A Case Study of Traditional and Alternative Monitoring Techniques for Solvent Contamination within Fractured Bedrock

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Abstract

Multiple plumes of chlorinated organic compounds (PCE, TCE, and *cis*-1,2-DCE) are present above drinking water standards in groundwater underlying Camp Stanley Storage Activity (CSSA). One such plume has migrated off-post and is now impacting more than 20 drinking water wells within the Middle Trinity Aquifer.

The off-post groundwater plume is defined by a series of traditional monitoring wells that monitor the Lower Glen Rose, Bexar Shale, and Cow Creek members of the Middle Trinity Aquifer. In the vicinity of CSSA, these geologic formations have been breached by stepwise normal displacements associated with the Balcones Fault Zone. As expected, the presence of faulting, fractures, and minor karstic features has resulted in a sometimes erratic and fluctuating distribution of contaminants. The hydrogeologic model is further complicated by a seasonally-dependent groundwater level swing of more than 150 feet, and the presence of a 60-foot thick confining unit within the Middle Trinity Aquifer.

In an effort to characterize the occurrence of solvents associated with this plume, CSSA has adopted a unique monitoring strategy to optimize the amount of both geologic and contaminant data available from standard boreholes. The most recent study incorporated the traditional methods of continuous rock coring, borehole geophysical and video surveys, and discrete interval packer testing along with less traditional characterization tools such as optical televiewers, borehole flow zone determinations, and multi-port wells. These innovative tools were used to maximize data collection at each point location; thereby accelerating the characterization process and saving money.

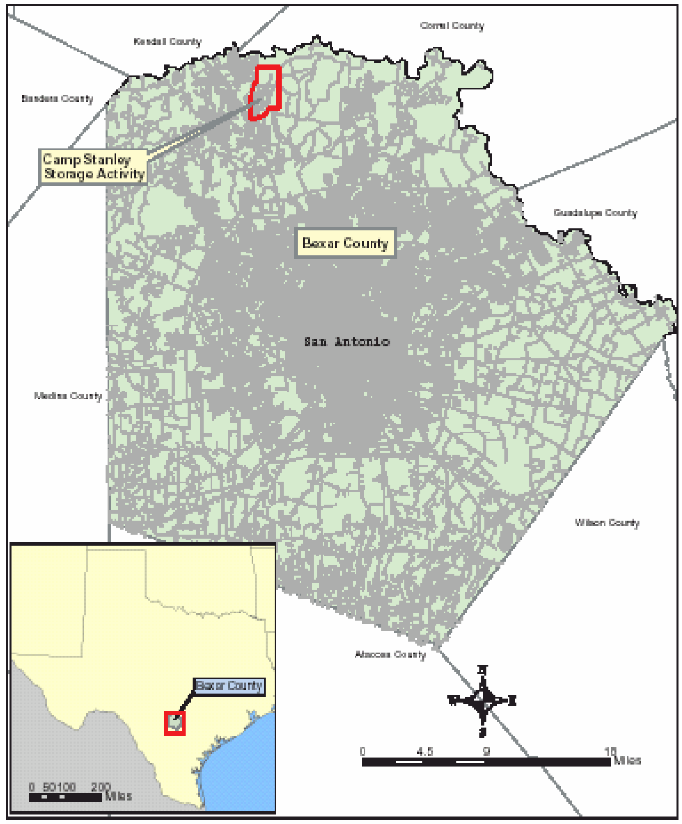
As part of this study, the effects of the open borehole completion typically used by groundwater consumers were investigated at an off-post location of known contamination. The effort included three boreholes continuously cored in the vicinity of the presumed source area, and one borehole adjacent to the off-post well with the greatest concentration of solvent contamination. Standard geophysical methods and borehole video were used for geologic correlation, the identification of porous features, and selection of discrete interval groundwater sampling depths using the straddle packer approach. Optical televiewer and hydrophysical technologies were used to further refine the borehole characterization approach. The results of all these data types were integrated to design and implement a Westbay™ multi-level monitoring system at both on- and off-post locations.

The characterization approach was successful in identifying structural features and intervals of preferential flow which conduct contaminants away from the source area. Both the multi-level monitoring approach and well construction study indicate that significant contamination exists chiefly in shallow bedrock pathways, and that concentrations attenuate by dilution within the main body of the aquifer. These results may indicate that simple changes in the construction of off-post drinking water wells may significantly improve groundwater quality and reduce or eliminate contaminant exposure. Cost savings resulted from maximizing the use of single boreholes as multi-level observation points to monitor the entire thickness of the aquifer in lieu of more costly traditional well clusters. Findings of this study can be used to guide the local public utilities and well installers in preventative well construction techniques that minimize the effects of aquifer contamination.

Background

Location, History, and Mission

CSSA is a 4,004-acre U.S. Army facility located in northwestern Bexar County about 19 miles northwest of San Antonio, Texas (figure at right). The land on which CSSA is located was used for ranching and agriculture until the early 1900s. During 1906 and 1907, six tracts of land were purchased by the U.S. Government and designated the Leon Springs Military Reservation. The lands included campgrounds and cavalry shelters. Historically, its mission was training, evolving to ordnance storage, maintenance, and testing.



In October 1917, the installation was redesignated CSSA. United States involvement in World War I spurred extensive construction to provide housing for temporary cantonments and installation support facilities.

In 1931, CSSA was selected as an ammunition depot, and construction of standard magazines and igloo magazines began in 1938. In addition to ammunition storage, CSSA lands are used to test, fire, and overhaul ammunition components.

Environmental Setting

CSSA is characterized by a rolling terrain of hills and valleys in which nearly flat-lying limestone formations have been eroded and dissected by streams draining to the east and southeast. The general morphology of this portion of Central Texas is the result of the Balcones Escarpment which extends westward from San Antonio and northward towards Austin, Texas. Soil cover is relatively thin, and bedrock is exposed in most areas other than stream valleys. The Cretaceous-age sediments of Central Texas were deposited as onlapping sequences on a submerged marine plain. CSSA is sited over older-aged deposits of the Travis Peak and Glen Rose Formations of the Trinity Group.

The Travis Peak Formation attains a maximum thickness of about 940 feet and is divided into five members as listed in ascending stratigraphic order: the Hosston Sand, the Sligo Limestone, the Hammett Shale, the Cow Creek Limestone, and the Bexar Shale (as a facies of the Hensell Sand). Overlying the Travis Peak Formation, but still a part of the Cretaceous-age Trinity Group, is the Glen Rose Limestone. Combined, these rocks form the Upper, Middle, and Lower Trinity Aquifers of Central Texas.

The Hammett Shale, which overlies the Sligo Limestone, has an average thickness of 60 feet. It is composed of dark blue to gray fossiliferous, calcareous, and dolomitic shale. Above the Hammett Shale is the Cow Creek Limestone, which is a massive fossiliferous, white to gray, shaley to dolomitic limestone that attains a maximum thickness of 90 feet downdip in the area. The youngest member of the Travis Peak Formation is the Hensell Sand, locally known as the Bexar Shale facies. The shale thickness averages 60 to 80 feet, and is composed of silty dolomite, marl, calcareous shale, and shaley limestone, and thins by interfingering into the Glen Rose Formation.

The Glen Rose Formation is split into two limestone members, referred to as the Upper Glen Rose and Lower Glen Rose. The Upper Glen Rose consists of beds of blue shale, limestone, and marly limestone with occasional gypsum beds (Hammond, 1984). Based on well log information, the thickness of the upper member reaches 500 feet in Bexar County. Where present the eroded thickness of this member at CSSA is can be up to 150 feet. The Lower Glen Rose consists of a massive fossiliferous limestone, grading upward into thin beds of limestone, marl, and shale (Ashworth, 1983). The lower member, according to area well logs, is approximately 320 feet thick in the CSSA area.

The predominant structural feature in the area is the Balcones fault zone (BFZ) escarpment. The BFZ is a series of high-angle normal faults that generally trend northeast and southwest. Total displacement in northwest Bexar County is approximately 1,200 feet. The faulting is a result of structural weakness in the underlying Paleozoic rocks and subsidence in the Gulf of Mexico basin to the southeast. The downdrop blocks outcrop as progressively younger strata from northwest to southeast across the fault zone. As part of the BFZ, normal faulting has occurred near the central area and the southeastern boundary of the installation. Faulting in the limestone units has juxtaposed strata of different ages, but fault scarps and traces are almost absent on the ground surface because the similar calcareous lithologies weather similarly.

Hydrogeology

The primary groundwater source at CSSA and surrounding areas is the Middle Trinity Aquifer, the most prolific producer with the best quality of water of the three Trinity Aquifers. The Middle Trinity Aquifer consists of the Lower Glen Rose Limestone, the Bexar Shale (Hensell Sand), and the Cow Creek Limestone. The average combined thickness of the aquifer members is approximately 460 feet. Most general purpose wells within this aquifer are completed as open holes without well screens to maximize groundwater withdrawal from the yielding portions of the aquifer.

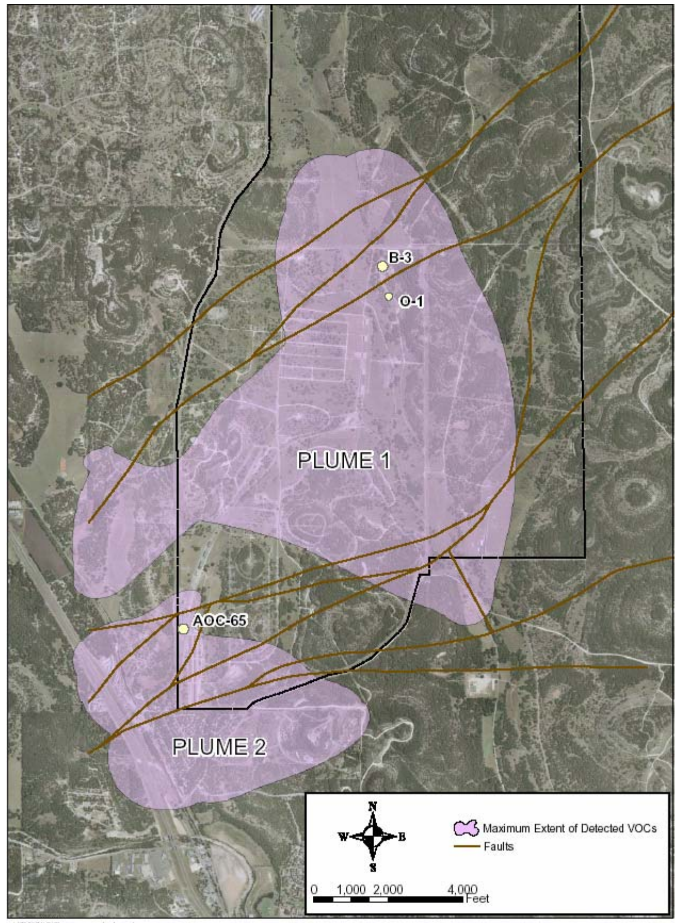
The Lower Glen Rose portion of the Middle Trinity Aquifer derives its recharge from direct precipitation on the outcrop and stream flow infiltration. In the vicinity of CSSA, the Bexar Shale acts as a hydrologic barrier to vertical leakage except where faulted; therefore, most recharge to the Cow Creek Limestone comes from overlying updip formations. It is inferred that the Cow Creek is in natural hydraulic communication with the Lower Glen Rose due to extensive faulting in the area. The bottom of the Cow Creek Limestone forms the base of the Middle Trinity Aquifer.

Contaminant Distribution

Solvent contamination (PCE and daughter products TCE and *cis*-1,2-DCE) was first detected during routine monitoring by the Texas Department of Health in 1991 in a post water supply well. Between 1992 and 1999, CSSA undertook a series of investigations to identify potential source areas for the groundwater contamination, which identified Solid Waste Management Units (SWMUs) B-3 and O-1 and Area of Concern-65 (AOC-65) as likely candidates. SWMUs O-1 and B-3 are centrally located within CSSA. SWMU O-1 was a lined oxidation pond and nearby B-3 was a landfill where spent solvents were utilized as an accelerant for burning refuse. AOC-65 is located near the post boundary in an area where ordnance maintenance and testing operations have historically been conducted. Starting in 1996, the first of 45 monitoring wells were installed, and has continued through September 2003. Off-post contamination was first reported by CSSA in December 1999 at a private well adjacent to the facility. Since that time, solvent contamination has been detected above the laboratories MDL in 26 off-post private and public water supplies. The U.S. Army has installed seven point-of-use treatment systems at those locations where concentrations exceed 80 percent of the federal maximum contaminant level (MCL) of 5 micrograms per liter (μg/L) for PCE and TCE.

Contamination from the past disposal activities has resulted in multiple groundwater units, referred to as Plume 1 (B-3 and O-1) and Plume 2 (AOC-65). The release of solvents to the environment has resulted in contamination of the Middle Trinity Aquifer, which is the primary drinking water source for the area. Contamination is most widespread within the Lower Glen Rose water-bearing unit. Locally, the Bexar Shale serves as a confining unit between the water-bearing Lower Glen Rose and Cow Creek limestones. Faults of the BFZ structurally influence and re-direct the groundwater flowpaths. Environmental studies have demonstrated that most of the contamination resides within the Lower Glen Rose.

The figure to the right shows the location and maximum extent of contaminants reported above the method detection limit between December 2002 and June 2003 within the Middle Trinity Aquifer.



Originating from SWMUs B-3 and O-1, Plume 1 has advectively migrated west-southwest to the CSSA well field (CS-9, CS-10, and CS-11) in addition to off-post private wells. VOC concentrations over 200 µg/L are present in Middle Trinity wells near the source area. Within the source area, concentrations in excess of 24,000 µg/L have been reported in near-surface perched water wells. However, over most of the plume area contaminant concentrations are below 1 µg/L. In contrast, little to no contamination within the Bexar Shale and Cow Creek has been consistently identified within Plume 1 except in association with open borehole completions. Trace concentrations associated with Plume 1 have been detected at off-post locations.

Contamination at Plume 2 originated at AOC-65, and has spread southward and westward from the post. The greatest concentrations of solvents are reported at the near subsurface adjacent to the source area (3,400 µg/L). Within the post, concentrations in excess of 100 µg/L have been reported in perched intervals above the main aquifer body in the LGR. However, once the main aquifer body is penetrated, the concentrations are diluted to trace levels. Off-post, concentrations in excess of MCLs have been detected in private and public wells with open borehole completions. Concentrations exceeding 30 µg/L have been reported 1,200 feet west-southwest of CSSA. Vertical profiling within that well show that discrete intervals within uncased upper strata contribute PCE concentrations over 90 µg/L. Only sporadic, trace concentrations of solvents have been detected in Bexar Shale and Cow Creek wells within Plume 2.

Traditional Monitoring Techniques

Although limited well drilling was initiated in 1996, the characterization of the Middle Trinity Aquifer beneath CSSA was accelerated in the year 2000 after off-post groundwater contamination was detected. At that time 15 wells were scoped to investigate the hydrogeologic nature and contaminant distribution within the Lower Glen Rose, Bexar Shale, and Cow Creek members of the Trinity Group. The drilling program included two sets of three-well clusters completed within each member of the Middle Trinity Aquifer, three well pairs within the Lower Glen Rose and Cow Creek members, and finally three single-well completions into the Lower Glen Rose.

The initial phase of well installations showed that the majority of the contamination is confined to the Lower Glen Rose portion of the aquifer. Hydraulic head data indicates that the Bexar Shale functions as a leaky aquitard between the two water-bearing units, and appears to be an effective barrier to the downward migration of contaminated groundwater. While there is a hydraulic connection between the Lower Glen Rose and Cow Creek members, the Cow Creek thus far appears not to be impacted except where cross-contamination has occurred within existing open borehole completions at public and private water supplies. Based on the initial assessment, a second phase of drilling 13 wells initiated in July 2002, and included one triple-well cluster within each member of the Middle Trinity Aquifer, one Bexar Shale well, three Cow Creek wells, and six single well completions into the Lower Glen Rose.

The goals of the investigations were to define the limits of contamination, assess the nature of the Middle Trinity Aquifer and potential karst features, and determine if the Bexar Shale served as an adequate aquitard to prevent the downward migration into the Cow Creek Limestone.

All wells were drilled using air rotary techniques to advance the wellbore into the limestone bedrock. To maximize the amount of data gathered from each borehole, varying data types were collected prior to well construction. These traditional methods of characterization are commonly used in environmental assessments and included lithologic and geophysical logging, drill-stem packer testing, discrete interval groundwater (DIGW) sampling, telescoping well construction, and low-flow sampling techniques.

The regulator-approved well construction design included 4-inch wells with no more that 25 feet of well screen to minimize inter-aquifer mixing of groundwater. In addition, welded steel surface casing was installed prior to proceeding to the next hydrologic unit.

Lower Glen Rose wells are single-cased completions; Bexar Shale wells are double-cased completions; and Cow Creek wells are triple-cased completions. For scale, a triple-cased well included a 16.5-inch diameter borehole to depths beyond 300 feet to accommodate 12-inch nominal diameter casing. Second string casings were 8-inches in diameter within a 12-inch borehole to 400 feet in depth. Finally, the 4-inch long-string casing is completed within an 8-inch nominal diameter borehole. This well design is time-consuming to install and costly due to required materials and labor hours. Typical well installations ranged from 10 days for a Lower Glen Rose well to 25 days for a triple-cased Cow Creek well. For each well drilled, an average of 30,000 gallons of groundwater required containment and treatment at the on-post granular activated carbon (GAC) unit.

Each well or cluster location was continuously cored for lithologic description, chemical sampling, and archival. Through both phases of drilling, over 9,200 feet of cored rock has been collected and archived. The coring has been an invaluable tool for a “hands-on” approach of characterizing the aquifer. The rock core has been made available for research to both the USGS and the University of Texas-San Antonio.

Geophysical Logging and Video Surveys

Borehole geophysical techniques employed for this project included short and long resistivity (8-inch, 16-inch, 32-inch, and 64-inch), spontaneous potential (SP), natural gamma ray, caliper logging, and a downhole camera surveys. Geophysical logging was performed in boreholes to identify soil/rock types before surface casing was installed, to determine appropriate intervals for packer tests, and to aid in the final design of the well. These logging methods yield information on borehole size changes, shale content, and formation conductivity. Results of the logging were then used to determine the depth and thickness of stratigraphic units. Geophysical data eliminates inconsistencies between the visual logging styles of differing site geologists, fills in data gaps lost due to poor drilling conditions, and produces a simple digital format for analyzing and comparing data between boreholes. The data has been integral in the development of the conceptual site model and an excellent tool for inferring structural features (e.g., faults) that would have been otherwise difficult to interpret.

Packer Testing and Sampling

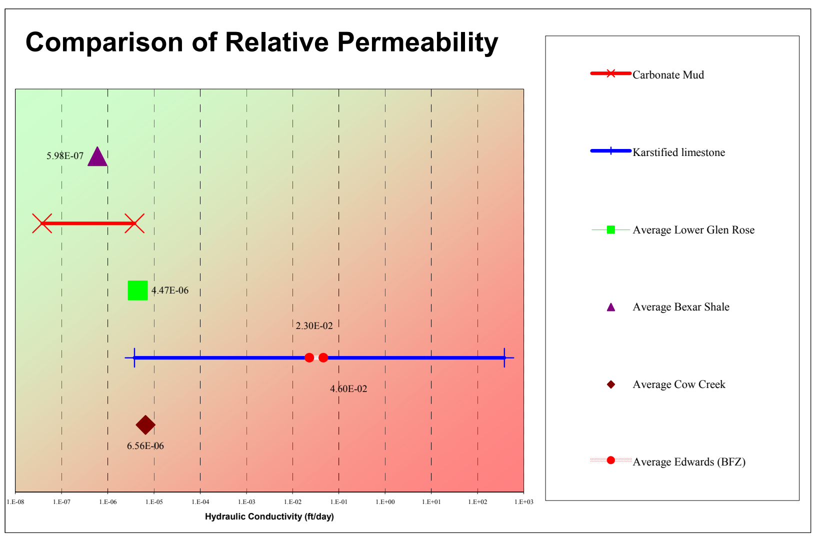
During its’ investigations, CSSA used variants of drill-stem packer testing to obtain qualitative data regarding hydraulic and contaminant characteristics in portions of the aquifer that were targeted for well installations. In an effort to yield as much data from a single borehole as practical, this methodology allowed data regarding the non-screened portions of the well to be attained prior to well construction. Two styles of packer testing that were implemented included injection packer tests for permeability testing, and DIGW sampling to obtain contaminant information throughout the thickness of the aquifer. Sampling intervals were based upon lithologic observations made during coring and interpretation of geophysical logs.

A drill-stem packer test is a permeability test conducted in a single borehole by sealing off one section of the borehole at a time with pneumatic rubber packers and pumping water into the isolated section. Packer tests can be performed at various depth intervals in an open hole. Thus, it may identify vertical distribution of the high and low hydraulic conductivity (K) layers. The permeability of the rock adjacent to the isolated section of the borehole is measured as a function of the pumping head (pressure) and the rate of water loss from the sealed section. The lower the pumping head, the higher the formation permeability. The higher the water loss, at the same pressure, the higher the formation permeability.

Three to six packer tests were performed on each of the new coreholes before they were completed as monitoring wells. The packers consisted of a 24-inch rubber sleeve which expanded against the wall of the nominal 4-inch borehole when pressure was applied. The testing of isolated sections of a borehole required the use of two pneumatic isolation packers separated by a length of perforated pipe. The spacing of packers (which govern the length of the test section) was generally between 5.5 and 12 feet apart. The double-packer assembly and inflating line were then lowered into the borehole on a string of pipe so the perforated section was opposite the interval to be tested.

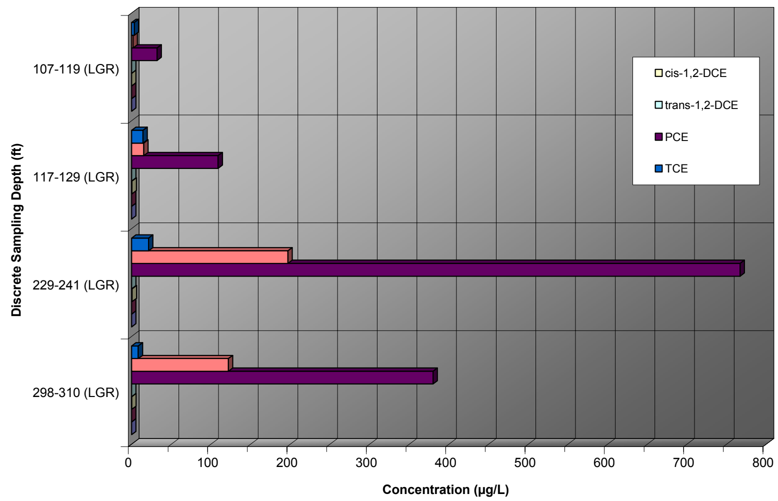
Clean, non-chlorinated water was used as the injection fluid source. Both pressure and injection rates were measured and recorded over time throughout the test, with measurements being made as frequently as possible during the early moments of the test. As the time of injection continued, changes in pressure and injection rate occurred more slowly; therefore, the frequency of measurement was decreased. The maximum measurement interval was normally 5 minutes. The pumping times and pressures were dependent on the depth, requirements of the test, and nature of the materials being tested. Each test was run until an equilibrium condition was established. This was considered to have been reached when four or five readings of pressure and flow taken at approximately 5-minute intervals were essentially constant. Some test intervals were unable to inject water into the formation at the maximum pressure attainable with the pump used. Those test intervals were deemed to be impermeable, and were denoted as zones of “no flow.”

An estimated value for K can be ascertained for a geologic media by measuring the pressure at which a discharge (Q) can be injected into a permeable formation. A total of 19 tests were conducted within the Lower Glen Rose, while 7 tests and 12 tests were completed in the Bexar Shale and Cow Creek Formations, respectively. Of the 38 tests attempted, 11 resulted in a “no flow” condition. With respect to the testing methodology, an impermeable condition was encountered in each of the hydrologic units, with the highest percentage of “no flow” conditions occurring in the Bexar Shale. When the entire test population is normalized to relative permeability, the data shows that the Lower Glen Rose and Cow Creek formations are 7.5 and 11 times more permeable than the Bexar Shale, respectively. According to the Handbook of Hydrology (Maidment, 1993) and with respect to the geologic terrain, the average Lower Glen Rose and Cow Creek Formations are typified by lower-permeable karstified limestone, while the Bexar Shale falls more closely toward a carbonate mud permeability (see chart above). For comparison, an average range for the Edwards Limestone hydraulic conductivity (Maclay, 1995) is included in the above diagram to illustrate the stages of karstic development between the Middle Trinity and Edwards Aquifers in Texas.



DIGW sampling zones were selected for screening samples because of their potential hydraulic characteristics based on interpretation of the geologic and geophysical logs. The general strategy was to gather groundwater data from permeable zones throughout the local portion of the Middle Trinity Aquifer. Yield of these zones is dependent upon many factors such as porosity, permeability, and transmissivity. Other major factors affecting sample collection are seasonal affects on groundwater levels. Some zones that could be easily sampled during wet seasons may be dry during the late summer and fall months. Analytical and general flow data provide information relevant to plume delineation and potential migration pathways for groundwater contamination.

DIGW samples were collected in 4.25-inch diameter coreholes utilizing a dual packer apparatus with an open interval of 12 feet. Packers were inflated by compressed nitrogen gas. A 1.5 horsepower pump was placed between the packers on the end of a 1-inch diameter pipe string. Sampling zones were selected based on observations recorded during the lithologic description, aided by review of the geophysical logs. When the formation freely yielded groundwater as determined by the site geologist, a pump was used to purge and collect discrete groundwater samples.



Each interval was normally purged of at least three volumes of water, or until the water was clear. In some instances, purging was carried out over an extended period of time for critically located intervals exhibiting poor yield. In these cases a sample was collected after alternating periods of pumping and recovery. Some zones exhibiting good flow had to be purged of larger volumes to reduce turbidity prior to sampling. Most of the intervals selected for DIGW samples in the Lower Glen Rose correspond stratigraphically from borehole to borehole. This allowed for direct observation of changes in contaminant concentrations in specific zones and layers at various distances from the source area. An example of the DIGW sampling result is presented in figure above and the table below.

CS-WB03 Discrete Interval Groundwater Sampling Results

Depth	PCE	TCE	*cis*-1,2-DCE	*trans*-1,2-DCE
(feet bgs)	**Concentration (µg/L)**			
107-119	32.1	3.36	<0.2	<0.7
117-129	109	14.4	0.47	<0.7
229-241	767	21.3	0.69	<0.7
298-310	380	8.37	0.25	<0.7
MCL	**5**	**5**	**70**	**100**

"<" = Less than Method Detection Limit

Alternative Monitoring Techniques

The first phases of drilling were successful in monitoring the major water-bearing units of the Middle Trinity Aquifer (i.e., the Lower Glen Rose and the Cow Creek). With the exception of several wells, the investigations indicated that contaminants were diluting and attenuating within the major portion of the aquifer to levels below the MCLs. However, the implementation of the DIGW sampling around the Plume 2 area indicated that significant residual contamination was harbored in the lower yielding portions of the upper strata of the Glen Rose Limestone. While CSSA had demonstrated that a well capable of yielding moderate quantities of uncontaminated groundwater could be completed within the plume limits, concern grew regarding the impact of the upper strata contamination within the open borehole supply wells of off-post consumers. Of the 40 off-post wells sampled, six wells showed contamination above the MCL for PCE and/or TCE.

Some near-surface work near the Plume 2 source area had indicated that concentrations of 3,400 µg/L were present to depths of 20 feet. In the same area, the DIGW sampling indicated elevated concentrations to 300 feet below grade within the low-yielding portions of the strata. Beyond that depth, contamination quickly attenuates within the high-porosity basal reef which constitutes the major portion of the Lower Glen Rose's ability to transmit groundwater. The next step of the investigation was to better-define the hydrologic regime and occurrence of contaminants within the upper strata of the Lower Glen Rose.

CSSA originally proposed installing a series of well clusters that would address the upper 300 feet of the aquifer in the Plume 2 vicinity. However, preliminary budgetary estimations indicated that the approach would be cost-prohibitive using the current approach of traditional well installations. A multi-level well technology was then considered.

The major goals of the next phase of work were to characterize the contamination in the upper 300 feet of Lower Glen Rose strata near the Plume 2 source area and evaluate the presence of contaminants within an existing off-post well. To be economically feasible, the monitoring criteria incorporated the use of multi-level monitoring in lieu of the traditional monitoring wells used previously at CSSA. Prior to well installation, the borehole were maximized for data availability utilizing the geophysical video surveying and DIGW sampling methods, plus newer techniques which included optical televiewer services and fluid conductivity measurements to estimate borehole flow.

The final work plan was to drill three source area multi-level wells to depths of 300 feet, just above the main water-bearing unit. The existing wells showed that the main water-bearing unit is not impacted by contaminants. This well design also eliminates the risk of potential cross-contamination into the major portion of the aquifer. A fourth well was drilled at an off-post location to twin an existing domestic well. This multi-port well was designed to penetrate the full thickness of the Middle Trinity Aquifer to gain insight into the nature of the unit. Cross-contamination was not considered a threat since the existing domestic open-hole well has allowed for the co-mingling of groundwater for decades.

Borehole Investigation

To start the project, the more traditional methods of coring, logging, and sampling were used to collect the baseline data consistent with the other phases of the environmental investigation. Each borehole was continuously cored using a HQ wireline coring system to a nominal diameter of 4.25 inches. In addition to the lithologic information gained from the coring process, the resultant aperture of the corehole was a satisfactory diameter for the installation of the multi-level system. Typically, coring advancement within the limestone matrix advanced at a rate of 100 feet per day.

Upon completion of a borehole, geophysical logging and video surveys were completed to digitally record the downhole condition. Gamma and resistivity logs were used for stratigraphic correlation and structural feature identifications. The caliper log in conjunction with the borehole video was instrumental in selecting potential packer locations for seating and sealing the eventual multi-level well system.

DIGW samples were also collected by the packer methods previously discussed to quickly assess the borehole location in terms of relative contamination. Typically, four to seven discrete sample collection intervals were attempted in a given corehole. Upon completion of the borehole testing, a borehole liner was installed to prevent the incidental migration of contaminated groundwater within the open hole. With the borehole secured, the drilling rig proceeded to the next location until all four coreholes, logging, and DIGW sampling were completed by the same method. Use of borehole liners resulted in mobilization cost-savings to the project. Subcontracted geological services, such as geophysical and video surveys, were conducted at all of the coreholes during one mobilization, and the liners prevented cross contamination between surveys. After all of the coreholes were drilled and tested, the borehole liners were used to allow sufficient time for data evaluation prior to well completion.

Borehole Liners

A lapse of several weeks occurred between significant operations at the four multi-level wellbores after coring. To prevent contaminant communication between separate hydrologic zones in the coreholes, Flexible Liner Underground Technologies (FLUTe™) liners were installed. The "socks" were installed prior to scheduled borehole inactivity, and then later removed the day before activities resumed at a well. The basic premise of the liner is to un-roll an impermeable fabric into a wellbore that seats and seals against the borehole, thus preventing groundwater from entering the borehole. Hydrostatic pressure of water introduced into the sock is used seal the liner firmly against the borehole. When needed, the liner is extracted from the ground to return the borehole to its natural condition.

Four liners were purchased by CSSA and manufactured by FLUTe according to specifications provided. The products consisted of one 540-foot and three 335-foot urethane-coated nylon fabric in tubular form. Ancillary installation and removal equipment was leased from FLUTe.

Liners were delivered on large reels in an inverted (inside-out) state. Liner tops were clamped onto a metal head, which in turn was clamped to the rim of short, temporary surface casings. The liners were filled with clean water causing them to descend into a hole. The liners everted (unrolled) into the holes under the weight of the added water. The material became pressed against the well walls, closing-off transmissive and permeable zones by the weight of the water inside. Once installed, the flexible liners sealed the boreholes against potential vertical flow of subsurface contaminants. The head of clean water within the liner was maintained above the head of groundwater to maintain positive pressure of the liner against the borehole wall.

Each sock came with a tether attached to its toe, and extended from the end of an installed liner up to the ground surface. The cord was pulled upward and the liner was peeled off the well walls from the bottom up. Clean water was periodically pumped out of the inside of the liner as it was pulled upward. The liner exited the wellhead inverted (inside-out) and was flattened out as it was re-wound onto its reel.

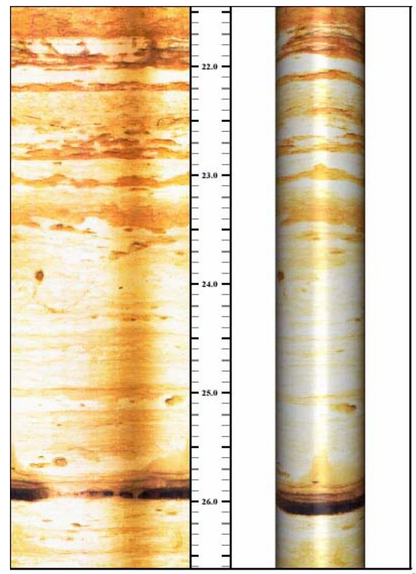
At each well location, the liners were installed following the drilling and were removed prior to optical televiewer and hydrophysical testing. The liners were then re-installed prior to the installation of the multi-level wells. With the liners in place and secure, ample time was available to study the collected data, design the multi-port wells, and mobilize the installation crew. Finally, the liners were removed for the last time and the wells were completed.

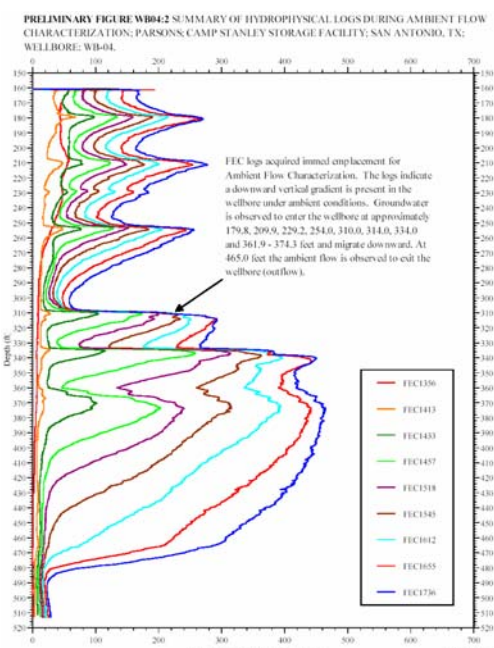
The borehole liners were successful by the virtue that they provide reasonable security in mitigating borehole cross flow while subcontractors were being mobilized to the site. The added benefit is that they allowed for a detailed evaluation of the collected data thereby allowing CSSA with the time necessary to make informed design decisions. However, deployment and recovery of the liners was time-consuming, especially in low permeability formations.

Optical Televiewer and Hydrophysical Logging

CSSA contracted with COLOG to provide optical televiewer and fluid conductivity services. COLOG operated proprietary processes including the Borehole Imaging Processing System (BIPS™) and Hydrophysical Logging (HpL™). These technologies were evaluated under this project as potential methods to replace coring and certain elements of packer testing. Utilizing both the traditional and newer techniques allowed for a side-by-side comparison of capability and economic feasibility.

The BIPS process provides an oriented, digital view of the borehole wall in a 360 degree fashion. The image on the right shows a sample of optical televiewer corehole data in its "unwrapped" state (left column) and a "wrapped" virtual core (right column). The optical televiewer is an outstanding method for visually identifying and orienting features as well as correlating stratigraphy between boreholes. This data was a primary tool in making the monitor zone selections for the multi-level wells. The optical televiewer is based on direct optical observation of the borehole wall face. Precise measurements of dip and direction of bedding and joint planes, along with other geological features, were possible in both air and clear fluid-filled boreholes during post-processing operations. As the instrument was lowered, the raw analog video signal from the camera was transmitted uphole via coaxial wireline to televiewer surface instrumentation, where the analog signal was digitized and recorded. Features were picked by COLOG throughout each well by visual inspection of the digital images and analyzed by computer. Orientations were based on magnetic north and were corrected for declination.

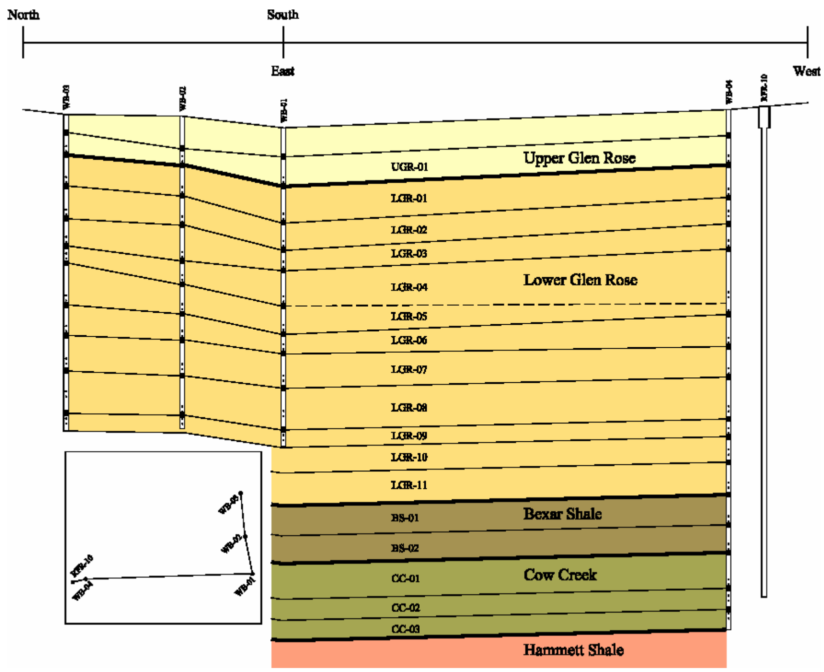




The HpL process was implemented as a technique to assess which parts of the borehole yield groundwater. By this method, the conductivity and yield of an interval thickness can be estimated by measuring the changes in fluid electrical conductivity after the emplacement of deionized (DI) water. HpL was conducted in two runs which included an ambient groundwater profile, and pumping (stressed method) while injecting the DI water. These ambient water quality logs were performed to provide baseline values for the undisturbed subsurface groundwater conditions prior to testing. During this process, fluid electrical conductivity changes of the fluid column were recorded. These changes occurred when electrically contrasted formation water was drawn back into the corehole by pumping, or by naturally occurring subsurface pressures (for ambient flow characterization). A downhole wireline HpL tool, which simultaneously measures fluid electrical conductivity (FEC) and temperature, was employed to log the physical and chemical changes of the emplaced fluid. Computer programs processed the data generated for identification and evaluation of the hydraulically conductive intervals and quantification of the interval-specific flow rates. In the graphic to the left, each line represents an HpL run since the initial time of DI water emplacement. Those sections of the graphic with nearly-horizontal lines represent those intervals within the borehole that yield a measurable quantity of groundwater. The yielding intervals identified by the HpL process were confirmed by the DIGW sampling conducted previously in the boreholes. The results of the HpL survey were very useful in determining hydrologic zones of interest and monitoring ports depths for the multi-level well designs. Upon completion of the HpL surveys, the FLUTe liners were again deployed to mitigate any down-hole contamination.

Multi-port Well Installation

CSSA selected the Westbay™ MP38 system as the most appropriate for the site conditions with regard to depth, fluctuating water tables, and because it's modular design was not limited to a set number of monitoring ports. Prior to the mobilization of the Westbay team, all collected data from the drilling and testing phase was evaluated and integrated into a conceptual site model (CSM). As shown in the figure to the right, the resultant CSM consisted of 17 unique monitoring zones with the Middle Trinity Aquifer. The CSM included the basal unit of the Upper Glen Rose, 11 divisions of the Lower Glen Rose, 2 divisions of the Bexar Shale, and 3 divisions of the Cow Creek.

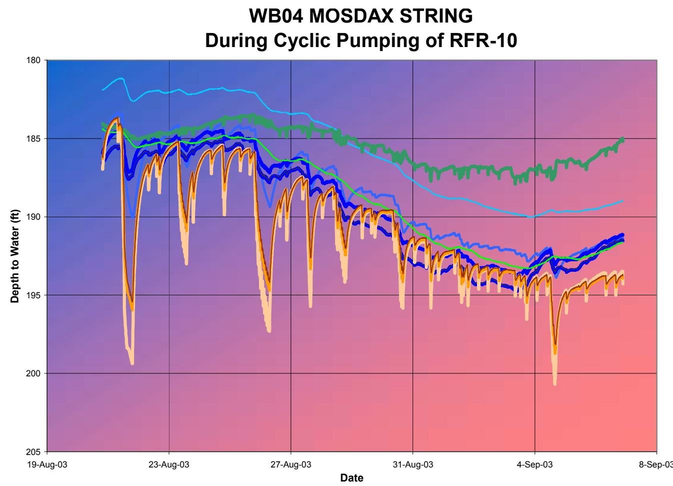


The Westbay MP38 system is composed of modular, interlocking components which include monitoring points, pumping ports, blank casing, and stiffened, water-filled packers to isolate the selected zones. Based upon the data gained from the borehole data, the 5-foot long packers were seated in zones of competent bedrock at depths with straight, smooth walls as confirmed by the caliper, video, and optical televiewer logs. Likewise, the monitoring and pumping ports were installed between the packer zones at depths of notable stratigraphic of structural features identified in the logs, with preference to those water-producing zoned identified during the HpL survey.

Prior to the installation of a well, the FLUTe liner was removed and approximately 3,000 gallons was purged from the wellbore as final development. The MP38 system was assembled at the wellhead and lowered into the well by the drilling contractor using a Smeal™ winch truck, drilling rig, or similar unit. A rigorous quality assurance protocol was used by the contractor to assure that each component was operating properly prior to their installation. All phases of the installation were thoroughly documented by the contractor, including the inflation of the hydraulic packers.

Hydraulic pressure data and groundwater sampling was conducted using the Westbay MOSDAX sampling probe. This instrument is a retrievable, wireline device that is lowered into and out of the well via a tripod and winch mechanism. Magnetic collars installed into the well components are used to locate the sampling port, and the MOSDAX probe has surface-operated robotic deployment to quickly and securely access the sampling port. Both absolute hydraulic pressure and temperature were obtained at each sampling port, in addition to retrieving as much as 1 liter of groundwater sample.

Multiple MOSDAX probes can be coupled together to simultaneously profile and log hydraulic head as shown to the right.



Open Borehole Construction Study

Previous sampling indicated that concentrations of 30 µg/L PCE are present within an off-post private drinking water well. With the landowners' permission, a study commenced to understand the nature and occurrence of contaminants in the well. The hypothesis was that minimal surface casing was allowing contaminated groundwater perched within the upper portions of the Lower Glen Rose to cross-contaminate the lower portions of the Middle Trinity Aquifer. The approach included twinning the existing supply well with a multi-level monitoring device, and studying and profiling the ranch well construction.

Wellbore Investigation

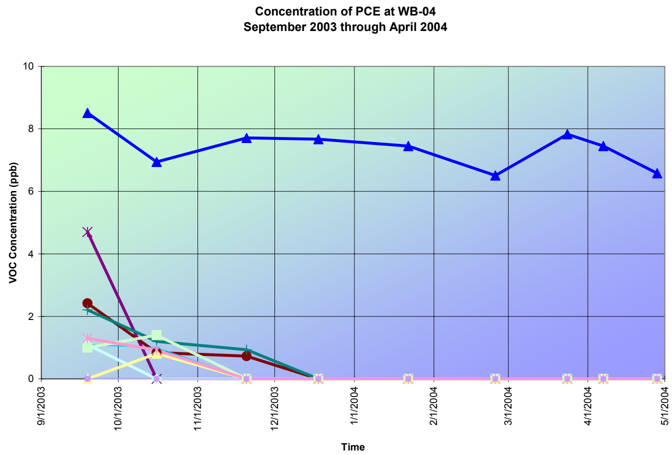
The construction study included removing the existing pump hardware and performing borehole geophysics, video logging, and DIGW sampling. Standard geophysics found the well to be completed throughout most of the Middle Trinity Aquifer to a depth of 483 feet. Specifically, the well construction consisted of a 20-foot length of steel surface casing with an open borehole completion drilled into the limestone bedrock to total depth. A large cavern was noted at the Lower Glen Rose/Bexar Shale contact, and is expected to be a combined result of faulting and washout related to previous well deepening activities. Correlation of the geophysical logs indicates that a fault with 17 feet of displacement exists between the ranch supply well and the multi-port well, which are located approximately 150 feet from each other.

Interval Groundwater Testing

The results of five DIGW packer tests conducted at the ranch supply well are shown in the table to the right. A large packer spacing (64 feet) was selected so that the well could be returned to service promptly.

Ranch Supply Well	*Concentration (µg/L)*			
Depth (ft)	PCE	TCE	*cis*-1-2-DCE	*trans*-1-2DCE
RFR-10 (WL-198')	91.7	16.2	0.56	<0.70
RFR-10 (201-265')	54.4	19.9	0.79	<0.70
RFR-10 (302-366')	5.07	<0.10	<0.20	<0.70
RFR-10 (360-424')	4.86	<0.10	<0.20	<0.70
RFR-10 (413-477')	9.02	1.29	0.37	<0.70

As with the on-post locations near the plume source area, elevated concentrations of VOCs were found in the uppermost and lower-yielding portions of the aquifer. PCE concentrations between 54.4 and 91.7 µg/L are present in the top two-thirds of the Lower Glen Rose. Dilution within the major water-bearing interval is occurring between 302 and 366 feet below grade. The last two samples originate from the Bexar Shale and Cow Creek, respectively. These samples indicate that the open borehole construction has allowed for the contaminants to co-mingle with groundwater deeper in the aquifer. Similar testing at new wells drilled on-post has shown the Bexar Shale and Cow Creek to be virtually contaminant-free when not in the presence of an existing open borehole completion.



Results for the off-post multi-port well have shown a similar trend as the ranch supply well. The graphic to the left indicates that single monitoring zone (LGR-09 at 310 feet) is the primary conduit of PCE contamination within the Middle Trinity Aquifer at the WB-04 location. The contamination in the other zones during the first three months has dissipated presumably since the natural groundwater flow through the borehole has been re-established. These results indicate that some cross-hole contamination occurred during the short time it took to install the well (one day), but has been restored to its natural condition over time. It also appears that inter-aquifer mixing of contaminants at the ranch supply well is limited to the immediate vicinity of the open borehole.

Conclusions

CSSA has installed over 40 traditional wells into the Middle Trinity Aquifer since 1996. In an ongoing effort to continually improve and refine the groundwater program, CSSA has evaluated alternative methods to aid in the detection and monitoring of groundwater plumes. The implementation of alternative techniques included optical televiewers, hydrophysical techniques, and multi-level monitoring devices. These methods were performed in conjunction with the traditional methods to compare results and cost effectiveness.

The optical televiewer provided inexpensive continuous borehole data in terms of stratigraphy, structure, and orientations. For future major projects, CSSA is considering replacing the traditional coring method with the televiewer data due to cost and time efficiencies. The hydrophysical data was an ideal method for quantifying intervals of borehole flow. The FLUTe borehole liners appeared to be effective in preventing downhole flow, and were the key to the effective and economical use of multiple contractor services. Multi-port wells allow for a large amount of groundwater data to be collected from a small footprint well. The cost of installing a 10-zone monitoring well was approximate to the cost of installing only two traditional-style wells. The benefit of the multi-port well was that five times the sampling intervals could be achieved for the same costs.

Finally, the data collected from on- and off-post wells activities indicate that most contamination of the Middle Trinity Aquifer in the CSSA vicinity is limited to the Glen Rose portion of the unit. Based on data from packer testing and multi-level well designs, contaminant concentrations present in off-post wells can be a result of well construction techniques with respect to length of surface casing. CSSA is currently working with the public and local drilling firms to encourage protective well designs for future off-post consumer wells. CSSA will continue with its proactive approach to off-post groundwater investigations. Point-of-use treatment systems will continue to be installed and maintained by CSSA at those locations that exceed 80 percent of the MCL in groundwater as a result of past facility operations.

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Biographical Sketches

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Brian Murphy, CSP is the Environmental Program Manager at Camp Stanley Storage Activity responsible for managing and administering the environmental activities on the installation, including an Administrative Order on Consent with US EPA, Region 6. Mr. Murphy has been the installation's program manager for over nine years responsible for areas under RCRA, CAA, SDWA, EPCRA, CWA, FIFRA, and TSCA. He has over 17 years in the environmental and safety fields. He received his B.S. in Fire Administration and Management from George Mason University.

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