An Investigation into the Recharge Pathways and Mechanisms In the Northern Segment of the Edwards Aquifer, Bell County, Texas

A final research report submitted to the Clearwater Underground Water Conservation District, Bell County, Texas (December, 2015)

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BAYLOR UNIVERSITY

Clearwater Underground Water Conservation District
Every drop counts!

Executive Summary

Efforts to learn more about the hydrologic processes in the Northern Segment of the Edwards Balcones Fault Zone aquifer revealed several important discoveries that will aid water management and direct future research needs. These discoveries are listed below with interpretations regarding their potential significance.

1. a. Synoptic water levels measured in 2013 included more wells than ever measured before (39) and revealed little change from 2010 synoptic levels. Overall aquifer levels, individual well levels, and general flow patterns remained similar to those previously measured.
   b. The synoptic water level data indicate that the aquifer weathered the epic drought of 2011 without any significant water level changes.

2. a. The presently known spring orifices in downtown Salado, Texas, east of Interstate Highway 35, appear to all be part of an integrated fracture system as documented by dye tracer tests.
   b. The connectivity of these springs through the fracture system implies that aquatic organisms such as the Salado Salamander should hypothetically be able to move about among the springs.

3. a. Two spring discharge points not previously described in the literature by Brune (1975) were documented through observation and dye tracer tests. These springs have been designated "Side Spring and Rock Spring".
   b. Finding dye in Side Spring which occurs in the area where Little Bubbly Spring (also called Little Boiling Spring) normally discharges during high aquifer levels indicates connectivity to the fracture system in this area even though Little Bubbly was not discharging during the dye tests. Finding dye in Rock Spring during the dye tracer tests indicates groundwater on the north side of Salado Creek may be connected through fractures to the springs on the south side.

4. a. The dye tracer test conducted in 2015 confirmed the flow directions and connectivity data from the 2013 tracer test under higher flow conditions and revealed groundwater flow velocities of approximately 350 feet/hour or almost 6 feet/minute.
   b. The fact that the same springs were all connected under both high and low flow conditions is important and indicates a well-developed fracture system with strong connectivity. The high groundwater flow velocities in the immediate area of the springs are important to consider in management decisions.

5. a. Specific conductance (SC) and temperature (T) measurements in cross sections of Big Boiling Spring as well as upstream and downstream of the confluence between Big Boiling Spring discharge and Salado Creek confirm the mixing patterns of groundwater and surface water from Big Boiling Spring and also confirm Rock Spring as a groundwater discharge point.
   b. The cross section data are important to quantify groundwater/surface water mixing, aid in habitat assessments, and aid in sample location selection.

6. a. Natural radon confirmed the location of Rock Spring and the groundwater/surface water mixing model of the SC and T cross sections.
   b. Natural radon appears to work as an indicator of groundwater discharge into surface water and can be used to quantify groundwater/surface water interactions near streams.

7. a. Nitrogen data from field and laboratory analysis showed values that are interpreted to be slightly above expected background levels but no nitrate values were observed to be over the drinking water limit. There were no strong trends but some of the higher values were found in the more developed areas.
   b. The nitrogen data warrant further investigation and monitoring.

8. a. Weather stations have been placed at three strategic locations within the aquifer outcrop and the Salado Creek watershed.
   b. Data from these weather stations will be useful in analyzing the rainfall and recharge response to specific springs.

9. a. Data collected with multi-parameter dataloggers in the cave well and several springs indicated rapid groundwater responses to large rainfall events. The data also show slight water quality changes.
   b. The multi-parameter datalogger data further refined the fracture system at the springs by indicating a slightly slower response to recharge at Doc Benedict Spring than adjacent Anderson Spring. The responses to recharge captured by the dataloggers also provide important timing information to aid in the development of future monitoring strategies.

10. a. A cutthroat flume and several V-notched weirs were constructed and employed to collect flow measurements at some of the smaller discharge points such as Little Bubbly and Side springs.
    b. The flume and weir assessments were useful in locating potential sites and selecting appropriate measuring devices.

11. a. Progress using LiDAR data to detect recharge features has been slow and time consuming but is progressing slowly.
    b. The LiDAR data still look promising for determining areas of important recharge potential.

Contents

Project Overview

A body of research was undertaken by Baylor University ("Baylor") to gain a deeper understanding of the Northern Segment of the Edwards Balcones Fault Zone (BFZ) Aquifer ("the Northern Segment"). Specifically, knowledge of how much recharge occurs and the pathways that recharge takes to the aquifer will greatly assist groundwater resource management. An enhanced scientific understanding of the Northern Segment will provide insight to the Clearwater Underground Water Conservation District (CUWCD) and community stakeholders, as well as support collaboration between the district and community in future decision-making processes.

Activities under this body of work focused on instrumentation, knowledge building, field tests and feasibility studies. Due to the timing of the FWS permitting process and prevailing hydrologic conditions, the body of research has evolved through the course of the project. Keeping in mind the overarching-goals of the study to improve understanding of recharge and groundwater flow in the Northern Segment, and through consultation between Baylor and CUWCD, research activities evolved and expanded to include several aspects not in the original proposal. Specifically, project components were added to investigate water chemistry of the Northern Edwards: surface and groundwater were analyzed repeatedly for natural radon, and wells were sampled for various chemical parameters including dissolved nitrates and phosphates.

After brief descriptions of project objectives, study area, and timeline, this report addresses topics of groundwater flow, water chemistry, aquifer response to recharge, and recharge features characterization. Each section describes the rationale for a given work, methods and instrumentation employed, and results. Project expenditures are summarized. Lastly, this report ends with a discussion of possible future work.

Project area

This body of research was conducted in the outcrop portion of the Northern Segment in Bell County (Figure 1). Focus was placed on the Salado Springs complex in downtown Salado due to ease of access, as well as their importance as critical habitat for the Salado salamander and a measure of CUWCD's DFC (Figure 2). Some sampling was also done in the down-dip portion of the aquifer for comparison.

There are three formations that comprise the Northern Segment of the Edwards Balcones Fault Zone aquifer. They are in ascending order; the Comanche Peak Formation, the Edwards Formation and the Georgetown Formation. All of these units are sedimentary rocks, Cretaceous in age, and comprised mainly of carbonate (limestones). The Edwards and Comanche Peak formations are part of the Fredricksburg Group and the Georgetown is part of the Washita Group. They are fairly well connected hydraulically and considered as one hydrostratigraphic unit referred to as the Edwards aquifer; specifically the Northern Segment of the Edwards Balcones Fault Zone aquifer. The underlying confining unit is the uppermost member of the Walnut formation, the Keys Valley member. It is comprised of carbonaceous clay material and referred to as a marl. The overlying confining unit is the Del Rio Formation (sometimes referred to as the Grayson Formation). The Del Rio is a carbonaceous clay-rich unit and often referred to as the Del Rio Clay. Upper Cretaceous units overlying the Del Rio Formation that crop out in the Salado Creek basin include the Buda Formation, Eagle Ford Group and the Austin Chalk. None of these are considered aquifers in this area. Figure 2 shows a map of the geologic units in the Salado Creek basin and environs.

Project timeline

The general timeline for this investigation into the Northern Segment is shown in Figure 3. In 2011, CUWCD connected with Dr. Joe Yelderman at Baylor University to conduct preliminary research and gather known knowledge on the Northern Segment. In 2012, the Salado Salamander (*Eurycea chisolmensis*) which is endemic to Salado Springs was proposed to be listed as endangered, further highlighting the need for an increased understanding of the Northern Segment in general and Salado Springs specifically. A formal contract was proposed to the CUWCD board in 2013 outlining this present body of research. In February of 2014, the Salado Salamander was officially listed by the U.S. Fish and Wildlife Service as threatened (Department of the Interior, 2014). Because of

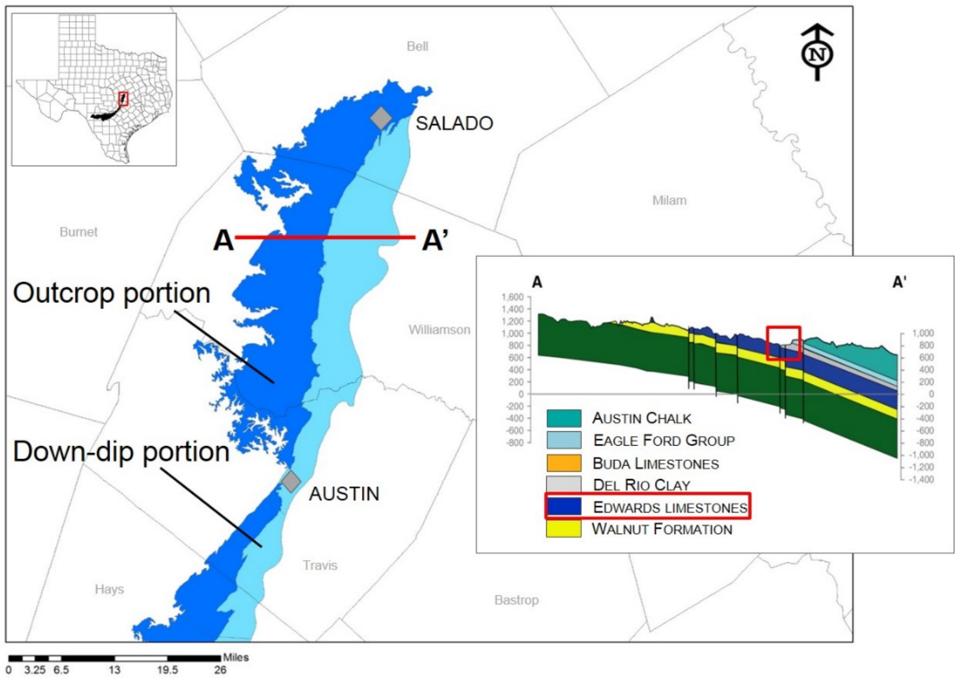


Figure 1: This study was conducted in Northern Segment of the Edwards Balcones Fault Zone aquifer in Bell County.

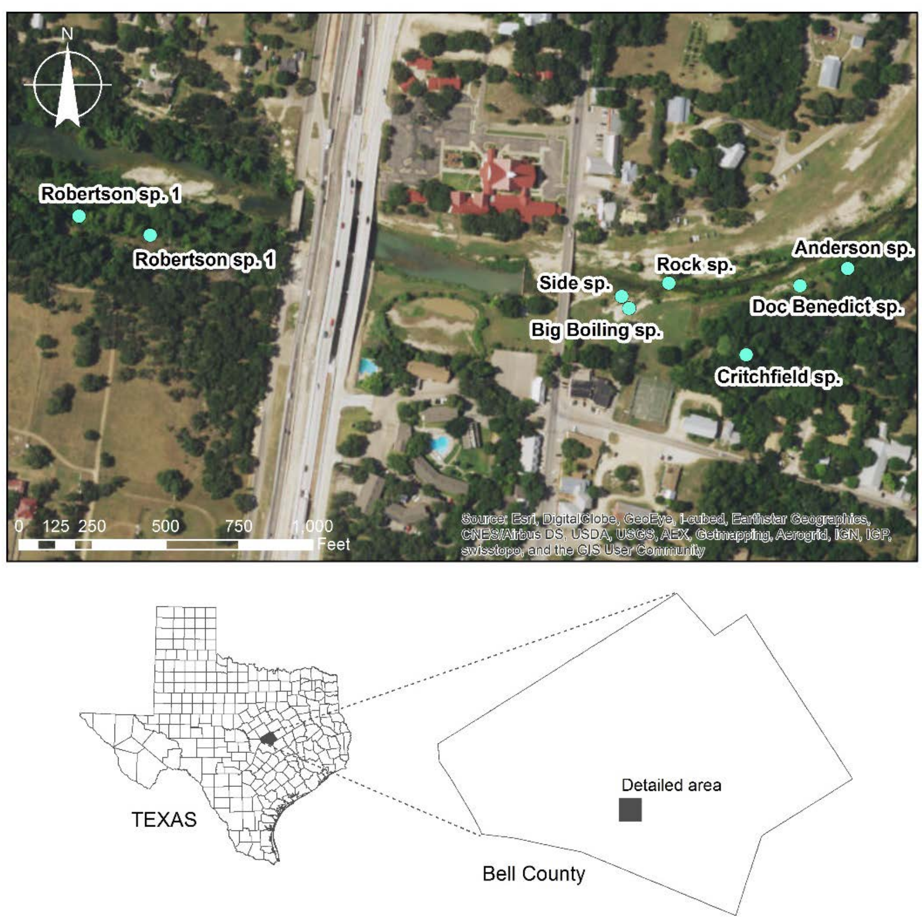


Figure 2: Location of springs in the Salado Springs complex, which was a focus area for this body of research due to ease of access and the springs' importance as a management parameter for CUWCD.

The listing, the Salado Springs complex became officially designated as critical habitat and a research permit was required to conduct tracer tests and install piezometers to study groundwater flow patterns in the complex. Ms. Stephanie Wong spearheaded the permit application process on behalf of CUWCD, and a five-year research permit was awarded to CUWCD in February 2015.

Although this report serves as a final summary of the research efforts completed under the 2013 contract between Baylor and CUWCD, there is still much to learn about the Northern Segment system. Collaborative efforts, monitoring, and data gathering are on-going.

Figure 3: Timeline for the Northern Segment research project. Key events for each year are listed.

Groundwater Flow

Synoptic Groundwater Level

In the summer of 2013, CUWCD spearheaded an effort to capture a synoptic water level in the Northern Segment. Synoptic water levels provide data that can be used to ascertain groundwater flow directions and periodic synoptic water level measurements provide a basis for assessing changes in flow directions and changes in the overall aquifer water volume. Two teams (Dirk Aaron and Joe Yelderman; and Todd Strait and Stephanie Wong) measured thirty-nine wells over two days in July 2013, resulting in a large and well-distributed data set over the outcrop and down-dip portions of the Northern Segment. Water levels were feet-to-water measurements obtained using the sonic water level meter. The water levels were converted to water elevations, hand-contoured, and then digitized for presentation (Figure 4). The predominant flow direction in the Northern Segment is southeast, from the outcrop to the down-dip portion of the aquifer. Flow is also deflected towards the northeast around Salado Springs. No cone of depression is evident in the Northern Segment at the contour interval used in Figure 4.

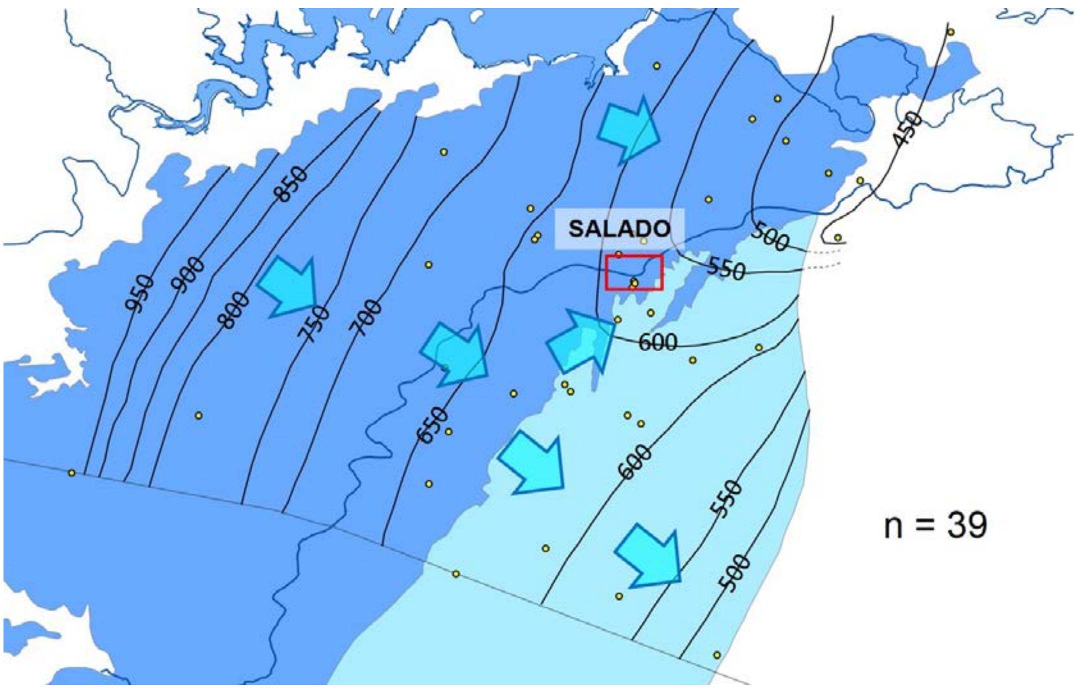


Figure 4: Synoptic surface of groundwater elevations in the Northern Segment.

Wells that were measured in 2013 and 2010 (the previous synoptic water level measurement) were plotted to compare water level change through time (Figure 5). Seven wells were measured in both 2010 and 2013. The assessment of the water levels in the well pairs showed little change. Two wells were identical, two wells showed a slight decline and two wells showed a slight rise. The 2013 water level in the seventh well pair was not usable but overall the water level data indicate there has not been a water level change to any great degree even though the time between 2010 and 2013 included the epic drought of 2011. The steady water levels indicate sustainable usage during this time period and imply effective groundwater management within the area.

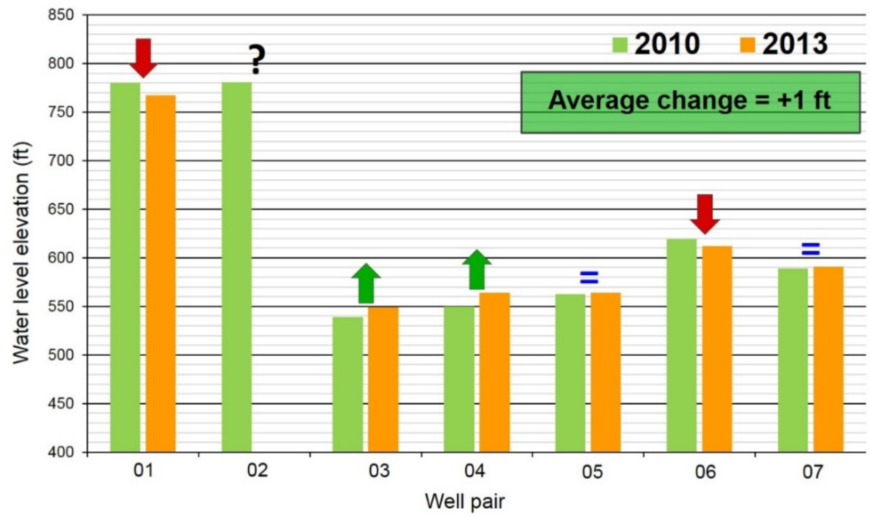


Figure 5: Water levels measured in 2010 and again in 2013 for seven Edwards aquifer well pairs in Bell County.

Dye Tracer Tests

Groundwater tracing techniques are a direct method of determining point-to-point groundwater travel times and flow directions in karst aquifers. Most tracer testing involves introducing nontoxic, fluorescent, dyes at injection points, such as caves, sinkholes, or wells. After injection, charcoal receptors and water samples are used to passively and actively collect water at wells and springs within the monitored area, and are analyzed for the presence of dyes. The dye tracer tests completed as part of this body of research was preceded by research by Mahler et al. (1998) who conducted a tracer test with particles. Clay particles were tagged with lanthanide cations (trivalent elements with periodic numbers 57 through 71). These were injected into the Stagecoach Inn Cave Well and detected at Big Boiling Spring, confirming a groundwater flow path between the cave and the springs.

Methodology overview

For this study, tracer tests using a single injection point and one fluorescent dye were conducted to investigate relatively short groundwater flow paths between the Stagecoach Inn Cave Well and springs in the Salado Springs complex (Figure 1). Traces tested the hypothesis that fractures like the one observable in the Stagecoach Inn cave support specific groundwater flow paths directly to specific springs and do not affect other springs in the area. All spring outlets, as well as other groundwater and surface water sites, were monitored along Salado Creek (Figure 6). Both passive and active sampling was employed to detect the presence or absence of dye at each monitor site. The first tracer test took place in the summer of 2013. At 8:30 am on July 31, 2013, one slug of 128 g of uranine dye was introduced into the Stagecoach Inn Cave Well. Detection sites were sampled until 8 pm of the same day. Charcoal receptors were collected and replaced at 8 pm, collected and replaced again at 9 am on August 1, 2013, and then collected on August 7, 2013. A second tracer test took place in the spring of 2015, under higher flow conditions. At 8:45 am on April 18, 2015, 74 g of uranine dye were introduced into the Stagecoach Inn Cave Well. Detection sites were sampled until 7 pm of the same day. Charcoal receptors were collected and replaced at 7 pm, collected and replaced again at 3 pm on April 19, 2015, and then collected on April 27, 2015.

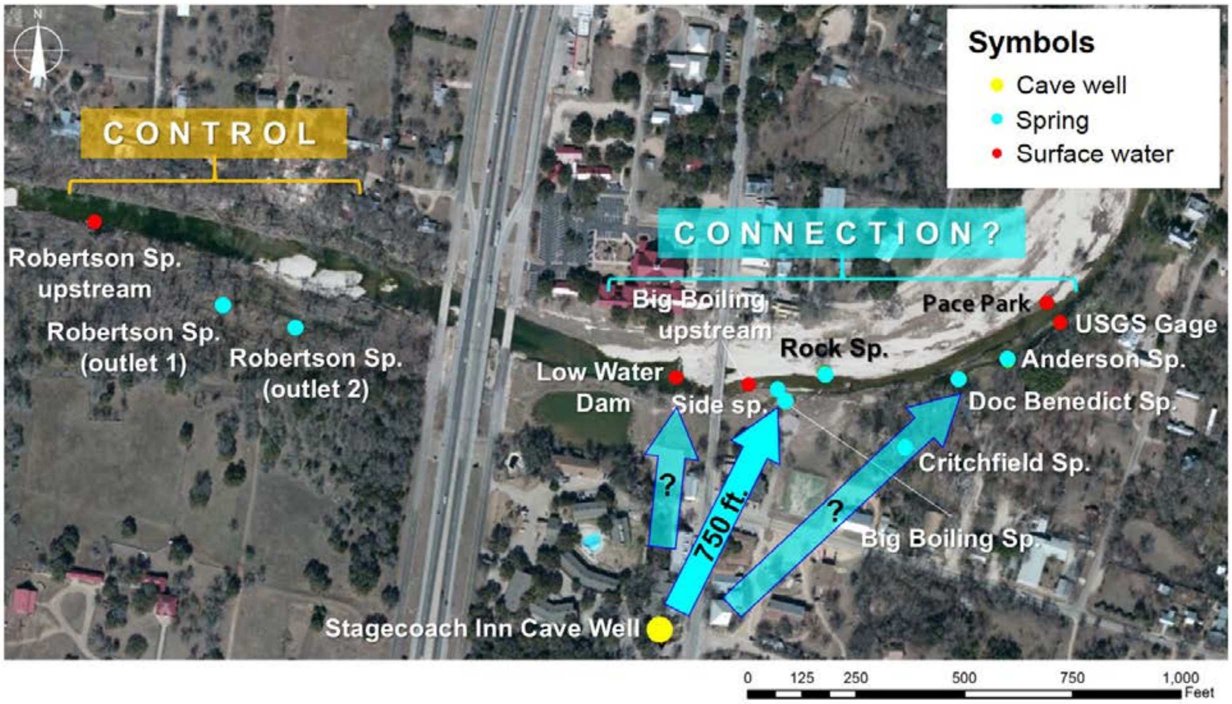


Figure 6: Conceptual overview of Salado Springs dye trace tests.

Dye

Sodium fluorescein, commonly called, "uranine", was selected for this study because of its nontoxicity, cost effectiveness, and ease of detection (Table 1). The dye used is fluorescent and used as colorants in medicine, foods, cosmetics, and industrial applications.

Table 1. Chemical characteristics of sodium fluorescein (uranine).

Common Name …………………………………………………	Uranine (sodium fluorescein)
Color Index ………………………………………………………	Acid Yellow
Generic Name Molecular Weight CAS Number ………..	73 376.27 518-47-8
Excitation Wavelength (nm) ………………………………….	493

Eosin was chosen as a secondary dye to complement and confirm the uranine trace during the summer 2013 tracer test. Because of the similarity of results to those of the uranine trace as well as research permit restrictions; eosin was not used for the spring 2015 tracer test.

Injection Point

For the Salado Springs tracer tests, the Stagecoach Inn Cave Well was selected for the injection point because it appears to represent a direct pathway to Big Boiling Spring, supported through previous published research as well as local anecdotal accounts. Tracer tests originating in karst features such as caves, sinkholes, or sinking streams (perennial) are expected to be more successful in reaching an aquifer flow path in a timely manner than those originating from other injection points. The straight-line distance between the cave and Big Boiling Spring is 747 ft. The straight-line distance between the cave and Anderson Spring, the most downstream spring in the complex, is 1258 ft.

Monitoring sites

A series of groundwater and surface water monitoring sites were selected, including all the named springs in the Salado Springs complex: Robertson Spring, Big Boiling Spring, Little Bubbly Spring, Critchfield Spring, Doc Benedict Spring, and Anderson Spring.

In the summer 2013 tracer test, all the named springs were monitored except Little Bubbly which was not flowing. Critchfield Spring was also not visibly flowing, but the spring pool contained standing water. Three upstream sites, where dye was not expected, were monitored as control points. These included Robertson Spring which was not flowing (but had standing water), immediately above the low-water dam between Main Street and Interstate Highway 35, and underneath the Main Street Bridge in Salado Creek. Additional to the named springs, a gravel seep associated with Big Boiling and Little Bubbly springs (“Side Spring”) was monitored. Stream sites that were downstream of springs had potential to experience dye. Monitored sites included the Big Boiling Spring run, the north bank across from Big Boiling Spring, the south bank downstream from Big Boiling Spring, the south bank at the USGS flow gage site, and the north bank in Pace Park across from the USGS flow gage (Figure 6).

A slightly refined suite of monitoring sights was chosen for the spring 2015 tracer test (Figure 6). All the named springs were flowing and were monitored except Little Bubbly. Control sites included two outlets of Robertson Spring (Robertson Spring was flowing during this test), Salado Creek upstream of Robertson Spring, immediately above the low-water dam between Main Street and Interstate Highway 35, and Salado Creek between the Main Street Bridge and Side Spring. In addition to the named springs of the complex, Side Spring and a groundwater discharge point on the north bank (“Rock Spring”) were monitored. The USGS flow gage and Pace Park were again used as surface water monitoring sites.

Sampling

Sampling for presence of dye included both passive (charcoal receptors) and active (automated and manual grab sampling) methods. For both tracer tests, charcoal receptors sometimes known as “bugs” were placed at all monitoring sites at least a week before each test to assess background concentrations of the tracer material and then also placed at each site during the test. For the summer 2013 test, water samples were collected at Big Boiling Spring frequently (every ten minutes) throughout the test using an ISCO automated sampler, while occasional grab samples (every two hours) were collected at the other sites. For the spring 2015 test, automated samplers were not available. Instead, at least one field assistant was assigned to manually sample each monitoring site. Big Boiling, Anderson, and Rock springs were sampled at 15 minute intervals; while Side Spring and all sites downstream of Big Boiling Spring were sampled at 1 hour intervals. Grab samples were also collected every time a charcoal receptor was collected. A control blank and field blank were collected every field day as quality control.

Lab preparation

An elution process was performed to analyze the level of dye picked up by the activated charcoal indicators. The packets of charcoal were air-dried and opened, and enough charcoal to fill the bottom of a plastic two-ounce Solo cup was removed from the packet. Fifteen milliliters of eluent, made up of a solution of 95% isopropyl alcohol and 5% potassium hydroxide, was added to the charcoal (Figure 7A). After an hour of elution time, the eluate was poured into 10 ml glass vials for analysis.

Water samples collected from Big Boiling Spring using an ISCO automatic were transferred to 10 ml glass vials for analysis. Manually-collected grab samples were collected using the same 10 ml glass vials.

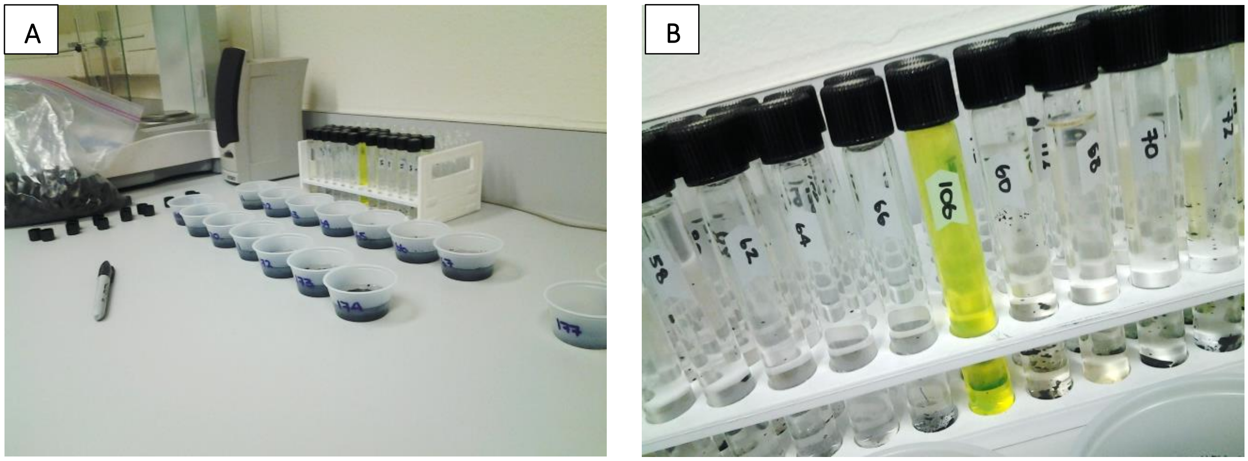


Figure 7. A) Set-up for eluting dye from the charcoal detectors; B) Samples that contained visible dye were at too high of a concentration for analysis. These samples were diluted for analysis, and then normalized back to 100% for comparison.

Sample analysis

All samples were analyzed as continuous scans on a Perkin-Elmer LS-50B Luminescence Spectrometer. The resulting spectra are emission referenced with $\Delta\lambda$ of 15 nm, scan speed of 750 nm/min, scanning range from 401 nm to 650 nm, and a 6.0 nm slit. Samples that contained dye concentrations exceeding the analysis limit of the fluorimeter were first analyzed as-is (Figure 7B). Following the initial analysis, the samples were diluted to a level that could be detected by the fluorimeter. For the samples in the summer 2013 trace, a 20% dilution (1 ml sample to 4 ml de-ionized water) was optimal for analysis. For the spring 2015 trace, a 33% dilution (3 ml sample to 6 ml de-ionized water) was optimal for analysis. The spectra produced were then normalized to 100% for comparison with the rest of the data.

All spectra were fitted using Fityk (version 0.9.8) curve fitting and data analysis program (Wojdyr, 2010). The spectra were fitted using Pearson Type VII functions. Peak fluorescence intensity values were converted to dye concentration in parts per billion (ppb) by creating a linear regression with the peak intensities of standards and their corresponding concentrations. The peak concentration for samples with quantifiable detections were plotted against time elapsed to construct breakthrough curves.

July 2013 trace results

Dye was detected at all monitoring sites downstream of Big Boiling Spring, and was not detected at either upstream monitoring sites or the control site (Figure 8). Peak concentrations and detection times for all monitoring sites are summarized in Table 2. One hundred twenty-eight grams of uranine dye was injected. Visually, uranine dye was strongly present at Big Boiling Spring and Anderson Spring (Figure 9). Sixteen grams of eosin dye was injected. Due to the small amount of dye, eosin was not visible at any monitoring site; however it was still detected at low levels at Big Boiling Spring.

Figure 8: Results of the summer 2013 dye trace test. Purple dots indicate locations of no dye detection. Green dots indicate spring and creek locations where uranine was detected. Arrows represent confirmations of groundwater flow between the injection point at Stagecoach Inn Cave Well and a spring.

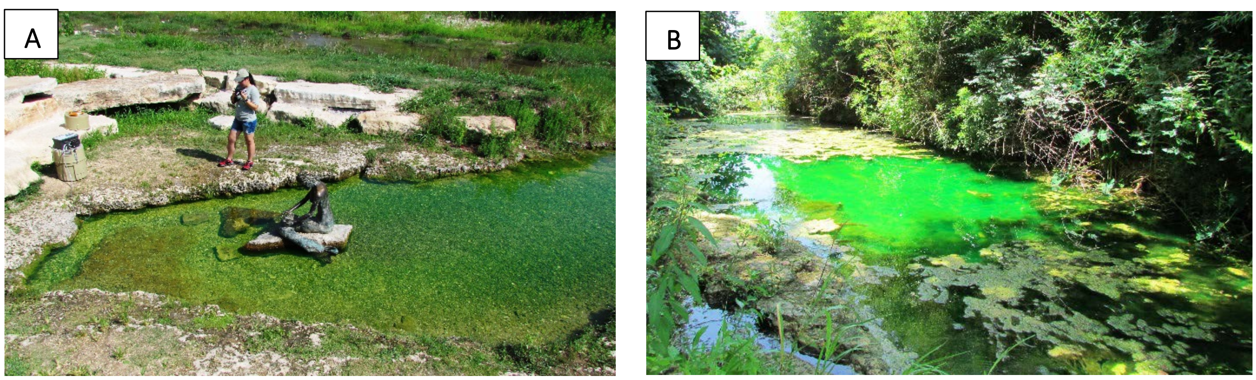


Figure 9: Big Boiling Spring (A) and Anderson Spring (B) both exhibited strong groundwater flow connection to Stagecoach Inn cave, as evidenced by visual detection of uranine at both sites.

Breakthrough curves for both uranine and eosin were plotted for samples collected using the ISCO auto-sampler at Big Boiling Spring (Figures 10 and 11). There are two major discharge points for Big Boiling Spring into the Big Boiling Spring pool; the ISCO auto-sampler sampled at the northern discharge point for the uranine trace and the southern discharge point for the eosin trace. The general shape of the breakthrough curves for uranine and eosin are similar, as are the peak detection times for both dyes (2.67 hours after injection of uranine, and 2.50 hours after injection of eosin). The amount of eosin injected was so small that the first portion of the breakthrough curve was not detected at quantifiable levels (that is, the dye was present at levels significantly above a blank, but was not quantifiable). However, a time of first detection for eosin may be estimated by extrapolating the breakthrough curve to its x-intercept. The extrapolated time of first detection for eosin is 2 hours after injection, which is comparable to the first detection time for uranine (1.83 hours). Groundwater velocities were estimated by dividing the distance between the injection site and Big Boiling spring pool (228 m) by the first and peak detection times for uranine and eosin. The average groundwater velocity between the injection site and Big Boiling spring pool was determined to be 0.0284 m/s (1.526 mi/d). The first and peak detection times, and calculated groundwater velocities for the uranine and eosin traces are summarized in Table 3. The similarity of first arrival times, peak times, calculated groundwater velocities, and the overall shape of the breakthrough curves for uranine and eosin indicate similar flow paths from the injection site to the northern and southern discharge points in Big Boiling springs pool.

Table 2. Peak uranine concentrations and detection times for grab samples collected along Salado Creek on July 31, 2013. No dye detection at a given site is indicated by "ND" ("No detect").

Site	Peak concentration (ppb)	Peak time (hh:ss)
Robertson Spring	Dry spring	--
Low water dam lake	ND	--
Main St. bridge	ND	--
Little Bubbly Spring	Dry spring	--
Side Spring	32.45*	12:31
Big Boiling Spring	137.45	10:40
Big Boiling confluence	20.82*	12:23
Big Boiling downstream	15.97*	12:26
Critchfield	2.20	10:37
Doc Benedict Spring	22.46	14:15
Doc Benedict fracture	22.16*	14:15
Anderson Spring	11.78*	14:02
USGS gage	10.08	16:33
North bank	30.26	14:03
Pace Park	12.81	18:36

** indicates peak concentrations that were also first detections.*

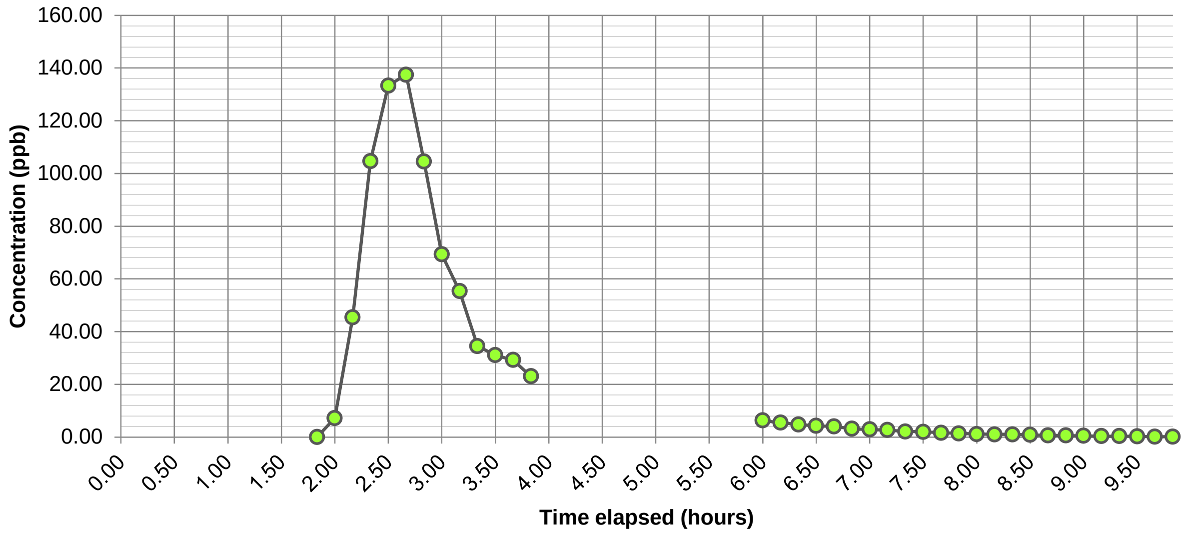


Figure 10. Breakthrough curve for uranine at Big Boiling Spring. Samples were collected with an auto-sampler at 10-minute intervals. First detection occurred at 1.83 hours after dye injection, and peak detection occurred at 2.67 hours (137.45 ppb). The data gap from hour 4 to 6 occurred while the auto-sampler was being re-set for the afternoon eosin trace.

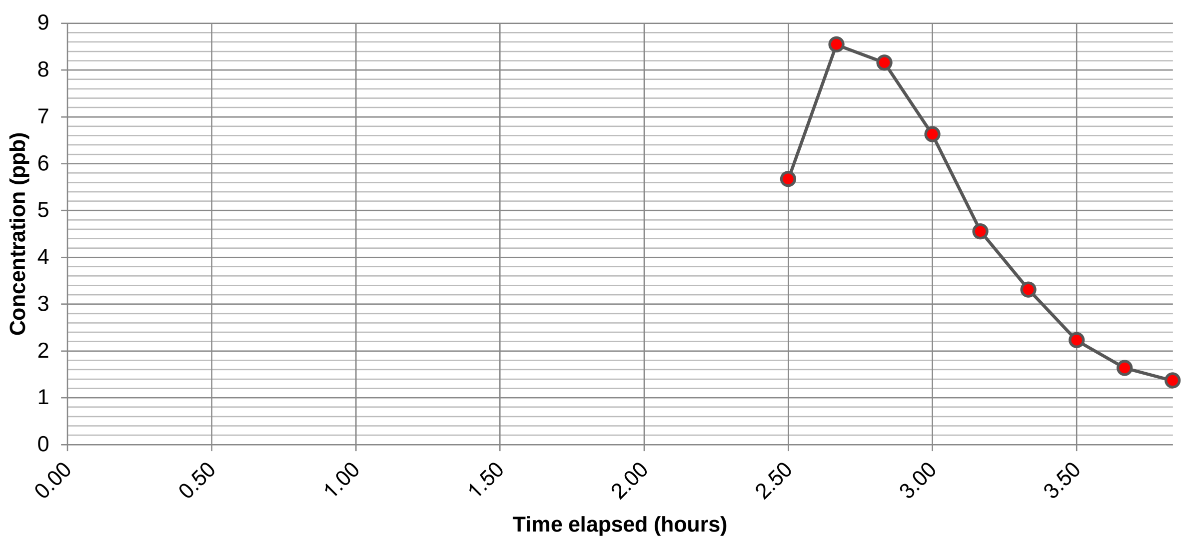


Figure 11. Breakthrough curve for eosin at Big Boiling Spring. Samples were collected with an auto-sampler at 10-minute intervals. First detection occurred at 2.50 hours after dye injection (5.67 ppb), and peak detection occurred at 2.67 hours (8.54 ppb).

Table 3. Groundwater velocity determined at Big Boiling Spring at first and peak detection times for both uranine and eosin traces. The injection point is 747 feet (228 meters) from Big Boiling Spring. The average groundwater velocity is 0.0284 m/s, or 1.526 mi/d. The first detection time for eosin was obtained by extrapolating the break-through curve to its x-intercept.

	URANINE			EOSIN		
	Time (h)	Velocity (m/s)	Velocity (mi/d)	Time (h)	Velocity (m/s)	Velocity (mi/d)
First detection	1.83	0.0346	1.858	2.0	0.0317	1.700
Peak detection	2.67	0.0237	1.273	2.67	0.0237	1.273

April 2015 trace results

Overall, the results of the second tracer test were very similar to those of the first test. Dye was detected at all monitoring sites downstream of Big Boiling Spring, and was not detected at any upstream monitoring sites (Figure 12). Peak concentrations and detection times for all monitoring sites are summarized in Table 4. Seventy-four grams of uranine dye was introduced to the Stagecoach Inn Cave Well. Visually, uranine dye was detected at Big Boiling, Side, Doc Benedict, and Anderson springs.

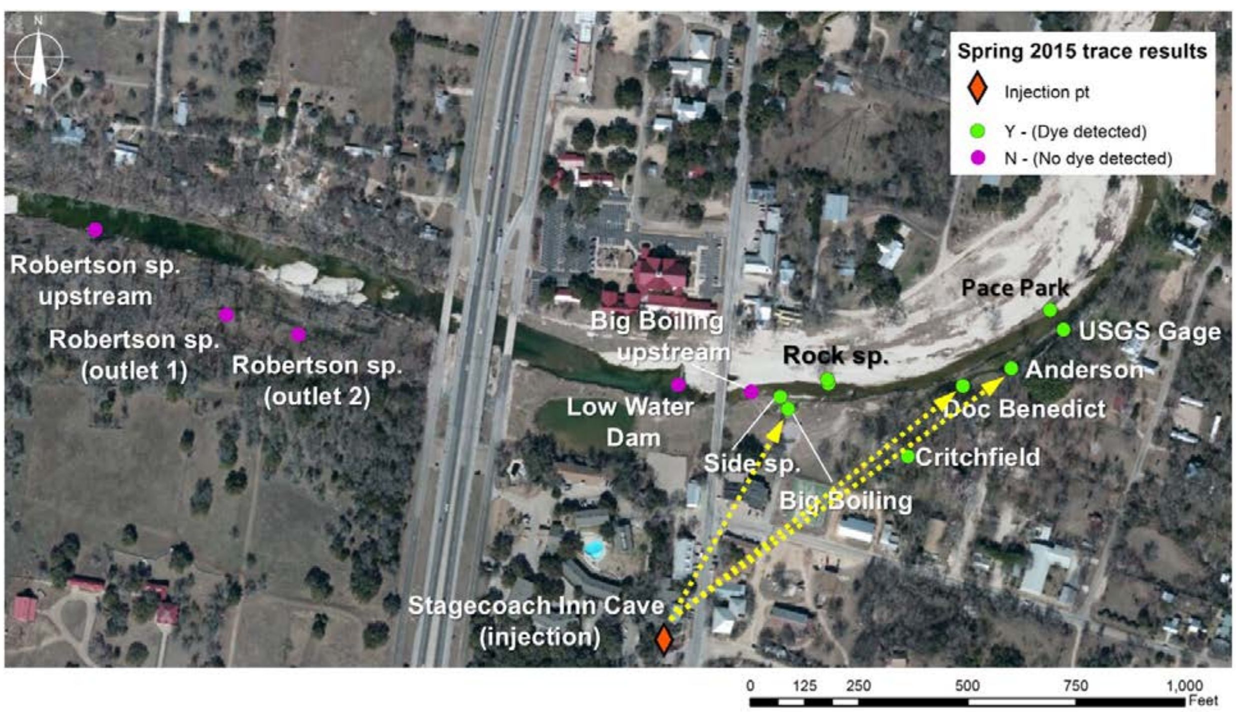


Figure 12: Results of the spring 2015 dye trace test. Purple dots indicate locations of no dye detection. Green dots indicate spring and creek locations where uranine was detected. Arrows represent confirmations of groundwater flow between the injection point at Stagecoach Inn Cave Well and a spring.

Groundwater velocities were estimated by dividing the distance between the injection site and each spring by the first and peak detection times for uranine. The average groundwater velocity between the injection site and Big Boiling spring was determined to be 0.0676 m/s. The average groundwater velocity from the injection site to Anderson Spring and Rock Spring were 0.0526 m/s and 0.0429 m/s respectively. The first and peak detection times, and calculated groundwater velocities for the traces are summarized in Table 5.

Table 4. Peak uranine concentrations and detection times for grab samples collected along Salado Creek on April 15, 2015. No dye detection at a given site is indicated by "ND" ("No detect").

Site	Peak concentration (ppb)	Peak time (hh:ss)
Robertson Spring	ND	--
Low water dam lake	ND	--
Salado Creek *(Main St. bridge to Side Spring)*	ND	--
Little Bubbly Spring	Dry spring	--
Side Spring	>1000 intensity units†	9:46
Big Boiling Spring	>1000 intensity units†	10:00
Critchfield Spring	8.14*	15:40
Doc Benedict Spring	>1000 intensity units†	10:44
Anderson Spring	>1000 intensity units†	11:35
USGS gage	10.96*	14:53
Rock Spring *(North bank)*	>1000 intensity units†	11:30
Pace Park	16.54*	15:02

** indicates peak concentrations that were also first detections.*
†denotes a sample with dye concentration that exceeded the detection limit of the fluorimeter. These samples are being re-analyzed.

Table 5. Groundwater velocity determined at Big Boiling, Anderson, and Rock springs at first and peak detection times. The injection point is 747 feet (228 meters) from Big Boiling Spring, 1258 feet (384 meters) from Anderson Spring, and 869 feet (265 meters) from Rock Spring.

	Big Boiling			**Anderson**			**Rock**		
	Time (h)	Velocity (m/s)	Velocity (mi/d)	Time (h)	Velocity (m/s)	Velocity (mi/d)	Time (h)	Velocity (m/s)	Velocity (mi/d)
First detection	0.75	0.0844	4.53	1.58	0.0675	3.62	1.25	0.0589	3.16
Peak detection	1.25	0.0507	2.72	2.83	0.0377	2.02	2.75	0.0268	1.44
Avg. velocity	--	*0.0676*	*3.63*	--	*0.0526*	*2.82*	--	*0.0429*	*2.30*

Discussion

Results of the dye tracer tests at Salado Springs confirmed a previous tracer test (Mahler et al, 1998) and the potential that anecdotal stories might be true regarding flow paths between the Stagecoach Inn Cave Well and Big Boiling Spring. The dye tracer tests showed that groundwater flows freely between the injection point in the Stagecoach Inn Cave Well and the major springs along Salado Creek in the downtown area, demonstrating excellent communication between groundwater in all the flowing springs in the study area. The tracer tests revealed a spring system where the series of major springs in the downtown Salado area (with the exception of Robertson Spring) were interconnected to each other under low flow conditions experienced on July 31, 2013, as well as higher flow conditions like those on April 18, 2015.

The first tracer test was conducted under low-flow conditions when Little Bubbly Spring showed no visible flow, Robertson spring had only standing water and Critchfield Spring had only standing water. Side spring was barely flowing but was thought to possibly be connected to those two spring flows. The presence of dye detected in the seep indicates this is probably the case. It was unclear if the dye detected at the north bank of Salado Creek was the result of groundwater discharge at this location or if dye had been transported by surface flow in the creek from Big Boiling Spring discharge.

The second dye tracer test was conducted under higher flow conditions than the first test and in a different season (spring compared to summer). The results were similar and confirming in that all the same spring outlets received dye as they did in the previous test. The results indicate the connectivity among the springs and fracture system is present under both high and low flow conditions. However, as one might expect, the first detection and peak detection times were less for the second test under the higher flow conditions.

Flow was hypothesized to be toward Salado Creek with a downstream component and this appears correct as no dye was detected in the three upstream sites but was detected in all the downstream sites on both tracer tests. The dye reached Big Boiling Spring first and the amount was greater than at other sites except for Anderson Spring. Anderson Spring had a very strong showing of dye that appeared to be related to its strong discharge flow rate. Dye reached Anderson Spring later than Big Boiling Spring presumably because of a greater distance from the injection point. Results of the tracer tests suggest that on this localized scale of several hundred meters, even under low-flow conditions such as those during the summer 2013 tracer test, the springs are interconnected hydrogeologically and act as one system interacting with Salado Creek.

Water Chemistry

Cross sections

Seasonally, Salado Creek has been profiled at three cross sections near Big Boiling Spring. Cross sectional profiling helps to monitor physical and chemical conditions, as well as comparison with previously-collected data (water depth, temperature, and specific conductance) at Salado Creek. Flow measurements were also taken. Water samples were collected periodically to monitor natural radon levels in the area.

The three cross-sections were located in Salado Creek (Figure 13): within the spring flow of Big Boiling Spring (cross section one), in Salado Creek upstream of the confluence of Big Boiling Spring (cross section two), and in Salado Creek downstream of the confluence of Big Boiling Spring (cross section three).

Figure 13. Diagram of Salado Creek showing key features. Cross-section locations are indicated by the red lines and labelled 1, 2, and 3.

Methods

All three cross-sections were taken perpendicular to flow direction (Figure 13). The measured parameters included: depth in feet (ft.), temperature in degrees Celsius (°C), specific conductance in micro-Siemens (μS/cm), and flow in feet per second (fps). Measurements were made across the creek using stadia rod or reel tape laid across the channel width. Depth was measured using a metal yard stick. Temperature and specific conductance were measured using a Solinst TLC meter (Solinst Model 107 TLC Meter; Solinst Canada Ltd., Georgetown, Ontario). Flow was measured using a Global Water flow meter (Global Water Instrumentation, College Station, Texas) or SonTek Flowtracker (SonTek, San Diego, California), and the discharge for each cross section was determined using the following equations:

$$Q = \sum q_x \tag{1.1}$$

where

$$q_x = \frac{(v_x d_x w_x)}{2} \tag{1.2}$$

where Q is the total discharge for a given cross section and is equal to the sum of each of the partial discharges (q_x) in cubic feet per second (cfs), v_x is the measured flow velocity in feet per second (fps) at interval x, d_x is the measured depth in feet, and w_x is the width of interval x in feet (equations modified from Michaud, 1991).

The specific conductance measurements were made in the natural water environment without the use of a stilling well or container, and without filtering the water. The water was very clear (spring flow and base flow conditions) but was flowing briskly except near the stream banks.

Results

Cross-section one is characterized by unusual consistency in temperature and specific conductance (Figure 14 and 15). Steady depth and temperature values are understandable for a spring flow discharge channel and the landscaped, un-shaded nature of the Big Boiling Spring pool. The slight changes in specific conductance may be the result of variability in flow velocities that could affect the reading. Similar specific conductance values suggest a single source of water; in this setting it is groundwater discharging from Big Boiling Spring. Furthermore, specific conductance values are similar to those measured at the Stagecoach Inn Cave, located to the south and up-gradient with regard to groundwater flow. The similar specific conductance values suggest that Big Boiling Spring and the Stagecoach Inn Cave are part of the same groundwater system.

Cross-section two is located in the natural channel of Salado Creek. The cross-section is consistently shallow, with warm water that is characterized by lower specific conductance than cross-section one. Temperature and specific conductance values were again fairly consistent across the section. The variation in temperature and specific conductance near the north bank (feet 18-23) are the result of very shallow, muddy conditions. Higher temperature and lower specific conductance values than those measured at cross-section 1 suggest that flow in Salado Creek upstream of Big Boiling Spring is dominated by streamflow rather than direct groundwater. Although flow in Salado Creek during these observations was dominated by baseflow from groundwater, a low-water dam immediately upstream is partly responsible for increased temperatures and lower specific conductance.

Cross-section three is located in the natural channel of Salado Creek, downstream of the confluence with Big Boiling Spring. Temperature and specific conductance values at this location show more variability than cross-sections one or two. This is to be expected since cross-section three is below the confluence of the spring and stream flow. Temperature and specific conductance at this location are intermediate values of those measured at cross-sections one and two (Figures 14 and 15), suggesting a mixing of stream water (represented by cross-section two) and groundwater discharging from Big Boiling Spring on the south side of the channel (represented by cross-section one). Temperature and specific conductance values, beginning at about 20 ft. of cross-section three, are similar to measurements from Big Boiling Spring. The temperature rises and specific conductance decreases from the south to the north in the middle section as more surface water influences the total water flow. A probable groundwater discharge on the north side of the channel at the end of cross-section three is likely responsible for the change in temperature and specific conductance. Similar temperature and specific conductance values also suggest a groundwater connection between the two discharge points (that is, Big Boiling Spring and the north bank discharge point). Such a connection has been confirmed through dye tracing.

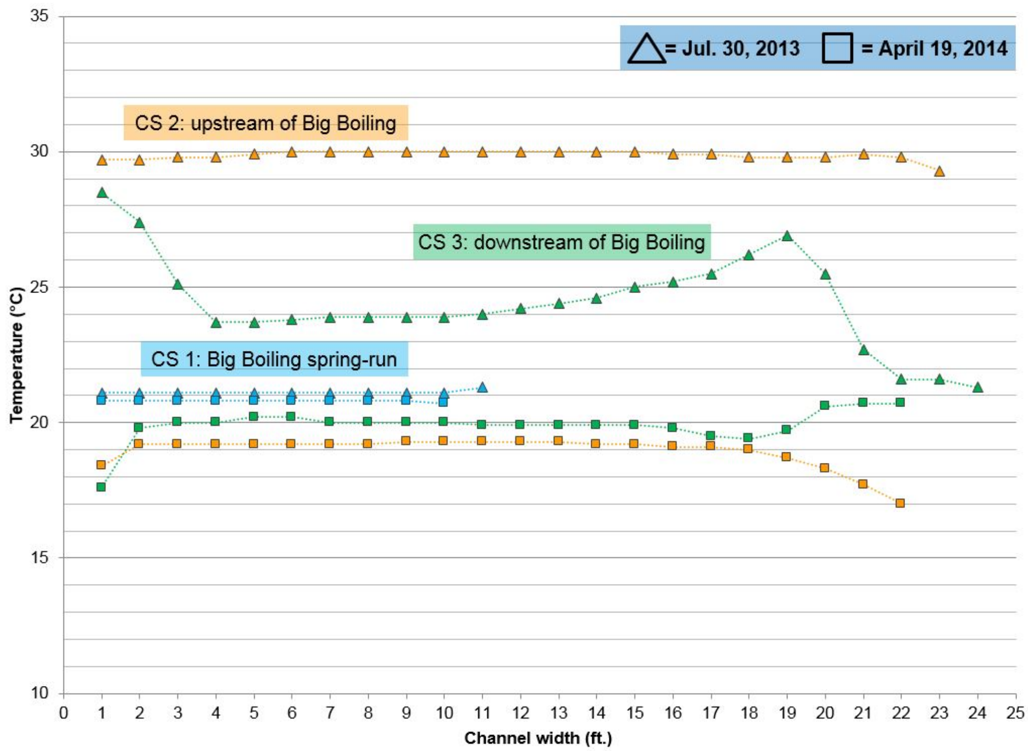


Figure 14: Temperature data for cross sections 1-3 at two time periods.

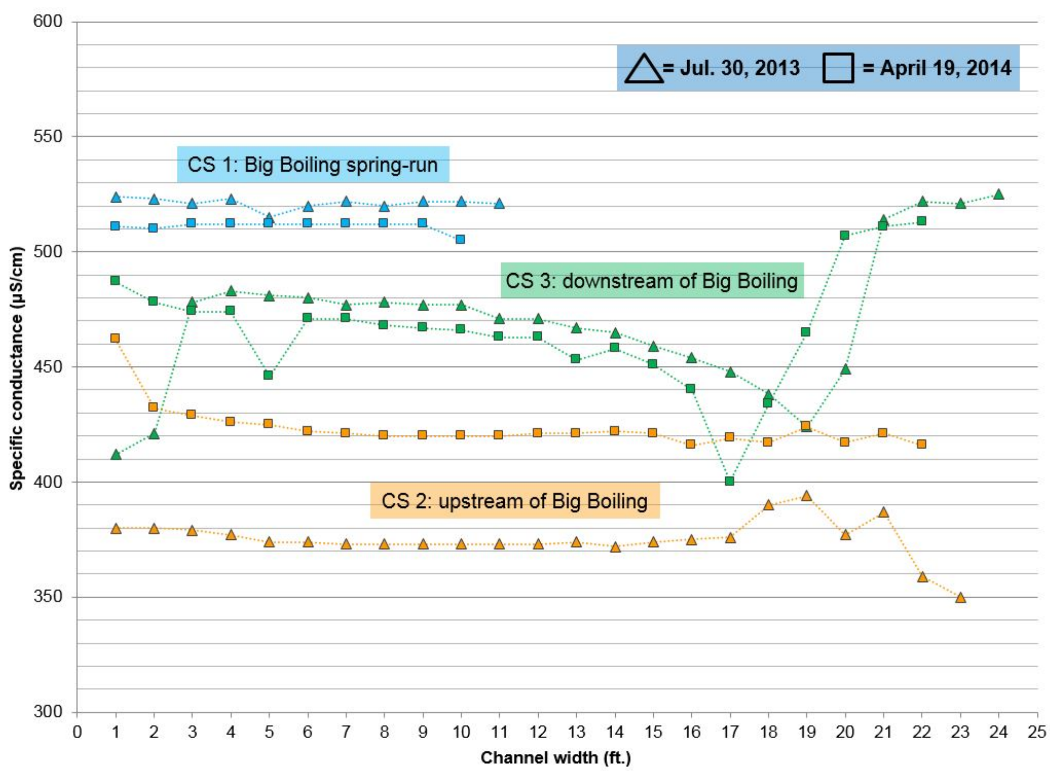


Figure 15: Specific conductance data for cross sections 1-3 at two time periods.

Summary

Cross-sections one and two are characterized by consistent values in the three measured characteristics: depth, temperature, and specific conductance. Low temperatures and high specific conductance values confirm groundwater-dominated flow in cross-section one, while high temperatures and low specific conductance values in cross-section two indicate stream-dominated flow. Cross-section three showed the most variability in the three measured characteristics and, furthermore, the values range between those of cross-sections one and two. Values at cross-section three suggest a mixing of groundwater and stream water, with groundwater input from Big Boiling Spring in the south and a probable groundwater discharge point in the north bank of Salado Creek.

Natural radon

Radon-222 is part of the decay chain of uranium-238 (due to the alpha-decay of radium-236), and has a relatively short half-life of 3.8 days. Radon is found naturally in trace amounts in the local soil and bedrock (Michel, 1987). It is assumed that there is no source material in the atmosphere and so the concentration of radon in rain is zero. As rain infiltrates the aquifer and interacts with source material (rocks and soils), the concentration of radon should increase until equilibrium is reached (Hoehn et al., 1992). As groundwater is discharged into a surface water body, the concentration of radon will decrease through decay and diffusion into the atmosphere (Figure 16), and is expedited through any aeration due to mixing and turbulence (Stellato et al., 2012; Neupane et al., 2014). Because of the short half-life of Rn-222, it has been useful for applications such as apparent age estimation of groundwater, infiltration rates, groundwater discharge location and magnitude, fracture aperture estimation, and contamination studies (Ellins et al., 1990; Lee and Hollyday, 1991). Radon was applied in the Salado Springs complex to identify locations and comparative magnitude of groundwater discharge. Radon is naturally-occurring and employs a minimally-invasive sampling method, which is especially attractive in a critical habitat setting such as Salado Springs.

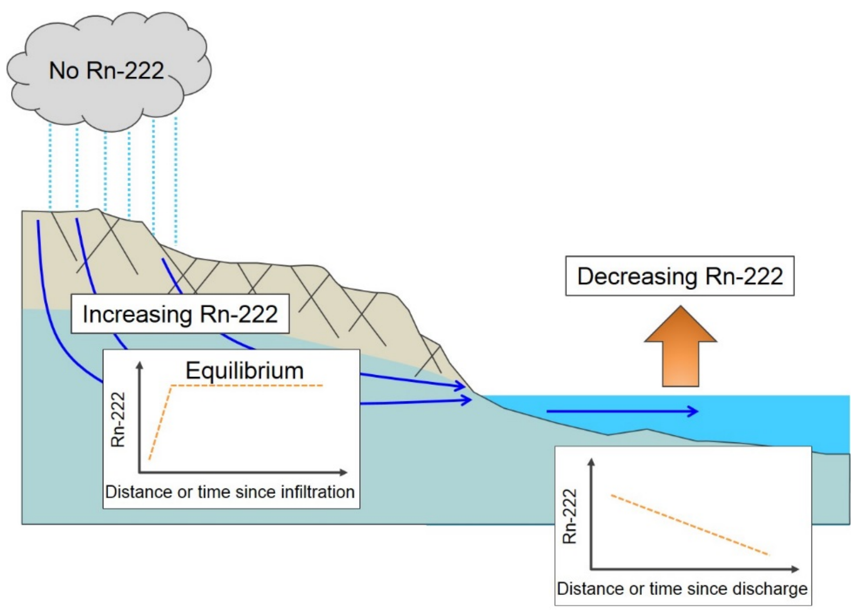


Figure 16: Conceptual model for radon-222 in a shallow groundwater system.

Methodology

Water samples analyzed for Rn-222 were collected using air-dried 250 ml glass bottles with septum caps. Each bottle was triple-rinsed with sample water before sample collection. Where possible, samples were collected by completely immersing the bottles in the stream or spring discharge and, after the bottle had filled completely, capped underwater to avoid aerial exposure. Samples were collected with no headspace. For stream samples, water was collected from the thalweg of the channel. Spring samples were collected as close to the point of discharge as possible. After collection, water samples were placed in a cooler for insulation from temperature fluctuations and protection during transport.

All the named springs in the Salado Springs complex were sampled to characterize the radon concentration of groundwater and monitor for seasonal change. Water was also collected at Main Street Bridge to characterize the radon concentration of surface water entering the Salado Springs system at downtown Salado. The complex was sampled in its entirety over three- to four-day campaigns during March 2014, May 2015, July 2015, and September 2015. On June 7, 2014, the main trunk of Salado Creek was sampled from its headwaters near Florence to the confluence with the Lampasas River to characterize radon concentration in the creek and identify points of groundwater addition.

Water samples were analyzed within 24 hours of collection to minimize loss of Rn-222 through radioactive decay. The activity of dissolved Rn-222 in each sample was measured using a RAD7 unit equipped with a RAD H_2O radon-in-water accessory (DURRIDGE Company, Inc., Billerica, Massachusetts). The RAD7 is an electronic radon detector that quantifies radon activity through alpha spectrometry. Air is recirculated through the water sample and RAD7 unit in a continuous closed loop to extract dissolved radon gas. As Rn-222 nuclei decay, characteristic alpha energies emitted by radon daughters, specifically ^{218}Po (6.00 MeV) and ^{214}Po (7.69 MeV), are detected by a solid-state, Ion-implanted, Planar, Silicon alpha detector as electrical signals which are then quantified and converted to digital form for output (DURRIDGE Company Inc., 2014a; 2014b). RAD7 results were corrected to account for radon activity decline due to radioactive decay from the time of sampling to analysis. The decay correction factor (DCF) was determined for each sample using the following equation:

$$DCF = e^{(T/_{132.4})}$$

where T is the decay time in hours, and 132.4 is the mean life of a Rn-222 atom in hours, calculated by dividing the product of 3.825 days (the half-life of Rn-222) and 24 hours per day by the natural logarithm of 2 (DURRIDGE Company Inc. 2014b).

Between every sample, the RAD7 was purged for a minimum of 15 minutes to flush the instrument of residual radon and lower the internal relative humidity to 6% or less. Also, a blank was measured between every sample to keep track of background radon levels.

Results

Radon-222 concentrations observed at downtown Salado are summarized for the March 2014 sampling campaign in Figure 17. Average radon-222 concentrations for groundwater and surface water are summarized in Table 6 for all sampling campaigns. Radon-222 concentrations in groundwater samples were consistently greater than those of surface water, about two times greater. Radon-222 concentrations just above and below the low water dam shows the effect of aeration to expedite diffusion of radon into the atmosphere, resulting in a lower concentration immediately below the low water dam. Low radon-222 content at the Main Street Bridge is indicative of surface water which has had opportunity to de-gas its radon-222, while water sampled from a spring orifice would not have had time for gas exchange with the atmosphere (Cook et al. 2003). The radon-222 concentration for Salado Creek just downstream from the Big Boiling spring confluence is an intermediate value between Main Street Bridge and Big Boiling spring, suggesting a mixing of surface and groundwater at that location. Variations in groundwater radon-222 concentrations likely reflect differences in flow path through the aquifer and degree of water-rock interaction.

The radon-222 concentrations along Salado Creek are summarized in Figure 18. The lower basin exemplifies the radon-222 conceptual model; surface water samples had radon-222 concentrations less than 10 pCi/L, and increases where there is groundwater contribution. In the upper basin, there were less data collected and the pattern is not as clear. Looking at the data longitudinally, however, reveals a rise-and-fall pattern in radon-222 concentrations along Salado Creek, where high values correspond to proximity to a groundwater source and lower values further away from a source. From radon-222 data, there are three reaches of Salado Creek that can be distinguished by points of groundwater contribution (Figure 18).

Discussion

Analysis of radon in the waters of Salado Creek and the Salado Spring complex was found to be feasible and appropriate for the study area. The short half-life of radon-222 is suited to a karst setting which can have very quick flow paths. Relatively short times required for analysis allow for repeated sampling and monitoring of spring conditions. The short half-life of radon-222 does limit the number of samples that can be collected and analyzed before concentrations decay and render samples unusable; this limitation was addressed by focused sampling over a few days (under the same hydrologic conditions). Lastly, radon-222 has a couple of additional advantages in this study area. It is a naturally-occurring tracer and does not require adding chemicals to the spring system. Also, sampling methods were minimally-to-non-invasive, which is an important consideration in a critical habitat setting.

Figure 17: Synoptic radon-222 concentration in groundwater and surface water at Salado Springs. Radon-222 concentrations are given in pCi/L. The abbreviations “N/M” and “N/F” mean “not measured” and “no flow” respectively.

Table 6. Average radon-222 concentrations in pCi/L for groundwater and surface water in the Salado Springs complex for sampling campaigns in 2014 and 2015.

	March 2014	May 2015	July 2015	September 2015
Groundwater	200.16	257.25	244.56	262.10
Surface water	84.75	n/m*	124.87	167.60

**n/m = not measured*

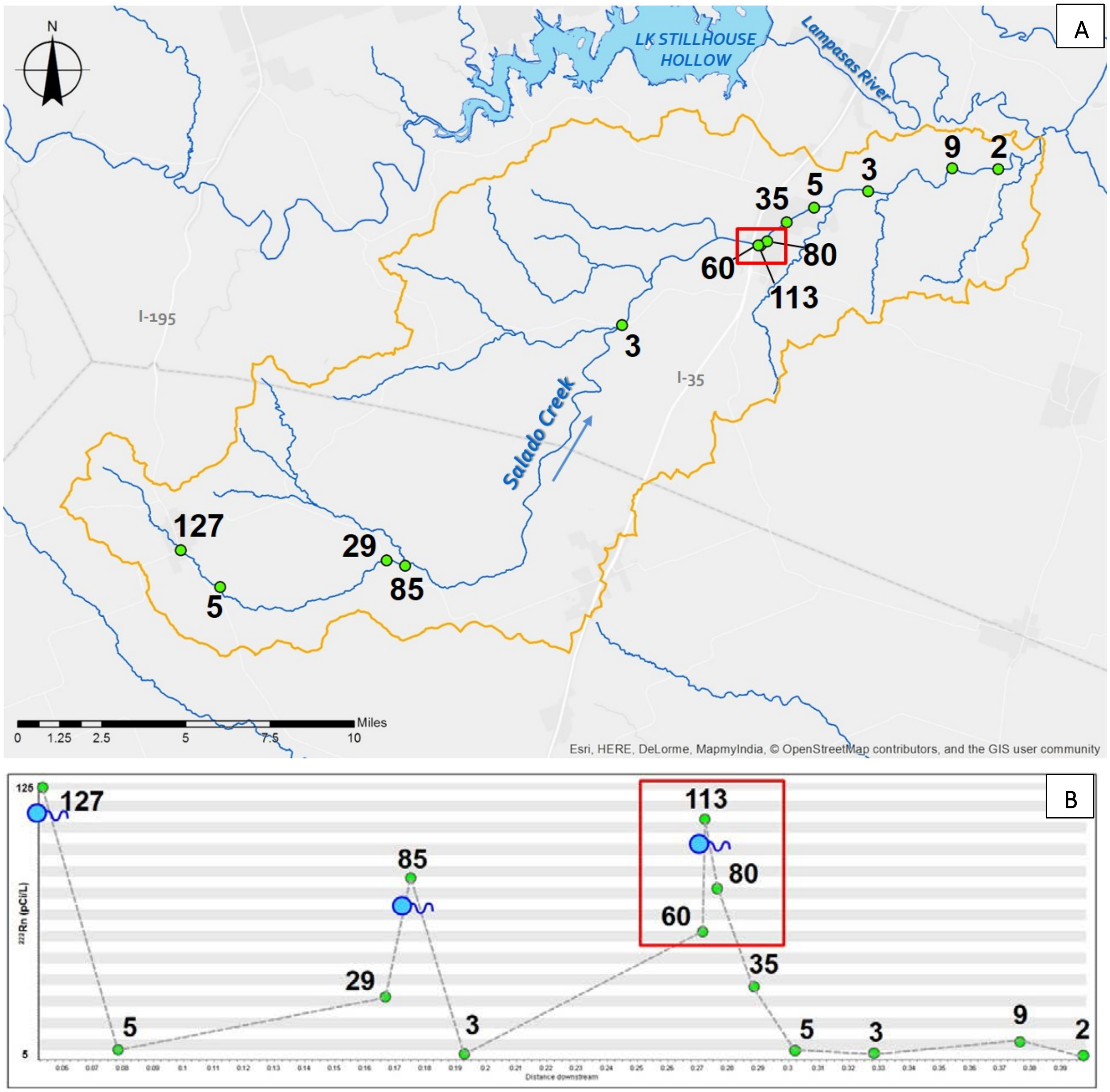


Figure 18: A) Map of the Salado Creek watershed, showing locations sampled for radon concentrations in June, 2014; B) A longitudinal plot of the same data, with radon concentrations on the Y-axis and distance down the channel on the X-axis, allowing spikes in radon concentration to be more easily seen.

Radon-222 concentrations in groundwater samples were consistently greater than those of surface water, which agrees with published research. Generally, a 2-4 times difference in surface and groundwater radon-222 concentrations have been reported (Burnett et al., 2010). The dichotomy of groundwater and surface water radon concentrations at Salado Springs can serve as end-members for groundwater and surface water in the study area. Radon concentration can complement other field measurements to identify, confirm, and monitor groundwater discharge sites. Radon concentrations also support the site of the USGS stream flow gauge (gauge #08104300) for tracking total spring complex discharge. As Figure 18 indicates, there are no major groundwater contributions to

Salado Creek downstream of the downtown springs. Additionally, tracer test data indicate that all the springs in the downtown section of the Salado Springs complex are connected. Radon and tracer test data indicate that the current site for the stream gauge is appropriate for monitoring Salado Springs.

North bank groundwater discharge: Rock Spring

Through conducting stream profiles at Salado Creek, the water chemistry at the north end cross-section 3 was observed to closely mirror that of water discharging from Big Boiling Spring. A brief investigation was undertaken to confirm groundwater discharge from underneath a boulder on the north bank of Salado Creek, referred to in this project as “Rock Spring”.

After a rain event on September 21, 2013, a plume of clear water was seen to be discharging into Salado Creek, which was highly turbid due to fine sediment being suspended during and after the rain event (Figure 19A). From this event, we observed that water was being discharged from underneath the north bank boulder, and that it was clearly different from water in the creek. Repeated temperature, specific conductance, and radon-222 readings were taken at this site (Table 7). The mean temperature at Rock Spring for all sampling events is 20.64°C, the mean specific conductance is 531 µS/cm, and the mean radon-222 concentration is 262.73 pCi/L. All these values fall into the range for what has been measured at the named springs in the complex, and confirm that the water being discharged from Rock Spring is groundwater.

Table 7. Water chemistry at Rock Spring confirming presence of groundwater.

Date	Temperature (°C)	Specific conductance (µS/cm)	Radon-222 (pCi/L)
April 19, 2014	20.7	513	236.98
November 6, 2014	20.9	513	239.21
January 15, 2015	16.2	525	286.95
July 29, 2015	22.7	505	252.24
September 18, 2015	22.7	601	298.28
Averages	*20.64*	*531*	*262.73*

After heavy rains and flooding in the spring of 2015, the Rock Spring site was unfortunately buried by gravels (Figure 19B). However, we were able to excavate some of the gravel to access the groundwater discharge point (Figure 19C). After allowing the disturbed sediment time to settle, water was sampled. The radon concentration was 252.24 pCi/L, indicating that groundwater was still discharging from this location.

The radon concentration, together with temperature and specific conductance data that mirror those of groundwater; strongly support the probability of a groundwater discharge point on the north bank of Salado Creek across from Big Boiling Spring. Previously, points of significant groundwater discharge into Salado Creek were identified on the south bank only. Positive dye detections at Rock Spring through the course of two tracer tests suggest connection with the groundwater flow system on the south side of Salado Creek. Additionally, augering on the north bank point bar caused turbidity in the water discharging from Rock Spring, suggesting groundwater contribution from the north side of Salado Creek (Figure 19D). Field observations, tests, and water analysis indicate that the water discharging from Rock Spring is groundwater, and that it is sourced from both the groundwater flow system from the south of Salado Creek as well as the north.

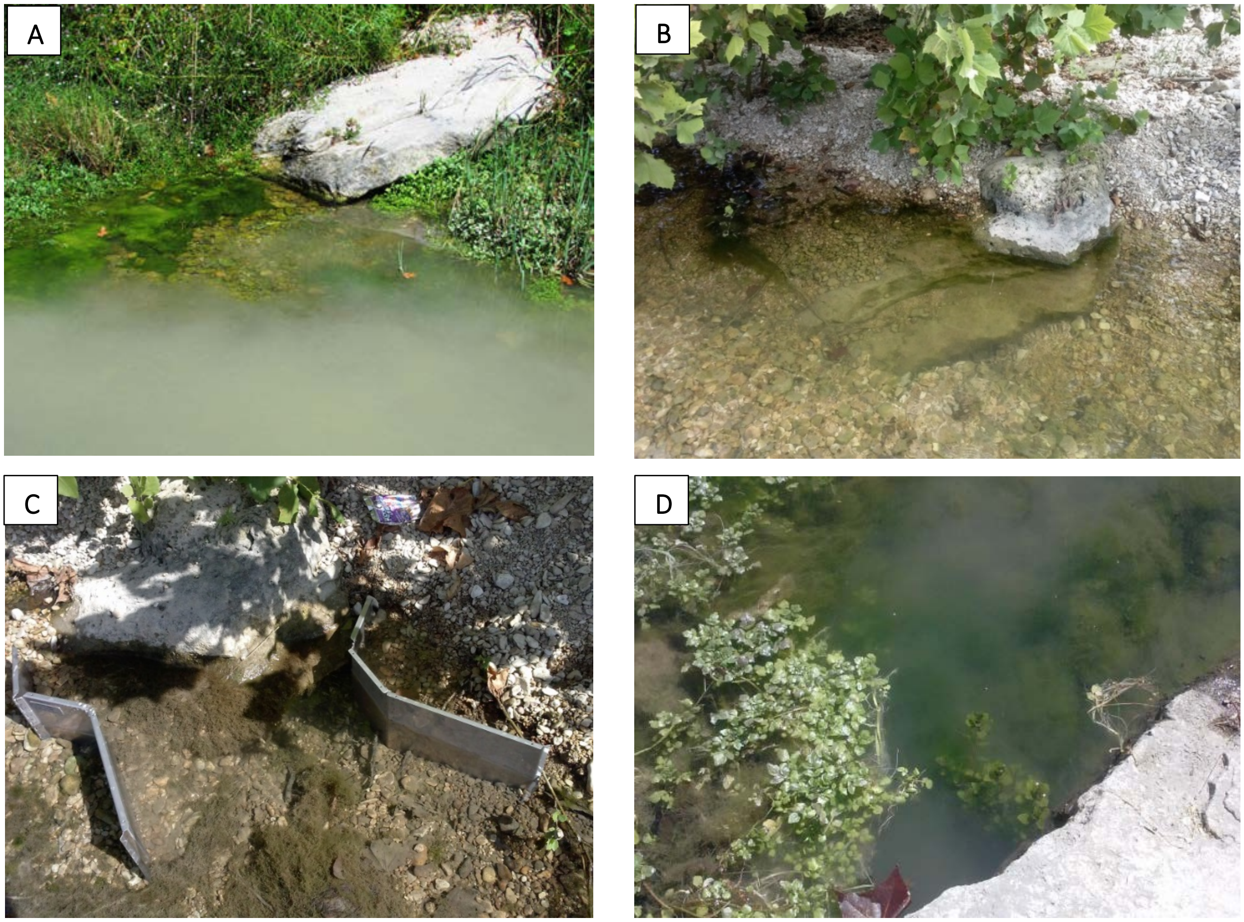


Figure 19: Groundwater discharge point from the north bank of Salado Creek. A) After a rain event, clear groundwater was observed to be discharging into Salado Creek which was cloudy due to suspended sediments (September 21, 2013); B) Rock Spring was buried by the gravel load carried by Salado Creek during spring flooding events (July 2, 2015); C) gravel around Rock Spring was excavated to sample the groundwater discharge point, and flume walls were used to prevent cave-in (July 29, 2015); D) augering on the north bank point bar caused sediment to be discharged from Rock Spring (March 28, 2015) .

Aquifer water chemistry

In summer 2014, a sampling campaign of wells in the Northern Segment was undertaken to determine baseline water chemistry. Baylor and CUWCD collaborated to visit about 30 non-permitted domestic wells. Twenty wells out of the thirty were sampled; sampling was limited to those wells that had a point of access between the wellhead and storage tank. Tested parameters included: temperature (°C), specific conductance (µS/cm), pH, radon-222 (pCi/L), and field nitrate (mg/L). Filtered samples were also collected and analyzed for dissolved nitrate and phosphate, and dissolved organic carbon at the Baylor Center for Reservoir and Aquatic Systems Research lab. Additionally, filtered samples were collected and sent to the USGS for nitrogen isotope analysis. Distribution of radon-222 and field nitrate in Northern Segment wells are mapped in Figures 20 and 21.

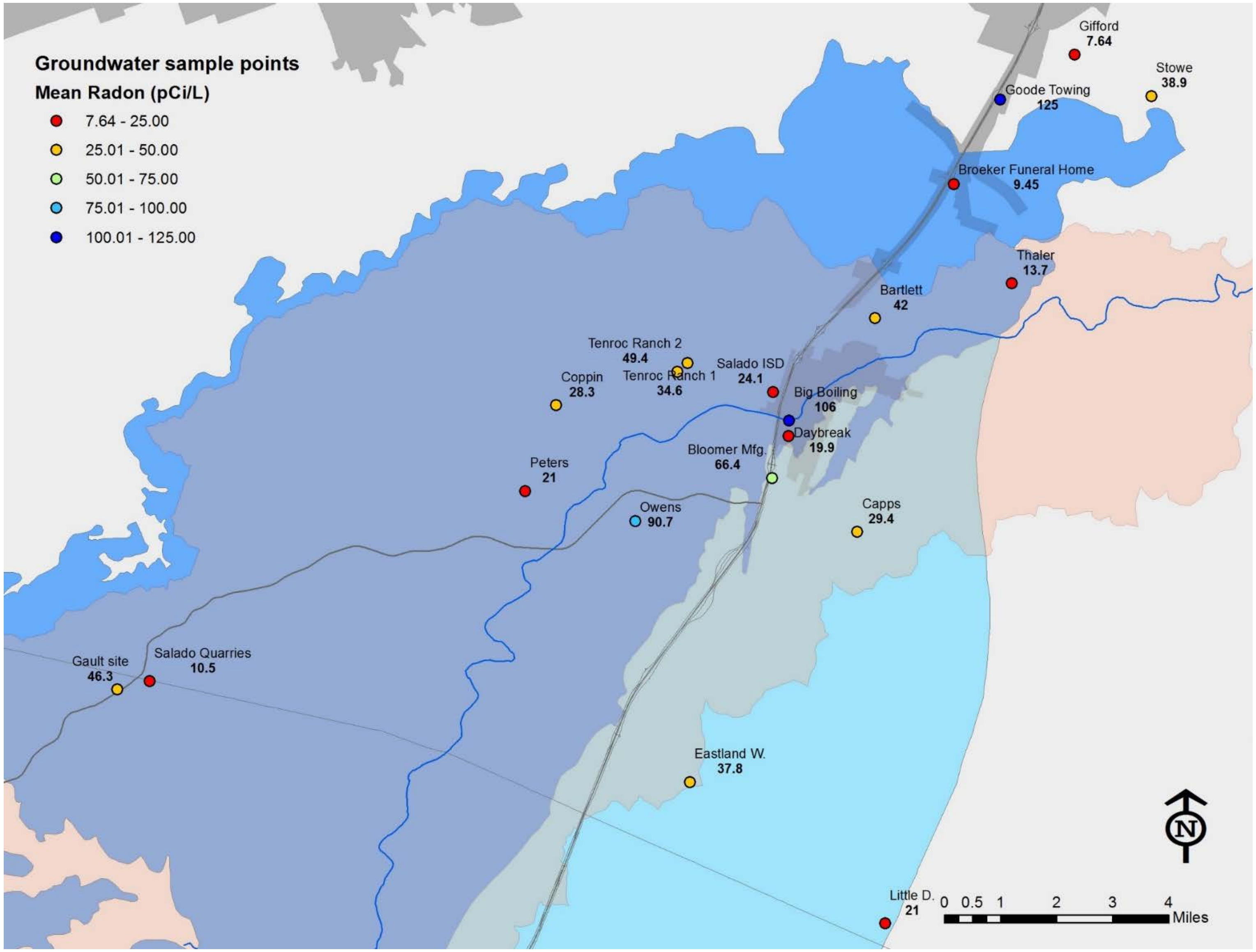


Figure 20: Concentration of radon-222 in water supply wells in the Northern Segment.

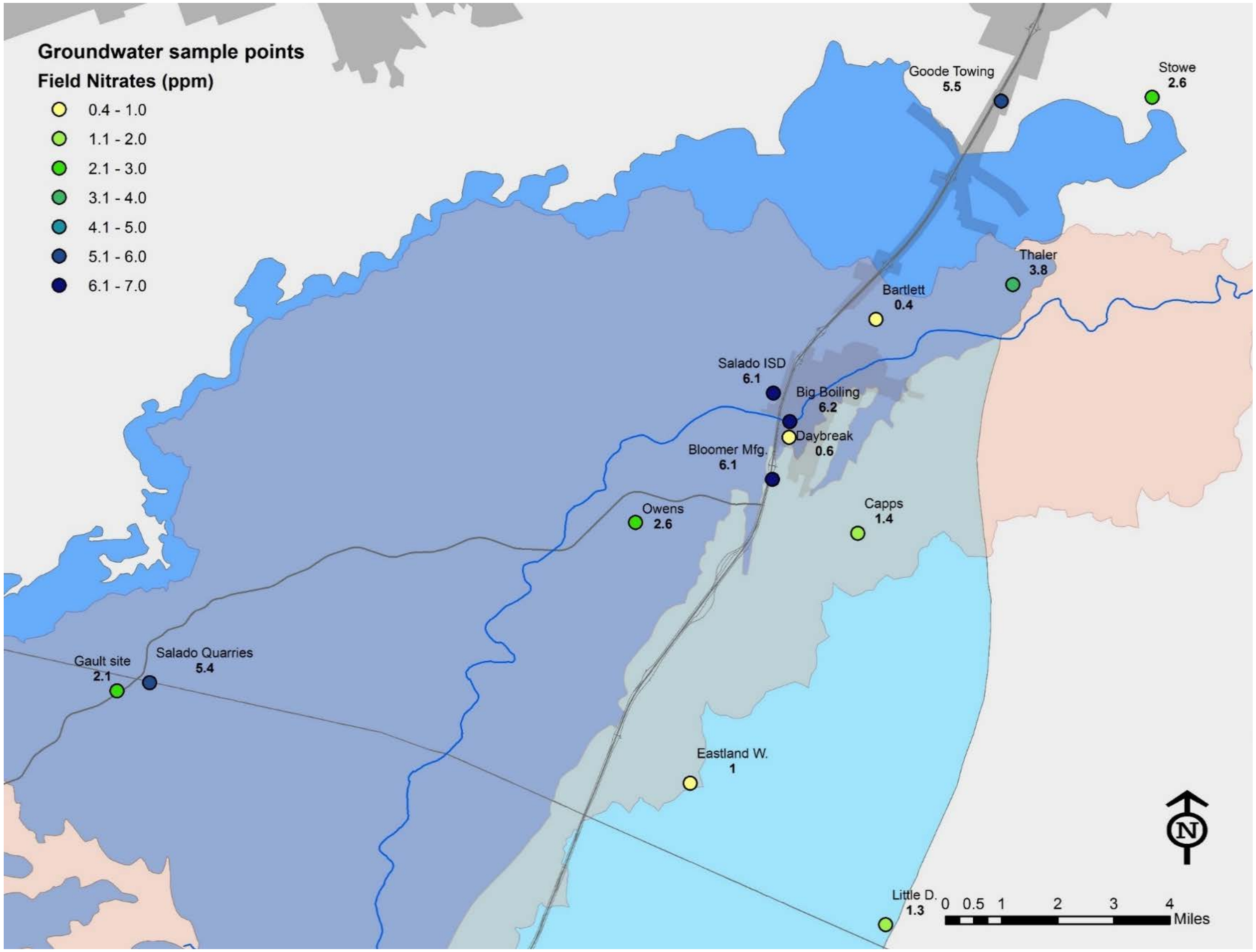


Figure 21: Concentration of nitrates in water supply wells, analyzed in the field.

Aquifer Response to Recharge

Weather stations and rain gauges

The distribution of rainfall over a given area can vary both spatially and temporally. Therefore, use of a single rain gauge and/or an average rainfall amount for an event may not be representative of reality. Accurately monitoring rainfall is relevant for flood prediction and hydrologic modelling (Arnaud et al., 2002; Singh, 1997). Since rainfall is the predominant form of recharge for the Northern Segment, it is important to monitor rainfall over the outcrop portion of the aquifer.

To begin capturing spatial and temporal rainfall variability over the Northern Segment, three Davis ISS (Integrated Sensor Suite) Vantage Pro2 weather stations (Davis Instruments, Hayward, California) were deployed to monitor precipitation. The positions of the three weather stations are shown in Figure 22. Precipitation amount is measured using a tipping bucket rain gauge that takes measurements in 0.01 inches. Other parameters monitored include temperature, wind speed, and barometric pressure. Weather conditions are logged once every 30 minutes. Weather station 1 was deployed at the Gault School of Archaeological Research near the county boundary between Bell and Williamson Counties on April 10, 2014. Weather station 2 was deployed on a private property in Salado on November 3, 2014; and the last weather station was deployed on a private property in the Hidden Springs housing development along FM 2843 on November 25, 2014. All weather stations have been in operation and collecting data for about a year, and are visited seasonally to download data and perform any necessary maintenance.

An advantage of the weather stations is their potential to ground-truth radar rainfall estimations, a product of the Next Generation Weather Radar (NEXRAD) program which utilizes Weather Surveillance Radar-1988 data and Precipitation Processing System (PPS) algorithms to estimate rainfall in a 4 km grid.

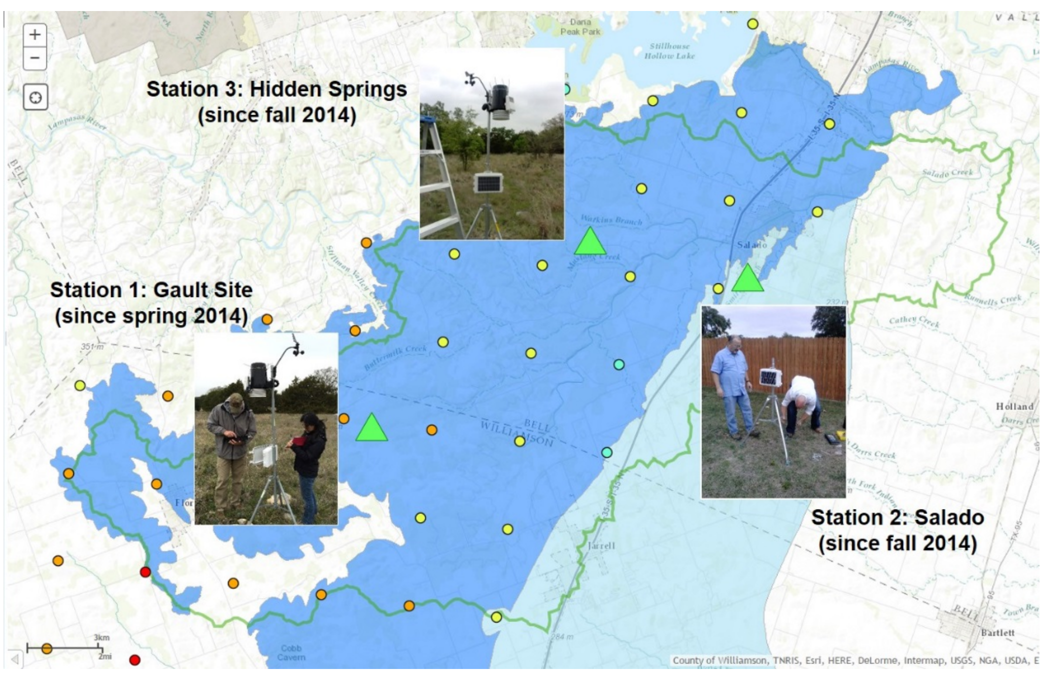
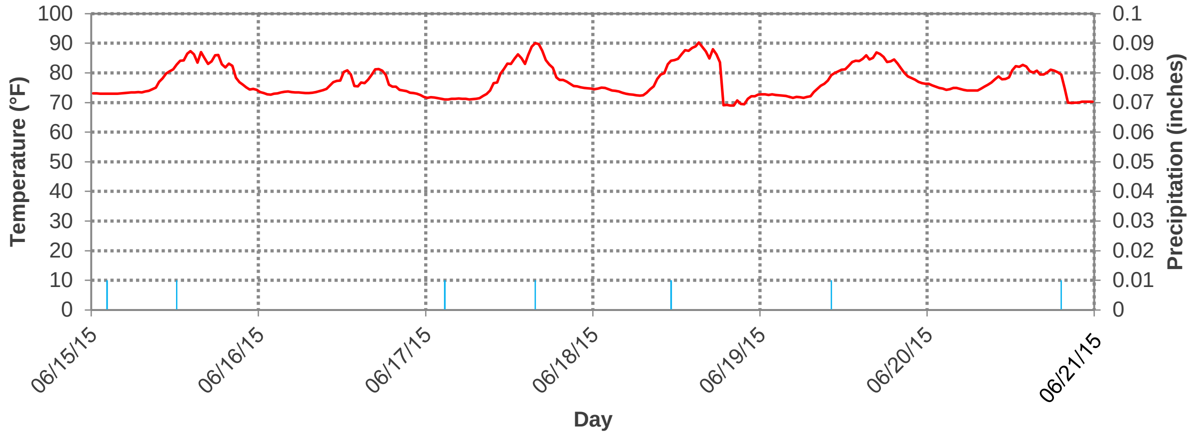


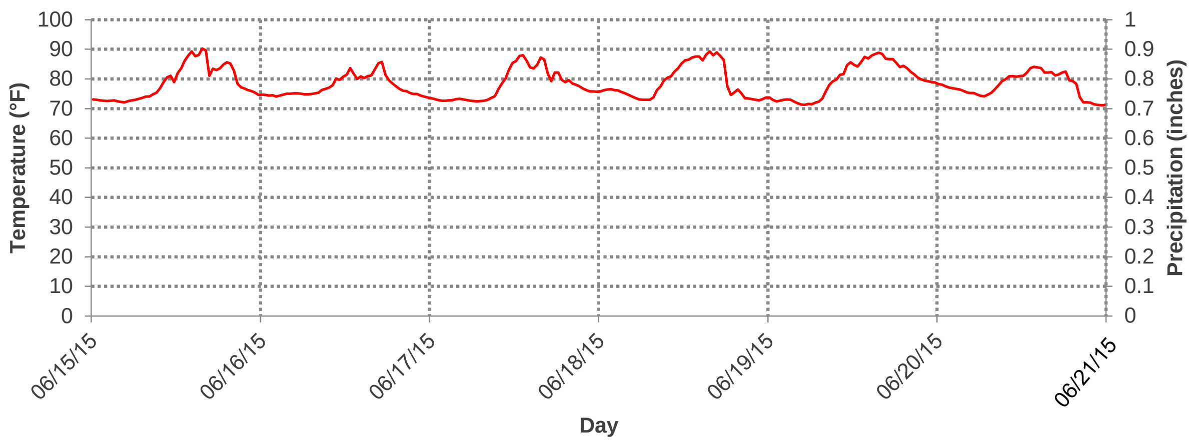
Figure 22: Location of where CUWCD weather stations are currently deployed. Locations were chosen to maximize coverage over the Northern Segment, particularly on the outcrop.

Temperature and precipitation data from June 15-20, 2015 are plotted in Figure 23 to illustrate the temporal, spatial, and intensity variability in rainfall over the Northern Segment; and highlight the importance of having more than one monitoring for these data. While temperature over the Northern Segment seems to by-and-large be

(A) Gault Site station



(B) Salado station



(C) Hidden Springs station

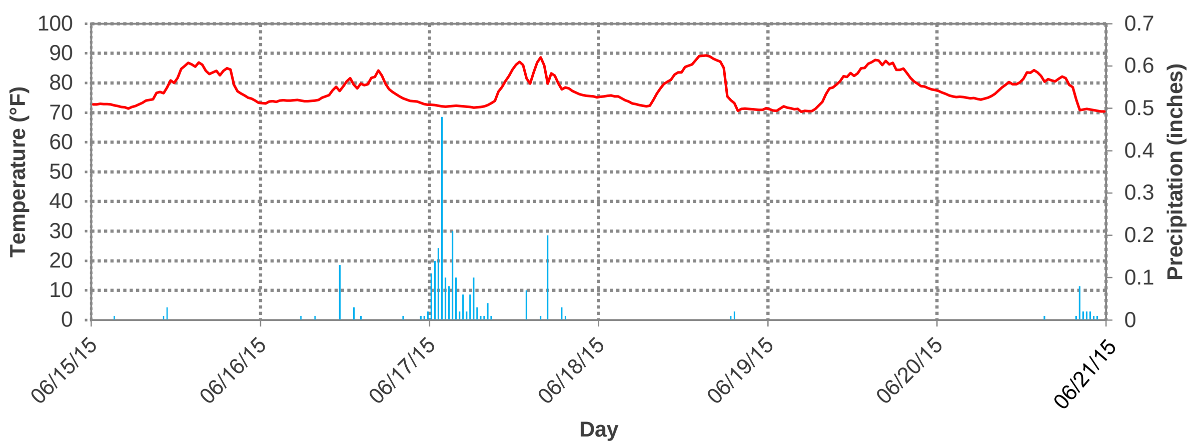


Figure 23: Example of data from CUWCD weather stations, June 15-20, 2015.

consistent in terms of amplitude (maximum and minimum temperatures ranging between 70-90°F) and pattern of daily fluctuation, rainfall over the Northern Segment is markedly different both in terms of amount and timing. For the rainfall that occurred over the period of June 15-20, the Gault Site weather station experienced small rains that were evenly spaced through time. Meanwhile, the Hidden Springs weather station experienced varying amounts of rain that peaked at 0.5 inches during the morning hours of June 17. No rainfall data is shown at the Salado weather station, but this is likely due to a faulty rain gauge. This rain gauge was replaced in fall 2015.

In addition to the weather stations, twelve 4-inch diameter rain gauges were obtained to gain additional ground-measurements of rainfall over the Northern Segment. Potential areas to deploy the rain gauges in the Northern Segment have been identified (Figure 24); Baylor will collaborate with CUWCD in spring and summer 2016 to finalize appropriate sites and set up the rain gauges. The rain gauges are standard CoCoRaHS (Community Collaborative Rain, Hail & Snow Network) gauges so that rainfall data can be uploaded to the National Weather Service CoCoRaHS national database.

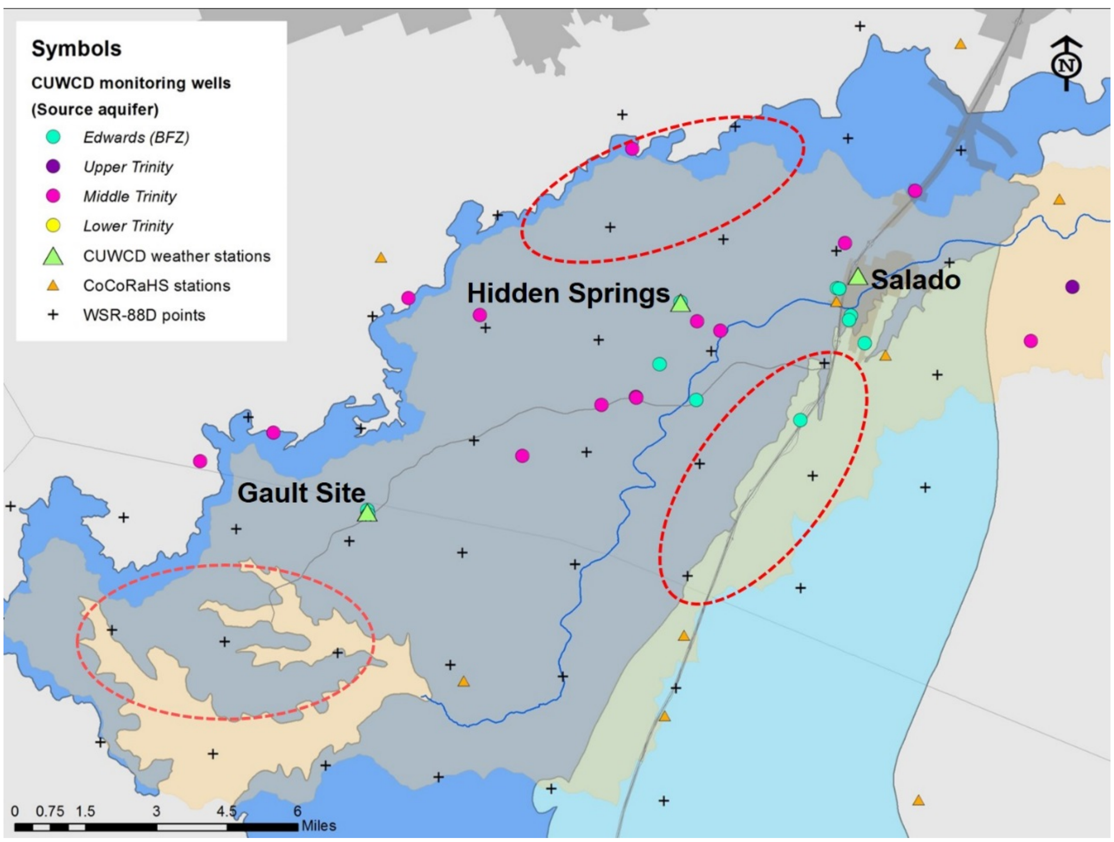


Figure 24: Map showing desirable areas to deploy twelve CoCoRaHS-standard rain gauges, indicated by red ovals. Baylor will work with CUWCD to choose the best sites.

Multi-parameter monitoring

A data logger in a Northern Segment cave is being used to establish baseline levels of water level, temperature, and specific conductance; as well as to monitor response to precipitation events at this location in the Northern Segment. An OTT CTD data logger (OTT Hydromet, Loveland, Colorado) was installed in the cave well underneath the Stagecoach Inn in Salado Texas on May 23, 2013 (Figure 25A). Measurements of water level (feet above the sensor), temperature (°C), and specific conductance (μS) were taken at an interval of logging a reading every 5 minutes initially. Due to a connection problem, the data logger was removed on May 28th. It was re-installed on June

1, 2013. The recording interval is the same (one reading every 5 minutes). After a year of collecting data, we found the amount of data logged at 5-minute intervals to be unnecessarily large especially during periods of no rain. The logging interval was therefore adjusted to once every 10 minutes to conserve battery power and datalogger memory in May of 2014. A large recharge event on May 26, 2015 dislodged the datalogger (Figure 25B). It was therefore removed from the cave for the summer. A datalogger was re-deployed on October 6, 2015 to continue monitoring; an identical OTT CTD datalogger with a longer vented cord was used.

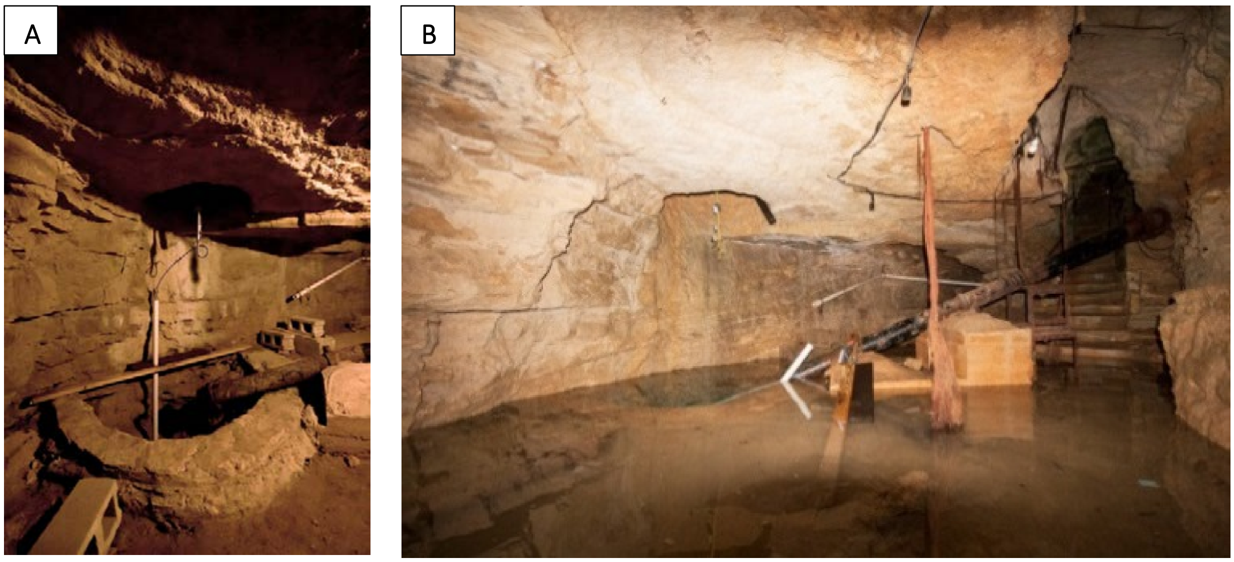


Figure 25: A multi-parameter datalogger has been deployed in the Stagecoach Inn cave well since May 2013 to collect data on water level, temperature, and specific conductance. (A) Setting of the datalogger in the cave well. The sensor is set inside a 2-inch PVC that is attached to a wooden board for stability, and the datalogger and connection port is suspended above the well to prevent submersion in a recharge event. (B) A large recharge event in May 2015 caused water level in the cave well to rise above the sides of the well and destabilized the datalogger, PVC, and wooden board.

Figure 26 shows water level, temperature, and specific conductance data respectively from May 1^{st} until the 26^{th} (2015), when the Stagecoach Inn Cave was flooded and destabilized the datalogger. Water level ranged from 3 ft. to 9.1 ft. above the sensor. Temperature values ranged between 69.40°F and 69.67°F with sharp, temporary drops in temperature that coincide with recharge events and the introduction of colder rain water to the aquifer. Specific conductance values ranged between 578 μS/cm and 595 μS/cm over the recording period. Following each rain, water level stabilized at a higher level, compared to water level at the beginning of May. Specific conductance seemed to peak with each rain event, and then stabilize at a lower level; this likely reflects the influence of more lower-specific conductance water producing a dilution effect. Although all the changes were slight in magnitude, they were the response one would expect from aquifer recharge in this season.

These data support several ideas about the Northern Segment at the Stagecoach Inn. A rise in water level before changes in chemistry indicate more remote recharge that changed head in the aquifer and “pushed old water out”. The small change in temperature and specific conductance indicate that the amount of recharge was small. Relatively rapid responses in temperature and specific conductance (i.e., less than four hours) indicate that groundwater velocities are fairly high, or that recharge is fairly close, or both.

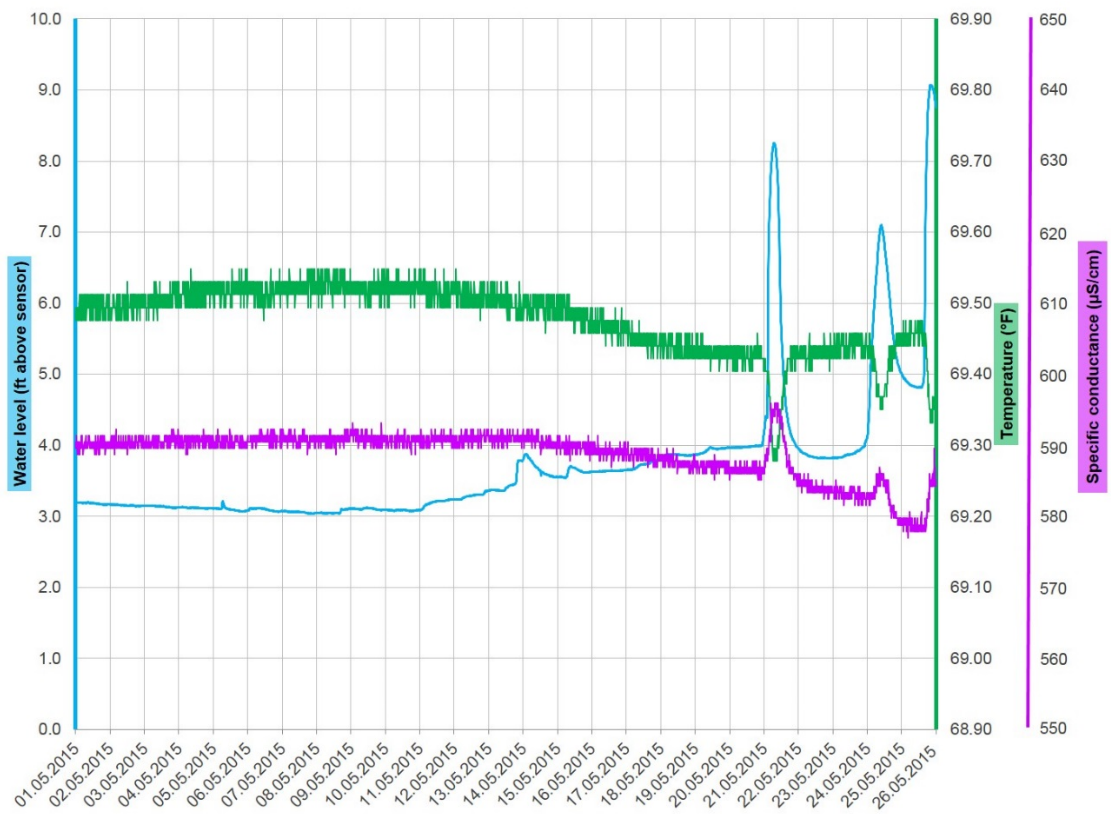


Figure 26: Hydrologic conditions at the Stagecoach Inn cave well in May 2015.

Four Solinst Leveloggers (Solinst Canada Ltd., Georgetown, Ontario) were also obtained through this contract. These dataloggers are able to monitor water level change, temperature, specific conductance. They are smaller, uncabled dataloggers that allow them to be easily hidden in spring openings and piezometers, which make them ideal for event-based deployments to monitor conditions at multiple springs over the course of a recharge event. Since they monitor the same parameters as the OTT CTD datalogger in the Stagecoach Inn Cave, the data can be correlated to gain further insight of aquifer response to recharge and spring connectivity.

An example of data collected using the Solinst Leveloggers is shown in Figure 27. By placing the Solinst Levelloggers in several spring outlets we were able to observe responses to recharge events with respect to specific conductance and temperature for multiple springs during the same event. The responses in Doc Benedict and Anderson springs shown in Figure 27 are similar but exhibit slight differences. The response patterns of decreased specific conductance as a result of the recharge event are similar in magnitude for both springs but the timing is distinctly different. Doc Benedict Spring appears to experience the decrease in SC slightly delayed after Anderson spring experiences this change. This is a little surprising because Doc Benedict Spring is closer to the cave well where connectivity was determined with the dye tracer test. The similarity of the responses again confirms the connectivity but the timing indicates Anderson Spring may be connected more directly with a separate fracture that is wider or straighter or perhaps Doc Benedict spring is connected with a fracture that branches off the main fracture going from the Stagecoach Inn Cave Well to Anderson Spring.

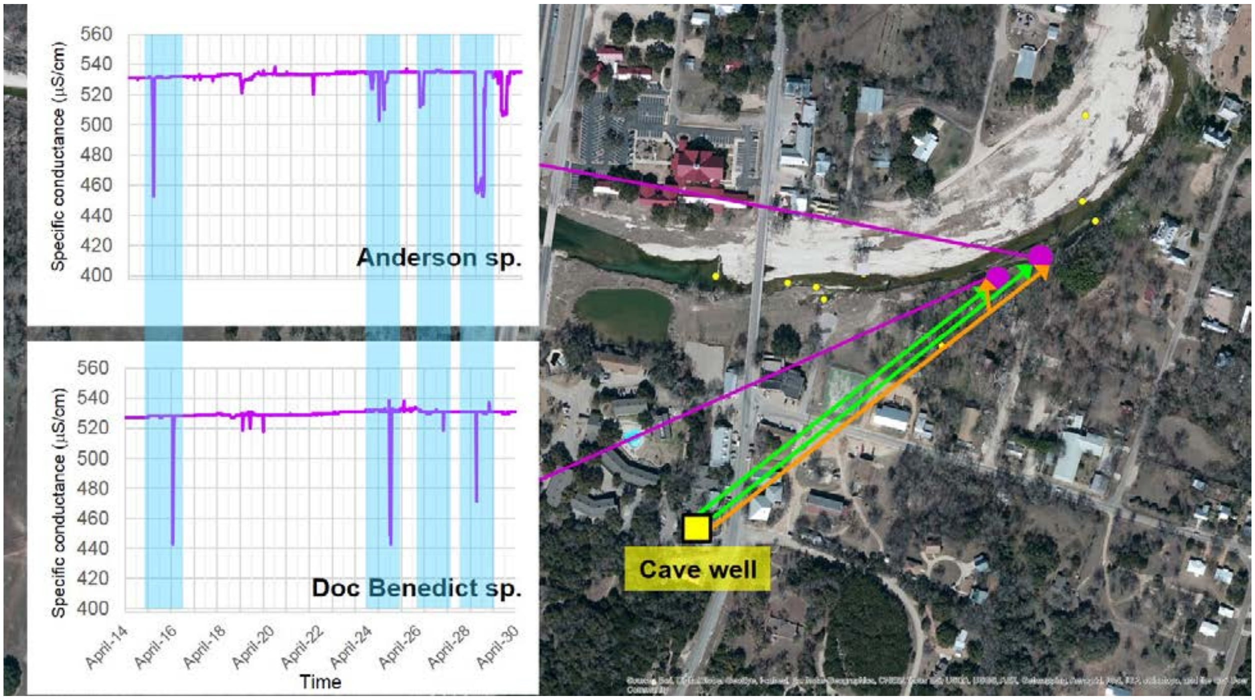


Figure 27: An example of specific conductance data from Anderson and Doc Benedict springs, collected using Solinst Leveloggers. The sampling frequency of the Leveloggers allows further interpretations to be made regarding spring connectivity and response to recharge.

Flumes and weirs

Flumes and weirs are two devices that can be used with pressure transducer data loggers to record flow and evaluate response to recharge. We have constructed several weirs and purchased two flumes. We have tested the flumes and weirs on Side Spring and Little Bubbly (Figures 28 and 29). Recent flow increases indicate redesigning some of the weirs is necessary. The flumes work fine but need protection and maintenance. Negotiations and planning for long-term monitoring at two locations (Critchfield and Robertson) are progressing and placement for all the flumes and weirs is anticipated in Spring 2016. Two other locations have been proposed and several other locations are needed.

Figure 28: Cutthroat flume at Side Spring, Salado, Texas, September 3, 2015. Volumetric discharge was calculated at 240 gallons per minute but the conditions did not meet the criteria for acceptable accuracy.

Figure 29: Cutthroat flume at Little Bubbly Spring, Salado, Texas, September 3, 2015. Volumetric discharge was 13 gallons per minute with an estimated 5% leakage.

Recharge Features Characterization

LiDAR

LiDAR, which stands for light detection and ranging, is an active remote sensing technology that utilizes pulsed lasers to measure various properties of targets of interest. LiDAR technology measures the relative distance between the scanning laser (air- or ground-based) and a target, and generates a point cloud representing the target surface (Figure 30-1). Each point has an associated x, y, and z coordinate. Surfaces can be generated from the point cloud using interpolation methods, which can then be analyzed for lineaments.

For this project, the original objectives were to: identify lineations and depressions using LiDAR data, differentiate between geologic and anthropogenic lineations and depressions, and identify geologic lineations that are potential recharge features by combining LiDAR output with rain data. LiDAR data that was commissioned by Bell County was obtained from the Central Texas Council of Governments in fall 2013. A proof-of-concept exercise to manipulate the LiDAR data and see if karst features could be detected was completed in summer 2015 (Figure xx). The workflow for identifying karst features involves generating digital elevation models and shaded surfaces from the LiDAR point cloud (Figure 30-2), then isolating and extracting those pixels that may indicate karst features. In our proof-of-concept exercise, those pixels were those that represented the lowest points of elevation (Figure 30-3). At this point in time, pixel extraction is through manual selection, which is slow due to the density of data generated by LiDAR – only very small areas can be dealt with at a time. Moving forward, the goal is to: 1) Expand the workflow to other areas of interest, and 2) Attempt to automate the selection process for lineations and depressions.

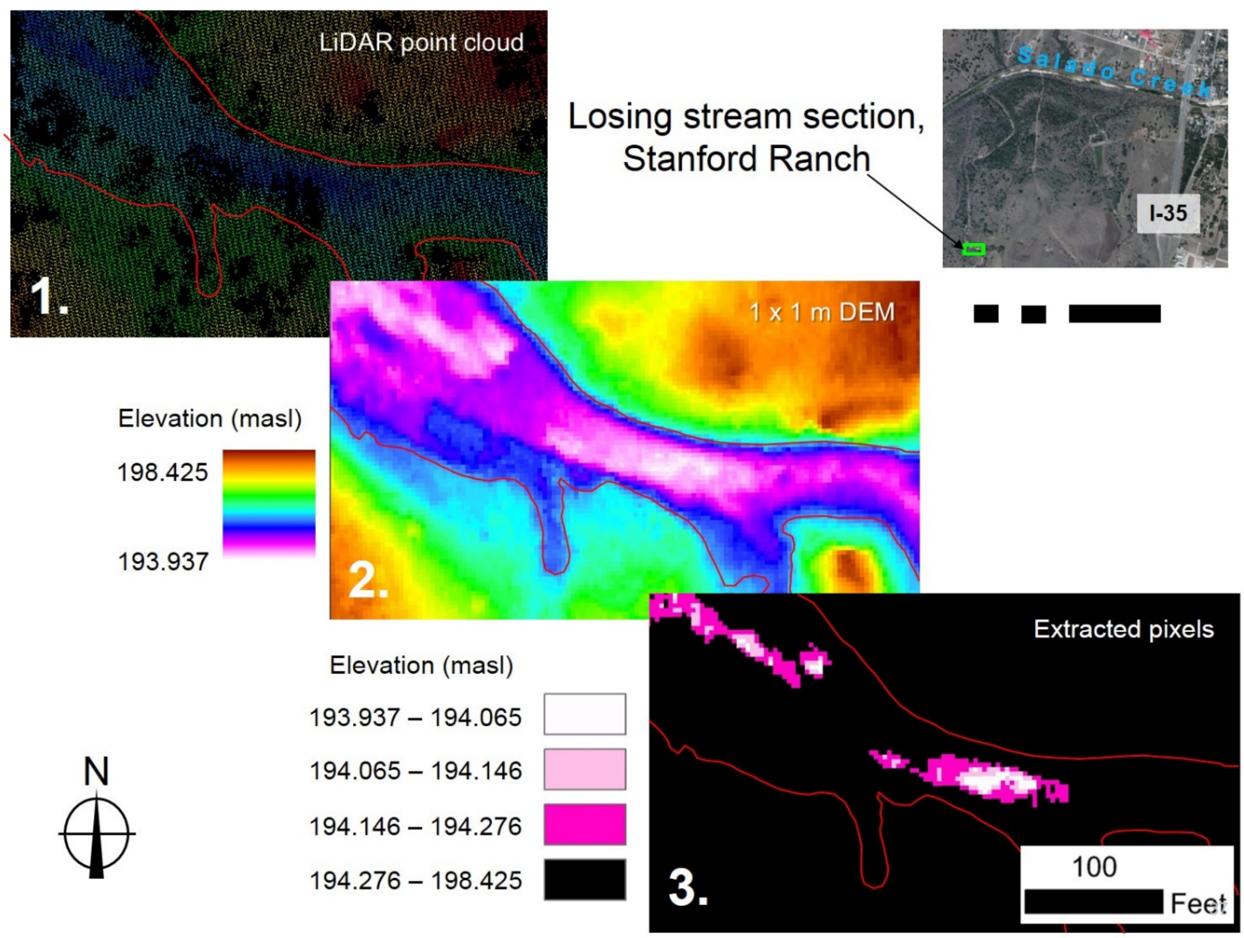


Figure 30: Overview of workflow for identifying karst features using LiDAR data.

Summary and Project Conclusions

This project has produced new data and new insights into the groundwater flow systems of the Northern Segment of the Edwards Balcones Fault Zone aquifer in the Salado Springs area. The findings are summarized below.

A clear difference between spring water (groundwater) and stream water (Salado Creek) has been documented for Specific Conductance and natural Radon concentrations. The spring water definitely possesses a higher specific conductance than the stream water. The higher specific conductance in the spring water compared to the surface water indicates higher dissolved solids values from longer residence times within the aquifer which resulted from more dissolution of the aquifer material. The turbulence of the stream and biota of the stream water allows for ionic components to be removed through bio-geochemical processes thereby decreasing the total dissolved solids and the specific conductance. The spring water also has higher radon concentrations interpreted as equilibrium conditions between the water and the aquifer material compared to water in the stream which has been able to de-gas more rapidly.

The connectivity for the known spring discharge points in the downtown area of Salado, Texas, east of Interstate Highway 35 has been documented under two different flow conditions. Two dye tracer tests were conducted that showed dye from the Stagecoach Inn Cave Well flowed to all the springs even though the flow rates varied. The connectivity implies that mobile aquatic organisms, such as the Salado Salamander, may be able to move throughout the spring system and that the entire group of springs could be considered as one overall spring system.

Recharge responses to the aquifer as represented by changes in water level, specific conductance and temperature in the Stagecoach Inn Cave Well are rapid. Water levels responded within an hour for the large rainfall event May 24^{th} and the water quality represented by specific conductance and temperature responded within a few hours. The rapid response is indicative of direct recharge paths and local recharge components.

Synoptic water level measurements indicated little change occurred between pre-drought and post-drought measurements in the Edwards aquifer even though the stream and spring flow had decreased. These data would indicate the aquifer was managed well and that current usage patterns appear sustainable under the current management.

New discharge points in the downtown area spring complex were documented during this study. A new discharge point named Rock Spring was documented on the North bank of Salado Creek in the downtown area across from Big Boiling Spring and the dye tracer tests indicated it was connected to the springs on the South side of the creek. A spring discharging from the south side of the creek through the alluvium just upstream from Big Boiling Spring discharge was also documented by dye as connected to the Stagecoach Inn Cave Well. This spring was named Side Spring and occurs near Little Bubbly Spring.

Project Experience / Concluding Thoughts

The results of this research contributed to the USFWS listing the Salado Salamander as threatened rather than endangered. The results also indicate the water quantity in the Northern Segment of the Edwards Balcones Fault Zone aquifer is being managed in a sustainable way in Bell County.

The results of the dye studies showing connectivity among the springs in the downtown Salado area indicate the USGS gage that is placed downstream of the springs can be used appropriately to monitor the water quantity in the spring system.

The application of data loggers to monitor water levels and water quality indicators appears feasible. A monitoring system using multi-parameter data loggers and periodic water sampling should be considered as development in the area continues. It is important to establish baseline parameters that can be used to assess changes that may occur over time.

References

- Arnaud, P., C. Bouvier, L. Cisneros, and R. Dominguez, 2002. Influence of rainfall spatial variability of flood prediction. Journal of Hydrology, 260(1-4): 216-230.
- Burnett, W.C., R.N. Peterson, I.R. Santos, and R.W. Hicks, 2010. Use of automated radon measurements for rapid assessment of groundwater flow into Florida streams. Journal of Hydrology, 380(2010): 298-304.
- Cook, P.G., G. Favreau, J.C. Dighton, and S. Tickrell, 2003. Determining natural groundwater influx to a tropical river using radon, chlorofluorocarbons and ionic environmental tracers. Journal of hydrology, 277(1-2): 74-88.
- Department of the Interior, Fish and Wildlife Service, 2014, Endangered and Threatened Wildlife and Plants; Determination of Threatened Species Status for the Georgetown Salamander and Salado Salamander Throughout Their Ranges; Final Rule. Federal Register, 79(36): 59 pp.
- Durridge Company, Inc. 2014a. RAD7 Radon Detector User Manual. Durridge Company, Inc., Billerica, MA. 79 pp.
- Durridge Company, Inc. 2014b. RAD H_2O User Manual. Durridge Company, Inc., Billerica, MA. 31 pp.
- Ellins, K.K., A. Roman-Mas, and R. Lee, 1990, Using ^{222}Rn to examine groundwater/surface discharge interaction in the Rio Grande de Manati, Puerto Rico. Journal of Hydrology, 114(1-4):319-341.
- Hoehn E., H.R. Von Gunten, F. Stauffer, T. Dracos, 1992, Radon-222 as a groundwater tracer: a laboratory study. Environment Science and Technology, 26:734-738.
- Lee, R.W. and E.F. Hollyday, 1991, Use of radon measurements in Carters Creek, Maury County, Tennessee, to determine location and magnitude of groundwater seepage. In Field Studies of Radon in Rocks, Soils, and Water. L.C.S. Gundersen and R.B. Wanty (eds.), pp.237-242. C.K. Smoley, Boca Raton, Florida.
- Mahler, B.J., P.C. Bennet, M. Zimmerman, 1998, Lanthanide-labeled clay: a new method for tracing sediment transport in karst. Ground Water, 36(5): 835-843.
- Michaud, J.P., 1991. A Citizens' Guide to Understanding and Monitoring Lakes and Streams. Washington State Department of Ecology, Olympia, WA.
- Michel, J., 1987, Sources In Environmental Radon, C.R. Cothern and J.E. Smith, Jr. (Eds.). Plenum Press, New York, 363 pp.
- Neupane, R.P., J.D. White, P.M. Allen, and S.I. Dworkin, 2014, A snapshot comparison of environmental tracers for estimating groundwater contribution to recession flow in a mountain stream. Hydrological Processes, *in press.*
- Singh, V.P., 1997, Effect of spatial and temporal variability in rainfall and watershed characteristics on stream flow hydrograph. Hydrological Processes, 11: 1679-1669.
- Stellato, L., F. Terrasi, F. Marzaioli, M. Belli, U. Sansone, and F. Celico, 2013, Is ^{222}Rn a suitable tracer of stream-groundwater interactions? A case study in central Italy. Applied Geochemistry, 32: 108-117.
- Wojdyr, M. 2010. Fityk: a general-purpose peak fitting program. Journal of Applied Crystallography, 2010 (43): 1126-1128.

Appendix
Radon-222 concentrations for Salado Springs

Table A1. Radon-222 content in groundwater and surface water at Salado Springs.

Site	March 2014	May 2015	July 2015	September 2015
Stagecoach Inn Cave Well	160.17	212.15	230.67	218.62
Robertson Spring	N/M	408.90	303.59	363.13
Main Street Bridge	61.52	N/M	124.87	167.60
Side Spring	192.12	185.08	222.42	236.88
Little Bubbly Spring	N/F	252.42	238.63	N/F
Big Boiling Spring	178.35	252.62	217.39	235.88
Critchfield Spring	167.44	310.64	238.27	244.69
Doc Benedict Spring	249.87	306.26	262.14	276.71
Anderson Spring	248.89	253.28	235.65	222.59
Rock Spring *(North bank)*	204.28	133.67	252.24	298.28