Section 6 (Texas Traditional) Report Review

Attachment to letter dated _____

TPWD signature date on report 2/4/08

Project Title: Hydrologic Delineation of Habitat and Management Zones for Rare Cave and Spring Salamander in the Austin, Texas Area

Final or Interim Report? Interim

Grant #: E-79-R

Reviewer Station: Austin ESFO

Lead station was contacted and concurs with the following comments:
☐ Yes ☐ No ☒ Not applicable (reviewer is from lead station)

Interim Report (check one):

☐ is acceptable as is

☐ is acceptable as is, but comments below need to be addressed in the next report

☐ needs revision (see comments below)

Final Report (check one):

☒ is acceptable as is

☐ is acceptable, but needs minor revision (see comments below)

☐ needs major revision (see comments below)

Comments:

FINAL REPORT

As Required by

THE ENDANGERED SPECIES PROGRAM

TEXAS

Grant No. TX E-79-R

Endangered and Threatened Species Conservation

Hydrologic Delineation Of Habitat And Management Zones For Rare Cave And Spring Salamander In The Austin, Texas, Area

Prepared by:

Beverley L. Shade, Lisa O'Donnell, George Veni, and David Johns

Carter Smith
Executive Director

Mike Berger
Division Director, Wildlife

4 February 2008

FINAL REPORT

STATE: Texas **GRANT NUMBER:** TX E-79-R

GRANT TITLE: Hydrologic Delineation Of Habitat And Management Zones For Rare Cave And Spring Salamander In The Austin, Texas, Area

REPORTING PERIOD: 1 Aug 06 to 31 Jan 08

OBJECTIVE(S):

To begin delineating groundwater drainage basins that provide habitat for rare cave and spring salamanders in the Austin, Texas area, and that will support the development of management plans for the species.

Segment Objectives:

Task 1: Preparation. All available information on caves and karst features in the study area shall first be obtained. Pertinent data will be plotted onto a Geographic Information System for comparison with spring, well, geologic, hydrologic, land owner, and infrastructure data to identify the sites most likely to yield a successful trace. Potential injection sites shall be identified, permission sought for access, and the actual injection sites selected based on the best combination of technical and logistical feasibility. Tracer packets shall be put in place for one week, then removed, and tests performed to detect dyes in the groundwater (some are used in various urban and industrial products and applications).

Task 2: Injection. Three non-toxic dyes, quantity and volume to be determined separately, shall mainly be used: uranine, eosin, and phloxine B. These are approved for use in drugs and cosmetics by the U.S. Food and Drug Administration. Other dyes commonly utilized in groundwater tracing may be used if warranted for technical reasons and if no public water supplies will be reached by the dyes. Whenever possible, dye shall be injected into multiple sites to simultaneously trace different injection locations to the discharge points. Depending on the injection site, the dyes may be added to flowing cave streams, or flushed into sinkholes or cave entrances. In the latter two situations, water will need to be brought to the site to flush the dye into the aquifer. Water from nearby buildings and fire hydrants shall be used whenever possible, or imported by trucks to the site. If the first tracer event (set of injections) was not successful, it shall be repeated with more dye, flush water, monitoring locations, and monitoring time until the dye is found.

Task 3: Detection. Packets of activated charcoal shall be placed at all accessible sites where the dye may be found. Additionally, automatic water samples may be used in some locations where it is most likely the dye will discharge. The packets and water samples shall be collected at intervals appropriate to the conditions of the trace and replaced with new packets and sample bottles until the dye has passed the site or there is reasonable certainty that the dye will not appear at the site. COA shall then evaluate and analyze water; 5-10% of the samples shall be split and sent to a separate lab for independent verification.

Task 4: Delineation. Following the results of the initial trace, additional traces may be conducted. Once the dye has been recovered, additional tracer events shall be performed where the injection points progressively increase their distance from the springs until the dye no long flows to the original springs but to other springs, thus delineating each spring's groundwater drainage divide. For this study, only one tracer event is planned. The results of this tracer event and especially the preparatory work will allow superior and more definitive planning for future traces once this pilot study establishes a database of effective injection and detection locations. COA shall then estimate the probable size of the springs' drainage basins.

Significant Deviation:

None.

Summary Of Progress:

Please see Attachment A.

Location: Travis County, TX

Cost: Costs were not available at time of this report.

Prepared by: Craig Farquhar **Date:** 4 February 2008

Approved by: [signature] C. Craig Farquhar **Date:** 4 Feb 08

PILOT PROJECT: HYDROGEOLOGIC DELINEATION OF HABITAT AND MANAGEMENT ZONES FOR THE JOLLYVILLE PLATEAU SALAMANDER IN THE AUSTIN, TEXAS AREA
FINAL REPORT FOR AUGUST-NOVEMBER 2007

Prepared by

Beverley L. Shade[1], Lisa O'Donnell[2], George Veni[1], and David Johns[2]

[1]George Veni and Associates
[2]City of Austin

submitted on 31 January 2008

In accordance with the Texas Board of Professional Geoscientists rules at 22 Texas Administrative Code, Part 39, Chapter 851, Subchapter C, §851.156, this report is signed and sealed on the title page to assure the user that the work has been performed by or directly supervised by the following professional geologist who takes full responsibility for this work

The computer-generated seals appearing on this document were authorized by the geologists listed below on 31 January 2008.

STATE OF TEXAS — BEVERLEY L. SHADE — GEOLOGY — 1198 — LICENSED — PROFESSIONAL GEOSCIENTIST

_______________________ 31 January 2008
Beverley L. Shade, Texas Professional Geoscientist No. 1198
4811 Duval St., Austin, Texas 78751
512-826-5027 • bev@zaraenvironmental.com

STATE OF TEXAS — GEORGE VENI — GEOLOGY — LICENSE # 682 — LICENSED — PROFESSIONAL GEOSCIENTIST

_______________________ 31 January 2008
George Veni, Ph.D., Texas Professional Geoscientist No. 682
507 E. Chapman, Carlsbad, New Mexico 88220-9283
505-234-1409 • gveni@warpdriveonline.com • 410-383-2276 (fax)

STATE OF TEXAS — DAVID A. JOHNS — GEOLOGY — No. 2799 — LICENSED — PROFESSIONAL GEOSCIENTIST

_______________________ 30 January 2008
David Johns, Texas Professional Geoscientist No. 2799
Watershed Protection, City of Austin Mailbox 1088, Austin, Texas 78767
512-974-2781 • david.johns@ci.austin.tx.us

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Summary

Three dye tracer tests were conducted concurrently as a pilot study to begin delineating the groundwater flowpaths and recharge area of Wheless Spring, located on the Lower Colorado River Authority's (LCRA) Wheless tract (Figure 1). This spring supports one of the largest populations of *Eurycea tonkawae*, the Jollyville Plateau salamander, in its known area of distribution. To locate suitable injection sites for the tracer study, karst surveys were conducted on the Wheless and Lehmann tracts between March and July 2007. Three karst features were identified for the injections and 17 spring/streambed sites were established for monitoring. On 23, 25, and 27 August 2007, dyes were injected into the three selected karst features, including a cave (WF27), a stream-sink (WF68), and a solutional sinkhole (WF94), which were all within 860 to 1,410 m (2,820 to 4,630 feet) of Wheless Spring.

By mid-September 2007, all three dyes were detected in at least one monitoring location. One of the dyes was detected in multiple monitoring locations. Eosin dye was detected at a small spring (WF98) about 130 meters (430 feet) from karst feature WF94, where it was injected, from 28 August 2007 until 3 November 2007 when the spring stopped flowing. Uranine dye, which was injected into the stream-sink WF68, was visually detected at Wheless Spring (about 1,100 m or 3,610 feet from WF68) and several rise points further downstream from 13-21 September 2007 and continued to be detected in low concentrations until sampling was discontinued on 15 November 2007. Uranine dye was also detected at spring WF98 (about 300 m or 980 feet from WF68) from 21 September 2007 until 3 November 2007 when the spring stopped flowing. Rhodamine WT dye was detected at Audubon Spring, which is about 480 m (1,570 feet) from the WF27 injection site, from at least 28 August through 21 September 2007 when the spring dried up due to lack of rain. Starting at the time of the injections, monitoring samples were collected weekly to define the main portion of the breakthrough curve, and then continued every two to three weeks until the dyes passed the monitoring sites in some cases, or the lack of precipitation caused the sampled springs to go dry.

Background

Biological Background

The Jollyville Plateau salamander (JPS), *Eurycea tonkawae*, is a small, neotenic salamander found in springs and caves in the Northern Segment of the Edwards Aquifer northwest of Austin, Texas, in Travis and Williamson counties. While it has no formal state or federal protection, in June 2005 the Save Our Springs Alliance submitted a petition to the U.S. Fish and Wildlife Service (USFWS) to list this species as threatened or endangered. On 13 December 2007, USFWS made a 12-month finding that listing the JPS as endangered or threatened is warranted but precluded due to other listing priorities (USFWS 2007). Major threats to the JPS include degradation of water quality, quantity, and habitat due to urban development over much of the recharge zone in this portion of the Edwards Aquifer and in the headwaters of the surface streams where the JPS occurs.

While significant declines have been observed at several long-term monitoring sites, Wheless Spring on the LCRA Wheless tract continues to support one of the largest JPS populations, based on long-term monitoring initiated by the City of Austin in 1997 (City of Austin 2001, 2005, 2006). Wheless Spring also provides much of the flow for Long Hollow Creek, which feeds Lake Travis. This is one of the few JPS sites where the headwaters of the surface stream are entirely within an existing system of preserves. However, it is unknown whether all of the recharge area for Wheless Spring is protected, since little is known of how water recharges and flows through the subsurface in the Northern Segment of the Edwards Aquifer. Groundwater flow in karst is often not controlled by surface topography and crosses beneath surface water drainage boundaries, so the sources and movements of groundwater to springs and caves inhabited by the JPS are poorly understood. Such information is critical to evaluating the degree to which JPS sites can be protected from urbanization. Because of the significance of the Wheless site to JPS conservation, the focus of this pilot dye-tracing study was to begin delineating the recharge area of and groundwater flow paths to this important spring.

As part of a separate project, the City of Austin initiated monthly mark-recapture surveys for the JPS at several sites including Wheless Spring from March-October 2007 (a report summarizing the results of this study is being drafted). Routine measurements included water flow and JPS counts. This provided an opportunity to closely observe the JPS at Wheless Spring during the dye-tracing. The toxicity of the dyes and concentrations used in this study were also researched to ensure no threat would occur to this species or its habitat. Other information basic to this study and report include Appendix A, is a glossary of geologic, biological, and karst terms used in this report, and Appendix B, a conversion index from the International System of Units used in this report, to English units.

Geological Background

Tracer tests are the only conclusive, unambiguous hydrologic measurements that connect discharge from karst springs and caves to recharge from surface catchments or features. Tests that utilize fluorescent dyes are the most common, cost effective, quantifiable, and safest for groundwater fauna and human water supplies. To date, most of the efforts to identify recharge areas and groundwater movement in the Edwards Aquifer using dye-tracing methods have been conducted in the San Antonio and Barton Springs segments. In the Northern Edwards Aquifer, the only known traces include dye injections in Whitewater Cave and Marigold Cave in the Buttercup Creek cave system, both of which discharged from a spring in the Cypress Creek watershed (Hauwert and Warton, 1997), injections near Stillhouse Hollow Springs in the Bull Creek watershed, injections near Spicewood Spring in the Shoal Creek watershed, and on a former site for a water treatment plant in the Bull Creek watershed (City of Austin, unpubl. data).

Groundwater flow and spring drainage basins in karst areas are difficult to accurately delineate by traditional methods such as potentiometric (water table) mapping. In the study area, water table maps are few, highly generalized, and mostly incomplete because there is generally insufficient groundwater to warrant the drilling of wells, which are the primary source of data for potentiometric mapping (e.g. Baker et al., 1986). Computer models of groundwater flow are critically dependent on detailed potentiometric mapping, so they cannot be developed for the study area with the available data. They also lack the ability to accurately delineate the complex groundwater flowpaths that occur in karst areas.

Guidelines for delineating karst spring and wellhead protection areas proposed by the U.S. Environmental Protection Agency (Schindel et al., 1996) and ASTM (American Society for Testing and Materials, 1995) recommend the use of fluorescent dyes to trace the flow of water from points of injection into the ground to detection points such as wells, where the groundwater is intercepted, and springs, which return it to the surface. Such tracer tests offer empirical, reproducible data that can be used to not only determine the direction of groundwater flow, but also velocity and the dilution and dispersion of the tracer. In such cases, tracers can serve as environmentally safe surrogates to predict the potential impacts of contaminants that might enter the groundwater system and salamander habitat.

Methods

Timing of work

In order to successfully carry out a tracer test, there must be sufficient flow through the system to carry the tracer from its injection site to potential monitoring sites. Due to a regional drought that lasted about a year and a half, water levels in the area were very low through the spring of 2007. The target of our study, Wheless Spring, was not flowing, so dye injections were postponed until suitable conditions were met. The drought ended in early summer of 2007, and heavy rains raised water levels so that Wheless Spring was flowing, as were many other ephemeral springs in the area. The heavy summer rains supported spring flow at most monitoring sites through October 2007. By the end of October, flow had decreased at all sites, and some sites had completely dried up. By mid-November 2007, flow had stopped at most of the monitoring sites, so sampling was discontinued.

Selection of Injection Sites

The database of the Texas Speleological Survey (TSS) was searched for karst features near Wheless Spring on the LCRA Wheless tract and adjacent properties. Speleologists, hydrologists, and biologists who are familiar with the area were consulted. No suitable injection sites were found in this process, because the areas of interest had not been searched for karst features. To locate potential karst features, two karst surveys were conducted. The LCRA provided funding for a professional karst survey of outcrops of Edwards Limestone on the Wheless property, while the City of Austin and George Veni and Associates organized a volunteer karst survey on the adjacent Lehmann property (Figure 2), owned by the The Nature Conservancy (TNC) of Texas. These projects, which were not anticipated and thus are not part of the Section 6 grant proposal, required hundreds of person hours, covered 3.95 km^2 (975 acres) and located 133 potential karst features. All of the karst features used in this study, except the historically known springs (Wheless Spring, Baker Spring and Audubon Spring) were unknown prior to these karst surveys. The properties where surveys were carried out are shown in Figure 2, and covered terrain above about 293 m (960 feet) of elevation above mean sea level, to ensure coverage of all outcrops of the Edwards Formation, where karst features are most likely to be found locally. The surveyed areas are all above the elevation of Wheless Spring.

After the karst surveys were completed in July 2007, the field notes for all features were reviewed and a subset of features was selected for geological assessment of their suitability as dye injection sites. Three injection sites were selected based on location and geologic interpretation of their ability to recharge water into the local groundwater system. The three features chosen were WF27 (Secretus Cave), WF68 (a stream sink), and WF94 (a solutional sinkhole). The features and their locations relative to Wheless Spring are shown on Figure 3. WF27 is located 1,410 m (4,630 feet) north of Wheless Spring. WF68 is located 1,090 m (3,580 feet) northwest of the spring, and WF94 is located 860 m (2,820 feet) northwest of the spring.

Selection of Dyes

Three dyes were selected for this investigation: uranine (sodium fluorescein), eosin, and rhodamine WT. These dyes have been previously used as groundwater tracers at other sites and their properties have been extensively documented in the hydrologic and karst-related literature. While several additional dyes are used in tracer studies, these were the three dyes available from the laboratory selected for this study. The laboratory and its contact information are given in a following section. All dyes except rhodamine WT are approved for use in drugs and cosmetics by the U.S.

Food and Drug Administration. Further, all of the dyes are non-toxic in the concentrations to which they are diluted in groundwater and discharged at wells and springs and pose no known threat to the quality of water supplies or aquatic biota (Smart 1984, Field et al. 1995). Previous traces have established a goal of keeping dye concentrations below 2 ppm over a 24 hour period.

Tracer Injections

The mass of dye for each site was based on experience with recent dye injections in the vadose zone both in the immediate area and elsewhere in central Texas. Equations such as those developed by Worthington and Smart (2003) can be powerful tools for estimating injection masses when the majority of the anticipated flow path is in the phreatic zone. However, the parameters which guide these equations are not the dominant controls on flow in the vadose zone. When much or all of the predicted flow path is in the vadose zone, such equations are inappropriate and do not yield good results.

When there is flowing water at an injection site, such as in a cave stream or a surface stream sink, dye is poured directly into the water, to follow that groundwater to its destination. One of the three injections conducted in this study was at a stream sink (WF68) and did not need to be flushed.

If there is no water at the selected injection site, as with many karst features or caves that do not provide human access to the water table, water must be supplied to carry the dye to the water table, where natural groundwater flow will then carry the dye downgradient. Sufficient flush water should be used to allow the dye to reach the local groundwater system. For this trace, the City of Cedar Park provided chlorinated water from a water tower located on the Wheless tract. The Wheless tract is only accessible by 4-wheel-drive roads, so hauling unchlorinated water from off-site was not feasible. To remove chlorine from the water, as well as to allow sufficient volumes of water for prewetting and flushing, water was hauled from the water tower to an open holding tank. The water was transported in a 1,136 L (300 gallon) rigid tank in the back of a pickup truck. The water was then drained out of the tank into a collapsible 11,356 L (3,000 gallon) swimming pool (Figure 4). The water was held in the pool for varying periods (several hours to overnight) to allow the chlorine to degas. Every stage of this process provided aeration to the water, encouraging additional degassing. From the pool, water was pumped through a discharge hose directly into the feature. WF27 is close to the road and required only 60 m (200 feet) of hose. WF94, on the other hand, required almost 400 m (1,310 feet)of discharge hose to be carefully laid out through dense brush (Figure 5).

Based on the geometry of features WF24 and WF94 and previous dye tracing experience in central Texas, the target flush volume for each site was 22,712 L (6,000 gallons). In addition to flushing, dry injection sites should also be wetted before injection. Prewetting the flow path reduces adsorption of the dye onto dry soil and bedrock surfaces. Dye loss through adsorption can be significant. Both sites were wetted immediately prior to injection with approximately 2,650 L (700 gallons).

Three injections were conducted in late August 2007 at the injection sites listed above. Details of the injections are summarized below and in Table 1. On 23 August 2007, 2.27 kg (5 lbs) of rhodamine WT were injected at WF27 (Secretus Cave). Before dye injection, the cave was wetted with 2,270-2,650 L (600-700 gallons) of water, from 9:30 - 9:35 a.m. Dye was carefully poured into the entrance of the cave at 9:45 a.m. The dye was then flushed with 22,712 L (6,000 gallons) of water, starting at 10:00 a.m and ending at 6:30 p.m.

On 25 August 2007, 1.36 kg (3 lbs) of eosin were injected at WF94. Before injection, the cave was wetted with about 2,650 L (700 gallons) of water, from 8:30 - 8:35 a.m. Dye was carefully poured into the sinkhole at 8:45 a.m. The dye was then flushed with 22,712 L (6,000 gallons) of water, starting at 9:00 a.m. and ending at 2:15 p.m.

On 27 August 2007, 0.91 kg (2 lbs) of uranine were injected at WF68. Since a small spring upstream (WF67) was flowing, the injection site did not need to be prewetted or flushed. Dye was carefully poured into the flow of the small stream just upstream of a losing stretch of streambed that is about 5 m (16 feet) long. At this time, all flow sank into the streambed and no flow went past the stream sink. From 11:00 - 11:10 a.m., dye was poured slowly into the stream to avoid creating a pulse of water that would slosh dye up onto the sides of the streambed. The flow at this time was estimated at 5 L/min (1.3 gpm), equivalent to about 7,200 L/day (1,900 gallons/day).

Table 1. Injection details

Site	Type	Date	Dye	Mass	Total Flush+Prewetting
WF27	cave	8/23/2007	rhodamine WT	2.27 kg (5 lbs)	24,982-25,362 L (6,600-6,700 gallons)
WF94	sinkhole	8/25/2007	eosin	1.36 kg (3 lbs)	25,362 L (6,700 gallons)
WF68	stream sink	8/27/2007	uranine	0.91 kg (2 lbs)	natural flow, 7,200 L/day (1,900 gallons/day)

The dyes can be detected through high-resolution analysis in the low parts-per-billion range, so all concentrated dye was handled with great care. For injection, the site was prepared by laying out a 4-mm-thick sheet of clear plastic. Injection supplies, including dye, were placed on the plastic sheeting. The person who injected the dye wore a tyvec suit with a hood, impermeable shoe covers, and several pairs of impermeable gloves. This person stood on the plastic sheeting, opened the dye container(s), and carefully poured the dye into the most obvious drain for the feature (Figures 6 and 7). Care was taken not to splash dye onto the surrounding area. The dye container was then closed and placed double-bagged in heavy-duty garbage bags for later decontamination. While standing on the plastic sheeting, the person removed the suit and outer layer of gloves so that the clothing was inverted and left on the sheeting. Finally, the person stepped out of the shoe covers and off of the plastic sheeting. With the inner pair of gloves, the person rolled the plastic sheeting and all trash which remained on top of it inward, creating a bundle of trash that was placed into a waiting garbage bag and then double bagged to avoid contamination. After injection, the site was inspected for potential splashes of dye and everyone involved with the dye injection washed their hands and any tools with a strong bleach-water solution.

Spring Monitoring

A network of 17 sites was established to monitor likely flowpaths from the injection sites. See Table 2 for a list of sites and Figures 8 and 9 for their locations. The sites were monitored with charcoal packets for the presence of the tracer dyes. Water samples were also obtained each time a charcoal packet was collected. Water samples provide direct measurements of dye concentration in the water, which allows quantification of the trace and determination of hydrologic properties of the traced portion of the aquifer; accurate quantifiable concentrations of the dye in the original spring water are not possible from the charcoal packets.

Table 2. Dye monitoring sites

Site Name	Type
Audubon Spring	spring
Baker Spring/Stewart Spring	spring
WF63	spring
WF67	spring
WF98	spring
WF101	spring
WF104	spring
WF105	spring
Wheless Spring	spring
Wheless downstream	streambed
Wheless upstream	streambed
Infeeder below Wheless	streambed
Long Hollow Creek	streambed
Long Hollow Infeeder	streambed
Cypress Creek	streambed
Downstream on west side	streambed
Fisher Hollow Creek	streambed

Alexander and Quinlan (1996) discussed the rationale and the techniques for using charcoal detectors and methods for the analysis of dyes. Charcoal adsorbs dye from the water that passes through the detector. It yields an integrated sample that, barring interference from other organic compounds, is a product of continual sorption of dye, whenever dye is present in water. The tracer detectors consist of small nylon screen mesh packets containing activated coconut charcoal. These packets were placed in springs close to the injection sites and in streambeds thought to be downstream of additional springs.

During the initial placement of the charcoal packets and during each replacement, a water sample was also collected for confirmation of charcoal results. When the detector was collected, it was placed in its own plastic bag and the bag was labeled with the site ID, collection date and time. All detectors were placed and retrieved using new disposable vinyl gloves. After collection, detectors were kept in coolers and shipped to the analysis laboratory. Detectors were supplied and analyzed by Ozark Underground Laboratory. The QA/QC procedures used by that facility can be obtained by contacting the laboratory at: Sales@OzarkUndergroundLab.com, 417-785-4289, or 1572 Aley Lane, Protem, Missouri 65733. Their website is: http://www.ozarkundergroundlab.com.

Background detectors were placed in all of the sites except Fisher Hollow Creek, the Long Hollow infeeder, Wheless upstream and the infeeder below Wheless (Figures 8 and 9) before the trace began. The first two sites were added to the monitoring network shortly after dye was injected.

The last two sites were added in mid-September, after dye appeared in visual quantities in the Wheless Spring area. The purpose of the background detectors was to minimize the chance that the dyes occurred at the monitoring sites in measurable quantities prior to injection, which would produce false-positive results. The background detectors were left in place for a week and were replaced just before the dye injections; all tested negative for dyes. After the dye injections, samples were collected every six to nine days for seven weeks, and then every twelve to fifteen days until sampling stopped on 15 November 2007. Sampling continued until either the dyes passed the monitoring sites, there was a reasonable certainty the dyes would not appear at the sites, or flow at the monitoring sites had ceased.

Results

All dyes were positively detected by 7 September 2007. One of the dyes, uranine, was detected at four sites, while eosin and rhodamine WT were each detected at one site. There were repeated and consistent detections of the dyes at the locations described below. The approximate flow paths and an inferred drainage divide are shown in Figure 10.

An important note on dye concentrations! Water samples were collected from the flow at a given monitoring site and analyzed directly, giving an exact concentration of dye in the water at the time of collection. The drawback to this type of sampling is that it provides point data and a dye trace based solely on water samples would require hundreds of samples and a much larger budget than was used in this project to ensure that dye did not discharge undetected from any of the monitoring sites. Charcoal detectors, as discussed in the Methods section, accumulate dye and other organic materials from the water for a period of time. There are a number of variables that affect how much dye is adsorbed to charcoal, and thus the reported "concentration" of dye in a charcoal sample does not necessarily represent the dye concentration in the water at any point in time. The major variables are the concentration of dye in the water at the monitoring site and the volume of flow that passes through the charcoal packet. It must be understood that the concentration of dye in water will vary while the packet is deployed. As well, it must be understood that the flow of water passing through the charcoal packet is unknown and varies for the duration of the sample, and that sample intervals varied. Therefore, proper interpretation of charcoal results requires remembering that the "concentrations" reported by the lab are not directly equivalent to concentrations of dye in the water and should be considered based on order of magnitude. Concentrations for the charcoal samples are given as ppb in this report because that is how they were reported by the consulting laboratory.

Eosin dye was detected at a small spring (WF98) near the eosin injection site (WF94). The distance from the injection site to WF98 is 130 m (430 feet). The first set of samples was collected on 28 August 2007, three days after the eosin injection, giving a minimum groundwater velocity of 1.6 m/hour (5.2 feet/hour). In the first set of samples, the charcoal packet had a moderate peak of eosin. The dye was too dilute at this time to be detected in the accompanying water sample. In the second set of samples, collected on 7 September 2007, the eosin peak in the charcoal packet was about five times larger, but the dye in the water at the time of collection was still too dilute to be detected. In the third set of samples, collected on 14 September 2007, there was still a strong eosin peak in the charcoal packet, and dye was measured in the water sample at a concentration of 1.51 ppb. In the set of samples collected on 21 September 2007, the dye was measured in the water sample at a concentration of 0.44 ppb, and the peak measured in charcoal had begun to decrease. After 21 September 2007, eosin was too dilute to be measured in the water sample, and the amount of eosin detected in the charcoal packets decreased regularly until the spring stopped flowing in mid-November 2007. These results suggest a relatively small mass of dye discharged compared to the injected mass of the dye. Based on the concentration of dye in water samples and observations of flow, less than 0.0001 g of eosin was recovered at WF98. This is significantly less than 1%. Thus, the entire mass of dye has not flowed past this point, although it is unlikely that much more dye remains upstream of WF98. Part of the dye was surely lost to adsorption to soil and bedrock surfaces following injection and to photodegredation in the pond at WF98. It is also possible that only part of the dye traveled to spring WF98, and part of the dye may flow to other locations, such as Wheless Spring. The distance to Wheless Spring is much greater and if eosin reaches the spring it could take weeks or months to arrive. Given the ephemeral nature of springflow in this area, that time could be extended considerably.

Uranine dye was also detected at spring WF98 in very low concentrations. All detections were close to the limit of detection, but the repeated occurrence in both charcoal and water samples validates the detection. Uranine arrived at WF98 by at least 21 September 2007, and continued to issue from the spring at similar levels until the spring stopped flowing in mid-November 2007. The distance from the injection site to WF98 is 300 m (980 feet), giving a minimum groundwater velocity of 12 m/day (40 feet/day). Analytical results from both water and charcoal samples are given in Table 3, and the results from the charcoal samples are plotted in Figure 11. Based on the concentration of dye in water samples and observations of flow, the mass of uranine dye recovered at WF98 was about $3x10^{-7}$ g, also significantly less than 1%.

Table 3. Dye results from monitoring site Spring WF98

Spring WF98				
	charcoal packets		water samples	
Out date	eosin (ppb)	uranine (ppb)	eosin (ppb)	uranine (ppb)
8/21/07 16:15	0	0	0	0
8/28/07 17:45	42.6	0	0	0
9/7/07 16:55	258	0	0	0
9/14/07 10:45	130	0	1.51	0
9/21/07 11:00	67	6	0.44	0
9/30/07 16:15	45	8	0	0
10/10/07 18:15	20	6	0	0.04
10/18/07 15:45	24	7	0	0
11/3/07 15:43	26	5	0	0
11/15/07 13:30	no springflow			

Rhodamine WT was detected at a small spring on the Travis Audubon Society's Baker Sanctuary tract. The spring is named Audubon Spring and has considerably lower discharge than Baker Spring, which lies to the north. The dye was detected in the first set of samples, collected on 28 August 2007, five days after injection. The distance from the injection site (WF27) to Audubon Spring is 480 m (1,570 feet), giving a minimum groundwater velocity of 3.8 m/hour (12.5 feet/hour). The flow at this spring was about 1 L/min (0.26 gallon/min) when the project started, and by 21 September 2007 had stopped flowing. However, the rhodamine WT peak at this site was very strong. The rhodamine WT concentration was over 2,300 ppb in the first charcoal sample. The peak eosin detection at WF98, by comparison, was about 260 ppb. Rhodamine WT was measured in the water sample at a concentration of 119 ppb. The implication of this strong peak, measured so soon after injection, is that the dye was carried to the water table by the 22,712 L (6,000 gallons) of flush water, and the flush water created enough gradient in that location to push the dye to the nearby spring. Had flow at the spring been monitored, it is likely that discharge would have been observed to slightly increase due to the pulse of flush water. In the second set of samples, rhodamine WT had a strong peak in the charcoal packet and the dye was measured in the water sample at a concentration of 36.4 ppb. In the third set of samples, the dye had a strong peak in the charcoal packet and was measured in the water sample at a concentration of 24.8 ppb. During this time, the flow from Audubon Spring had decreased to an almost imperceptible level. The final samples were collected on 21 September 2007, when only a small puddle of water was left to mark the spring. Still, both charcoal and water samples showed a significant concentration of the dye. The spring was visited with every collection and fresh charcoal packets were set out in case new rains generated springflow, but no additional flow occurred before sampling was discontinued in mid-November 2007.

While the dye concentrations at Audubon Spring site were high, the flow volume was quite low. The measured concentrations do not account for all the dye injected at WF27. Based on the concentration of dye in water samples and observations of flow during the sampling period, less than 0.001 g of rhodmine WT was recovered at Audubon Spring. This is significantly less than 1% of the dye injected. Some dye was certainly lost to adsorption to soil and rock surfaces during injection and travel to the discharge site, but rhodamine WT is quite stable, and it is not likely that dye was lost to degradation. Some dye may have traveled by alternate routes to different discharge points. Some dye is probably still in storage between the injection site and Audubon Spring, and will continue to be flushed from the spring when springflow resumes. Analytical results from both water and charcoal samples are given in Table 4, and the results from the charcoal samples are plotted in Figure 12.

Table 4. Dye results from Audubon Spring

Audubon Spring - rhodamine WT		
Out date	**charcoal (ppb)**	**water (ppb)**
8/21/07 9:30	0	0
8/28/07 14:45	2,380	119
9/7/07 9:35	4,030	36.4
9/13/07 14:40	1,560	24.8
9/21/07 9:10	566	17.7
9/30/07 17:30	no springflow	
10/12/07 11:45	no springflow	
10/18/07 11:45	no springflow	
11/5/07 11:40	no springflow	
11/15/07 13:30	no springflow	

Uranine was detected at Wheless Spring and in the spring run about 30 m (100 feet) downstream. The distance from the uranine injection site (WF68) to Wheless Spring is 1,100 m (3,610 feet). The dye was present in concentrations of at least 10.9 ppb by 7 September 2007, giving a minimum groundwater velocity of 4.1 m/hour (13.5 feet/hour. In the next set of samples, collected on 13 September 2007, uranine was measured in water samples from Wheless Spring at a concentration of 11.4 ppb, and in the spring run downstream at 12.4 ppb. There are numerous small spring outlets in the streambed downstream of the main spring pool. While some water flowed into the spring run from upstream, dye was never detected in that water.

Dye was visually detected at Wheless Spring and downstream of the spring in much lower concentrations than were detected at Audubon Spring, where there was no visible coloration of the water. This is because uranine dye is much more fluorescent than any of the other dyes by about an order of magnitude, and also because the deep pools at Wheless Spring and in the spring run below provided a relatively deep, clear water column in which to see the dye. In contrast, the rise pool at Audubon Spring is only a few centimeters deep and very muddy. The dye at Wheless was first sighted during sample collection on the evening of 13 September 2007, and was present in roughly the same concentration on the following day. The water was iridescent green in color (Figure 13), indicating that it was likely to be the uranine injected on 25 August 2007 at the stream sink feature (WF68). During the JPS mark-recapture surveys conducted from 17-19 September 2007, water in the deeper pools at the Wheless Spring site and in the downstream tributary that joins Long Hollow Creek about 30 m (100 feet)south of Wheless Spring was more strongly colored than on 13 September 2007, indicating that the dye concentration had increased. None of the JPS individuals observed during the mark-recapture survey showed any apparent physical or behavioral responses to the dye.

The tributary below Wheless had not been previously sampled for dye, but it is reasonable to assume that dye arrived at a probable nearby spring in the tributary at about the same time as in the rest of the Wheless Spring area. This other spring almost certainly discharges from a distributary conduit from the main conduit which leads to Wheless Spring; distributary conduits are often found at karst springs. This site was added to the monitoring network on 21 September 2007, and a faint green color could be seen in the deeper pools and downstream tributary. The coloration of the water at this time was less than when originally sighted, indicating the dye traveled as a slug without much dispersion, and that the main slug of dye had passed by 21 September 2007.

Uranine dye was detectible in Wheless Spring until springflow ceased at the beginning of November 2007. However, the concentration had decreased to 0.8 ppb in the water sample and to less than 40 ppb in the charcoal sample. Flow also decreased in the Wheless spring run and in the downstream tributary, but did not completely stop. Dye was detected in both sites through the end of sampling on 15 November 2007, with water concentrations of 0.2 ppb and charcoal concentrations of less than 30 ppb. While it is impossible to calculate the exact volume of uranine dye discharged in the Wheless spring area, it is likely that much of the dye passed through this area, and other unmonitored seeps from distributary conduits. Based on dye concentrations in water samples and observations of flow, at least 0.05 g of uranine dye were recovered in the Wheless Spring area. This accounts for 0.005% of the dye injected, the highest percent recovery of any of the dyes. While the low final concentrations may be somewhat the result of low discharge, they still indicate that the dye had mostly flushed from the system. Analytical results from both water and charcoal samples are given in Table 5, and the results from the charcoal samples are plotted in Figure 14.

Table 5.
Uranine dye detected at Wheless Spring and adjacent discharge points

	Wheless Spring		Wheless Downstream		Infeeder south of Wheless	
Out date	**charcoal (ppb)**	**water (ppb)**	**charcoal (ppb)**	**water (ppb)**	**charcoal (ppb)**	**water (ppb)**
8/21/07 17:50	0	0	0	0	no sample collected	
8/28/07 16:30	0	0	0	0	no sample collected	
9/7/07 13:15	sample missed		2,940	10.9	no sample collected	
9/13/07 17:00	3,610	11.4	6,090	12.4	no sample collected	
9/21/07 13:40	385	2.9	427	5.9	place 1st packet	7.2
10/1/07 10:15	110	2.2	1930	2.1	423	3.7
10/10/07 16:40	53	1	521	1.1	109	1.4
10/18/07 14:30	38	0.8	176	1.2	44	0.8
11/3/07 14:05	no springflow		61	0.4	57	0.3
11/15/07 11:20	no springflow		28	0.2	22	0.2

Conclusions & Future Work

The intent of this pilot study was to begin delineating the groundwater flowpaths and recharge area of Wheless Spring. The study was successful toward that goal; multiple flowpaths were defined from recharge points to down-gradient discharge points. Additionally, a drainage divide was located on one side of the recharge area.

The pattern of dye detections indicates a drainage divide between Wheless and Audubon Springs. The location of this drainage divide is not precisely known but probably runs along the east-west ridge that lies to the north of Wheless Spring; its location could be better pinpointed by a future dye injection into the stream-sink WF63, shown in Figure 15. The boundaries of the Wheless spring drainage basin to the west have been demonstrated to extend up onto the northeast-southwest trending ridge. Since the spring can only collect water from areas of higher elevation, the boundaries of the drainage area to the west must fall above 250 m (820 feet) elevation. The area defined by this contour to the west lie almost entirely in the LCRA property. However, it must be noted that any area on the LCRA property that lies above 250 m (820 feet) elevation may contribute to spring flow, and unless future tracer work defines a smaller catchment area, any development on those portions of the Wheless tract could impact water quality at Wheless Spring. It is important to remember that in a karst system, the boundaries of drainage areas are not fixed; they can shift based on changes in the local water table. To best understand the hydrologic system that feeds Wheless Spring, future tracer studies should be carried out at additional locations under a variety of hydrologic conditions.

Our understanding of this system, and consequently our ability to protect water quality at Wheless Spring, will be improved by additional tracer studies. Recommended areas for potential future injection sites are shown in Figure 16 that would better define the boundaries of the spring's drainage basin. The first priority is to establish the boundaries of the drainage area where they may be outside of the BCP. Logistics for these traces will be more difficult than for the pilot study, because they will require work on private land. To the south, it is possible that the ridgeline south of the Wheless tract contributes to Wheless Spring. Dye traces should be conducted further south along the main ridge, either on the Wheless tract or on private land until the drainage divide is located. This will require additional karst surveys to locate appropriate injection and monitoring points. To the east, the boundary of the drainage basin is unknown. Dye traces should be conducted on the Lehman tract and the upland between Long Hollow Creek and Cypress Creek to establish the drainage divide on that side. This will require additional karst surveys to locate appropriate injection and monitoring points. Dye injections on the Lehman tract that require flushing will be difficult due to lack of road access. To the north and west, the constraints of topography indicate that the drainage area of the spring likely falls within the current boundaries of the BCP. However, should the protections of the BCP be jeopardized for some reason, such as for construction projects, we strongly recommend that additional tracing be done to better define the spring drainage basin in those areas, such as injections at karst features WF63, WF52, and WF70, as shown on Figure 15.

Acknowledgements

This pilot dye-tracing project was funded by a matching Section 6 grant from the Texas Parks and Wildlife Department and U.S. Fish and Wildlife Service. This project would not have been possible without the additional support of several partners. The LCRA funded a comprehensive karst survey on the Wheless tract to find suitable injection sites. The TNC allowed access for karst surveys on the adjacent Lehmann tract. The City of Cedar Park provided water for the injections. LCRA, TNC, and Travis Audubon Society provided access for monitoring springs on the Wheless, Lehmann, and Baker Sanctuary tracts. Finally, volunteers assisted with the karst survey on the Lehman tract and with the dye injections.

Bibliography

Alexander, E. Calvin Jr., and James F. Quinlan. 1996. Introduction to practical techniques for tracing groundwater in carbonates and other fractured rocks. In *Guidelines for Wellhead and Springhead Protection Area Delineation in Carbonate Rocks*, G.M. Schindel, J.F. Quinlan, G.J. Davies, and J.A. Ray, US EPA Region IV Groundwater Protection Branch, 195 pp.

City of Austin. 2001. Jollyville Plateau water quality and salamander assessment. Water Quality Report Series COA-ERM 1999-01. Watershed Protection and Development Review Department, Environmental Resource Management Division. Austin, Texas.

City of Austin. 2005. Summary of Jollyville Plateau salamander data (1997 – 2005) and status. Report prepared by Lisa O'Donnell, Martha Turner, P.E., Ellen Geismar, and Mark Sanders. City of Austin, Watershed Protection and Development Review Department, Environmental Resource Management Division. Austin, Texas.

City of Austin. 2006. Summary of Jollyville Plateau salamander data (1997 – 2006) and status. Report prepared by Lisa O'Donnell, Martha Turner, Mark Sanders, Ellen Geismar, Sara Heilman, and Laura Zebehazy. City of Austin, Watershed Protection and Development Review Department, Environmental Resource Management Division. Austin, Texas.

Culver, David C. 1982. Cave life, evolution and ecology. Harvard University Press, Cambridge, Massachusetts, 189 pp.

Field, M., R. Wilhelm, J. Quinlan, T. Aley. 1995. An assessment of the potential adverse properties of fluorescent tracer dyes used for groundwater tracing. Environmental Monitoring and Assessment 38:75-96.

Hauwert, N. and M. Warton. 1997. Initial groundwater tracing study of the Buttercup Creek area, Cedar Park, south Williamson County, Texas. Mike Warton & Associates. Cedar Park, Texas.

Jackson, Julia A., ed. 1997. Glossary of Geology, fourth edition. American Geological Institute, Alexandria, Virginia.

Smart, Peter L. 1984. A review of the toxicity of twelve fluorescent dyes used for water tracing. NSS Bulletin 46:21-33.

U.S. Fish and Wildlife Service. 2007. Endangered and threatened wildlife and plants; 12-month finding on a petition to list the Jollyville Plateau salamander (*Eurycea tonkawae*) as endangered with critical habitat; proposed rule. December 12, 2007. Federal Register, 72(239):71,040-71,054.

Worthington, S.R.H., and Smart, C.C. 2003. Empirical determination of tracer mass for sink to springs tests in karst. In *Sinkholes and the Engineering and Environmental Impacts of Karst*, Proceedings of the ninth multidisciplinary conference, Huntsville, Alabama, Barry F. Beck, ed., American Society of Civil Engineers, Geotechnical Special Publication, No. 122, 287-295.

APPENDIX A
Glossary of Geologic, Karst, Biological, Archeological, and Paleontological Terminology

This glossary is broad in scope to assist nonspecialists reviewing this report, but is not meant to cover all possible terms. Additional karst definitions and geologic terms can be found in the geological dictionary of Jackson (1997); for biospeleological terms see Culver (1982).

Alluvium: Stream-deposited sediments, usually restricted to channels, floodplains, and alluvial fans.

Antecedent precipitation: Precipitation (usually rainfall) that occurred prior to a given time or event. Usually refers to the amount of rain prior to a storm whose effect is measured on a stream, spring, or water well hydrograph.

Aquiclude: Rocks or sediments, such as shale or clay, which do not conduct water in significant quantities.

Aquifer: Rocks or sediments, such as cavernous limestone and unconsolidated sand, which store, conduct, and yield water in significant quantities for human use.

Aquitard: Rocks or sediments, such as cemented sandstone or marly limestone, that transmit water significantly more slowly than adjacent aquifers and that yield at low rates.

Artesian: Describes water that would rise above the top of an aquifer if intersected by a well; sometimes flows at the surface through natural openings such as fractures.

Base level: The level to which drainage gradients (surface and subsurface) are adjusted, usually a surface stream, relatively impermeable bedrock, or water table. Sea level is the ultimate base level.

Baseflow: The "normal" discharge of stream when unaffected by surface runoff; derived from groundwater flowing into the stream channel.

Borehole: A drilled hole, commonly used for fluid or mineral extraction and injection, or for the monitoring or testing of geologic parameters.

Breakthrough curve: The plotted concentration of a groundwater tracing agent as it occurs at a monitored location; a complete plot includes the time of injection, time of first appearance, time when it becomes undetectable, and intermediate concentrations at each sampled period.

Cave: A naturally occurring, humanly enterable cavity in the earth, at least 5 m in length and/or depth, in which no dimension of the entrance exceeds the length or depth of the cavity (definition of the Texas Speleological Survey).

Conduit: A subsurface bedrock channel formed by groundwater solution to transmit groundwater; often synonymous with cave and passage, but generally refers to channels either too small for human entry, or of explorable size but inaccessible. When used to describe a type of cave, it refers to base level passages that were formed to transmit groundwater from the influent, upgradient end of the aquifer to the effluent, downgradient end.

Conduit flow: Groundwater movement along conduits; usually rapid and turbulent.

Cretaceous: A period of the geologic time scale that began 135 million years ago and ended 65 million years ago.

Depression: A sinkhole-like feature that is not formed by karst processes or has not yet been proven karstic in origin.

Depth: In relation to the dimensions of a cave or karst feature, it refers to the vertical distance from the elevation of the entrance of the cave or feature to the elevation of its lowest point. See *vertical extent* for comparison.

Dip: The angle that joints, faults or beds of rock make with the horizontal; colloquially described as the "slope" of the fractures or beds. "Updip" and "downdip" refer to direction or movement relative to that slope.

Diffuse flow: Laminar and very slow groundwater movement within small voids of primary and secondary porosity, excluding conduit and fissure flow; "intergranular" flow.

Discharge: The water exiting an aquifer, usually through springs or wells; also the amount of water flowing in a stream.

Drainage basin: A watershed; the area from which a stream, spring, or conduit derives its water.

Drainage divide: Location where water diverges into different streams or watersheds. On the surface they usually occur along ridges or elevated areas. In aquifers, they occur along highs in the potentiometric surface between groundwater basins.

Endemic: Biologically, refers to an organism that only occurs within a particular locale.

Fault: Fracture in bedrock along which one side has moved with respect to the other.

Floodplain: The flat surface that is adjacent and slightly higher in elevation to a stream channel, and which floods periodically when the stream overflows its banks.

Fracture: A break in bedrock that is not distinguished as to the type of break (usually a fault or joint).

Fracture flow: Groundwater movement along fractures and bedding planes that usually have been enlarged by solution. Flow is laminar to turbulent, and generally constitutes a moderate to large volume of groundwater in karst aquifers.

Grade: The continuous descending profile of a stream; graded streams are stable and at equilibrium, allowing transport of sediments while providing relatively equal erosion and sedimentation. A graded profile generally has a steep slope in its upper reaches and a low slope in its lower reaches.

Groundwater drainage basin: Area where surface water enters the ground and flows into a cave via fractures, conduits, and passages whose connection to the surface is inferred but not observed. It includes areas that drain into cave passages beyond the physically explored portion of a cave, where evidence suggests the likely presence of such passages.

Head: The difference in water level elevations that creates the pressure for water movement down a gradient.

Headward: In the direction of greater elevation; typically refers to upstream or up a hydraulic gradient.

Hydrogeology: The study of water movement through the earth, and the geologic factors that affect it.

Hydrology: The study of water and its origin and movement in atmosphere, surface, and subsurface.

Impermeable: Does not allow the significant transmission of fluids.

Joint: Fracture in bedrock exhibiting little or no relative movement of the two sides.

Karst: A terrain characterized by landforms and subsurface features, such as sinkholes and caves, which are produced by solution of bedrock. Karst areas commonly have few surface streams; most water moves through cavities underground.

Karst feature: Generally, a geologic feature formed directly or indirectly by solution, including caves; often used to describe features that are not large enough to be considered caves, but have some probable relation to subsurface drainage or groundwater movement. These features typically include but are not limited to sinkholes, enlarged fractures, noncavernous springs and seeps, soil pipes, and epikarstic solution cavities.

Karst preserve: An area that can preserve the ecosystem of a cave, group of caves, or karst fauna area in perpetuity. These areas meet the requirements of the U.S. Fish and Wildlife Service and may vary slightly in character based on site-specific issues and factors.

Length: In relation to the dimensions of a cave or karst feature, it refers to the summed true horizontal extent of the cave's passages or the feature's extent.

Lithology: The description or physical characteristics of a rock.

Passage: An elongate, humanly traversable, roofed portion of a cave or karst feature; usually a conduit for groundwater flow.

Permeable: Allows the significant transmission of fluids.

Permeability: Measure of the ability of rocks or sediments to transmit fluids.

Phreatic: The area below the water table, where all voids are normally filled with water.

Piracy: The natural capture of water from a watershed, stream, aquifer, or cave stream, and its transmission to a different watershed, stream, aquifer, or cave stream.

Piping: See *suffosion*.

Pit: A vertical cavity extending down into the bedrock; usually a site for recharge, but sometimes associated with collapse.

Porosity: Measure of the volume of pore space in rocks or sediments as a percentage of the total rock or sediment volume.

Potentiometric surface: A surface representing the level to which underground water confined in pores and conduits would rise if intersected by a borehole. See *water table*.

Reach: The length of a stream or stream segment; often used to denote similar physical characteristics.

Recharge: Natural or artificially induced flow of surface water to an aquifer.

Resurgence: See *spring*.

Seep: A spring that discharges a relatively minute amount of groundwater to the surface at a relatively

Sheetwash: Surface water runoff that is not confined to channels but moves across broad, relatively smooth surfaces as thin sheets of water.

Sink: See *sinkhole*.

Sinkhole: A natural indentation in the earth's surface related to solutional processes, including features formed by concave solution of the bedrock, and/or by collapse or subsidence of bedrock or soil into underlying solutionally formed cavities.

Sinking stream: A stream that losses all or part of its flow into aquifer. See *swallet*.

Speleogenesis: The process of cave origin and development.

Spring: Discrete point or opening from which groundwater flows to the surface; strictly speaking, a return to the surface of water that had gone underground.

Surface water drainage basin: The area where surface water flows into a cave's entrance(s) or into karst features directly associated and known to connect to the cave, such as sinkholes and solutionally enlarged fractures.

Swallet: A surface stream that loses all of its baseflow into a cave or sinkhole. The stream channel may extend beyond the swallet, but it would contain only overflowing floodwaters.

Tracer test: The injection of a non-toxic, traceable substance, often a fluorescent dye, into a groundwater system, and its recovery at a downgradient location (usually a spring). This technique is commonly used in karst areas to define groundwater flow paths and travel times.

Turbulent flow: Variable movement of water particles along very irregular paths. Typical flow regime of cave streams.

Unconfined: Pertaining to aquifers having no significant impermeable strata between the water table and the land surface.

Vadose: Pertaining to the zone above the water table where all cavities are generally air-filled, except during temporary flooding.

Water table: The boundary of the phreatic and vadose zones. A potentiometric surface that is specific to unconfined aquifers.

APPENDIX B

Conversions:
International System of Units to English Units

MULTIPLY	BY	TO GET
Length		
centimeters (cm)	0.3937	inches (in)
meters (m)	3.281	feet (ft)
kilometers (km)	0.621	miles (mi)
Area		
square meters (m^2)	10.76	square feet (ft^2)
square kilometers (km^2)	0.3861	square miles (mi^2)
square kilometers (km^2)	247.1	acres (ac)
Volume		
liters (L)	0.264	gallons (gal)
cubic meters (m^3)	264.17	gallons (gal)
cubic meters (m^3)	0.00081	acre-feet (a-f)
Flow		
liters per second (L/s)	0.0353	cubic feet per second (cfs)
liters per second (L/s)	15.85	gallons per minute (gpm)
cubic meters per second (m^3/s)	35.31	cubic feet per second (cfs)
cubic meters per second (m^3/s)	1,585	gallons per minute (gpm)
cubic meters per second (m^3/s)	70.05	acre-feet per day (a-f/d)
Temperature		
degrees Celsius	multiply by 1.8 then add 32	degrees Fahrenheit

Figure 1.
Location of study area in Travis County, Texas

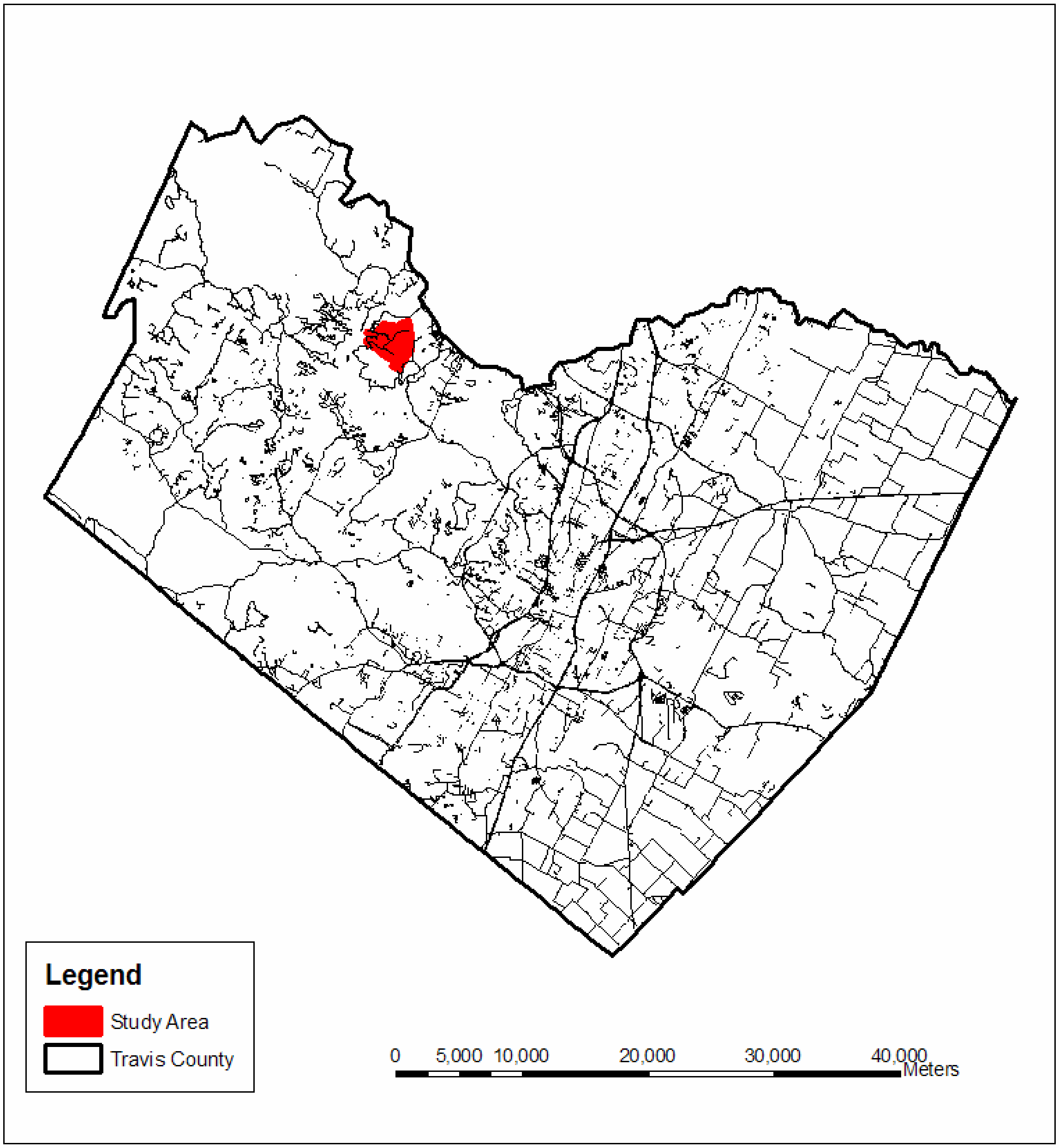

Figure 2.
Areas surveyed for karst features

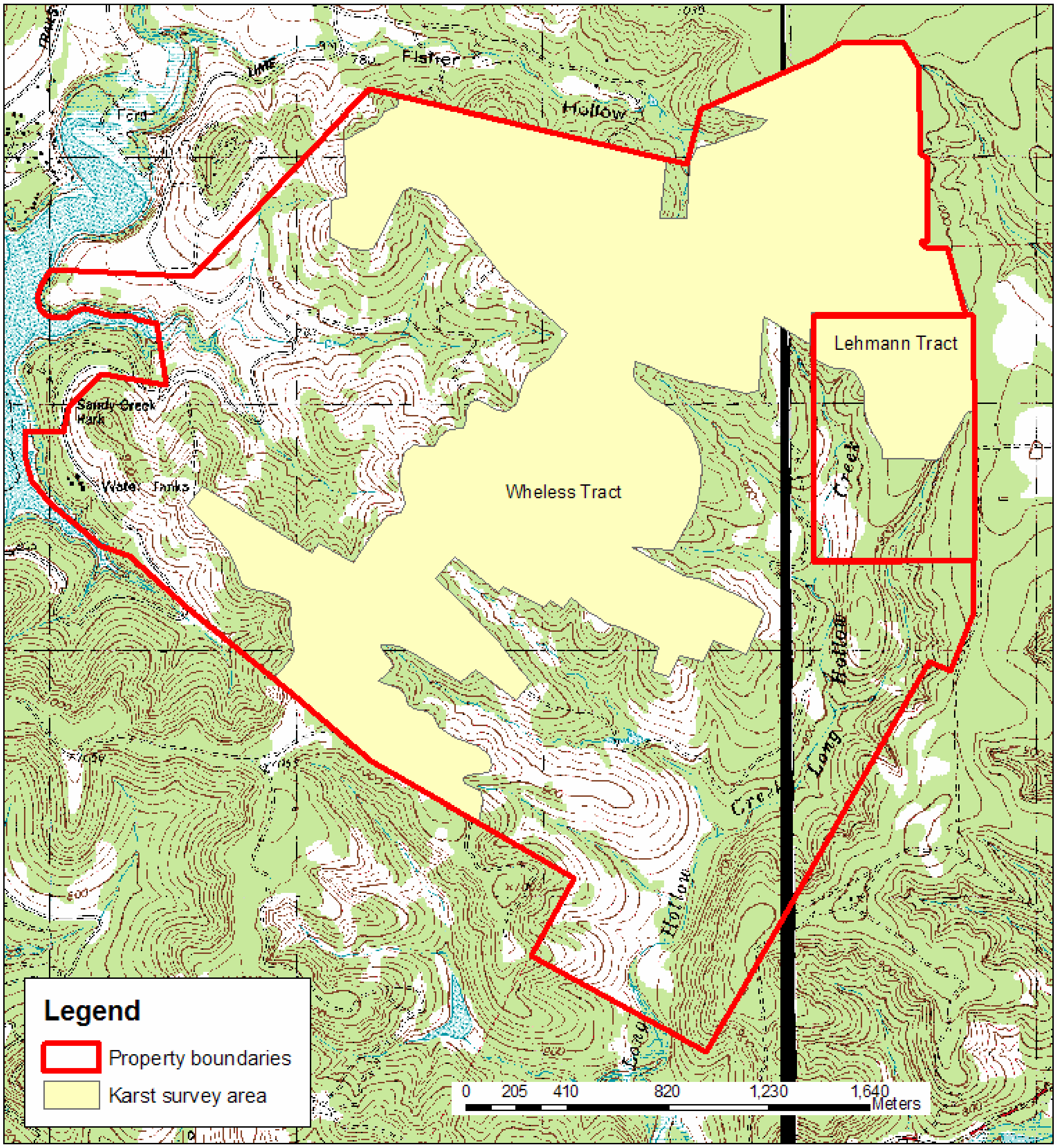

Figure 3.
Injection sites relative to Wheless Spring

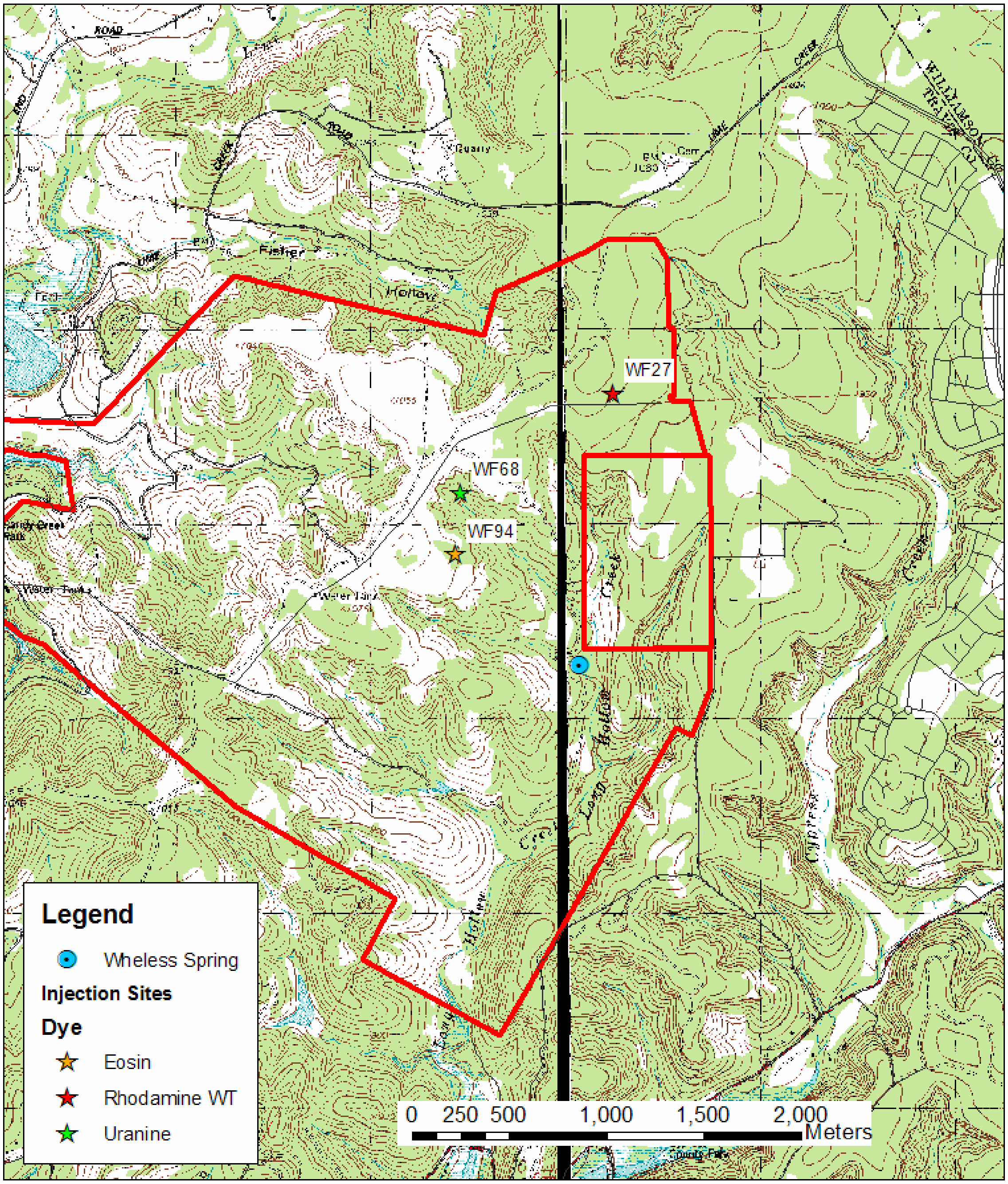

Figure 4.
Portable water tank for prewetting and flushing dye into injection sites

Figure 5.
Prewetting injection site WF94

Figure 6.
Injecting eosin dye at site WF94

Figure 7.
Site WF94 after injection, before flushing

Figure 8.
Monitoring sites

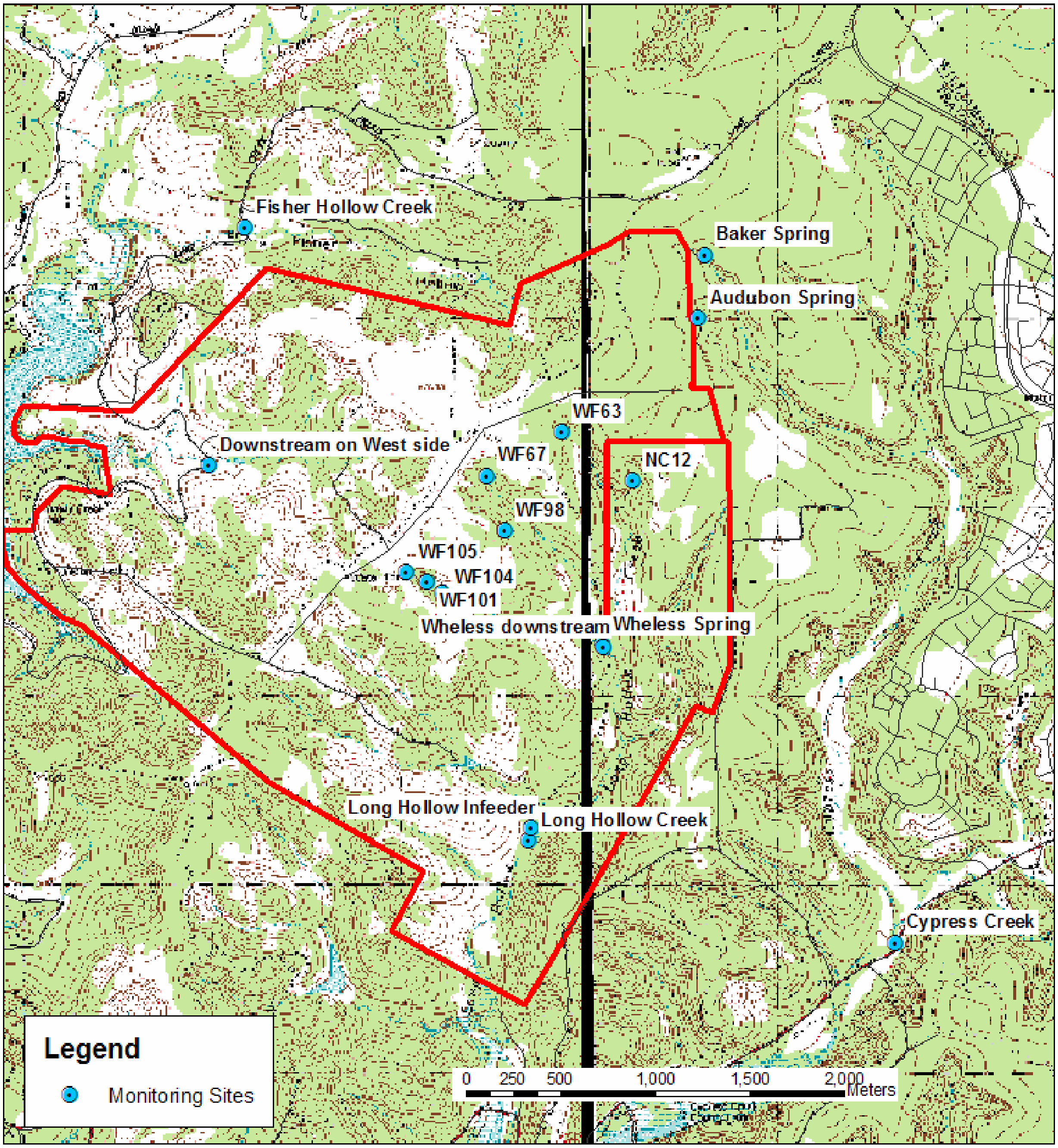

Figure 9.
Detail of monitoring sites near Wheless Spring

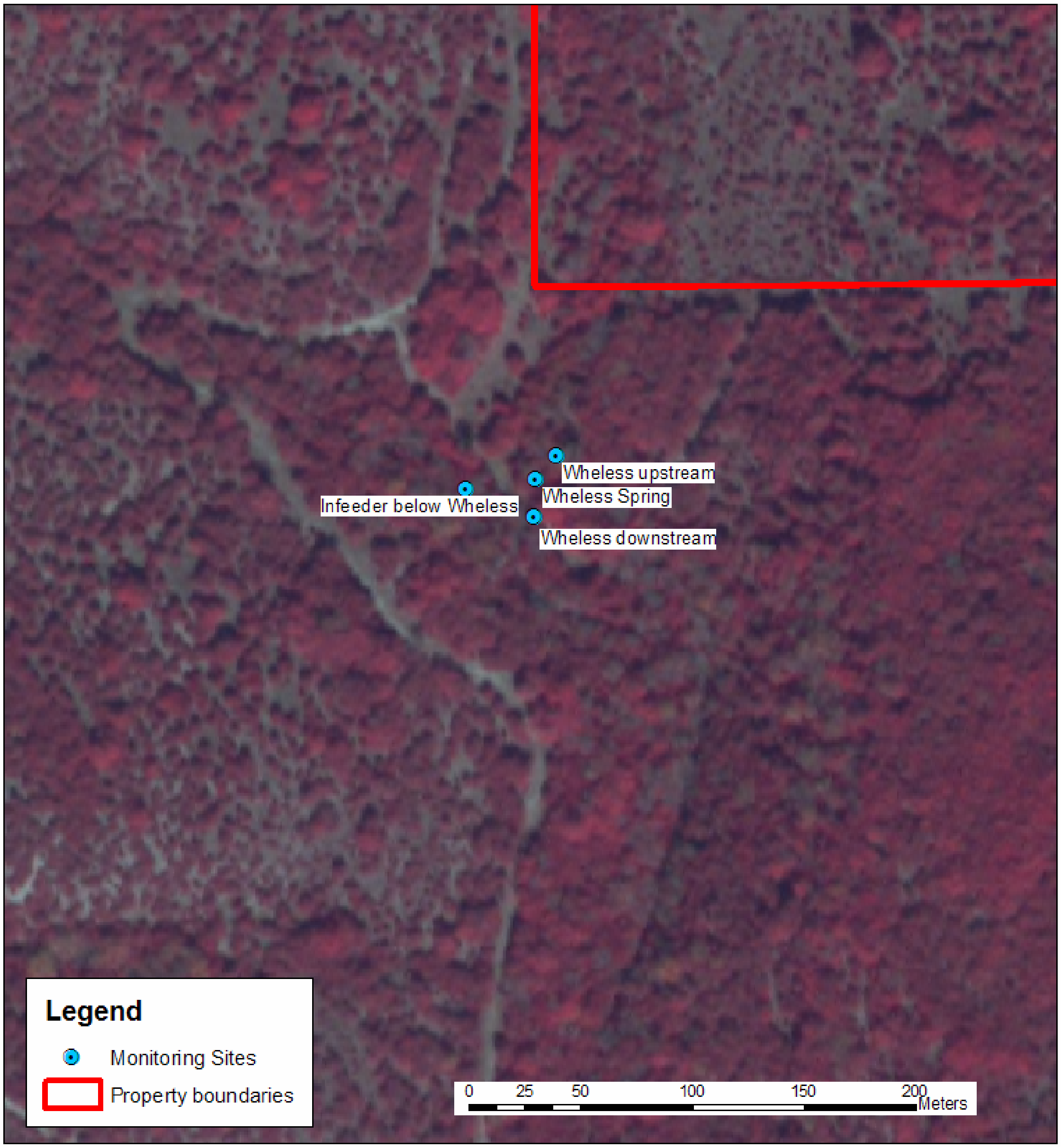

Figure 10.
Tracer results (Black arrows are probable flow paths: dashed line is approximate location of drainage divide)

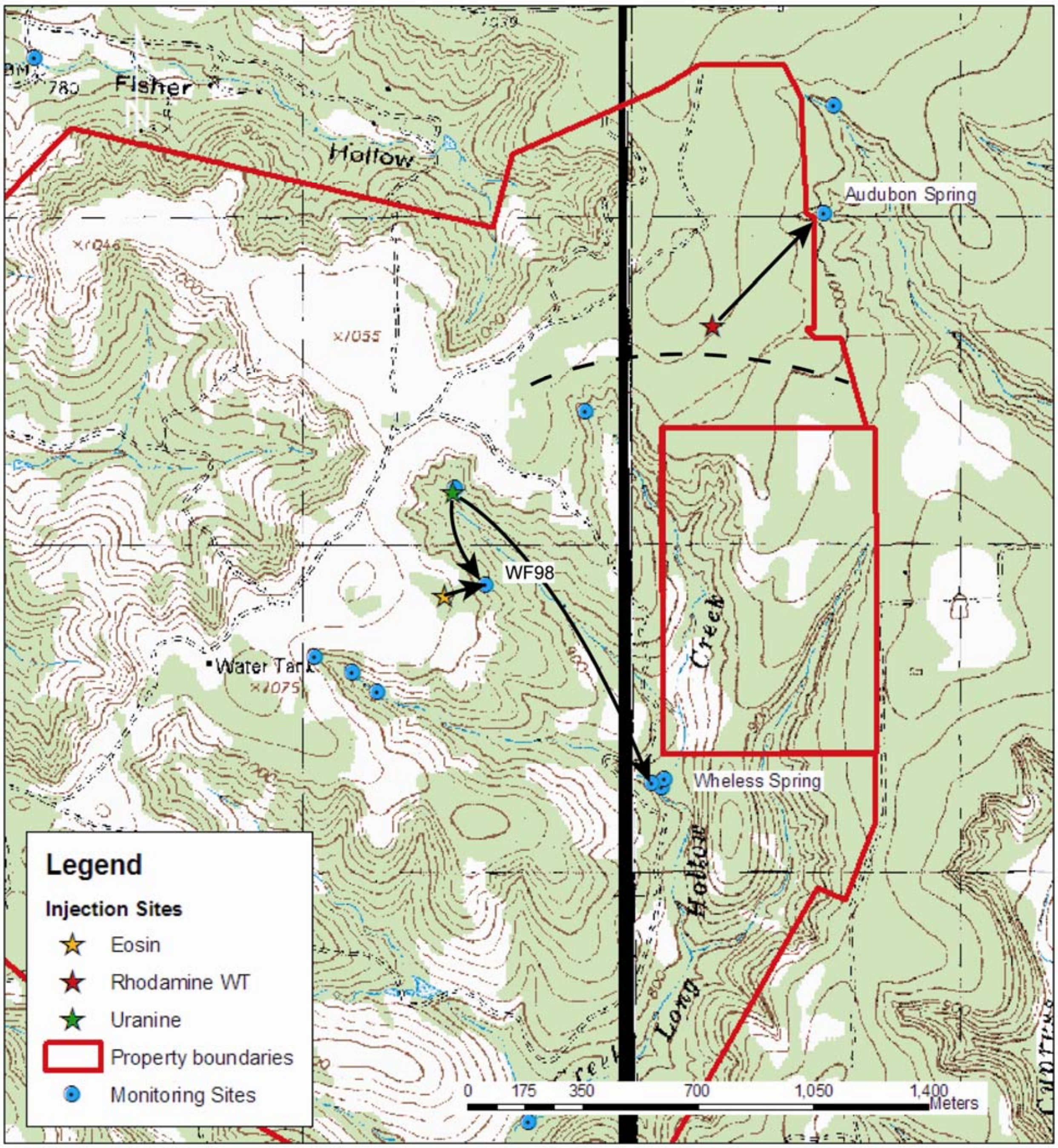

Figure 11.
Dye detected in charcoal at Spring WF98, by removal date

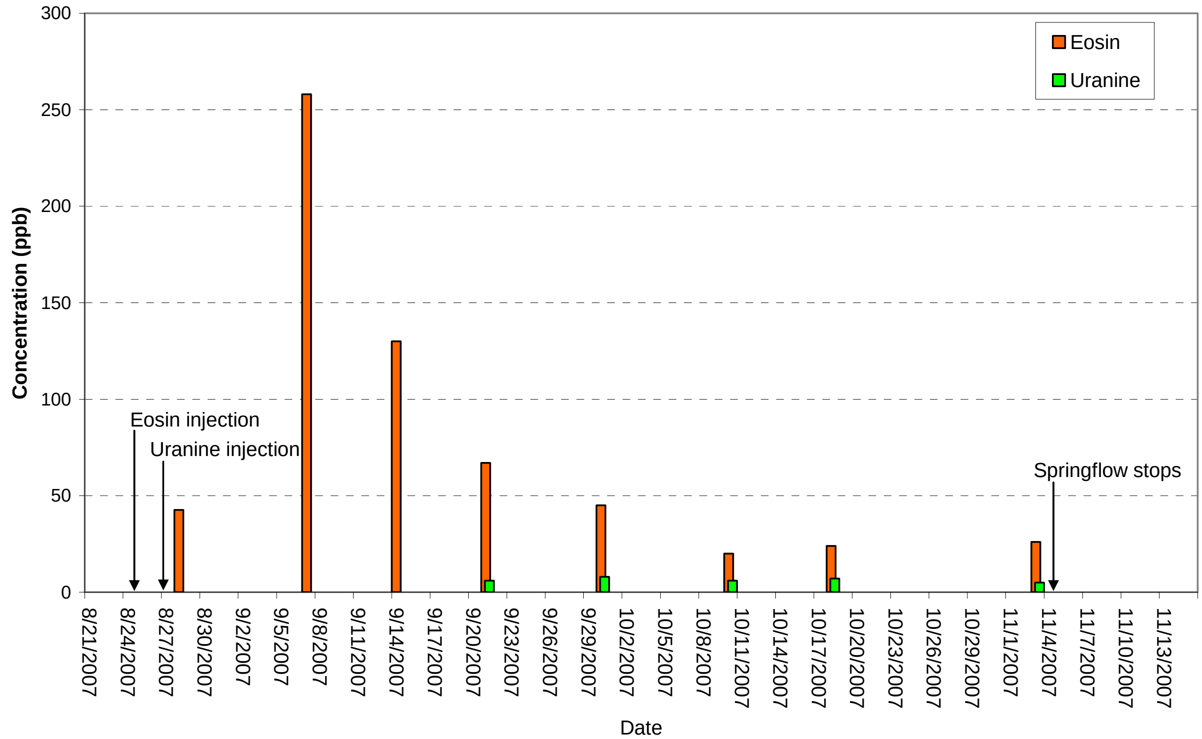

Figure 12.
Rhodamine WT detected in charcoal at Audubon Spring, by removal date

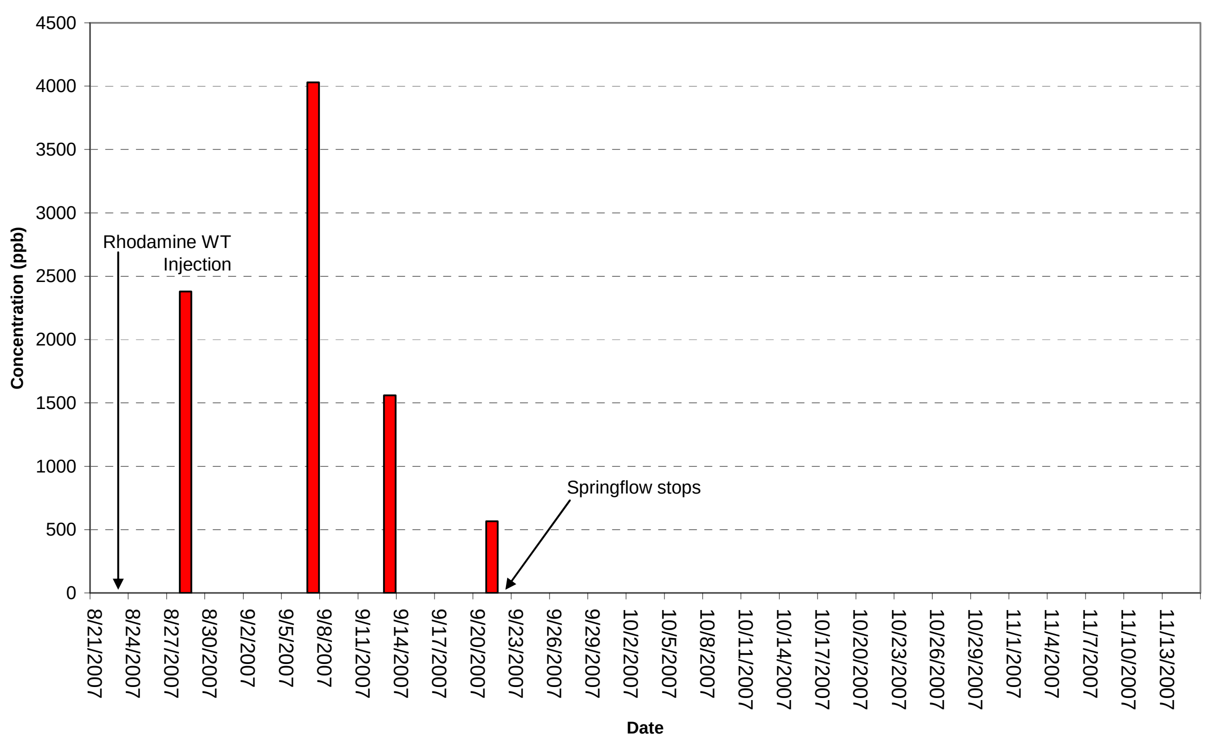

Figure 13.
Uranine dye flowing from Wheless Spring on 13 September 2007
(green tint to water is most obvious in patches of sunlight)

Figure 14.
Uranine dye detected at Wheless Spring and adjacent discharge points

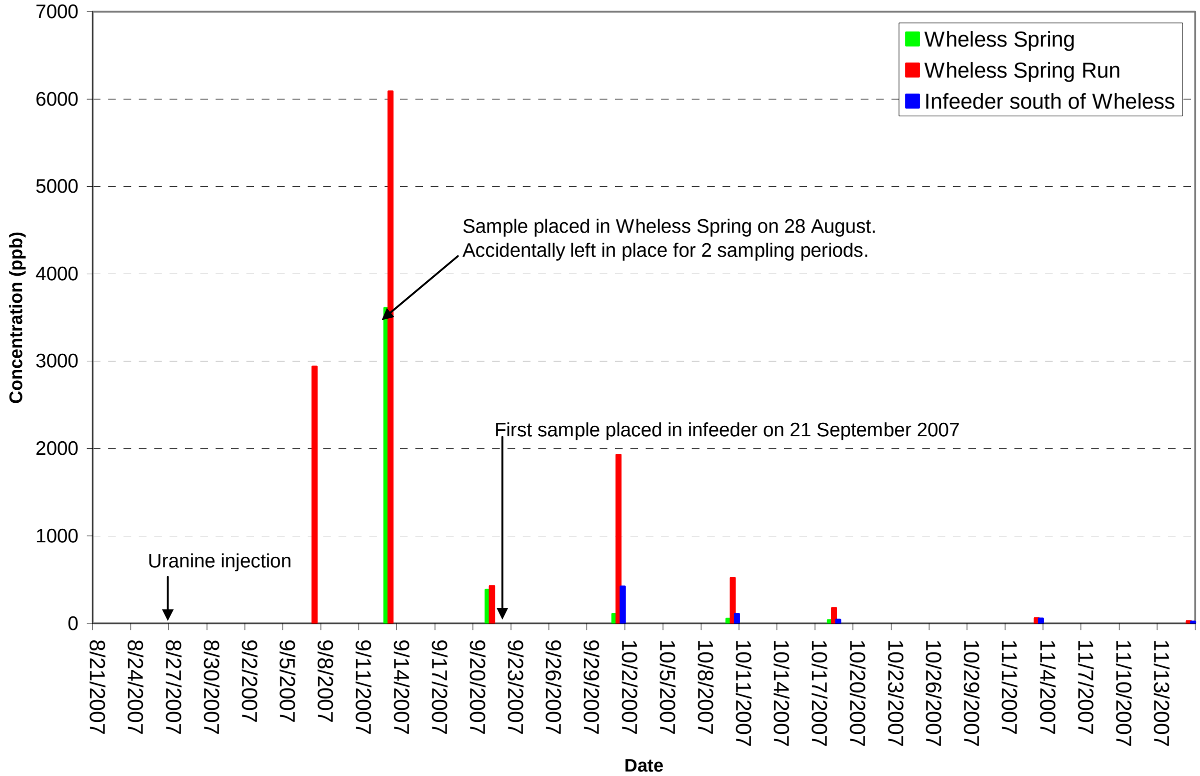

Figure 15.
Recommended future injection sites to refine drainage basin boundaries common to Wheless, Audubon, and Baker Springs

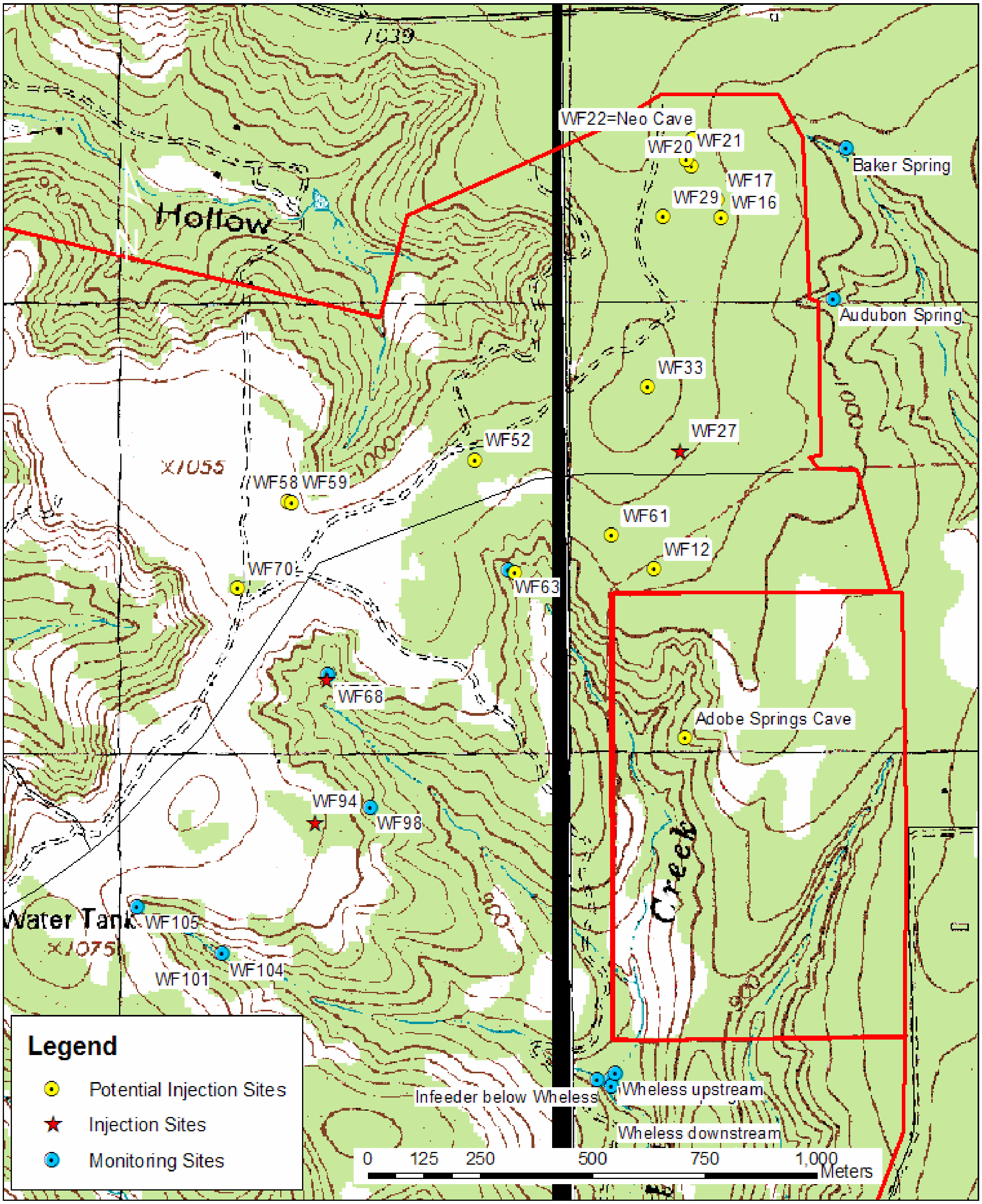

Figure 16.
Areas where additional tracing is needed to better define the Wheless Spring drainage basin