundwater Conservation District Survey Results

Prepared by the River Systems Institute

September 12, 2006

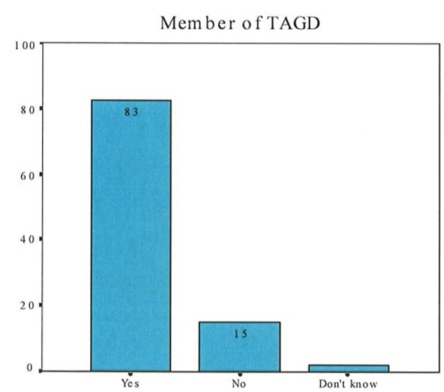
Introduction

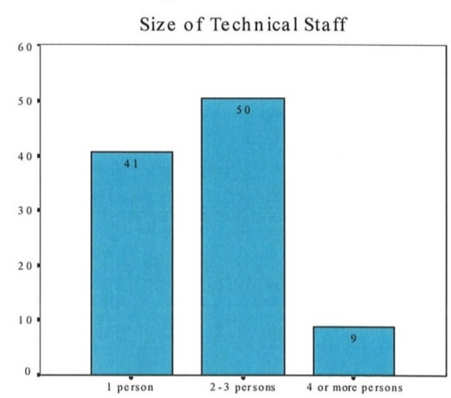
The following is a summary of results of the survey distributed to Groundwater Conservation District (GCD) board members and staff during the summer of 2006. This summary includes details of the distribution and response rates, and summarizes the main results of the survey. A copy of the original survey is attached to the end of this document.

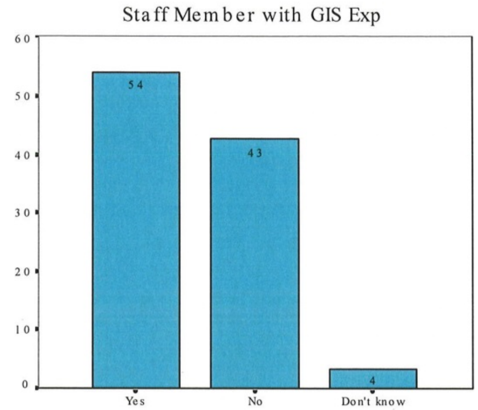
If you have any questions about the results, feel free to contact the River Systems Institute at 512-245-9200.

Survey Distribution

- 706 Surveys Mailed
- 143 Returned
- 20% Response Rate
- Questionnaire Sent to 94 Districts
- Most (83%) districts are members of TAGD
- 2-3 person technical staff is the most common size (50%)
- Over half of the districts (54%) have a staff member with GIS experience

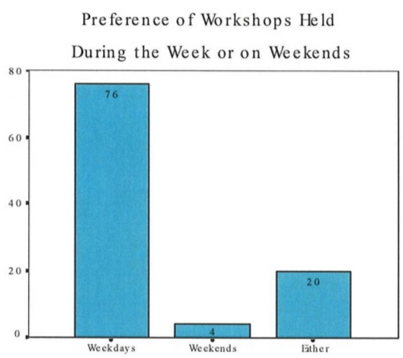


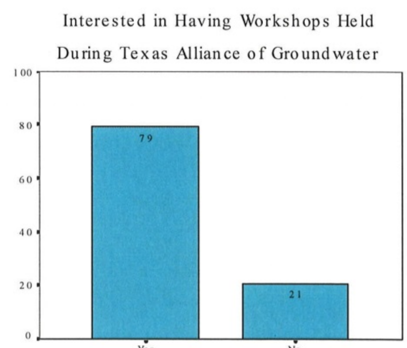


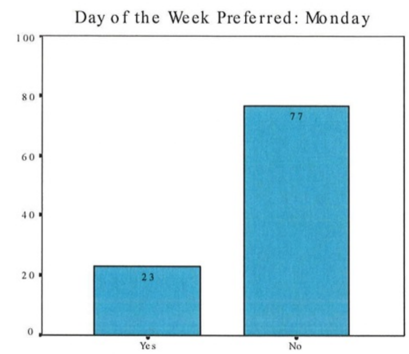


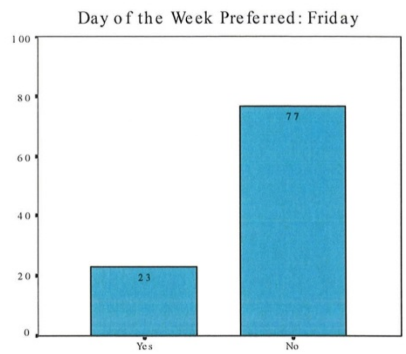
Survey Results

- Strong support shown for the benefit of both workshop courses and technical/ administrative assistance
- Preference for weekdays over weekends for workshops, excluding Mon. and Fri.
- Strong interest in having workshops during TAGD quarterly meetings






Day of the Week Preferred: Monday
100
80
60
40
20
0
23
77
Yes
No


Day of the Week Preferred: Friday
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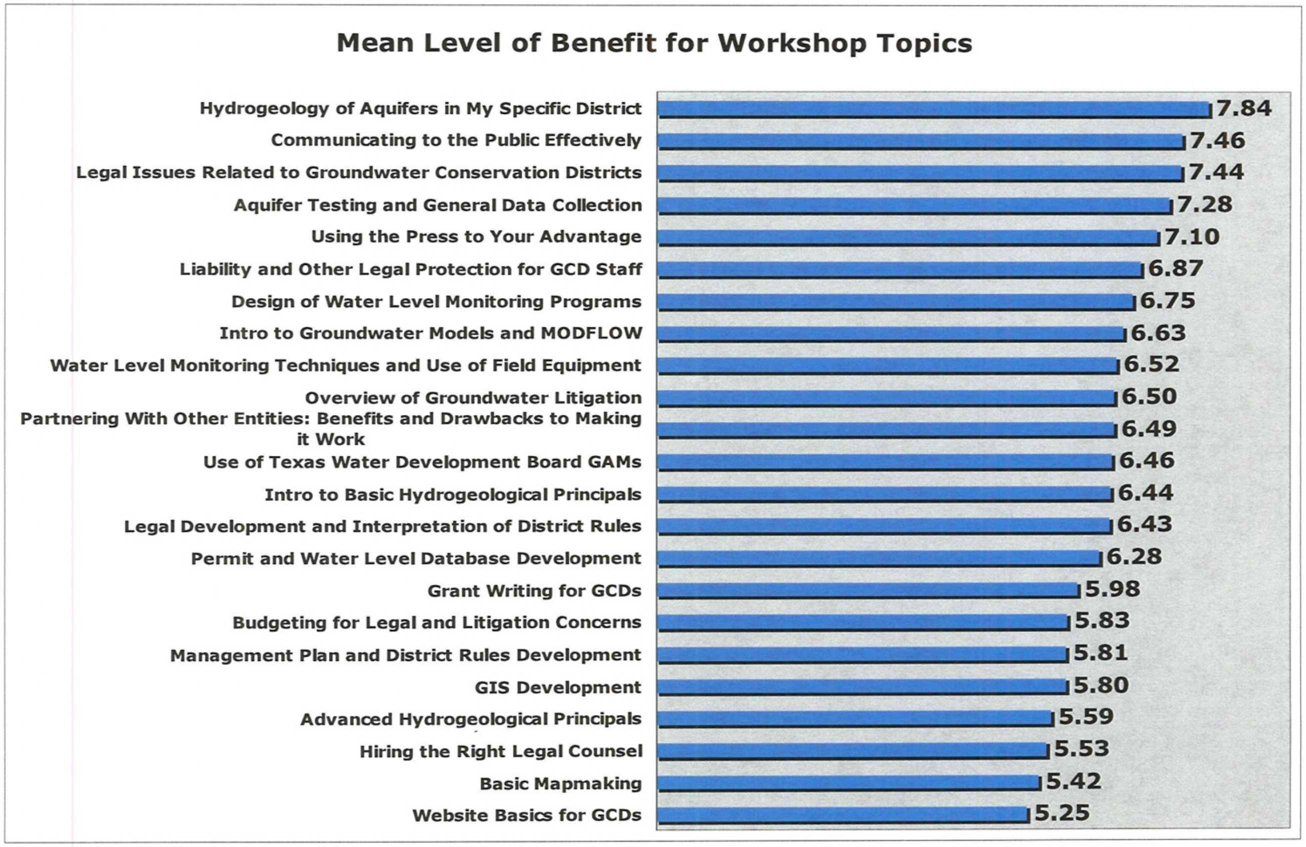
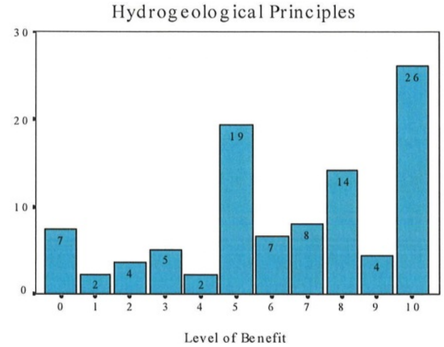
80
60
40
20
0
23
77
Yes
No

A Look At The Workshop Topics

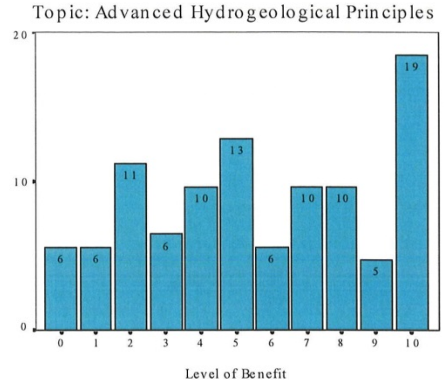


Specific Results of Workshop Topics Survey

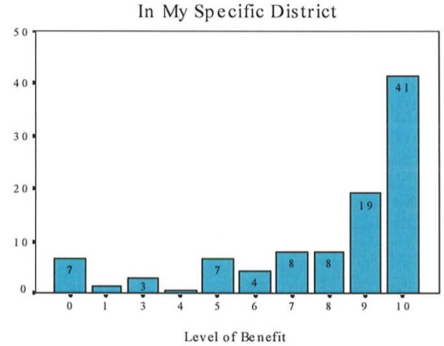
Topic: Intro to Basic Hydrogeological Principles



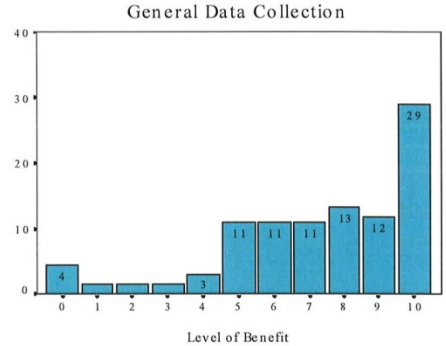
Topic: Advanced Hydrogeological Principles



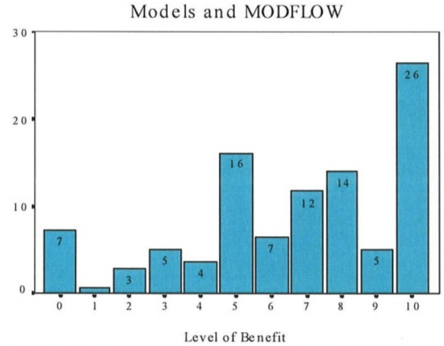
Topic: Hydrogeology of Aquifers In My Specific District



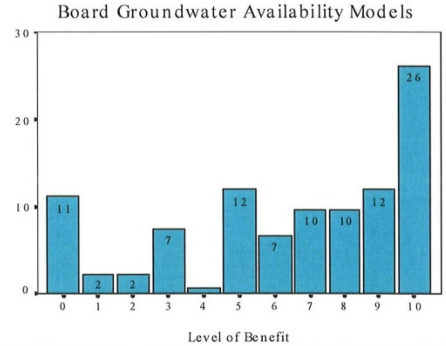
Topic: Aquifer Testing And General Data Collection



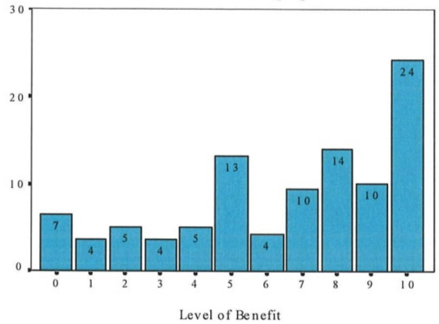
Topic: Intro to Groundwater Models and MODFLOW



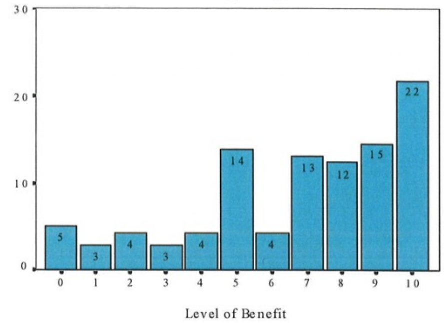
Topic: Use of Texas Water Development Board Groundwater Availability Models



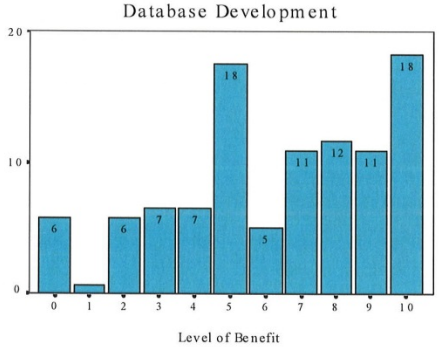
Topic: Water Level Monitoring Techniques And Use of Field Equipment



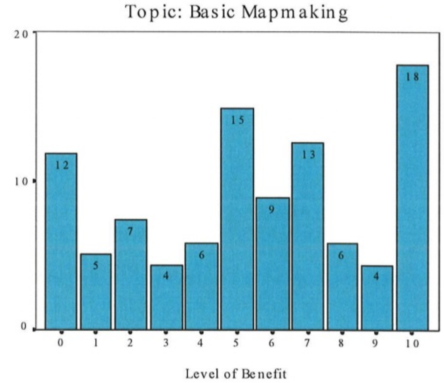
Topic: Design of Water Level Monitoring Programs



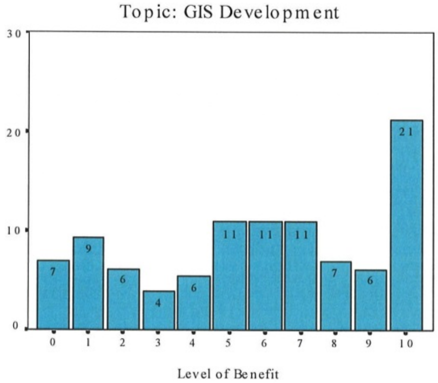
Topic: Permit and Water Level Database Development



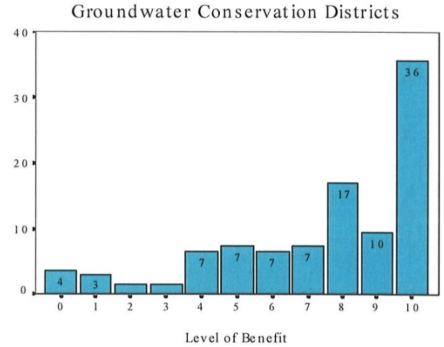
Topic: Basic Mapmaking



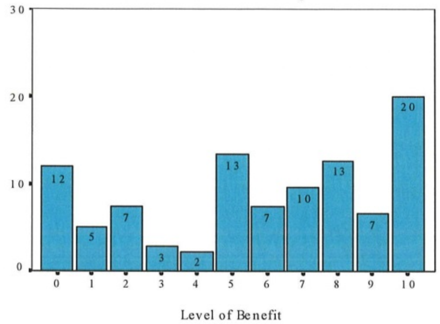
Topic: GIS Development



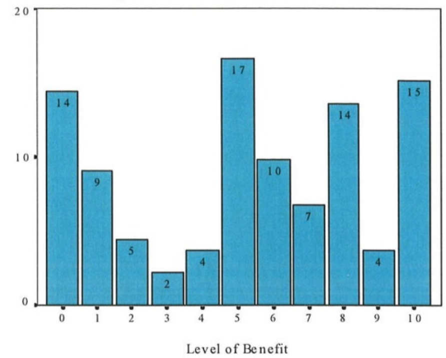
Topic: Legal Issues Related To Groundwater Conservation Districts



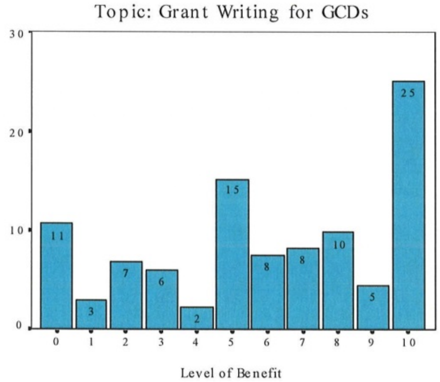
Topic: Management Plan And District Rules Development



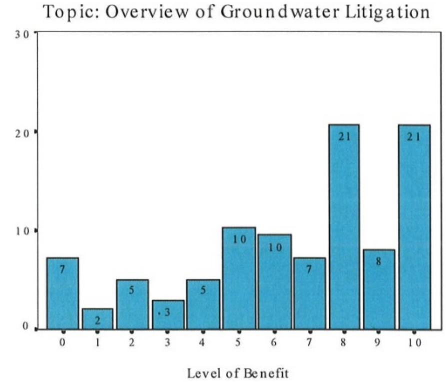
Topic: Website Basics for GCDs



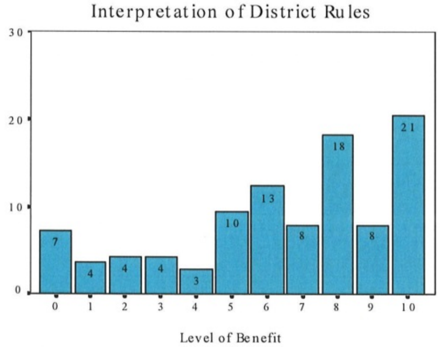
Topic: Grant Writing for GCDs



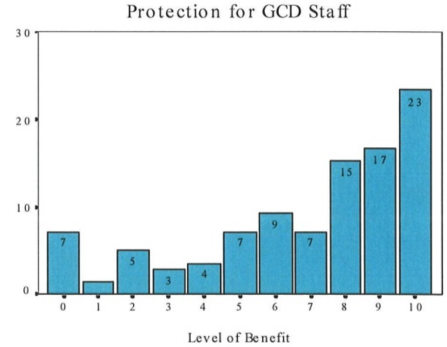
Topic: Overview of Groundwater Litigation



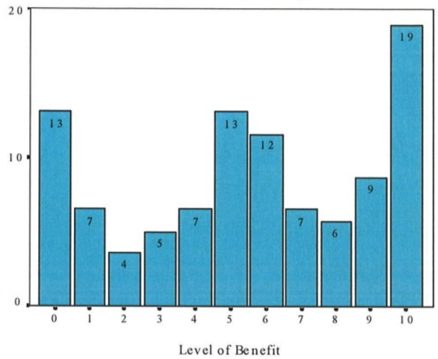
Topic: Legal Development And Interpretation of District Rules



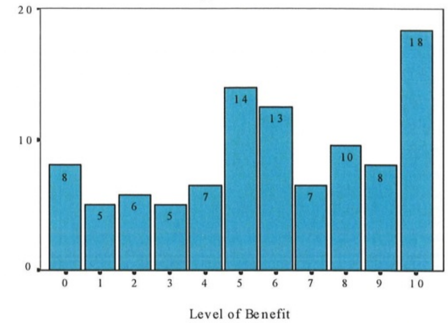
Topic: Liability and Other Legal Protection for GCD Staff



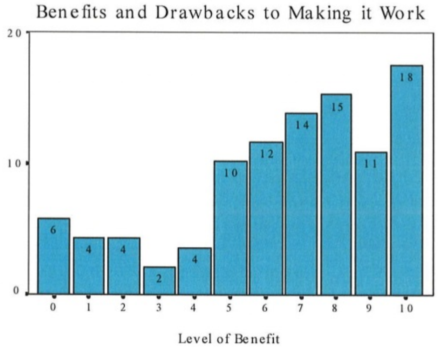
Topic: Hiring the Right Legal Counsel



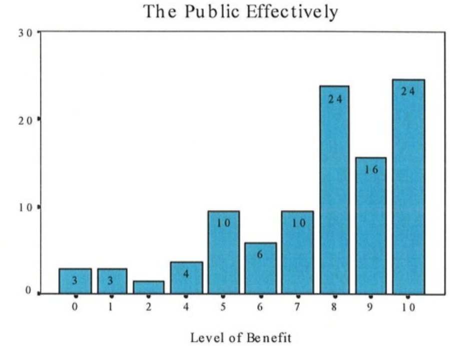
Topic: Budgeting for Legal And Litigation Concerns



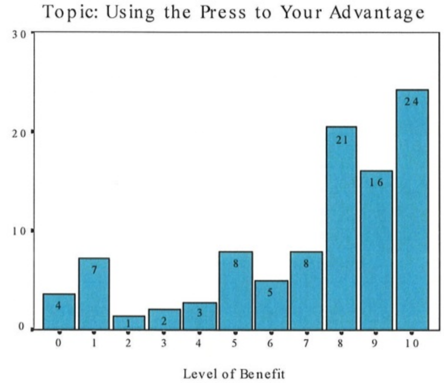
Topic: Partnering with Other Entities: Benefits and Drawbacks to Making it Work



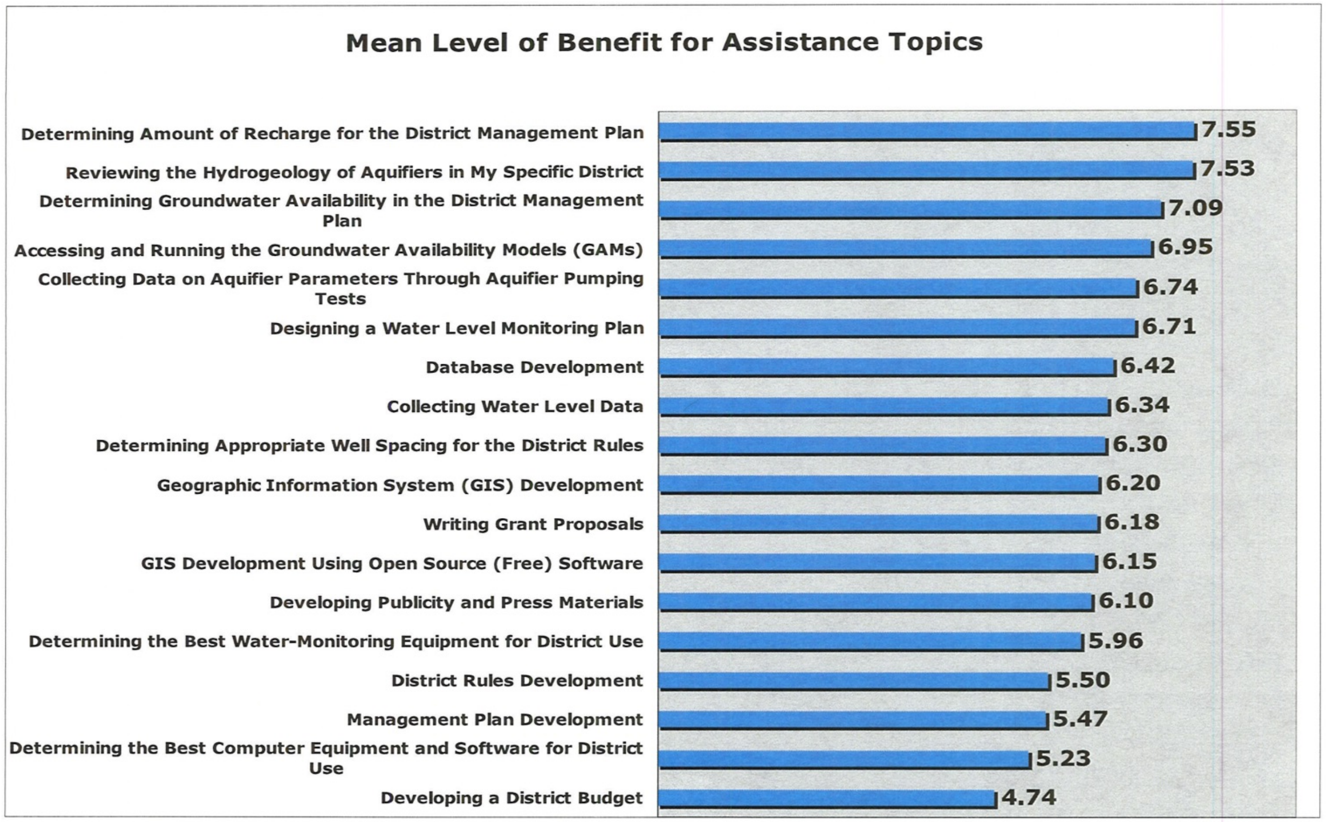
Topic: Communicating To The Public Effectively



Topic: Using the Press to Your Advantage



A Look At Types Of Assistance



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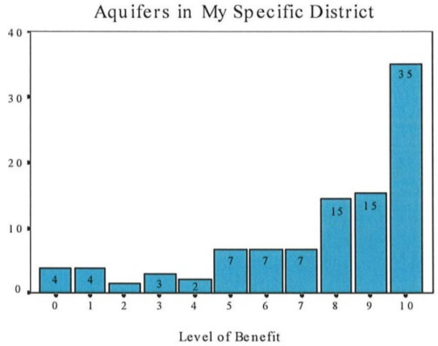
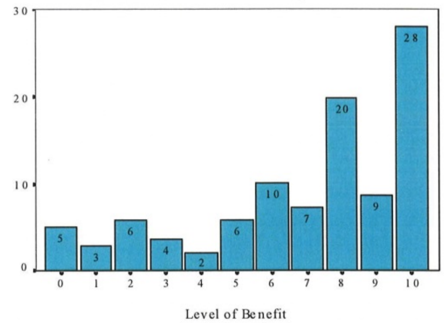
Specific Results of Assistance Topics Survey

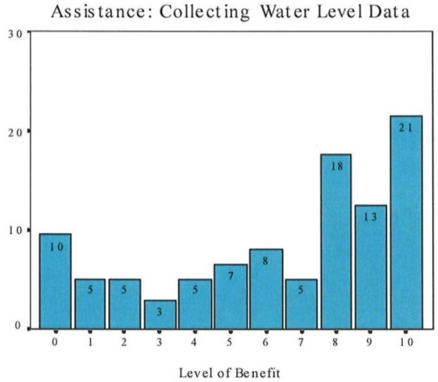
Assistance: Reviewing the Hydrogeology of Aquifers in My Specific District



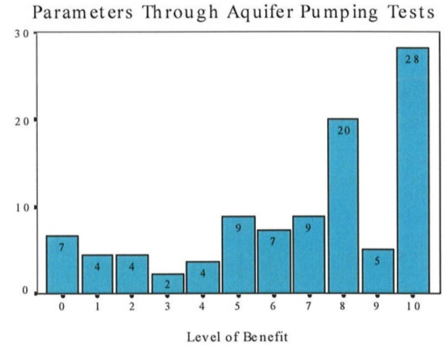
Assistance: Accessing and Running the Groundwater Availability Models



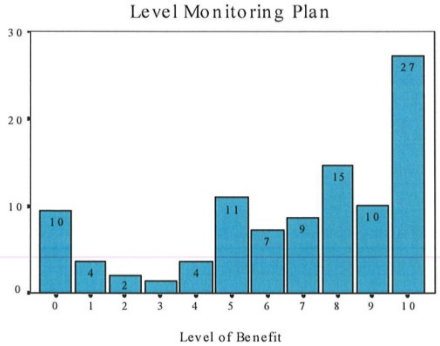
Assistance: Collecting Water Level Data



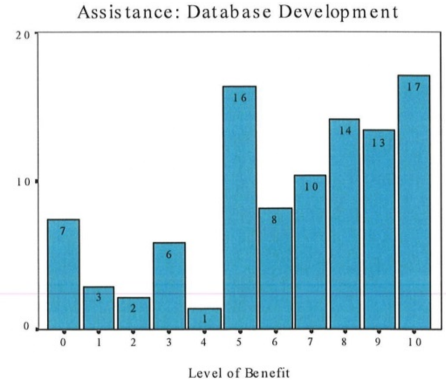
Assistance: Collecting Data on Aquifer Parameters Through Aquifer Pumping Tests



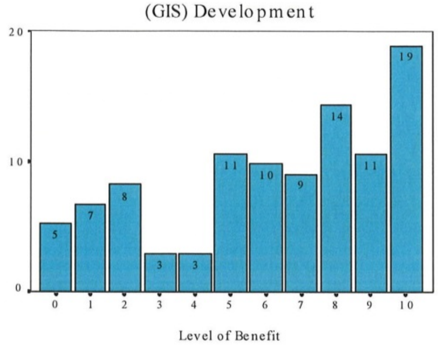
Assistance: Designing a Water Level Monitoring Plan



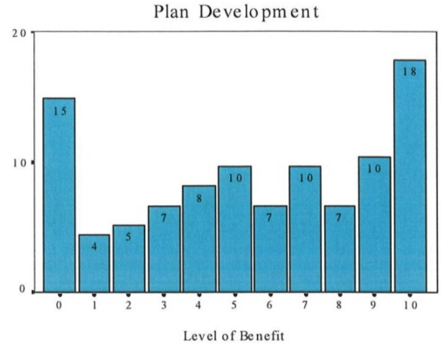
Assistance: Database Development



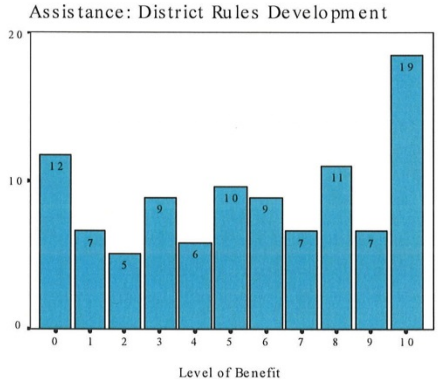
Assistance: Geographic Information System (GIS) Development



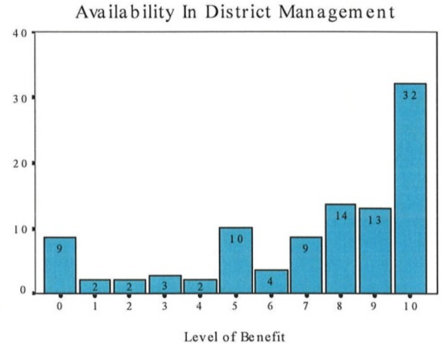
Assistance: Management Plan Development



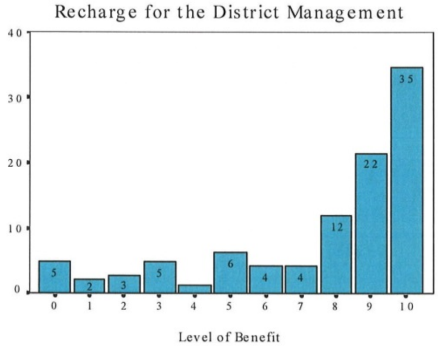
Assistance: District Rules Development



Assistance: Determining Groundwater Availability In District Management

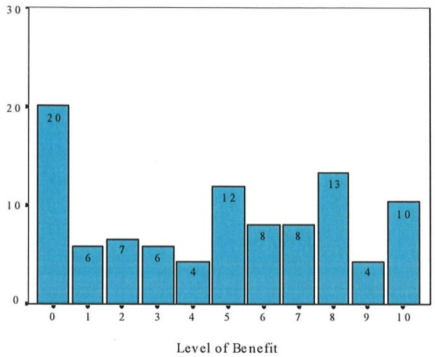


Assistance: Determining Amount of Recharge for the District Management

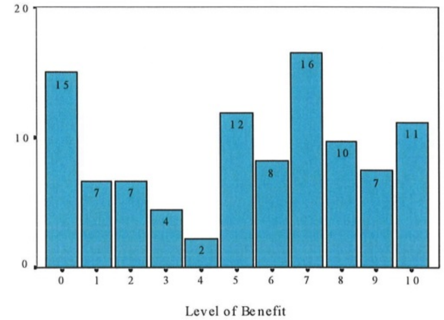


Assistance: Determining Appropriate Well Spacing for the District Rules

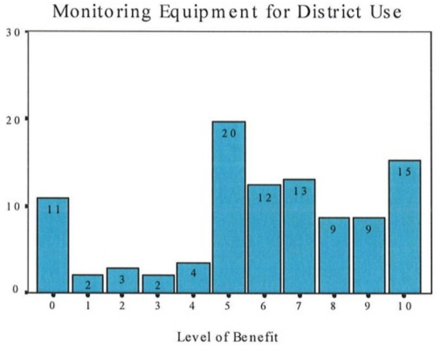
Assistance: Developing a District Budget



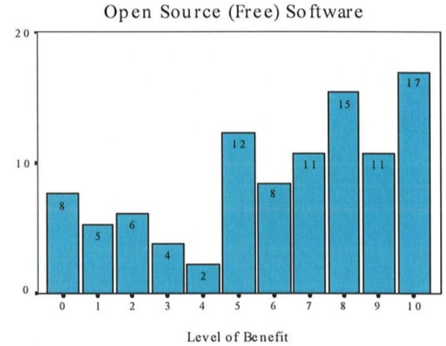
Assistance: Determining Best Computer Equipment and Software for District Use



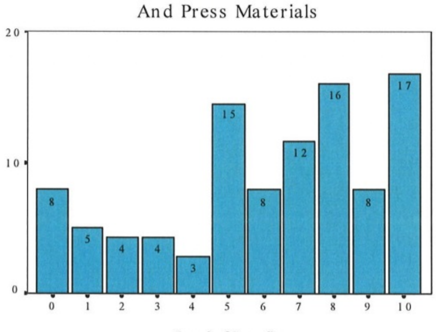
Assistance: Determining the Best Water-Monitoring Equipment for District Use



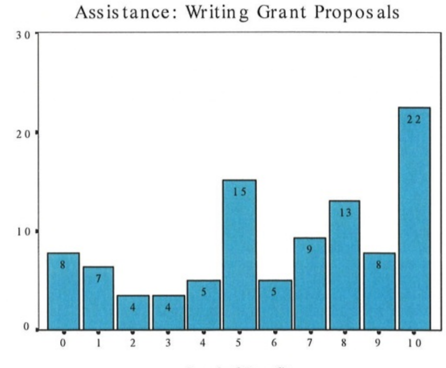
Assistance: GIS Development Using Open Source (Free) Software



Assistance: Developing Publicity And Press Materials



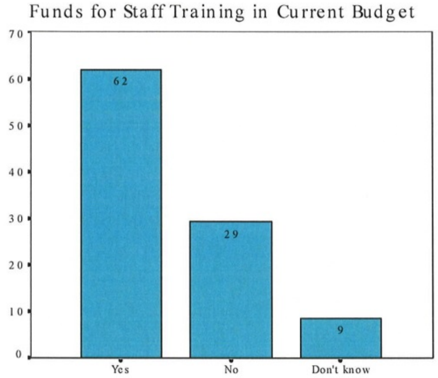
Assistance: Writing Grant Proposals



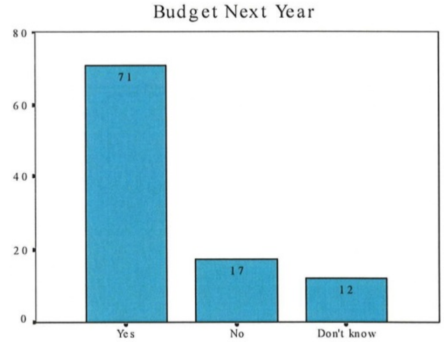
Travel and Budget

- The majority of districts have both current (62%) and future (71%) funds available for staff training
- Most (62%) have $300 or more budgeted per staff member
- 120 miles is the maximum distance most (44%) are willing to travel to attend a workshop

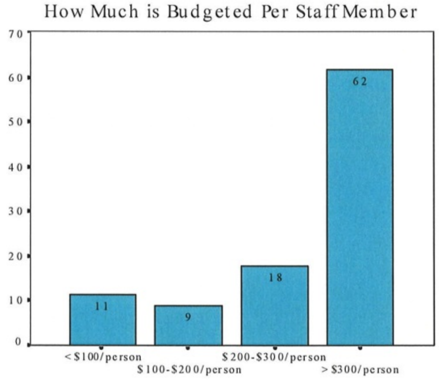
Funds for Staff Training in Current Budget



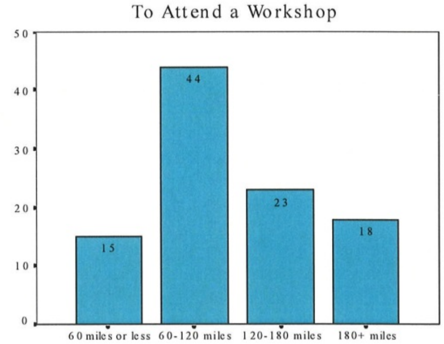
Funds for Staff Training in Budget Next Year



How Much is Budgeted Per Staff Member



Distance Willing to Travel To Attend a Workshop



III. Description of Training Workshop

Groundwater Conservation District Training Workshop: Area-Specific Hydrogeology Overview

Introduction

This workshop will provide an overview of fundamental hydrogeology for the aquifers existing in the specific area, i.e. groundwater conservation district or groundwater management area.

Topics covered

1. Brief overview of fundamental hydrogeology, focusing on the various types of aquifers and the geologic settings for those aquifers.

2. Discussion of the specific aquifers within the area boundaries, including the following aspects:

    a. Area extent of each aquifer, indicating boundaries, outcropping zones, and confined zones

    b. Geologic and hydrogeologic characteristics of each aquifer, including geologic setting, general permeability information, typical well yields, the distribution of those characteristics throughout the aquifer, and a general overview of the productivity of the aquifer (i.e., locations of the more productive zones)

    c. Recharge, including recharge areas, modes of recharge, relative rates, and a comparison of recharge rates to current and projected groundwater pumping

    d. Naturally-occurring discharge, including springs, wetlands, baseflow to streams, and interformational flow.

    e. Water quality within each aquifer, including the general quality of the water, the distribution of fresh vs. brackish vs. saline waters, and the locations of "bad water lines"

3. A discussion of the potential concerns specific to the aquifers within the area boundaries (e.g., reduced spring flows, reduced base flow to streams, significant over-drafting of the aquifer(s), salt water intrusion, etc.)

Skills and Knowledge Gained

In general, participants in the workshop will gain a better understanding of the specific aspects of the aquifers in their districts as discussed above. The objective in presenting this material is to give the participants and understanding of the aquifer-specific concerns that will affect the management of their groundwater resources in the future.

All participants in the workshop will receive a bound copy of “Hydrology Lecture notes v. 2.2” as well as hard copies of all presentation materials. These will also be available on-line in PDF format.

Water conservation District Training Workshop: Water-Level Monitoring Programs

Introduction

This workshop will describe the elements of a comprehensive water-level monitoring program.

Topics Covered

1. Water Levels and Water-Level Monitoring – This module will include explanation of the techniques of water-level measurement using the following methods and procedures: 1) steel tape measurement, 2) electric tape measurement, 3) air line measurement, 4) water-level measurement in flowing wells, 5) determining status of well, such as static, recently pumped or pumping, 6) determining a measuring point, and 7) continuous monitoring techniques. This module will also include data-collection and field recording techniques using handheld computers (PDA’s). All procedures included will be standard techniques of field data collection of the USGS.

2. Pontentiometric Mapping- This module will include the techniques used by the USGS to create a potentiometric map in either an unconfined or confined aquifer. The techniques will be explained to include both digital contouring with software packages and manual contouring using paper and pencil and the caveats associated with both.

3. Aquifer Testing – This module will include the basic methods of collecting aquifer test data and calculating aquifer properties such as transmissivity, hydraulic conductivity, and storage. These parameters can be used to calculate hypothetical drawdown at a given distance from a pumping well and can also be used to improve ground-water flow model calibration information.

4. Basic Geophysical Log Analysis – This module will include the introductory concepts of borehole geophysical log data and explanation of various uses of these data. Borehole geophysical data can be very helpful in determining aquifer thickness, lithology, water-bearing potential, fracture analysis, head, and flow contributions of specific intervals.

Skills and Knowledge Gained

Participants will gain a better understanding of the elements included in a comprehensive water-level monitoring program. Participants will have the skills to use several different methods to determine water levels and to use PDAs to collect data in the field. They will have an understanding of the techniques used to create photentiometric maps of aquifers, calculate basic aquifer properties, and analyze basic geophysical log data.

Groundwater Conservation District Training Workshop: Groundwater Availability Model (GAM)

Introduction

This workshop will provide an overview on the use of the groundwater availability model(s) that The Texas Water Development Board has developed for a specific area.

Topics Covered

1. Assets and liabilities of groundwater modeling in general
2. Description of the GAM or GAMs for the specific groundwater district or groundwater management area.
3. Model limitations
4. How to use the model
5. Differences of scale (regional model versus local model)

Skills and Knowledge Gained

In general participants will better understand how to use modeling tools to evaluate water-management strategies, assess groundwater availability trends under normal and drought conditions, and determine desired future condition of an aquifer.

Specifically, participants will have the skills to be able to (1) understand how the GAM or GAMs for their district function; (2) understand the limitations of the GAM or GAMs for their district; (3) be able to frame questions that the model can address; (4) understand the assets and liabilities of the GAM or GAMs; and (5) understand how regional models differ from local models.

Workshop participants will receive maps of their area, handouts listing specific publications available and an electronic copy of the presentation for their district.

Groundwater Conservation District Training Workshop: Communicating Effectively with the Public

Introduction

This workshop will provide an overview on developing and implementing a strategic communications plan for groundwater conservation districts.

Topics covered

Workshop topics will include the follow:

1. Strategic Communications Plan: what a strategic communication plan entails, why groundwater conservation districts need one, how to develop a plan, how to execute the plan.

    a. Objectives

b. Key messages
c. Timelines
d. Landscape: political, economic, water marketing

2. Communications Tools: how districts can develop communications tools in affordable ways; how to “take the first step”

3. Using Tools: how districts can get their message to the public in affordable ways.

   a. Public meetings
   b. Presentations to groups
   c. Media
   d. Online communications

Skills and Knowledge Gained

Participants will leave this workshop with an understanding of:

- How a strategic communications plan helps GCDs carry out their roles and responsibilities.
- How to develop communications tools.
- How to use communications tools.

Handouts/takeaways will include:

- Workshop summary
- Checklists
- Exercises – completed by individual participants so that information applies to their own districts

IV. Workshop Attendees and Feedback

NOVEMBER 14, 2009 WORKSHOP

A. Workshop Announcement

River Systems Institute, in association with the Texas Alliance for Groundwater Districts is hosting a one-day workshop on tools for managing groundwater. The workshop will include modules on implementing a water-level monitoring program and using groundwater availability models.

Water-Level Monitoring

Participants will be provided information on using several water-level monitoring methods and procedures: 1) Steel tape measurement; 2) Electric tape measurement; 3) Air line measurement; 4) Water-level measurement in flowing wells; 5) Determining status of well; 6) Determining a measuring point; 7) Continuous monitoring techniques. Participants will also review data collection and field recording techniques using handheld computers (PDA). This workshop module will also discuss electronic and manual techniques for creating aquifer contour maps.

Presenter: Greg Stanton, Hydrologist and Groundwater Specialist with the U.S. Geological Survey

Groundwater Availability Models (GAMs)

Participants will be provided information to help them: 1) Understand GAM developed by the Texas Water Development Board for the Queen City/Sparta and Carrizo-Wilcox (Northern) aquifers; 2) Be familiar with the limitations of the models; 3) Frame questions to be addressed by models; 4) Understand the assets and liabilities of groundwater modeling and 5) Understand the difference between regional scale models and local scale models.

Presenter: Andy Donnelly, Hydrogeologist with the Texas Water Development Board

The workshop will be held:

Wednesday, November 14, 2007

9:30-4:30 PM

Nacogdoches City Council Chambers

Nacogdoches, Texas

Directions to the workshop are attached.

To register for this workshop please call the River Systems Institute at 512-245-9200 or e-mail Michael Abbott at MA01@txstate.edu.

B. Workshop Attendees

RSI / TAGD Workshop

Water Level Monitoring/Groundwater Availability Models
November 14, 2007
Groundwater Management Area #11
Nacogdoches, TX

Tom Martin	Neches Trinity Valley Groundwater Conservation District	Staff	tnfish@dctexas.net
Roy Rodgers	Neches Trinity Valley Groundwater Conservation District	Staff	rrodgers@ntvgroundwater.org
Larry Dorman	Panola Groundwater Conservation District	Staff	jldorman@swbell.net
Clayton LaGrone	Panola Groundwater Conservation District	Board	jldorman@swbell.net
David Alford	Pineywoods Groundwater Conservation District	Staff	david@pgcd.org
Janet Grubbs	Pineywoods Groundwater Conservation District	Staff	janet@pgcd.org
Len Luscomb	Rusk County Groundwater Conservation District	Staff	rcgcd@suddenlinkmail.com
Diana Martinez	Rusk County Groundwater Conservation District	Staff	rcgcd@suddenlinkmail.com
RD Wittner	Rusk County Groundwater Conservation District	Board	rcgcd@suddenlinkmail.com
David Powell	Rusk County Groundwater Conservation District	Board	rcgcd@suddenlinkmail.com
Jane Moore	River Systems Institute	Staff	lm47@txstate.edu

C. Water Level Monitoring Survey

Water-Level Monitoring

River Systems Institute Pilot Workshop

Summary of Responses
November 14th Workshop

How useful was the workshop in describing water-level monitoring?

Very Useful	Somewhat Useful	Neutral	Not Very Useful	Not at all Useful
4	6			

How useful was the content of the workshop?

Very Useful	Somewhat Useful	Neutral	Not Very Useful	Not at all Useful
3	7			

What could we do to improve?

Allow more time for the workshop

How useful was the format of the workshop?

Very Useful	Somewhat Useful	Neutral	Not Very Useful	Not at all Useful
5	5			

What could we do to improve?

Target tools covered to participants

How effective was the speaker's presentation style?

Very Useful	Somewhat Useful	Neutral	Not Very Useful	Not at all Useful
6	4			

How useful were the worksheets?

Very Useful	Somewhat Useful	Neutral	Not Very Useful	Not at all Useful
4	6			

What could we do to improve?

Very helpful

To what extent will the workshop help you address your water-level monitoring issues?

Very Useful	Somewhat Useful	Neutral	Not Very Useful	Not at all Useful
4	6			

I found the workshop very helpful and will share material with my board

Please list other improvements that could be made when workshop is held again.

Allow more time

Additional Comments

Good workshop for new staff

Appreciate assistance available through USGS

D. Groundwater Availability Model Survey

Groundwater Availability Models (GAMs)

River Systems Institute Pilot Workshop

Summary of Responses
November 14th Workshop

How useful was the workshop in describing the GAMs used by TWDB?

Very Useful	Somewhat Useful	Neutral	Not Very Useful	Not at all Useful
5	5			

How useful was the content of the workshop?

Very Useful	Somewhat Useful	Neutral	Not Very Useful	Not at all Useful
6	4			

What could we do to improve?

Allow more time for the workshop

How useful was the format of the workshop?

Very Useful	Somewhat Useful	Neutral	Not Very Useful	Not at all Useful

5	5			

How effective was the <u>speaker's presentation style?</u>

Very Useful	Somewhat Useful	Neutral	Not Very Useful	Not at all Useful
5	5			

How useful were the <u>worksheets?</u>

Very Useful	Somewhat Useful	Neutral	Not Very Useful	Not at all Useful
5	5			

What could we do to improve?

Need more printed material

To what extent will the workshop help you understand use of the GAMs?

Very Useful	Somewhat Useful	Neutral	Not Very Useful	Not at all Useful
5	4	1		

As new General Manager, I found workshop very helpful

Please list other improvements that could be made when workshop is held again.

Allow more time

NOVEMBER 28, 2009 WORKSHOP

A. Workshop Announcement

River Systems Institute, in association with the Texas Alliance for Groundwater Districts is hosting a half-day workshop on Communicating Effectively with the Public.

Public Relations and Communication

Workshop participants will gain an understanding of:

- How a strategic communications plan helps groundwater districts carry out their rules and responsibilities.
- How Districts can develop communication tools and effectively get their message to the public in affordable ways.

Presenter: Laura Raun;
Founder/CEO of Laura Raun
Public Relations

The workshop will be held in conjunction with the TAGD fall meeting on:

Wednesday, November 28, 2007

8:30-Noon

TWDB Board Room

Stephen F. Austin Building

Austin, Texas

To register for this workshop please call the River Systems Institute at 512-245-9200 or e-mail Michael Abbott at MA01@txstate.edu.

B. Workshop Attendees

RSI / TAGD Workshop

Communicating Effectively with the Public
November 28, 2007
Room 170, Stephen F. Austin Building
Austin, TX

Gary Franklin	Barton Springs/Edwards Aquifer Conservation District	Board	Garyfranklin2@austin.rr.com
Julie Jenkins	Barton Springs/Edwards Aquifer Conservation District	Staff	jjenkins@bseacd.org
Cheryl Maxwell	Clearwater Underground Water Conservation District	Staff	cmaxwell@ctcog.org
John Jones	Culberson County Groundwater Conservation District	Staff	water@telstar1.com
Dana Carmean	Hays Trinity Groundwater Conservation District	Staff	manager@haysgroundwater.com
Janet Gutherie	Hemphill County Underground Water Conservation District	Staff	hemphillcuwcd@amaonline.com
Jerry Kirby	Kimble County Groundwater Conservation District	Staff	kcwd@cebridge.net
Joe Cooper	Middle Trinity Groundwater Conservation District	Staff	mtgcd@out-town.com
Westin Burris	Middle Trinity Groundwater Conservation District	Staff	mtgcd@out-town.com
Lee Sweeten	Real-Edwards Conservation & Reclamation District	Staff	lsweeten@swtexas.net
Garrett Engelking	Refugio Groundwater Conservation District	Staff	gengelking@rgcd.org
Mike McGuire	Rolling Plains Groundwater Conservation District	Staff	mmcguire@rpgcd.org
Rima Petrossian	Texas Water Development Board	Staff	Rima.Petrossian@twdb.state.tx.us
Matt Nelson	Texas Water Development Board	Staff	Matt.Nelson@twdb.state.tx.us

C. Communicating Effectively with the Public Feedback

Communicating Effectively with the Public
River Systems Institute Pilot Workshop

Summary of Responses
November 28th Workshop

How useful was the workshop in explaining how to communicate effectively with the public?

Very Useful	Somewhat Useful	Neutral	Not Very Useful	Not at all Useful
8	3			

How useful was the <u>content</u> of the workshop?

Very Useful	Somewhat Useful	Neutral	Not Very Useful	Not at all Useful
7	4			

What could we do to improve?

Allow more time for the workshop (2)

Better time management (2)
Cut out some of the exercises
Limit participation in exercises (2)
Stay away from isolated specifics

How useful was the format of the workshop?

Very Useful	Somewhat Useful	Neutral	Not Very Useful	Not at all Useful
6	5			

What could we do to improve?

Good agenda and worksheets; need better time management to complete (2)
Cut out some of the content
Limit participation in exercises to volunteers
Target tools covered to type of public working with

How effective was the speaker's presentation style?

Very Useful	Somewhat Useful	Neutral	Not Very Useful	Not at all Useful
7	4			

What could we do to improve?

Good give and take; speaker often rushed
Speaker needs more time (2)
Need more examples; especially of what not to do

How useful were the <u>worksheets?</u>

Very Useful	Somewhat Useful	Neutral	Not Very Useful	Not at all Useful
7	4			

What could we do to improve?

Quite helpful – I will re-read and share my notes with my colleagues
Very effective worksheets
The worksheets and exercises required too much time
Print tips on the forms
Need more printed material/notes. I spent too much time taking notes that could have been handed out.

To what extent will the workshop help you address your communications challenges?

Very Useful	Somewhat Useful	Neutral	Not Very Useful	Not at all Useful
7	4			

Especially helpful to new general manager
Do more of the workshops

Please list other improvements that could be made when workshop is held again.

More time needed if full participation in exercises is desired. (2)
Better time management to avoid rushing through sections. (3)
Avoid introduction of isolated topics by participants that overwhelm or bog down the message.
Limit participation in exercises to avoid skipping or rushing through other material.
Consider starting later to allow participants to commute to workshop.
Use of microphone would have helped.
Consider separate sections/sessions on communications and working with media.
More discussion with participants about what actually works for them.

Additional Comments

Extremely beneficial to hear issues of other GCDs.
Encourage GCDs to work together to address similar issues.
Encourage new GCDs to attend this workshop. (3)
Very good ideas presented in workshop. I benefited from the program.

V. Training DVD's and CD's (see attachments)

DVD 1: Conducting Meetings
DVD 2: Human Resources for GCD
DVD 3: Communicating Effectively with the Public
CD: Legal Primer for Administering GCD

VI. Hydrogeologic Study for HTGCD

Cypress Creek/Jacob's Well Hydrogeologic Report

November, 2008

PREPARED FOR
Texas State University - River Systems Institute
San Marcos, Texas

PREPARED BY
The Hays Trinity Groundwater Conservation District

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1.0 Introduction

Cypress Creek, located in the Wimberley, TX area, is a major contributor to the aesthetics and lifestyles of the residents of the Wimberley Valley. It is also an important economic factor that drives the local tourist economy. Jacob's Well, an artesian spring, provides the majority of flow in Cypress Creek and has been described as the "heart and soul" of the Hill Country. Blue Hole, located in Cypress Creek just upstream of Wimberley, is a swimming hole that has been enjoyed by generations of local residents and considered one of the top swimming holes in Texas.

Other than a small number of individual residential rainwater harvesting systems, the Wimberley Valley is totally dependent on groundwater for its potable water. With the continued rapid growth and development of the Wimberley Valley, and several hot, dry Texas summers, a great deal of pressure has been placed on the groundwater resources of the community. Flows from Jacob's Well were significantly reduced during the droughts of 2005–2006 and 2008 and the spring ceased to flow in 2000 for the first time in recorded history.

2.0 Purpose

In recognition of the importance of Cypress Creek and Jacob's Well to the Wimberley Valley, the Hays Trinity Groundwater Conservation District (HTGCD) was awarded a grant from the Texas State University–River Systems Institute (RSI), the Way Family Foundation, and the Meadows Foundation to study the hydrogeology of the Cypress Creek Watershed (Figure 1). The purpose of the Cypress Creek/Jacob's Well Hydrogeologic Study is to define the hydrogeologic setting,

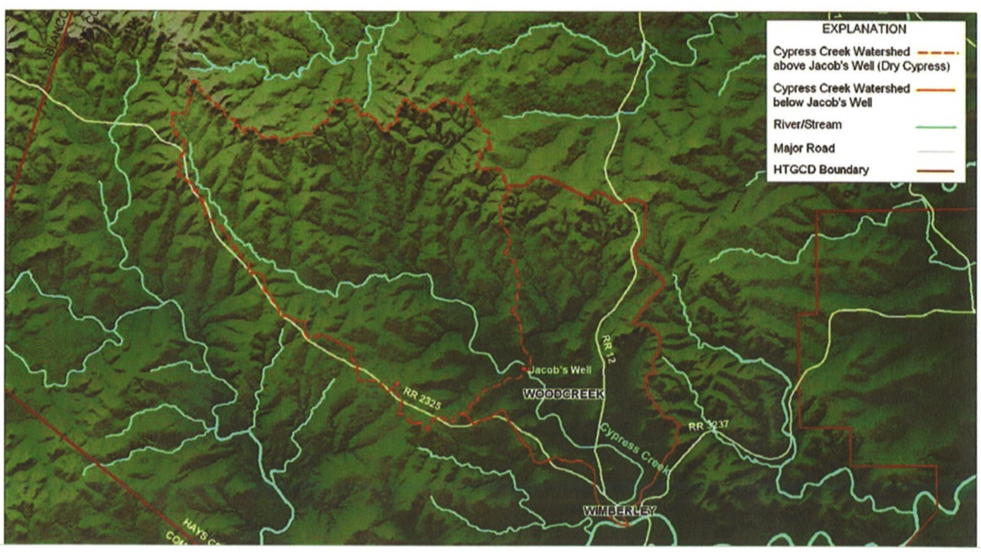


Figure 1. Cypress Creek/Jacob's Well Study Area

interaction of surface water and groundwater, water quality and local stratigraphy, and to identify a set of metrics to monitor in order to preserve the flow of Cypress Creek and Jacob's Well to the extent possible.

3.0 Scope of Work

The scope of the Cypress Creek/Jacob's Well Hydrogeologic Study included the following:

1. Compile existing sources of well, groundwater and surface water data relevant to Cypress Creek/Jacob's Well.

2. Develop a surface-feature map depicting the Cypress Creek drainage basin above Jacob's Well.

3. Develop a working base geological map for the Jacob's Well groundwater basin and record relevant data on springs, wells and geologic data.

4. Develop procedures to routinely compile data on water levels throughout the Cypress Creek watershed.

5. Develop contour maps of water-level elevations in the Middle Trinity aquifer.

6. Compare water chemistry in Jacob's Well with water chemistry of water wells throughout the watershed.

7. Identify metrics that would be used to monitor in order to preserve the flow of Cypress Creek and Jacob's Well.

8. Partner with University of Texas researchers to develop a report that describes the most probable sources of water in Cypress Creek and Jacob's Well.

9. Prepare a multi-phased plan for completion of a comprehensive Hydrogeologic analysis of the Cypress Creek watershed.

This work is also part of a larger project, the Cypress Creek Project, being conducted by Texas State University to develop a model could be used to predict water quality impacts on Cypress Creek and water availability with future development within the watershed.

This report is a work in progress and presents preliminary conclusions regarding the geology and hydrogeology of Cypress Creek. Additional data collection and analyses are continuing on many of the areas of study presented in this report. As additional data are collected and analyzed, some of the conclusions contained herein may be further clarified and expanded. The report also identifies many potential areas of further study that could be taken on by university students and classes, area volunteers and other professionals.

4.0 Summary of Study Methodology

Published literature was reviewed and existing data were collected from a number of Texas state agencies, prior academic studies, volunteer scientists, cave divers, water supply corporations, individual land owners and well owners. New geologic, hydrogeologic, and water quality data were collected and analyzed.

Published literature was reviewed related to the geology and hydrogeology of the Cypress Creek and Jacob's Well area were utilized to gain an understanding of the regional hydrogeologic setting. Following the literature review, a conceptual model of the local geology was developed based on aerial photo analysis, field mapping, water-well construction records, drill cutting descriptions and geophysical log analysis. Positional information of field data was obtained using Global Positioning System (GPS) equipment and the data were recorded in a Geographical Information System (GIS) relational data base that allowed the data to be plotted in map form.

A conceptual model of the subsurface poteniometric surface and flow regime in the Middle Trinity Aquifer was developed based on water-level data from area wells, the Blanco

River, Cypress Creek and data on the discharge rate and stage level at Jacob's Well. Jacob's Well was obtained from the United States Geological Survey's (USGS) continuous monitoring system that is funded by a grant from the Texas Commission on Environmental Quality (TCEQ).

The relationships between precipitation, surface water flows and groundwater recharge rates were explored by compiling and analyzing precipitation data and USGS stream flow data from the Blanco River and Onion Creek in Hays County and discharge rates at Jacob's Well.

Groundwater quality data were compiled and analyzed from the USGS continuous monitoring system, the Texas Water Development Board (TWDB), TCEQ, sampling efforts subsidized by the HTGCD and conducted by volunteer cave divers in Jacob's Well, and ongoing research subsidized by HTGCD of a Masters degree candidate from the University of Texas at Austin.

The TWDB databases provided historic water quality data from water wells and provided water well records that included data on the geology, water quality and quantity. Volunteer cave divers performed important work in mapping, photographing and describing the subsurface conduit extending below Jacob's Well and in collecting water quality samples from the conduit. Volunteer Professional Geologists assisted the District Geologist, Al Broun, in conducting field reconnaissance and reviewed results of Mr. Broun's geologic analysis. Significant data collection sites are shown in Figure 2 and detailed in Table 1.

5.0 Further Explanation of Data Sets and Sources of Data

5.1 GPS Data Collection

GPS location data were collected by the HTGCD over a four-year period (2005–2008), and continues to be measured as necessary for all significant field data points. During this study, locational coordinates and elevations relative to mean sea level were surveyed using a Trimble Pro XRS surveying system that provides submeter accuracy for latitude and longitude and accuracy within a few meters for elevation (see www.trimble.com). Locations surveyed include geologic features of interest, such as marker beds or contacts, water wells, and river and stream road crossings. To date, the HTGCD has collected GPS coordinates for 163 data points within the study area (Table 2).

5.2 Contribution of Volunteer Divers

A team of volunteer divers have conducted numerous dives down Jacob's Well, providing invaluable information about the Well's subsurface structure, geology, and water chemistry (Figure 3). A video of the divers exploring Jacob's Well is available at <http://www.haysgroundwater.com >. A stratigraphic column and structural cross section were developed for the well based on depth measurements, GPS data, still photos and video gathered by the divers. Divers collected water samples on October 22, 2007 which were analyzed to examine differences in water quality among the different subsurface karst tubes feeding into the Well, groundwater from the Trinity Aquifer, and surface water from Cypress Creek and the Blanco River. Divers also installed and retrieved temperature transducers at the mouths of the main tubes and the mouth of Jacob's Well.

Figure 3. Diver Entering Second Chamber of Jacob's Well

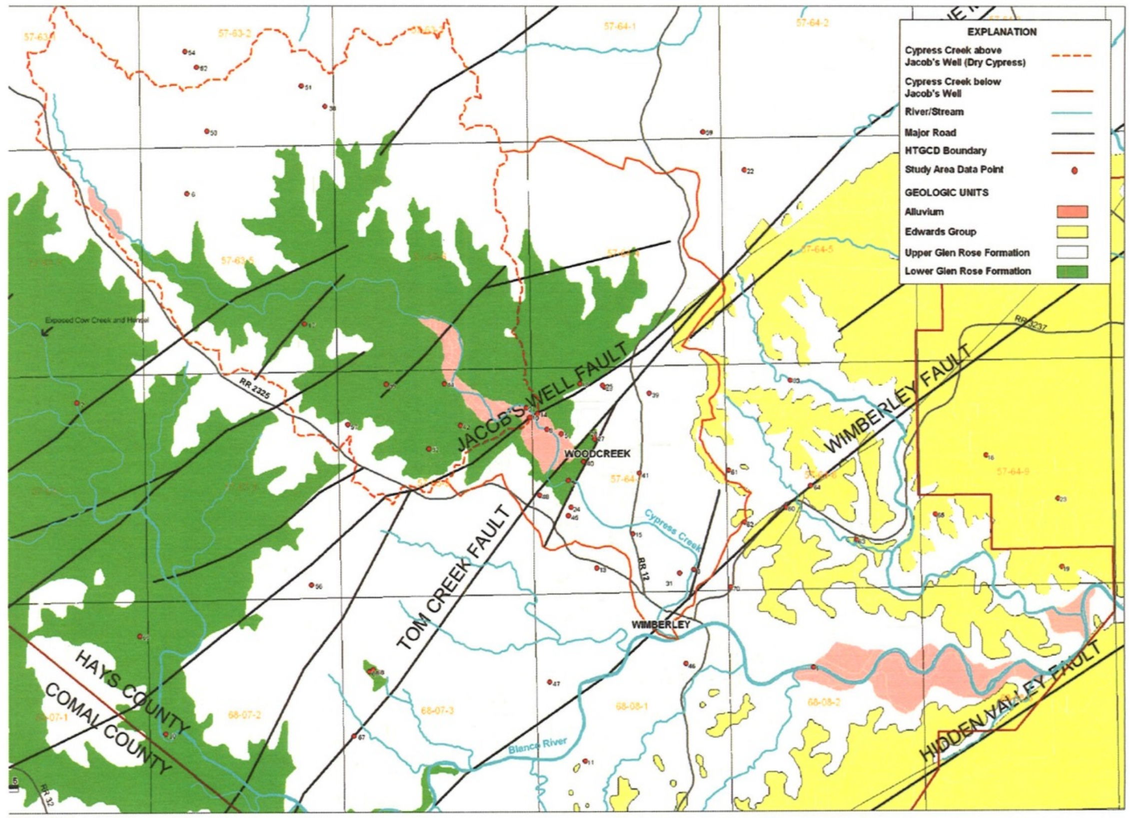


Figure 2. Cypress Creek/Jacob's Well Study Area Data Points (base map from Geologic Atlas of Texas, faults modified by HTGCD)

5.3 Water Well Inventory For the Study Area (State Well Reports/Drillers' Logs)

Drillers's logs (also known as: State Well Reports) provide data about water well completion, location, ownership and gross information about the geology, karst, faults, fractures, water levels, and productive capacity of the aquifer encountered. Drillers are required to submit these reports to the State of Texas and to the groundwater conservation district with jurisdiction for the area where the well was completed in order to document the completion of a water well. The State Well Reports are potentially a valuable source of information but are often incomplete with important information often missing from the form.

A water-well inventory based on drillers' logs was completed for the study area in order to understand the distribution of water wells, to understand which hydrogeologic units are targeted for water production, and to estimate how much demand is placed on each aquifer. Records for 924 wells were obtained for the study area in electronic and hardcopy format from the three state agencies (TWDB, TCEQ and Texas Department of Licensing and Regulation (TDLR)) that each maintain part of the historic record of these documents.

The TWDB has an incomplete inventory of drillers' logs online in their WIID database <http://wiid.twdb.state.tx.us/>. The WIID data base contains a small fraction of historic paper records but a relatively complete record of wells drilled in the last several years. The majority of the historic drillers' logs were obtained from the TCEQ, which maintains paper copies of the older records.

A water-well inventory database was assembled from the records of the 924 wells located in the study area and is maintained by the HTGCD.

5.4 Geophysical Logs and Cuttings

Geophysical logs and drill cuttings from water wells drilled during the last several years, were used in conjunction with surface geological mapping, to develop a subsurface geological model of the area.

Geophysical logs are the graphical display of data generated from electrical probes lowered into open boreholes, or completed wells, that collect continuous or point source data about the geologic and/or well materials passing the probe. These logs provide information about the geologic units penetrated by a well in a graphic format. The geologic units may then be correlated between wells enabling a geologist to develop subsurface geologic models of the area.

Drill cuttings are the chips of rock that are brought up during well drilling from the geologic unit encountered by the drilling bit. Drill cuttings were typically collected and lithologically described on 10-foot depth intervals of the drill bit. For example, in a given well cuttings samples were collected and described while the drill bit penetrated from 400 to 410 feet below ground-level, from 410 to 420, from 420 to 430, etc. The drill cuttings' descriptions provide physical evidence of the geologic material that can be compared to with the geophysical logs.

Figure 4. Geophysical Logs and Cutting Analysis

Geophysical logs and drill cuttings were collected from water wells that were being drilled by the landowners so that the HTGCD's primary expense was the cost of the geophysical log alone. This approach was an economical way to further our understanding of the subsurface hydrogeologic framework of the aquifer system.

Basic exploration geology methods were applied for field mapping and evaluating groundwater resources. Cuttings samples and geophysical logs (natural gamma), were collected from Hays County water wells with the cooperation of local landowners and drilling companies, and analyzed for lithostratigraphic data and the identification of rock units. Geophysical logs and rock cuttings are archived at the HTGCD offices.

Based on the drill cuttings obtained from water wells, field observations and a review of regional geologic literature, a type geophysical log was created to identify contacts between various rock units present in the study area. A description of the type log, description of statigraphic units. The type geophysical logs are included in Appendix 1. Copies of all other geophysical logs are available for review at the HTGHD.

The logs were correlated and the resulting stratigraphic and structural interpretation was tied to the outcrop and available literature. Using the interpreted data, a series of three structural cross sections were built, including a profile through Jacob's Well. Within the study area, geophysical logs were run on wells. Drill cuttings were collected and analyzed from 10 wells.

5.5 Structural Geologic Air Photo Analysis

The location of lineaments, linear features of the landscape which may represent potential geologic faults and fractures, were plotted on aerial photography using two methods of air photo interpretive analysis. First, Stereo photo pairs (approximate scale 1:24,000) from October 1997 were obtained from the Texas Natural Resource Information System (TNRIS). The photographs were viewed with a stereo scope and were used to plot lineaments. Second, Google Earth™ was utilized to further delineate potential structural lineaments. Google Earth allows for landscape views from all angles and complements the traditional air photos.

5.6 Geologic Field Mapping

The potential geologic structures identified on aerial photos were ground truthed through extensive field work. Geostructural trends (strike and dip) for faults, fractures, and joint sets were measured. These measurements were then plotted using a Rose diagram and interpreted to compare with the aerial photo results. Field mapping techniques were used to identify and locate stratigraphic features such as marker beds and stratigraphic contacts (Figure 5).

Figure 5. Geologic Field Mapping Methods

5.7 USGS Jacob's Well Station

The USGS station at Jacob's Well was installed in April 2005 through a grant from the TCEQ under their "continuous water quality monitoring program". The Wimberley Valley Watershed Association led the grant application effort and the HTGCD was a significant supporter. The USGS maintains the station and displays data on their website <http://waterdata.usgs.gov/usa/nwis/uv?site_no=08170990>. The station collects 15 minute data for temperature, precipitation, stream velocity, discharge, gage height, specific conductance, turbidity, and acoustic signal strength. Sixty days of 15 minute data are available at a time, as well as daily data for the period of record, April 2005 to present. The TCEQ provides the ongoing funding for operating the station. The real-time data available on the USGS site are provisional data and have not been reviewed or edited. Data are edited at the end of each water year (September

30) by the TCEQ and published within six months of that date. The period of data analysis performed in this report is from the initiation of data collection in April, 2005 through June, 2008. This period is referred to as the period of record. The data from October, 2007 through June, 2008 used in this report is provisional.

Precipitation data is available from the USGS for the period of record. The precipitation data is preliminary: the USGS publishes preliminary data on their website then checks the data for potential sources of error before publication. However, the precipitation data is not published and therefore has not been checked for error. Anomalies in precipitation data have been observed; at times the precipitation gage has shown a spike when rainfall has not occurred. Therefore, the precipitation data is better used as a reference, rather than a reliable source of data. In this report, precipitation data collected by NOAA in Wimberley is referenced.

Figure 6. Jacob's Well

5.8 USGS Blanco River and Onion Creek Gages

The United States Geological Survey (USGS) station on the Blanco River is located at the crossing of the Blanco River and Ranch Road 12 in Wimberley, Texas. The USGS maintains the station and displays data on their website <http://waterdata.usgs.gov/usa/nwis/uv?site_no=08171000>. Discharge measurements are available from 1924 to present; temperature and gage height data are available from 1987 to present; and specific conductance, pH, and dissolved oxygen value data are available from 1997 to present. Sixty days of 15 minute data are available at a time, as well as daily data for the period of record. The real-time data available on the USGS site are provisional data and have not been reviewed or edited. Data is edited at the end of each water year (September 30) and published within six months of that date. The USGS maintains a similar station on Onion Creek, located at the crossing of the creek and Ranch Road 1826 near Driftwood, Texas. The USGS maintains the station and displays data on their website <http://waterdata.usgs.gov/usa/nwis/uv?site_no=08158700>.

5.9 Water-Level Monitoring

The HTGCD initiated a groundwater level monitoring program in 1999. Today, water levels at 41 privately owned wells are monitored monthly across the district, with 17 of these wells located within the study area. Monitoring of the wells is done with the permission and cooperation of the well owner. Public water supply companies with water supply wells in the area also collect and submit monthly water level data to the HTGCD. These combined water level data were used to determine general groundwater trends across the study area and to construct potentiometric surface maps. In May 2008, a larger water level survey was conducted by the HTGCD across the Cypress Creek study area. With the cooperation of individual landowners and water supply companies, 53 water levels were measured within the study area.

Water levels are typically measured with an e-line. An e-line is a wire lowered into the well that sends an electronic signal back to the surface when water is encountered. The accuracy of the e-line is considered to be ±0.05 feet. Expressing the water level in terms of mean sea elevation has an accuracy of ± several meters (±≈ 6 feet) due to the accuracy of the GPS measurement to determine elevation datum at the well head.

Surface water levels are measured and recorded periodically from numerous locations along Cypress Creek and the Blanco River. Surface water elevations are typically obtained from bridges and road crossings that have been surveyed for location and elevation.

In Situ Level Troll 300 pressure-temperature transducers have been placed in seven wells within the study area. These transducers record water pressure measurements that can be converted to water elevation on 15-minute intervals. The data will be used to monitor the aquifer's response to precipitation events and will aid in determining the source of recharge to the wells. Due to the lack of rainfall during the period of this study, no transducer data is presented in the report. The transducers will remain deployed into the future.

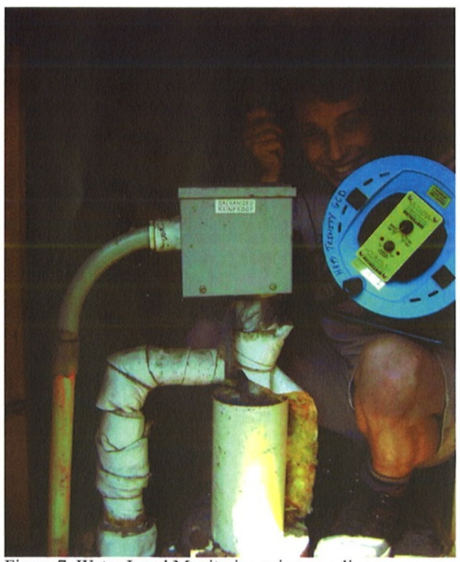


Figure 7. Water-Level Monitoring using an e-line

5.10 Water Quality

Water quality data were compiled from a number of public sources. Data were downloaded from the TWDB website for a number of wells district wide, and additional water quality data were available from the water availability studies conducted by subdivision developers under Hays County Development Rules. Water quality data (temperature, specific conductivity and turbidity) for Jacobs' Well were available from the USGS station.

Water samples were collected by divers at Jacob's Well on two occasions. Water samples were also collected at different points along Cypress Creek and the Blanco River and compared with the water quality at Jacob's Well. Typically, water samples are analyzed for a suite of anions and cations including calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, hardness and total dissolved solids.

A study, partially funded by the HTGCD, to be completed in late 2008 or early 2009, is being conducted by a masters student from the University of Texas at Austin. The study includes conducting a water quality study of Jacob's Well using measurements of water levels and water chemistry in ground and surface waters upgradient from Jacob's Well to characterize the source of baseflow to the spring.

5.11 Blue Hole

Blue Hole is a swimming hole located on Cypress Creek in Wimberley, Texas. The HTGCD performed preliminary field work to measure the dimensions of the hole and determine if underwater springs were contributing to the flow of water at Blue Hole. Horizontal transects were set up at 50 foot intervals down the length of Cypress Creek, and water depth was measured every five feet along the horizontal transects. Vertical temperature profiles were conducted at several locations along the Creek and individual temperature measurements were taken at a number of locations (Figure 8).

Figure 8. Blue Hole on Cypress Creek

7.0 Geology of the Trinity Group: Cypress Creek Study

7.1 Geologic Setting

The Trinity Group in western Hays County is Lower Cretaceous in age, extending from the Neocomian to the Albo-Aptian. The geologic section consists of the wedge-edge of a shallow-water, carbonate shelf which onlapped the thrusted Paleozoic rocks of the buried Ouachita Mountains. The Llano Uplift and highlands to the west and northwest were the provenance for a coarse-clastic sedimentary base (Sycamore/Hosston) that shoals upwards in a series of carbonate-dominated sequences. Tectonic movement during Early Miocene time resulted in a series of northeast-southwest striking, en-echelon, normal faults that cut the Lower Cretaceous sedimentary rocks and dropped the section by as much as 1,200 feet to the south-southeast (Balcones Fault Zone).

The purpose of the geology section of this report is to provide a geologic framework for analyzing the hydrogeology of the Cypress Creek Basin (Figure 12). For a complete and detailed study of the lithostratigraphy and sequence stratigraphy of the Trinity, the reader is directed to publications by David Amesbury, 1974; Lozo, Smith and Strickland, 1956; and Bob Perkins, 1974. Recent work by R. Scott, 2007 and Bill Ward, 2007 cover the detailed lithology, sequence stratigraphy and paleontology of the Glen Rose Formation. Other major reports used in the HTGCD analysis are listed in the bibliography.

7.2 Lithostratigraphy

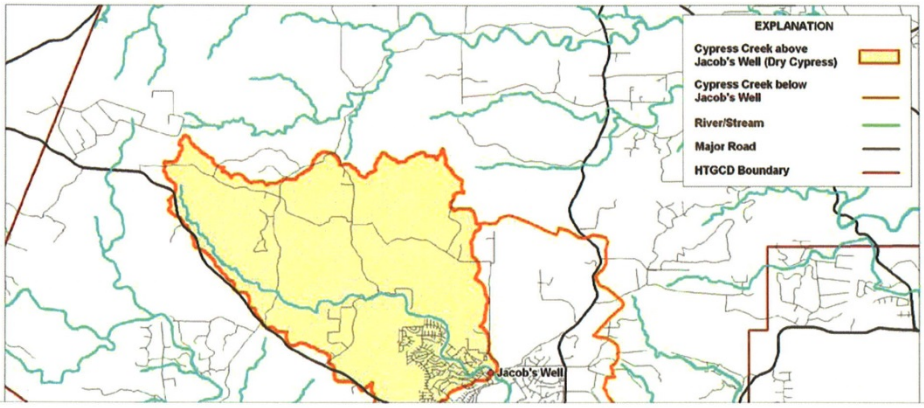
The Trinity Group is approximately 1000 feet thick in the project area and rests unconformably over the Paleozoic thrusted fold belt. The section onlaps the Llano Uplift to the west-northwest and thickens to the southeast towards the Lower Cretaceous shelf margin. The Trinity is divided into three hydrogeologic units: The Upper Trinity, the Middle Trinity and the Lower Trinity. The primary aquifers in the project area are the Middle Trinity—including the Lower Glen Rose and Cow Creek formations, and the Lower Trinity—including the Sligo and Hosston formations. The general stratigraphy is shown on Figure 14.

7.3 Lower Trinity (300 feet thick)

7.3.1 Sycamore/Hosston Formation

The coarse clastic Sycamore Formation outcrops in Blanco County and the northwest corner of Hays County. The Sycamore represents those sedimentary rocks equivalent to the subsurface Hosston Formation. The basal conglomerates and sands are fluvial, representing early Cretaceous erosion of the Llano highlands. Geophysical logs and cuttings samples of the Hosston in western Hays County are interpreted as stacked fluvial channel sands, shoreline sandstones and siltstones with silty shale overbank deposits.

The Hosston is 95 feet thick at the Brushy Top No. 3 well drilled along Highway 281 in Blanco County, approximately 5 miles west northwest of the study area. The formation is water-bearing at that location and rests unconformably over Paleozoic shale. At Willis No.1, drilled on the bank of Dry Cypress Creek in Hays County, the Hosston is 170 feet thick. The formation produces water from a basal conglomerate and sand unit that sits directly on the Paleozoic. Most Hosston water wells are partial penetrations with total depth some distance above the Paleozoic section. Further southeast along the Dry Cypress Creek, Dry Cypress/Byrum No. 1 well penetrated 65 feet of Hosston Formation. At the base is a siltstone, pale red-brown, mottled yellow-gray, hard with fine fractures; this unit is overlain by a very fine grained sandstone with rare pebbles, quartz grains and dolomite clasts; sandstone, dolomitic, very fine grained, quartz grains, tite, very light gray-green with dolomite nodules. Near the top of the unit is 18 feet of water bearing sandstone, fine-grained, silty, quartz grains, pale yellow-brown, with limestone clasts. The unit coarsens upwards to grit with very coarse angular quartz grains and sandstone.



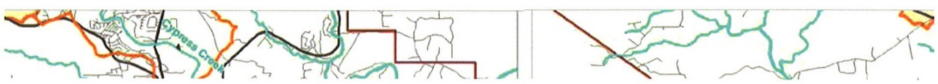


Figure 12. Cypress Creek/Jacob's Well Study Area showing watershed boundaries

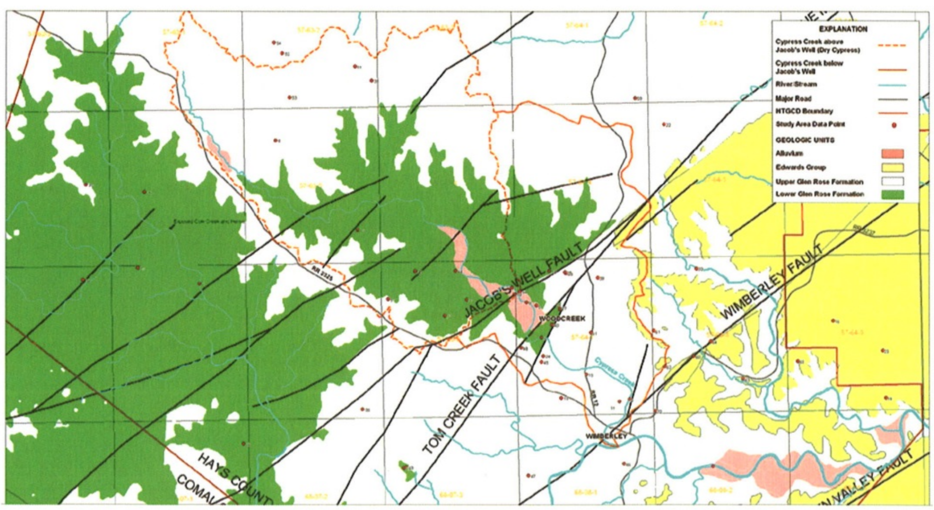


Figure 13. Cypress Creek/Jacob's Well Study Area Geologic Map (base map from Geologic Atlas of Texas, faults modified by HTGCD)

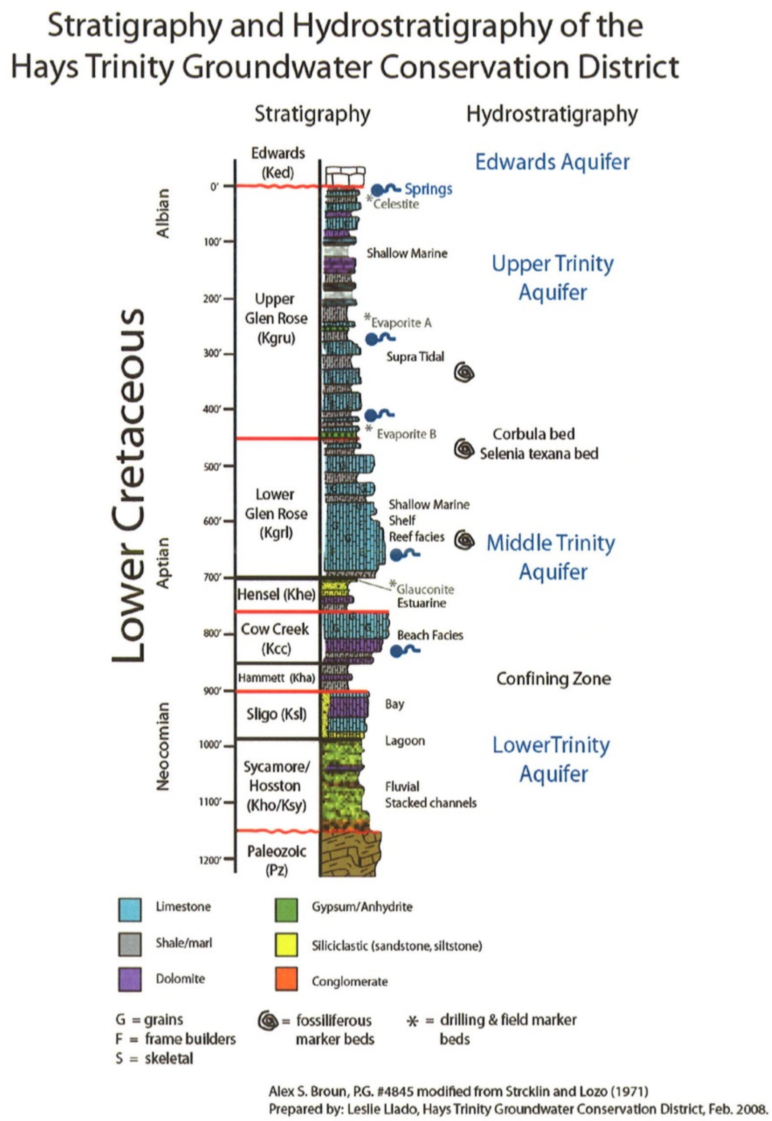
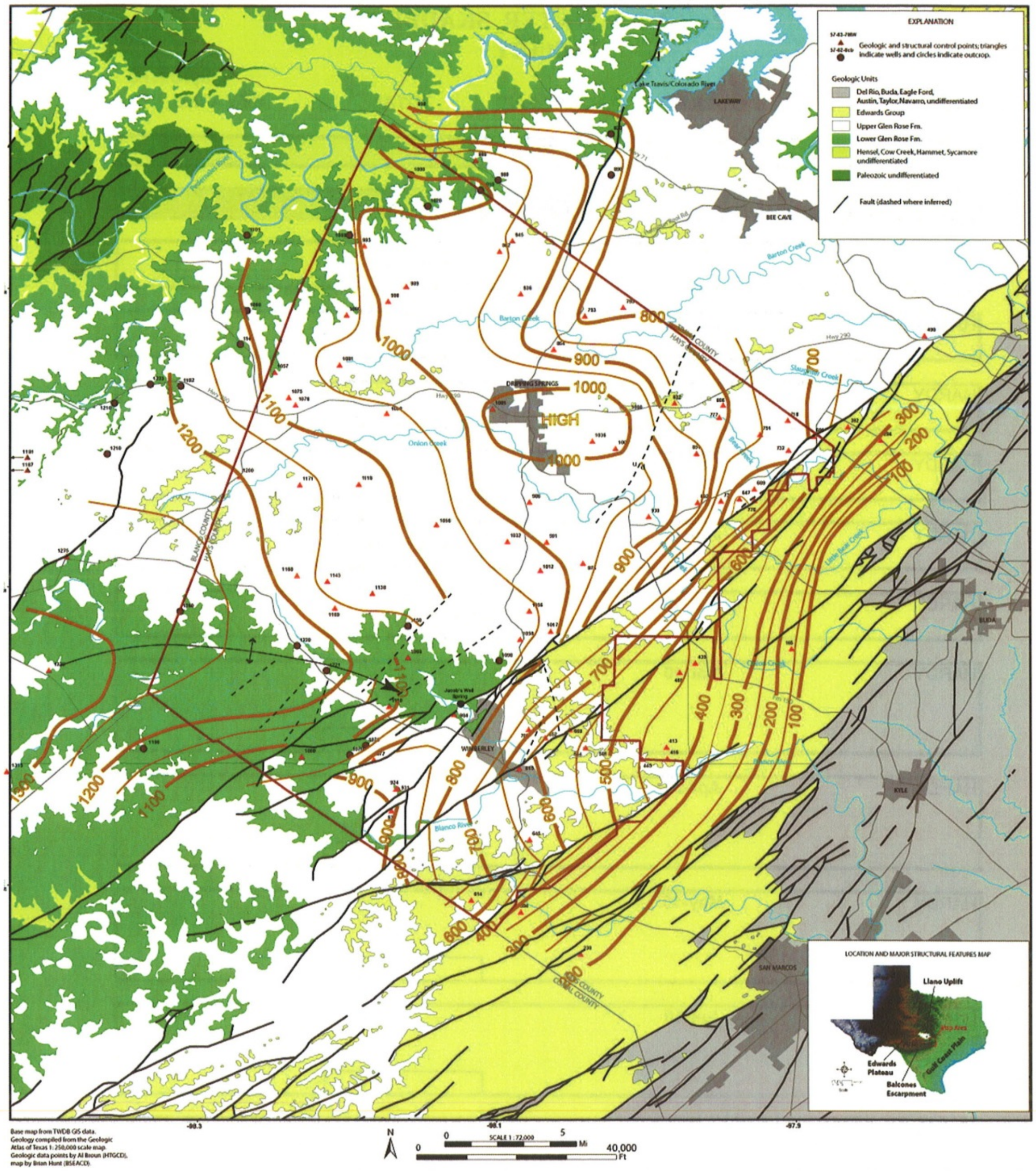
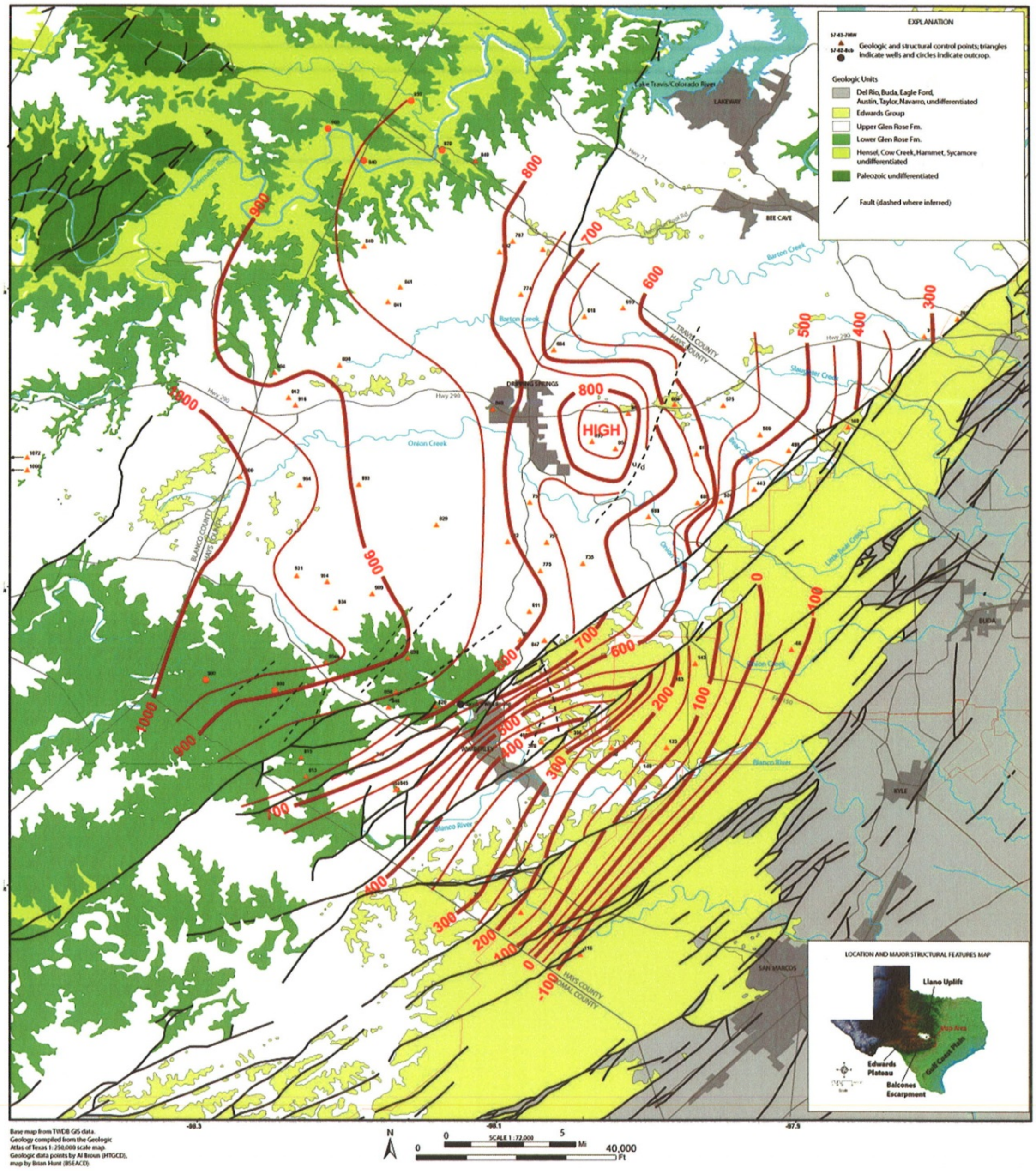


Figure 14. Stratigraphic Column



STRUCTURE CONTOUR OF THE TOP OF THE LOWER GLEN ROSE FORMATION
March 2007



STRUCTURE CONTOUR OF THE TOP OF THE COW CREEK LIMESTONE
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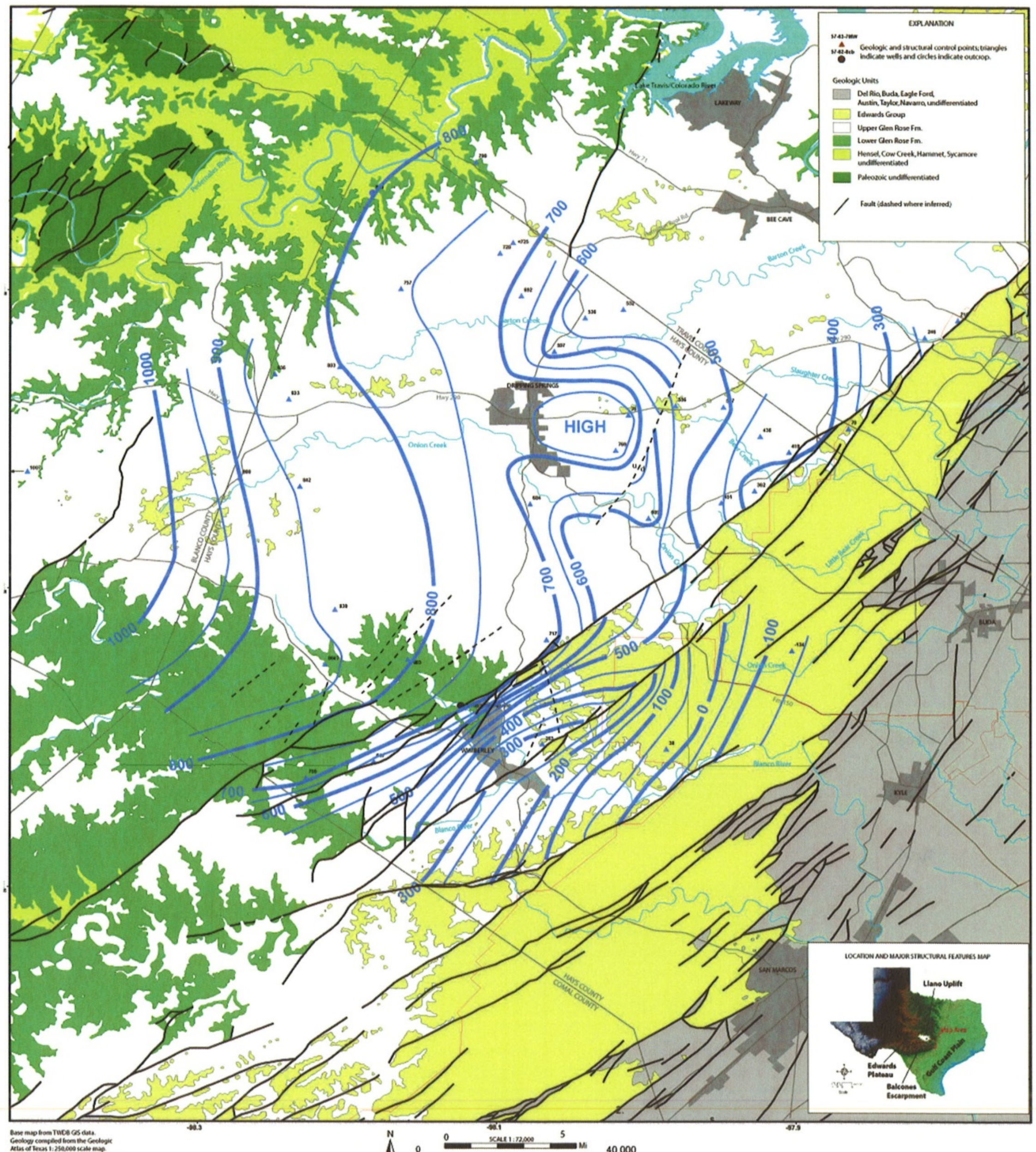
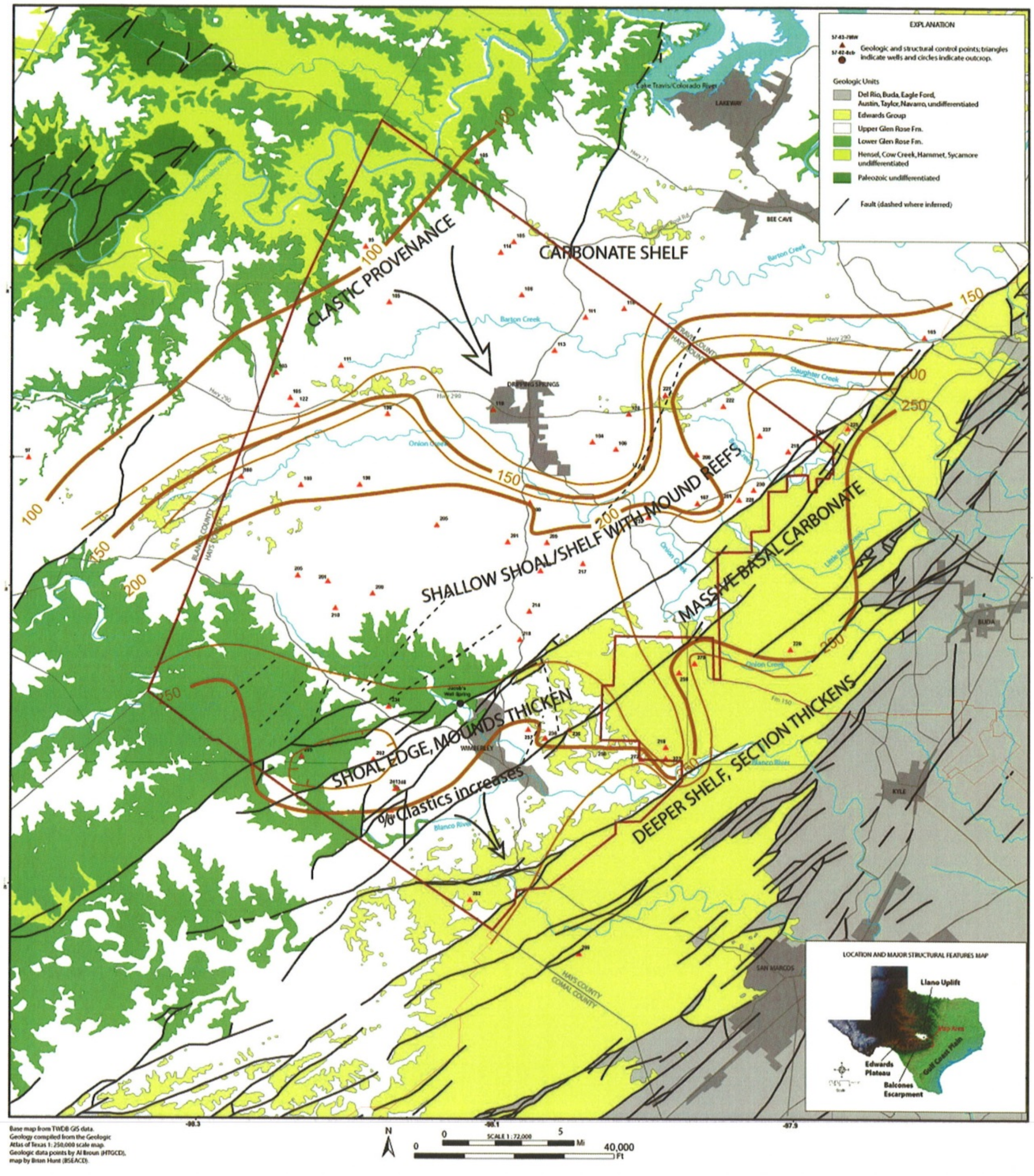


Base map from TWDB GIS data.
Geology compiled from the Geologic Atlas of Texas 1:250,000 scale map.
Geologic data points by Al Broun (HTGCD), map by Brian Hunt (BSEACD).

STRUCTURE CONTOUR MAP OF THE TOP OF THE HAMMETT SHALE
March 2007



ISOPACH OF THE LOWER GLEN ROSE FORMATION
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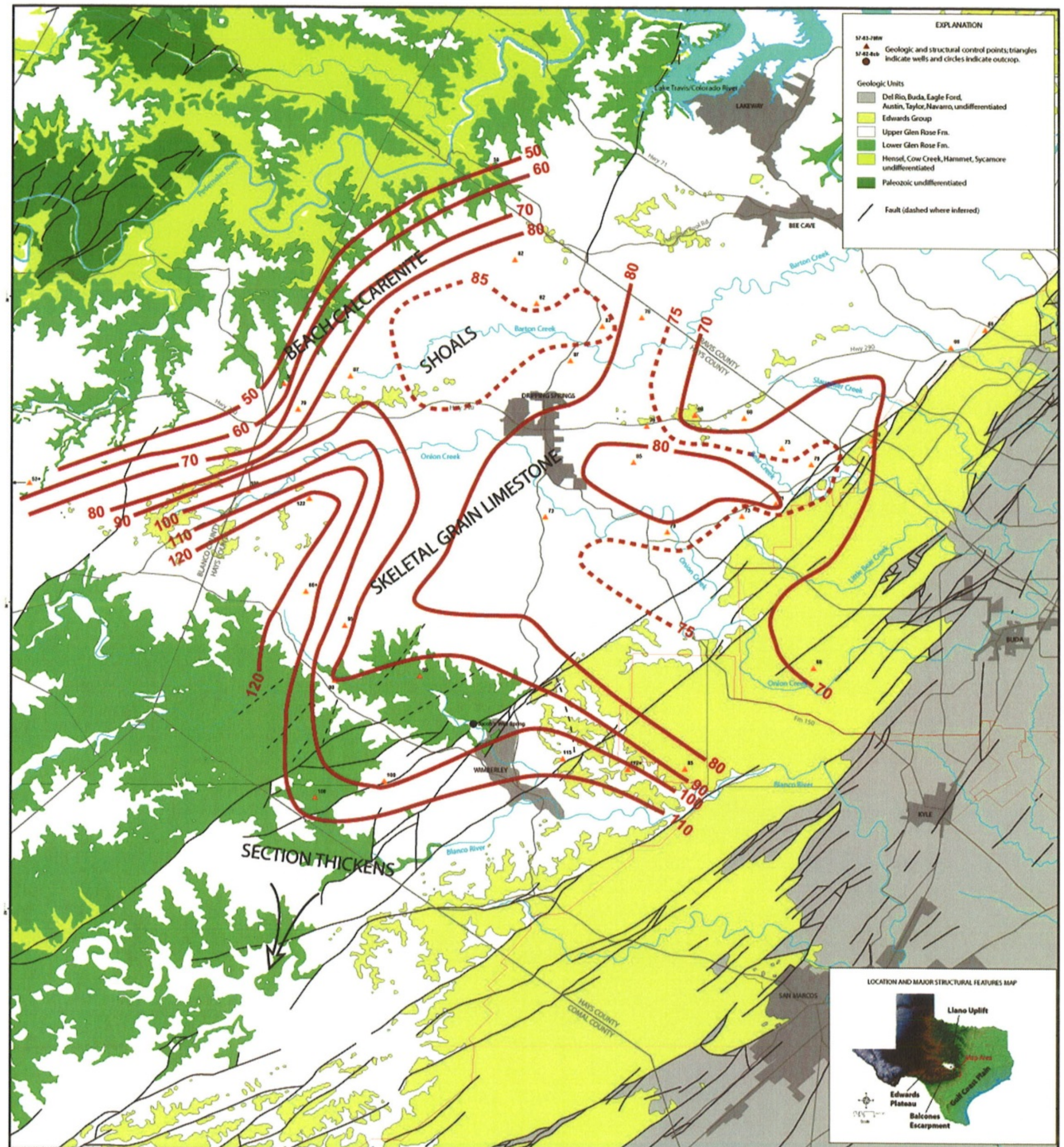
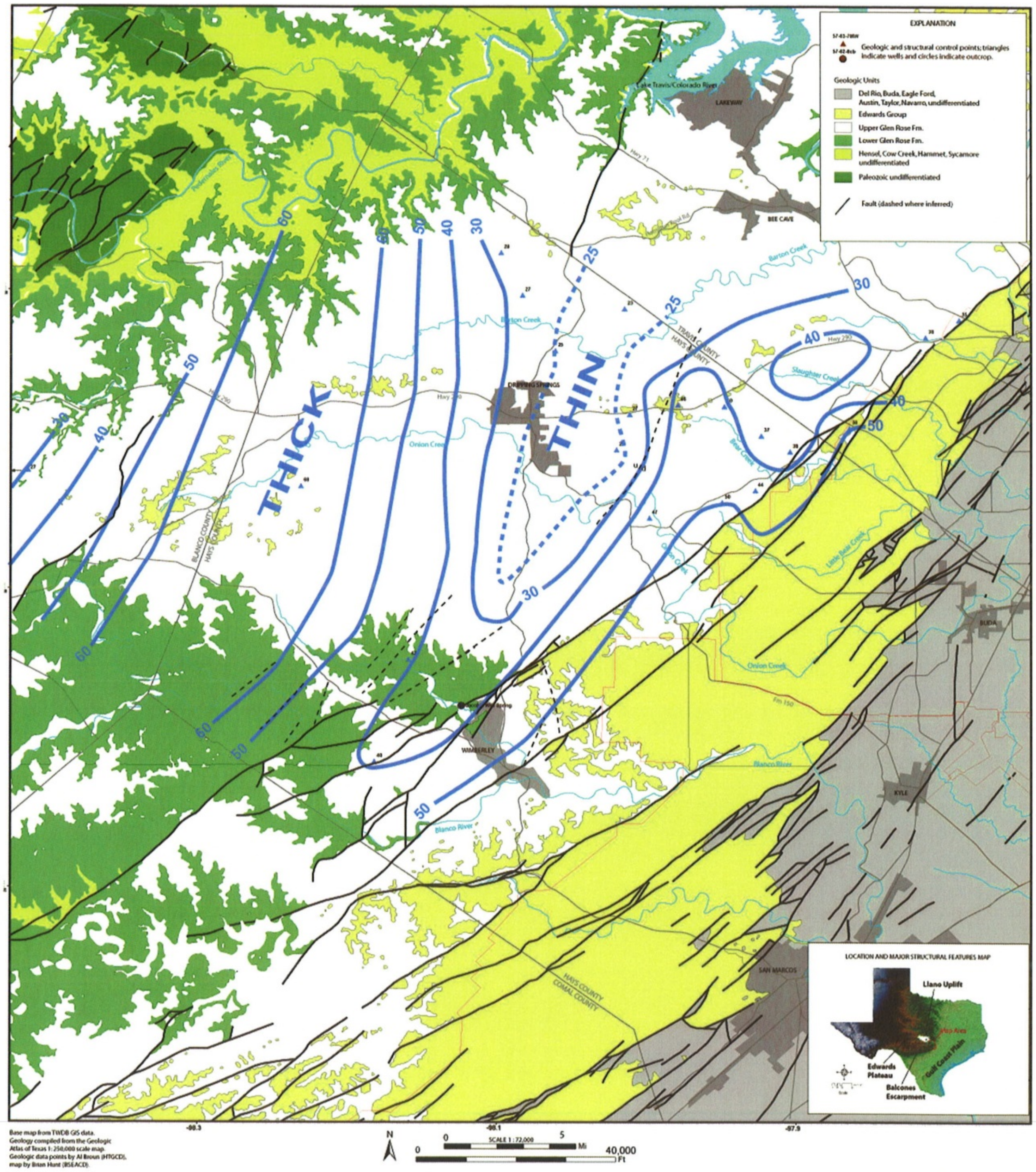


Base map from TWDB GIS data.
Geology compiled from the Geologic Atlas of Texas 1: 250,000 scale map.
Geologic data points by Al Broun (HTGCD), map by Brian Hunt (BSEACD).

ISOPACH OF THE COW CREEK LIMESTONE
March 2007



Base map from TWDB GIS data.
Geology compiled from the Geologic Atlas of Texas 1:250,000 scale map.
Geologic data points by Al Broun (HTGCD), map by Brian Hunt (BSEACD).

ISOPACH MAP OF THE HAMMETT SHALE
March 2007

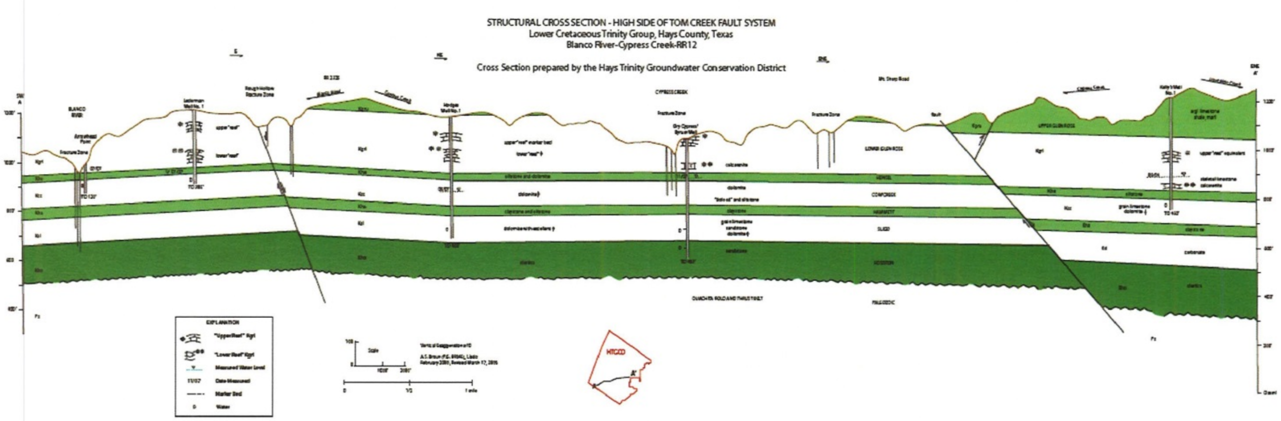


Figure 21. Structural Cross Section A-A'

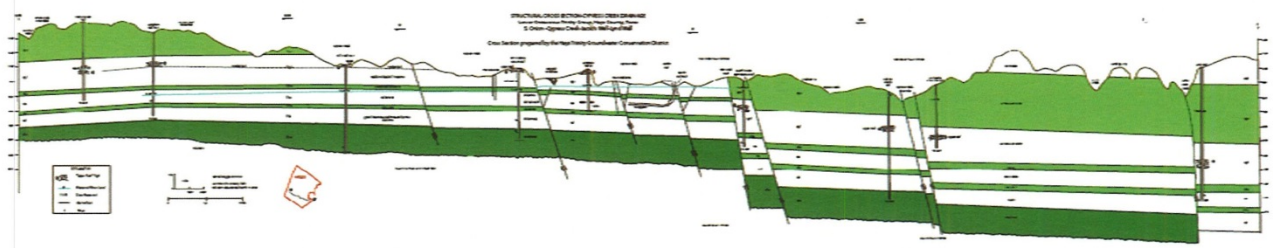


Figure 22. Structural Cross Section B-B'

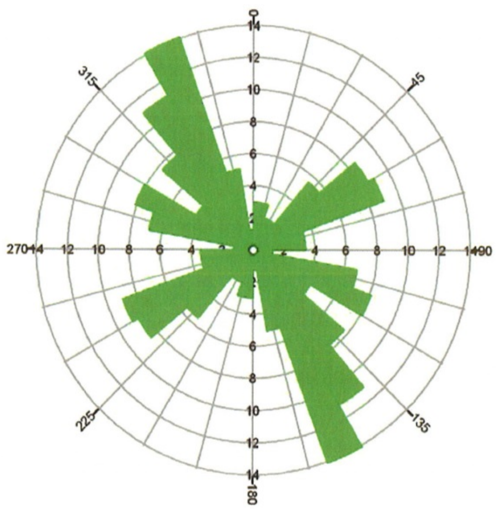


Figure 23. Structure Measurements—Rose Diagram

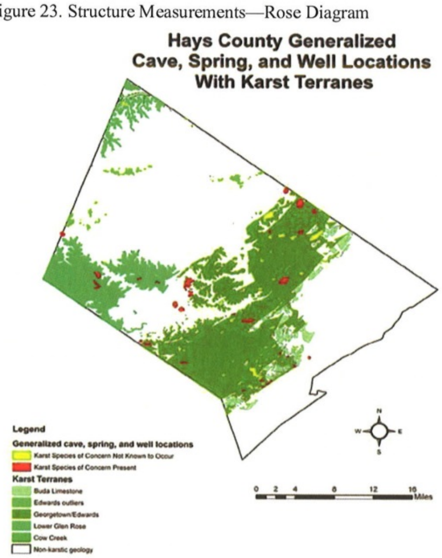


Figure 24. Cypress Creek/Jacob's Well Study Area Karst Features (from Hays County Habitat Conservation Plan)

Faults identified using the aerial photo analysis were ground truthed, then incorporated into a new study area fault map. Schumacher and Saller (2008) measured strike and dip on over 230 structural features in the area. Refernece Appendix 3. A rose diagram of the faults and fractures in the Cypress Creek watershed is included as Figure 22. The measured faults and fractures trend 45–60° (the major strike of the BFZ) or are conjugate features offset by 60°(105–120°).

A study was performed by to delineate critical karst regions within Hays County as part of the Hays County Habitat Conservation Plan (www.hayscountyhcp.com). Figure 24 shows all geologic outcrops that may contain caves and karst features and also delineates areas with known caves and karst features. A number of the mapped karst features occur within the Cypress Creek/Jacob's Well study area (Figure 23)

8.0 Occurrence and Flow of Groundwater

8.1 Precipitation

The amount of annual precipitation has varied greatly since the USGS gauging station was installed in Jacob's Well in April 2005. Since then, there have been two drought periods, April 2005–February 2007 and September 2007–June 2008. As measured by NOAA in Wimberley (Table 3), the average monthly rainfall during the two drought events was 2.1" and 1.4", respectively. The period March 2007 through August 2007 was significantly wetter, with average monthly rain fall exceeding 7.3". Over the entire period of record as measured in Austin, TX since 1856, average annual rainfall is 33.57", or an average of 2.8" per month.

8.2 Hydrostratigraphy of the Cypress Creek Area

Within the Cypress Creek area the principal aquifer that provides groundwater to the area's residents is the Trinity aquifer. The Trinity aquifer is composed of the Trinity Group geologic units described in Section 7 with the hydrostratigraphy shown in Figure 14. As it's name suggests, this aquifer is divided into three hydrostratigraphic units, the Upper, Middle, and Lower Trinity (Figure 13). The Trinity Aquifers behave as a more or less semi-confined or leaky aquifer system (Muller, 1990; Muller and McCoy, 1987). Each of these aquifers has a distinct hydrostatic pressure head (water level). The Lower Trinity Aquifer has the lowest hydrostatic head while the Middle and Upper Trinity aquifers have respectively higher heads. This arrangement of water-levels can be interpreted to mean that groundwater moves downward at a slow rate through the low-permeability strata (aquitards) to the aquifers below, while being able to move laterally at higher rates (Muller, 1990; Muller and McCoy, 1987).

The Upper Trinity Aquifer consists of the Upper Glen Rose formation. Where present, the aquifer can yield small amounts of water to wells. Ranch, wind mills, and historical hand dug wells were often completed in the Upper Trinity. The Upper Glen Rose contains relatively shallow, locally perched water in many areas of the county. The Upper Glen Rose gives rise to the “dripping springs” (despite what the granite marker at the springs says) after which the City of Dripping Springs is named. These aquifers are limited in aerial extent. The Upper Glen Rose produces water to the southeast in the Balcones Fault Zone.

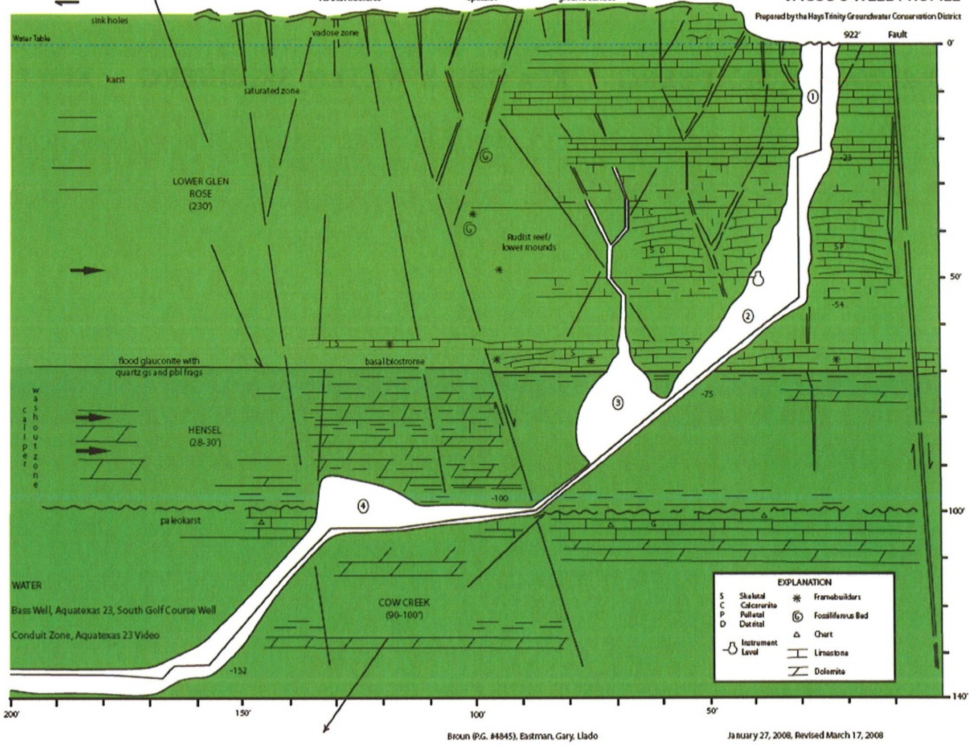
Recharge to the Upper Trinity Aquifer is from direct precipitation in areas where the aquifer is exposed at the surface (Figure 13). Within the study area, the Upper Glen Rose contains layers of competent clay and marl that inhibit surficial recharge and restricts the downward migration to the Middle and Lower Trinity Aquifers.

The Middle Trinity Aquifer, consisting of the Lower Glen Rose, Hensel, and Cow Creek formations, directly underlies the Upper Trinity Aquifer. The Middle Trinity Aquifer is the primary aquifer in the study area for residential and public water supply wells. In most areas, the calcarenite and dolomitic facies of the Hensel Formation act as a semi-confining layer over the Cow Creek formation (Figure 25. Jacob’s Well Cross Section). Where exposed on the surface, particularly in the Woodcreek area along Dry Cypress Creek, the Lower Glen Rose has faults, fractures and karst features which allow for rapid and significant recharge of precipitation runoff. The many direct pathways to the subsurface enhance local recharge and limit the amount of runoff into dry Cypress Creek.

The Hammett Shale is a confining layer, separating the Middle Trinity aquifer from the Lower Trinity aquifer. The Lower Trinity aquifer consists of the Sligo and Hosston formations.

The geologic units that make up the Lower Trinity aquifer do not occur at the surface in the study area. Water in the Lower Trinity is under artesian pressure meaning that water-levels in the Lower Trinity rise above the upper contact with the confining Hammett Shale in wells. Under predevelopment water level conditions the groundwater gradient is downward from the Middle Trinity to the Lower Trinity. However, in areas where heavy pumping occurs in the Middle Trinity, and the head is reduced below that of the Lower Trinity, the hydraulic gradient could be reversed so leakage would move upward from the Lower to the Middle Trinity. This means it is particularly important for wells that penetrate through the Middle to the Lower Trinity must be properly completed to minimize the man-induced leakage between aquifers.

With increased use of the groundwater due to population growth in the area and inadequate well spacing control, the Middle Trinity aquifer is becoming stressed and unable to meet the demands of the development. Drillers are completing an increasing number of wells in the Lower Trinity aquifer. Because the Lower Trinity is a confined aquifer that appears to recharge very slowly, and because its hydraulic relationship to Middle Trinity is dynamic and not well understood, the HTGCD is initiating a study of water levels and usage in the Lower Trinity aquifer to gain a better understanding of this important resource. Specific areas of study include lower Trinity recharge rates, potentiomtric head relation between the middle and Lower Trinity Aquifers, influence of the



Balcones Fault Zone and inadequate well construction methods.

Figure 25. Jacob's Well Structural Cross Section

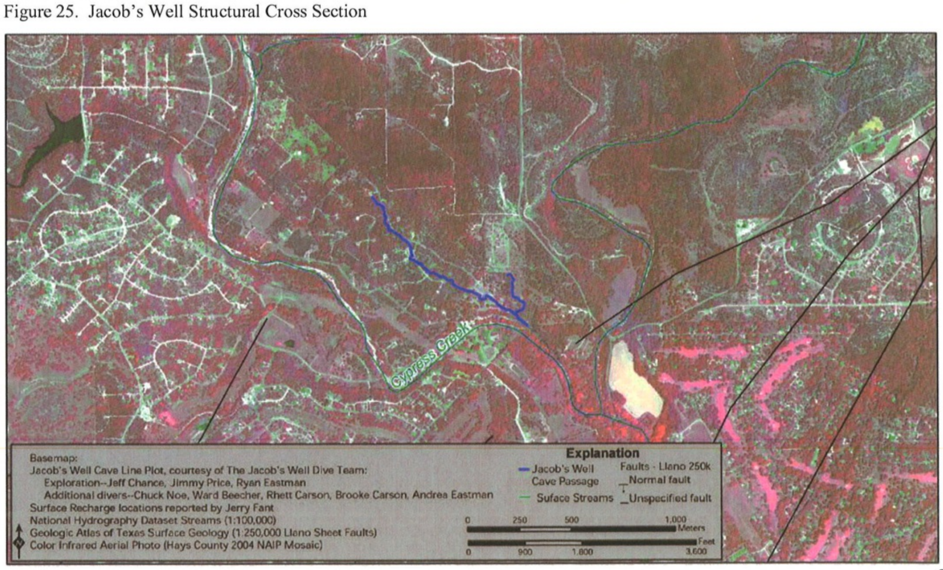


Figure 26. Alignment of Jacob's Well (from Gary, 2007)

On a regional basis, there is very little recharge from precipitation on a surface outcrop because very little of this aquifer crops out anywhere (Ashworth et al, 2001). The primary means of recharge to the Lower Trinity is by leakage from overlying and underlying aquifers (Ashworth et al, 2001). Ashworth (1983) notes that the primary source of Lower Trinity recharge is from leakage in updip areas north and west of the District where the Hammett Shale is thin or absent. Where the Hammett is present and faulted some recharge/leakage across the Hammett shale probably occurs (Ashworth, 1983). Tritium studies of well water from the Lower Trinity across the Hill Country indicate that there is not 'recent water' ('recent water' has not been exposed to the atmosphere since 1952) in the Lower Trinity (Ashworth et al, 2001; USGS, 1997). Surficial 'recharge to' or 'discharge from' the aquifer may occur in the northern tip of Hays County where the Pedernales River has incised to a point where it runs across the Lower Trinity. Other than this stretch of the Pedernales River, the Lower Trinity is not exposed at the surface within the District.

Within the study area the roll of faulting related to discharge from the Lower Trinity is not clearly understood. In some cases faults probably act as barriers and in other areas they act as preferential flow pathways. Ongoing research work conducted by the University of Texas may shed some light on the contribution of Lower Trinity waters to flows at Jacob's Well.

With increased use of the groundwater due to population growth in the area and inadequate well spacing control, the Middle Trinity aquifer is becoming stressed and unable to meet the demands of the development. As a result, drillers are completing an increasing number of wells in the Lower Trinity aquifer. As a result, the HTGCD is initiating a study of water levels and usage in the Lower Trinity aquifer to gain a better understanding of this important resource. Future research topics include:

- Inventory of Lower Trinity wells and construction methods;
- Evaluation of water-level changes over time;
- Water quality and changes over time;
- Age dating the Lower Trinity water to better understand rates of recharge;
- The dynamic vertical and lateral hydraulic relationship to other aquifers;
- Hydraulic significance of faults and the Balcones Fault Zone; and
- Integrity of the Hammet Shale as an aquitard.

9.0 Hydrostratigraphy of Jacob's Well

The northwest – southeast profile of Jacob's Well depicts the subsurface stratigraphy and karstic nature of the well as extrapolated from interpreted geophysical logs in nearby well locations (Figure 24). Particularly useful were the Aqua Texas Well No. 23 and South Golf Course wells (see cross section B-B') and observations and videos from cave divers (Figure 26).

At Jacob's Well, the Lower Glen Rose formation is identified in the subsurface and in surface outcrop by an upper and a lower rudistid reef/mound buildup (Figure 27). Reef-core and skeletal–detrital reef margin facies provide porous and permeable zones for local, shallow aquifers. The upper reef is an excellent aquifer in the Wimberley Valley fault block. The Hensel formation, (mudstone, dolomite and siltstone) acts as a confining unit to the Cow Creek and as a soluble conduit for groundwater transmission. Cow Creek grain limestone and porous, vuggy dolomite are the primary aquifer lithologies for the Middle Trinity in the upper Cypress Creek area. A large, open conduit (~ 8" – 12" diameter) can be observed in the Aqua Texas Well No. 23 videotape within the Cow Creek. This interval corresponds to the main cavern passageway elevation in Jacob's Well.

Figure 27. Lower Glen Rose Rudistid Sample

Both the underlying Sligo and Hosston (Lower Trinity) contain aquifers along the line of cross section. These aquifers are porous, vuggy dolomite and the middle Sligo produces water at the Dry Cypress/Byrum Well. Interpreted channel sands contain water at several locations in the Hosston. Cross section A-A' intersects section B-B' at the Dry Cypress/Byrum Well.

The opening of Jacob's Well in the bed of Cypress Creek occurs in the Lower Glen Rose unit of the Middle Trinity Aquifer. The nearly vertical shaft of Jacob's Well probably follows a former fracture or joint set that has been enlarged by solution. Approximately 70 feet below the mouth of the spring is the contact between the Lower Glen Rose and Hensel Member. There are two large caverns at the contact. At 100 feet is the contact between the Hensel and Cow Creek. The passageway ("A" tunnel) becomes roughly parallel to the horizontal bedding and continues several thousand feet in a paleokarst zone of the Cow Creek. Several smaller tunnels branch off the main shaft. The "B" and "C" tunnels intersect the "A" tunnel 350 feet and 3,600 feet, respectively from the mouth of the well. The "A" tunnel is roughly parallel to the conjugate facture orientation. At the current time the divers have mapped in excess of 5,000 feet of passages linked to Jacob's Well. Several passages terminate in constrictions that divers cannot proceed beyond; others are still in the process of being fully explored.

9.1 Groundwater Flow

9.1.1 Recharge and Discharge

Water enters the aquifer through the direct infiltration of precipitation at the ground surface and flow loss from the base of streams and rivers. The amount of recharge from precipitation is primarily dependant on the rainfall intensity, duration, permeability and slope of the surficial geology. In areas of exposed bedrock, that has extensive surface fracturing and faulting, recharge is significantly greater than in those areas where competent, unfractured bedrock is exposed.

Discharge of groundwater from an aquifer occurs in several ways. Groundwater discharges into streams and provides base flow to the streams. Most of the base flow of streams and rivers in the Hill County is due to groundwater

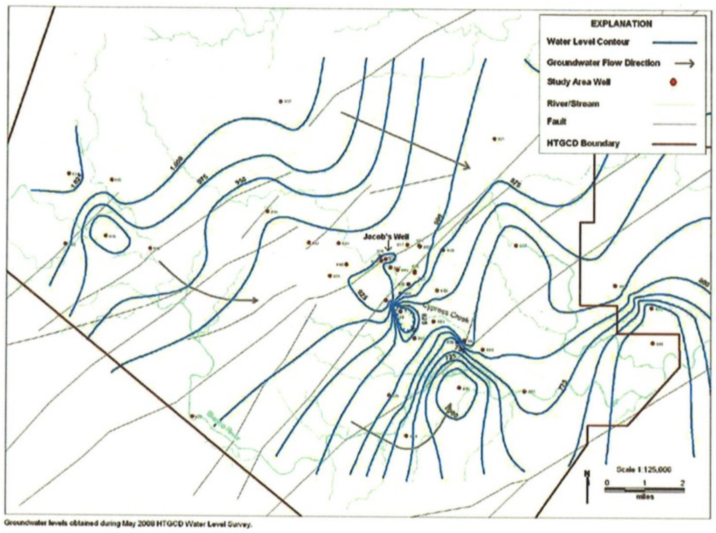


Figure 28. May 2008 Potentiometric Surface Map

discharge. Another type of natural discharge is groundwater loss to evapotranspiration near the ground surface. Artificial discharge occurs through the pumping of groundwater from wells.

The movement of groundwater primarily occurs in secondary permeability features such as fractures, faults, karst features and along bedding planes in the carbonate rocks of the Trinity Group. Groundwater storage and flow does occur in the matrix of the carbonate rocks but it is very slow. Under unconfined groundwater conditions, the drainage of matrix water into the secondary features probably provides most of the base flow of surface water features during low precipitation periods. In areas of confined groundwater in fractured and karst aquifers, recharge typically occur in areas of up dip outcrop and/or downward leakage through the semi-confining strata.

9.1.2 Groundwater Flow Directions

The general direction of groundwater flow in the Middle Trinity Aquifer in the study area is in a south-easterly direction parallel to the regional fracture pattern and perpendicular to the regional fault system (Figure 28, Table 5). Most of the wells used to develop the potentiometric map are in the Cow Creek. The Cow Creek aquifer is under confined conditions in the Cypress Creek watershed. The Hensel, when it contains a basal shaley –claystone section, is the confining unit for the underlying Cow Creek. Calcrete or caliche deposits may also play a role in the sealing nature of this aquitard. Hopkins 1982 analyses the sedimentation and pedogenesis of the Hensel Formation in central Texas.

Flow in the Lower Glen Rose aquifer is likely under unconfined conditions, with flow occurring on top of the Hensel, though a sufficient number of wells were not identified to construct a potentiometric surface map of the Lower Glen Rose. The May 2008 (Fig. 28) potentiometric map is indicative of groundwater levels during an extended drought period and therefore represents base flow conditions. The Cow Creek aquifer is under confined conditions in the Cypress Creek watershed. The potentiometric surface flattens out in the lower reaches of the Dry Cypress Creek watershed above Jacob's Well. Jacob's Well is a constant head discharge point which maintains the water levels in the vicinity of the well. The tightening of the potentiometric contours across the major fault zone downgradient from Jacob's Well indicates the faults are partially restricting flow. The depressions shown on the potentiometric surface map south of Jacobs' Well on the downthrown fault block to the southeast are due to pumping of several public water supply wells. Insufficient data were gathered from Lower Trinity wells during this study to determine the direction of groundwater flow for this aquifer. As of October 2008 the HTGCD is initiating data collection efforts on the Lower Trinity Aquifer throughout the

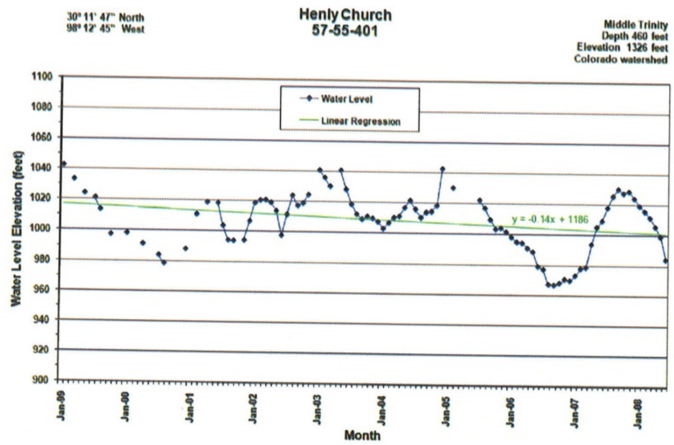


Figure 29. Henly Church Well (Middle Trinity)

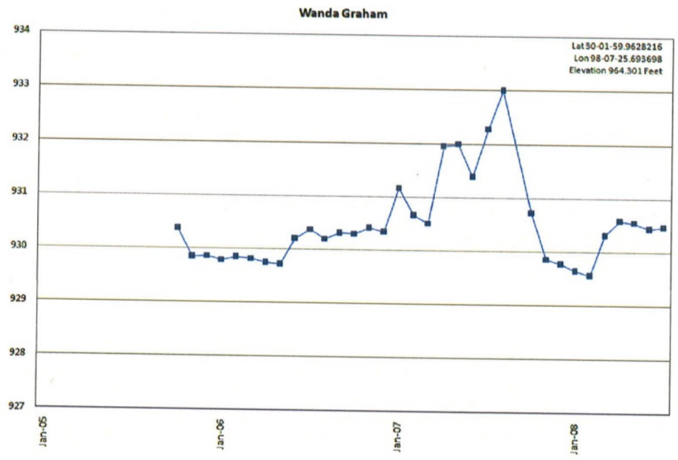


Figure 30. Graham Well (Middle Trinity)

entire District as part of a newly initiated research effort.

Groundwater level data from wells monitored by the HTGCD has helped to classify aquifer characteristics in different parts of the district (Figures 29-31). In the northern part of the district, near Dripping Springs, water levels from wells completed in the Middle Trinity are highly variable, depending on precipitation and pumping. Wells completed in the Middle Trinity in northern Hays County fluctuated as much as 75 feet in the drought of 2005-2006 (Figure 29 Henley Church). Water levels rose by the same amount during the wet period of 2007. Wells located closer to Jacob's Well showed a relatively slight variation in water level.

The Graham Well (Figure 30), located on the northeast side of Cypress Creek downstream from Jacob's Well, showed a four foot variation in water levels between January 2006 and present. Other wells located near Jacob's Well on the up thrown fault block exhibited similar trends in water levels.

This comparative dampening of water level fluctuations suggests that the highly fractured and karstic nature of the aquifer in the Cypress Creek watershed maintains a quasi equilibrium between regional aquifer flows and discharge from Jacob's Well even during drier periods. This area of Trinity aquifer may be referred to as the Cypress Creek Trinity aquifer pool because its behavior is distinct from other potions of the aquifer. Jacob's Well is acting as the spill point for the Cypress Creek pool and creates relatively steady water levels within the study area by variable rates of discharge from the spring directly related to net inflows to the pool. During wetter periods, discharges at the springs increase, preventing water levels from rising in the pool, and during drier periods, flows decline until water levels drop below the elevation of the mouth of the spring when spring flows will stop.

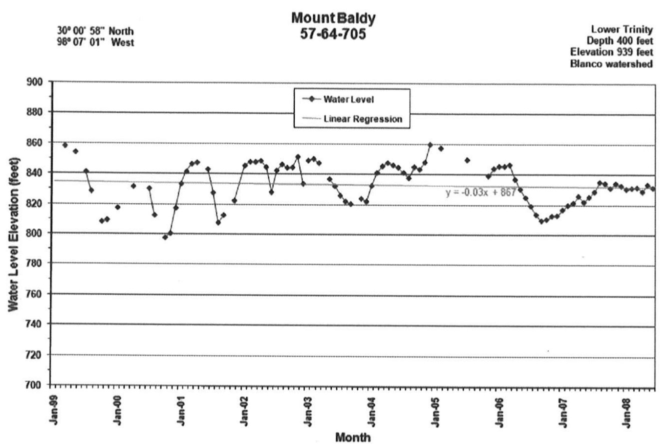


Figure 31. Mount Baldy (Middle Trinity)

foot decline during the 2006 drought). Linear regression trend lines developed from water levels from the Henley Church and Mt Baldy wells indicate a long term water level decline over the last ten years.

During periods when spring flows are declining, water levels in the Cypress Creek pool will not begin to decline like other parts of the aquifer until some time after spring flow stops completely.

Water levels on the downthrown fault block to the southeast of Jacob's Well as measured at the Mt Baldy Well (Figure 31), trended similarly to those wells in northern Hays County, but the declines were somewhat less (50 foot versus 75

9.1.3 Recharge to the Cow Creek Limestone/Jacob's Well

Recharge to the Cow Creek Limestone may occur in several ways. Direct recharge from precipitation occurs in up dip areas where the Cow Creek is exposed at the surface in Blanco County. Vertical leakage down through the up dip Upper and lower glen Rose and Hensel also contribute to recharging the Cow Creek. Within the study area, the Cow Creek is exposed beneath and along the banks of the Blanco River near Valley View Road. The area of outcrop is shown on Figure 13. Flow in the Blanco River may also provide recharge to the Cow Creek in this area.

The major source of recharge to the Cow Creek occurs west of the Cypress Creek watershed from the downward leakage of water from the Upper

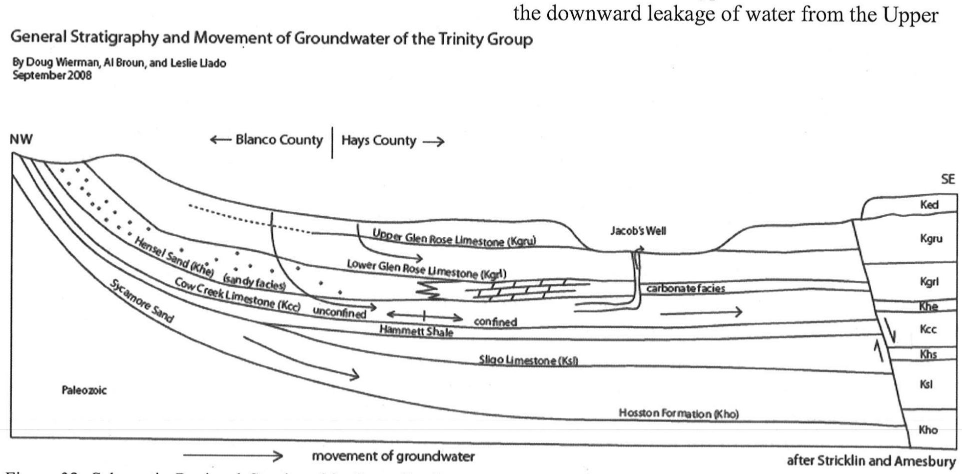


Figure 32. Schematic Regional Stratigraphic Cross Section Trinity Group Trinity Group

and Lower Glen Rose and Hensel where these formations are exposed at the surface and exposed to precipitation (Figure 32). Water moves downward into the Cow Creek and down dip towards the Balcones Fault Zone. As the overlying Hensel changes facies from a sand to a calcareinite/dolomite facies it tends to act as a confining layer creating artesian conditions in the Cow Creek. Groundwater under artesian conditions in the Cow Creek provides the majority, if not all of the base flow at Jacob's Well.

Recharge rates between 1.5% and 11% of total precipitation have been estimated for the Trinity aquifers in the Hill County (Mace, 2000). The TWDB's Groundwater Availability Models assume an estimated recharge rate of approximately 4.7% of annual precipitation for this area (Jones, 2004). Assuming average annual precipitation of 33.5" per year, the annual rate of recharge is 1.34" per year at 4.7% recharge. Using the range of estimated recharge values (1.5%-11%), recharge could be between 0.5" and 3.7" per year.

Recharge from storm events may enter the subsurface and provide direct recharge to the Well through surficial karst features in the area. Dye tracing studies during storm events would be necessary to confirm this recharge pathway.

9.2 Jacob's Well Discharge

9.2.1 Base Flow

Data analysis has shown distinct differences in the flow of Jacob's Well during base flow and storm conditions. Base flow from the well originates from the artesian conditions in the Cow Creek member of the Middle Trinity Aquifer. Base flow, calculated from average daily discharge values at the Jacob's Well station for the two droughts periods on record were 3.4 cubic feet per second (cfs) and 5.9 cfs for the periods April 2005-February 2007 and September 2007 through June 2008, respectively. The average mean daily discharge rate for the wet period March 2007-August 2008 was 23.9 cfs. The average discharge rate for the period of record was 7.25 cfs. These base flow values of base flow are consistent with historical flow measurements reported by Brune (1981), as shown below:

Date	Flow in cfs
8/5/24	6
10/28/37	6
12/6/37	2.9
1/6/56	2.4
4/4/62	4.2
7/10/74	3.5

The annual volume of recharge into the Trinity Aquifer within the Cypress Creek watershed is not sufficient to provide for all of the base flow from Jacob's Well. The average base flow from Jacob's Well for the period of record is 7.25 cfs or a total of 16,710 acre-feet/year.

Using the NOAA precipitation data from Wimberley for the period of record, there was 104.6 inches of precipitation. Assuming a recharge rate of 4.7%, there was 4.9 inches of recharge which results in 4,263 acre-feet of recharge in the Dry Cypress watershed. The total discharge from Jacob's Well during the period of record was 16,710 acre-feet, or roughly 4 times the calculated recharge volume. Aquifer base flow discharge from the entire watershed area is considerably greater when discharge to production wells and downgradient flow through the fault zone is considered.

The difference indicates that recharge rates are either considerably higher than estimated or the recharge to aquifer occurs over an area much larger than just the Cypress Creek watershed. In fact, a large up dip regional recharge area extends into Blanco County and receives precipitation that directly recharges the Glen Rose, Hensel and Cow Creek Formations.

9.2.2 Storm Flow

Jacob's Well responds very quickly to rain events. As shown on the Jacob's Well hydrograph (Figure 32), the well often responds to storm events in less than an hour or two, and peak discharge can occur within a few hours. During the wet period of 2007, discharges of over

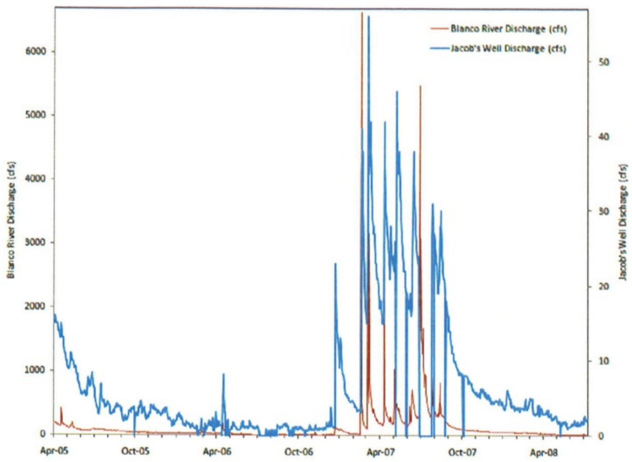


Figure 33. Jacob's Well/Blanco River Hydrographs

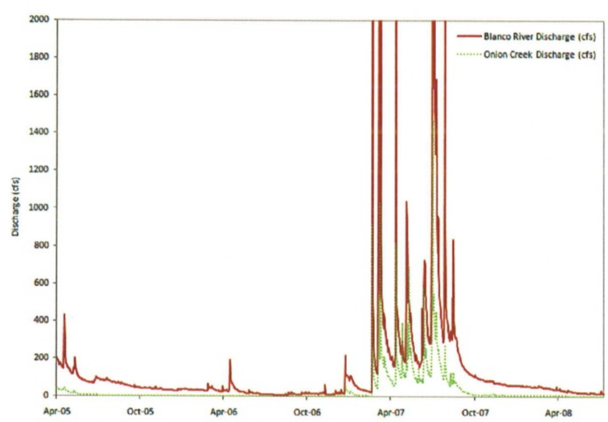


Figure 34. Onion Creek/Blanco River Hydrograph

40 to 50 cfs were common during storm events. The rapid response of discharge from a major precipitation event is probably due to one of two reasons. If the source of storm discharge is from increasing head and unconfined flow in the

Lower Glen Rose, then direct surface recharge near the well via surficial karst features is the likely source. If increased discharge from precipitation originates from confined groundwater flow in the Cow Creek, then a more distant source of increased head is probably the cause.

As discussed earlier in the report, a number of surficial karst features (sinkholes and caves) in the study area have been identified. These surficial features may be points of recharge for storm flows from large precipitation events at Jacob's Well. A study of rainfall occurrence recorded by Next Generation Radar (NEXRAD) and the relationship to recharge at Jacob's Well and Barton Springs was performed by a graduate student at UT-Austin (Budge, 2008). A copy of the study is included in Appendix 3. The results of the recharge study of NEXRAD data at the north and west of the well. See Figures 13 and 14 in Appendix 3. The study provides information that can be used in designing future dye studies in these areas to evaluate if the local surficial karst features are contributing to the storm surges in Jacob's Well.

Comparison of discharge records from the Blanco River at Wimberley and Jacob's Well shows that discharge between the two coincides the majority of the time. In general, if discharge of the Blanco River increases, discharge at Jacob's Well also increases. However, in April 2006 and January 2006, discharge at Jacob's Well peaked while discharge on the Blanco remained constant (Figure 33). Onion Creek, north of Jacob's Well near Dripping Springs, shows a discharge record in response to rainfall nearly identical to that of the Blanco River (Figure 34), suggesting that these discharge trends are perhaps related more to similar rainfall than connections between the Blanco River and Jacob's Well.

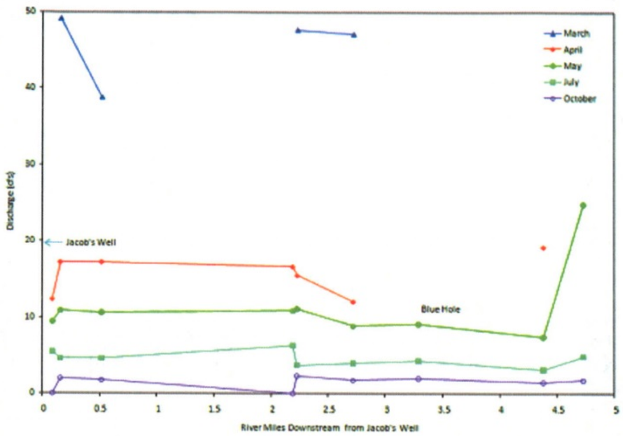


Figure 37. Cypress Creek Stream Gaging

replicate the absolute differences in temperatures consistently, but are consistent on a relative basis. The discharge from Jacob's Well has been considerably less than the 19 cfs flow rate during the April 21, 2007 dive. Absolute and relative temperature variations are likely more pronounced during high flow periods. Higher

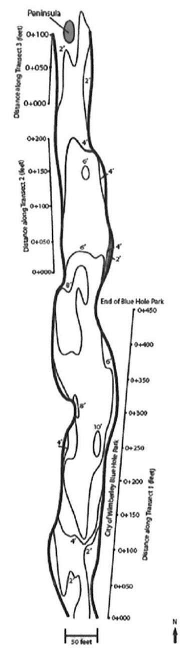
quality transducers are needed to determine consistent absolute temperature values.

9.2.4 Groundwater Pumping in the Vicinity of Jacob's Well

Groundwater discharge from the Middle Trinity Aquifer also occurs from the pumping of groundwater from wells. There are both low volume residential wells and high volume public water supply wells in the watershed. Through aerial mapping, the HTGCD estimates that there are approximately 520 residential wells are located upgradient of the major fault block in the vicinity of Jacob's Well. There are four public water supply companies in this area drawing water from the Middle Trinity/Cow Creek. Using public water supply pumping records and residential use estimates made by the HTGCD, the average discharge (pumping) from wells over the period of record at Jacob's Well is approximately 1 cfs, or 722 acre-feet/year. As stated earlier, the average base flow from Jacob's Well is approximately 7.25 cfs. During periods of low flow from Jacob's Well (1-2 cfs) during drought periods, the pumpage of wells may equal the discharge at Jacob's Well. Reductions in pumpage during drought conditions will increase the discharge of Jacob's Well and increase the flow in Cypress Creek.

A pump test (Wet Rock, 2008) performed at a proposed public water supply well near Jacob's Well in December, 2007 indicated that the pumpage of high capacity wells in the vicinity of Jacob's Well cause the observed cyclical variations in base flow discharge. A daily cycle of base flow increases and decreases occurs at Jacob's Well. There are typically three cycles per day with a magnitude of approximately 1 cfs. The new well (Well 23) is located approximately 580 feet from Jacob's Well and was pumped foraproximately 2 days. During the pump test, transducers were placed in two other nearby public water supply wells, Well 21 & Well 22, to observe changes in water level. Well 23 was pumped at 325 gpm for approximately 2 days. Wells 21 and 22 continued their normal pumping cycles during the pump test. When water levels for Wells 21, 22, and 23 are overlain with Jacob's Well discharge for the same period of time, Well 21 shows a direct correlation between pumping cycles and cycles of Jacob's Well discharge. (Figure 36) Discharge from Jacob's well is reduced by approximately 1 cfs during each pumping cycle from Well 21. Pumping cycles occur approximately three times daily. The drawn down from pumping at Well 23 caused a general lowering of discharge at Jacob's Well. As previously mentioned, a karst feature was observed in a downhole video of Well 23 at the same elevation of the main tunnel in Jacob's Well. The pump test indicates that Wells 21 and 23 are in direct communication with Jacob's Well and discharges from the water supply wells cause a reduction flow at Jacob's Well and Cypress Creek.

Depth Contour Map of Blue Hole on Cypress Creek in Wimberley, Texas



Map shows 2-foot depth contours down to a maximum depth of 10.8' below water level at elevation 843'.
Transect 1 spans the length of the City of Wimberley's Blue Hole Park, while transects 2 and 3 are along private property from the end of Blue Hole Park to Cypress Creek.
Depth survey of Blue Hole performed in August 2008 by the HTGCD.

Figure 37. Blue Hole Depth Contour

9.3 Flow Gain/Loss in Cypress Creek

A stream gauging project was conducted in 2005 by a Texas State University Student (Dedden 2006) A monthly stream gauging program was conducted during baseflow conditions between March and October 2005. Surface runoff into Cypress Creek during storm events was not measured during this study.

The data indicate that Cypress Creek had very little net loss or gain in flow between Jacob's Well and Cypress Creek at RR12 in Wimberley (Figure 37). Immediately downstream of Jacob's Well, Cypress Creek flows over several major faults. The Upper Glen Rose is considerably more competent and resistant to stream losses through the bed of the stream. Since Cypress Creek above Jacob's Well is typically dry, the majority of base flow to Cypress Creek originates from Jacob's Well discharge and the flow of Cypress Creek is directly dependent on maintaining flow at Jacob's Well.

9.4 Flow Gain/Loss in the Blanco River in area of Cow Creek/Hensel Outcrop

A summary of gain/loss studies for the study area was compiled by Slade (2007), Appendix 4, including the area of exposed Cow Creek and Hensel along reach of the Blanco River near Valley View Road (Figure 12). Data from the USGS 1955 and 1963 studies indicated a net gain to the Blanco River of 7.50 and 16.82 cfs, respectively. These results indicate there is a net loss of groundwater throughout this reach of the stream and there was not significant recharge to the aquifer in this area. Gain/loss studies are typically performed in low or base flow conditions (Slade, 2007).

These data may not be representative of current conditions. A net decline in water levels over time has occurred in the Trinity Aquifer over the last ten years as noted on the linear regression trend lines for the Henley Church and Mt Baldy wells. (Figures 29 & 31). A regional decline in groundwater levels would tend to promote more stream loss into the aquifer. Additional gain/loss studies at varying flow conditions are needed to confirm current conditions. Additional geologic mapping, structure delineation and groundwater level data is needed to fully evaluate the significance of the previous gain/loss studies in this stream reach.

Elevated stream levels during rainfall events may cause additional recharge to the aquifer from stream flow in this area. There is the possibility that increased flow in the Blanco River during a storm event may be the source of storm surge flow in Jacob's Well. A possible pathway for groundwater flow from the area of exposed Cow Creek at the Blanco River flowing to Jacob's Well along the northeast-southwest trending regional faults. The potentiometric heads in this area along the Blanco River are sufficiently high to promote flow towards the well, though the potentiometric surface map indicates this area is cross gradient of Jacob's Well. The data generated by the water level transducers deployed in the area may give some indication of the source of the storm surge flow.

9.5 Blue Hole

Preliminary field work was performed at Blue Hole during July-August 2008 determine if there were springs in the base of the hole that contributed additional base flow to Cypress Creek. A depth profile was performed from water surface to streambed depth measurements taken at the edges of Blue Hole and 10-foot intervals horizontally across Blue Hole. These horizontal transects were measured every 50 feet along the banks of Blue Hole to create a contour map of the bottom of Blue Hole. (Figure 37) The depth profile shows no significant drops in depth along the extent of Blue Hole.

In an attempt to locate potential springs in the hole, a survey utilizing a thermal imaging camera was conducted with the assistance of UT Austin. The camera shows differences in water temperature that may be indicative of spring flow. No significant temperature differences were noted. It should be noted that this preliminary study of Blue Hole was conducted under prolonged drought conditions any shallow springs that may normally be present have dried up. Further work is necessary during varying flow conditions to determine if there are springs in Blue Hole under higher flow conditions.

10.0 Water Quality From Area Wells and Surface Water

Water quality data were collected from a number of groundwater wells around the district (Table 6), Cypress Creek, the Blanco River, and Jacob's Well. Well sample data was obtained primarily public water supply wells reported on the TWDB databases. The data typically represents water quality in the Middle Trinity Aquifer. Surface water samples were collected by the HTGCD. Naturally occurring cations and anions have been analyzed to characterize the water chemistry. The results are summarized in Table 6. No manmade chemical such as pesticides or herbicides were analyzed.

Results from this water chemistry data were plotted using a Piper Diagram (Piper 1944), which show the relative concentrations of the major cations and anions, giving a visual comparison of water chemistry between different samples. (Figure 39). In general, the alkaline cations (calcium and magnesium) exceed the alkali cations (sodium and potassium). Weak acids such as bicarbonate and carbonate exceed the stronger acids (sulfate and chloride) (Piper, 1953). The water quality is very typical of a carbonate dominated hydrogeologic system.

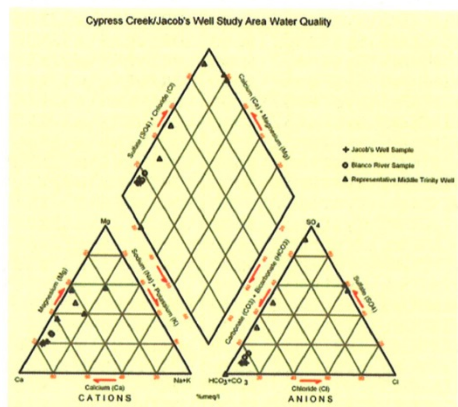


Figure 39. Study Area Piper Diagram

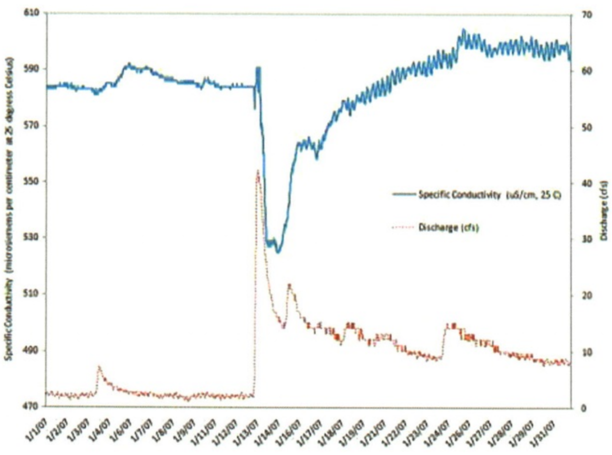


Figure 40. January 14-16, 2007 Storm Surge Discharge, Specific Conductance

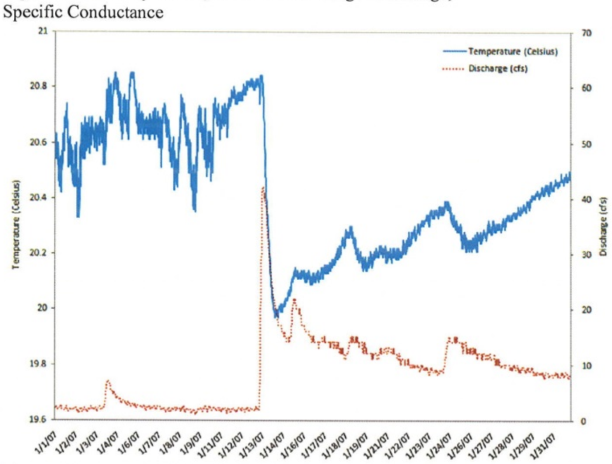


Figure 41. January 14-16, 2007 Storm Surge Discharge, Temperature

10.1 Water Quality from Jacob's Well USGS Station

The 15 minute water quality data from the USGS Jacob's Well station for the period of record were analyzed over the period of record. Water quality conditions during baseflow, drought, and storm surges were studied. Specific conductance, turbidity, and temperature remain fairly constant during baseflow conditions, but change significantly during storm surges.

Analysis of discharge water quality data suggests that a different component of flow other than normal base flow influences discharge during storm surges. For example, during the January 14-16, 2007 storm (Figures 40-42), discharge increased from 1.9 to 41 cfs and distinct changes in water quality were observed. Specific conductivity decreased from approximately 590 to 530 microsiemens per second as the discharge of the well increased. Temperature data followed a similar trend, decreasing approximately one degree Celsius. The reduction in temperature suggests that a significant portion of the storm discharge may originate from the "B" tube, which transports the coolest water into the well. Both temperature and specific conductivity returned to pre-storm levels as the discharge returned to pre-storm levels. Turbidity increased during the storm surge.

Planning for a storm surge water quality sampling event has been completed and sampling will occur during the next significant rain event. Samples will be taken from the mouth of Jacob's Well and sites on the Blanco River during the duration of the storm and analyzed for anions, cations, and possible other chemical parameters. This sampling event will help explain the difference in water quality seen in Jacob's Well, possibly identifying different sources of water to the well during storms. This work could help delineate recharge pathways that come into play and identifies characteristic changes in water quality during storm events.

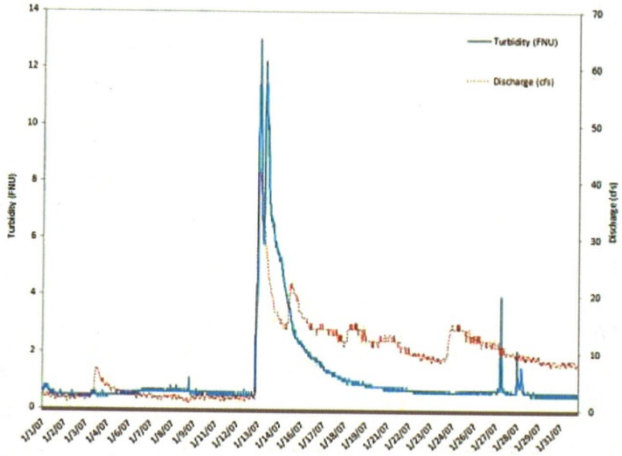


Figure 42. January 14-16 2007 Storm Surge Discharge, Turbidity

11.0 Summary

The long-term protection of the flow of water in Cypress Creek and prediction of how current and future natural and human impacts might affect the system requires a firm understanding of the science of the watershed. This study has provided valuable information regarding the hydrology of Cypress Creek, the origin of groundwater at Jacob's Well and the geologic setting of the watershed. The study has also identified many areas where additional study is necessary to more completely understand the watershed and the flow of water in Cypress Creek.

The key to maintaining the flow of water from Jacob's Well, the primary contributor of water to the creek, lies in understanding and protecting the base flow of the Well. This study has shown that the base flow is provided by artesian groundwater discharge from the Cow Creek formation. Base flow originates from recharge in up dip areas of the Middle Trinity Aquifer in western Hays County and Blanco County. Management of groundwater pumpage from the Cow Creek aquifer up gradient of Jacob's Well will aid to maintain flow, though under current pumping conditions, natural drought/wet conditions will continue to have the greatest effect on the flow from Jacob's Well. If pumping is significantly increased upgradient of Jacob's Well, there will be a detrimental impact to the flow in Cypress Creek.

The origin of storm surge discharge is not well known and requires additional study. While producing large amounts of discharge from Jacob's Well and high flows in Cypress Creek, the storm events are of limited duration and are not as important as base flow to the health of the creek.

Potential impacts from existing and future development in the area on recharge and water quality were not addressed in this study. These are keys areas that need future research. The following two sections identify metrics to track the health of Cypress Creek and additional areas of study for future researchers. They present both research and educational opportunities for a wide range of groups, from elementary school students to college graduate students.

12.0 Metrics to Monitor Health of Jacob's Well/Cypress Creek Flow

There are numerous metrics that when used in conjunction with each other, will provide a method for monitoring and predicting the flow from Jacob's Well/Cypress Creek.

- Direct Measurement of Discharge from Jacob's Well: Through the establishment of the USGS gauging station at the well, real time data at 15 minute intervals has been collected since April, 2005. The data provides the real time information needed to develop and correlate other predictive metrics. http://waterdata.usgs.gov/tx/nwis/uv?site_no=08170990

- Blanco River and Onion Creek Flows: Real time flow discharge measurements (15 minute) are collected at the Blanco River at Highway 12 in Wimberley (http://waterdata.usgs.gov/tx/nwis/uv/?site_no=08171000&agency_cd=USG) and at Onion Creek in Driftwood (http://waterdata.usgs.gov/tx/nwis/uv?site_no=08158700). Though not correlated directly with Jacob's Well discharge in this report, the base flow of these two streams is derived from Trinity Aquifer discharge making stream discharge an indicator of aquifer levels.

- Standardized Drought Indices: the Standard Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), and Crop Moisture Index (CMI) are generally indicators based on precipitation but are used to predict the severity of drought (http://www.txwin.net/Monitoring/Meteorological/Drought/indices.htm). The PDSI is primarily an index of meteorologic drought, but also takes into account hydrologic factors such as precipitation, evaporation and soil moisture. The SPI is a drought probability index that considers only precipitation. The CMI is an index designed to monitor short term moisture conditions across major crop producing regions. It is not a good extended drought monitor but is useful in monitoring pre- and early drought development (Information from on drought indices from the TWDB - http://www.txwin.net/Monitoring/Meteorological/Drought/indices.htm).

- Local Precipitation: Measurement of local precipitation in an immediate indictor of storm discharge from Jacob's Well.

- Groundwater Withdrawal in the Watershed: The increased withdrawal of groundwater from wells in the vicinity of Jacob's Well will reduce the long term discharge from Jacob's Well and Cypress Creek. HTGCD collects pumpage reports from permitted users in the area.

- Groundwater Levels: A network of dedicated monitoring wells specifically designed and constructed to monitor the various members of the Trinity Aquifer would provide the data necessary to develop the relationship between aquifer water levels and Jacob's Well discharge. Drought triggers to reduce groundwater pumpage could be developed from the monitoring well data.

- Future development in the watershed: Documenting future development activities in the watershed, such as increased impervious cover and new wells, could enable the development of metrics relating to groundwater/surface flow and water quality.

13.0 Recommendations and Future Work

The work performed during this study answered many questions, but raised additional questions. Additional works needs to be performed to fully understand the nature of the flow of Jacob's Well and Cypress Creek. Specific areas of future investigation should include:

- Perform storm event water quality sampling program (weather permitting) at Jacob's Well to aid in determining the source of storm flow

- Continued the existing water level monitoring program including maintaining and expanding the network of pressure transducers

- Collect available information and water levels from wells completed in the Lower Trinity Aquifer to determine groundwater flow directions and establish a baseline of water levels.

- Install series of dedicated monitoring wells be permanent water level monitoring points, stratigraphic control, water quality sampling and hydraulic testing. (Also serve as teaching aids)

- Perform geologic field reconnaissance and map the Cow Creek/Hensel outcrop along the Blanco River near Valley View Road

- Integrate data into TSU Cypress Creek Watershed Study

- Perform periodic loss/gain studies along Cypress Creek/Blue Hole and the Blanco River

- Establish and maintain a series of precipitation monitoring stations throughout the Cypress Creek watershed and further west towards the outcrop areas of the Cow Creek, Hensel and Lower Glen Rose in Blanco County.

- Perform temperature surveys along the base of Blue Hole during different flow stages to determine if significant spring discharge occurs in the hole.

- Initiate a program of periodic water quality sampling for man-made pollutants during both base and storm flow conditions.

- Develop predictive groundwater model for the watershed that accounts for changes in groundwater withdrawal

- Conduct dye trace studies in surficial karst features near Jacob's Well

- Develop computerized visualization or other graphics for public education purposes

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Tables

Table 1. Study Data Points Legend

ID	Name	Control Type	Latitude	Longitude	Elevation (ft)
001	Blanco at Hidden Valley	Point	29.98561	-98.06533	784
002	Blanco at Valley View	Point	30.03682	-98.22284	967
003	Blue Hole	Point	30.00396	-98.09072	843
004	Blue Hole Well	Well	30.00066	-98.08300	920
005	Camp Young Judea	Well	30.02948	-98.11880	955
006	Chapman	Well	30.07488	-98.19849	1237
007	Cox Well	Well	30.01426	-97.96387	1072
008	Cypress Creek at Jacob's Well Road	Point	30.03037	-98.12185	919
009	Cypress Creek at Woodcreek	Point	30.02092	-98.11749	903
010	Field	Well	30.03272	-98.12560	945
011	Glenn	Well	29.96918	-98.11490	1080
012	Gottschall	Well	30.08902	-97.80664	1376
013	Goulas	Well	30.00475	-98.11166	960
014	Graham	Well	30.03332	-98.12380	964
015	Gumbert Windmill	Well	30.01077	-98.10377	885
016	Hanson	Well	30.02411	-98.02730	1074
017	Hargrave	Well	30.05049	-98.17371	1165
018	Hays County Pct 3 Well	Well	30.03870	-98.11468	1044
019	Hermosa Paloma	Well	30.00319	-98.01144	1122
020	Holbrook 2	Well	30.03806	-98.10944	1073
021	Jacob's Well	Point	30.03443	-98.12619	924
022	Ken Downing	Well	30.07742	-98.07840	1216
023	Middleton	Well	30.01596	-98.01199	1013
024	Mount Baldy	Well	30.01602	-98.11694	938
025	Mountain Crest	Well	30.03832	-98.10975	1171
026	Mustang Ridge Well #54A	Well	30.03028	-97.82361	1165
027	MW #1	Well	30.02889	-98.11161	976
028	MW #2	Well	30.02845	-98.11169	965
029	Norb Gorman	Well	30.08389	-97.84972	1263
030	Rohan	Well	29.97572	-98.20495	942
031	Sabino Ranch	Well	30.00344	-98.09384	890
032	Sect 25 Well	Well	30.02720	-98.14730	1043
033	Skyline Estates	Well	30.03861	-98.06917	1120
034	Stillwell #1	Well	30.03817	-98.25873	1079
035	Stillwell #4	Well	30.06367	-98.25751	1203
036	Stillwell #5	Well	30.06154	-98.23931	1125
037	Stillwell #6	Well	30.04122	-98.24178	1106
038	Storm Ranch Toenail	Well	30.09050	-98.16854	1297
039	Vasgaard	Well	30.03671	-98.09974	1161
040	WC Well #11	Well	30.02432	-98.11419	942
041	WC Well #12	Well	30.02203	-98.10229	1026
042	WC Well #21	Well	30.03141	-98.14041	1003
043	WC Well #22	Well	30.03926	-98.15620	1042
044	WC Well #23	Well	30.03907	-98.14368	1053
045	WWSC #3	Well	30.01444	-98.11750	920

Table 1. Study Data Points Legend

046	WWSC #4	Well	29.98667	-98.09278	860
047	WWSC #5	Well	29.98389	-98.12222	990
ID	Name	Control Type	Latitude	Longitude	Elevation (ft)
048	WWSC #6	Well	30.01833	-98.12361	1080
049	WWSC #7	Well	29.98694	-97.88500	940
050	WWSC #8	Well	29.98694	-97.88389	1000
051	Mount Sharp Ranch "New Well"		30.09433	-98.17367	1290
052	Faith Ranch (Dunn)-heat exchange		30.09806	-98.19611	1378
053	Longhorn Trail Well No.1		30.08631	-98.19406	1329
054	Pump Station No. 1 (Bill Dunn W.A.S.)		30.10097	-98.19850	1413
055	Bischoff Well No. 1		30.24167	-98.01667	1032
056	Wallace Well No. 1 (Rusty Wallace)		30.00250	-98.17306	1087
057	Bass Well No. 1		30.03192	-98.16467	1146
058	Motal Well No.1		30.12297	-98.09914	1178
059	High View Ranch Well No. PW-1		30.08460	-98.08719	1366
060	Crainshaw No. 2		30.01517	-98.07067	935
061	Greco No.1		30.02222	-98.08278	1159
062	Dunn Well No. 1 OW		30.01258	-98.07964	1153
063	Dunham Well No.1		30.00888	-98.05556	904
064	Readymix Well No. 3		30.01910	-98.06530	1008
065	White Wing Well		30.01336	-98.03853	1044
066	Shellman Well (Mike Shellman)		29.99369	-98.21019	1015
067	Keyser Well No. 1		29.97472	-98.16444	990
068	Las Misiones Well No. 2		29.98670	-98.16000	986
069	Las Misiones Well No. 3		29.98640	-98.16100	995
070	Wimberley Blue Hole		30.00067	-98.08300	921
071	Panarama Well (Westmoreland)		29.95853	-98.08739	1068
072	True Ranch No. 1		30.03028	-97.82361	1137
073	Willis Well No.1		30.05464	-99.67772	1087

Table 2. GIS Table

Date	Name	Measurement Type	Latitude	Longitude	Elevation (ft)
8/8/2005	HTG001	Point	30.20874	-98.29961	1254
8/8/2005	HTG002	Corbula Bed	30.20921	-98.29615	1223
8/8/2005	HTG003	Point	30.19379	-98.31715	1216
8/8/2005	HTG004	Corbula Bed	30.19872	-98.31601	1211
8/8/2005	HTG005	Montor Well	30.17838	-98.05344	1118
8/8/2005	HTG006	Well	30.18546	-98.05103	1172
8/8/2005	HTG007	Well	30.03878	-98.08315	1178
8/8/2005	HTG008	Point	30.03190	-98.10217	1051
8/9/2005	HTG009	Montor Well	30.02948	-98.11880	955
10/3/2005	HTG010	Point	30.02158	-98.10723	1007
10/3/2005	HTG011				
10/3/2005	HTG012				
10/3/2005	HTG013				
10/3/2005	HTG014	Corbula Bed	30.05151	-98.19903	1221
10/3/2005	HTG015	Corbula Bed	30.08411	-98.27952	1260
10/4/2005	HTG016	Well	30.10411	-98.09821	1191
10/4/2005	HTG017	Well	30.10175	-98.10418	1176
10/4/2005	HTG018				
10/4/2005	HTG019	Well	30.10147	-98.10475	1171
10/4/2005	HTG020	Spring	30.11159	-98.11354	1220
10/4/2005	HTG021	Montor Well	30.10400	-98.11988	1245
10/4/2005	HTG022				
10/4/2005	HTG023	Spring	30.10004	-98.13087	1247
10/4/2005	HTG024	Corbula Bed	30.02757	-98.12897	984
10/4/2005	HTG025	Corbula Bed	30.00506	-98.18628	1070
10/5/2005	HTG026	Corbula Bed	30.06527	-98.21521	1220
10/26/2005	HTG027	Well	30.01915	-98.06529	1007
10/26/2005	HTG028	Well	30.00954	-98.01195	1063
10/27/2005	HTG029	Montor Well	30.01602	-98.11694	939
10/27/2005	HTG030	Well	29.98312	-98.15920	982
10/27/2005	HTG031	Well	29.98568	-98.16002	990
10/27/2005	HTG032	Montor Well	30.03332	-98.12380	964
10/27/2005	HTG033	Montor Well	30.01077	-98.09623	885
10/27/2005	HTG034	Well	30.10427	-98.10117	1189
10/27/2005	HTG035	Well	30.19812	-98.21586	1288
10/27/2005	HTG036	Montor Well	30.19601	-98.10744	1191
10/27/2005	HTG037	Well	30.14568	-97.96703	1067
10/27/2005	HTG038	Well	30.13893	-97.96826	1041
10/27/2005	HTG039	Well	30.13839	-97.96916	1054
12/21/2005	HTG040	Well	30.01915	-98.06527	1008
12/21/2005	HTG041	Well	30.00955	-98.01195	1064
12/21/2005	HTG042	Well	29.98644	-98.16099	995
12/21/2005	HTG043	Well	29.98669	-98.16004	986
12/21/2005	HTG044	Corbula Bed	30.07619	-98.15416	1158
12/21/2005	HTG045	Corbula Bed	30.05700	-98.10399	1098

Table 2. GIS Table

Date	Name	Measurement Type	Latitude	Longitude	Elevation (ft)
12/22/2005	HTG046	Well	30.14520	-97.98146	1071
12/22/2005	HTG047	Well	30.13869	-97.95893	1098
1/6/2006	HTG048	Montor Well	30.12894	-97.95609	990
1/7/2006	HTG049	Montor Well	30.03817	-98.25873	1079
1/7/2006	HTG050	Well	30.03839	-98.25994	1090
1/7/2006	HTG051	Well	30.05272	-98.26321	1089
1/7/2006	HTG052	Montor Well	30.06367	-98.25751	1203
1/7/2006	HTG053	Montor Well	30.06154	-98.23931	1125
1/7/2006	HTG054	Corbula Bed	30.01030	-98.17750	1076
1/7/2006	HTG055	Montor Well	30.00805	-98.17668	1106
1/9/2006	HTG056	Well	30.18203	-97.93296	929
1/9/2006	HTG057				
1/9/2006	HTG058	Well	30.18350	-97.93305	946
1/9/2006	HTG059	Well	30.18416	-97.93792	919
1/9/2006	HTG060	Well	30.18379	-97.93659	912
1/9/2006	HTG061	Well	30.18555	-97.94236	994
4/29/2006	HTG062	Montor Well	30.00515	-98.01156	1122
4/29/2006	HTG063	Point	30.03676	-98.22239	977
4/29/2006	HTG064	Corbula Bed	29.99919	-98.22514	1125
4/29/2006	HTG065	Montor Well	30.13087	-98.13720	1240
4/29/2006	HTG066	Montor Well	30.09050	-98.16854	1297
4/29/2006	HTG067				
4/29/2006	HTG068				
4/29/2006	HTG069				
4/29/2006	HTG070	Monitor Well	30.09819	-98.23246	1407
4/30/2006	HTG071	Well	30.20399	-98.01248	1186
4/30/2006	HTG072	Well	30.21089	-98.00691	1095
4/30/2006	HTG073	Well	30.21405	-98.00567	1082
4/30/2006	HTG074	Well	30.20802	-98.01119	1138
5/11/2006	HTG075	Well	30.14959	-97.97203	1007
2/19/2007	HTG076	Fault	30.04529	-98.10179	1046
2/19/2007	HTG077	Fault	30.02495	-98.14473	1051
2/24/2007	HTG078	Monitor Well	30.05891	-98.15423	1072
2/24/2007	HTG079	Well	30.06891	-98.09232	1229
2/25/2007	HTG080	Monitor Well	30.01426	-98.03613	1072
2/25/2007	HTG081	Monitor Well	30.00066	-98.08300	921
2/25/2007	HTG082	Spring	30.03446	-98.12615	923
3/9/2007	HTG083	Monitor Well	30.21520	-98.01304	1092
3/9/2007	HTG084	Monitor Well	30.17812	-97.96280	1015
3/9/2007	HTG085	Monitor Well	30.17987	-97.94808	952
3/9/2007	HTG086	Monitor Well	30.15292	-97.98370	1111
3/9/2007	HTG087	Monitor Well	30.12961	-98.01432	961
3/10/2007	HTG088	Opening	30.04942	-98.22011	1074
3/10/2007	HTG089	Opening	30.04923	-98.22030	1075
3/10/2007	HTG090	Opening	30.04711	-98.22085	1065
3/10/2007	HTG091	Well	30.00443	-98.17719	1111
3/10/2007	HTG092	Monitor Well	30.07742	-98.07840	1218

Table 2. GIS Table

Date	Name	Measurement Type	Latitude	Longitude	Elevation (ft)
3/10/2007	HTG093	Monitor Well	30.17025	-98.07406	1170
3/10/2007	HTG094	Monitor Well	30.21085	-98.00051	1178
3/11/2007	HTG095	Monitor Well	30.03398	-98.14634	1026
3/11/2007	HTG096	Monitor Well	30.03940	-98.23522	1154
3/11/2007	HTG097	Monitor Well	30.04122	-98.24178	1106
3/11/2007	HTG098	Monitor Well	30.18447	-98.13926	1128
3/11/2007	HTG099	Monitor Well	30.19629	-98.21244	1326
3/11/2007	HTG100	Monitor Well	30.24623	-98.15667	1296
3/11/2007	HTG101	Monitor Well	30.25882	-98.12980	1230
3/11/2007	HTG102	Monitor Well	30.21282	-98.13314	1309
3/11/2007	HTG103	Monitor Well	30.12585	-98.10344	1193
3/11/2007	HTG104	Monitor Well	29.92384	-98.08271	1019
5/17/2007	105	pws-well	30.02203	-98.10229	1026
5/17/2007	106	pws-well	30.02432	-98.11419	942
5/17/2007	107	pws-well	30.03832	-98.10975	1171
5/17/2007	108	pws-well	30.03141	-98.14041	1003
5/17/2007	109	pws-well	30.03907	-98.14368	1050
5/17/2007	110	pws-well	30.03926	-98.15620	1042
5/17/2007	111	Point	30.03443	-98.12619	924
5/17/2007	112	Point	30.00059	-98.20022	953
5/18/2007	113	pws-well	30.02719	-98.14730	1043
5/18/2007	114	pws-well	30.03398	-98.14632	1022
5/18/2007	115	pws-well	30.03641	-98.13874	958
5/18/2007	116	pws-well	30.02484	-98.11356	945
5/18/2007	117	pws-well	30.02889	-98.11161	976
5/18/2007	118	pws-well	30.02845	-98.11169	965
9/28/2007	119	Monitor Well	30.04208	-98.10844	1078
9/28/2007	120	Monitor Well	30.03878	-98.08314	1182
9/28/2007	121	Point	30.03037	-98.12185	919
9/28/2007	122	Point	30.02092	-98.11749	903
9/28/2007	123	Point	30.01255	-98.10412	879
9/28/2007	124	Point	30.00390	-98.09084	860
9/28/2007	125	Point	30.00363	-98.09098	862
9/28/2007	126	Point	29.99675	-98.09721	828
9/28/2007	127		30.03682	-98.22284	967
9/28/2007	128		29.96746	-98.18955	879
9/28/2007	129		29.98561	-98.06533	785
9/28/2007	130	Monitor Well	30.04144	-98.17798	1171
9/28/2007	131	Monitor Well	30.04125	-98.20857	1222
9/28/2007	132	Monitor Well	30.15461	-98.08636	1044
9/28/2007	133	Monitor Well	30.15110	-98.08718	1078
9/28/2007	134	Monitor Well	30.15108	-98.08628	1076
9/28/2007	135	Monitor Well	30.25281	-98.20097	1071
9/28/2007	136		30.33293	-98.18293	860
9/28/2007	137		30.33296	-98.18217	794
9/28/2007	138		30.33332	-98.18206	755
9/28/2007	139		30.33285	-98.18129	724

Table 2. GIS Table

Date	Name	Measurement Type	Latitude	Longitude	Elevation (ft)
9/28/2007	140		30.25370	-98.16826	1202
9/28/2007	141	Monitor Well	30.19985	-98.00891	1257
9/28/2007	142	Monitor Well	30.20143	-97.99171	1181
9/28/2007	143	Monitor Well	30.19801	-97.98029	1081
9/28/2007	144	Monitor Well	30.24165	-98.01965	1024
9/28/2007	145	Monitor Well	30.17756	-97.90293	861
6/15/2008	146	Monitor Well	30.14843	-98.05025	1049
6/15/2008	147	Monitor Well	30.03671	-98.09974	1161
6/15/2008	148	Point	30.01283	-98.10403	890
6/15/2008	149	Monitor Well	30.00344	-98.09384	890
6/15/2008	150	Monitor Well	29.96918	-98.11490	1080
6/15/2008	151	Monitor Well	30.01596	-98.01199	1013
6/15/2008	152	Monitor Well	30.02411	-98.02730	1074
6/15/2008	153	Point	30.00396	-98.09072	843
6/15/2008	154	Monitor Well	30.00475	-98.11166	960
6/15/2008	155	Monitor Well	29.97572	-98.20495	942
6/15/2008	156	Point	29.99015	-98.19973	918
6/15/2008	157	Point	30.00051	-98.20018	956
6/15/2008	158	Point	29.97128	-98.17803	944
6/15/2008	159	Monitor Well	30.07488	-98.19849	1237
6/15/2008	160	pws-well	30.03907	-98.14368	1053
6/15/2008	161	Monitor Well	30.03272	-98.12560	945
6/15/2008	162	Monitor Well	30.03870	-98.11468	1044

Table 3. NOAA Monthly Precipitation Data (inches), Wimberley, TX

Apr-05	0.95
May-05	4.13
Jun-05	0.57
Jul-05	4.41
Aug-05	1.12
Sep-05	1.95
Oct-05	1.36
Nov-05	0.97
Dec-05	0.15
Jan-06	0.65
Feb-06	0.69
Mar-06	2.92
Apr-06	2.32
May-06	3.30
Jun-06	2.49
Jul-06	0.45
Aug-06	0.83
Sep-06	2.92
Oct-06	3.57
Nov-06	2.08
Dec-06	2.63
Jan-07	7.33
Feb-07	0.06
Mar-07	8.02
Apr-07	2.73
May-07	6.88
Jun-07	4.79
Jul-07	18.63
Aug-07	2.54
Sep-07	2.69
Oct-07	2.13
Nov-07	0.98
Dec-07	0.55
Jan-08	0.62
Feb-08	0.21
Mar-08	2.00
Apr-08	2.66
May-08	1.09
Jun-08	0.18

Table 4. Summary of Stratigraphic Contacts

ID	Control Type	Latitude	Longitude	Elevation	UGR Top Elevation	LGR Top Elevation	Hensel Top Elevation	Cow Creek Top Elevation	Hammett Top Elevation	Sligo Top Elevation	Hosston Top Elevation	Paleozoic Top Elevation	Logs	Comments
057	Outcrop	30.08411	-98.27952	1260		1260								
058	Outcrop	30.25000	-98.24278	1090		1090								
059	Outcrop	30.29167	-98.24278	1105		1105								geologic map point
060	Outcrop	30.29167	-98.18611	1060		1060								geologic map point
061	Outcrop	30.30778	-98.14306	1020		1020								geologic map point
062	Outcrop	30.32500	-98.15222	1000		1000								geologic map point
063	Outcrop	30.23139	-98.24639	1140		1140								geologic map point
064	Outcrop	30.24778	-98.18778	1060		1060								geologic map point
065	Outcrop	30.05700	-98.10399	1098		1098								geologic map point
066	Outcrop	30.02757	-98.12897	984		984								
067	Outcrop	30.06527	-98.21521	1220		1220								
068	Outcrop	30.00506	-98.18628	1070		1070								
069	Outcrop	30.07619	-98.15416	1158		1158								
070	Outcrop	30.05151	-98.19903	1221		1221								
071	Outcrop	30.19872	-98.31601	1211									surface sec	after Perkins
072	Outcrop	30.01030	-98.17750	1076		1076								
073	Outcrop	30.20921	-98.29615	1223		1223								
074	Outcrop	30.32222	-98.10417	980		980								geologic map point
075	Outcrop	30.34778	-98.04167	820		820								geologic map point
076	Outcrop	30.32500	-98.04167	890		890								geologic map point
077	Outcrop	30.31667	-98.11389	1010		1010								geologic map point
078	Outcrop	30.20833	-98.27917	1182		1182								geologic map point
079	Outcrop	30.00833	-98.30000	1190		1190								geologic map point
080	Outcrop	30.17083	-98.32000	1210		1210								geologic map point
081	Outcrop	30.33333	-98.17833	840				840						geologic map point
082	Outcrop	30.33944	-98.13556	820				820						geologic map point
083	Outcrop	30.35111	-98.19778	900				900						geologic map point
084	Outcrop	30.36667	-98.15222	850				850						geologic map point
085	Outcrop	30.31597	-98.17365	800					800					not a well, outcrop
086	Outcrop	30.27157	-98.20851	873				873						

Table 4. Summary of Stratigraphic Contacts

087	Outcrop	30.27155	-98.20522	954			954						
088	Outcrop	30.27304	-98.20118	1079		1079							
ID	Control Type	Latitude	Longitude	Elevation	UGR Top Elevation	LGR Top Elevation	Hensel Top Elevation	Cow Creek Top Elevation	Hammett Top Elevation	Sligo Top Elevation	Hosston Top Elevation	Paleozoic Top Elevation	Logs	Comments
089	Outcrop	30.29944	-98.20778	840							840			geologic map point; sycamore sand
090	Outcrop	30.33194	-98.16667	820							820			geologic map point; sycamore sand
091	Outcrop	30.34278	-98.25000	880								880		geologic map point
043	Well													
044	Well	30.03906	-99.34367	1050			879	852					Geophy log - video	no samples
092	Well	30.03064	-98.21639	990			950	924					Geophysical log	no samples
093	Well	30.15172	-97.96333	932	909	689	459	443	362	318	225		Geophysical	no samples
094	Well	30.03192	-98.16467	1146		1110	880	846					Geophysical	pump @ 340
095	Well	30.19806	-97.98028	1083		806	584	575	507	467	375		Geophysical	samples
096	Well	30.21419	-99.33731	1323		1038	846	823					Geophysical log	samples
097	Well	30.24167	-98.01667	1032		832	642	612	542	517	482		Driller's log	samples
098	Well	30.18955	-97.94475	980	930	718							Geophysical	date of log
099	Well	29.89557	-98.05948	960	760	230	-56	-116					Driller & Geophysical	
100	Well	30.16239	-98.39553	1435		1270	1090	1072	1007		980		Geophysical log	no samples
101	Well	30.15300	-98.39572	1472		1266	1106	1060					Geophysical log	no samples
102	Well	30.24722	-98.05639	1148		829	645	618	536				Geophysical	no samples
103	Well	29.92531	-98.11964	1137	1101	614	352	301					Geophysical	
104	Well	30.18611	-97.91139	905	885	392	242	140	70	20	-3		Geophysical	Picks from Randy Williams
105	Well	29.85744	-98.07067	919		394							Geophysical log	no samples
106	Well	30.14556	-97.96333	1060	1040	776							Geophysical	fault 390 Klgr rept
107	Well	30.01517	-98.07067	935		702	445	409					Geophysical log	samples
108	Well	30.10597	-98.20928	1365		1160	964	931					Geophysical	samples below 200'

Table 4. Summary of Stratigraphic Contacts

													log	
109	Well	30.25278	-100.00083	1071		1071	946	896	806				driller's log	samples
110	Well	30.05892	-98.15422	1068			932	898	803	761	650		Geophysical	
ID	Control Type	Latitude	Longitude	Elevation	UGR Top Elevation	LGR Top Elevation	Hensel Top Elevation	Cow Creek Top Elevation	Hammett Top Elevation	Sligo Top Elevation	Hosston Top Elevation	Paleozoic Top Elevation	Logs	Comments
111	Well	30.00888	-98.05556	904		554							no logs	samples
112	Well	30.01258	-98.07964	1153		652	416	378	263				Geophysical log	samples available, 20' interval(pumpd @14gpm)
113	Well	30.11214	-98.05786	1141		973	744	731					Geophysical log	samples available
114	Well	30.15867	-98.24664	1390		1200	1020	1000	900				Driller	no geophy log
115	Well	30.09806	-98.19611	1378		1108							Geophysical	heat exchange well
116	Well	30.24683	-98.67931	1117		960	767	743	659	634	602		Geophysical log	samples
117	Well	30.17819	-98.05247	1140		939							Geophysical	smpls & wtr smpl
118	Well	30.33333	-98.11667	990		980	875	840	790		725	523		Sligo missing
119	Well	30.19361	-98.03250	1240		895	685	660					Drillers log	samples
120	Well	30.14633	-97.97150	1050	1000	647	419						Driller & Geophysical	
121	Well	30.25197	-98.03522	1126		826	636	610	532	509	478		Geophysical	samples
122	Well			1159	1079	716								
123	Well	30.15421	-98.21349	1379		1171	991	964	842	774	724	524	Geophysical	wildcat
018	Well			1027			840	813					Geophysical	no samples
124	Well			1041		933							Geophysical	no samples
125	Well	30.25944	-98.09167	1218		968	828	774	692	665	628		Geophysical	
126	Well	30.12269	-98.07761	1066		991	786	756					Geophysical	
019	Well	30.00319	-98.01144	1083	896	416	193						Geophysical	smpls @ 20' intrvl
127	Well	30.08460	-98.08719	1366		1056	842	811					Driller & Geophysical	
128	Well	30.04139	-99.67778	1170			937	905	800	760			driller's log	samples, no log
129	Well	30.18083	-97.93048	947	867	691	475	455					Geophysical	date of log
130	Well	30.28883	-98.09617	1310		979	840	787	<725				Geophysical	
131	Well	30.28333	-98.07728	1305		950	795	765	685	650	630		no logs	samples
051	Well	30.06892	-98.09233	1220		1058	840	803					Geophysical	

Table 4. Summary of Stratigraphic Contacts

132	Well	30.17309	-97.94436	974	874	732	514	498	419	381	288		Geophysical	
133	Well	30.15461	-98.18100	1315		1118	922	893					Geophysical	no Sligo top
134	Well	30.28611	-98.17806	1155		1023	900	840						
135	Well	29.97472	-98.16444	990		930	680						no logs	some samples
ID	Control Type	Latitude	Longitude	Elevation	UGR Top Elevation	LGR Top Elevation	Hensel Top Elevation	Cow Creek Top Elevation	Hammett Top Elevation	Sligo Top Elevation	Hosston Top Elevation	Paleozoic Top Elevation	Logs	Comments
052	Well	29.98670	-98.16000	986		924	683	645					Geophysical	
136	Well	29.98640	-98.16100	995		931	683	644	552				Geophysical	
137	Well	30.04133	-98.20861	1205			971	946					Geophysical log	samples
053	Well	29.98417	-98.02139	780	705								Geophysical	
138	Well	30.08631	-98.19406	1329		1169	959	934	839	815			Geophy. Log to 500	no samples, poor production from Sligo, completed in Kcc
139	Well	30.08258	-99.83864	1318		1166	951	931	833				Geophysical log	no samples
140	Well	30.00689	-98.02519	1020	895	445	199	146					Geophysical log	no samples
141	Well			890		527	274	253					Geophysical log	no samples- WAS
142	Well	30.10306	-98.01350	985		735	498	480	392				Geophysical log	samples
143	Well	30.00417	-98.21278	1060			855	815					Driller & samples	no geophysical log
144	Well	29.90131	-98.05897	970	654	269							Geophysical log	no samples
145	Well	30.05183	-98.00436	1018	914	453	174	163					Geophysical log	no samples
146	Well			1130		1110	894	860					Geophysical	no samples- Pump test
147	Well	30.05000	-98.19167	1194			994	954	864	834	664	554	driller's log	no samples
148	Well	30.12297	-98.09914	1178		1032	831	802					Geophysical	
149	Well	30.09433	-98.17367	1290		1138	930	909					Driller & Geophysical	
024	Well	30.01600	-98.11700	938		818	573	531					Geophy. Log to 348	no samples
150	Well	30.06861	-98.07861	1257		1107	887	847	717				no logs	samples

Table 4. Summary of Stratigraphic Contacts

151	Well	30.23633	-97.86911	838	755	490	325	312	246	208	139		Geophysical	off map
152	Well	29.95853	-98.08739	1068	1043	645							Geophysical	
153	Well	30.20139	-97.99167	1174	1116	800	585	572	508	460	378		Geophysical	samples
154	Well	30.22875	-98.07347	1127		900	711	684	597	572	544	327	Geophysical	samples
155	Well	30.10097	-98.19850	1413		1143	946	914					Geophysical	samples, test
ID	Control Type	Latitude	Longitude	Elevation	UGR Top Elevation	LGR Top Elevation	Hensel Top Elevation	Cow Creek Top Elevation	Hammett Top Elevation	Sligo Top Elevation	Hosston Top Elevation	Paleozoic Top Elevation	Logs	Comments
156	Well	30.19272	-98.16489	1260		1098	908	885					Geophysical	no
157	Well	30.01910	-98.06530	1008		669	433	396					Geophysical	
158	Well	30.14520	-97.98150	1071	985	739	538	524	451	401			Geophysical	
159	Well	30.00950	-98.01200	1063	892	413	195	123	38				Geophysical	
160	Well	30.28297	-98.10339	1282		992	848	802	720	692	664	509	Geophysical	
161	Well	30.26369	-98.15794	1182		1025	889	841	757				Geophysical	samples
162	Well	30.14472	-98.08694	1059		986	786	757	684				Geophysical	samples
163	Well	30.19600	-98.10740	1191		1001	803	780					Geophysical	log to 420, samples
030	Well			952			759						Geophysical	no samples
164	Well	30.36111	-98.15000	800								500		1927 well report
165	Well	30.19131	-97.98239	1085		777							Geophysical	heat exchange well
166	Well	30.05237	-97.99522	1014	949	616							Driller	faulted section? Horst?
167	Well	30.05583	-97.99600	1005	912	435	156	143					Geophysical	fault 770 sec rpt
031	Well	30.00367	-98.09411	871		716	474	435	340	302	184		Geophysical	samples
168	Well	30.13667	-98.02158	1005		930	698	688	609	562	457	257	Geophysical	745 may be Mz grbn
169	Well	30.17139	-97.99498	1115	1080	851	645	612					Geophysical	pump@ 520'
170	Well	30.21611	-98.22750	1241		1096	954	894	836				Driller & Geophysical	
171	Well	30.20222	-98.21972	1270		1114	970	912	833				Driller & Geophysical	no samples
172	Well	29.99369	-98.21019	1015			845	813	705				Geophysical	
173	Well			888		352	116	100	26	-12	-112		Geophysical	no samples, BSEAD
174	Well	30.18186	-97.96006	1045	983	751	524	509	436	399	306		Geophysical	smpls start at 500'
175	Well	30.06361	-97.94306	865	623	165	-134						Geophysical	
176	Well	30.17419	-98.03964	1112		907	696	670					Geophysical	smpls described
028	Well	30.02853	-99.01175	964		851	612	581					Geophysical	no samples

Table 4. Summary of Stratigraphic Contacts

177	Well	30.24592	-97.85099	844				285	216	181	104		Geophysical	off map
178	Well	30.10714	-98.08108	1207	1176	1012	809	775					Geophysical	
179	Well	30.23189	-99.00847	1254		987	796	774	698				Geophysical	no samples
180	Well	30.13229	-98.13834	1246		1056	851	829					Driller & Geophysical	
181	Well	30.10089	-99.67689	1342		1122	917	896					Geophysical log	Samples, Top CC est. below T.D.
ID	Control Type	Latitude	Longitude	Elevation	UGR Top Elevation	LGR Top Elevation	Hensel Top Elevation	Cow Creek Top Elevation	Hammett Top Elevation	Sligo Top Elevation	Hosston Top Elevation	Paleozoic Top Elevation	Logs	Comments
182	Well			1137		1094	867	836	753	710			Geophysical log	no samples- WAS
026	Well			1165		1108	880	847	764				geophysical log	no samples- WAS
183	Well	30.25381	-99.66825	1202		1045	906	855	767				Geophysical log	samples
184	Well	30.19810	-98.21590	1288		1114	956	916					Geophysical	
185	Well	30.00250	-98.17306	1087		1007	775	747	657	617	487		Driller & samples	no geophysical log
186	Well	29.90227	-98.07427	1005	847								Geophysical	
187	Well	30.25528	-98.16500	1231		1035	893	841					Driller & Geophysical	
188	Well	30.19986	-98.00906	1247	1143	832	613	604	536	490	406		Geophysical log	samples
189	Well	30.01336	-98.03853	1044		501	251	206					Geophysical log	no samples
190	Well	30.05464	-99.67772	1087			963	926	842	799	687	517	Geophysical log	samples
004	Well	30.00067	-98.08300	921		619							Geophysical log	no samples
191	Well	30.22022	-98.19161	1428		1080	932	890	803				Geophysical	
192	Well	30.14444	-97.99444	1055		892	705	695					Driller & Geophysical	
193	Well	30.17876	-97.89330	817	512	294							Geophysical	date of log

Table 5. May 2008 Water Levels

ID	Measurement Type	Latitude	Longitude	Elevation (ft)	Depth (ft)	WL below MP (ft)	Water Level Elevation (ft)
001	Point	29.98561	-98.06533	784			784.00
002	Point	30.03682	-98.22284	967			967.18
003	Point	30.00396	-98.09072	843			843.16
004	Well	30.00066347	-98.08299726	920		116.17	803.83
005	Well	30.02948	-98.11880	955	250	38.71	916.55
006	Well	30.07488	-98.19849	1237	~500	328.60	907.23
007	Well	30.01426	-97.96387	1072		258.25	814.17
008	Point	30.03037	-98.12185	919			918.63
009	Point	30.02092	-98.11749	903			902.94
010	Well	30.03272	-98.12560	945		18.49	926.44
011	Well	29.96918	-98.11490	1080		325.23	754.65
012	Well	30.08902	-97.80664	1376		381.35	985.65
013	Well	30.00475	-98.11166	960		127.65	832.34
014	Well	30.03332	-98.12380	964		33.75	930.55
015	Well	30.01077	-98.10377	885		40.55	844.34
016	Well	30.02411	-98.02730	1074		234.87	837.42
017	Well	30.05049	-98.17371	1165		238.40	926.60
018	Well	30.03870	-98.11468	1044		120.45	921.58
019	Well	30.00319	-98.01144	1122		418.83	702.76
020	Well	30.03806	-98.10944	1073		147.19	923.56
021	Point	30.03443	-98.12619	924			924.11
022	Well	30.07742	-98.07840	1216		320.89	895.16
023	Well	30.01596	-98.01199	1013		292.51	714.44
024	Well	30.01602	-98.11694	938	400	106.88	831.12
025	Well	30.03832	-98.10975	1171	480	246.30	922.22
026	Well	30.03028	-97.82361	1165		248.68	916.32
027	Well	30.02889	-98.11161	976	450	49.10	925.48
028	Well	30.02845	-98.11169	965	446	48.05	914.85
029	Well	30.08389	-97.84972	1263	490	200.00	1063.00
030	Well	29.97572	-98.20495	942		35.00	906.75
031	Well	30.00344	-98.09384	890		124.25	765.32
032	Well	30.02720	-98.14730	1043	284	118.92	921.48
033	Well	30.03861	-98.06917	1120	705	304.10	815.00
034	Well	30.03817	-98.25873	1079		74.26	1004.96
035	Well	30.06367	-98.25751	1203		173.67	1029.30
036	Well	30.06154	-98.23931	1125		111.30	1014.19
037	Well	30.04122	-98.24178	1106		180.47	925.96
038	Well	30.09050	-98.16854	1297		291.23	1005.30
039	Well	30.03671	-98.09974	1161		284.90	873.68
040	Well	30.02432	-98.11419	942	400	36.50	903.04
041	Well	30.02203	-98.10229	1026	590	171.45	851.66
042	Well	30.03141	-98.14041	1003	400	79.50	919.96
043	Well	30.03926	-98.15620	1042	300	118.60	921.30
044	Well	30.03907	-98.14368	1053		130.10	923.35
045	Well	30.0144444	-98.1175	920	500	254.00	666.00
046	Well	29.986667	-98.092778	860	550	179.00	681.00
047	Well	29.9838889	-98.1222222	990	550	164.00	826.00
048	Well	30.0183333	-98.1236111	1080	380	136.00	944.00
049	Well	29.98694444	-97.885	940	580	181.00	759.00
050	Well	29.98694444	-97.88388889	1000	550	293.00	707.00

Table 6. Combined Water Quality Data

Well Name	Date Sampled	pH	Spec. Cond.	Fluoride	Calcium	Magnesium	Sodium	Potassium	CO3	HCO3 Calc
Hermosa Paloma	12/14/2005	n/a	n/a	0.8	117.2	43.8	8.8	n/a	n/a	341
Jacobs Well Spring	4/14/1986	7.6	0.18	0.2	91	13	7	1	n/a	328
Jacobs Well Spring	6/28/1988	7	0.24	0.3	95	19	7	1.5	n/a	342
Jacobs Well Spring	3/29/2005	7.13	0.16	0.18	88.3	11.6	6.39	0.94	n/a	308
Kelly's Country	10/13/2004	n/a	n/a	2.9	118	78.8	27.4	n/a	n/a	415
Las Misiones	5/1/2005	7.1	450	0.9	34.4	20	16.6	n/a	n/a	n/a
Little Arkansas	12/3/1999	n/a	2600	4.44	354	292	21.2	n/a	n/a	258
Mount Baldy Well	8/20/1975	7.9	0.18	0.5	70	30	7	0	n/a	331
Mustang Ranch Subdivision	6/17/2008	7.63	584	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Quicksands GC Maintenance 1	6/28/1994	7.92	n/a	0.28	100	21	10	1.8	n/a	380
Robert Maltsberger 5764709	4/15/1986	7.3	640	0.2	98	14	8	1	n/a	342
Robert Maltsberger 5764710	4/15/1986	7.7	620	0.2	94	13	7	1	n/a	338
Wimberley VFW	5/8/1986	8	0.14	1	58	44	6	2	n/a	351
Wimberley WSC 5764712	8/6/2003	7.04	0.17	0.38	74.2	29.7	6.69	1.67	n/a	350
Wimberley WSC 5764712	11/4/1998	6.98	0.18	0.34	73.8	29.9	7.36	1.93	n/a	329
Woodcreek Well 11	4/14/1986	7.9	620	0.2	83	20	7	1	n/a	340
Woodcreek Well 11	6/28/1988	7.4	529	0.3	85	28	7	1.8	n/a	356
Woodcreek Well 12	6/28/1994	7.41	474	0.41	66	32	7.8	2.7	n/a	323

Table 6. Combined Water Quality Data

Well Name	Date Sampled	Chloride	Sulfate	TDS	Total Hardness	Alkalinity	Nitrate - N	Iron
Hermosa Paloma	12/14/2005	14	270	677	473	280	<.01	<.2
Jacobs Well Spring	4/14/1986	12	17	315	n/a	n/a	2.75	n/a
Jacobs Well Spring	6/28/1988	11	18	332	n/a	n/a	3.1	n/a
Jacobs Well Spring	3/29/2005	9.68	13.7	293	n/a	n/a	1.11	n/a
Kelly's Country	10/13/2004	<10	156	611	619	340	<.1	<.2
Las Misiones	5/1/2005	<10	21	304	168	n/a	<.01	<.2
Little Arkansas	12/3/1999	13.65	2364	2472	2086	212	<0.1	0.24
Mount Baldy Well	8/20/1975	13	23	306	n/a	n/a	< 0.4	n/a
Mustang Ranch Subdivision	6/17/2008	12.4	22.3	332	318	n/a	0.628	0
Quicksands GC Maintenance 1	6/28/1994	16	13	364	336	311	3.49	n/a
Robert Maltsberger 5764709	4/15/1986	14	15	336	302	280	8.82	n/a
Robert Maltsberger 5764710	4/15/1986	13	13	320	288	277	3.72	n/a
Wimberley VFW	5/8/1986	15	30	341	n/a	n/a	< 0.04	n/a
Wimberley WSC 5764712	8/6/2003	11.3	21	331	n/a	n/a	0.76	n/a
Wimberley WSC 5764712	11/4/1998	12.1	27.4	329	n/a	n/a	0.49	n/a
Woodcreek Well 11	4/14/1986	12	17	319	289	279	1.9	n/a
Woodcreek Well 11	6/28/1988	11	22	341	327	292	1.51	n/a
Woodcreek Well 12	6/28/1994	11	37	329	297	265	0.08	n/a

Appendices

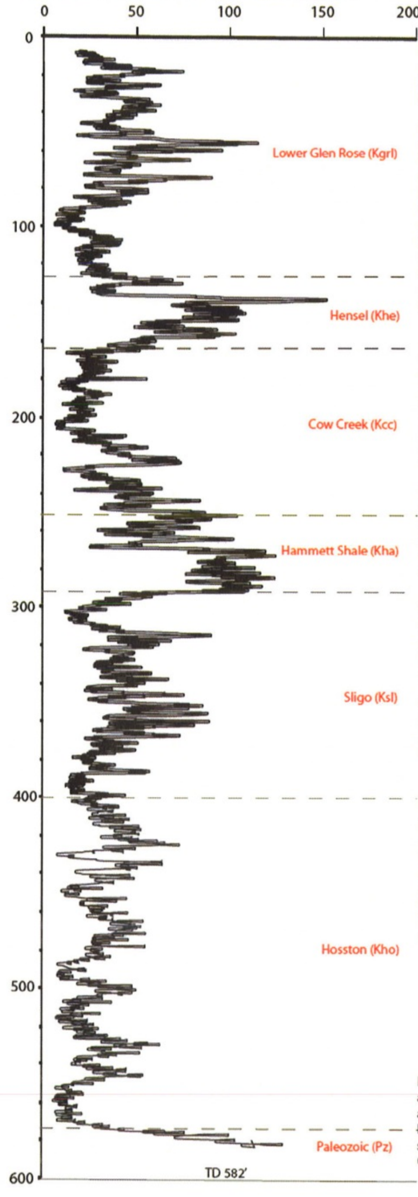
Appendix 1

Type Geophysical Logs

Willis Well No. 1
37 Timberline Road, Hays County, Texas, N 30 03' 16.7", W 98 10' 39.8", Elevation 1087'

The Willis Well is located on a bluff overlooking Dry Cypress Creek. It is an excellent type well for the basin as it spudded in the Lower Glen Rose and bottomed in the Paleozoic.

Natural Gamma (API Cs) and Interpreted Stratigraphy



Exposed at the surface is a monoplurid-skeletal biostrome located near the base of the upper "reef/mound". The "flood" zone is represented by the sharp, shale spikes at 50'-55'. The basal "mound/reef" lithofacies unit is equivalent to the "Narrows" biostrome.

Lower Glen Rose – Hensel contact: 124' (963'amsl). The basal, Lower Glen Rose section is transitional with the underlying Hensel and it is not always a clear log pick. Cuttings samples at the contact are helpful and often contain a flood of glauconite, scattered quartz grains and some pebble fragments. On the geophysical log, the contact is sharp at the Willis well, occurring at 124', with an abrupt increase in CPS. This change is interpreted as Hensel shale. The Hensel is 37' thick in this well and consists of shale, silty dolomite and siltstone. An outcrop above the bank of the Blanco River in Hays County is orange-brown, finely laminated siltstone. The Hensel is predominantly arkosic, coarse clastic and red mudstone to the west in Blanco County. It thins and changes facies to the east-southeast, where the upper Hensel clastics interfinger with Lower Glen Rose carbonate. The Hensel appears to be a confining unit for the Cow Creek when the lithofacies is a fine-grained shale/claystone.

Hensel – Cow Creek contact: 161' (926' amsl). This is a sharp, well defined contact on the gamma log. It is a sequence boundary representing sea-level change and sub-areal to near surface exposure over much of the report area. The Cow Creek is 84' thick at Willis. The upper unit is normally a grain-skeletal limestone, with chert and scattered coarse quartz grains. The rocks are often fractured and dolomitized. Underlying dolomite is f-m crystalline, sucrosic, porous, gray-brown ("brown sands") and water bearing.

Cow Creek – Hammett contact: 245' (842' amsl). The basal Cow Creek can be seen on the log and in samples in a gradual transition to the underlying Hammett. Drilling contractors often mistake shales/claystones in the lower Cow Creek for Hammett. The actual contact is a sharp break on the Gamma log with an abrupt increase of CPS. A gummy, gray-green claystone is the typical lithology marker of the upper Hammett.

Hammett - Sligo contact: 288' (799' amsl). The Hammett formation is 43' thick at this location and contains siltstone, thin dolomites, and claystone. It is the confining unit or aquitard to the Lower Trinity aquifer. The basal contact shows a sharp break in the Gamma log with Hammett claystone overlying Sligo limestone. Cuttings often show reworked limestone clasts in the calcareous basal claystone.

The upper Sligo has a very distinctive signature on the Gamma log that can be correlated throughout the District. The Sligo is 112' thick at this locations but thins to the west. The upper section is an oolitic-skeletal limestone with a micritic matrix. Underlying the tite limestone is a porous dolomite that is water bearing in several local wells.

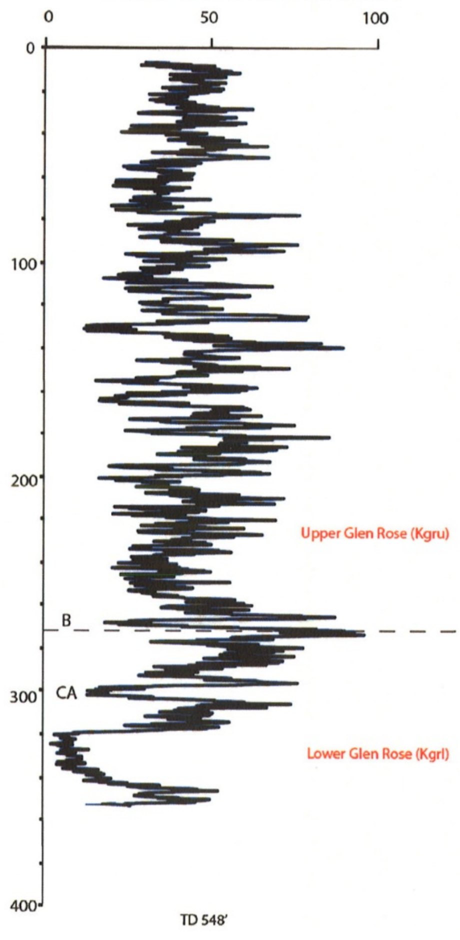
Sligo - Hosston contact: 400' (687' amsl). The carbonate, siltstone, and shale Sligo overlies the clastic Hosston at 400'. There is a break in the Gamma log at this level but it is not a distinctive signature at this location. The best pick here is with the corroboration of samples. The cuttings indicate the onset of lagoon-fluvial sandstones and siltstone in the Hosston vs. the more marine overlying Sligo Formation. The environment of deposition call is speculative. Hosston channel sands can be inferred from the Gamma signature however, and several are water bearing in the area. The Willis Well encountered water at 560', probably in a basal conglomerate.

Hosston - Paleozoic contact: 570' (517' amsl). The Hosston is 170' thick at this location. The contact with the underlying Paleozoic is sharp on the Gamma log at 570'. The basal Hosston conglomerates contain clasts of Paleozoic rocks in other District wells. In the Willis well the Paleozoic section appears to be undurated shale similar to samples seen in Blanco County wells. This is the only well in the Cypress Creek project area that encountered confirmed Paleozoic rocks.

Pump Station Well - TH 1
2950 Pump Station Road, Hays County, Texas, N 30 06' 3.5", W 98 11' 54.6", Elevation 1413'

The Pump Station Well was drilled in 2005 as part of a Water Availability Study. Upper Glen Rose limestone outcrops at the surface and the well TD is 560' in the Cow Creek dolomite.

Natural Gamma (API Cs) and Interpreted Stratigraphy



Upper Glen Rose – Lower Glen Rose contact: 270' (1143'amsl). The accepted stratigraphic contact between the Upper Glen Rose and the Lower Glen Rose is placed at the base of the "Corbula bed" in outcrop. This exposed contact can be mapped at the surface and with air photos. It is difficult however, to find the marker bed in the subsurface with cuttings or on geophysical logs.

The subsurface "contact" indicated at 270' can be correlated in geophysical logs throughout the District and has been observed in wells in Travis and Blanco counties. When the Corbula is actually noted in cuttings it is usually found within 5'-10' of the marker. It is suggested that this log marker be used as the mappable subsurface contact between the Kgru and Kgrl in Hays County.

Marker bed "B", noted on the log, is a sharp, ("anhydrite") negative Gamma kick that may be a single or a double spike. The contact is placed just below the spike. This spacing is taken from observed surface sections that show the upward sequence: Salinia Texana zone, Corbula Bed, solution zone "anhydrite" and "box-work features". The District wide signature is a 10'-20' "fining upward" sequence broken by the contact and the "anhydrite" spike, and a 5-15' "coarsening upward" sequence as shown on the Pump Station geophysical log. The contact may be interpreted as a type II sequence boundary as indicated by this change in depositional architecture.

The marker bed "CA" is normally found in the subsurface some 30' below the Kgru-Kgrl contact. Although identified as a carbonate in this well, the marker correlates with a Lower Glen Rose anhydrite bed in Blanco County and in northwest Hays County.

The Lower Glen Rose upper mound/reef (Rudistid) unit is clearly indicated on the log from 315'-343'. The rock unit thickens to the east and is 70' thick and water bearing in the Crainshaw well, located along the Wimberley bypass. The upper "reef" unit is correlated to the Pipecreek reef in Bandera County (Perkins, 1974).

Appendix 2

Cypress Creek-Structural Analysis

HAYS TRINITY GROUNDWATER CONSERVATION DISTRICT

Cypress Creek Project-Structural analysis:

Characteristics of the Glen Rose formation in and around the Cypress Creek watershed and their implications on groundwater flow

Hays County, TX

June- August 2008

Wesley Schumacher

Stephen Saller

Abstract:
Located along the Balcones Escarpment in Central Texas is a rapidly growing development corridor that contains some of the fastest growing counties in the country. The primary water source in this region has historically been groundwater and recent development has resulted in increased demand on aquifer resources. Understanding the structural geology of a tectonically altered carbonate rock region can yield important information regarding flow regimes of local groundwater. In the Cypress Creek watershed of Hays County, TX, the Balcones Fault Zone has created extensive faulting and jointing patterns throughout the Glen Rose and underlying formations. These geostructural trends correspond to the principle tectonic stresses applied to the rock. Measurements of these trends are recorded and presented herein. The karstic nature of the aquifer that has developed subsequent to the jointing and faulting in the Upper and Lower Glen Rose is complex and still under study. The interpretation of groundwater flowpaths, storage, residence times and yield is reliant on the understanding of the structural nature of the aquifer. It is our hope that this report increases understanding of the aquifer and thus allows for better management of its resources.

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Introduction

The geologic study of the Cypress Creek watershed is an essential stepping stone to the understanding of groundwater dynamics in Hays County and the Trinity aquifer as a whole. The Lower Cretaceous carbonate units exposed in central Texas contain aquifers which are relied upon as essential water supplies for some cities and agriculture in the region. The Trinity aquifer is the lowest Cretaceous stratigraphic aquifer in the region and one of the most understudied. Through a grant from Texas State University the Hays Trinity Groundwater Conservation District (HTGCD / the district) has begun laying the groundwork for a comprehensive geologic and hydrogeologic understanding of the aquifer. This knowledge will allow the district to plan future development and insure desired future conditions for the aquifer and the natural areas that rely on it. HTGCD geologist Alex S. Broun is overseeing the geologic inquiry of the Cypress Creek watershed. The long term goal for this project is to provide geologic data that can be used by physical hydrology modelers to help determine karstic flow regimes in order to better assess the state of groundwater used by the people of Hays County.

Geologic Setting

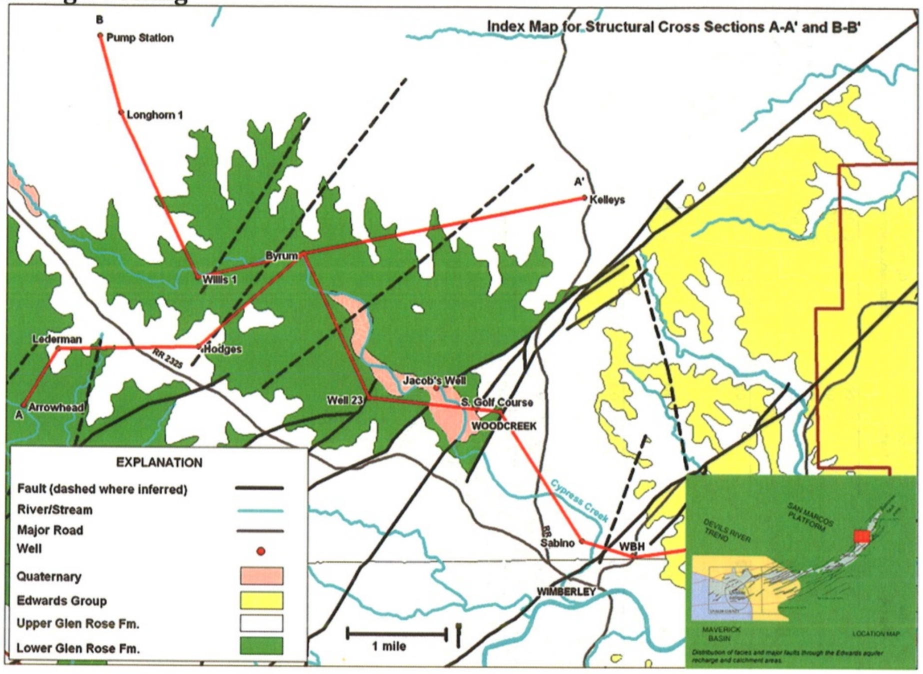

Fig 1- Map for Structural Cross Sections A-A' and B-B' (Llado 2008)

The focus area of this geologic study is the watershed of the Cypress Creek in Hays County. This creek contains the largest artesian spring in the county - Jacobs Well. The spring contributes the majority of flow in Cypress Creek and above the spring the creek remains dry except in times of high rainfall. The watershed is comprised of the Cretaceous carbonate exposures of the upper and lower units of the Glen Rose formation. The regional stratigraphy is flat, with bedding dips typically less than one degree to the southeast. (Stricklin 1974) Despite this, the area is structurally complex due to the Balcones Fault Zone (BFZ) running through the southern portion of the study area.

The units of the Glen Rose formation are downthrown to the southeast in a series of normal faults associated with the BFZ. These faults vary in their throw from a few inches to hundreds of feet. This juxtaposes younger strata to the southeast with older units on the northwest and affects both the lateral and cross-formational flow of groundwater. (Milanovic 04) Whether the faults increase groundwater communication or impede it is uncertain and likely site specific.

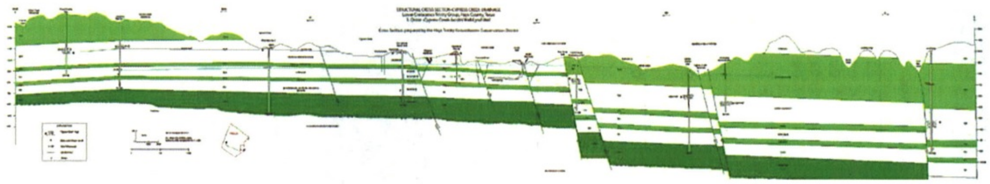

Fig 2- Cross section A-A' showing the downfaulting of Cretaceous rocks in the Balcones fault zone (Broun 2008)

The Glen Rose formation is divided into the Upper Glen Rose (Kgru) and the Lower Glen Rose (Kgrl). The boundary between the two is identified by a marker bed of calcite cemented skeletal grainstone named the Corbula bed after its identifier fossil *Eoursivivas harveyi* (formerly *Corbula maritinae*). (Ward 2007) The Corbula bed ranges in thickness from a few inches to a foot and is often rust colored to orange in color though it may appear grey and unstained. The Corbula bed often contains ripple marks indicating a subtidal depositional environment.

The upper Glen Rose averages 450ft in thickness and is composed of alternating and interbedded shale and carbonate mudstone units. This alternating stratigraphy results in a distinctive "stair step" topography in outcrop. Structurally the upper Glen Rose behaves like a moderately competent rock. Fracturing can be observed in the resistant limestone units, however the shale and marly units tend to absorb and stall fracturing. (Ferrill 2008)

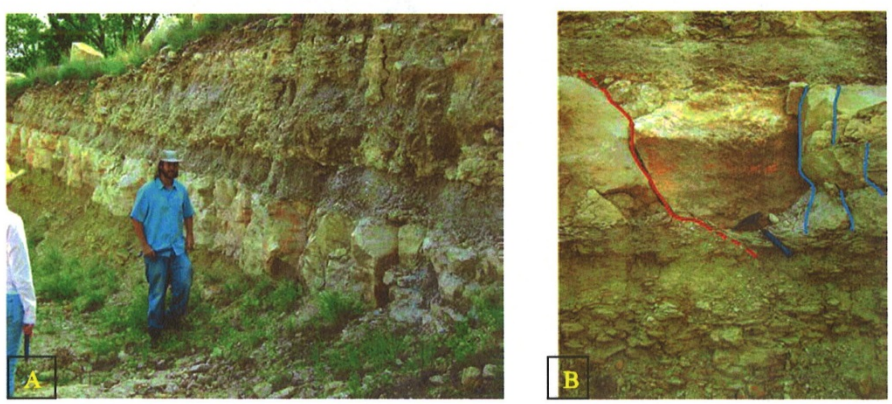

Fig 3- A) Example of Kgru in roadcut. B) Alternating shale and limestone units in upper Glen Rose showing fault and joint stalling in shales. Red lines indicate fault surface. Blue indicates joints.

The lower Glen Rose is a more competent unit composed of two major "Rudistid reefs" and multiple other thinner beds of limestone with minor shale beds dispersed near the top of the section. (Stricklin 1974) The stratigraphy of the lower Glen Rose is much more massive in nature and averages 250ft in thickness. The greater competence of these more massive units results in more abundant and more visible fracturing. Also the greater structural competence results in greater continuity of joints and fault scarps. Unlike the shale rich upper Glen Rose the lower Glen Rose allows faults and joints to transect much of its thickness without stalling or sealing the fractures. (Ferrill 2008)

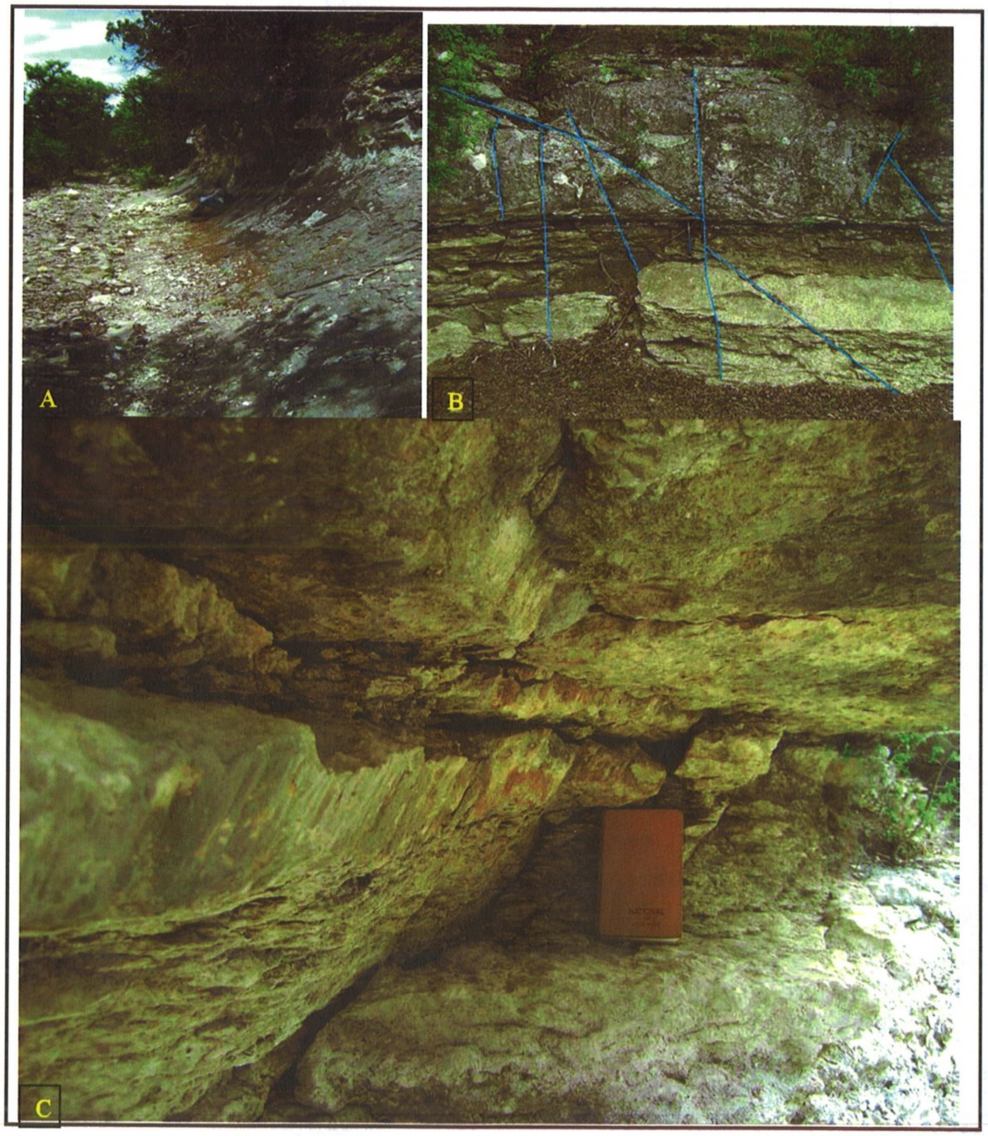

Fig 4- A) and B), examples of the Lower Glen Rose (Kgrl) outcropping on the Lin Lila Ranch. B) Blue lines indicate joint surfaces. C) Fault scarp with notebook for scale.

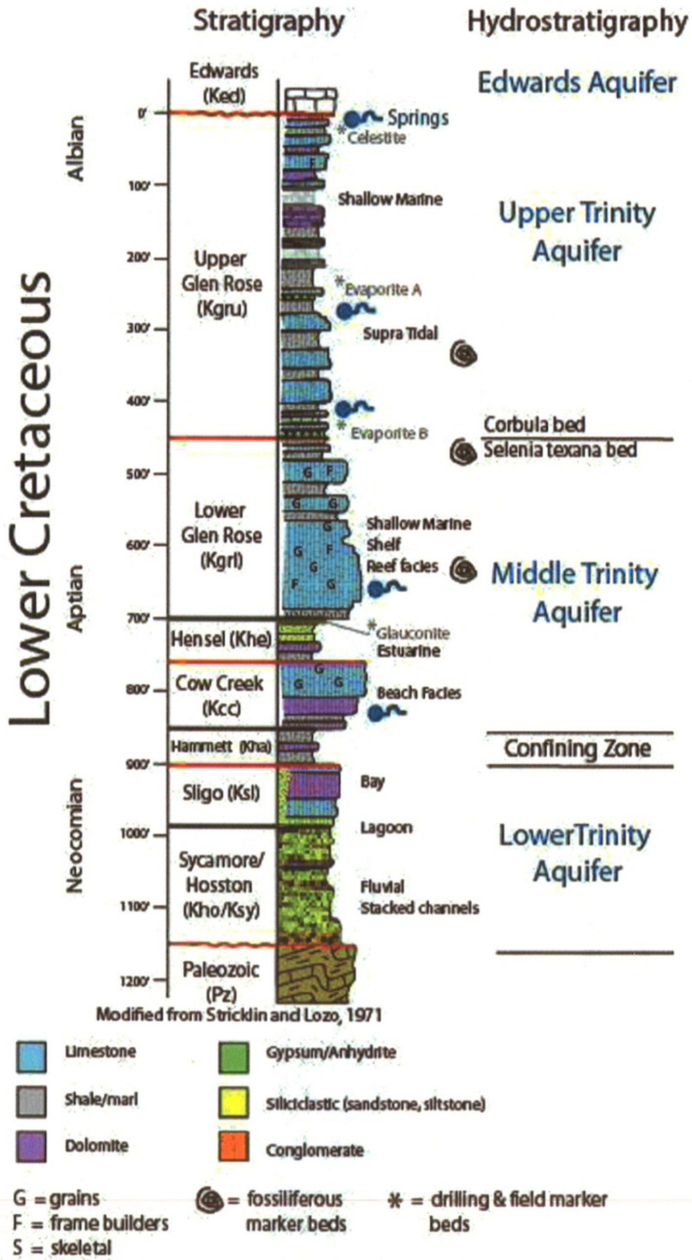

Fig 5- Stratigraphic Column (Broun 05)

Hydrologic setting

The Cypress Creek watershed overlies the recharge zone of the upper and middle zones of the Trinity aquifer. The upper zone of the Trinity aquifer is located stratigraphically in the upper Glen Rose. Due to its alternating layered stratigraphy of shales and carbonates, the upper Glen Rose is prone to contain numerous perched water tables rather than saturating through its thickness from the bottom up as a porous media unconfined aquifer would. The preferential fracturing in the more competent beds juxtaposed with the fracture stalling and sealing shales produces alternating zones of free water flow and aquitards. This results in numerous seeps and conduit springs throughout the area of Kgru exposure. These shallow perched water tables served as the first groundwater sources for settlers during early colonization by Europeans. However, as development has increased in the region and populations have become denser, these small volume aquifers have been depleted and few remain flowing during droughts.

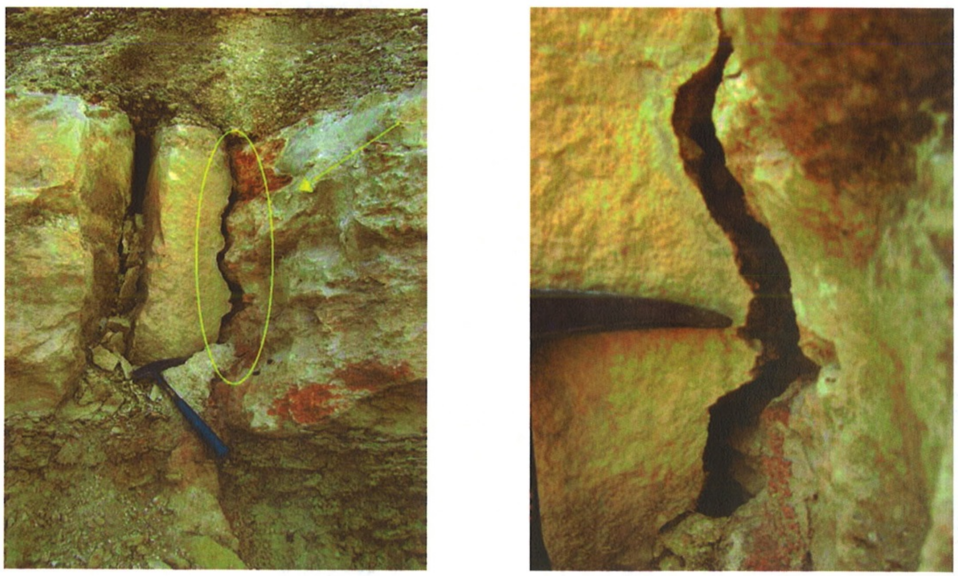

Fig 6- Water enlarged and karstified joint surface in the upper Glen Rose. Note flow channel is confined to the competent limestone bed.

The lower Glen Rose forms the upper portion of the middle Trinity aquifer. The water table is found in this unit, varying depending on the seasonal rainfall patterns. The MiddleTrinity aquifer provides the majority of the groundwater used by the cities of Woodcreek and Wimberley because it produces a large volume of water with low overall TDS. The massive reef formations that dominate the Kgrl fracture more readily than the limestone units found in the Upper Glen Rose. These structural features have greatly influenced the karstification of the entire unit. The faulting and jointing of the competent limestone units create passageways for meteoric water to seep into the rock, where it forms channels and cave networks in the subsurface. "The distribution of vugs, caverns, and smaller solution channels follow the direction of tectonic or lithographic discontinuities." (Milanovic 04) As such, it is reasonable to assume that the orientation of water flow channels corresponds to the faulting and jointing patterns throughout the region. This effect is evidenced by the orientation of surface drainages such as the Blanco River along fault traces.

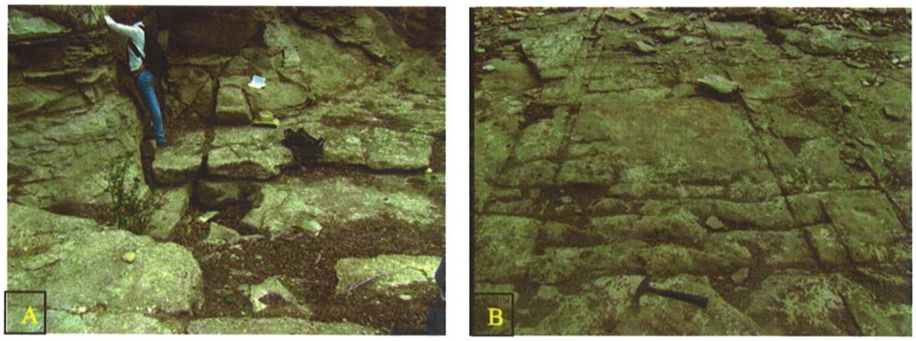

Fig 7- A) suspected sink hole found along fault scarp in the lower Glen Rose. B) Jointed pavement of lower Glen Rose.

Data Collection

-Structural Data

The collection of structural data is a fundamental tool for analyzing rock characteristics and determining preferential groundwater flow paths in aquifers. As such, the more outcrops one can find with clear structural features, the more complete the picture that can be drawn from this data.

Fig 8- Tools of the trade, Brunton® Compass and Garmin® GPS.

For this project, data was collected using a Brunton Compass, a precise compass and inclinometer that can measure the strike and dip of rock features. After noting these measurements, the location was recorded using a Garmin HCX Vista GPS hand held device.

There were three primary types of features that were measured for this study – bedding planes, jointing surfaces, and faults.

- Bedding Plane Data – The strike and dip of a bedding plane are very general measurements to take. However, these measurements are somewhat difficult in instances where the overall dip averages less than 1 degree. However bedding planes are important as they have been observed controlling flow paths.
- Joint Surface Data – "The basic factor of permeability in a carbonate rock mass is jointing." (Milanovic 04) The strike and dip of a joint surface provides insight into how a formation reacted to tectonic stresses. A joint is a fracture with no displacement of bedding. Joints are by far the most prolific type of data in this study. Most joints were near vertical in orientation.
- Fault Data – The strike and dip of a fault surface are the most important pieces of structural data collected. Our data set contains few recorded fault sets, as it is difficult to find a surface that has clear bedding offset and slikenslides. Additionally, the major faults in the area do not provide easily obtainable structural data. Often the downthrown side is buried beneath the surface, and the footwall side is exposed to weathering resulting in the destruction of the original fault plane. The faults can be more easily mapped from air photos than the ground.

-Locating Stratigaphic Markers

The marker bed for the contact between the Upper and Lower Glen Rose is the "Corbula bed", a fossil rich grainstone bed that ranges from a few inches thick to up to a full foot. In some places, it occurs as two or more layers. This bed works well as a marker in outcrop, as it resists weathering more than the surrounding beds, and is quite distinct in its appearance, as shown in figure 9. However, it is too thin to show up very well in geophysical well logs.

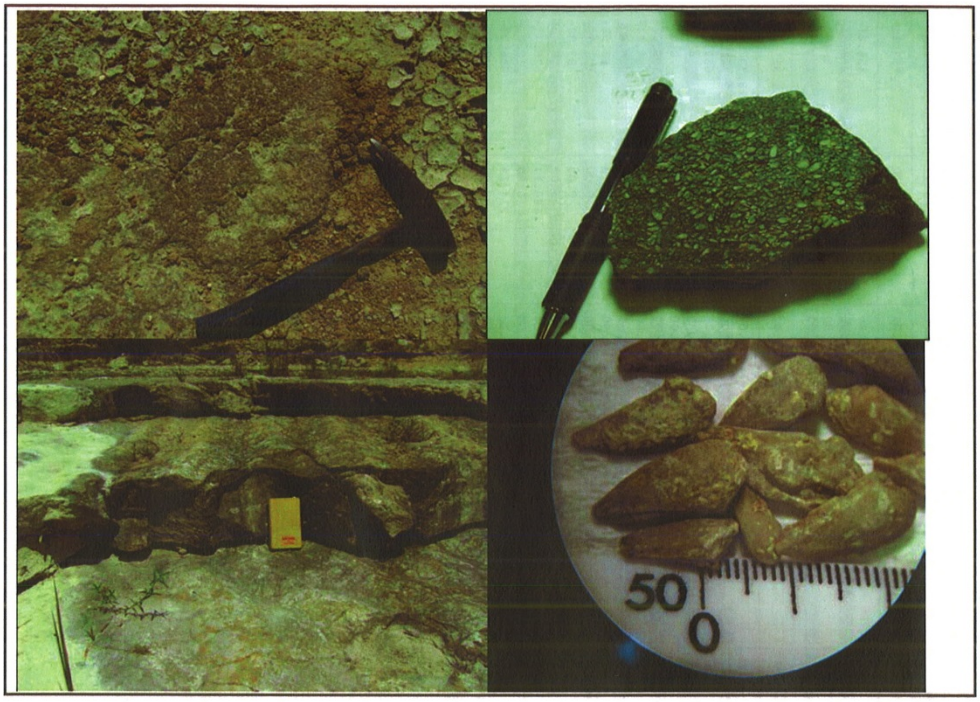

Fig 9- From top left clockwise: Corbula bed in outcrop, Corbula hand sample, large Corbula bed outcrop with ripple wave forms, microscope view of weathered out *Eoursivivas harveyi* on 1/50 inch scale.

In order to find this bed in the field, the important locator beds above and below the Corbula were also studied. Roughly a meter above the Corbula bed, in the Upper Glen Rose, lies a boxwork "anhydrite bed". This bed is yellowish in color, poorly lithified, and contains a three dimensional boxwork of infilled cracks formed by the dissolution of evaporitic anhydrite. The anhydrite does not appear on the surface outcrop but does persist in the subsurface.

Lying directly below the Corbula bed and extending a few meters below is the *Salenia texana* interval which is the most species diverse bed in the Lower Glen Rose strata. (Ward 2007) This highly fossiliferous zone is particularly useful in recognizing the location of the Corbula bed.

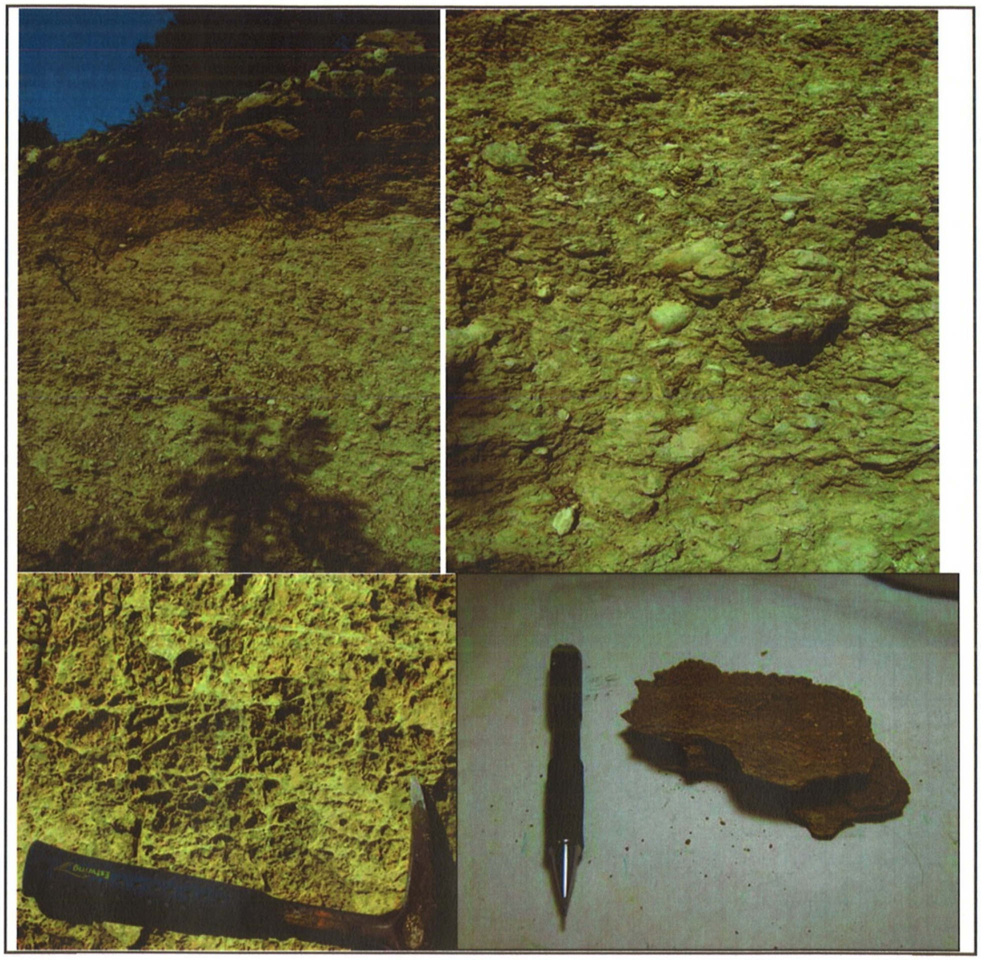

Fig 10- from top left clockwise: Salina Texana interval in outcrop, close up of *Salenia texana* zone, boxwork in outcrop, hand sample of boxwork

-Sample Collection

In order to verify strata and make more detailed observations about a unit, rock samples were occasionally collected in the field. Important beds, such as the evaporate boxwork, Corbula, and *Salenia texana* layers were all sampled and examined in the office. In addition, samples were taken from each of the major formations in the study area – including the Hensel and the Cow Creek. If there is something that can be gained from a lab analysis of these rocks, they have been cataloged and stored in the HTGCD office. Groundwater samples were also collected where flowing springs or wells were available. Those samples were repropriated to Sarah Davidson at the Jackson School of Geosciences for study.

-Ground Truthing

Ground Truthing for this project consisted of fieldwork and confirmation of geologic assessments from prior studies. For this project, ground truthing consisted primarily of tracing the boundary between the upper and lower Glen Rose, confirming fault structures suggested on air photos, and confirming recharge points such as sinkholes. The comparative figures used for this study were air photos that had had structural features marked by Al Broun, and geologic maps of the area as compiled by DeCook. In some instances, such as with a large throw fault, it is difficult to find evidence on the outcrop. However, using the data that is available, inferences can be made about the locations of these structures, such as finding a smaller throw fault that is a piece of a much larger damage zone.

Fig 11- Example of marked air photo showing inferred fault structures.

-Field Work Summary

Stage one of this project involved driving down just about every road in the watershed in order to find bedding exposures. This phase has been completed. The next stage involves less driving and more on foot inspection of large properties for outcrops. This is where air photo observation plays an important role. By identifying where potential outcrops are located, the district can obtain permission to walk some of the properties where the gaps in field data exist. By filling in these spatial gaps a more complete and clear view of the watershed will be possible.

Resultant Data

-Structural Mapping

The stress history of the region is typical for that of a normal fault zone. In the Miocene, 15-20 million years ago, the horizontal stress on the region from the NW-SE direction was reduced. This shifted the dominant principle stress axis to the vertical plane, and made this NW-SE direction the minor stress axis. The resulting fault strikes trended perpendicular to this minor axis, or NE-SW. (Jordan 1977) Though the major displacement faults trend this direction, there are many minor faults throughout the region that formed antithetically or at a 60 degree angle.

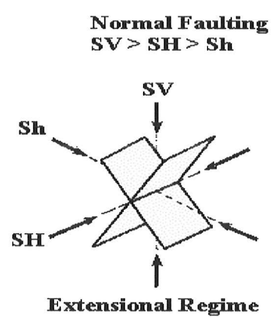

Figure 12- Stress Diagram of region, SV is the vertical stress, SH is the major horizontal stress, Sh is the minor horizontal stress. Faulting occurs along the planes, running NE-SW. (Wolter 2006)

After collecting over 200 data points across the Cypress Creek watershed, these points were entered into Rockworks® and Mapinfo® GIS in order to conceptualize the results. Figure 13 below displays a map of the watershed area with the locations and orientations of the joint and fault data that were collected. The majority of the joints in the area are vertical or nearly vertical. Those points do not have a dip indicated. There are still sections of the watershed that need to have data collected, however permission must be obtained to access these properties.

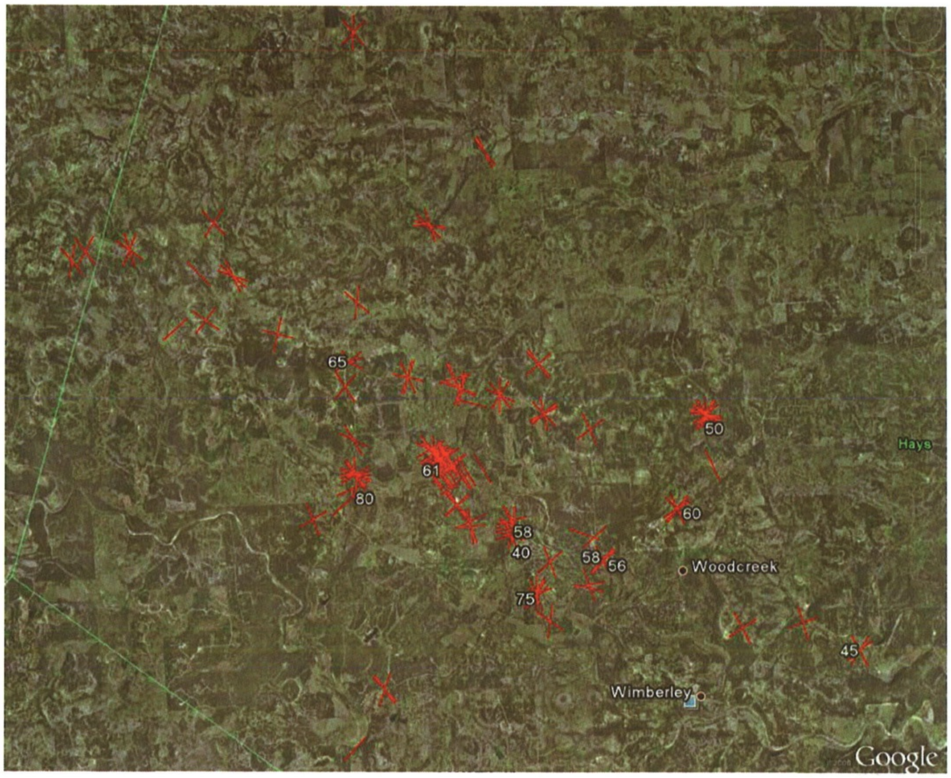

Fig 13- Total Structural Map of the Cypress Creek Watershed.

The general structural trends of the region are best recognized when presented in a rose diagram. As seen in Figure 14, the most prevalent orientation of jointing was found to be in the direction of the region's minor stress axis (310-330˚), and perpendicular to the normal faulting that resulted from the vertical stress (45-60˚). This alignment of jointing and the overall low angle dip of bedding to the southeast indicates a dominant flow direction of groundwater in the Middle Trinity aquifer along this access. This flow vector would of course need to be confirmed through dye tracing or chemical evolution modeling of ground waters. With regard to carbonate systems such as the Glen Rose formation, "The most important joint systems are those formed by tensile stress." (Milanovic 04)

The secondary orientation of joints is aligned with the Balcones Fault Zone, and represents the 90° joint set to the minor stress axis. In addition, many of the located minor faults fall into this set, as they are part of the much larger fault zone. Twin minor trends also exist, as 60° conjugates to the existing patterns. "This [joint generated] porosity represents the controlling force in the karstification process." (Milanovic 04)

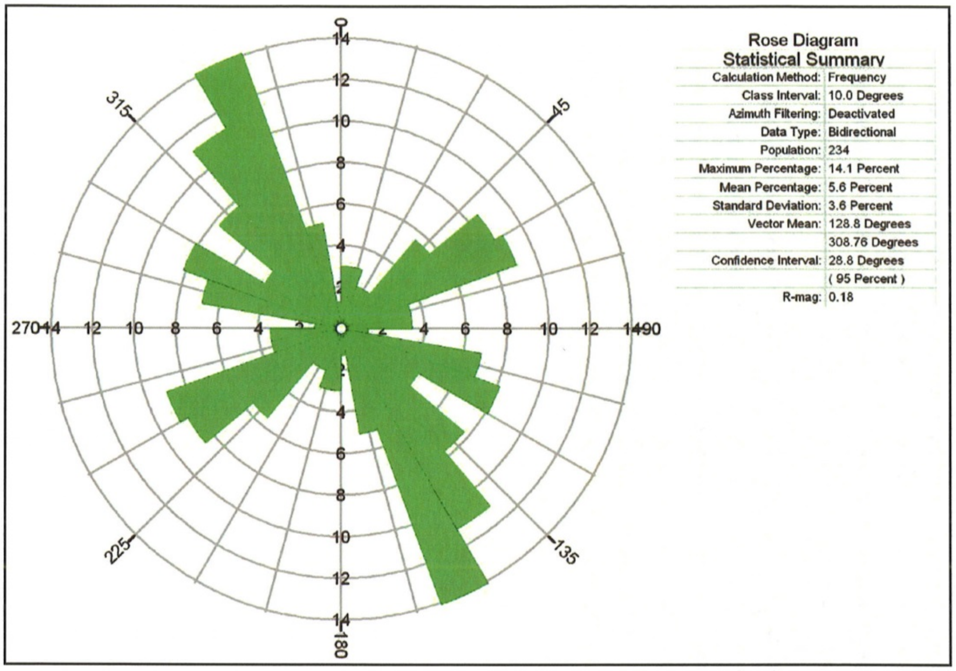

Figure 14- Rose Diagram of Joints and Faults in the Cypress Creek Watershed

Figure 15 displays a map of the Cypress Creek Watershed with the ground truthed faults displayed in red. These faults either fall within the dominant trend of 45-60˚ (the typical BFZ strike within the region) or are conjugates offset by 60˚ (105-120˚). The conjugate trend exhibits an interesting correlation, as it seems to correspond with the A tunnel of Jacob's Well. Jacob's Well is located very near a major fault that falls within the dominant fault trend. It is possible that the A tunnel follows a conjugate fault away from this major fault.

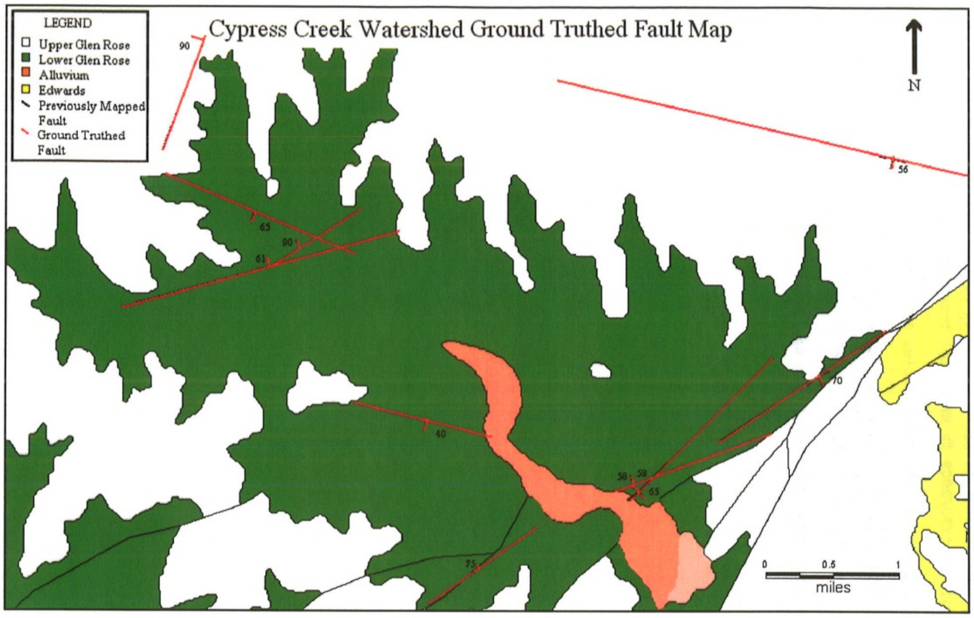

Figure 15- Ground Truthed Fault Map of Cypress Creek Watershed

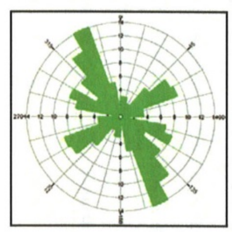

Fig 16- Artificial color image of Jacob's Well site with line plot of explored cave passage. Rose diagram of region structure for comparison.

One of the major goals of this study was to locate and trace the Corbula Bed with GPS coordinates. Land access limited what could be found in the study area; however, over 20 points on roadside or access-granted property were taken and compared with previous maps. Below, Figure 17 displays a topographic map joined with the previously completed trace of the Upper and Lower Glen Rose. The red line indicates this contact corresponding with the ground truthed locations.

Figure 17- Corbula Bed trace in Cypress Creek Watershed

The previously completed work matches well with the true contact location. In some places, the geologic map was within a few meters of the actual Corbula bed outcrop location; in others, tens of meters. For use in determining large throw faults it should be accurate enough. Again, there are large sections of land that could not be accessed due to property rights. There are no traced Corbula locations shown in the northwest section of the watershed due to this. It is possible that large throw faults could exist in these areas and have not been located; work should be done in the future to complete this survey by gaining access to some of these properties.

- Karstification

Groundwater recharge and discharge within the watershed was noted whenever observed in the field. Each of these examples demonstrates how groundwater is interacting with the carbonate rocks of the region.

Figure 18- from top left clockwise, two shots of a sinkhole in lower Glen Rose along fault scarp, Glen Rose fracture filled with a stained calcitic matrix, discharge flowing from joint in upper Glen Rose

Analysis

The existing mapped location of the lower and upper Glen Rose contact should be adequate for analyzing the structure of the area with regard to large throw faults. (Decook 1954)

There is substantial evidence that the area of the watershed was weakened by a minor stress axis bearing 310-330˚ NW – SE and was faulted by en echelon normal faults due to the unbalanced vertical stress. The resultant fracturing in the Upper and Lower Glen Rose formation produced a directional joint pattern and anisotropic secondary porosity. However, the more competent beds of the lower Glen Rose suffered the most extensive and enduring fracturing. These fractures are the most likely features to develop into flow conduits. Where exposed these features are more likely to develop into recharge or discharge points. This is especially true in channel bottoms as "permeability and porosity development is enhanced for carbonate rocks located in valley bottom settings." (Milanovic 2004)

There is sufficient evidence to assume that the lower Glen Rose takes significant recharge from meteoric water through fault and joint related sinkholes. These holes can be quite large, but even very tight openings in jointing patterns can allow for recharge, as "openings with a width of only .5-2 micrometers contain free gravitational water." (Sokolv 1962) In the lower Glen Rose, though regional groundwater flow should move laterally along the limestone-shale bedding planes, the fact that these fractures often continue through shale beds into the next limestone layer suggests that there may be deep percolation into the aquifer.

Future Work Considerations

Though important steps have been taken in recording the geologic structure of the Cypress Creek watershed, there are still more work to be done to complete the data set. The cooperation of local property owners is necessary in order to have access to several important areas in the region. Several key sites have been identified as target areas, and contact information on the residents of these areas has been collected. Cooperation needs to start with a mutual understanding that the number one goal with regards to future living and development in the area needs to be sustainability.

Well planned, large scale dye trace studies should also be considered for the region. These might be the most accurate manner in which to determine the true nature of the interaction between the surface karst systems and the groundwater flow paths.

Acknowledgements

A special thanks to the individuals who were generous enough to devote their time and energy to the Hays Trinity Groundwater Conservation District. In addition, none of this work could have been accomplished without the guidance of Al Broun, whose passion for the general well being of the people in Hays County keeps him going when he should be relaxing.

Thank you very much Lila Calhoun and the Calhoun family, the data and pictures taken from the beautiful Calhoun Ranch were instrumental in the completion of this report.

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Appendix (list of data points, locations, and information)

Name	Date	Easting	Northing	Elevation	Latitude	Longitude	Type	Strike	Dip
A 001	18-JUN-08 9:20:23AM	587638.2	3325313	1203	-98.0909	30.05577	joint	335	90
A 002	18-JUN-08 10:01:05AM	586973.4	3323634	1182	-98.0979	30.04067	location		
A 003	18-JUN-08 10:29:59AM	586583.7	3324137	1055	-98.1019	30.04523	fault	64	70
A 003	18-JUN-08 10:29:59AM	586583.7	3324137	1055	-98.1019	30.04523	fault	50	60
A 003	18-JUN-08 10:29:59AM	586583.7	3324137	1055	-98.1019	30.04523	joint	134	90
A 003	18-JUN-08 10:29:59AM	586583.7	3324137	1055	-98.1019	30.04523	joint	224	90
A 003	18-JUN-08 10:29:59AM	586583.7	3324137	1055	-98.1019	30.04523	joint	246	90
A 003	18-JUN-08 10:29:59AM	586583.7	3324137	1055	-98.1019	30.04523	joint	156	90
A 004	18-JUN-08 11:12:16AM	586790.3	3321989	980	-98.0999	30.02583	corbula		
A 005	18-JUN-08 11:26:27AM	588242.3	3320693	948	-98.085	30.01403	joint	332	90
A 005	18-JUN-08 11:26:27AM	588242.3	3320693	948	-98.085	30.01403	joint	242	90
A 005	18-JUN-08 11:26:27AM	588242.3	3320693	948	-98.085	30.01403	joint	334	90
A 005	18-JUN-08 11:26:27AM	588242.3	3320693	948	-98.085	30.01403	joint	244	90
A 006	18-JUN-08 11:55:01AM	587673	3319517	854	-98.091	30.00347	corbula		
A 007	18-JUN-08 2:26:38PM	583628.8	3322628	939	-98.1327	30.03182	corbula		
A 008	20-JUN-08 10:45:49AM	586745.1	3325284	1077	-98.1001	30.05557	corbula		
A 009	20-JUN-08 11:28:14AM	586072.3	3325428	1102	-98.1071	30.05692	corbula		
A 010	20-JUN-08 12:19:52PM	586449.7	3325662	1080	-98.1032	30.059	corbula		
A 011	20-JUN-08 12:33:09PM	586377.5	3325440	1088	-98.1039	30.057	corbula		
B 001	23-JUN-08 10:35:01AM	587522.3	3326753	1272	-98.0919	30.06877	joint	215	90
B 001	23-JUN-08 10:35:01AM	587522.3	3326753	1272	-98.0919	30.06877	joint	304	90

B 001	23-JUN-08 10:35:01AM	587522.3	3326753	1272	-98.0919	30.06877	joint	110	58
B 001	23-JUN-08 10:35:01AM	587522.3	3326753	1272	-98.0919	30.06877	joint	310	90
B 001	23-JUN-08 10:35:01AM	587522.3	3326753	1272	-98.0919	30.06877	joint	105	69
B 001	23-JUN-08 10:35:01AM	587522.3	3326753	1272	-98.0919	30.06877	joint	305	90
B 001	23-JUN-08 10:35:01AM	587522.3	3326753	1272	-98.0919	30.06877	joint	220	90
B 001	23-JUN-08 10:35:01AM	587522.3	3326753	1272	-98.0919	30.06877	joint	223	90
B 001	23-JUN-08 10:35:01AM	587522.3	3326753	1272	-98.0919	30.06877	joint	280	90
B 001	23-JUN-08 10:35:01AM	587522.3	3326753	1272	-98.0919	30.06877	fault	105	51
B 001	23-JUN-08 10:35:01AM	587522.3	3326753	1272	-98.0919	30.06877	fault	100	55
B 001	23-JUN-08 10:35:01AM	587522.3	3326753	1272	-98.0919	30.06877	fault	100	50
B 001	23-JUN-08 10:35:01AM	587522.3	3326753	1272	-98.0919	30.06877	joint	280	90
B 001	23-JUN-08 10:35:01AM	587522.3	3326753	1272	-98.0919	30.06877	joint	328	90
B 001	23-JUN-08 10:35:01AM	587522.3	3326753	1272	-98.0919	30.06877	joint	330	90
B 001	23-JUN-08 10:35:01AM	587522.3	3326753	1272	-98.0919	30.06877	joint	240	90
B 001	23-JUN-08 10:35:01AM	587522.3	3326753	1272	-98.0919	30.06877	fault	108	56
B 001	23-JUN-08 10:35:01AM	587522.3	3326753	1272	-98.0919	30.06877	joint	180	90
B 002	23-JUN-08 12:33:26PM	583964.3	3322050	1021	-98.1292	30.02658	joint	284	90
B 003	23-JUN-08 12:41:55PM	583979.7	3322141	1004	-98.1291	30.0274	joint	342	90
B 003	23-JUN-08 12:41:55PM	583979.7	3322141	1004	-98.1291	30.0274	joint	263	90
B 004	23-JUN-08 1:08:17PM	582824.8	3321181	1096	-98.1411	30.01882	joint	305	90
B 004	23-JUN-08 1:08:17PM	582824.8	3321181	1096	-98.1411	30.01882	joint	305	90
B 004	23-JUN-08 1:08:17PM	582824.8	3321181	1096	-98.1411	30.01882	joint	12	90
B 005	24-JUN-08 1:15:13PM	584237.2	3326502	1187	-98.126	30.06673	joint	155	90
B 005	24-JUN-08	584237.2	3326502	1187	-98.126	30.06673	joint	156	90

	1:15:13PM								
B 005	24-JUN-08 1:15:13PM	584237.2	3326502	1187	-98.126	30.06673	joint	60	90
B 006	24-JUN-08 1:32:53PM	584214.4	3325081	1127	-98.1264	30.05392	corbula		
B 007	24-JUN-08 2:08:44PM	580656.1	3327835	1127	-98.1631	30.079	joint	115	90
B 007	24-JUN-08 2:08:44PM	580656.1	3327835	1127	-98.1631	30.079	joint	194	90
B 007	24-JUN-08 2:08:44PM	580656.1	3327835	1127	-98.1631	30.079	joint	209	90
B 007	24-JUN-08 2:08:44PM	580656.1	3327835	1127	-98.1631	30.079	joint	110	90
B 007	24-JUN-08 2:08:44PM	580656.1	3327835	1127	-98.1631	30.079	joint	208	90
B 008	24-JUN-08 2:17:27PM	580493.3	3328129	1151	-98.1648	30.08167	joint	330	90
B 008	24-JUN-08 2:17:27PM	580493.3	3328129	1151	-98.1648	30.08167	joint	258	90
B 008	24-JUN-08 2:17:27PM	580493.3	3328129	1151	-98.1648	30.08167	joint	261	90
B 008	24-JUN-08 2:17:27PM	580493.3	3328129	1151	-98.1648	30.08167	joint	340	90
B 009	24-JUN-08 2:38:53PM	579183.4	3328234	1150	-98.1783	30.0827	fault	200	90
B 009	24-JUN-08 2:38:53PM	579183.4	3328234	1150	-98.1783	30.0827	joint	155	90
B 009	24-JUN-08 2:38:53PM	579183.4	3328234	1150	-98.1783	30.0827	joint	283	90
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B 010	24-JUN-08 3:04:29PM	578327	3328272	1271	-98.1872	30.0831	location		
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B 013	25-JUN-08 11:04:12AM	577542.9	3328754	1311	-98.1953	30.0875	joint	260	90
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B 014	25-JUN-08 11:36:50AM	577875	3330402	1331	-98.1918	30.10235	joint	192	90
B 014	25-JUN-08 11:36:50AM	577875	3330402	1331	-98.1918	30.10235	joint	130	90
B 015	25-JUN-08 11:54:57AM	580032.8	3332473	1241	-98.1692	30.1209	joint	105	90
B 015	25-JUN-08 11:54:57AM	580032.8	3332473	1241	-98.1692	30.1209	joint	165	90
B 015	25-JUN-08 11:54:57AM	580032.8	3332473	1241	-98.1692	30.1209	joint	105	90
B 016	25-JUN-08 12:41:03PM	581686.5	3334440	1188	-98.1519	30.13853	joint	335	90
B 016	25-JUN-08 12:41:03PM	581686.5	3334440	1188	-98.1519	30.13853	joint	320	90
C 001	30-JUN-08 10:50:20AM	576304.3	3324388	1203	-98.2085	30.04818	joint	245	90
C 001	30-JUN-08 10:50:20AM	576304.3	3324388	1203	-98.2085	30.04818	joint	160	90
C 002	30-JUN-08 11:17:45AM	576472.1	3323592	1208	-98.2068	30.04098	corbula		
C 003	30-JUN-08 12:26:46PM	578059.7	3319510	1029	-98.1906	30.00405	joint	325	90
C 003	30-JUN-08 12:26:46PM	578059.7	3319510	1029	-98.1906	30.00405	joint	25	90
C 003	30-JUN-08 12:26:46PM	578059.7	3319510	1029	-98.1906	30.00405	joint	323	90
C 003	30-JUN-08 12:26:46PM	578059.7	3319510	1029	-98.1906	30.00405	joint	315	90
C 004	30-JUN-08 12:54:40PM	577127.4	3317878	955	-98.2004	29.98938	joint or fault	230	90
C 005	30-JUN-08 1:10:52PM	574622.2	3318873	1118	-98.2263	29.99852	corbula		
C 006	30-JUN-08 1:19:49PM	574742.4	3318933	1117	-98.2251	29.99905	corbula		
C 007	30-JUN-08 1:22:00PM	574729.2	3318979	1120	-98.2252	29.99947	corbula		
C 009	01-JUL-08 12:31:18PM	591520.2	3319885	923	-98.0511	30.0065	joint	40	90
C 009	01-JUL-08 12:31:18PM	591520.2	3319885	923	-98.0511	30.0065	joint	332	90
C 009	01-JUL-08 12:31:18PM	591520.2	3319885	923	-98.0511	30.0065	joint	331	90
C 009	01-JUL-08 12:31:18PM	591520.2	3319885	923	-98.0511	30.0065	joint	240	45
C 010	01-JUL-08 1:08:49PM	589945.7	3320755	969	-98.0673	30.01447	joint	75	90
C 010	01-JUL-08	589945.7	3320755	969	-98.0673	30.01447	joint	345	90

	1:08:49PM								
D 001	02-JUL-08 12:27:42PM	580205.6	3325504	1036	-98.1679	30.058	joint	332	90
D 002	02-JUL-08 12:38:18PM	580054.8	3325479	1036	-98.1695	30.05778	joint	335	90
D 002	02-JUL-08 12:38:18PM	580054.8	3325479	1036	-98.1695	30.05778	joint	325	90
D 002	02-JUL-08 12:38:18PM	580054.8	3325479	1036	-98.1695	30.05778	joint	60	90
D 003	02-JUL-08 12:49:12PM	579958.1	3325515	1033	-98.1705	30.05812	fault	256	61
D 004	02-JUL-08 12:57:28PM	579887.4	3325513	1040	-98.1712	30.0581	joint	320	90
D 004	02-JUL-08 12:57:28PM	579887.4	3325513	1040	-98.1712	30.0581	joint	321	90
D 005	02-JUL-08 1:03:33PM	579738.6	3325427	1034	-98.1728	30.05733	joint	328	90
D 005	02-JUL-08 1:03:33PM	579738.6	3325427	1034	-98.1728	30.05733	joint	318	90
D 006	02-JUL-08 2:06:56PM	580511.6	3325406	1016	-98.1648	30.0571	joint	325	90
D 007	02-JUL-08 2:11:09PM	580573.9	3325455	1018	-98.1641	30.05753	joint	330	90
D 008	02-JUL-08 2:15:23PM	580692.4	3325506	1016	-98.1629	30.05798	joint	330	90
D 009	02-JUL-08 2:42:28PM	580337.5	3325706	1040	-98.1666	30.05982	joint or fault	235	90
D 010	02-JUL-08 2:48:24PM	580334.1	3325734	1056	-98.1666	30.06007	fault	236	90
D 011	02-JUL-08 2:55:30PM	580240.4	3325798	1058	-98.1676	30.06065	joint	335	90
D 012	02-JUL-08 3:03:43PM	580203	3325860	1062	-98.1679	30.06122	joint	325	90
D 013	02-JUL-08 3:06:58PM	580192.8	3325940	1062	-98.168	30.06193	joint	330	90
D 014	02-JUL-08 3:10:44PM	580123.7	3325949	1062	-98.1688	30.06202	joint	333	90
D 014	02-JUL-08 3:10:44PM	580123.7	3325949	1062	-98.1688	30.06202	joint	245	90
E 001	07-JUL-08 10:38:06AM	583051.6	3321809	1074	-98.1387	30.02447	corbula		
E 002	07-JUL-08 11:08:06AM	582481.2	3322000	1035	-98.1446	30.02623	joint	215	90
E 002	07-JUL-08 11:08:06AM	582481.2	3322000	1035	-98.1446	30.02623	joint	185	90
E 002	07-JUL-08 11:08:06AM	582481.2	3322000	1035	-98.1446	30.02623	joint	260	90

E 003	07-JUL-08 11:12:01AM	582468.8	3321943	1042	-98.1447	30.02572	joint	160	90
E 003	07-JUL-08 11:12:01AM	582468.8	3321943	1042	-98.1447	30.02572	joint	220	90
E 004	07-JUL-08 11:18:31AM	582459.7	3321862	1046	-98.1448	30.02498	fault	235	75
E 005	07-JUL-08 11:30:24AM	582582.8	3321739	1074	-98.1436	30.02387	corbula		
E 006	07-JUL-08 11:50:10AM	582908.8	3322838	966	-98.1401	30.03377	joint	160	90
E 006	07-JUL-08 11:50:10AM	582908.8	3322838	966	-98.1401	30.03377	joint	235	90
E 007	07-JUL-08 12:25:11PM	581947.6	3323947	995	-98.15	30.04383	joint	110	90
E 007	07-JUL-08 12:25:11PM	581947.6	3323947	995	-98.15	30.04383	joint	190	90
E 007	07-JUL-08 12:25:11PM	581947.6	3323947	995	-98.15	30.04383	joint	185	90
E 007	07-JUL-08 12:25:11PM	581947.6	3323947	995	-98.15	30.04383	joint	155	90
E 008	07-JUL-08 12:35:24PM	581885.7	3324059	1010	-98.1506	30.04485	joint	80	58
E 008	07-JUL-08 12:35:24PM	581885.7	3324059	1010	-98.1506	30.04485	joint	150	90
E 009	07-JUL-08 2:27:08PM	584399.1	3322780	939	-98.1247	30.03313	fault	225	58
E 009	07-JUL-08 2:27:08PM	584399.1	3322780	939	-98.1247	30.03313	fault	55	63
E 009	07-JUL-08 2:27:08PM	584399.1	3322780	939	-98.1247	30.03313	fault	50	56
E 009	07-JUL-08 2:27:08PM	584399.1	3322780	939	-98.1247	30.03313	fault	52	51
E 009	07-JUL-08 2:27:08PM	584399.1	3322780	939	-98.1247	30.03313	joint	125	90
E 010	07-JUL-08 2:41:52PM	584339	3322860	940	-98.1253	30.03387	fault	252	58
E 011	08-JUL-08 10:27:06AM	583906	3323579	989	-98.1297	30.04038	joint	110	90
E 011	08-JUL-08 10:27:06AM	583906	3323579	989	-98.1297	30.04038	joint	112	90
E 012	08-JUL-08 10:33:20AM	584202.5	3323476	1041	-98.1266	30.03943	joint	234	90
E 013	08-JUL-08 11:08:34AM	581843.8	3323643	1018	-98.1511	30.0411	joint	152	90
E 013	08-JUL-08 11:08:34AM	581843.8	3323643	1018	-98.1511	30.0411	joint	260	90
E 013	08-JUL-08	581843.8	3323643	1018	-98.1511	30.0411	fault	105	40

	11:08:34AM								
E 014	08-JUL-08 11:23:41AM	581867	3323760	1010	-98.1508	30.04215	joint	105	90
E 015	08-JUL-08 11:32:03AM	581918.1	3323810	1008	-98.1503	30.0426	joint	125	90
F 001	09-JUL-08 10:44:43AM	575598.2	3329631	1343	-98.2154	30.09553	joint	198	90
F 001	09-JUL-08 10:44:43AM	575598.2	3329631	1343	-98.2154	30.09553	joint	285	90
F 002	09-JUL-08 10:51:46AM	573589	3330112	1287	-98.2363	30.1	joint	125	90
F 002	09-JUL-08 10:51:46AM	573589	3330112	1287	-98.2363	30.1	joint	225	90
F 003	09-JUL-08 11:00:29AM	572713.4	3329920	1243	-98.2454	30.09832	joint	55	90
F 004	09-JUL-08 11:17:06AM	569902.8	3331956	1365	-98.2744	30.11685	joint	320	90
F 004	09-JUL-08 11:17:06AM	569902.8	3331956	1365	-98.2744	30.11685	joint	195	90
F 005	09-JUL-08 11:25:31AM	570294.6	3332215	1308	-98.2703	30.11917	joint	322	90
F 005	09-JUL-08 11:25:31AM	570294.6	3332215	1308	-98.2703	30.11917	joint	322	90
F 005	09-JUL-08 11:25:31AM	570294.6	3332215	1308	-98.2703	30.11917	joint	215	90
F 006	09-JUL-08 11:41:28AM	573451.7	3331447	1320	-98.2376	30.11205	joint	315	90
F 007	09-JUL-08 11:48:15AM	574430.5	3331311	1465	-98.2274	30.11077	joint	110	90
F 007	09-JUL-08 11:48:15AM	574430.5	3331311	1465	-98.2274	30.11077	joint	130	90
F 007	09-JUL-08 11:48:15AM	574430.5	3331311	1465	-98.2274	30.11077	joint	335	90
F 008	09-JUL-08 12:05:24PM	573972.4	3332817	1589	-98.2321	30.12438	joint	135	90
F 008	09-JUL-08 12:05:24PM	573972.4	3332817	1589	-98.2321	30.12438	joint	220	90
F 009	09-JUL-08 12:33:35PM	571558.4	3332186	1387	-98.2572	30.11883	joint	125	90
F 009	09-JUL-08 12:33:35PM	571558.4	3332186	1387	-98.2572	30.11883	joint	165	90
F 009	09-JUL-08 12:33:35PM	571558.4	3332186	1387	-98.2572	30.11883	joint	210	90
G 001	14-JUL-08 10:00:18AM	578166.4	3337975	1233	-98.1882	30.17067	joint	230	90
G 001	14-JUL-08 10:00:18AM	578166.4	3337975	1233	-98.1882	30.17067	joint	320	90

G 001	14-JUL-08 10:00:18AM	578166.4	3337975	1233	-98.1882	30.17067	joint	185	90
G 002	14-JUL-08 10:10:06AM	579997.8	3332440	1259	-98.1696	30.1206	joint	275	90
G 002	14-JUL-08 10:10:06AM	579997.8	3332440	1259	-98.1696	30.1206	joint	135	90
G 003	14-JUL-08 10:52:47AM	580945.2	3327408	1103	-98.1601	30.07513	joint	105	90
G 004	14-JUL-08 11:17:06AM	582889.4	3328414	1308	-98.1399	30.08408	joint	315	90
G 004	14-JUL-08 11:17:06AM	582889.4	3328414	1308	-98.1399	30.08408	joint	235	90
G 004	14-JUL-08 11:17:06AM	582889.4	3328414	1308	-98.1399	30.08408	joint	325	90
G 005	14-JUL-08 12:37:09PM	582961	3327015	1192	-98.1392	30.07145	joint	245	90
G 005	14-JUL-08 12:37:09PM	582961	3327015	1192	-98.1392	30.07145	joint	250	90
G 005	14-JUL-08 12:37:09PM	582961	3327015	1192	-98.1392	30.07145	joint	170	90
G 005	14-JUL-08 12:37:09PM	582961	3327015	1192	-98.1392	30.07145	joint	235	90
G 005	14-JUL-08 12:37:09PM	582961	3327015	1192	-98.1392	30.07145	joint	135	90
H 001	15-JUL-08 9:54:12AM	580304.6	3325143	1081	-98.1669	30.05473	joint	240	90
H 002	15-JUL-08 10:17:11AM	580407.8	3324658	1147	-98.1659	30.05035	corbula		
H 003	15-JUL-08 10:24:23AM	580365.1	3324571	1164	-98.1664	30.04957	joint	135	90
H 003	15-JUL-08 10:24:23AM	580365.1	3324571	1164	-98.1664	30.04957	joint	234	90
H 003	15-JUL-08 10:24:23AM	580365.1	3324571	1164	-98.1664	30.04957	joint	140	90
H 003	15-JUL-08 10:24:23AM	580365.1	3324571	1164	-98.1664	30.04957	joint	238	90
H 003	15-JUL-08 10:24:23AM	580365.1	3324571	1164	-98.1664	30.04957	joint	236	90
H 003	15-JUL-08 10:24:23AM	580365.1	3324571	1164	-98.1664	30.04957	joint	150	90
H 004	15-JUL-08 10:41:18AM	580470	3324499	1160	-98.1653	30.04892	corbula		
H 005	15-JUL-08 10:57:15AM	580505.4	3324490	1157	-98.1649	30.04883	corbula		
H 006	15-JUL-08 11:02:28AM	580639.5	3324617	1156	-98.1635	30.04997	corbula		
H 007	15-JUL-08	580734.1	3324642	1155	-98.1625	30.05018	corbula		

	11:05:43AM								
H 008	15-JUL-08 11:08:21AM	580701.1	3324543	1160	-98.1629	30.0493	corbula		
H 009	15-JUL-08 11:13:24AM	580787.4	3324382	1166	-98.162	30.04783	corbula		
H 010	15-JUL-08 11:17:28AM	580975.1	3324433	1159	-98.16	30.04828	corbula		
H 011	15-JUL-08 11:21:19AM	581068.4	3324406	1159	-98.1591	30.04803	corbula		
H 012	15-JUL-08 11:23:20AM	581070.4	3324358	1161	-98.1591	30.0476	corbula		
H 013	15-JUL-08 11:25:36AM	581035.4	3324308	1169	-98.1594	30.04715	corbula		
H 014	15-JUL-08 11:30:58AM	580971.7	3324231	1166	-98.1601	30.04647	corbula		
H 016	15-JUL-08 12:10:14PM	580721.4	3323962	1111	-98.1627	30.04405	joint	175	90
H 016	15-JUL-08 12:10:14PM	580721.4	3323962	1111	-98.1627	30.04405	joint	268	90
H 016	15-JUL-08 12:10:14PM	580721.4	3323962	1111	-98.1627	30.04405	joint	160	90
H 017	15-JUL-08 12:19:01PM	580771.6	3324123	1139	-98.1622	30.0455	joint	70	90
H 018	15-JUL-08 12:22:02PM	580779.2	3324189	1152	-98.1621	30.0461	corbula		
H 019	15-JUL-08 12:44:42PM	580774.6	3325255	1101	-98.1621	30.05572	corbula		
H 020	15-JUL-08 1:52:38PM	579989.1	3325892	1078	-98.1702	30.06152	joint	150	90
H 020	15-JUL-08 1:52:38PM	579989.1	3325892	1078	-98.1702	30.06152	joint	235	90
H 020	15-JUL-08 1:52:38PM	579989.1	3325892	1078	-98.1702	30.06152	joint	240	90
H 020	15-JUL-08 1:52:38PM	579989.1	3325892	1078	-98.1702	30.06152	joint	135	90
H 021	15-JUL-08 1:58:33PM	579902	3325934	1079	-98.1711	30.0619	joint	145	90
H 021	15-JUL-08 1:58:33PM	579902	3325934	1079	-98.1711	30.0619	joint	245	90
H 021	15-JUL-08 1:58:33PM	579902	3325934	1079	-98.1711	30.0619	joint	190	90
H 022	15-JUL-08 2:06:12PM	579838.9	3325994	1081	-98.1717	30.06245	joint	245	90
H 022	15-JUL-08 2:06:12PM	579838.9	3325994	1081	-98.1717	30.06245	joint	145	90
H 023	15-JUL-08 2:09:52PM	579801.6	3326053	1081	-98.1721	30.06298	joint	125	90

H 023	15-JUL-08 2:09:52PM	579801.6	3326053	1081	-98.1721	30.06298	joint	135	90
H 023	15-JUL-08 2:09:52PM	579801.6	3326053	1081	-98.1721	30.06298	joint	0	90
H 023	15-JUL-08 2:09:52PM	579801.6	3326053	1081	-98.1721	30.06298	joint	245	90
H 024	15-JUL-08 2:18:52PM	579776.6	3326173	1077	-98.1723	30.06407	fault	110	65
H 025	15-JUL-08 2:29:48PM	579710.6	3326186	1077	-98.173	30.06418	joint	115	90
H 025	15-JUL-08 2:29:48PM	579710.6	3326186	1077	-98.173	30.06418	joint	245	90
H 025	15-JUL-08 2:29:48PM	579710.6	3326186	1077	-98.173	30.06418	joint	145	90
H 015	15-JUL-08 11:36:34AM	580898.4	3324144	1163	-98.1609	30.04568	corbula		
I 001	21-JUL-08 10:09:25AM	581138.5	3325583	947	-98.1583	30.05865	joint	150	90
I 002	21-JUL-08 10:30:27AM	577560.5	3325577	1095	-98.1954	30.05883	joint	180	90
I 002	21-JUL-08 10:30:27AM	577560.5	3325577	1095	-98.1954	30.05883	joint	115	90
I 002	21-JUL-08 10:30:27AM	577560.5	3325577	1095	-98.1954	30.05883	joint	260	90
I 002	21-JUL-08 10:30:27AM	577560.5	3325577	1095	-98.1954	30.05883	joint	150	90
I 002	21-JUL-08 10:30:27AM	577560.5	3325577	1095	-98.1954	30.05883	joint	140	90
I 002	21-JUL-08 10:30:27AM	577560.5	3325577	1095	-98.1954	30.05883	joint	110	90
I 002	21-JUL-08 10:30:27AM	577560.5	3325577	1095	-98.1954	30.05883	joint	95	90
I 002	21-JUL-08 10:30:27AM	577560.5	3325577	1095	-98.1954	30.05883	joint	150	90
I 002	21-JUL-08 10:30:27AM	577560.5	3325577	1095	-98.1954	30.05883	joint	245	90
I 002	21-JUL-08 10:30:27AM	577560.5	3325577	1095	-98.1954	30.05883	joint	150	90
I 003	21-JUL-08 10:45:55AM	577553.5	3326564	1168	-98.1954	30.06773	joint	115	90
I 003	21-JUL-08 10:45:55AM	577553.5	3326564	1168	-98.1954	30.06773	joint	150	90
I 004	21-JUL-08 10:54:55AM	577414.5	3328055	1236	-98.1967	30.0812	joint	148	90
I 004	21-JUL-08 10:54:55AM	577414.5	3328055	1236	-98.1967	30.0812	joint	227	90
I 005	21-JUL-08	581750.2	3327601	1189	-98.1518	30.07682	joint	140	90

	11:07:03AM								
I 005	21-JUL-08 11:07:03AM	581750.2	3327601	1189	-98.1518	30.07682	joint	115	90
I 005	21-JUL-08 11:07:03AM	581750.2	3327601	1189	-98.1518	30.07682	joint	185	90
I 005	21-JUL-08 11:07:03AM	581750.2	3327601	1189	-98.1518	30.07682	joint	220	90
J 001	28-JUL-08 10:51:11AM	586615.6	3319666	930	-98.1019	30.00488	joint	125	90
J 001	28-JUL-08 10:51:11AM	586615.6	3319666	930	-98.1019	30.00488	joint	215	65
J 001	28-JUL-08 10:51:11AM	586615.6	3319666	930	-98.1019	30.00488	joint	155	90
J 002	28-JUL-08 11:19:09AM	574023.9	3324196	1035	-98.2322	30.04658	joint	140	90
J 003	28-JUL-08 11:37:24AM	573887.9	3323147	1083	-98.2336	30.03713	joint	115	90
J 003	28-JUL-08 11:37:24AM	573887.9	3323147	1083	-98.2336	30.03713	joint	225	90
J 003	28-JUL-08 11:37:24AM	573887.9	3323147	1083	-98.2336	30.03713	joint	178	90
J 004	28-JUL-08 11:49:56AM	574387.6	3322443	1074	-98.2285	30.03075	joint	145	90
J 004	28-JUL-08 11:49:56AM	574387.6	3322443	1074	-98.2285	30.03075	joint	245	90
J 005	28-JUL-08 12:03:04PM	572239.8	3321816	1187	-98.2508	30.02522	joint	145	90
J 005	28-JUL-08 12:03:04PM	572239.8	3321816	1187	-98.2508	30.02522	joint	222	90
J 006	28-JUL-08 12:15:23PM	573088.8	3321997	1147	-98.242	30.0268	joint	115	90
J 006	28-JUL-08 12:15:23PM	573088.8	3321997	1147	-98.242	30.0268	joint	165	90
J 006	28-JUL-08 12:15:23PM	573088.8	3321997	1147	-98.242	30.0268	joint	165	90
J 007	28-JUL-08 12:25:33PM	573811.6	3321337	1131	-98.2346	30.0208	joint	135	90
J 007	28-JUL-08 12:25:33PM	573811.6	3321337	1131	-98.2346	30.0208	joint	130	90
J 007	28-JUL-08 12:25:33PM	573811.6	3321337	1131	-98.2346	30.0208	joint	225	90
J 007	28-JUL-08 12:25:33PM	573811.6	3321337	1131	-98.2346	30.0208	joint	135	90
J 008	28-JUL-08 12:41:03PM	571942.3	3319858	1188	-98.254	30.00757	joint	250	90
J 008	28-JUL-08 12:41:03PM	571942.3	3319858	1188	-98.254	30.00757	joint	160	90

J 009	28-JUL-08 1:08:58PM	577354.2	3319244	966	-98.198	30.0017	joint	135	90
J 009	28-JUL-08 1:08:58PM	577354.2	3319244	966	-98.198	30.0017	joint	98	90
J 009	28-JUL-08 1:08:58PM	577354.2	3319244	966	-98.198	30.0017	joint	245	90
J 009	28-JUL-08 1:08:58PM	577354.2	3319244	966	-98.198	30.0017	joint	152	90
J 009	28-JUL-08 1:08:58PM	577354.2	3319244	966	-98.198	30.0017	joint	140	90
J 010	29-JUL-08 11:55:54AM	575025.4	3323177	943	-98.2218	30.03733	joint	155	90
J 011	29-JUL-08 12:05:21PM	574975	3323262	919	-98.2224	30.0381	fault	115	90
J 012	29-JUL-08 12:09:05PM	574981.1	3323314	932	-98.2223	30.03857	joint	230	90
J 012	29-JUL-08 12:09:05PM	574981.1	3323314	932	-98.2223	30.03857	joint	115	90

Appendix 3

Delineating Contributing Areas in Two Texas Karst Aquifers Using NEXRAD Rainfall Estimates

Delineating contributing areas in Two Texas Karst Aquifers using NEXRAD rainfall estimates

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Abstract

Coupling spring discharge and Next Generation Radar (NEXRAD) using cross-correlation analysis provides a powerful tool for understanding the relationship between groundwater recharge and discharge in a karst aquifer. NEXRAD provides a spatial estimate of precipitation based on reflectivity measurements and traditional precipitation gages. NEXRAD data are available for a 10-year period on an hour time step for the entire United States. This study combines NEXRAD precipitation data with spring discharge data to develop maps of contributing areas for two karst springs in Central Texas, USA. By calculating the cross-correlation of each NEXRAD measurement to spring flow data for the same period of time a map showing the locations of hydraulically connected locations to the spring can be developed. We prepare contributing area maps for both Barton Springs and Jacob's Well, two karst springs near Austin, Texas, USA. Barton Springs is an area with a precise estimate of the recharge area. The current map of the recharge area and the NEXRAD derived map show good agreement in the spatial location of the recharge areas. Conversely, Jacob's Well has not been sufficiently studied to delineate a contributing area map. This study provides an estimate of the location of the contributing area. The methodology provides insights to water regulators and stakeholders in managing and developing future study plans for the aquifer.

1. INTRODUCTION

Characterizing karst aquifers is a challenging task. Karst refers to a geologic terrain or surface landscape with distinctive characteristics of relief and drainage arising primarily from dissolution of rock (or soils) by natural waters. A typical scenario for karst development may include, tectonic stress or overburden produce fractures in the matrix, enlarging of the fractures through dissolution to form caverns, conduits, sinkholes that act as preferential flow paths for groundwater and discrete recharge features. Due to the formation of these preferential flow paths, characterizing the flow direction through a karst aquifer is difficult. Dye tracer experiments and models (analytical, numerical and stochastic) have been used to help characterize these aquifers.

The Karst Water Institute (2007) estimates that over 25 percent of the world's population derives its water supply from karst aquifers. Because of the difficulty in characterizing flow paths and discrete recharge locations within these aquifers, they are prone to contamination. Furthermore, contamination can spread rapidly throughout the aquifer as it travels through the network of conduits that are typical in karst aquifers. Therefore, characterizing karst aquifers both in terms of travel times and geo spatial location of recharge features is important for aquifer protection and management.

Padilla and Pulido-Bosch (1995) discuss the use of cross-correlation analysis in characterizing karst systems. They used the correlation of precipitation and spring discharge to develop the conceptual understanding of a karst aquifer. The cross-correlation analysis was useful in determining the dominant flow type (conduit flow or matrix flow) of the karst aquifer along with estimating the lag time between precipitation events and increased discharge at a spring. They conducted numerical experiments to illustrate the different responses of cross-correlation analysis and applied the methods to field data to characterize several karst aquifers. This method has been extended by Larocque (1998), Lee, (2000), and Panagopoulos & Lambrakis(2006) to establish a method for characterizing aquifer systems. Larocque used more than one precipitation gage in characterizing the La Rochefoucauld karst aquifer near Charten, France; Lee used multiple observation wells in discussing the heterogeneities of their study area; Pangopoulos & Lambrakis applied the methods to two karst aquifers in Greece.

Cross-correlation analysis has been extended for use with spatially varying precipitation to estimate, the location of the aquifer recharge zones. Over the last decade, the use of radar to track and estimate precipitation totals has allowed the increased analysis of precipitation variation The WSR-88D weather radar network (NEXRAD) covers the majority of the continental USA. It is archived by the US National Weather Service in a 4 km by 4 km grid pattern. Figure 1 shows an example of the gridded precipitation estimate for the states of New Mexico, Oklahoma, and Texas. By extracting rainfall depth estimates from each location on the grid overtime, the data from each cell can be used as a rain gage in cross-correlation analysis. The differences in the results from cross-correlation analysis at each location can be used to estimate locations where precipitation is relatively more or less likely result in increased flow at a spring.

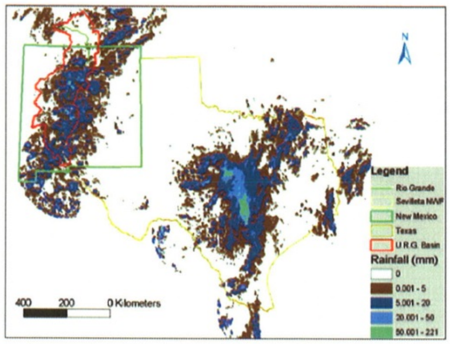

Figure 1 shows an example of the gridded precipitation estimate for the states of New Mexico, Oklahoma, and Texas (Xie, 2005)

In this paper we give background information on our field sites (two karst aquifers in Texas), briefly discuss the methods used to perform the spatial cross-correlation analysis, discuss the application of spatial cross-correlation analysis to our field sites. Each of these is discussed in the following sections.

2. BACKGROUND

Two karst springs in Central Texas, USA were investigated as part of this study. They include Barton Springs and Jacob's Well (Figure 2). A summary of the hydrogeology of the springs and surrounding areas and a comparison of the sites are contained in the follows.

Figure 2 – Relative locations of Barton Springs and Jacob's Well in Texas

2.1. Barton Springs

Barton Springs is located in the Edwards Aquifer near Austin, Texas. The Barton Springs Aquifer (BSA) is a karstic aquifer that roughly coincides with the Balcones Fault System Texas. The aquifer is a cretaceous age limestone and is bounded above by the Del Rio Clay and the Glen Rose limestone below. The aquifer is generally defined by four general boundaries laterally shown in Figure 3; 1) the up-dip boundary is the Mt. Bonnell fault, 2) the down-dip boundary is the bad water line where water quality (TDS) rises above 1000 ppm, 3) A groundwater divide near Onion Creek, and 4) the Colorado river where a series of springs discharge (Senger, 1994). Water quality in the aquifer is generally good and is the sole source of potable water for nearly 66,000 residents (BSEACD, 2003). The current delineation of the recharge zone of the aquifer (see Figure 3) runs from the Mt. Bonnell Fault east to the outcrop of the Del Rio Clay formation. The springs are considered one of the most important aspects of Austin, Texas. Within the last thirty years environmental concerns about the Edwards Aquifer and the rapid development of the area that recharges the springs have caused the future of Barton Springs to become the subject of intense debate.

The current conceptual understanding of flow in BSA is based on many previous reports and studies including (Scanlon, 2004, Hauwert, 1994, Senger, 1994). The majority of groundwater recharge is from infiltration through five streams that flow over the recharge zone. Water enters the aquifer through sink holes in the stream beds. Estimates for the percentage of recharge vary from 50% (Hauwert,2006) to 80% (Slade,1986). The more recent work by Hauwert suggests that some of the recharge previously believed to infiltrate into the aquifer through stream beds actually infiltrates into sink holes away from the stream beds. In either case the majority of groundwater recharge occurs in discrete locations through the delineated recharge zone of the aquifer.

Figure 3 shows the boundaries of the Barton Springs Aquifer with left to right: the contributing zone, the recharge zone, and the confined or artesian zone (BSEACD, 2003).

2.2. Jacob's Well

Jacob's Well is a large spring located near Wimberley, Texas, USA. It produces water from a 30 m deep vertical cavern in Cretaceous age Glen Rose Limestone. The base of the cavern is connected to conduits large enough for divers to navigate. Figure 4 shows the spring orifice. The spring forms the headwaters of Cypress Creek, a tributary of the Blanco River. The unique spring is a center of cultural and historical significance to the surrounding community. Few studies exist detailing the recharge sources for the spring, but during a recent drought, the spring stopped flowing for the first time in recorded history (WVWA, 2007). After this, the USGS began monitoring discharge and water quality at a 15-minute sampling frequency.

Figure 4 – The orifice of Jacob's Well spring at the headwaters of Cypress Creek.

2.3. Selection of the Field sites

Barton springs and Jacob's well were selected based on several criteria. These include 1) comparison of the sites; 2) recorded spring discharges; 3) previous dye tracing experiments. Each of these criteria are discussed below.

2.3.1. Comparison of the sites

Both Barton Springs and Jacob's Well are springs discharging from Cretaceous limestone aquifers. Both are used as indicators of the health of groundwater system in the surrounding communities (BSEACD, 2007, WVMA,2007). Groundwater flow to Barton Springs has been the subject of many studies. But, little work has been done to understand the hydrogeology of Jacob's Well. Hence, Barton Springs was selected as a location to test whether or not cross-correlation using NEXRAD data can reproduce what is generally accepted as the recharge pattern in the aquifer. Applying the same methods to Jacob's Well may allow a better understanding of where recharge is most likely to affect Jacob's Well.

2.3.2. Recorded Spring Discharge

To conduct the cross-correlation analysis both the precipitation and spring discharge data are needed. The period of record for Stage III NEXRAD data is 1994 to present. Barton Springs discharge has been recorded on a 15-minute time step for this entire period. Therefore, the study can be conducted for any time period within the NEXRAD period of record. However, spring discharge at Jacob's Well only has a period of record from 2005 to present. This limits the range of dates usable for this analysis.

2.3.3. Previous Dye Tracing Experiments

Dye tracing experiments at each spring were key to selecting the sites used for the field application. In the case of Barton Springs the City of Austin, Texas and the Barton Springs/Edwards Aquifer Groundwater Conservation District (BSEACD) have conducted over 20 dye-trace experiments in the delineated recharge zone for Barton Springs, shown in Figure 5. Dye tracing provides supporting evidence that the delineated recharge zone for BSA travels to Barton Springs. Matching results of the cross-correlation analysis to the delineated recharge zone supports the hypothesis that we can identify where spring water is coming from using cross-correlation analysis. A dye tracing experiment in 2005 was conducted at Jacob's Well that recovered no dye. This is the only recorded dye trace experiment to occur at the spring. Results from cross-correlation analysis were used to investigate possible reasons that no dye was recovered from the test and to identify locations where further dye-tracing experiments might be conducted.

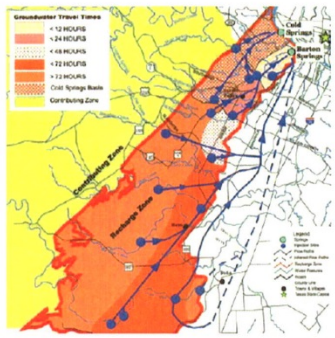

Figure 5 Numerous dye-trace experiments have been carried out within the Barton Springs portion of the Edwards Aquifer Recharge zone. Estimated pathways are signified by blue lines (BSEACD, 2003).

3. METHODOLOGY

Four major steps are involved in developing contributing areas with NEXRAD data. The steps are:

- Collect NEXRAD Data
- Create NEXRAD Time Series
- Run Cross-Correlations Using R Software (R)
- Display Results in GIS

These steps are discussed in the following sections.

3.1. Collect NEXRAD Data

The NWS maintains a database of several years of NEXRAD data on their servers. The location of the servers is http://dipper.nws.noaa.gov/hdsb/data/nexrad/nexrad.html . Data are generally available from 1994 thru 2004 in stage III format. The data are stored in UNIX tar archive files that allow for more efficient transfer of files. Because these files are in a UNIX format and pre-cautions should be taken to ensure the values are correctly read on Windows and Linux workstations.

3.2. Create NEXRAD Time Series

The archived stage III NEXRAD data described in the previous section are available from the NWS in the "xmrg" file format. XMRG is a binary format that stores rainfall depths for a provided set of locations. The NWS also provides source code in the C language called "read_xmrg" (NWS, 2007) to aid in the translation of the files to ASCII values. Each file contains the total rainfall depth estimates for a one hour period. In order to create time series data from these hourly estimates each xmrg file for a specified time period must be read and parsed to extract values for a given location. Given the large period of record (1994-present) the amount of computing to accomplish this task can be overwhelming. The "read_xmrg" program from the NWS was expanded to aid in the processing of more than one xmrg file. Altering the executable allowed the creation of an ASCII comma-delimited file containing the stage III precipitation estimates at each specified NEXRAD cell location for the period of record.

3.3. Run Cross-Correlation Analysis in R Software

Below we describe the steps needed to carry out the cross-correlation calculations necessary in this methodology. We will briefly define cross-correlation analysis. Then, the commands used in R to carry out the analysis are discussed. Finally, pre-processing both the spring discharge and NEXRAD time-series data into a format usable by R is discussed.

3.3.1. Cross-Correlation Equations

Cross-correlation analysis is based on the correlation coefficient. A correlation coefficient is a statistical measure of how well two variables co-vary. A correlation coefficient of 1 represents perfect match in variation of the data about a mean value. A correlation coefficient of -1 two sets of data perfectly mismatch about the meanof each data. Cross-correlation is calculated by carrying out the calculation of the correlation coefficient at several lag intervals. Then, these correlation coefficients are plotted versus the lag to create a correlagram (see Figure 6). The key aspects of the correlagram that this research uses are the maximum correlation coefficient and the lag distance that produces the maximum correlation. Padilla (1995) noted the maximum correlation represents the timing of the impulse response of the aquifer. Furthermore, the value of the maximum correlation is greater when the rainfall and the spring discharge time-series are more correlated and vice versa.

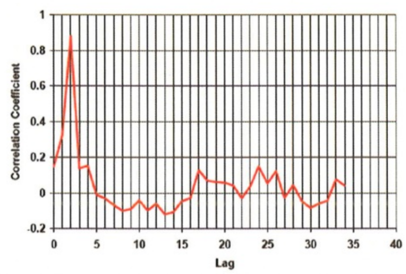

Figure 6 – A correlagram, created from hypothetical data, illustrating the maximum correlation at a lag of 2.

3.3.2. Statistical Significance

Similar work with spatial varying readings and cross-correlation analysis has been conducted by neuroscientists. They use spatial cross-correlation analysis to estimate locations on the brain responsible for control of specific bodily functions (Wiegner et al, 1987, Zygierewicz, 2006). Kwan (2004) described the methodology for calculating a threshold value above which the correlation is statistically significant. The following steps outline the process for determining statistical significance:

- randomize the time-series for 99 iterations
- run the cross-correlation analysis on all 99 cases
- the maximum value of correlation from these cases is the significance threshold
- if the maximum correlation for the non-randomized data is larger than the significance threshold, then the result is statistically significant

Calculating the statistical significant threshold provides a quantitative measure as to whether the maximum correlation values from the correlagrams not necessarily based on random occurrence.

3.3.3. R Software

R software (R Software, 2007) is an open-source statistical computing environment used throughout the world by both industry and academicians. Based on command line arguments and scripting routines the package can be used to automate complex statistical analysis. All cross-correlation equations used in this study are built into the base R software package. R source files were generated to organize commands that carried out the analysis. Figure 7 shows an example R source file generated to carry out each of the R commands necessary for running the cross-correlation analysis for one NEXRAD cell including statistical significance calculations. Included in the commands are output commands for creating GIS files.

```
p<-read.table("daily.txt1_prp.txt")
r<-read.table("daily.txt1_flw.txt")
attach(r)
rd<-aggregate(V3,list(Day=V1),mean)
detach(r)
attach(p)
pd<-aggregate(V3,list(Day=V1),sum)
detach(p)
ld<-ccf(rd[2],pd[2],lag.max=50)
dev.print(jpeg, file="./tmpjpgs/cell1.jpg", width=1024, height=768)
dev.off()
write.table(ld$acf,"GISOUT.txt",row.names=FALSE,col.names=FALSE,sep="
",eol=",",append=TRUE)
write.table(which.max(ld$acf),"GISOUT.txt",row.names=FALSE,col.names=FALSE,sep=",",eol=",",a
ppend=TRUE)
write.table(max(ld$acf),"GISOUT.txt",row.names=FALSE,col.names=FALSE,sep=",",eol="\n",append
=TRUE)
win.graph(width=4,height=4,pointsize=12)
```

Figure 7 – R source code for carrying out the cross-correlation for an individual cell of NEXRAD data

3.3.4. Spring Discharge Pre-Processing

Figure 8 shows the discharge hydrograph at Barton Springs from 1994 thru 2004. The level of the flow at the springs varies on a daily basis. Also, there is a larger pattern on a temporal scale revealing periods of relatively high discharge amounts and low discharge amounts. These time periods roughly coincide with the rainy season and dry seasons in the central portion of the State of Texas (TWDB, 2007).

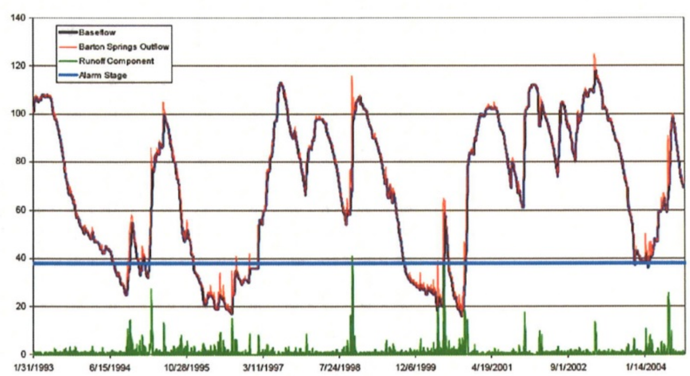

Figure 8 Barton Springs hydrograph from 1993 to 2004 including estimates of baseflow.

The effects of the large scale temporal patterns on correlagrams are illustrated in Figure 9. The correlagram resulting from cross-correlation analysis of the unaltered discharge data indicates a porous media response. This is seen in the lack of a sharp peak in the initial lag periods and the

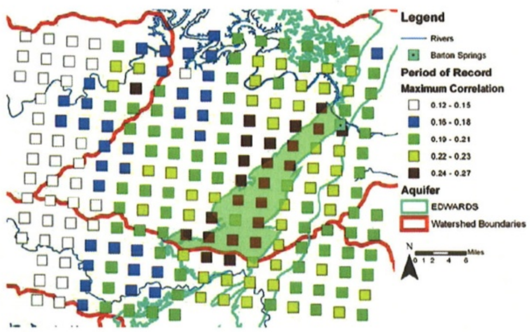

Figure 10 Maximum correlation for each NEXRAD cell with respect to precipitation vs. discharge at Barton Springs. Currently defined recharge zone (see Figure 3) shaded in green.

4. FIELD APPLICATION OF CROSS-CORRELATION ANALYSIS

The algorithms discussed in the previous section were applied to data collected from both Barton Springs and Jacob's Well. The analyses of these data are discussed in the following sections.

4.1. Barton Springs

Figure 9 shows an example correlagrams from the cross-correlation analysis of Barton Springs discharge and precipitation. The response shows the maximum correlation at three days of lag. The value for maximum correlation is 0.27. The significant correlation value is representing by the dashed line at a value of 0.13. For this correlagram the maximum correlation is well defined and above the significant threshold. The spatial variation in the maximum correlation is shown in Figure 10. The recharge zone as delineated by the BSA is also shown in the figure. The highest maximum correlations generally follow the delineated recharge zone for the aquifer. Figure 11 shows the same region only the values represent the difference between the maximum correlation and the statistical significance threshold value. The average significance threshold is 0.15 with a standard deviation of 0.024. Again, the locations where the difference between the maximum correlation and the significance threshold are highest are located in and near the delineated recharge zone.

The locations of highest maximum correlation and the largest difference both follow the delineated boundary with exception of a various locations directly up-dip of the Mt. Bonnell Fault. While the Mt. Bonnell fault is is the recharge zone boundary, these correlation values suggest that precipitation in this region recharges the aquifer.

4.2. Jacob's Well

The shape of the correlagrams for calculated at Jacob's Well are similar to those for Barton Springs. And example correlagram is shown in Figure 12. In most cases the maximum correlation value was higher than the statistically significant threshold. Figure 13 and 14 show both the maximum correlation and statistically significant difference plot respectively.

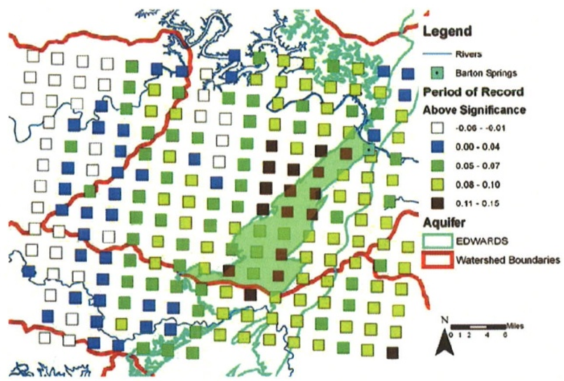

Figure 11 Plot of difference between maximum correlation value and the statically significant value for each NEXRAD cell in the study domain. Currently defined recharge zone (see Figure 3) shaded in green.

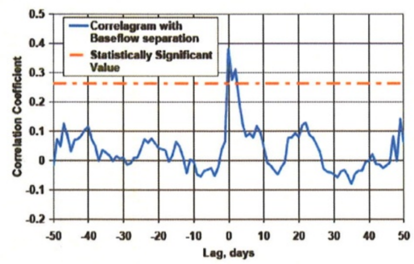

Figure 12 Correlagram of a NEXRAD cell near Jacob's Well.

While there is no delineated recharge zone for this spring the pattern highest maximum correlation is consistent with the general structure in the area. Figures 13 and 14 also contain the delineated catchment zone using topographic relief. For the most part the highest values of maximum correlation lie to the northwest of the spring and within the topographic catchment. Moving to the south and east reveals lower and lower values of maximum correlation indicating that the likely recharge zone is up-dip of the spring.

The previously discussed dye-tracing experiment conducted at spring that recovered no dye was conducted at the site marked by the red box in Figure 13. The location resides just outside of the highest maximum correlation values. This suggests that reason no dye was recovered was lack of hydraulic connection between the selected dye injection location and the spring. It would be more likely to recover dye if it were injected into the aquifer in a location to the north and west.

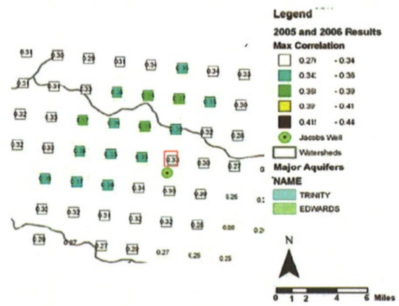

Figure 13 Maximum correlation plot near Jacob's well for data from 2005 and 2006. The red square indicates the location of a previously conducted dye-trace study.

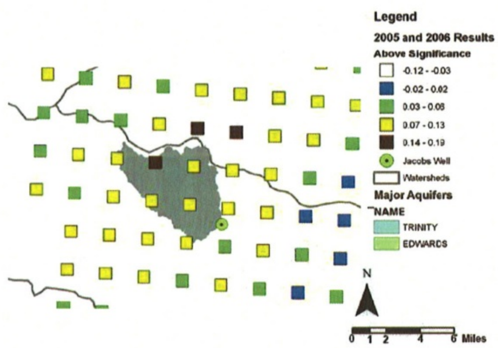

Figure 14 Plot of amount above the statistically significant value NEXRAD cells near Jacob's well. The darkened area is the surface water catchment above Jacob's well derived from the 10 m DEM of the area.

5. SUMMARY AND CONCLUSIONS

Results from cross-correlation analysis of NEXRAD and spring discharge data provide a delineation map of likely recharge locations for two karst aquifers in Texas. Both quantitative (statistical significance measurements) and qualitative (GIS mapping) analysis were used to test the usefulness of this tool in selecting and delineating these regions. In both cases a reasonable map of recharge locations was created based on the highest values of maximum correlation and the plot difference from maximum correlation. By itself the cross-correlation analysis does not provide a comprehensive method for delineating small scale recharge features, it provides and excellent tool for preliminary analysis of recharge locations in karst springs where field data are sparse and a screening tool for the selection of dye-tracing injection locations.

6. ACKNOWLEDGMENTS

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Appendix 4

Cypress Creek Habitat and Watershed Assessment (2005-2006)

Cypress Creek Habitat and Watershed Assessment (2005-2006)
Master of Science Thesis Data

John Eric Dedden
(ericdedden@txstate.edu)

Texas State University Graduate Student
Edwards Aquifer Research and Data Center

Advisors
Dr. Glenn Longley, EARDC Director
Rene A. Barker, P.G. 5592, Staff Hydrogeologist
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EARDC (512) 245-2329

Written comm., 2007
(this is a Master of Science thesis that is still a work in process as of Jan. 26, 2008)

Explanation of John Eric Dedden's Data Presented Below:

From: Barker, Rene A [mailto:rb42@txstate.edu]
Sent: Tuesday, October 23, 2007 8:47 PM
To: Doug Wierman; Andrew Backus
Cc: lesliellado@gmail.com; ericdedden@txstate.edu; RAYMOND643@aol.com; Barker, Rene A; rockwhacker@yahoo.com
Subject: Retry: Gain-Loss Info from Eric Deddon's Thesis (Cypress Creek) Research

Well, the "package" folder didn't seem to work very well. So here we go again, but with individual files.
<<CypCrk_profile.xls>> <<CypCk Gain-Loss (composite).xls>> <<CypCk_Locations.doc>> <<FinalCypCkPR.doc>> <<Site 7 jpg.JPG>> <<Site 8_9 jpg.JPG>> <<Sites 1_2_3 jpg.JPG>> <<Sites 4_5_6 jpg.JPG>> <<CypCkSites.jpg>> <<CypCkDescriptions.doc>>

The attached information results from Eric Dedden's Cypress Creek Habitat and Watershed Assessment (2005-2006).

Until his thesis is published, Eric's work should be cited as from: John Eric Dedden, Texas State University (San Marcos) graduate student, written comm., 2007)

What you're getting has been culled down and pretty extensively reviewed by Raymond, me, or both.

Although we threw out a lot of data that didn't add up to Raymond's and my (USGS-oriented) standards, we were pretty tough on Eric. So, I think it's appropriately valid, given the circumstances. I wouldn't hesitate to use what is attached.

Looking again at these (composite) gain-loss plots, I suspect there might be more of an upstream-to-downstream pattern than I had remembered. Typically, there appears to be mostly gain between Sites 1 & 2 and loss between 5 & 6. Is this pretty much what you're reporting, Eric?

I think you'll find Eric's work a worthy addition to your database.

Rene
EDWARDS AQUIFER RESEARCH & DATA CENTER
RENE A. BARKER, Hydrogeologist
(512) 947-9609
rb42@txstate.edu

PRESS RELEASE: For Immediate Release
DATE: May 13, 2005
SUBJECT: Hydrologic Study Requests Cooperation of Wimberley Area Residents
By Rene Barker, Texas State University

Texas State University (Texas State) and the Hays Trinity Groundwater Conservation District (HTGCD) are asking Wimberley Valley residents to consider the benefits of cooperating with efforts to establish a network of observation wells in the area's Trinity aquifer. Funded in part by the Wimberley Valley Watershed Association, a study is being conducted along Cypress Creek by Texas State's Edwards Aquifer Research and Data Center (EARDC) to develop a database of groundwater and surface-water conditions and document the status of the associated aquatic (fish and macroinvertebrates) ecosystem. Property owners who are willing to volunteer their wells for the measurement of water levels will contribute substantially toward a better understanding of important interactions between the local hydrologic and ecological environments.

Texas State graduate student Eric Dedden, wading Cypress Creek to measure streamflow below Jacob's Well.

According to Texas State graduate student Eric Dedden (pictured above), the Cypress Creek watershed is being canvassed for property owners who would like to participate in the study by volunteering access to their water wells. With assistance from the HTGCD, observation wells are being selected on the basis of whether a given well's construction allows for the measurement of water levels in the Trinity aquifer. The selected observation wells will be used to measure groundwater levels concurrently with observations of streamflow (including springflow) and aquatic habitats along Cypress Creek. "We are screening wells on both sides of the creek, between Jacob's Well and the Blanco River, with the hope of identifying at least 15 to 20 observation wells," says Dedden. The resulting water-level data will be used to construct maps of the groundwater surface, delineate the principal directions of groundwater flow, and evaluate the extent of hydraulic connection between the creek and adjacent aquifer. "Without a willingness on the part of property owners to grant access to their wells, the all-important interpretive phase of my research would impossible," explains Dedden. In addition to being the basis for Dedden's master's thesis, all information gained from this study will be available to local residents.

Wimberley Valley residents have long recognized that their personal health—as well as that of the local economy—depends largely on the environmental stability of the Cypress Creek watershed, a tributary to the Blanco River. Wimberley's tourism industry is owed in large part to the aesthetic value of these watercourses; both are augmented by springflow from the Trinity aquifer, which—except for that resulting from rainwater collection systems—provides all of the area's drinking water. The continuity of springflow requires that the aquifer receive sufficient recharge to offset the effects of discharge, including groundwater withdrawals (pumpage). In addition to being one of the more efficient tools for detecting imbalances between recharge and discharge, tracking groundwater levels over time is a means of better understanding the effects of pumpage on springflow.

The Cypress Creek watershed is blessed with some of the most prolific springs in central Texas, including Blue Hole and Jacob's Well. Blue Hole and its adjacent surroundings are destined to become city and county parks. Jacob's Well, a major contributor to Cypress Creek, emerges—from deep below the streambed—about three miles northwest of Wimberley. Although intermittent in its upper reaches above Jacob's Well, Cypress Creek is considered perennial below this natural spring. For the first time in recorded history, however, Jacob's Well failed to flow during much of year 2000. "The realization that groundwater levels had dropped below Cypress Creek was a huge wake-up call to the citizens of Wimberley Valley," recalls David Glenn, chief of the Hays Trinity Aquifer Volunteer Advisory Group.

Exactly why Jacob's Well stopped flowing is unknown; however, recent increases in groundwater demand are likely contributors. Pumpage has increased significantly over the last few decades as a result of the area's explosive growth in population, particularly north of the Blanco River. This increasing use of groundwater has placed unprecedented stress on the Trinity aquifer, which conceivably has affected the amount of springflow from both Jacob's Well and Blue Hole.

In addition to the planned water-level observations, streamflow measurements are being made at eight sites along the creek. Likewise, fish and macroinvertebrate collections will be made from riffle, run, and pool habitats in four different channel reaches. The results—which are expected to establish a scientific baseline of relations among groundwater, surface water, and aquatic habitats in the watershed—will transfer to a larger study of the entire Blanco River Basin that is funded jointly by the Texas Nature Conservancy and the River Systems Institute (Texas State) in San Marcos.

Under the direction of Dr. Glenn Longley (Director, EARDC), the Cypress Creek study is being made in cooperation with HTGCD and supervised by Raymond Slade and Rene Barker, staff hydrogeologists at EARDC. For additional information, readers are invited to call EARDC at (512) 245-2329 or Stefani Campbell (Manager, HTGCD) at (512) 858-9253.

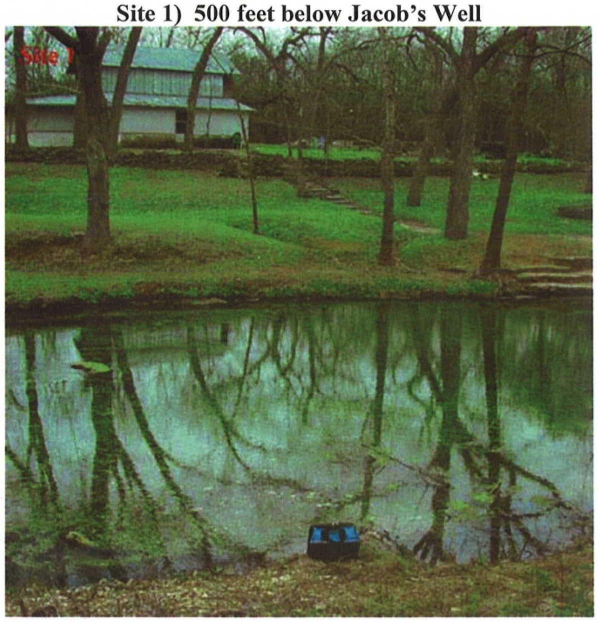
Rene Barker, Box 553, Dripping Springs, Texas 78620
Phone: (512) 947-9609; Email: rb42@txstate.edu

Streamflow Measurement Sites

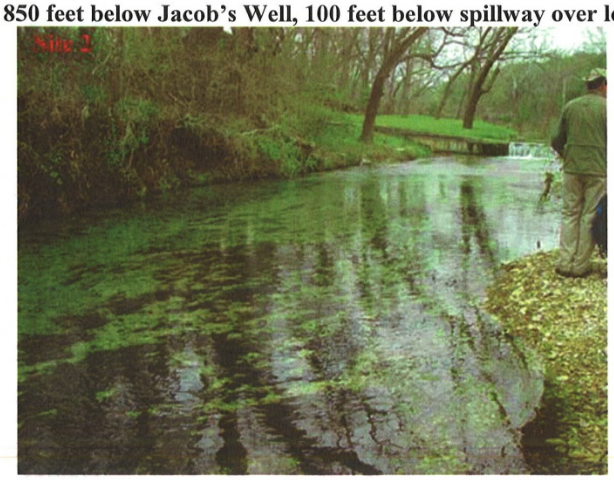
SECTION	ELEVATION	RIVER FEET AND MILE	DESCRIPTION		
1)	935 feet	500 0.09	500 ft below Jacob's Well		
			LATITUDE	(-)	98 07 31
			LONGITUDE		30 02 01
2)	932	850 0.16	850 ft below Jacob's Well, 100 ft below spillway		
			LATITUDE	(-)	98 07 28
			LONGITUDE		30 01 57
3)	920	2750 0.52	300 ft below Jacob's Well Rd, Eagle Rock Ranch		
			LATITUDE	(-)	98 07 16.5
			LONGITUDE		30 01 49
4)	877	11550 2.19	Jim Jackson property, upstream		
			LATITUDE	(-)	98 06 42
			LONGITUDE		30 00 51
5)	87	11750 2.23	Jim Jackson property, downstream		
			LATITUDE	(-)	98 06 42
			LONGITUDE		30 00 50
6)	867	14350 2.72	Above FM 12 bridge, Cypress Creek Cottages		
			LATITUDE	(-)	98 06 19
			LONGITUDE		30 00 45
7)	854	17350 3.29	Gumbert property, above Blue Hole		
			LATITUDE	(-)	98 05 47
			LONGITUDE		30 00 37
8)	838	23150 4.38	Cypress Haven Rentals, below Blue Hole		
			LATITUDE	(-)	98 05 35
			LONGITUDE		29 59 56
9)	835	24950 4.73	Below FM 12 bridge, downtown Wimberley		
			LATITUDE	(-)	98 05 52
			LONGITUDE		29 59 47

Photos of Streamflow Measurement Sites

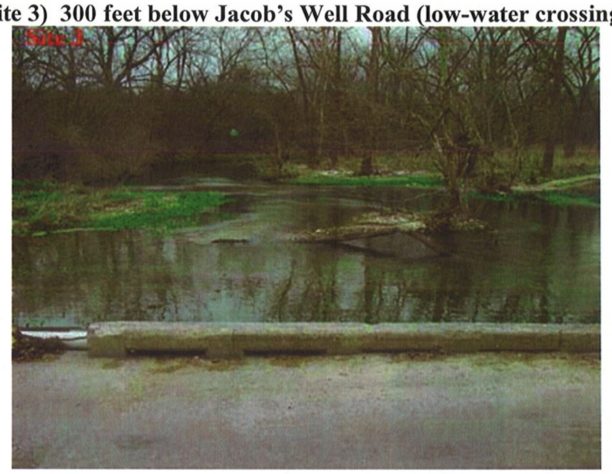
Site 1) 500 feet below Jacob's Well



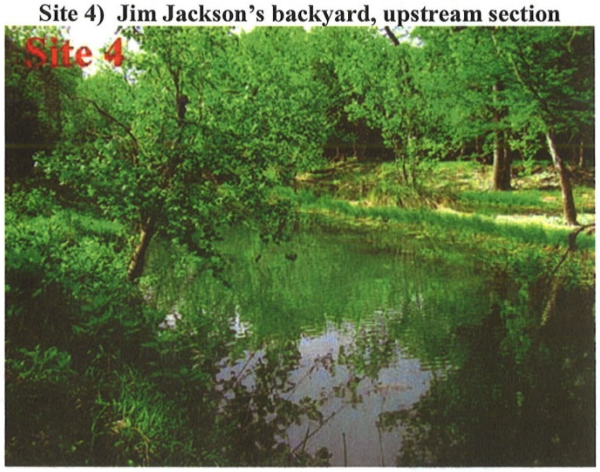
Site 2) 850 feet below Jacob's Well, 100 feet below spillway over low dam



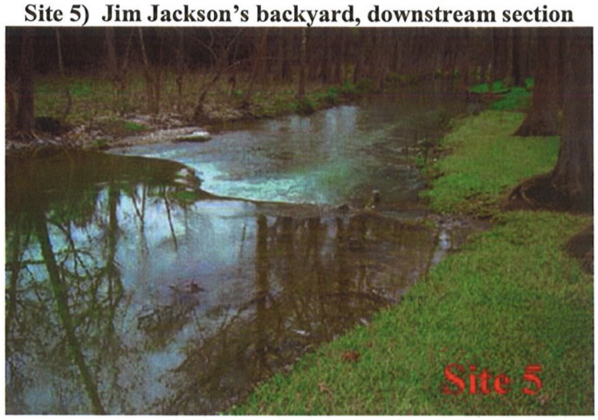
Site 3) 300 feet below Jacob's Well Road (low-water crossing)



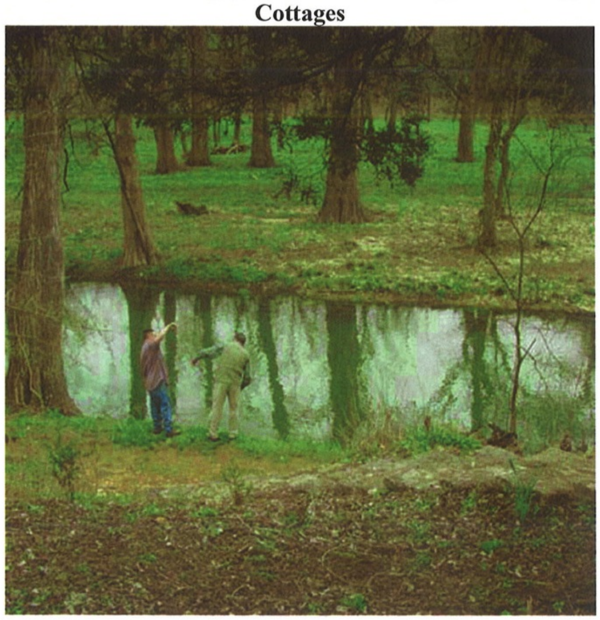
Site 4) Jim Jackson's backyard, upstream section



Site 5) Jim Jackson's backyard, downstream section



Site 6) 250 meters above FM 12 bridge, north of Wimberley, behind Cypress Creek Cottages



Site 7) Gumbert Property (above Blue Hole Campground)

=== Insert Site 7 image here ===

Site 8) Cypress Creek Haven Apartments (below Blue Hole Campground)

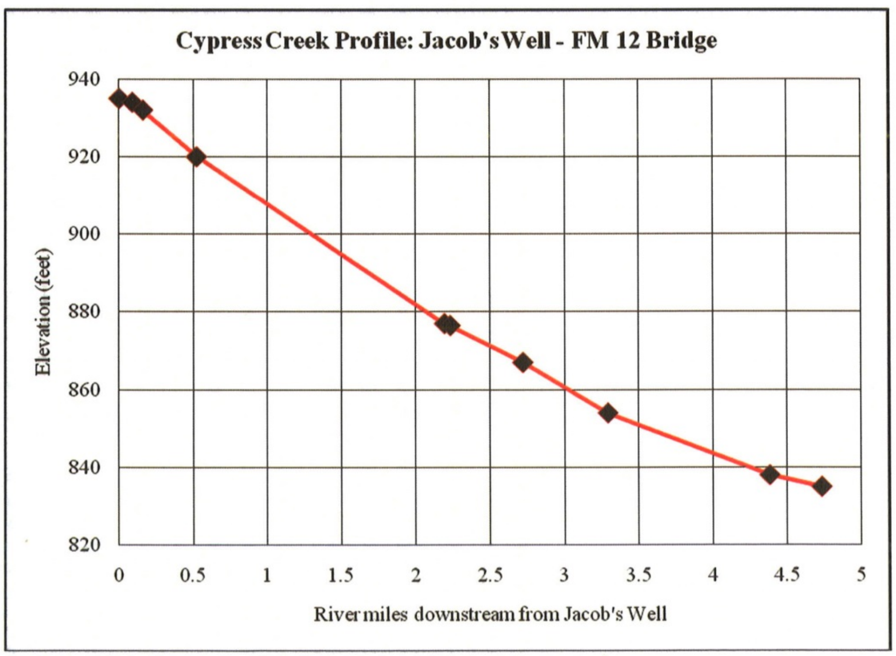
Site 9) Below FM 12 Bridge, downtown Wimberley

=== Insert Site 9 image here ===

Streamflow Measurement Data

Cypress Creek Profile Data and Chart

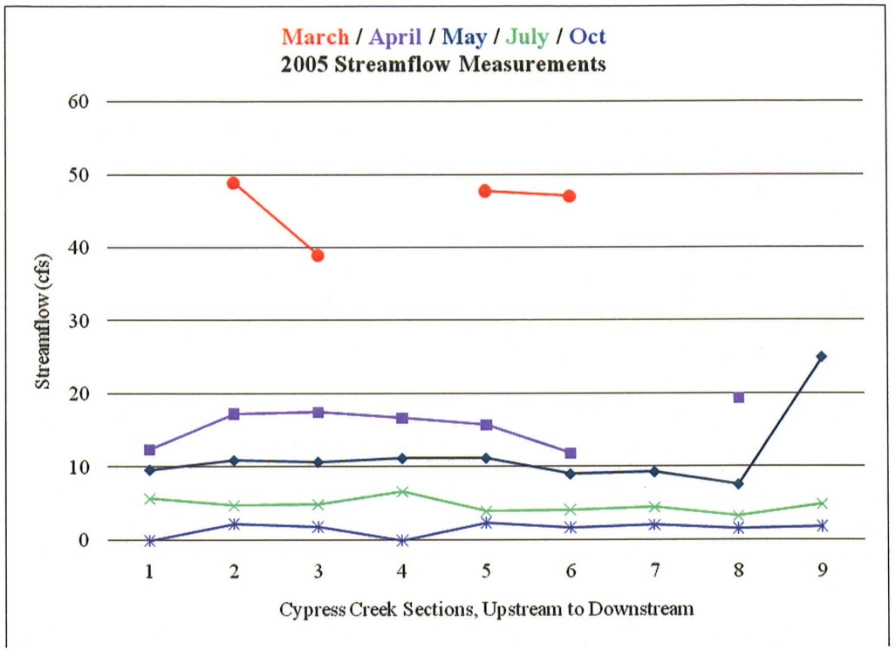
Site	Cum Feet	River Mile	Elevation
0	0	0	935
1	500	0.09	934
2	850	0.16	932
3	2750	0.52	920
4	11550	2.19	877
5	11750	2.23	876.5
6	14350	2.72	867
7	17350	3.29	854
8	23150	4.38	838
9	24950	4.73	835



Cypress Creek Streamflow Measurement Data and Chart

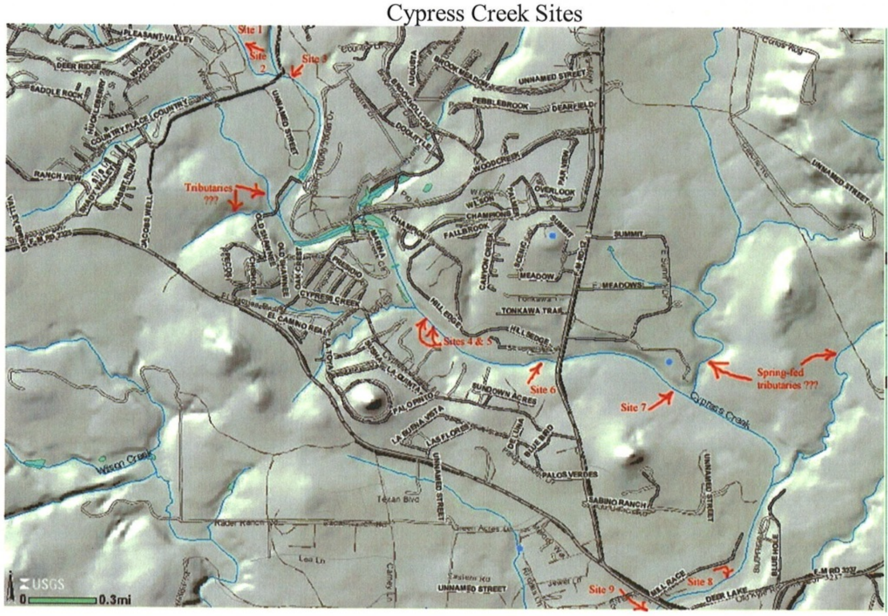
SECTION	ELEVATION	DESCRIPTION
1	935	500 feet below Jacob's Well
2	932	850 feet below Jacob's Well, 100 feet below dam spillway
3	920	300 feet below Jacob's Well Road low-water crossing (Eagle Rock Ranch)
4	877	Jim Jackson property, upstream
5	876	Jim Jackson property, downstream
6	867	Above FM 12 bridge, Cypress Creek Cottages
7	854	Gumbert property, above Blue Hole
8	838	Cypress Haven Rentals, below Blue Hole
9	835	Below FM 12 bridge, downtown Wimberley

SECTION	03.11.05	04.23.05	05.21.05	07.04.05	10.02.05
1		12.363	9.635	5.663	0
2	48.945	17.335	10.935	4.775	2.205
3	39.022	17.552	10.711	4.852	1.87
4		16.678	11.184	6.647	0
5	47.801	15.802	11.212	3.968	2.388
6	47.1	11.882	9.025	4.136	1.676
7			9.295	4.442	2.061
8		19.39	7.581	3.274	1.625
9			24.96	4.88	1.85
		Average	Average	Average (3)	

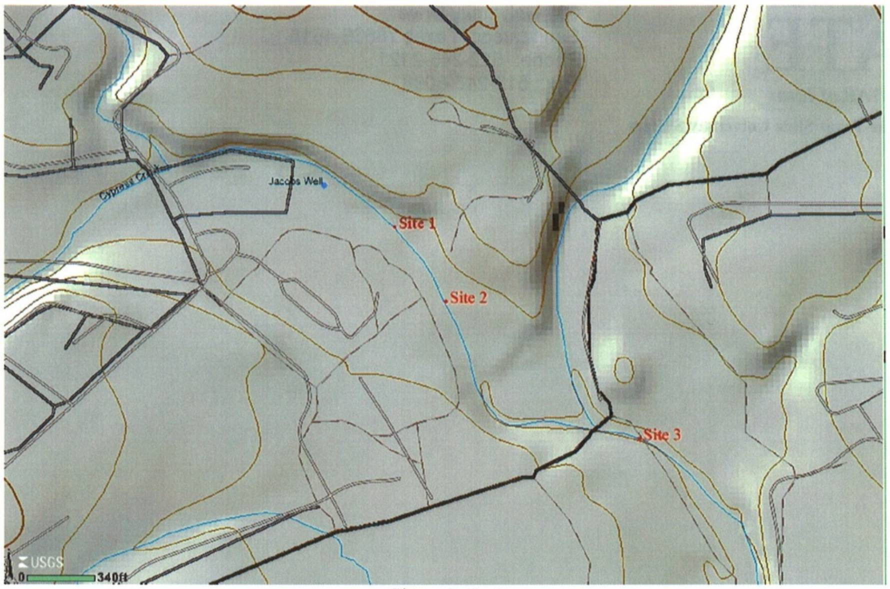

March / April / May / July / Oct
2005 Streamflow Measurements
Streamflow (cfs)
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
Cypress Creek Sections, Upstream to Downstream

Additional Images

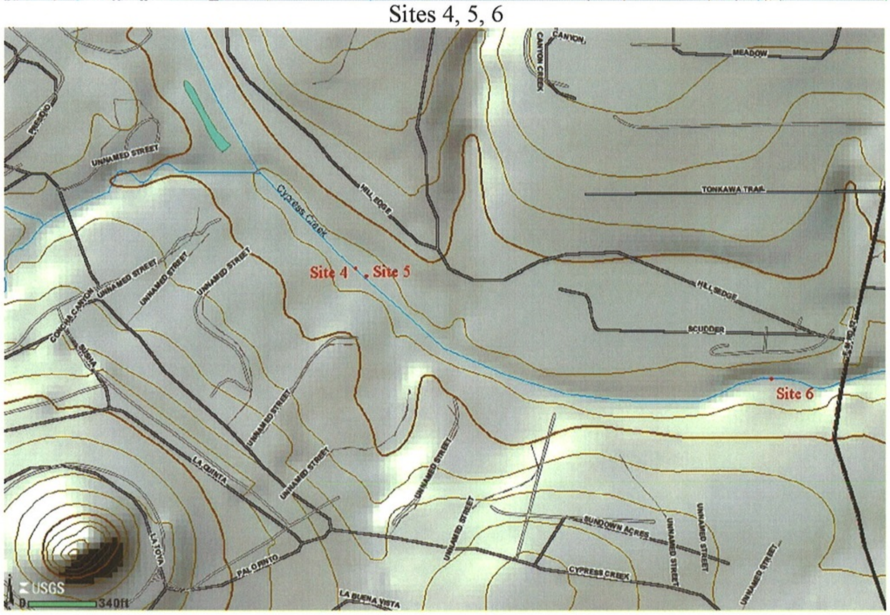
Cypress Creek Sites



Sites 1, 2, 3



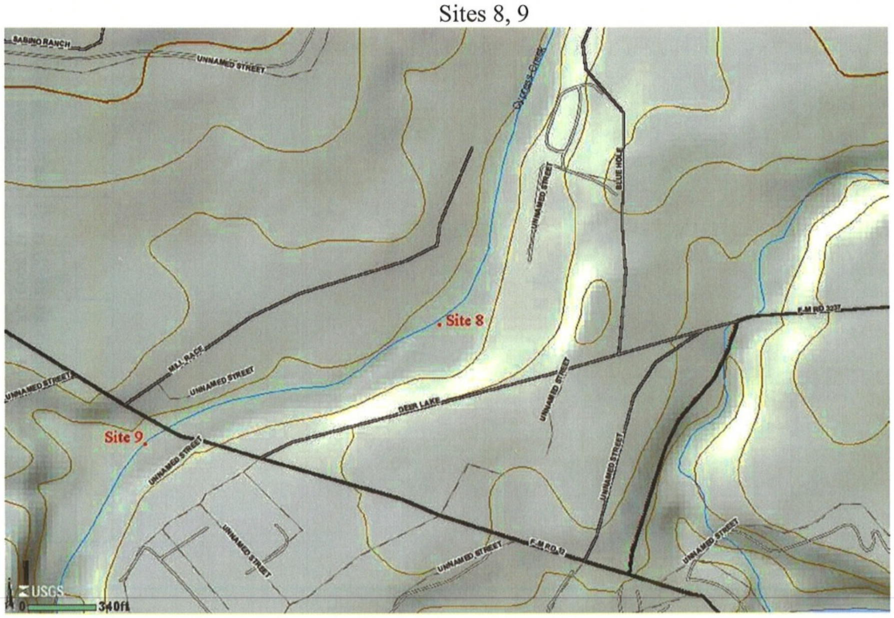
Sites 4, 5, 6



Site 7


SUMMIT
UNNAMED STREET
Site 7
Cypress Creek
USGS
0
340ft

Sites 8, 9


UNNAMED STREET
Cypress Creek
BLUE HOLE
Site 8
MILL RACE
UNNAMED STREET
DEER LAKE
Site 9
F.M RD 12
USGS
0
340ft

END

Cypress Creek Habitat and Watershed Assessment (2005-2006)
Master of Science Thesis Data

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Texas State University Graduate Student
Edwards Aquifer Research and Data Center

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EARDC (512) 245-2329

Written comm., 2007
(this is a Master of Science thesis that is still a work in process as of Jan. 26, 2008)

Appendix 5

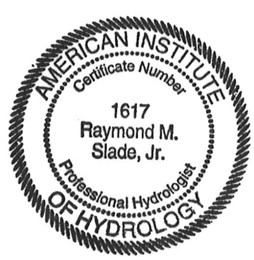
Analyses of Streamflow Gain-Loss Studies for the Trinity Aquifer in Hays County, Texas

Analyses of Streamflow Gain-Loss Studies for the Trinity Aquifer in Hays County, Texas

Prepared for the Hays Trinity Groundwater Conservation District

January 4, 2007

By Raymond M. Slade, Jr., PH
Certified Professional Hydrologist



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Analyses of Streamflow Gain-Loss Studies in Hays County, Texas

Introduction

A drought report funded by the Hays Trinity Groundwater Conservation District (Slade, 2006) identified sites and databases and provided monitoring and analyses recommendations for groundwater-levels, streamflow, and precipitation in Hays County. However, a database or analyses for recharge to and discharge from streambeds in the Trinity aquifer do not exist for the County. Such data and information are needed so that conceptual and hydrologic models can be developed to provide water-movement and water-budget information for the Trinity aquifer in Hays County. Without such information, water cannot be effectively managed in the county.

Although no direct recharge data or information can be identified for the County, the US Geological Survey (USGS) has conducted many streamflow gain-loss studies for several Hays County streams (Slade and others, 2002). These data provide discharge gains and losses for subreaches of streams throughout Texas—data that represent streambed recharge or discharge for adjacent underlying aquifers. This report presents flow gain-loss data for all known such studies associated with Hays County: 2 studies on the Pedernales River, 2 on Onion Creek, and 7 on the Blanco River. The Pedernales River is northwest of Hays County but on the outcrop of the Trinity aquifer upgradient from the Trinity aquifer in Hays County, thus probably associated with recharge to the Hays County Trinity aquifer.

Additionally, in 2005 a student at the Edwards Aquifer Research and Data Center at Texas State University conducted several streamflow gain-loss studies on a reach of Cypress Creek. Those data also are presented and analyzed in this report.

Objectives

The objectives for this report are to:
1. document locations and rates for streambed recharge and discharge for each stream where such data are available.
2. analyze the recharge-discharge data for trends and patterns that might be associated with flow conditions or seasons.
3. provide recommendations for data needed to better quantity major locations and ranges in recharge and discharge rates for streambeds on the Trinity aquifer in Hays County.
4. present recommendations, based on available data and the findings, for locations where stream recharge enhancement would provide substantial increases in recharge volumes, and present potential methods for accomplishing enhanced recharge.

Approach

1. Obtain all know streamflow gain-loss data associated with the Trinity aquifer in Hays County, including such data in Blanco County because this county contains outcrops of the Trinity aquifer that probably provide water to the Hays County Trinity aqufier.
2. Prepare, for each flow study, a map that presents all stream sites that define the subreaches and present associated gain or loss flow values.
3. Document the differences and ranges in recharge/discharge rates for stream reaches.
4. Discuss the possible fates for water in reaches with substantial recharge.
5. Based on the findings and to the extent possible, identify the subreaches with the greatest flow losses.
6. Based on the findings from number 5, present recommendations for flow studies or other studies needed to further quantity the amount and locations for major sources of recharge to the Trinity aquifer.
7. Based on the findings from number 5, present recommendations for locations and methods or practices where stream recharge enhancement would provide substantial increases in recharge volumes, and discuss other data and studies that could document potential volumes from the enhancement.

Background

Method for Gain-Loss Studies

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. In 2002, the data for all known flow studies were aggregated into a report presented on compact disk (Slade and others, 2002). This study carries the documentation of gain-loss studies a step farther: The gains and losses in stream subreaches (channel segments between flow-measuring sites in a reach) were compared to major and minor aquifer outcrops in digital and geographic information system (GIS) databases.

That report also summarized 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.

Approach for 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 adjacent main-channel measurement sites by equating inflows to outflows plus flow gain or loss in the subreach:

$$Qu + Qt + Qr = Qd + Qw + Qe + Qg, \qquad (1)$$

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,

$$Qg = Qu + Qt + Qr - Qd - Qw - Qe. \qquad (2)$$

For most streams, bank storage and underflow (flow parallel to the stream through shallow channel-bed deposits) are considered negligible or minimal. The streamflow discharge for each tributary to the subreach is measured so that the gain or loss in flow attributed to the stream bed can be calculated for the subreach. Each subreach is defined as the main channel length between an upstream and downstream site measured on the main channel. Therefore, the number of subreaches is one less than the number of meausurements made on main channels.

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 Texas Commission on Environmental Quality. However, the USGS cannot verify that all inflow or outflow sources for the reaches were accounted for.

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 subreache 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.

Hays County Streamflow Gain-Loss Studies

The streamflow studies deemed pertinent to the Trinity aquifer in Hays County represent all those conducted in the county and those conducted in Blanco County immediately west of Hays County. The data for these studies are taken from Slade and others (2002) and a summary of these studies is presented in table 1.

An explanation for the data in table 1 is as follows:

1. The streamflow study number represents that as presented in the source report (Slade and others (2002).
2. The reach length in miles is determined from a USGS topographic map (scale 1:24,000).
3. The total number of measurement sites represents those on the main channel and those on the flowing tributaries to the main channel.
4. The number of measurement sites on the main channel represents the sites used to define each subreach for which channel gains or losses are calculated. For example, the first site on the main channel represents the upstream end of the first subreach while the second site on the main channel represents the downstream end of the first subreach. The second site on the main channel also represents the upstream end of the second subreach while the third site represents the downstream end for the second subreach. Based on this definition, the number of subreaches for which channel gains or losses are calculated represents one less than the number of sites on the main channel.

The other column headings in table 1 are deemed to be self explanatory. Table 1 documents: two studies on Onion Creek (1958 and 1980); two studies on the Pedernales River (1956 and 1962); and seven studies on the Blanco River. The locations of the sites where the flow measurements were made on the main channels are presented in figure 1. Even though the studies were conducted many years ago, their data are deemed to be pertinent to current stream gain-loss characteristics because the hydrologic systems associated with these stream systems are believed to have undergone only minimal if any changes since the studies were conducted. Also, human-instigated withdrawals and return flows are believed to be minimal on these streams.

Streamflow Gains and Losses in Subreaches of the Streams

The discharge difference between adjacent main-channel streamflow measurement sites was calculated in order to determine the gain or loss for each subreach between the measuring sites. Tables 2-4 present the gains and losses for each of the studies conducted for the three streams. The streamflow gains and losses for subreaches on the Trinity aquifer outcrop are summarized in this report while gains and losses on the Edwards aquifer are not summarized. The major objective of this report is to identify loosing reaches thus those areas are emphasized in this report. All of the subreaches identified with a "*" in the gain-loss column of the tables and in the figures represent subreaches where no flow was observed. Therefore, it is unknown if these subreaches would gain or loose discharge if flow had been present.

Because of the karstic nature of the Trinity aquifer, faults and fractures within the streambeds probably account for most of the flow losses. Increases in the width of the streamflow in a channel exposes greater wetted area to fractures which probably cause increases in recharge. Therefore, the discharge loss for loosing subreaches probably increases with increased flow conditions and decreases with decreased flow conditions. All streamflow gain-loss studies were conducted during conditions deemed as steady-state, which occur only during extreme low flow conditions. Therefore, flow losses in loosing reaches as identified by these studies can be expected to increase during higher flow conditions. The measured streamflow discharge values for the stream sites are not contained in this publication but, for studies prior to 1958, are available by the Texas Board of Water Engineers (1960). Such discharges for the 1962 and 1963 studies are published by the U.S Geological Survey (1970), and data for the 1980 study on Onion Creek are published by Slade (1982, p. 39-40).

For tables 2-4, the latitude and longitude of the upstream end of each subreach is presented on the same row with the gain or loss for that subreach. The latitude and longitude in the next row represents the downstream end of that same subreach. Based on this method of identifying each subreach, a latitude and longitude for the downstream end of the last subreach is not presented but can be located on a map based on the length of the subreach from its upstream end.

Although a recharge or discharge rate is individually attributed to each subreach defined by the measuring sites, it should be noted that streambed recharge for some subreaches might represent the same water that discharges from the streambed at downstream subreaches. Likewise, streambed discharge at some subreaches might later represent the same water that recharges at downstream subreaches. Dye tracer studies could be used to distinguish between common recharge-discharge waters for a stream.

Pedernales River Flow Studies

Table 2 presents the gains and losses for the two USGS studies conducted on the Pedernales River. Figure 2 presents the locations of the sites that define the subreaches and the gain and loss values for these studies. As table 1 shows, channel gains dominate losses by 4.76 ft^3/s for study number 77 (January 9-17, 1956) and by 12.31 ft^3/s for study 79 (May 15-21, 1962). However, as table 2 shows, flow losses were substantial for several subreaches in each study.

Both flow studies began in Gillespie County—the 1956 study ends in Johnson City while the 1962 study continues throughout Blanco County. The gains and losses in Gillespie County probably do not influence groundwater in Hays County thus are not discussed in this report. The subreaches within Blanco County are identified in the fifth column of table 2. The 1962 study indicates the Pedernales River to be gaining streamflow throughout the reach downstream (east) from Johnson City. However, both studies indicate that the river is loosing water for the reach upstream (west) of Johnson City. For example, 8 of the 10 subreaches measured west of Johnson City show losses rather than gains in streamflow (fig. 2).

Onion Creek Flow Studies

Table 3 presents the gains and losses for the two USGS studies conducted on Onion Creek. Figure 3 presents the locations of the sites that define the subreaches and the gain and loss values for these studies. As table 3 shows, only the upper most 2 subreaches for the 1958 study are on the outcrop of the Trinity aquifer and only the upper most subreach for the 1980 study is on the Trinity. All three of these subreaches indicate a gain in streamflow. The 1980 study begins at Farm Road 150 between Dripping Springs and Buda but the 1958 study begins at Farm Road 12 just south of Dripping Springs. However, flow gain-loss data have not been collected on Onion Creek upstream from Farm Road 12 thus it is unknown if that reach gains or looses flow.

Blanco River Flow Studies

Seven studies have been conducted by the USGS on the Blanco River in Blanco and Hays Counties. (table 4). The locations of the sites that define the subreaches and the gain and loss values for the 3 studies conducted in 1924 are presented in figure 4; those for the two 1955 studies are in figure 5; and those for the 1957 and 1963 studies are in figure 6.

Subreaches on the Blanco River in eastern Blanco County were studied in the January 1955 and 1963 studies. The stream was dry in this area during the 1955 study but the upper most subreach for the 1963 shows a substantial flow loss in the reach immediately west of the Blanco-Hays County line (fig. 6).

An area presenting substantial and consistent flow losses on the Blanco is within about a 3-mile reach between the Blanco-Hays County line and Wimberley (fig. 5 and 6). Immediately upstream from the reach the stream travels in a southeast direction. At the upstream end of the reach, the stream sharply meanders to the west, then to the south, and finally to the east at the end of the reach (at almost at 90-degree angles) before continuing in the original southeast direction. Only the January 1955 and 1963 studies contained flow data for this reach, but both studies indicate substantial losses in this area (fig. 5 and 6).

Details for this loosing reach are presented in figure 7 (Rene Barker, written communication, 2006). The site locations in red represent the upstream end of loosing subreaches for the 1955 and 1963 studies while the blue symbols represent gaining subreaches. Geologic faults through the stream loss area align with the spring at Jacobs Well suggesting that the recharge losses might be at least a partial source of water for this spring. Additionally, the shape of the stream reach and the geologic characteristics suggest the possibility that geologic collapse might have occurred in the area—such collapse could be associated with preferential pathways for subsurface water from the loosing reach to Jacobs Well.

Finally, although the 1963 flow study ended at Wimberley, each of the other six studies ends many miles east of Wimberley. Each of these studies indicates a consistent and substantial recharge loss on a reach north of San Marcos. (fig. 4, 5, and 6). The extent of this loosing reach cannot be identified based on the flow studies because of the considerable length for many of the subreaches. Considering the location of this area with respect to San Marcos Springs (in San Marcos), it is suggested that this reach on the Blanco River might be a substantial recharge source for those springs.

Cypress Creek Flow Studies

A student working with the Edwards Aquifer Research and Data Center at Texas State University conducted five flow gain-loss studies on Cypress creek during relatively steady-state flow conditions during 2005. A list of the site locations and the measured discharges for the sites are presented in table 5 and graphs showing the measured streamflow at each site and for each of the five studies are presented in figure 8. The gains or losses in flow between the sites were not calculated for the subreaches but can readily be determined from table 5 and figure 8.

Although the first study (March 2005) appears to indicate a flow loss for the reach from site 2 to 3, such is not indicated for that subreach based the other four studies. Also, the apparent flow gain from site 8 to 9 for the May 2005 study is not substantiated by the other studies. It is likely that the site 3 measured flow for the March study and the site 9 measured flow for the May study are erroneous.

The five flow studies were conducted during various flow conditions and do not indicate a substantial loss or gain for any of the 8 reaches defined by the 9 measuring sites. Therefore, it is likely that Cypress Creek does not represent a substantial source for recharge of discharge for the Trinity aquifer.

Pedernales River

Findings

The two flow studies indicate the river to be gaining flow east of Johnson City but loosing flow west of the city. Based on the 2 flow studies, it appears that recharge rates are substantial on this reach of the river.

Recommendations

1. The Pedernales River east of Johnson City appears to be gaining flow but this conclusion is based on only one flow study and based on few discharge measurements. Additional flow studies in this reach based on more measurements would provide more detail regarding the extent and rates for the flow gains.
2. A hydrologic and geologic analyses need to be conducted to determine if and to what extent the Pedernales River in Blanco County west of Johnson City contributes recharge to the Trinity aquifer in Hays County.
3. If that reach of the river contributes substantial recharge to the Hays county Trinity aquifer, then the District should conduct, during different flow conditions, 2 or 3 additional flow loss studies on this reach of the river. The flow studies should be conducted during high flow conditions different than those occurring during the 2 existing studies.
4. After additional flow studies are conducted, an attempt should be made to statistically relate recharge rates for each of the flow studies to the same date streamflow discharge occurring at the USGS streamflow gaging station on the Pedernales River at Johnson City. If the recharge rates and river flow conditions are significantly correlated, long-term recharge rates can be documented based on the statistical correlation and long-term flow discharges at the station (daily flow data since 1939).
5. If this reach of the Pedernales contributes substantial recharge to the Hays County Trinity aquifer, potential recharge enhancement management practices should be considered as a method to increase recharge rates to the Hays County Trinity aquifer from the river.

Onion Creek

Findings

The 2 flow studies on Onion Creek were conducted to document recharge to the Edwards aquifer. Flow gain-loss data for the Trinity aquifer in Hays County are limited to only the lowest subreach, which indicates a gain in flow.

Recommendations

1. A few flow gain-loss studies need to be conducted on Onion Creek from its headwaters throughout its contact with the Trinity aquifer. Such studies need to be conducted during relatively high flow conditions in order to document the extent of recharge or discharge from the creek to the Trinity aquifer.
2. After such studies are conducted, the data should be analyzed in an attempt to quantify the locations and extent of recharge to and discharge from Onion Creek to the Trinity aquifer.

Blanco River

Findings

Flow gains: Analyses of the 7 flow studies indicate 3 reaches were substantial stream gains are occurring.

a. a reach immediately upstream from that of reach "b" below (fig. 6),
b. A reach immediately downstream from that of reach "b" below (fig. 6),
c. A reach immediately upstream and downstream from Wimberley (fig. 4-6)

Flow losses: Analyses of the studies identify three subreach areas where flow losses are substantial:

a. a reach immediately west of the Blanco-Hays County line (fig. 6),
b. about a 3-mile reach between the Blanco-Hays county line and Wimberley (fig. 7), and,
c. a reach north of San Marcos (fig. 4-6).

Recommendations

1. Additional flow studies for the 3 gaining reaches identified above would provide more definitive information regarding the extent and rates for the gains.
2. The District should conduct, during different flow conditions, 2 or 3 additional flow loss studies for each of the 3 reaches defined above. The flow studies should be conducted during high flow conditions different than those occurring during the existing studies.
3. For each of the reaches, data and information should be obtained in order to determine the fate of the water lost in these reaches. The limited available data suggest that recharge from the 3-mile reach between the Blanco-Hays county line and Wimberley provide flow to Jacobs Well, and the recharge from the reach north of San Marcos probably provide flow to San Marcos Springs.
4. Additional data should be collected for the loosing reach immediately west of the Blanco-Hays County line and the 3-mile loosing in order to determine if water from those reaches discharges to Jacobs Well.

   a) Along with additional flow gain-loss measurements, the 2 reaches should be investigated for any geologic data or information that might indicate the fate for water lost in the reaches.
   b) If additional flow gain-loss data and/or geologic data indicate either reach to be a possible water source for Jacobs Well, dye should be injected in the reaches and sampled at Jacobs Well and in wells along potential flow paths from the reach to Jacobs Well.
   c) If either reach is indicated as a possible source for Jacobs Well discharge, attempts should be made to statistically relate the recharge rates for each flow study to the same date streamflow discharge for the USGS streamflow station on the Blanco River at Wimberley. If the recharge rates and river flow conditions are significantly correlated, long-term recharge rates can be documented based on the statistical correlation and long-term flow discharges at the station (daily flow data since 1924).
   d) If either reach is indicated as a major source of flow from Jacobs Well, attempts should be made to statistically relate the long-term recharge data to the discharge data for Jacobs Well in order to document long and short term water-budget analyses (inflow and outflow) for this spring. Also, water quality data should be used along with the flow data to calculate water budgets for water-quality loads.
   e) If either of these reaches of the Blanco contribute substantial water to Jacobs Well, potential recharge enhancement management practices should be considered as a method to increase recharge rates which would enhance the discharge from Jacobs Well.

Cypress Creek

Five flow gain-loss studies were conducted on Cypress Creek during various flow conditions by the Edwards Aquifer Research and Data Center at Texas State University. The studies indicate that, with the exception of Jacobs Well, no subreaches on the creek contain substantial gains or losses in streamflow.

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Table 1. Characteristics of US Geological Survey flow gain-loss studies in Hays and Blanco Counties

[mi, miles; ft^3/s, cubic feet per second; ft^3/s-mi, cubic feet per second per mile; Cr, Creek; USGS, U.S. Geological Survey; --, not applicable; R, River; TBWE, Texas Board of Water Engineers; Fk, Fork; ft, feet;

Note: Eight digit streamflow-gaging stations used to identify some reaches. **Table continued on bottom part of page.**

Streamflow study no.	Major river basin	Stream name	Reach identification	Date of study	Reach length (river miles)	Total no. of measurement sites	No. of measurement sites on main channel
75	Colorado	Onion Cr	FM 12 to mouth	4/23-24/1958	59.2	21	9
76	Colorado	Onion Cr	FM 150 (08158700) to US 183 (08159000)	5/28/1980	35.4	19	14
77	Colorado	Pedernales R	below Harper to near Johnson City (08153500)	1/9-17/1956	70	69	39
79	Colorado	Pedernales R	Harper to Hamilton Pool	5/15-21/1962	88.7	43	23
97	Guadalupe	Blanco R	10 mi upstream of Wimberley to NE of San Marcos	3/15-16/1955	33.3	7	6
98	Guadalupe	Blanco R	9 mi below Blanco to Wimberley (08171000)	2/25-3/4/1963	27.1	28	20
99	Guadalupe	Blanco R	above Halifax Cr to near Kyle	7/22/1924	4.2	3	3
100	Guadalupe	Blanco R	upstream from Little Blanco R to NE of San Marcos	1/24-28/1955	49.6	33	30
101	Guadalupe	Blanco R	Wimberley (08171000) to Kyle (08171300)	7/10-14/1957	16.2	8	7
102	Guadalupe	Blanco R	Wimberley to near Kyle	6/12/1924	19.4	3	3
103	Guadalupe	Blanco R	Wimberley to near Kyle	7/15-16/1924	19.4	4	4

Streamflow study no.	Major river basin	Stream name	Major aquifer outcrop(s) intersected by reach	Total gain or loss (-) in reach ft^3/s	Gain or loss per mile of reach (ft3/s-mi)	Reference for data
75	Colorado	Onion Cr	Edwards, Trinity	-24.9	-0.421	TBWE (1960)
76	Colorado	Onion Cr	Edwards, Trinity	-82.7	-2.336	Slade and others (1982)
77	Colorado	Pedernales R	Edwards-Trinity (Plateau), Trinity	4.76	0.068	TBWE (1960)
79	Colorado	Pedernales R	Trinity	12.31	0.139	USGS (1963)
97	Guadalupe	Blanco R	Edwards, Trinity	-10.3	-0.309	TBWE (1960)
98	Guadalupe	Blanco R	Trinity	25.9	0.956	USGS (1964)
99	Guadalupe	Blanco R	Edwards	-13.1	-3.119	TBWE (1960)
100	Guadalupe	Blanco R	Edwards, Trinity	-2.65	-0.053	TBWE (1960)
101	Guadalupe	Blanco R	Edwards, Trinity	-13.9	-0.858	TBWE (1960)
102	Guadalupe	Blanco R	Edwards, Trinity	14.0	0.722	TBWE (1960)
103	Guadalupe	Blanco R	Edwards, Trinity	-12.8	-0.66	TBWE (1960)

Table 2. Streamflow gains and losses from flow studies on the Pedernales River
[dd, degrees; mm, minutes; ss, seconds; ft^3/s, cubic feet per second; mi, miles; --, not applicable]

Note: Eight digit streamflow-gaging stations used to identify some subreaches

Streamflow study no. and date	Latitude of upstream end of subreach (dd mm ss)	Longitude of upstream end of subreach (dd mm ss)	Major aquifer outcrop intersected by subreach	Minor aquifer outcrop intercepted by subreach	Gain or loss (-) in subreach (ft^3/s)	Length of subreach (river mi)	Location of upstream end of subreach (river mi)	Descriptive location of upstream end of selected subreaches
77 Jan 1956	30 17 04	99 13 41	Edwards-Trinity Plateau	Gillespie County	0.3	0.5	0	2 mi below Harper
77	30 16 43	99 13 24	Edwards-Trinity Plateau, Trinity	--	0.0	1.8	0.5	
77	30 15 56	99 12 00	Trinity	--	0.0	1.7	2.3	
77	30 15 54	99 10 28	Trinity	--	-0.05	1.7	4	
77	30 14 59	99 10 00	Trinity	--	-0.55	2.6	5.7	
77	30 14 29	99 07 59	Trinity	--	0.2	0.9	8.3	
77	30 14 24	99 07 14	Trinity	--	-0.1	2.2	9.2	
77	30 14 15	99 06 04	Trinity	--	-0.1	1.9	11.4	
77	30 14 27	99 04 43	Trinity	--	*	1.4	13.3	
77	30 13 54	99 03 37	Trinity	--	*	1.8	14.7	
77	30 13 24	99 02 18	Trinity	--	0.05	1.5	16.5	
77	30 12 52	99 01 19	Trinity	--	0.05	1.5	18	
77	30 12 33	99 00 17	Trinity	--	0.3	1.1	19.5	
77	30 12 32	98 59 26	Trinity	--	0.7	0.8	20.6	
77	30 12 26	98 58 45	Trinity	--	-0.1	0.1	21.4	
77	30 12 21	98 58 41	Trinity	--	0.2	2.0	21.5	
77	30 12 29	98 57 00	Trinity	--	0.08	1.6	23.5	
77	30 13 28	98 55 49	Trinity	--	0.29	0.9	25.1	
77	30 13 14	98 55 09	Trinity	--	-0.06	1.1	26	
77	30 13 21	98 54 20	Trinity	--	0.14	1.7	27.1	
77	30 13 11	98 52 33	Trinity	--	-0.24	2.2	28.8	
77	30 13 23	98 51 18	Trinity	--	-0.09	1.3	31	
77	30 13 07	98 49 45	Trinity	--	-0.06	2.1	32.3	

77	30 13 28	98 49 04	Trinity	--	0.41	2.2	34.4	
77	30 13 28	98 49 04	Trinity	--	0.05	1.8	36.6	
77	30 13 52	98 48 24	Trinity	--	1.6	1.6	38.4	
77	30 13 46	98 44 57	Trinity	--	1.16	1.5	40	
77	30 13 48	98 43 56	Trinity	--	-0.05	3.1	41.5	
77	30 13 43	98 42 09	Trinity	--	-0.27	2.1	44.6	
77	30 13 55	98 41 16	Trinity	--	1.13	2.1	46.7	
77	30 14 31	98 39 17	Trinity	--	-0.86	1.2	48.8	
77	30 14 16	98 37 13	Trinity	Gillespie County	1.4	2.2	50	
77	30 15 43	98 34 32		First subreach in Blanco Co.	-0.12	4.3	52.2	
77	30 16 19	98 32 58	--	--	-0.45	1.7	56.5	
77	30 16 06	98 31 34	--	--	-0.32	1.6	58.2	
77	30 16 10	98 31 13	--	--	-0.03	2.2	59.8	

* - Denotes that no flow occurred within reach thus gain or loss during flow conditions is unknown

Table 2. Streamflow gains and losses from flow studies on the Pedernales River (cont.)

Streamflow study no. and date	Latitude of upstream end of subreach (dd mm ss)	Longitude of upstream end of subreach (dd mm ss)	Major aquifer outcrop intersected by subreach	Minor aquifer outcrop intercepted by subreach	Gain or loss (-) in subreach (ft^3/s)	Length of subreach (river mi)	Location of upstream end of subreach (river mi)	Descriptive location of upstream end of selected subreaches
77 Jan 1956	30 18 11	98 30 24	--	--	0.51	1.3	62	
77	30 19 10	98 29 20	--	Ellenburger-San Saba	-0.36	6.7	63.3	
79 May 1962	30 14 05	99 03 52	Trinity	Gillespie County	0.36	3.7	14.3	county road crossing
79	30 14 05	99 03 52	Trinity	--	-0.37	2.6	18	
79	30 12 32	98 59 27	Trinity	--	0.39	2.4	20.6	1 mi above SH 16
79	30 12 28	98 57 22	Trinity	--	1.23	4.7	23	
79	30 13 07	98 53 47	Trinity	--	0.12	3.7	27.7	
79	30 13 24	98 50 26	Trinity	--	-0.51	3.0	31.4	
79	30 13 37	98 49 05	Trinity	--	1.52	4.0	34.4	US 290
79	30 14 17	98 47 01	Trinity	--	0.72	4.7	38.4	
79	30 14 04	98 45 21	Trinity	--	2.68	2.6	43.1	
79	30 14 03	98 41 29	Trinity	--	2.3	3.7	45.7	
79	30 14 22	98 39 07	Trinity	--	-0.9	3.8	49.4	
79	30 14 42	98 35 43	Trinity	Gillespie County	0.7	3.8	53.2	
79	30 16 19	98 32 42	--	First subreach in Blanco Co.	-1.17	3.0	57	FM 1320
79	30 17 05	98 30 04	--	--	0.42	3.1	60	
79	30 19 13	98 29 25	--	--	-1.4	2.1	63.1	
79	30 19 24	98 27 52	--	Ellenburger-San Saba	0.3	2.6	65.2	
79	30 18 16	98 25 18	--	Ellenburger-San Saba	-1.87	2.2	67.8	
79	30 17 27	98 24 00	Trinity	Ellenburger-San Saba	0.3	3.7	70	gaging station (08153500)
79	30 17 54	98 21 46	Trinity	Ellenburger-San Saba	1.3	9.4	73.7	
79	30 18 10	98 18 34	Trinity	Ellen.-San Saba, Marble Falls	4.15	7.6	83.1	

79	30 18 42	98 14 13	Trinity	--	1.2	5.8	90.7	
79	30 20 12	98 11 45	Trinity	--	0.84	6.5	96.5	

* - Denotes that no flow occurred within reach thus gain or loss during flow conditions is unknown

Table 3. Streamflow gains and losses from flow studies on Onion Creek

[dd, degrees; mm, minutes; ss, seconds; ft^3/s, cubic feet per second; mi, miles; --, not applicable;

Note: Eight digit streamflow-gaging stations used to identify some subreaches

Streamflow study no. and date	Latitude of upstream end of subreach (dd mm ss)	Longitude of upstream end of subreach (dd mm ss)	Major aquifer outcrop intersected by subreach	Minor aquifer outcrop intercepted by subreach	Gain or loss (-) in subreach (ft^3/s)	Length of subreach (river mi)	Location of upstream end of subreach (river mi)	Descriptive location of upstream end of selected subreaches
75 Apr 1958	30 09 38	98 05 27	Trinity	--	33.0	10.0	0	at FM 12, estimate
75	30 07 39	98 00 36	Trinity	--	2.2	4.0	10	
75	30 05 00	98 00 25	Edwards, Trinity	--	2.9	6.0	14	
75	30 03 06	97 57 36	Edwards	--	-6.7	5.6	20	
75	30 04 11	97 53 10	Edwards	--	-3.0	3.4	25.6	
75	30 05 07	97 50 53	--	--	13.6	12.1	29	
75	30 09 32	97 46 07	--	--	14.5	14.0	41.1	
75	30 11 19	97 37 09	--	--	-81.4	4.1	55.1	
76 May 1980	30 04 59	98 00 28	Trinity	--	7.6	1.8	46	at FM 150
76	30 05 15	97 59 06	Edwards, Trinity	--	-5.8	1.5	44.2	
76	30 04 37	97 58 43	Edwards	--	-2.0	1.4	42.7	
76	30 03 37	97 58 39	Edwards	--	-1.0	1.4	41.3	
76	30 03 06	97 57 34	Edwards	--	-34.5	1.4	39.9	
76	30 03 00	97 56 15	Edwards	--	-21.3	1.1	38.5	
76	30 03 41	97 55 34	Edwards	--	-35.7	3.4	37.4	
76	30 04 12	97 53 09	Edwards	--	0.06	1.3	34	
76	30 04 24	97 52 07	--	--	0.97	1.2	32.7	
76	30 04 35	97 51 05	--	--	0.29	0.7	31.5	
76	30 05 08	97 50 51	--	--	3.5	7.1	30.8	
76	30 08 06	97 47 51	--	--	5.9	7.8	23.7	
76	30 10 40	97 44 40	--	--	-0.72	5.3	15.9	

Table 3. Streamflow gains and losses from flow studies on Onion Creek

[dd, degrees; mm, minutes; ss, seconds; ft^3/s, cubic feet per second; mi, miles; --, not applicable;

Note: Eight digit streamflow-gaging stations used to identify some subreaches

Streamflow study no. and date	Latitude of upstream end of subreach (dd mm ss)	Longitude of upstream end of subreach (dd mm ss)	Major aquifer outcrop intersected by subreach	Minor aquifer outcrop intercepted by subreach	Gain or loss (-) in subreach (ft^3/s)	Length of subreach (river mi)	Location of upstream end of subreach (river mi)	Descriptive location of upstream end of selected subreaches
75 Apr 1958	30 09 38	98 05 27	Trinity	--	33.0	10.0	0	at FM 12, estimate
75	30 07 39	98 00 36	Trinity	--	2.2	4.0	10	
75	30 05 00	98 00 25	Edwards, Trinity	--	2.9	6.0	14	
75	30 03 06	97 57 36	Edwards	--	-6.7	5.6	20	
75	30 04 11	97 53 10	Edwards	--	-3.0	3.4	25.6	
75	30 05 07	97 50 53	--	--	13.6	12.1	29	
75	30 09 32	97 46 07	--	--	14.5	14.0	41.1	
75	30 11 19	97 37 09	--	--	-81.4	4.1	55.1	
76 May 1980	30 04 59	98 00 28	Trinity	--	7.6	1.8	46	at FM 150
76	30 05 15	97 59 06	Edwards, Trinity	--	-5.8	1.5	44.2	
76	30 04 37	97 58 43	Edwards	--	-2.0	1.4	42.7	
76	30 03 37	97 58 39	Edwards	--	-1.0	1.4	41.3	
76	30 03 06	97 57 34	Edwards	--	-34.5	1.4	39.9	
76	30 03 00	97 56 15	Edwards	--	-21.3	1.1	38.5	
76	30 03 41	97 55 34	Edwards	--	-35.7	3.4	37.4	
76	30 04 12	97 53 09	Edwards	--	0.06	1.3	34	
76	30 04 24	97 52 07	--	--	0.97	1.2	32.7	
76	30 04 35	97 51 05	--	--	0.29	0.7	31.5	
76	30 05 08	97 50 51	--	--	3.5	7.1	30.8	
76	30 08 06	97 47 51	--	--	5.9	7.8	23.7	
76	30 10 40	97 44 40	--	--	-0.72	5.3	15.9	

Table 4. Streamflow gains and losses from flow studies on the Blanco River

[dd, degrees; mm, minutes; ss, seconds; ft^3/s, cubic feet per second; mi, miles; --, not applicable]
Note: Eight digit streamflow-gaging stations used to identify some subreaches

Streamflow study no. and date	Latitude of upstream end of subreach (dd mm ss)	Longitude of upstream end of subreach (dd mm ss)	Major aquifer outcrop intersected by subreach	Minor aquifer outcrop intersected by subreach	Gain or loss (-) in subreach (ft^3/s)	Length of subreach (river mi)	Location of upstream end of subreach (river mi)	Descriptive location of upstream end of selected subreaches
97 Mar 1955	29 59 39	98 11 45	Trinity	--	-0.2	11.3	16.3	at Fishers Store road crossing
97	29 59 36	98 05 18	Edwards, Trinity	--	0.3	11.0	27.6	gaging station at Wimberley (08171000)
97	30 00 24	97 57 24	Edwards	--	-10.1	1.8	38.6	
97	30 00 09	97 55 57	Edwards	--	-0.3	0.1	40.4	
97	30 00 08	97 55 57	Edwards	--	*	9.1	40.5	

98 Feb 1963	30 05 56	98 20 29	Trinity	--	-1.51	5.3	0	at east crossing of Chimney Valley Rd
98	30 03 53	98 18 36	Trinity	--	*	1.6	5.3	
98	30 03 04	98 18 46	Trinity	--	*	2.7	6.9	
98	30 02 37	98 14 59	Trinity	--	*	1.1	9.6	
98	30 03 03	98 14 03	Trinity	--	-0.94	0.7	10.7	
98	30 02 40	98 13 42	Trinity	--	0.08	0.8	11.4	
98	30 01 56	98 13 15	Trinity	--	4.08	0.2	12.2	
98	30 01 49	98 13 07	Trinity	--	2.92	0.9	12.4	
98	30 01 24	98 13 04	Trinity	--	-1.46	0.1	13.3	
98	30 01 16	98 13 10	Trinity	--	-2.44	0.2	13.4	
98	30 01 09	98 13 07	Trinity	--	0.47	0.3	13.6	
98	30 01 00	98 13 08	Trinity	--	-0.34	0.3	13.9	
98	30 00 53	98 12 55	Trinity	--	0.02	0.6	14.2	
98	30 00 51	98 12 24	Trinity	--	13.94	0.6	14.8	
98	30 00 21	98 12 18	Trinity	--	0.49	3.1	15.4	

98	29 58 28	98 11 58	Trinity	--	-1.4	1.9	18.5	
98	29 57 18	98 10 07	Trinity	--	3.0	2.8	20.4	
98	29 58 07	98 08 07	Trinity	--	2.7	1.6	23.2	
98	29 58 34	98 06 51	Trinity	--	6.29	2.3	24.8	

99 July 1924	30 00 23	97 57 23	Edwards	--	-4.6	2.0	11.4	1 mi above Halifax Creek
99	30 00 20	97 56 03	Edwards	--	-8.5	2.2	13.4	0.75 mi below Halifax Creek

100 Jan 1955	30 05 56	98 20 29	Trinity	--	*	4.8	0	at east crossing of Chimney Valley Rd
100	30 03 54	98 18 20	Trinity	--	*	3.3	4.8	
100	30 03 05	98 17 32	Trinity	--	*	0.9	8.1	
100	30 03 18	98 16 49	Trinity	--	*	0.5	9	
100	30 03 09	98 16 10	Trinity	--	-0.1	0.2	9.5	
100	30 02 43	98 14 56	Trinity	--	*	2.8	9.7	
100	30 01 54	98 13 12	Trinity	--	*	1.1	12.5	

* - Denotes that no flow occurred within reach thus gain or loss during flow conditions is unknown

Table 5. Characteristics of Texas State University Streamflow gain-loss studies for Cypress Creek in Hays County

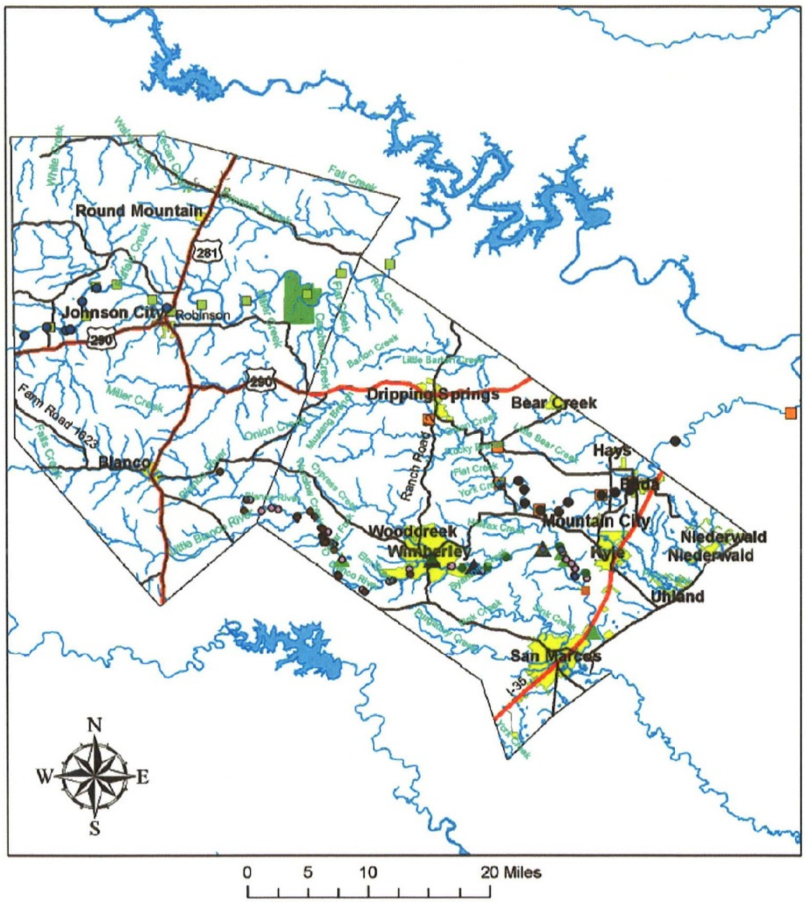
Site Descriptions (downstream order)

Site 1	**Jacob's well - Immediately below Jacobs well - contact: David Baker.**
Site 2	Jacob's well below spillway - Approximately 500 meters downstream of Jacobs well - contact: Jay Nickel.
Site 3	Rehmet - 50 meters downstream of Jacobs Well Road bridge, on Eagle Rock Ranch - contact: Pokey Rehmet.
Site 4	**Upstream Jackson 300 meters - contact Jim Jackson**
Site 5	**Jacksons Place - contact Jim Jackson, 600 Cypress Creek Lane**
Site 6	**Cypress Creek Cottages - contact owner Cypress Creek Cottages**
Site 7	**Gumberts Place - contact: Eddie Gumbert**
Site 8	**Creekhaven upstream of RR12 bridge - contact: pat @creekhaven .com**
Site 9	**300 meters downstream of RR12 bridge - contact pat @creekhaven.com**

Streamflow discharge data for Cypress Creek studies. Data in units of ft^{3}/s

Date	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9
3/11/2005	--	48.945	39.022	--	47.801 cfs	47.1	--	--	--
4/23/2005	12.363	17.335	17.552	16.678	15.802	11.882	--	19.053	--
5/21/2005	9.635	10.935	10.711	11.184	11.212	9.025	9.295	7.581	25.83
7/4/2005	5.663	4.775	4.852	6.647	3.968	4.136	4.442	3.274	3.896
10/2/2005	0	2.205	1.87	0	2.388	1.676	2.061	1.625	1.85

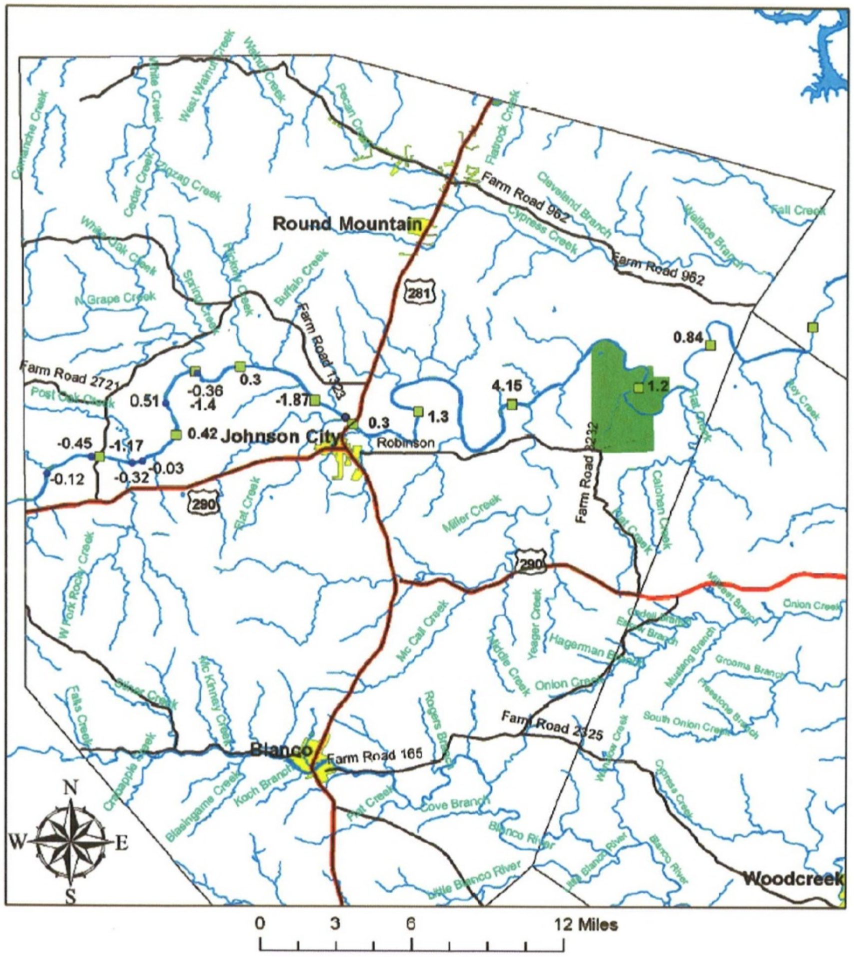
Figure 1
Locations of Streamflow gain/loss studies in Blanco and Hays Counties



Note: Flow study dates are designated by unique colors and for the site locations.

Streamflow gains and losses between the flow study sites are presented in figures 2 through 6 and data for the sites are presented in tables.

Figure 2
Streamflow Gains and Losses for the Pedernales River



1 inch equals 5 miles

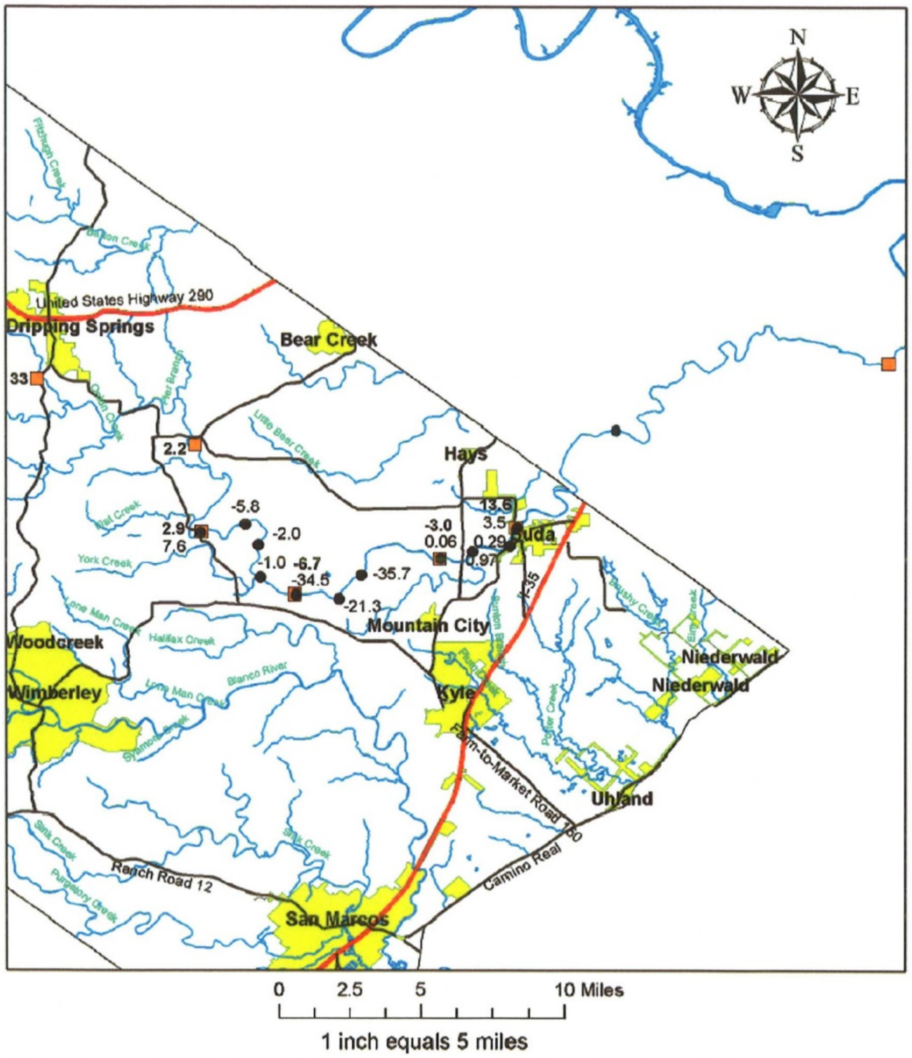
Data values at each symbol represent the streamflow gain or loss (negative value) in cubic feet per second for the stream reach from that point to the adjacent downstream point. The stream flows from west to east.

The 1956 study is represented by purple circles. The 1962 study is represented by yellow squares.

For streamflow gain/loss studies with common sites, the discharge value for the earlier study is shown on top of that for the later study.

The data are presented in tables within the report.

Figure 3
Streamflow Gains and Losses for Onion Creek



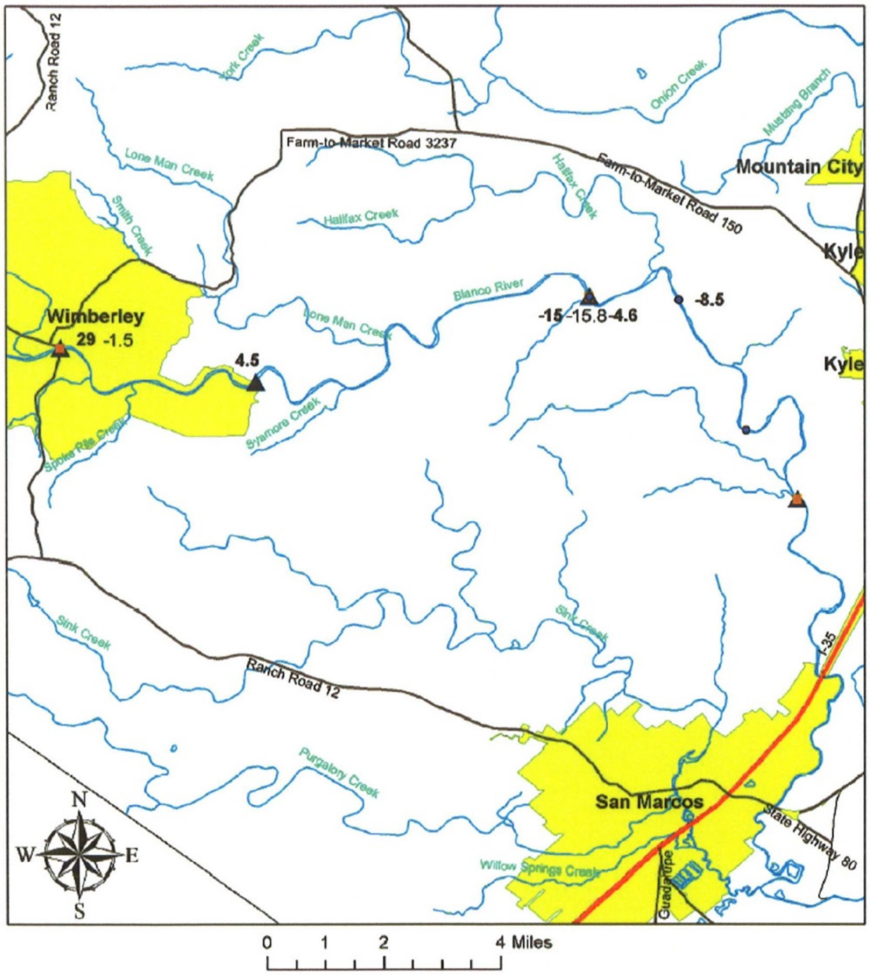
Data values at each symbol represent the streamflow gain or loss (negative value) in cubic feet per second for the stream reach from that point to the adjacent downstream point. The stream flows from northwest to southeast.

The 1958 study is represented by orange squares and the 1980 study is represented by blue circles.

For streamflow gain/loss studies with common sites, the discharge value for the earlier study is shown on top of that for the later study.

The data are presented in tables within the report.

Figure 4
Streamflow Gains and Losses for the Blanco River (1924)



1 inch equals 2 miles

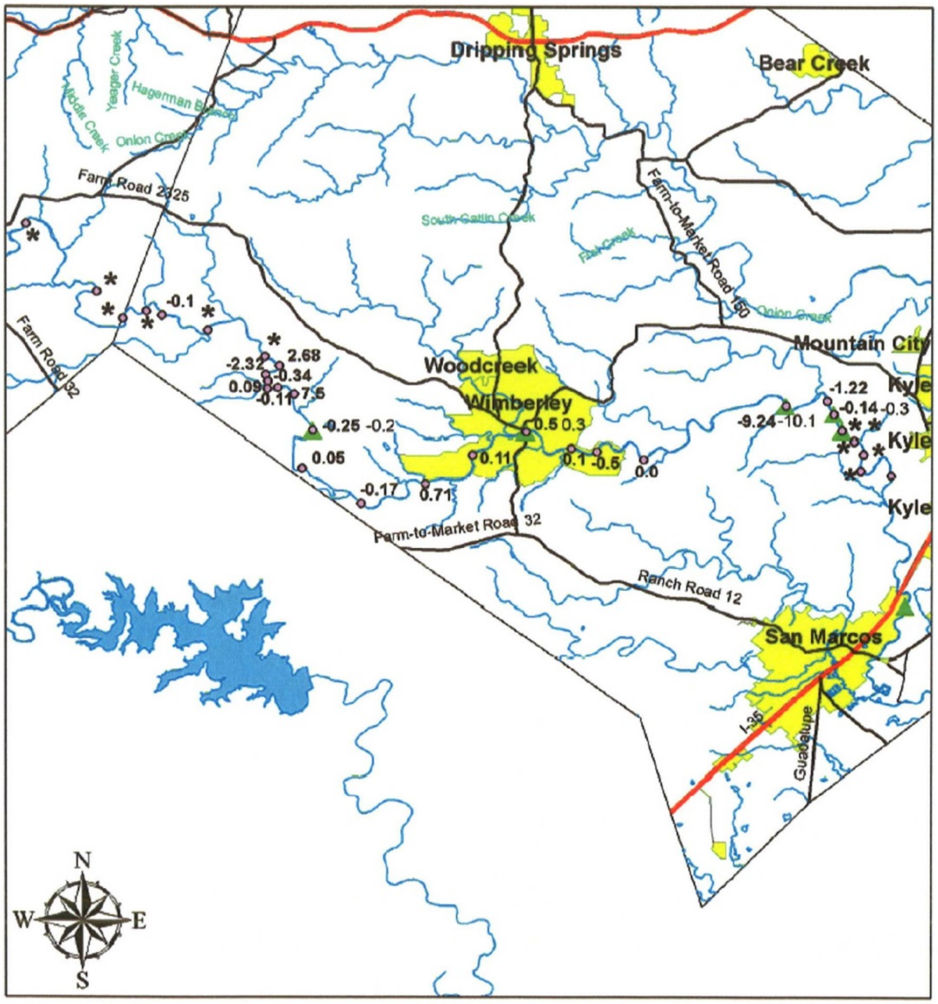
Data values at each symbol represent the streamflow gain or loss (negative value) in cubic feet per second for the stream reach from that point to the adjacent downstream point. The stream flows from west to east.

The June 1924 study is represented by orange squares, the July 15, 1924 study is represented by blue triangles, and the July 22, 1924 study is represented by purple circles.

For streamflow gain/loss studies with common sites, the discharge values are presented in order from left to right to represent the earliest to latest studies.

The data are presented in tables within the report.

Figure 5
Streamflow Gains and Losses for the Blanco River (1955)



1 inch equals 5 miles

Data values at each symbol represent the streamflow gain or loss (negative value) in cubic feet per second for the stream reach from that point to the adjacent downstream point. The stream flows from west to east.

The January 1955 study is represented by pink circles. The March 1955 study is represented by green triangles.

* represents a reach that had no flow thus gain or loss is unknown.

For streamflow gain/loss studies with common sites, the discharge value for the earlier study is shown to the left of that for the later study.

The data are presented in tables within the report.

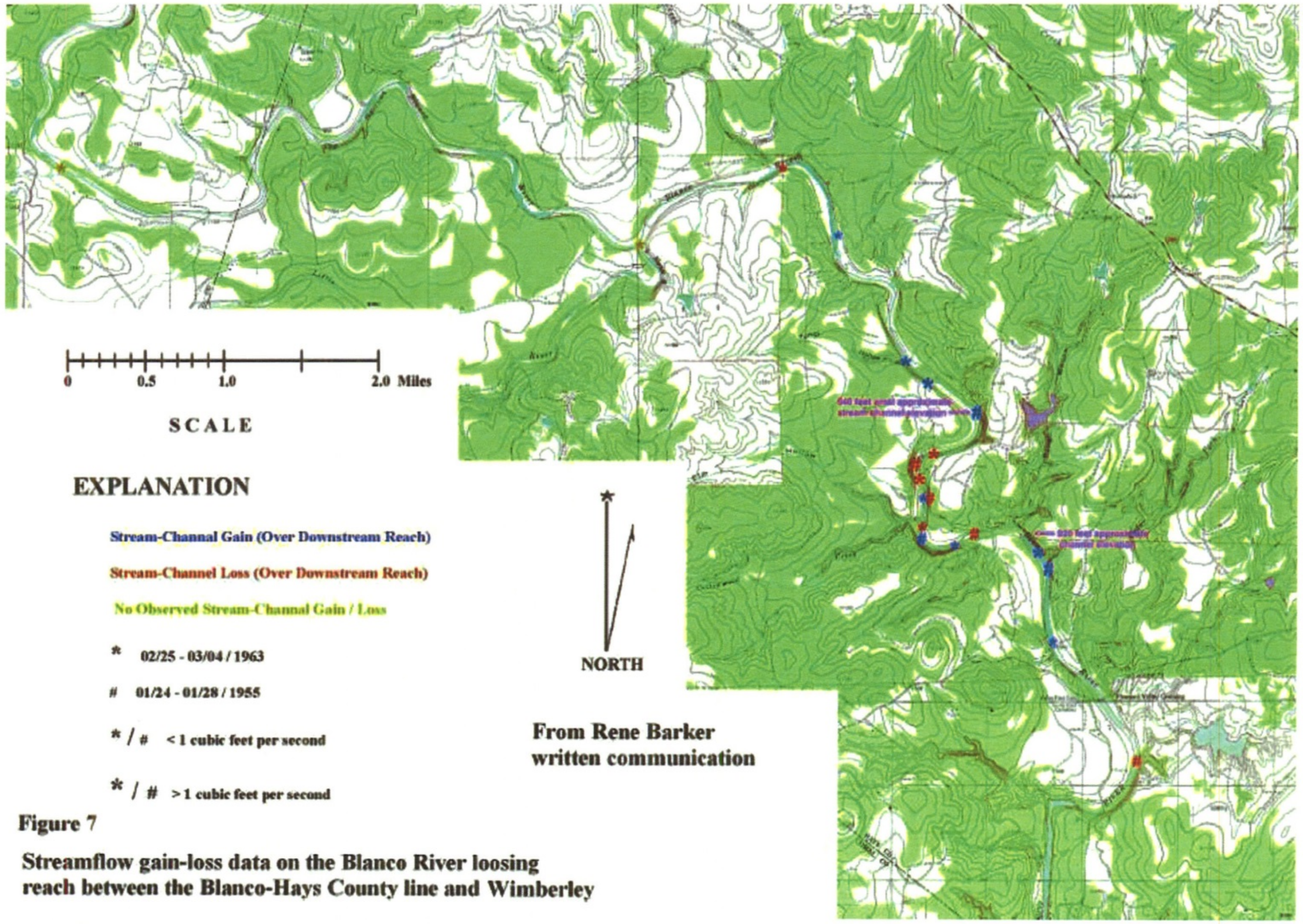


Figure 7

Streamflow gain-loss data on the Blanco River loosing reach between the Blanco-Hays County line and Wimberley

Figure 8

Cypress Creek Streamtlow Studies

March, April, May, July, and October 2005